Design and Life Cycle Cost of a Vertical Ground Source Heat Exchange System for the Smith College Field House

by

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Abstract

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Committed to becoming a carbon neutral campus by 2030, Smith College is transitioning towards geothermal energy for campus heating and cooling. Energy Consultants have been hired to conduct an economic and phasing analysis to prepare a district energy master plan. In conjunction with this planning effort, this thesis designed and evaluated the life cycle cost of a vertical ground source heat pump system for the Field House as a pilot demonstration project.

A building energy model of the Field House was constructed in Trace 700. A sensitivity analysis identified eight sensitive unknown design parameters, including wall construction, ventilation and infiltration rate, window, wall and floor u-factor and wall height. The model was validated with existing oil usage data. The calibrated model estimates a total annual energy consumption within 4% difference from the oil data.

With this model of building heating load, a ground-source heat pump (GSHP) was designed. The design included the calculation of five key parameters, namely the total and individual borehole flow rate, borehole thermal resistance, total borehole length, number of boreholes and the power of the water and heat pumps. Two methods of borehole length calculation were compared, and a final design was proposed that detailed three boreholes at 600 ft, with a flow rate of 2.4 gpm per well coupled with three heat pumps of 0.6 tons.

A life cycle cost analysis was conducted over a period of thirty years for four design options, including (1) the existing oil-based system, (2) a GSHP system, (3) a GSHP system with medium level building retrofit and (4) a GSHP system with deep level building retrofit. While remaining on oil requires the least cost over the next 30 years, that solution does not meet our carbon neutrality goals and offsets are not being considered as a viable path. As a result, the GSHP only option ranked the least among the three remaining options in terms of the total converted present worth at year 30, $285,000, closely followed by GSHP + Deep, which also reduced the annual heating demand by 28.9%. Economically, it is not worthwhile to retrofit a load bearing masonry building unless a deep retrofit is conducted.

Future work is recommended to improve system efficiency and reduce total life cycle cost. Specifically, work is identified in areas of thermal modeling to provide more accurate temperature profile of the system. A PV system is also recommended to provide electricity for the geothermal system heat pumps. This framework provides a useful way to compare potential carbon tax policy frameworks.

For Connie,
And all the happiness that quietly crept in with her.

Acknowledgments

First and foremost, I would like to thank Professor Denise McKahn, my thesis and research advisor, whose unconditional support and belief in me have been instrumental in the completion of this thesis as well as my undergraduate education. Her dedication and passion for teaching and research have been a constant inspiration for me throughout my years at Smith, without which I would not have become who I am today.

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This thesis cannot be completed without the generous financial support from Mike Howard and the partial funding for the drilling of test boreholes from Constellation, an Exelon Company.

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Acronyms

A . . . Annual worth
ACH . . . Air Changes per Hour
$ASHRAE$ . . . The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BHE . . . Borehole Heat Exchanger
C . . . Capital cost
CAD . . . Computer-aided Design
COP . . . Coefficient of Performance
DN . . . Diametre Nominal
E . . . Sum of all anticipated equipment repair and replacement cost
F . . . Future worth
$GCHP$ . . . Ground-Coupled Heat Pump
$GSHP$ . . . Ground Source Heat Pump
$HDPE$ . . . High-density Polyethylene
$HVAC$ . . . Heating, Ventilation and Air Conditioning
HW . . . Heavyweight
LCC . . . Life Cycle Cost
M . . . Sum of annul maintenance cost
$MT\ eCO_2$ . . . Metric Tons of Carbon Dioxide Equivalent
OA . . . Outdoor Air
P . . . Present Worth
PV . . . Photovoltaic
S . . . The salvage value of the system at the end of the life cycle
$SCAMP$ . . . Sustainability and Climate Action Management Plan
SDR . . . Standard Dimension Ratio
TOE . . . Tons of Oil Equivalent
VAV . . . Variable Air Volume

Symbols

To differentiate theoretical and modeled values, x, from measured data or variables calculated using measurements, $\bar{x}$, an overbar is used. Derivatives are denoted as $d()/d()$.

A list of variable and parameter symbols, definitions and units is provided below, any deviations from these units will be explicitly stated in the text:

$A\ldots$ contact area (m^2)
$c_p\ldots$ specific heat at constant pressure (J/kgK)
$d, D\ldots$ diameter (m)
$f\ldots$ Moody friction factor (unitless)
$h\ldots$ convective heat transfer coefficient (W/m^2K)
$i\ldots$ interest, discount rate ()
$k\ldots$ thermal conductivity (W/mK)
$L\ldots$ length (m)
$\dot{m}\ldots$ mass flow rate (kg/s)
$n\ldots$ period of time (years)
$P\ldots$ sensitivity analysis output (unitless)
$P\ldots$ pressure (Pa)
$q, Q\ldots$ energy in the form of heat (J)
$\dot{q}, \dot{Q}\ldots$ heat flow rate (J/s)
$r\ldots$ radius (m)
$R\ldots$ thermal resistance (Km/W)
$Re\ldots$ Reynolds Number (unitless)
$S\ldots$ sensitivity coefficient (unitless)
$T\ldots$ temperature (°C)
$\dot{v}\ldots$ velocity of the fluid (m/s)
$\dot{V}\ldots$ volumetric flow rate (m^3/s)
$\dot{W}\ldots$ energy rate in the form of electricity (J/s)
$x\ldots$ x, or horizontal direction (unitless)
$X\ldots$ sensitivity analysis input (unitless)
$\alpha\ldots$ thermal diffusivity (m^2/day)
$\rho\ldots$ density (kg/m^3)
$\mu\ldots$ viscosity (Ns/m^2)

A list of the subscript and superscript symbols and definitions is provided below:

avg ...	average
b ...	borehole
$cond$ ...	related to conductive heat transfer
$conv$ ...	related to convective heat transfer
f ...	circulating fluid
$fitting$ ...	pipe fitting
$friction$ ...	friction
g ...	ground
gr ...	grout
h ...	hourly
i ...	index
in ...	input
m ...	monthly
out ...	output
p ...	pipe
pi ...	pipe inner rim
po ...	pipe outer rim
s ...	contact surface
$total$ ...	total
u ...	center-to-center distance between pipes
$w, water$ ...	water
y ...	yearly, annual
$1m$ ...	one month
$10y$ ...	ten years
$6h$ ...	six hours
∞ ...	at infinity

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Appendix

Chapter 1

Background and Introduction

This thesis presents a design and life cycle cost analysis of a vertical ground source heat pump system for the Smith College Field House. In this chapter, global and institutional context of the utilization of geothermal energy are discussed and an introduction to the technology of harnessing geothermal energy is included.

1.1 Global and Institutional Contexts for Geothermal Energy

The issues surrounding climate change continue to be a major global concern. In 2015, the United Nations has called the world to "ensure access to affordable, reliable, sustainable and modern energy for all" after adopting the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs)[17]. In countries around the world, sustainable energy conversion technologies have been fast developing, policies have been established to provide incentives for the use of renewable energy and goals have been set by institutions as well as corporations to reduce carbon emissions. While progress has been made, climate change continue to be an imminent threat. As identified by a report from the Intergovernmental Panel on Climate Change (IPCC) in 2018, a reduction of average earth temperature of 2 °C before 2030 was adjusted to a new goal of 1.5 °C, which can only be achieved given "unprecedented and urgent action"[24].

In this context, research institutions and organizations have been invested in developing carbon neutral conversion technologies and improving system efficiency for thermal and electricity generation. Efforts have also been made to make renewable energy systems more financially accessible. Figure 1.1 shows the main sources of renewable energy, including solar, wind, marine, hydro, bioenergy and geothermal energy. In terms of energy potential, if fully developed and converted, these sources possess an equivalent of 3078 times the current global energy needs, as shown by Figure 1.2.

Throughout the world, the use and application of geothermal energy has been increasing over the past years. According to reports from the World Geothermal Congress 2010 in Bali, Indonesia ([31]), by the end of 2009, a total of 48,493 MWt was generated for worldwide direct utilization of geothermal energy, an increase of almost 72% from 2005 and growing at an annual compound rate of 11.4% [14]. Geothermal energy has served as a capable replacement of fossil fuels, leading to

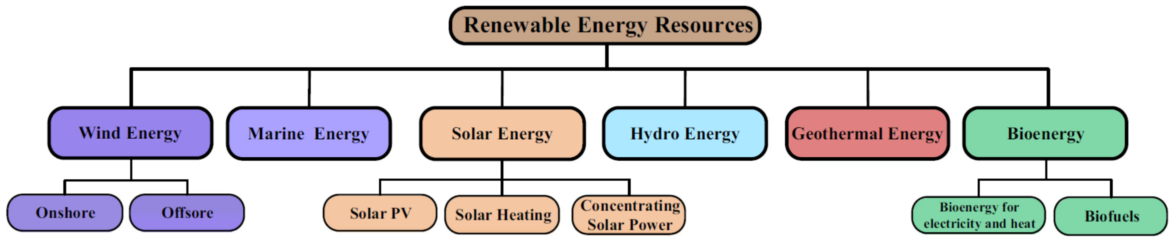


Figure 1.1: Types of Renewable Energy Sources[5].

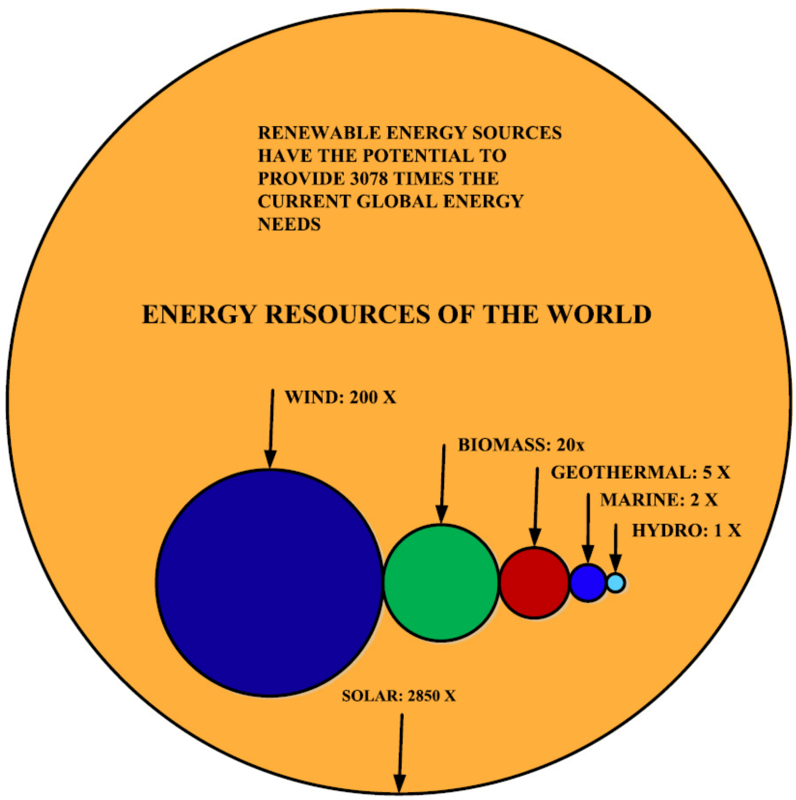


Figure 1.2: The Potential of Renewable Energy Sources. Geothermal energy resources, if all converted to useful work, could meet the needs of current global energy needs by five times. The circles here indicate relative magnitude of available resources [5].

a reduction of 55 TOE (tons of oil equivalent) of fuel oil for both electricity generation and direct use, and a total of 50 TOE of carbon emission [14]. Geothermal energy installations have been increasingly adopted in the United States as well, which ranks number one in the total electricity produced and number two in direct use of geothermal energy in 2009 and 2010, respectively [7].

Some limitations and advantages exist for the utilization of geothermal energy. One of the major limitations for geothermal power generation is location. System efficiency is highly dependent on several variables, one of which is the thermal condition of the ground at the chosen location. High subsurface temperature is needed for electricity and power generation, which limits the location of geothermal based power plants to places with naturally higher temperatures. Figure 1.3 shows the geothermal resources in the United States that are ranked based on temperature profile from 3 to 10 km below the soil surface, a depth that is needed for power generation. The level of favorability decreases as location shifts from west to east, making States like Oregon and California ideal locations. Despite the requirement on deep ground temperature profiles for power generation, the direct use of geothermal energy to meet heating and cooling needs is more accessible to all, as it only requires heat from the "shallow" surface of the ground, commonly from 200 to 500 ft [12]. In addition, geothermal energy also has advantages in terms of having the largest capacity factor (the number of hours a power plant can produce per 24-hour period), not dependent on weather conditions, and having an inherent storage capacity and a relatively low operating cost [7].

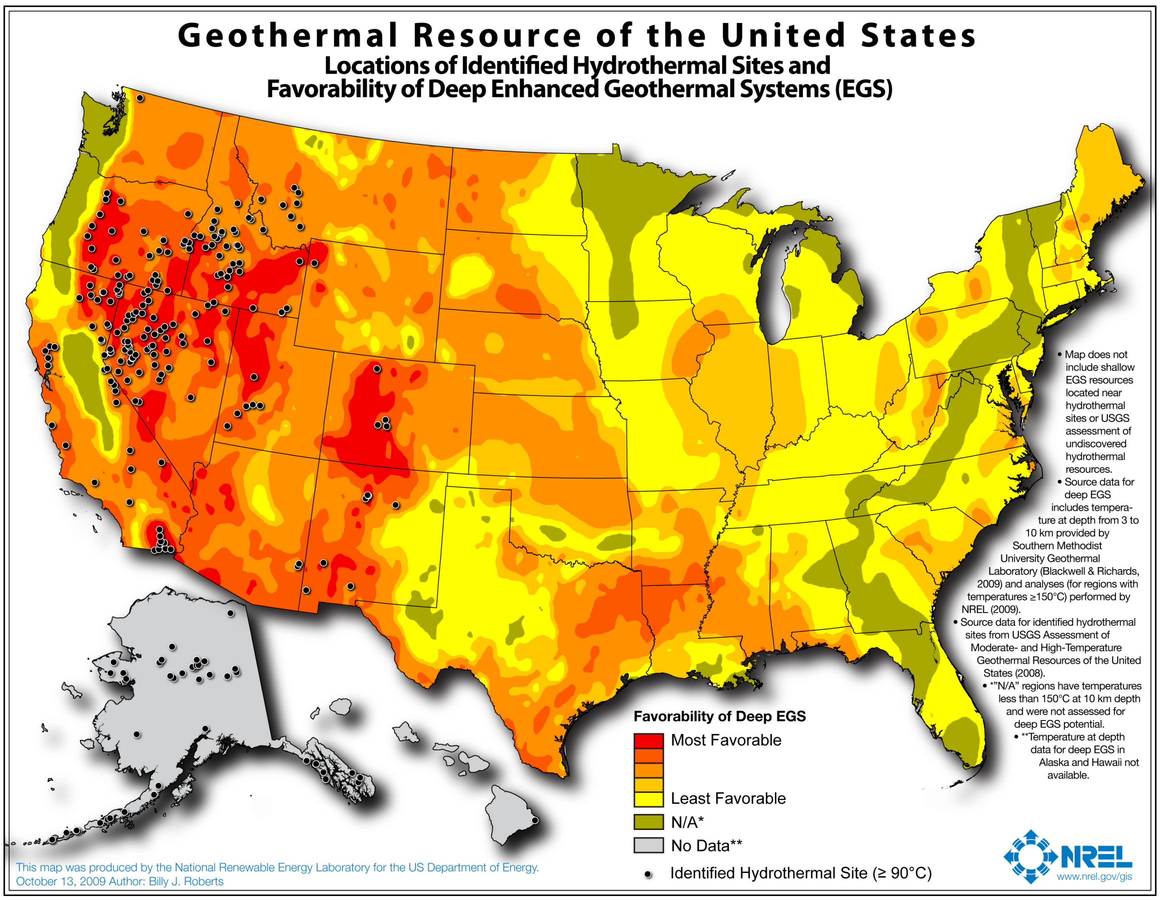


Figure 1.3: Geothermal Resources of the United States [29]

1.1.1 Sustainability Planning Efforts at Smith College

Smith College has been actively involved in sustainable planning efforts for the past few years. After signing the Carbon Commitment (Formerly known as the American College and University

Presidents' Climate Commitment) in 2007, Smith College published a Sustainability and Climate Action Management Plan (SCAMP) in 2010 to achieve carbon neutrality by 2030 [4]. The SCAMP, a detailed plan analyzing our current sources of carbon emissions, shows that the burning of fossil fuels for campus heating and cooling accounts for 23800 MT eCO_2 (metric tons of carbon dioxide equivalent), or 85% of all college carbon emissions. Carbon reduction strategies were then implemented which enabled the construction of a large laboratory and research building, Ford Hall, to come online with no added carbon footprint. In 2016, the Smith College Study Group on Climate Change evaluated carbon mitigation strategies and the feasible options for transitioning to a non-carbon based energy infrastructure in consultation with Integral Group [8, 23]. They identified the utilization of ground source heat exchange as one instrumental step toward carbon neutrality and evaluated the degree to which the existing distribution system remains centralized [8].

At the start of the Fall 2018 semester, the College selected energy consultants, MEP and Associates, to develop a District Energy Master Plan that evaluates phasing opportunities and life cycle costs as the College transition toward a geothermal heating and cooling system. A pilot project that involves drilling of a test borehole near the athletic fields has been developed to evaluate the soil and hydraulic characteristics as well as provide an understanding of the ground conditions essential for the design of the geothermal system. A grant was received by Constellation, an Exelon Corporation, to fund geologic and thermal modeling research on the pilot system.

1.2 Geothermal Energy Conversion Strategies

Geothermal energy is energy available in rocks and ground water beneath the soil surface. The temperature of the earth remains stable, on average $15°C$ for the first 100 m, in comparison to the ground surface temperature, which greatly varies throughout the year. This thermal stability makes the ground a perfect heat reservoir, capable of heat extraction and rejection. Starting at around 10 meters, or 32 feet, the temperature of the earth follows a relatively linear increase with respect to depth. This linear relationship, characterized by the geothermal gradient, is about $30°C$ every 1 km, in general. Heat can be extracted from or rejected to the ground via a heat exchange system, where a circulating fluid, called the geothermal working fluid, circulates through the ground and returns back to the surface. Heat is transferred between the geothermal fluid and the ground such that the fluid increases in temperature when heating is needed and decreases in temperature when cooling is needed. The contact length (often expressed as depth) for which the geothermal fluid needs to be in contact with the ground directly affects the heat extraction/rejection rate, which is controlled by the demand of heating/cooling or electricity generation.

Common ways of utilizing geothermal energy are: 1. direct use for heating and cooling and 2. electricity and power generation. Combined electricity and heat generation, a method that uses waste heat from power generation for district heating, is another common option. Figure 1.4 shows ways of utilizing geothermal energy based on ground temperature. Generally speaking, direct usage of geothermal energy is not confined to low or medium temperature, but rather fits the category as long as geothermal energy is used directly owing to its temperature [3]. However, direct use, primarily in the form of geothermal heat pumps (68.3% of all installed geothermal capacity globally), is less demanding of the ground temperature (between 10°C to 25°C) and depth, and is widely used for residential building space heating and cooling [14]. Geothermal based power plants, on the other hand, rely on heat engines, which can employ a Rankin Cycle to convert high temperature (at least 100°C) ground heat into electricity. In the following sections, system setup for the direct-use and power generation will be discussed in detail.

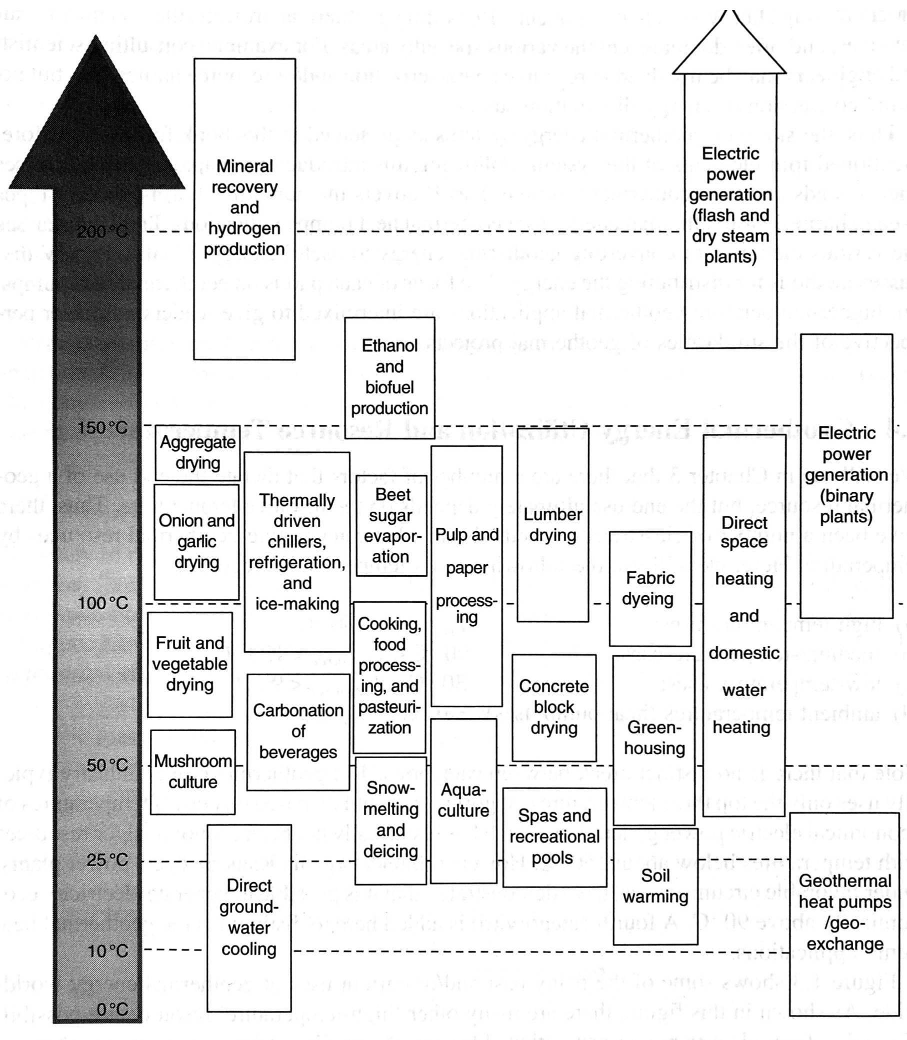


Figure 1.4: Utilization of Geothermal Energy based on Ground Temperature [3]

1.2.1 Geothermal Power Plants

Currently, geothermal based power generation relies on the use of hydrothermal resources, which have three components required for electricity generation: fluid, heat and permeability [19]. There are three main types of geothermal power plants: binary, flash steam and dry steam. A binary power plant is the most common type, feasible for temperatures up to 175°C. In a binary power plant, the geothermal fluid remains in liquid phase. After circulating through the supply wells, as shown in Figure 1.5, the liquid-phase fluid exchanges heat with a lower-boiling-point working fluid which then gets expanded in the turbine and condensed back to liquid phase, in a closed loop. A path for the working fluid would be 4 → 4' → 1 → 2 → 3 → 4. On the other hand, a flash steam power plant, shown in figure 1.6, uses two-phase fluid separated from single-phase geothermal fluid in the separator. The steam fraction then goes through a typical expansion in the turbine and a condensation in the condenser. This system operates in an open loop, where the condensed water returns back to the geothermal reservoir through an injection well. The water fraction from the separator, also called waste water, condenses and can be utilized for potential direct heat uses. A dry steam power plant, only exists in a few locations worldwide, is similar to a flash steam power plant but uses geothermal fluid that is in superheated vapor phase when extracted from the wells. This configuration has the highest requirement for both well depth and ground temperature.

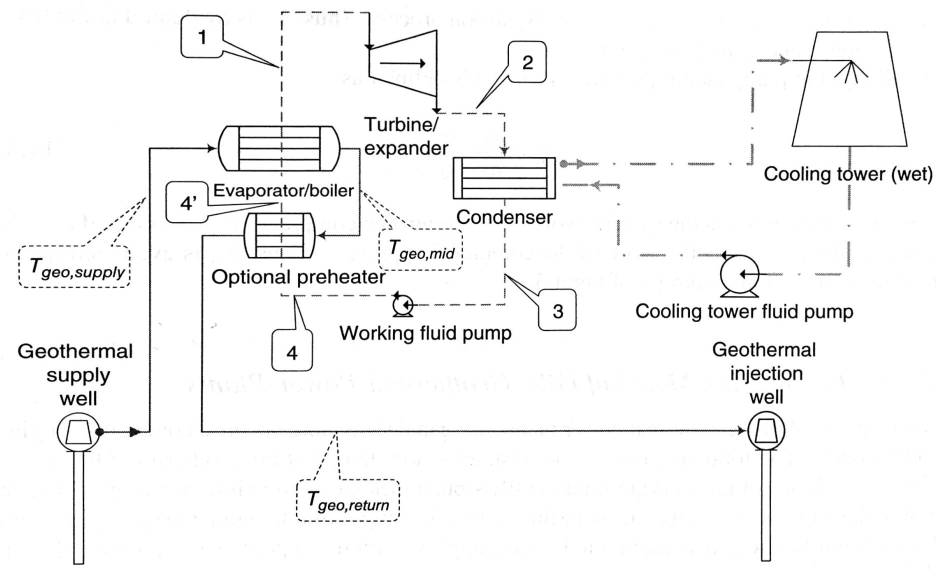


Figure 1.5: Schematic of a Binary Power Plant [3]

1.2.2 Direct Uses of Geothermal Energy

When geothermal energy is used directly for thermal purposes, as opposed for conversion into another form of energy such as electricity, the process is called a direct use. There remains debate about whether geothermal heat pumps belong to the direct use category. For instance, Chiasson argues that since a heat pump is needed for temperature amplification, which indicates that the resource temperature is not high enough to be used directly, it should be its own category [3]. However, for the sole purpose of separation from power generation, geothermal heat pumps are included as applications of direct uses of geothermal energy in this work.

Other than geothermal heat pumps, the most popular way to leverage direct use geothermal resources includes swimming pools and spas, space heating and greenhouse heating, as illustrated by

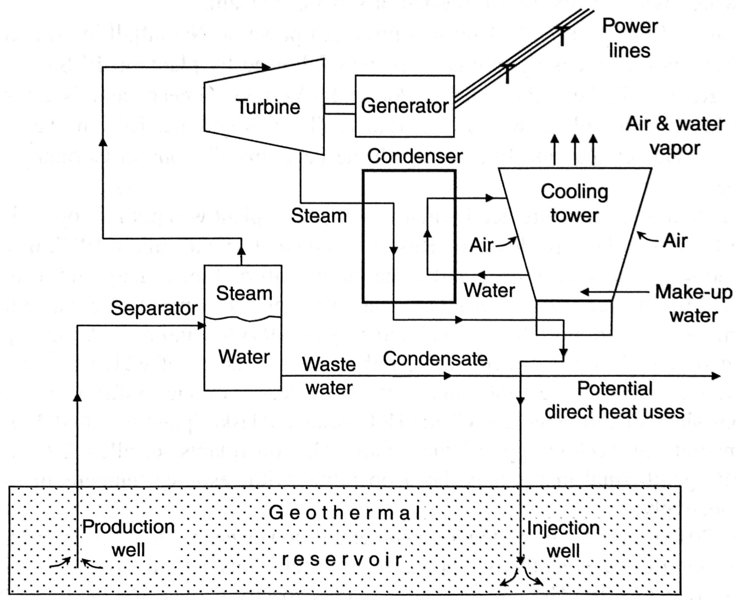


Figure 1.6: Schematic of a Flash Power Plant [3]

Figure 1.7, together making up about 45% of total geothermal energy use [14].

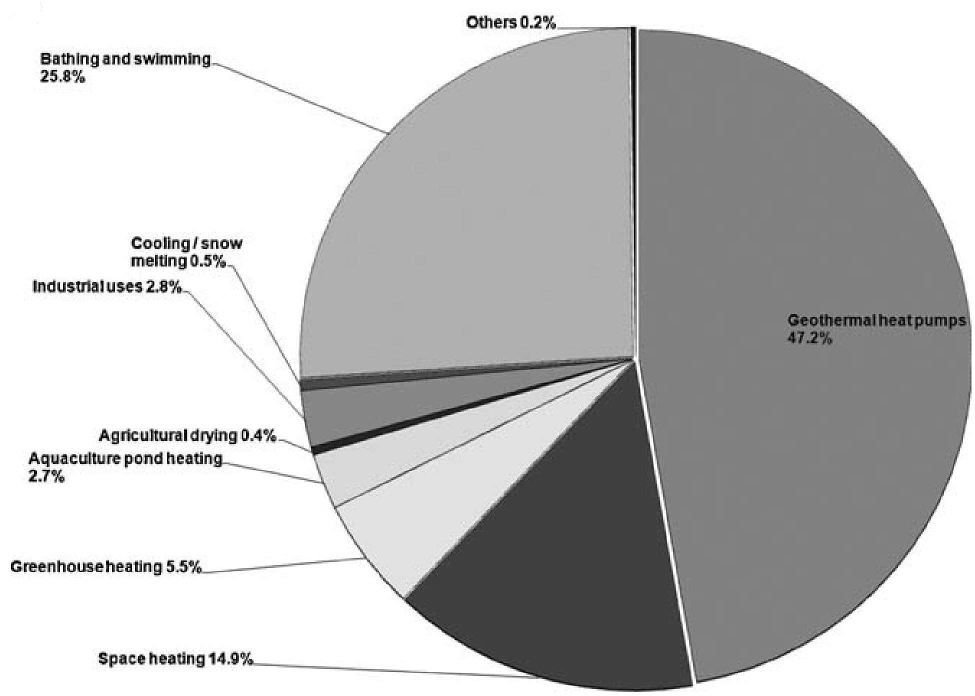


Figure 1.7: Percentage of Total Geothermal Energy Use by Types Worldwide [14]

Geothermal heat pumps, often known as ground source heat pump (GSHP) systems, is the most popular and accessible way of directly using geothermal energy, and involves coupling of heat pumps with low temperature thermal energy from the earth. This type of heat exchange is achieved by pumping geothermal fluid to the ground through a channel, most often pipes, and having heat to travel from or to the fluid due to temperature difference between the fluid and the ground. Heat is then pumped and distributed from the heat pump above the ground to various locations. As technology develops, nowadays, ground source is not only restricted to the earth, but also includes groundwater, surface water and other forms of reservoir.

Ground Heat Exchange Configurations

There are five main ground heat exchange configurations for ground source heat pump systems, as shown in Figure 1.8. A **groundwater well** (Figure 1.8a) is an open loop system where underground water is pumped to a heat pump or directly to usage from the bottom of a borehole, and is discharged to a suitable receptor, such as an aquifer, to an unsaturated zone. A **standing column well system** (Figure 1.8b) is a semi-open-loop system where ground water is pumped to a heat pump from the bottom of a deep borehole, but is returned to the same borehole after use. These boreholes are usually up to 15 cm in diameter, and allow water infiltration throughout the length of the borehole.

The **horizontal Slinky** (Figure 1.8d) and **the surface water closed loop** (Figure 1.8e) are similar in borehole orientation and the mechanism of heat extraction/rejection. A circulating fluid travels in horizontally laid pipes to exchange heat with either the ground or an open channel, such as a pond, lake or other water reservoir. A slinky shape is popular for maximizing contact area for heat exchange.

For close-loop systems, a **vertical borehole heat exchange system** (Figure 1.8c), also known as a vertical borehole heat exchanger (BHE), is the most commonly used configuration. A vertical BHE features a closed-loop HDPE pipe installed in a vertical borehole ranging from 60 to 90m (200 to 300 ft), though drilling conditions may have it go over 150m (400 ft). A standard HDPE pipe has a diameter betweem 25 to 40mm (3/4 to 1 1/4 in). Two configurations of the pipe are common, one of which is a single U-tube, in which the medium, usually water, circulates the ground through a u-shaped tube; the other is a coaxial tube, featuring one single pipe in the center of the borehole and water flowing into the ground from the annulus/central to the central/annulus. Both configurations and flow direction are illustrated in Figure 1.9.

For larger heating or cooling loads, multiple boreholes are connected in parallel to form a geothermal BHE field. These boreholes are designed to extract or reject thermal energy to/from the ground at a temperature called T_g, using the medium fluid, with an average temperature T_f of inlet T_{in} and outlet T_{out}. The space in between the borehole and the pipe is usually filled with grout, materials with low thermal conductivity such as bentonite, to prevent heat intervention between pipes.

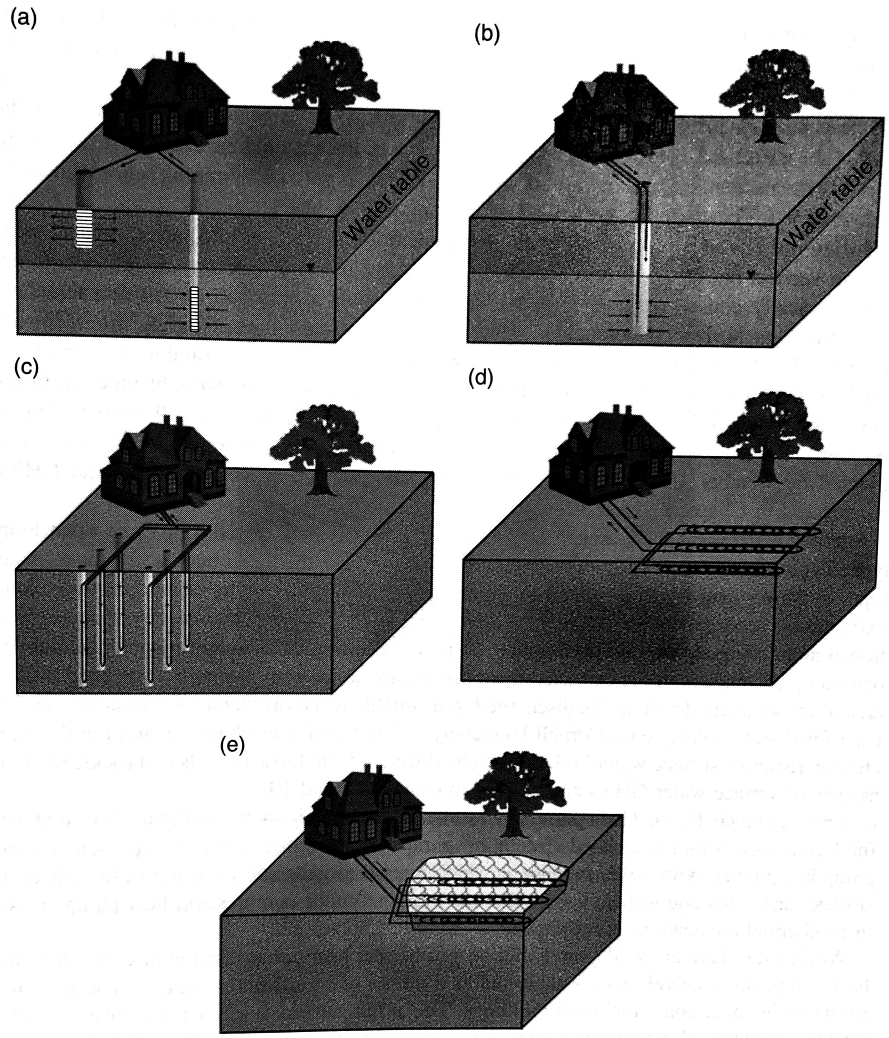


Figure 1.8: Schematic of Ground Source Heat Pumps: (a) groundwater well, (b) standing column well, (c) vertical closed-loop borehole, (d) horizontal Slinky, and (e) surface water closed loop [3]

1.2.3 Geothermal Heat Pumps

For geothermal BHE based space heating and cooling projects, after exchanging heat with the ground, the circulating fluid is amplified via heat pumps and directed to residential houses or buildings, to complete its heating or cooling cycle through another heat exchange with that environment. For instance, in heating modes, when room temperature is lower than ground temperature, the circulating fluid travels from the room/building, to the heat pumps before entering the BHE wells. With relatively low T_{in}, it extracts heat from the ground in the pipe, returns to the ground, being pumped into the building and heat the room. A graphic illustration of this example is shown in Figure 1.10.

A geothermal heating/cooling system can be centralized or decentralized, depending on current heating system configuration, as well as land availability. A centralized geothermal field features one complete field that generates and distributes heat through pipes that reach the entire campus

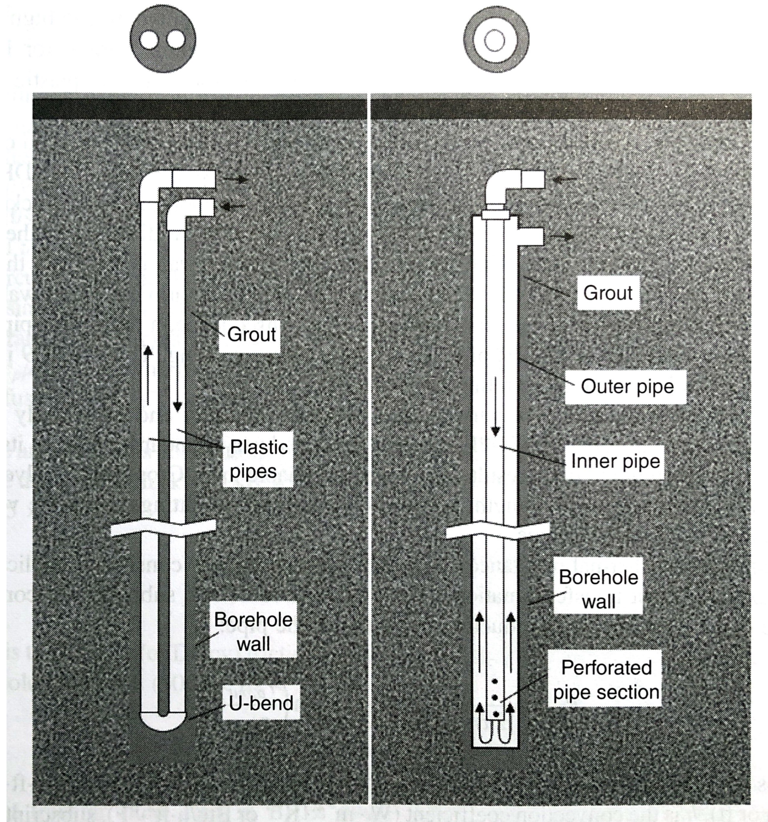


Figure 1.9: The two common BHE Pipe Configurations: U-tube (left) and Coaxial pipe (right) [3]

while a decentralized field comprises several fields, each responsible for heating of a local region. An example of a decentralized field at Smith College would be a field at Athletic Field heating the main campus and a field at the Quadrangle residential area for its own heating.

1.3 Contributions

This project details the design of a a vertical ground source heat pump system with u-tube configurations and provides a design to be implemented in the summer of 2019 as a pilot project for demonstration and research purposes. This work also guides the phasing and economic analysis for the District Energy Master Plan. This modeling and analysis framework could be incorporated into retrofit analysis with carbon tax policy implications to evaluate alternative energy systems [26].

In Chapter 2, a building modeling process of the Field House is explained, including model development, sensitivity analysis, model calibration and validation and a annual heating load is calculated. Chapter 3 presents the design process of a vertical ground source heat pump system and illustrates detailed assumptions and calculations that are used to generate design parameters, such as borehole length and heat pump power. Chapter 4 presents a life cycle cost analysis of the GSHP system design and closely quantifies the cost-benefit balance of four design options. Chapter 5

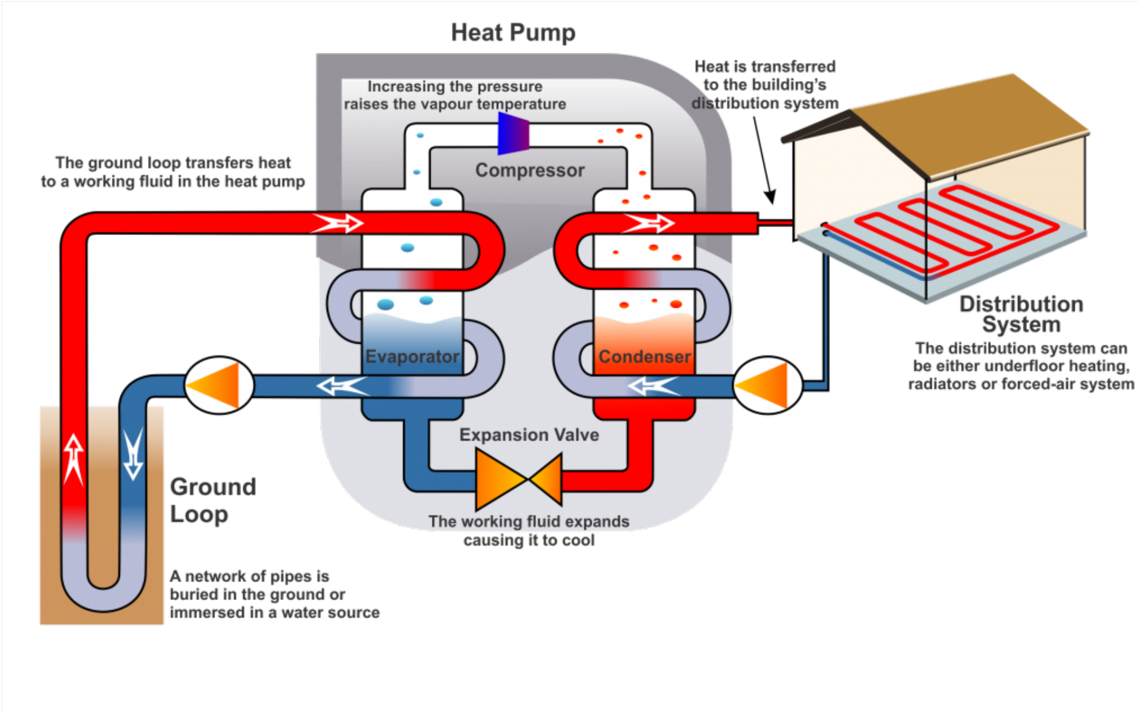


Figure 1.10: An Schematic of a Vertical BHE System Coupled with Heat Pumps for Heating [16]

concludes the work and identifies future directions.

Chapter 2

Building Energy Modeling of the Field House

In this chapter, an energy modeling process for the Field House will be presented. Trace 700, a commercial software for building energy modeling, is used to simulate the annual energy consumption of the Field House. Sensitivity analysis of building parameters is conducted for model calibration with existing oil consumption data of the boilers and to account for uncertainties from unknown building variables.

2.1 Building Energy Modeling in Trace 700

Trace 700 is a Windows based energy software developed by TRANE®, for building performance modeling and existing load calculations for building envelope, air conditioning, electricity consumption. It can also be used to generate suggestions for system design parameter values, as well as economics calculation and life cycle cost.

Users input weather data when creating a project, by selecting the location of the building. Weather is then incorporated from an internal library. Users can also override library data by manually changing variables such as dry/wet bulb temperature. Three major components in the Trace 700 main project navigator, shown in Figure 2.1 are the Create Rooms, Create Systems and Create Plants tabs. In Create Rooms, users construct a virtual building by creating rooms and inputing values and setup options for various building components in each room, including basic dimensions, walls and envelopes, internal loads, airflows and indoor partitions and other structures. A overall building energy consumption profile is then calculated.

In Create Systems, users define the HVAC (Heating, ventilation, and air conditioning) air distribution system by choosing the type of heating and cooling systems that serve in the buildings. Users can choose from a list of systems including unit heaters, fan coil, radiation, single zone, VAV, water source heat pump and so on. Once a system is selected for heating and cooling, users can further specify details of these systems in terms of the dedicated outdoor air (OA) system, temperature and humidity, and fans and coils. Trace 700 will then calculate corresponding power and electricity loads on the air distribution system based on previous total energy consumption calculated in Rooms. Users also need to assign rooms to air distribution systems so that potential zones can be created to reflect the reality of the building.

In Create Plants, users choose and setup configurations for building cooling and heating equipments, including air-cooled chillers, boilers, gas-fired heat exchangers and others. Users can further setup details, such as boiler efficiency, about these utilities in the Heating/Cooling Equipment tabs or setup base utility such as domestic hot water load in the Base Utility tab. Users can also assign air distribution systems to plants to designate heating/cooling loads on these plants.

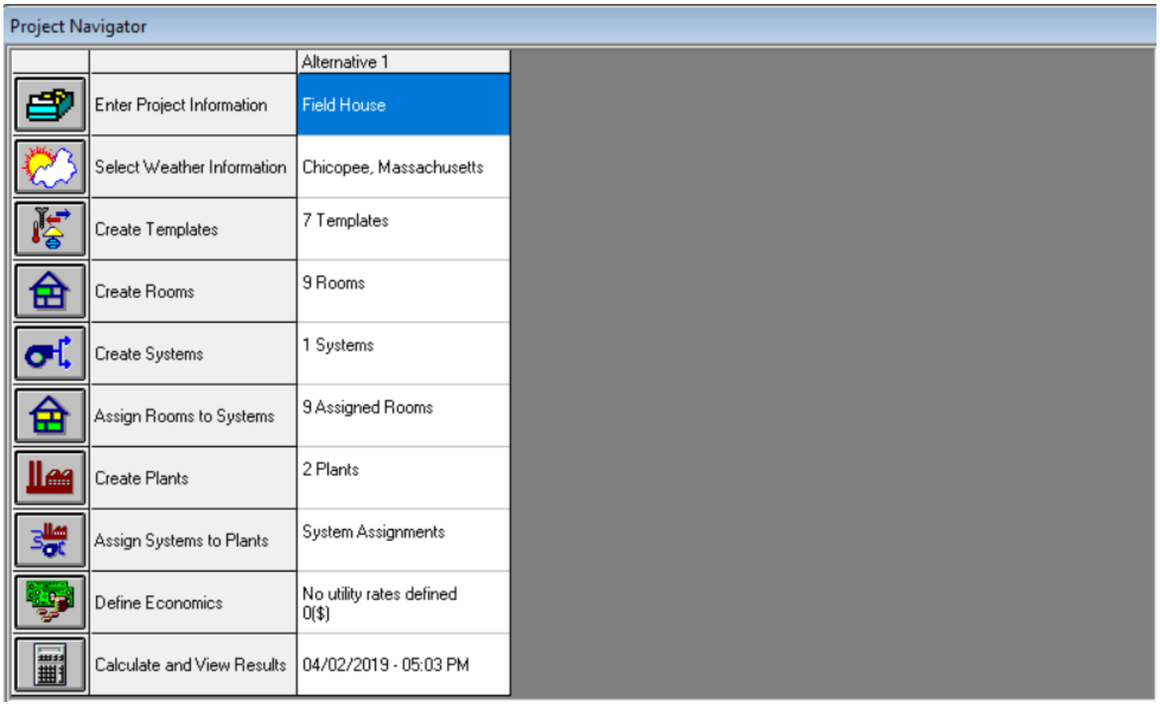


Figure 2.1: An Overview of Trace 700 Main Project Page.

2.2 Model Development and Calibration

In this section, a building model of the Field House is developed and calibrated in Trace 700. The process and result of obtaining known building parameters are discussed and unknown parameters are identified to calibrate the model. A sensitivity analysis is conducted for all unknown building parameters and configuration options in the Create Rooms section. Sensitive building parameters are identified and assumptions are made to approximate them with greatest precision possible. Additional adjustments and assumptions for unknown air-side system configurations, domestic hot water usage and modeling the geometry of the basement are also be discussed. The building model is tuned to match the total energy converted from oil usage by the boilers within a reasonable percentage difference.

2.2.1 Acquiring Building Information

A building model for the field house is constructed in Trace 700 based on information about building parameters acquired from a variety of sources, including field investigation, personal conversations with the facilities staff, existing documents about building structures and envelopes, CAD drawings, as well as reasonable assumptions based on similar building types (complete model input see Appendix A). Since the Field House has already been built, challenges remain for fully obtaining information on the building, especially for undocumented building dimensions, as well as wall and attic composite materials. In the following paragraphs, the initial modeling process based on known parameters is discussed. Unknown parameters are listed and a sensitivity analysis is conducted. Sensitive unknown parameters are then calibrated based on reasonable assumptions and a final building energy model is developed and compared to existing annual oil consumption of the Field House.

Figure 2.2: The Building Exterior of the Field House.

The Field House is a load bearing masonry [9], three-story (basement, first floor and attic) house located on the athletic field, as shown in Figure 2.2. It is primarily used by student athletes for equipment storage, gathering and occasional showering. Figure 2.3 shows the layout of the first floor, with a floor area of 3116 ft^2. Trace 700 defines a room as the smallest space for which a user can calculate loads and recommends that a user create one room for every single space surrounded by walls (detailed definition see Trace 700 manual in Appendix B.1). Therefore, five rooms in total are created for the first floor. “Office Area”, “Kitchen”, and “Lounge” are existing rooms labeled on the drawing. A room called “Middle” is designated to the area to the left of the lounge, with a dimension of 37’3” × 20’7 1/2”. Similarly, a “Stairs” room is created for the closed area on the left right corner, with a dimension of 34’10 1/2” × 22’1/2”. The dimension of the attic and the basement is not available from any existing CAD drawings or any other documented sources. The total area of the attic is assumed to be equal to the total area of the first floor. Assumptions about further geometry and energy modeling regarding the basement will be discussed in Model Calibration.

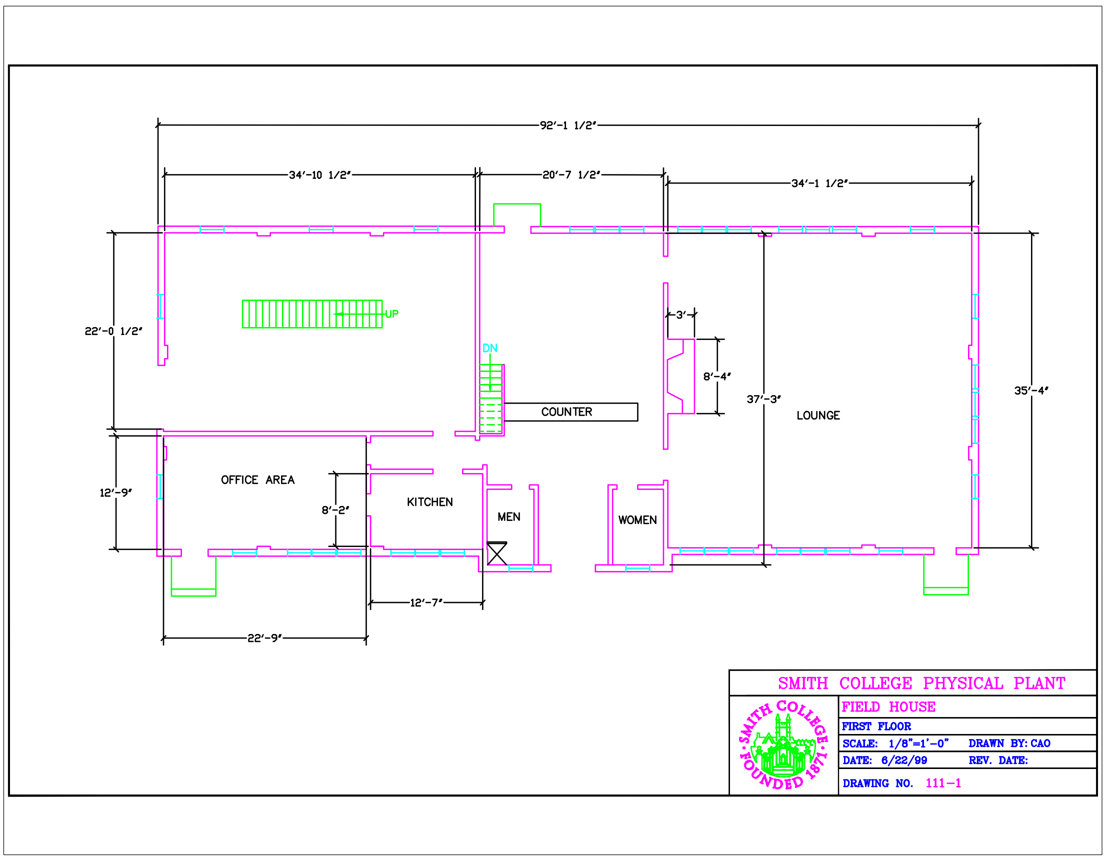


Figure 2.3: A CAD Drawing of the First Floor of the Field House.

Observations suggest that the thermostat setpoint on the first floor are the same and the overall temperature change is insignificant between rooms. Therefore, no partitions have been created for rooms, which corresponds to the suggestion by Trace 700, saying that “It is not necessary to model a partition if there is not a significant thermal difference between the spaces adjacent to it.” (detailed definition see Trace 700 manual in Appendix B.2). All rooms on the first floor are grouped into one zone, for the same reason. From observation, there are no thermostats in the attic or the basement, or any other type of conditioning system. Therefore, the attic and the basement are grouped into unconditioned zones. Information about building interiors, including the material of roof, doors, interior partitions, lighting, flooring and ceiling is acquired from the Building Attribute Spreadsheet documented from past building energy efforts in [9] and [10].

Information about the building air-side distribution system, such as the heating source, the heating distribution system and the heating end devices is acquired from [9]. Existing boiler specifics are obtained from personal field investigation at the Field House (scanned notes in Appendix H.1). Information about domestic hot water usage inside the Field House, such as sports team shower schedule is obtained from conversations with sports team members and coaches.

Figure 2.4: Boilers for Heating and Domestic Hot Water at the Basement of Field House.

The Field House is not connected to the college central steam system, but entirely relies on oil fired steam boilers in the basement shown in Figure 2.4 [9]. There is also no cooling system for the Field House. However, due to restrictions of Trace 700, energy consumption reports can only be generated if heating and cooling plants are available. Therefore, boilers are added to heating plants to simulate the boilers in the basement, and default equipments are added to the cooling plant, with pump capacity reduced to zero. Additionally, fans are also configured as to cycle with heating load only. This precaution has been verified by Current Annual Energy Consumption Report (Appendix E.1) which suggests that energy consumed by cooling load is only 0.3% of total energy consumption.

All known information is inputed to the building model following the categorization of Rooms, Systems and Plants. Unknown parameters remain as default to allow sensitivity analysis to be done before they are categorized as sensitive or non-sensitive and tuned.

2.2.2 Sensitivity Analysis

Sensitivity Analysis is used to identify unknown building details that significantly influence heating load. For the Rooms setting, there are parameters that are not specified in documents but can be reasonably assumed based on existing information or buildings of similar settings, such as the u-factor of walls and floors, the infiltration rate, and the unknown dimensions of the attic and the basement. There are other parameters that are harder to assume, such as the acoustic ceiling resistance, heat gain of the lighting system, and the time lag of the room due to thermal mass. In addition, there are several other characteristics of the Field House that are not available in Trace 700, such as the unique geometry of the basement, or a geothermal ground-sourced heating system.

Therefore, a sensitivity analysis is conducted to determine and calibrate unknown variables that have a significant impact on model behavior. A sensitivity analysis measures the variance of an output given a variance of the input of a parameter. An initial input, X_i, which generates an output $\bar{P}_i$, is changed by a certain fraction, δX, to an input with error, $\tilde{X}_i$, which generates an output with error, $\tilde{P}_i$. The sensitivity coefficient, S_i , is defined as the ratio of the fraction of change in input to the fraction of change in output, illustrated by Equation 2.1 [2]. Therefore, a high sensitivity coefficient indicates a sensitive parameter, where a percentage change of its output is much greater than that of its input.

$$S_i = \frac{\frac{\delta P}{\bar{P}_i}}{\frac{\delta X}{X_i}} = \frac{X_i}{\tilde{X}_i - X_i} \frac{\tilde{P}_i - \bar{P}_i}{\bar{P}_i} \tag{2.1}$$

A sensitivity error analysis is conducted to all variables in the Create Rooms section. Initially, this analysis is done to all variables from room to room. An example procedure would be to change the wall u-factor in Kitchen by 5%, keeping the wall u-factor in other rooms constant, and calculate a corresponding sensitivity coefficient, before repeating this process for every variable and for every room. After this is done to every room, variables with $S_i > 0.005$ (which is the third quartile of the total sensitivity coefficients) are selected to proceed to an overall sensitivity analysis.

An overall sensitivity analysis entails the same process done with an uniform variable change in all rooms at the same time. An example procedure would be to change the wall u-factor by 5% in every room simultaneously before calculating the sensitivity coefficient. A justification of this process is that since seven out of the eight variables selected from before are the same for all rooms, when one variable changes, this influence carries out to all rooms. It is therefore more representative of reality to quantify and compare the influence of each variable on all rooms. The only variable that varies from room to room, namely the glass/window percentage, is excluded from this round of analysis since there would be no real-life implication of doing so.

Table 2.1 shows the result from the overall sensitivity analysis of seven of the eight selected variables. All textual options, such as types of window and floor has been converted to numerical values in the form of u-factor, and therefore refer to the level of insulation they provides. For Window Type, 0.6 Btu/hr$\cdot ft^2 \cdot {}^\circ F$ is the u-factor of a double clear 1/8" and 0.28 Btu/hr$\cdot ft^2 \cdot {}^\circ F$ is the u-factor of a triple 1/4". For Floor Type, 0.2666 $\cdot ft^2 \cdot {}^\circ F$ is the u-factor of a 2" wood floor and 0.09599 $\cdot ft^2 \cdot {}^\circ F$ is that of a 2" wood floor with 2" insulation. For the purpose of consistency with the nomenclature of Trace 700, original labels, such as Window Type and Floor Type are kept in the table and the graph, but refer to u-factor and levels of insulation rather than the type, as explained before.

Table 2.1: Sensitivity Analysis Results*

Building Parameter	X_i	$\tilde{X}_i$	$\bar{P}_i$ (kBTU)	$\tilde{P}_i$ (kBTU)	S_i
Window Type (Btu/hr$\cdot ft^2 \cdot {}^\circ F$)	0.6	0.28	227210	177404	0.4110
Wall Height (ft)	8	10	227210	245629	0.3243
Wall Construct (Btu/hr$\cdot ft^2 \cdot {}^\circ F$)	0.12207	0.04511	227210	209388	0.1244
Floor Type (Btu/hr$\cdot ft^2 \cdot {}^\circ F$)	0.2666	0.09599	226957	137751	0.6142
Ventilation (cfm/person)	20	21	266461	268415	0.1467
Infiltration (ACH)	0.7	0.3	226957	210917	0.1237

* Glass/Window Percentage not included.

Figure 2.5 compares the sensitivity coefficients from six of the seven most sensitive building parameters, with Glass/Window Percentage data omitted due to its uncomparable nature. Based on the graph, window type, wall height and floor type are the top three most sensitive parameters, and all seven of them, including Glass/Window Percentage, will be carefully calibrated in the next section.

2.2.3 Parameter Calibration and Assumptions

For Glass/Window Percentage, a site evaluation of the dimensions of the windows was made to compare the ratio of glass to wall area. Different rooms have slightly different percentages because they have a different window surface area. For instance, as shown in neon blue color in Figure 2.3, the lounge generally has at least 4 units of windows per wall, while the stairs area only has one unit of window on one side and three on the other. The average of window percentage is set to 30% with fluctuations based on the specific number of windows per wall.

Window Type, or the u-factor of windows, is determined by observations of windows on site, which indicates a double pane model. Thickness is assumed to be 1/8", as opposed to 1/4", which is the other option in Trace, based on a best estimation by eye of the windows.

Similarly, based on personal conversations and existing facility building attributes sheets [9], wall height is set to 8 ft, wall composite is set to 4" HW Concrete with 2" of insulation and floor

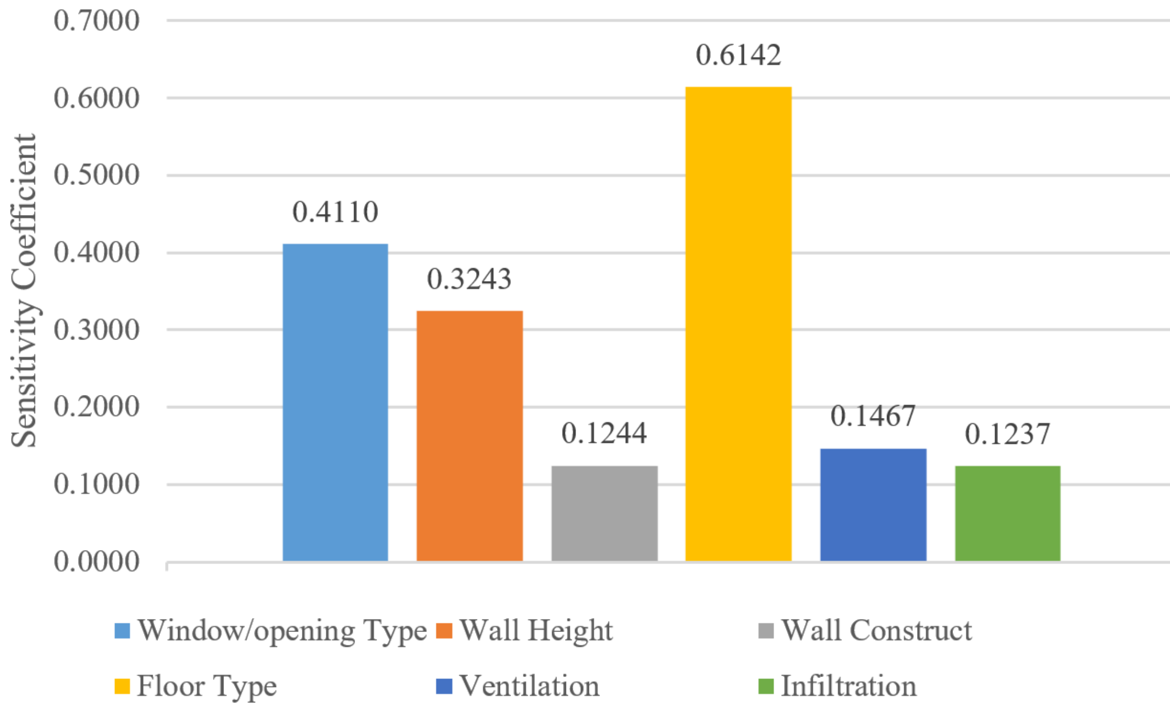


Figure 2.5: Sensitivity Coefficient for Six Most Sensitive Unknown Building Parameters

type is set to 2" wood floor, without any insulation.

The ventilation system in the Field House is a somewhat complicated matter. There is a set of exhaust heat recovery ventilation ducts in the attic, as shown in Figure 2.6 and 2.7, but the specifics of which is not documented in any existing facility sources available. The condition of these ducts are unknown and there are no testing reports indicating its performance. Due to lack of information, no exhaust heat recovery system is setup in the model and the ventilation rate is estimated based on a most basic ventilation system, which includes a ventilation method of "equal to the sum of outdoor air". In Etta's thesis, ventilation rate for load bearing masonry is assumed to be 0.08 cfm/ft^2 [9]. This estimation is also supported by the ventilation rate of a warehouse, which is setup in Trace with a similar ventilation schedule, one that is relatively constant throughout the day and non-dependent on its occupants, and has a ventilation rate around 0.05 cfm/ft^2. Therefore, the ventilation rate of all rooms, except the basement, is set to be 0.08 cfm/ft^2, while the basement is set to be zero, based on field observation.

Infiltration rate is determined based on existing blower door tests for Morris and Lawrence House in 2010. Two blower door tests were done for each building, one before and one after a retrofit. An estimated annual infiltration rate before any sealing is 0.63 ACH for Morris and 0.53 ACH for Lawrence. These two buildings are identical to each other in design and construction. Both number are slightly smaller than the estimated infiltration rate for design for these houses, which

Figure 2.6: Ventilation Ducts in the Attic-1

Figure 2.7: Ventilation Ducts in the Attic-2

has an average of 0.65 ACH (full blower door reports see Appendix C). Based on field observations and personal conversations, a conservative estimation of 0.7 ACH is used for all rooms.

During the field investigation, it is also observed that the boilers also provide heat for domestic hot water usage, a portion of energy that is not yet determined. Domestic hot water is mostly used by water taps in the kitchen, and showers in the bathroom. Personal conversations with sports team managers suggest that these showers are rarely used by student athletes, only once to twice every month and occasionally when teams from other regions come visit and play. Originally, based on an estimated usage (100 gallon/hr) that is more frequent than what the manager suggests, only an increase of 42 kBTU (out of 280,000 kBTU) in annual energy usage is noted. Therefore, domestic hot water usage is assumed to be negligible in this model.

The geometry of the basement is another challenge for the model, in that there is no existing geometry setup in Trace that is capable of fully describing its space layout. In addition to a regular space estimated to be about 21 ft $\times$ 15 ft, there are two hollow spaces that are about 6.5 ft above the ground, extending from the west and east side of the interior wall into the ground. Figure 2.8 shows one of these spaces.

Several modeling approaches are used, and the best method is selected based on how close the energy consumption value is compared to the oil data. In the selected method, the basement is divided into three sub-rooms: a large room with the dimensions of 21 ft $\times$ 15 ft, and two identical small rooms with the dimensions of 10 ft $\times$ 10 ft. Partitions are created for the large room for all five directions (north, south, west, east and top ceiling). The ceiling is set to be adjacent to the Middle room on the first floor while the west and east partitions further divide into four: two that are adjacent to the ground, and two that are adjacent to the small rooms. The ceiling shared by the basement and the Middle room is assumed to have a smaller than average u-factor. Floors and

Figure 2.8: One of the Two Irregular Spaces in the Basement

partitions for the small rooms are also created, where the top ceilings are set to be adjacent to the Kitchen room and the Lounge room, according to the orientation. A drawback of this method is the mistreating of the open entrance of the two small spaces as an additional partition. To amend for this problem, a maximum u-factor of the partitions is chosen to simulate heat convection through the openings.

After model calibration, a final annual energy consumption of the Field House is calculated by Trace 700 to be 286,498 kBTU/yr.

2.2.4 Model Validation

The building model is validated by the total energy generated from the boilers in the basement. Existing data shows the consumption of number 2 fuel oil for the academic year 2014-2015 and 2015-2016 to be 2031 gallons and 1928 gallons, respectively (obtained from personal conversation with Gary Hartwell). An average heating value of 139400 BTU/gal for a number 2 fuel oil is used [32]. An average annual energy usage of the Field House is then calculated to be 275,942,300 BTU/yr, or 275,942 kBTU/yr. The Trace 700 building model, which generates an annual heating load of 286,498 kBTU/yr, is within 4% of difference from the oil data, and is therefore validated. (Full report in Appendix E.1).

Chapter 3

Ground Source Heat Exchange System Design for the Field House

This chapter documents the system design process of a vertical ground source heat exchange system for the Smith College Field House. Given the heating load estimated in Chapter 2, here the ground-source heat pump (GSHP) system design variables are identified, in order to calculate the required bore length, number of boreholes, required fluid volumetric flow rate, and heat pump size.

3.1 System Overview

This section introduces the system configuration and main components of a ground source heat exchange system. Generally speaking, a complete heating and cooling system using geothermal energy consists of three major components: vertical ground-coupled heat exchangers, or simply called the ground loops, heat pumps, and the distribution system. A basic system configuration illustrating these three components is shown in Figure 3.1.

As discussed in Chapter 1, a GSHP system consists of one or multiple borehole heat exchanger(s) (BHE) that are connected in parallel or series. Ground-coupled heat pump (GCHP) is a subcategory of GSHPs, and refers to closed-loop ground-source heat pumps. The most popular is the vertical GCHP, or more commonly called the vertical BHE. The design of these heat exchangers depends on a variety of system variables, such as site conditions, including ground thermal properties, heating/cooling loads, geothermal fluid properties, borehole dimensions and configurations, such as borehole length, number of boreholes needed and average temperature of the geothermal fluid, and the size of heat pumps, including their power input and electricity consumption. Additionally, though not included in this design, borehole plumbing diagrams and system wiring schematics are also part of a final design package.

For geothermal based heating and cooling system for a residential building where borehole wells are located near the building, heat pump unit(s), connecting to the output of the vertical BHEs, amplify and pump the heat to an optional heat storage unit or directly to the building.

The most popular option is the water-to-air heat pump, where heat is exchanged between the geothermal fluid from the ground loops and the liquid refrigerant in the water coils in the pumps,

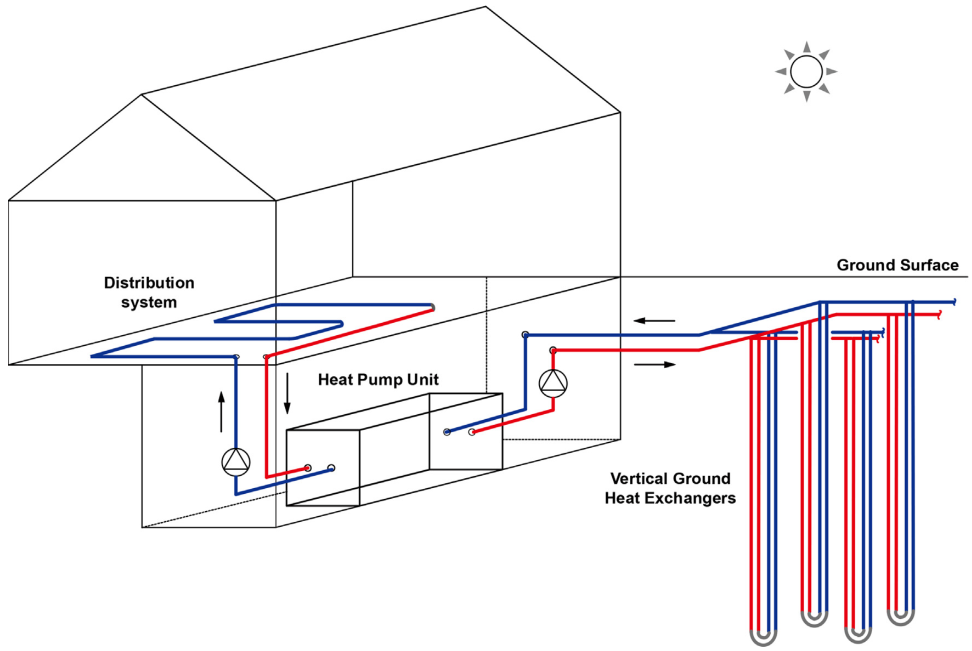


Figure 3.1: Configuration of a Vertical Ground Source Heat Pump System [13]

and is ultimately distributed from an air-based fan to the distribution system inside the building, usually a forced-air system. Similarly, a water-to-water heat pump uses water on both the ground loop coil and the building loop coil, and is often used for hydronic heating and cooling, dedicated domestic water heating, and outdoor air preconditioning [12]. The schematic for both heat pumps is illustrated in Figure 3.2. A third type of heat pump is a direct-expansion GCHP, which uses a buried copper piping network as one of the heat pump coils, through which refrigerant is circulated and heat is exchanged. Heat is then distributed inside a building in a variety of ways. Currently, Smith uses steam pipes to carry heat from the central heating plant, which is then distributed inside buildings through baseboards. Other distribution systems such as radiant heating systems are also commonly used.

This design focuses on the vertical BHEs and the heat pump sizing, and only discusses potential sizing of the distribution system based on existing information. A hydronic loop is currently located below the first floor subfloor, between the joists, in the Field House. This layout is a sub-optimal radiant system that would be removed and require installation of a new distribution system.

3.2 System Design

The design of a vertical ground source heat pump system have several inter-related variables that have an influence on the overall system thermal performance. However, it is also economically unjustifiable or technically impossible to obtain information on every variable. In some situations, exact value of some variables, such as the thermal conductivity of the ground at 400 ft, is often unavailable until a costly drilling and thermal response test is conducted. In other situations, as-

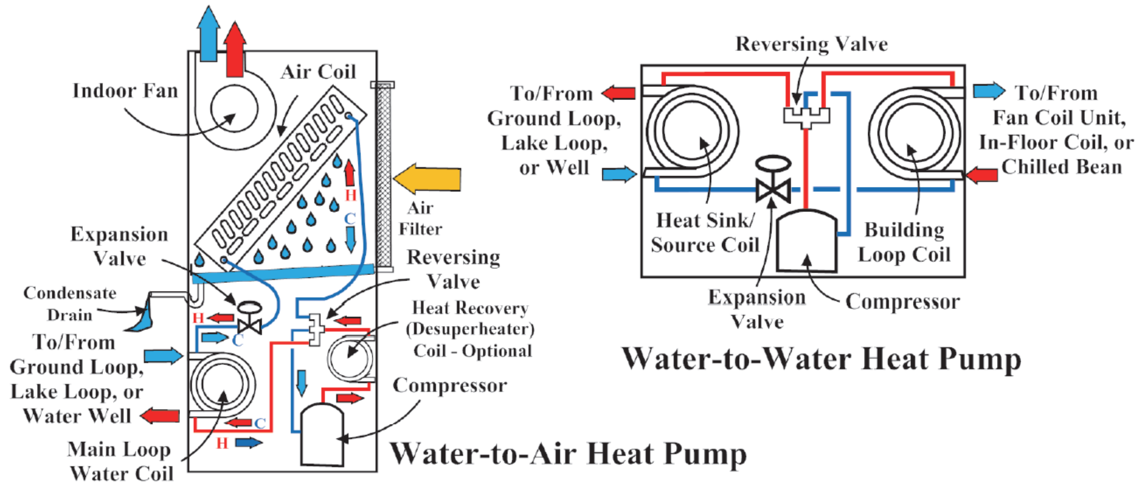


Figure 3.2: Schematic of a Air-to-Water Heat Pump (Left) and a Water-to-Water Heat Pump (Right) [12]

sumptions about other variables must be made based on reliable evidence and common practice, in order to efficiently proceed with necessary calculations. Therefore, the following sections strive to present a comprehensive, yet efficient design process that has taken both the economic and technical constraints into consideration.

3.2.1 Design Variables and Process

The performance of any geothermal-based heat exchanger relies on the heat exchange process between the ground and a circulating fluid. Therefore, understanding the thermal performance of a BHE and variables that significantly contribute to its performance, is crucial for designing a system that meets the heating load adequately and efficiently.

A typical vertical BHE with a single U-tube, as shown in Figure 3.3, comprises of a cylindrical borehole that has a U-shaped tube inside, with grout filled between the pipes and the borehole wall.

There are two types of heat transfer involved in the thermal performance of a BHE: heat conduction and heat convection. Heat conduction occurs when a thermal gradient is present, across or within solid material, where as convection occurs, in this application, between the surface of a solid and the surrounding fluid. Convection occurs from the working fluid in the pipe to the surface of the pipe wall while conduction occurs through he pipe and grout. Both conduction and convection occur from the grout to the rock and/or ground water.

For this design, conduction is assumed in the horizontal x direction, as described by the following equation.

$$\dot{Q}_{cond} = k\frac{dT}{dx} \tag{3.1}$$

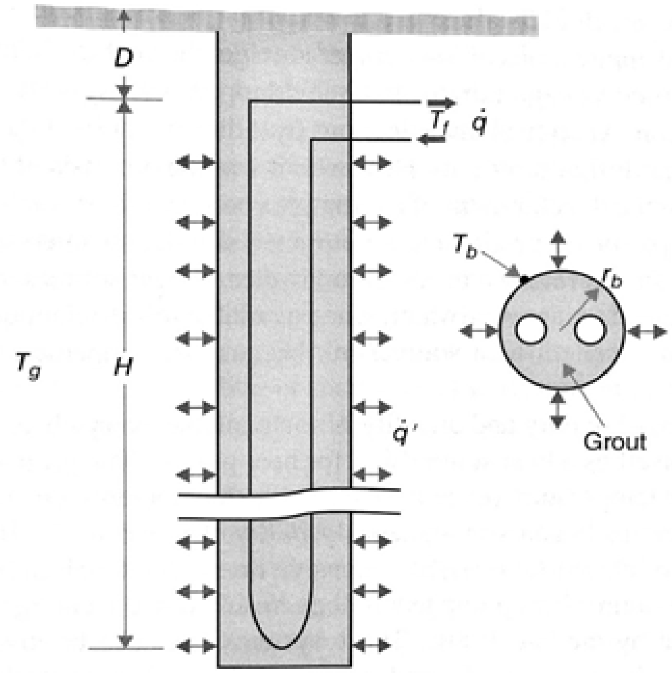


Figure 3.3: Schematic Diagram of a geothermal borehole heat exchanger (BHE) comprised of a single U-tube grouted in a vertical borehole. [3]

Heat convection occurs between the circulating fluid and the pipe walls, and is summarized by Equation 3.2, where T_s is the temperature at the contact surface of the fluid and the solid, and T_∞ is the temperature infinitely far away from the contact surface (at the middle of the pipe).

$$\dot{Q}_{conv} = h\Delta(T_s - T_\infty) \tag{3.2}$$

Based on these heat transfer mechanisms, parametric studies have been done to identify variables that most significantly influence BHE thermal performance. Eskilson [6] and Hellström [11] identified five most important design parameters for the thermal performance of a borehole heat exchanger as follow:

1. the ground thermal conductivity,
2. the borehole thermal resistance,
3. the undisturbed ground temperature,
4. the heat extraction/rejection rate, and
5. the mass flow of the circulating fluid.

Since many design variables have an inter-dependent relationship, such as mass flow of the fluid and the borehole thermal resistance, some variables need to be assigned pre-determined values so that others can be calculated. Figure 3.4 represents the relationship between variables and sequence of calculations.

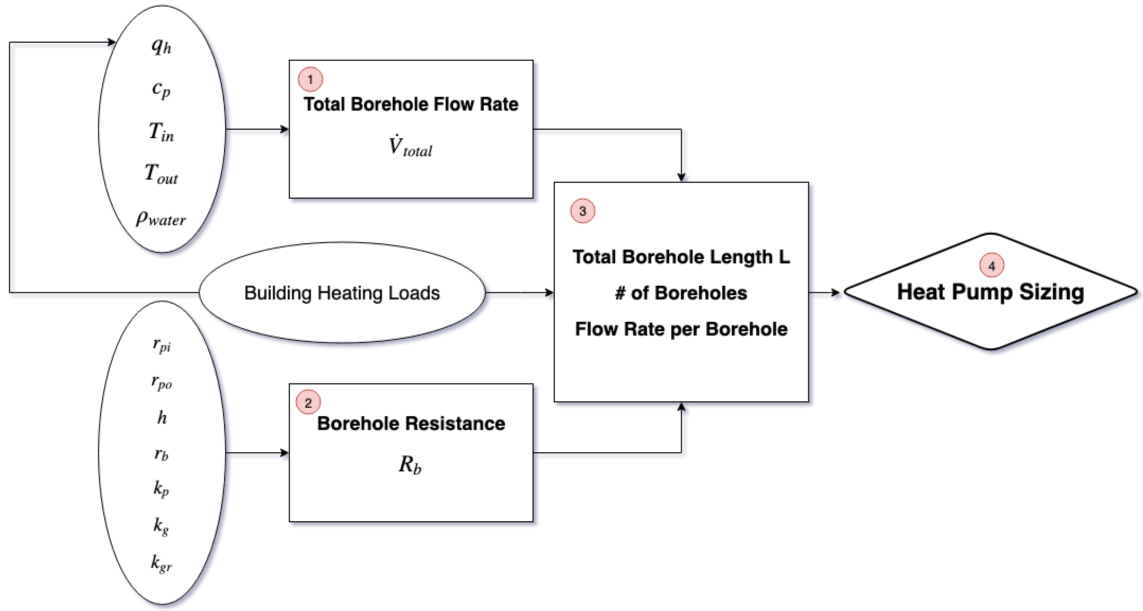


Figure 3.4: Flowchart of the Calculation Procedure for Total Flow Rate, Borehole Resistance, Borehole Length and Heat Pump Sizing.

Table 3.1 summarizes the values used for pre-determined design variables, which are categorized into ground heating loads, ground properties, fluid properties and borehole dimensions. The following sections will discuss specific assumptions in obtaining these values and explain the process to calculate borehole flow rate, borehole thermal resistance, total borehole length, number of boreholes and the power of the heat pumps.

3.2.2 Total Borehole Volumetric Flow Rate

As Equation 3.3 stated, the total mass flow rate, $\dot{m}$, is dependent on the total energy leaving the fluid $\dot{Q}_{out}$, the specific heat capacity of water c_p, and the change of temperature of the fluid $T_{out} - T_{in}$. For this design, 80% of the hourly peak load $\dot{q}_h$ (values in Table 3.1) is used for $\dot{Q}_{out}$. This assumption is made in correspondence with MEP Associates. Mass flow can then be converted to volumetric flow using Equation 3.4.

$$\dot{Q}_{out} = c_p \dot{m}(T_{out} - T_{in}) \tag{3.3}$$

$$\dot{m} = \dot{V_{total}} \cdot \rho \tag{3.4}$$

To determine values for inlet and outlet temperature, T_{in} and T_{out}, some assumptions are made. For this design, it is assumed that the fluid only engages in heat transfer for the downward trip, which is a distance of roughly the length of a BHE, 600 ft, and remains at the temperature it reaches

Table 3.1: Design Parameters for a Vertical BHE.

Design Parameters	**Values**
Ground Heating Loads (80%)	
Annual Load q_y (W)	11661
Monthly Peak Load q_m (W)	17283
Hourly Peak Load q_h (W)	19200
Ground Properties	
Average Soil Thermal Conductivity k_g (W $\cdot$ $m^{-1}K^{-1}$)	4
Thermal Diffusivity α ($m^2 \cdot day^{-1}$)	0.086
Undisturbed Ground Average Temperature T_g (°C)	15
Fluid Properties	
Specific Heat Capacity of Water C_p (J $\cdot$ $K^{-1}kg^{-1}$)	4180
Density of Water ρ (kg $\cdot$ m^{-3})	1000
Viscosity of Water μ (N s$\cdot m^{-2}$)	0.001307
Convective Heat Transfer Coefficient for Water h (W $\cdot$ $m^{-2}K^{-1}$)	1000
Temperature at BHE Inlet T_{in} ($^\circ C$)	4
Temperature at BHE Outlet T_{out} ($^\circ C$)	14
Average Temperature of Circulating Fluid T_{avg} ($^\circ C$)	9
Borehole Dimensions	
Borehole Radius r_b (m)	0.0762
Pipe Inner Radius r_{pi} (m)	0.013
Pipe Outer Radius r_{po} (m)	0.016
Pipe Thermal Conductivity k_p (W $\cdot$ $m^{-1}K^{-1}$)	0.46
Grout Thermal Conductivity k_{gr} (W $\cdot$ $m^{-1}K^{-1}$)	1.6
Center-to-Center Distance Between Pipes L_u (m)	0.051

at the bottom of the pipe for the rest of the upward trip. Another important assumption is that the average fluid temperature, T_{avg}, is the arithmetic mean of the inlet (T_{in}) and outlet (T_{out}) fluid temperature, and is calculated as $\frac{T_{in}+T_{out}}{2}$. Again, this is an oversimplification. Numerical and analytic methods, not included in this design, have been studied in the past for more accurate temperature profile modeling that provides methods for average temperature calculations. Temperature of the working fluid at the inlet of the BHE, T_{in}, is determined based on case studies of GCHP designs by Philippe [28] in a similar heating setting. The system was designed for a temperature difference between inlet and outlet of 10 °C. Outlet temperature, T_{out}, and arithmetic average fluid temperature, T_{avg}, are calculated accordingly, as shown in Table 3.1.

3.2.3 Borehole Thermal Resistances

The borehole thermal resistance, R_b, is analogous to that for a circuit and is significant in optimizing the thermal performance of a BHE, in that the smaller the total borehole resistance, the shorter the total borehole length needs to be. The way a single borehole is configured can be seen as equivalent to a circuit, where the ground, the grout and the pipe form a series circuit and the total resistance can be calculated by adding all the resistances together as if in a series circuit. Hellström [11] developed a model for calculating borehole resistance, which states that the total borehole resistance, R_b, for a single borehole is equal to the sum of the resistance of the grout, R_{gr}, and the total resistance of the pipe, $R_{p,total}$ [28].

$$R_b = R_{gr} + R_{p,total} \tag{3.5}$$

where the total resistance of the pipe as half the sum of the convection thermal resistance and the conductive thermal resistance of the pipe.

$$R_{p,total} = \frac{R_{conv} + R_p}{2} \tag{3.6}$$

Equations for calculating the convective resistance, R_{conv}, thermal resistance of the pipe, R_p and the grout, R_{gr} are:

$$R_{conv} = \frac{1}{2\pi r_{pi} h} \tag{3.7}$$

$$R_p = \frac{ln(\frac{r_{po}}{r_{pi}})}{2\pi k_p} \tag{3.8}$$

$$R_{gr} = \frac{1}{4\pi k_{gr}}[ln(\frac{r_b}{r_{po}}) + ln(\frac{r_b}{L_u}) + \frac{k_{gr} - k_g}{k_{gr} + k_g} ln(\frac{(r_b)^4}{(r_b)^4 - (\frac{L_u}{2})^4})] \tag{3.9}$$

Some assumptions need to be made regarding the estimation for the thermal conductivity of the ground, the grout and the pipe, as well as for borehole dimensions.

Without a thermal response test, the exact thermal conductivity of the ground cannot be determined. Therefore, an average soil thermal conductivity is determined based on existing information about ground composition at the Field House provided by Professor John Brady from the Geoscience Department at Smith. Figure 3.5 shows that red sandstone has dominated more than half of the existing 40 m of the ground, as schist takes over after that. Average thermal conductivity of sandstone and schist is given by [12] as 3.5 and 4.5 W $\cdot$ $m^{-1}K^{-1}$, respectively. Therefore, an average of 4 W $\cdot$ $m^{-1}K^{-1}$ is used for this design.

Undisturbed ground temperature, T_g, is another variable that cannot be fully determined without a thermal response test. Chiasson [3] provides an average ground temperature vs depth graph, as shown in Figure 3.6, which indicates that average temperature for winter experiences rapid increases starting from 5 °C to 15 °C at around 10 ft, but increases at a steady rate of 3 °C per 100 m after that. According to this figure, at 600 ft, which is the borehole length for this thesis work, temperature is expected to reach 21 °C. In addition, [12] also suggests using ground water temperature as a reference. Figure 3.7 shows an average ground temperature in the west Massachusetts area of around 50 °F, or 10 °C. An average between 10 °C and 21 °C, 15 °C, is used for this project, which is slightly lower than the average shown in 3.6 because Massachusetts is in the north and

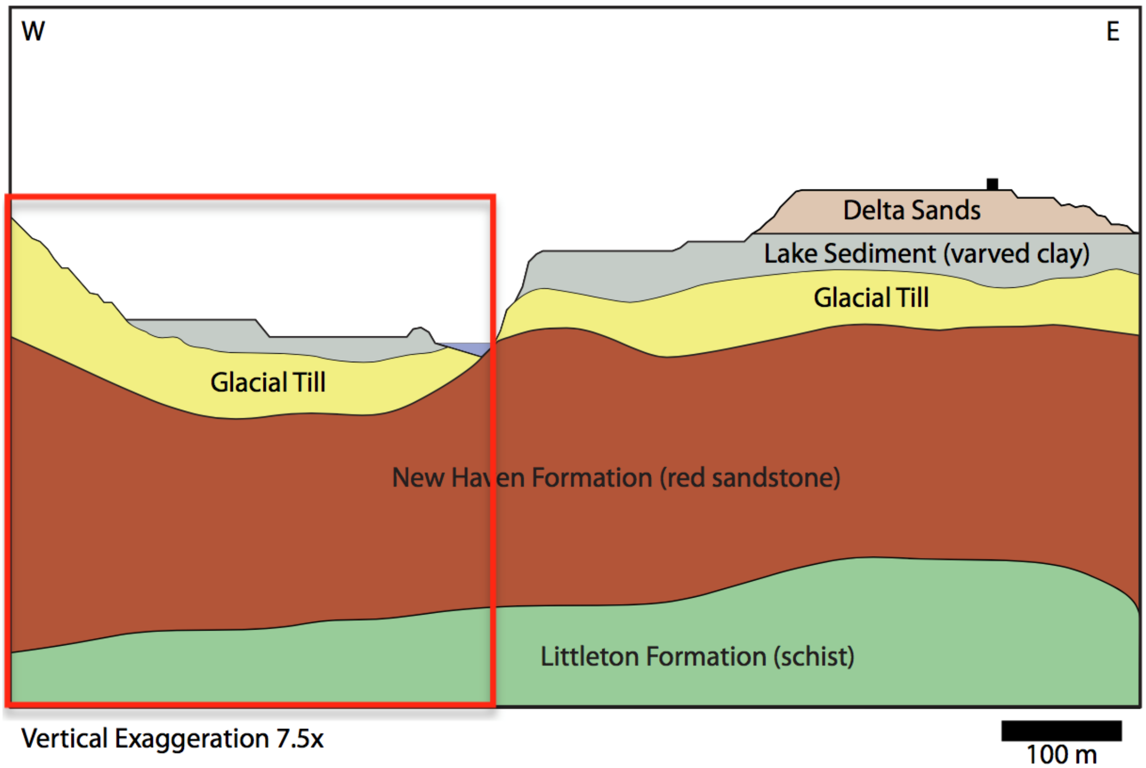


Figure 3.5: Ground Composition of the Field House (marked within the red square) up to around 320m. (John Brady)

potentially has lower surface temperature.

Borehole dimensions are determined based on a variety of sources. Personal conversations with Professor Aaron Rubin provided information on borehole diameter (6 in) and pipe nominal diameter (1 1/4 in). A DN32, SDR 11 HDPE pipe is selected based on known criteria, and inner pipe radius is calculated given minimum pipe thickness of a SDR 11 HDPE pipe, provided by P.E.S, Industrial and Productive Company [27]. The thermal conductivity of a HDPE pipe is determined by taking an average of three thermal conductivities of HDPE pipes, provided by INEOS Olefins & Polymers USA [33]. Similarly, a variety of thermal conductivity of bentonite grout are provided by the [12] and an average of 1.6 W $\cdot\, m^{-1}K^{-1}$ is used.

For the thermal diffusivity of the ground and center-to-center distance between pipes, default values are used based on case studies provided in [28].

ASHRAE has developed a borehole thermal resistance calculator that is used in this project to estimate these thermal resistances [12].

3.2.4 Borehole Sizing

Borehole sizing refers to the calculation of the total borehole length, L, required to meet a certain heating load. Method One states that L is a function of volumetric flow rate, $\dot{V}_{total}$, building heating

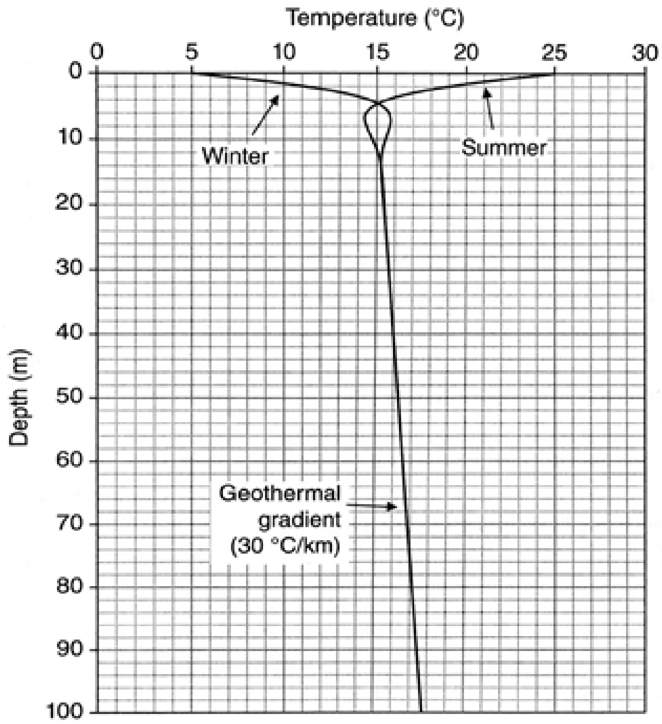


Figure 3.6: Ground Temperature vs Depth (0-100 m) below the Earth's Surface. [3]

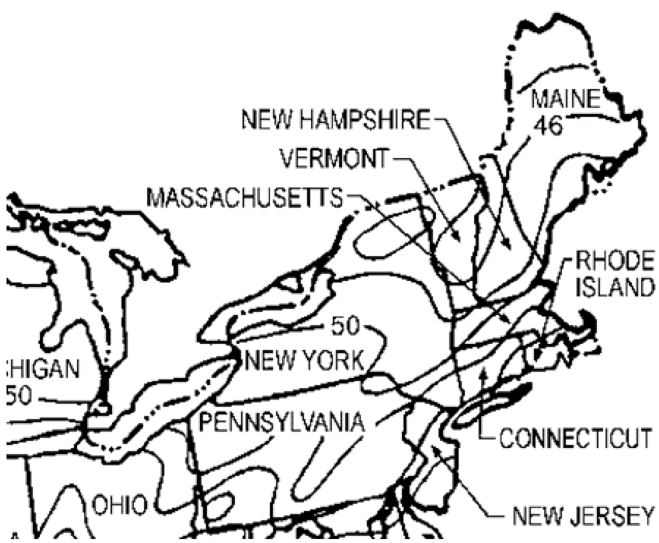


Figure 3.7: Ground water contour map of the New England area. [12]

loads, q_h (q_m and q_{yr} are optional depending on the method), borehole thermal resistance, R_b (other borehole thermal resistances over a different time period are optional), average temperature of the fluid, T_{avg}, undisturbed temperature of the ground, T_g, and an optional temperature penalty, T_p, as characterized in

$$L = \frac{q_h R_b}{T_{avg} - T_g} \tag{3.10}$$

Philippe[28] adjusts Equation 3.10 and introduces a slightly more extensive Method Two for borehole length calculation that incorporates annual, q_{yr}, and monthly loads, q_m, as well as effective thermal resistances for various durations of time periods, in

$$L = \frac{q_h R_b + q_y R_{10y} + q_m R_{1m} + q_h R_{6h}}{T_{avg} - (T_g + T_p)} \tag{3.11}$$

where T_p is the temperature penalty, are effective ground thermal resistances for 10 years, 1 month and 6 hours of heat load. Temperature penalty, T_p is used to account for the effect of thermal interferences, and recommended for the calculation of more than 4 boreholes. Equations for R_{10y}, R_{1m}, R_{6h} and T_p can be found in [28], which also provides access to a spreadsheet tool developed by ASHRAE that is used in this project to calculate borehole length L from Equation 3.11. Results calculated using Method One and Two are compared in Section 3.3, where a final borehole length L is selected.

For heating loads, as discussed before, 80% of the hourly peak load, q_h, is used for Equation 3.10. Original heating loads values are obtained from reports generated by Trace 700 (Appendix E.1) in different units. Annual load, q_{yr}, is converted from kBTU to W, over a duration of the total heating season, which is assumed to be 8 months, instead of 12 months. Monthly peak load, q_m, is manually chosen to be February, based on monthly oil consumption displayed in the Monthly Energy Consumption Report in Appendix E.1. This value is then converted from therms to W over a duration of a month. Hourly peak load is also manually selected to be the fifth hour on weekdays in February, based on Hourly Energy Consumption Report in Appendix E.1. This value is converted from BTUh to W, over a duration of an hour. Converted q_{yr} and q_m are then used for Equation 3.11. All heating values that are used to size the borehole (namely 80% of their original value) are summarized in Table 3.1. Assumptions for T_{avg} is discussed in Section 3.2.2 where as assumptions for T_g is discussed in Section 3.2.3.

The number of boreholes is calculated by dividing the total borehole length L by the length per borehole, which is 600 ft. Volumetric flow rate per borehole can then be calculated by equally dividing the total $\dot{V}_{total}$ with the number of boreholes needed.

3.2.5 Heat Pump Sizing

Figure 3.8 shows a basic heat pump unit in heating mode. The Coefficient of Performance (COP) describes the relationship between the electricity input, $\dot{W}_{in}$, and the energy output, $\dot{q}_{out}$ which is 80% of the hourly heating load, and indicates the level of efficiency at which a heat pump operates. The larger the COP, the less amount of electricity is needed to pump or amplify a fixed amount of heat. For all heat pumps in this project, COP is assumed to be 3, which is likely to be an underestimation, since MEP Associates suggest a possible COP of GSHP to be around 6. Equation 3.12 is used to calculate the power of each heat pump for the three BHEs needed. It is also assumed that each BHE is coupled with one heat pump.

$$COP = \frac{\dot{q}_h}{\dot{W}_{in}} \tag{3.12}$$

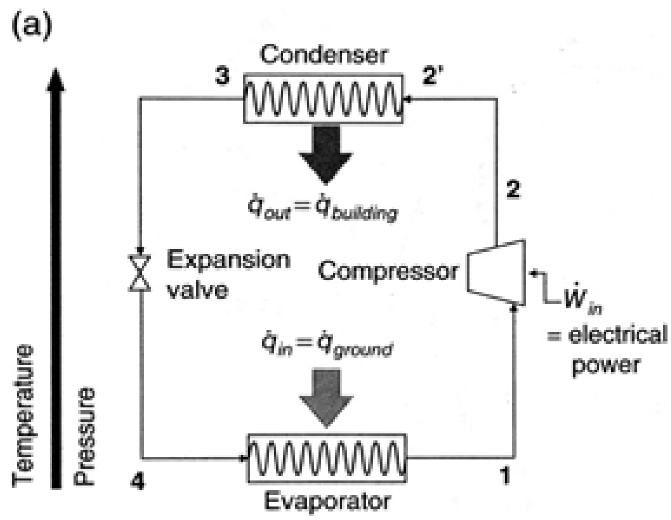


Figure 3.8: Schematic of a Heat Pump in Heating Mode [3]

For a closed-loop system, the power needed for the water pumps to circulate the fluid in the boreholes is equal to the pressure loss due to irreversible friction losses in the pipes and ducts. This is because for a closed-loop, the velocity and elevation of the inlet and outlet are the same. Therefore, the total power of a water pump is described in Equation 3.13, where the total loss due to friction can be further expanded into pressure loss due to friction with the pipes, and from the fittings [3]. Since $\Delta P_{fitting}$ is really small, it is neglected in this design process. It is also assumed that each borehole has its own water pump.

$$\dot{W} = \dot{V}\Delta P_{friction} = \dot{V}(\Delta P_{pipe} + \Delta P_{fitting}) = \dot{V}\Delta P_{pipe} \tag{3.13}$$

where $\dot{V}$ is the volumetric flow rate of the fluid. ΔP_{pipe} can then be calculated using Equation 3.14.

$$\Delta P_{pipe} = \frac{fL\rho\dot{v}^2}{2D} \tag{3.14}$$

In this equation, f is the dimensionless Moody friction factor (one way of calculating which is shown in Equation 3.15), $\dot{v}$ is the fluid velocity (m/s), L is the length of the pipe, and D is the pipe inside diameter.

$$f = (0.79 \cdot ln(Re) - 0.64)^{-2} \tag{3.15}$$

The expression for Re, the Reynolds number, is shown in Equation 3.16.

$$Re = \frac{\rho v D_{fluid}}{\mu} \tag{3.16}$$

where $\dot{v}$ is the velocity of the fluid, D_{fluid} is the diameter of the fluid, and μ is the viscosity of the fluid.

3.3 Design Results

The total mass flow, $\dot{m_{total}}$, is calculated to be 0.46 kg/s, which is equal to 7.3 gpm of total volumetric flow rate, $\dot{V_{total}}$.

Borehole thermal resistances are calculated using the ASHRAE tool spreadsheet [28] as follow: R_{conv} = 0.012 mK/W , R_p = 0.069 mK/W, R_{gr} = 0.097 mK/W and R_b = 0.138 mK/W.

Method One gives a total borehole length L of 442 m, or 1449 ft. This results in a total of three borehole wells. Based on this result, initially, temperature penalty was not used for Equation 3.11. Using Method Two, ASHRAE calculator [28] generates a total borehole length of 1114 m, or 3655 ft, which results in 6 borehole wells. This result is a bit of a surprise, since the number of wells has doubled from results calculated with method One. In addition, since the number of wells is larger than four, temperature penalty should be taken into consideration. Therefore, additional parameters required for calculating the temperature penalty are added, namely distance between boreholes as 6.1m, and the borefield aspect ratio as 4 (meaning wells are lined up in 1×4 configuration). After taking into account the temperature penalty, the number of wells is reduced to 4, with 603 ft per well for a total of 735 m or 2413 ft.

Overall, Method Two (including the temperature penalty) produced a much larger total borehole length than Method One. This is mostly because Method Two has incorporated multiple heating loads across a variety of time frames, which greatly increases the numerator in Equation 3.10.

For this design project, calculated results from Method One is used, which generates a volumetric flow rate of 2.4 gpm per well (full spreadsheet Appendix D). Although, it is important to acknowledge that for systems that are intended to last for years, and especially for geothermal systems that have a significant imbalance between heating and cooling load, understanding and taking into account the thermal performance over a long period, in addition to short-term performance, is crucial in properly sizing the BHEs.

Assuming each BHE has its own heat pump gives a total of three heat pumps of 2133 W/well, or 0.61 ton/well (full calculation see Appendix D). Also assuming that each BHE has its own water pump generates a total of three water pumps of 1.1 W/well to ensure the circulation of water within the BHEs (full calculation see Appendix D). Energetic needs for the distribution system within the house are not discussed in this design process.

Chapter 4

Life Cycle Cost Analysis

System designs are often justified and implemented by evaluating the economic impact. In this chapter, a life cycle cost calculation is conducted for the vertical GSHP design from Chapter 3 to provide an economic scope of work. Life cycle costs for additional retrofit options are also conducted and compared with that for the current system design to shed some light on the decision making process for a most cost-beneficial option for future design projects. The key driver for this analysis is determining the life cycle cost based on the degree of the building retrofit in order to guide capital planning.

4.1 Overview

In this section, a basic procedure of a life cycle cost calculation is presented, and its significance explained. Common practice of a building retrofit is also described to provide some background information about the process, such as the components it usually entails, and specifically, about the impact of retrofits on capital cost.

4.1.1 Life Cycle Cost Calculation

Life cycle cost (LCC) analysis provides a framework of assessing the total cost of a project during a set period of time. Generally, any cost, including capital cost and costs generated in the future, is included in the calculation to provide as thorough an analysis as possible. A LCC calculation is useful in many ways. First, it provides an economic perspective in evaluating the effectiveness and the benefits of a project. For any design project to be implemented in real life, the cost of it is an important factor, which lead to its second benefit. A LCC is especially useful in design selection of several options that are similar in the technical aspects but differs in their benefits and costs.

Overall, a basic LCC calculation is captured in Equation 4.1,

$$LCC = C + M + E + R - S \tag{4.1}$$

where C is the capital cost, or the initial cost of a system, M is the sum of annual maintenance cost, E is the sum of annual energy cost, R is the sum of all anticipated equipment repair and replacement cost, S is the salvage value of the system at the end of the LCC period [15]. For this system, LCC is comprised of three main categories - capital cost, annual cost and salvage, which then correspond to three types of value: present worth (P), annual cost or revenues (A) and future worth (F).

Present worth is what the cost is, in today's dollar value. All capital costs that one pays once at the beginning of a project, including installation, drilling, construction and so on, are present worth. Annual costs include the cost for annual maintenance and energy consumption, and other forms of cost that occur every year. Salvage refers to a recuperated value, if it were salvaged at the end of the LCC period. For instance, if the salvage rate is 20% of the capital cost at present worth, then that would be the amount one would receive in the last year, n. Not every project has materials that are worth salvaging as salvaging itself also means an extra output of labor. At end of life, there is no significant difference between salvage value of these systems. Therefore salvage value is neglected. It is important that all future costs are converted to their present worth. Equation 4.2 and 4.3 are the two most common calculations that converts between present worth, future worth and annual cost. Equation 4.4 is used to estimate annual cost that are predicted to escalate at a rate that is different from the inflation rate [15].

$$P = \frac{F}{(1+i)^n} \tag{4.2}$$

$$P = A \cdot \frac{1-(1+i)^{-n}}{i} \tag{4.3}$$

$$P = A \cdot (\frac{1+E}{I-E} \cdot (1-(\frac{1+E}{I-E})^N)) \tag{4.4}$$

where P is present worth, F is future worth, A is annual worth, n is the period of time over which a certain cost happens and i is the interest, or discount rate.

There are also pre-calculated tables that provide conversion factors at certain discount rates that allow the process of converting all costs to one type of value to be more efficient. Figure 4.1 is an example of this type of tables provided by the FE Reference Handbook 9-5 [18]. The letter on the right indicates the original type of a value while the letter on the left indicates the target.

Factor Table - i = 1.00%

n	*P/F*	*P/A*	*P/G*	*F/P*	*F/A*	*A/P*	*A/F*	*A/G*
1	0.9901	0.9901	0.0000	1.0100	1.0000	1.0100	1.0000	0.0000
2	0.9803	1.9704	0.9803	1.0201	2.0100	0.5075	0.4975	0.4975
3	0.9706	2.9410	2.9215	1.0303	3.0301	0.3400	0.3300	0.9934
4	0.9610	3.9020	5.8044	1.0406	4.0604	0.2563	0.2463	1.4876
5	**0.9515**	**4.8534**	**9.6103**	**1.0510**	**5.1010**	**0.2060**	**0.1960**	**1.9801**
6	0.9420	5.7955	14.3205	1.0615	6.1520	0.1725	0.1625	2.4710
7	0.9327	6.7282	19.9168	1.0721	7.2135	0.1486	0.1386	2.9602
8	0.9235	7.6517	26.3812	1.0829	8.2857	0.1307	0.1207	3.4478
9	0.9143	8.5650	33.6959	1.0937	9.3685	0.1167	0.1067	3.9337
10	**0.9053**	**9.4713**	**41.8435**	**1.1046**	**10.4622**	**0.1056**	**0.0956**	**4.4179**

Figure 4.1: A Screenshot of an Interest Rate Table at i = 1% [18]

4.1.2 Background on Building Retrofits

In the United States, buildings consume more than 40% of the total energy produced, out of which 32% is for space heating and cooling [25]. While it is very difficult to eliminate heat loss from buildings, a building retrofit can improve the condition of the building and significantly reduce heating and cooling energy consumption. As building envelope material degrades overtime, the exterior surfaces of the building, called the building envelope, degrades, resulting in greater heat loss. In battling with heat leakage, residents have to increase the total amount of energy required to heat the building. Retrofitting existing buildings, therefore, provides an opportunity to improve building performance. At Smith College, with well over 100 buildings on campus, approximately 2 buildings a year undergo a significant retrofit. Retrofits, then provide the college an opportunity to reduce campus heating load, but at a significant cost. As a result, buildings are retrofit not just to reduce heat load, but also to address deferred maintenance and improve accessibility. Often, retrofitting an existing building is more cost-beneficial than building a new building, since retrofits often improve building heating and cooling efficiency and reduce energy demands.

With a model of heat load for a design alternative as shown in Chapter 2, the LCC of scenarios can be calculated to evaluate retrofit options. By inputing typical methods of retrofit to an existing building model, and comparing results in terms of both energy reduction and efficiency, total LCC calculations can be compared.

There are several degrees of retrofits that target different heat transport mechanisms. One of the most common and least labor intensive is sealing. Sealing a building targets convective heat transfer and minimizes unwanted air movement across the building envelopes through gaps in materials. In fact, sealing can often reduce up to 30% of total heating and cooling cost [20]. A blower door test is often conducted before sealing is done, to quantify the amount of air leakage a building has. Weather stripping and caulking holes can be conducted simultaneously with blower door tests to determine whether sealing has achieved its target infiltration rate [9].

A significantly more invasive retrofit is to add wall insulation. The ability to conduct heat in building envelope materials is measured by the so-called "R-value". R-value is used to quantify the thermal resistance of building insulation and indicates the resistance to conductive heat transfer [21]. The larger an R-value is for a material, the more resistive it is to heat conduction. Building envelope insulation has a major effect in reducing building energy consumption, but is also very costly, as the next section will illustrate. Additional changes to the attic insulation, namely increasing the R-value of the attic, is also practiced to specifically reduce the unwanted heat gain through the roofs in the summer. For building with wall cavities, like wood-framed buildings, insulation can be added by accessing wall cavities from the exterior. The degree to which wall and attic insulation can be added is very dependent on the building construction and occupied space finishes.

Window replacement is another way of reducing conductive and convective heat transfer through the building envelope. Typical window configurations include single, double and triple pane glass windows, representing an increasing resistance to heat conduction. Pressurized gas or vacuum is often used as a filling between the panes, to further increase thermal conductivity. Convective heat transport is reduced by setting the window within the structure with improved sealing.

4.2 Cost Benefit Analysis for Design and Retrofit Options

In this section, four design + retrofit options are created and their LCC calculated. Four different options are evaluated, namely the LCC over a period of 30 years for:

1. the current oil-based heating system
2. a geothermal GSHP system with no building retrofit
3. a geothermal GSHP system with medium level retrofit, which includes window replacement and attic insulation to R42
4. a geothermal GSHP system with deep level retrofit, which includes window replacement, attic insulation to R42, an overall sealing of the building and wall insulation to R21

The specific details and assumptions about cost components and LCC related parameters, such as discount rate, is included in the next section.

4.2.1 Acquiring Cost Information and Assumptions

Overall cost components are divided and discussed based on the category they fall into. Capital costs include the overall cost for the geothermal GSHP installation, window replacement, attic insulation and sealing, envelope insulation and sealing. Annual cost includes annual oil consumption and electricity consumption for the pumps in the GSHP system. Additional assumptions about annual maintenance costs and salvage value is discussed. Discount rate, i, for capital cost, oil and electricity are calculated or obtained from reliable sources, which are also included in this section.

Table 4.1: Building Dimensions and Pump Power of the Field House

Parameters	Value
Building Length (ft)	92.125
Building Width (ft)	36.83
Floor-To-Floor Height (ft)	8
Tilted Roof Length (ft)	52
Gross Area (ft^2)	6781
Roof Area (ft^2)	1872
Total Wall Cavity (ft^2)	4126.56
Number of Windows	34
Oil Consumption (gal)	1979.5
Total Pump Annual Energy Consumption, Geothermal only (kWh)	36870
Total Pump Annual Energy Consumption, Geothermal + Medium (kWh)	30778
Total Pump Annual Energy Consumption, Geothermal + Deep (kWh)	27846

Capital Cost

The overall installation cost for a geothermal GSHP system, including the cost of drilling, piping, labor, as well as the cost for heat pumps, is estimated via two methods. Review has been done to examine the overall geothermal GSHP installation capital cost in existing projects for a similar institutional context. Technical and economic parameters in geothermal systems in 17 college, universities and other institutions have been evaluated, and an average cost for the overall capital installation cost is \$50,000 per well (complete spreadsheet in Appendix F). Estimates have also been made by MEP Associates to be about \$46,000 per well (at a depth of 600 ft per well). Both numbers agree fairly well and a capital cost of \$ 46,000 per well is selected, since there is a consistency in borehole depth per well between this design and MEP's.

Total installed window replacement cost of \$1500 per window is obtained through personal conversation with Professor Denise McKahn and Facilities Management staff based on previous contracts for windows of this size (notes see Appendix H.2). According to the CAD drawing, there are currently 36 windows at the Field House. A field investigation indicates that there are two windows that have been removed, shown in Figure 4.2. There is one extra window on the attic that is not documented in the CAD drawing, and two that half-size in comparison to the others, shown in Figure 4.3, and is adjusted to half of a regular window in terms of cost. Therefore, the adjusted number of windows is 34. In Trace 700, window replacement is done by adjusting the u-factor of each window. Pre-retrofit, the u-factor of a double-pane clear 1/8" window is set to 0.6 $Btu/hr \cdot ft^2 \cdot^\circ F$. Post-retrofit, the window u-factor is 0.3 $Btu/hr \cdot ft^2 \cdot^\circ F$, based on local building code regulations on building retrofit thermal performances [30].

Insulation cost is estimated, based on information obtained via personal conversation with Professor Denise McKahn shown in Appendix H.2, at an installed cost of \$15,000 for insulating a 1400 ft^2 building with spray foam to achieve R21 at 3.0 inches thick. A cost per square foot is calculated, see Appendix H.2, by dividing \$15,000 over the total area of wall cavity and roof, and is equal to \$4.55/ft^2. Total building wall cavity is calculated using existing building dimensions shown in Table 4.1. The cost for wall sealing, which is one of the actions for a deep retrofit, is calculated by multiplying \$4.55 with the total wall cavity surface area. In Trace 700, wall insulation is done by adjusting the u-factor of wall material. R21 is added in series to the original R-value of 0.122 $Btu/hr \cdot ft^2 \cdot^\circ F$ for a 4" HW Concrete with 2" insulation and converted to a u-factor of 0.034 $Btu/hr \cdot ft^2 \cdot^\circ F$. It is important to note that this cost does not account for building false walls within the interior of the load bearing masonry building, which currently has no wall cavity.

For attic insulation, the rate of \$4.55/ft^2 is doubled and applied to the total roof area of the attic, to achieve R42. Adjusted attic roof u-factor is calculated by adding R42 in series with the original roof u-factor, 0.157 $Btu/hr \cdot ft^2 \cdot^\circ F$, as 0.02 $Btu/hr \cdot ft^2 \cdot^\circ F$. In addition, when adding insulation, spray foam is also applied as part of the process, which reduces the infiltration rate in the attic, from 0.7 ACH to 0.3 ACH, an average post-sealing rate based on blower door tests for Morris and Lawrence House (Appendix C).

Additional cost for overall building sealing (excluding the attic) is estimated based on personal

Figure 4.2: One of the Two Windows at the Field House that were Removed

Figure 4.3: One of the Two Half-Size Windows (left) at the Field House

conversation with Professor Denise McKahn (notes in Appendix H.2). The overall schedule is assumed to be two days, with 8 hours of work per day, done by three people at a rate of $30/hr. This results in a total cost of $1440 for overall building sealing. In Trace 700, an overall building sealing is reflected by adjusting infiltration rate of all rooms, except for the basement, from 0.7 ACH to 0.3 ACH, for similar reasonings as the attic sealing.

For discount rate, it is assumed that this project is federally funded and all capital cost follows federal discount rates, which is about 2.5% based on reports by the Federal Reserve Bank of New York [22].

Annual Cost

The schedule and components for annual maintenance for both the oil-based or the geothermal-based heating system are assumed to be the same, regardless of the degree of retrofit. Therefore, there is no calculation of annual maintenance cost in LCC calculations, since all four options have the same rate.

For the oil-based heating system, the costs for #2 oil is $2.75/gallon, based on personal conversation with Karl Kowitz. The total oil consumption is 2031 gallons for academic year 2014 to 2015 and 1928 gallons for academic year 2015 to 2016 (obtained from personal conversation with Gary Hartwell). An average of 1979.5 gallons is used and assumed as the annual oil consumption for thirty years. An escalation rate is manually calculated using data provided by the EIA database. The rate for #2 oil on April 16th, 2009 is $1.422/gallon, while the rate on April 16th, 2019 is $2.082 [1]. Equation 4.4 is used to manually calculate the escalation rate, which is 4% for #2 oil.

The consumption of electricity for the heat pumps and water pumps is calculated for options 2, 3 and 4 in the same way as described in Section 3.2.5 by assuming these pumps are in operation full day for the entire heating season of 8 months, which is likely to be an overestimation. After buildings have been retrofitted, an efficiency increase and a drop in heating demand may lead to less number of borehole BHEs. The cost of electricity is $0.155/kWh and will escalates to $0.187/kWh in year 20 (obtained from personal conversation with Karl Kowitz). An approach similar to oil discount rate calculation is used and a discount rate is calculated manually using Equation 4.2, as 1%.

4.2.2 Results and Comparisons

Figure 4.4 illustrates the total present worth for all four design and retrofit options. A medium retrofit reduces 17.2% of total annual heating demand (Appendix E.2), while a deep retrofit reduces 28.9% (Appendix E.3). The total present worth of three geothermal design options are ranked from high to low as Geothermal + Medium >Geothermal + Deep >Geothermal only, which indicates that a medium degree retrofit is both costly, on average $6/ft^2$ more than a geothermal-only option, and inadequate in effective energy reduction, more than 10% less energy reduction than a deep retrofit option (Full LCC calculation table in Appendix G).

	Current	Geothermal	Geothermal + Medium	Geothermal + Deep
		Capital Cost		
Installation		$138,000.00	$138,000.00	$92,000.00
Retrofit			$68,035.20	$88,251.05
window replacement			$51,000.00	$51,000.00
attic insulation/sealing			$17,035.20	$17,035.20
envelope insulation				$18,775.85
envelope sealing				$1,440.00
Total Capital Cost	$0.00	$138,000.00	$206,035.20	$180,251.05
		Annual Cost		
Oil Purchase	$5,443.63			
Electricity Purchase		$5,714.84	$4,770.55	$4,316.12
Total Annual Cost	$5,443.63	$5,714.84	$4,770.55	$4,316.12
		Present Worth		
Capital Cost - > Present Worth	$0.00	$138,000.00	$206,035.20	$180,251.05
Annual Cost -> Present Worth	$94,131.16	$147,486.79	$123,116.97	$111,389.04
Discount Rate for Annual	4.00%	1.00%	1.00%	1.00%
Present Worth Factor for Annual	17.29	25.81	25.81	25.81
Total Present Worth	$94,131.16	$285,486.79	$329,152.17	$291,640.09
S.F. Cost	$13.88	$42.10	$48.54	$43.01

Figure 4.4: Life Cycle Cost Calculation for Four Design + Retrofit Options

Figures 4.5 and 4.6 show the overall comparison of present worth and present worth per square foot of the four options. Cost per square foot is very close for a system with only the geothermal system and that with a deep level retrofit. This is achieved because the amount of heating reduction a deep retrofit is able to accomplish is enough to reduce the number of wells from three to two, which reduces the overall electricity consumption of the pumps. Specifically, while the capital cost is higher for a deep retrofit option, due to a total cost of $88,251 on the deep retrofit, annual electricity consumption of the pumps drastically reduces compared to the options with three heat pumps as specific heat pump power is shown in Table 4.1.

Overall, there are several points worth noticing. First, the total cost of any geothermal system is significantly larger than the original oil-based system. This is due to a shift from oil to electricity as well as a capital investment for the GSHP system, where as the initial installation of the existing boilers system is not included in the LCC calculations and still has significant life remaining.

For future geothermal system designs, borehole configurations with higher efficiency and control methods such as system dynamic control and thermal modeling should be considered in order to maximize system thermal performance to reduce unnecessary annual and capital cost. In order to optimize the cost-benefit relationship between building retrofit and building system design/upgrade, thorough simulation of building retrofit consequences should be made and quantified in terms of energy reduction as well as life cycle cost reduction. This ties into the third point, which is that based on results from the LCC and cost-benefit studies of the four options, a medium level building retrofit is not recommended as an action towards effective energy reduction nor cost reduction, as the total

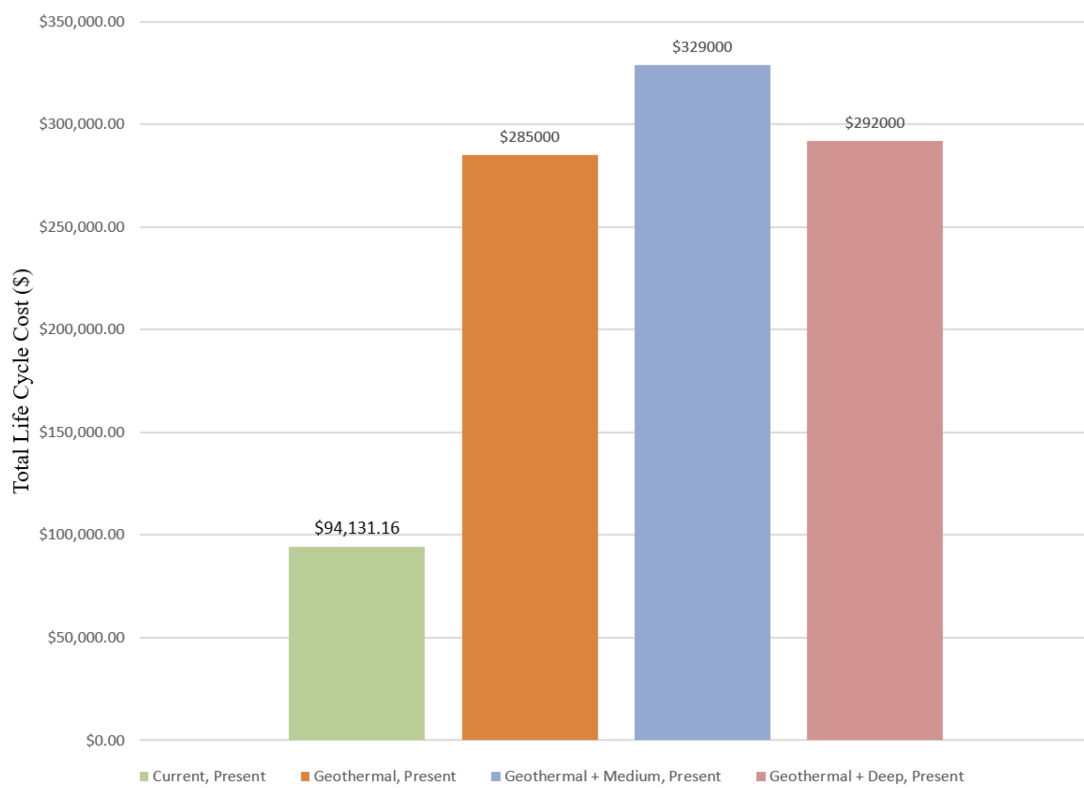


Figure 4.5: Total Life Cycle Present Worth Comparisons For Four Design and Retrofit Options at Year 30

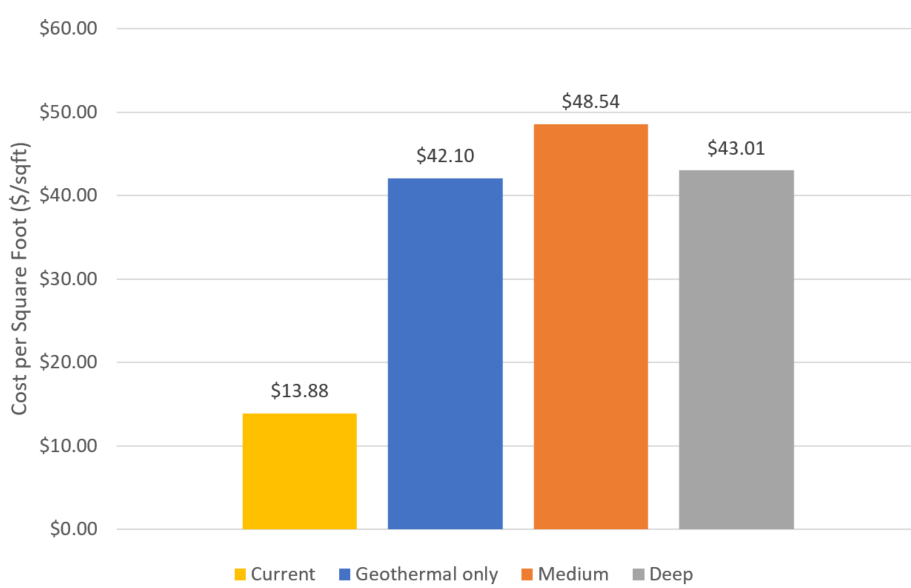


Figure 4.6: Total Life Cycle Present Worth per Square Foot For Four Design and Retrofit Options

cost for a medium option ranks the highest among the four options over a period of thirty years. Perhaps, an “all or nothing” strategy should be adopted. Load bearing masonry buildings should not be retrofit at all, unless a deep level retrofit is performed. The reasoning for a geothermal only system is its economic viability, while a deep level retrofit is beneficial from both the environmental and economic perspectives.

Chapter 5

Conclusion and Future Work

This chapter concludes the thesis work on building energy simulation, ground source heat pump system design and life cycle cost analysis for the Field House. Directions for future work are also identified.

5.1 Conclusion

The goal of this thesis was to (1) design a vertical ground source heat pump system for the Smith College Field House and (2) conduct life cycle costs analysis over a period of thirty years and compare calculated cost-benefits of four different design coupled retrofit options.

A building energy model of the Field House was constructed in Trace 700 following a procedure of 1) information acquisition, 2) sensitivity analysis of unknown parameters, and 3) model calibration. The model was validated against oil consumption data. A sensitivity analysis identified eight sensitive unknown design parameters including wall construct, ventilation and infiltration rate, window, wall and floor u-factor and wall height. Assumptions about these parameters are made, with additional adjustments made for the geometry of the basement and the domestic hot water usage. The model was tuned to existing oil usage data for academic year 2014-2015 and 2015-2016. A calibrated model estimates a total energy consumption of 286,498 kBTU/yr, which is within 4% difference from the oil data.

The design and calculation process of a GSHP was discussed and two of the five most important design variables were selected as the borehole thermal resistance and the mass flow of the circulating fluid. The overall design included the calculation and assumptions for five key parameters, namely the total and individual borehole flow rate, borehole thermal resistance, total borehole length, number of boreholes and the power of the water and heat pumps. Two methods of borehole length calculation, one that incorporates only one set of heating demand and the other accounts for three heating demands over a different period of time, were compared. The effect of thermal interference was briefly addressed quantitatively by the temperature penalty. A final design specifies the system setup of three boreholes at 600 ft, with a flow rate of 2.4 gpm per well coupled with three heat pumps of 0.6 tons.

A life cycle cost analysis was conducted over a period of thirty years for four design options, including (1) the current oil-based system, (2) a GSHP system with no building retrofit (3) a GSHP system with medium level building retrofit and (4) a GSHP system with deep level building retrofit. The GSHP only option required the least total converted present worth, $285,486, among the three geothermal based design options, closely followed by GSHP + Deep of $291,640, which also reduced the annual heating demand by 28.9%. Recommendations regarding the level of retrofit were given for future design projects. Specifically, an "all or nothing" strategy was proposed that suggested either not to retrofit or retrofit at a deep level. Additional observations were also made about the significant increase in cost from an oil-based system to a geothermal based system, which could be alleviated by designing systems of higher energy efficiency.

5.2 Future Work

Three potential directions for future work are identified. First, a thermal modeling of the borehole temperature profile is recommended, to provide a quantitative study of the thermal behavior of a BHE. More specifically, a control-oriented model can be used to monitor and respond to system changes quickly, which has the potential to improve the system efficiency. Temperature sensoring along the depth of the borehole wells to obtain more accurate thermal profiles of the ground is also an area for future work. It is expected that a borehole will be drilled and instrumented during the summer of 2019. These results have influenced the decision not to retrofit the building prior to installation of the GSHP system.

In addition, other renewable energy sources can be incorporated in the design. For instance, the electricity needed for the three 0.6 ton heat pumps can be generated by a PV system. Prior design of a PV system for electricity generation has been made for the Field House, the documentation of which is attached in Appendix I for future reference.

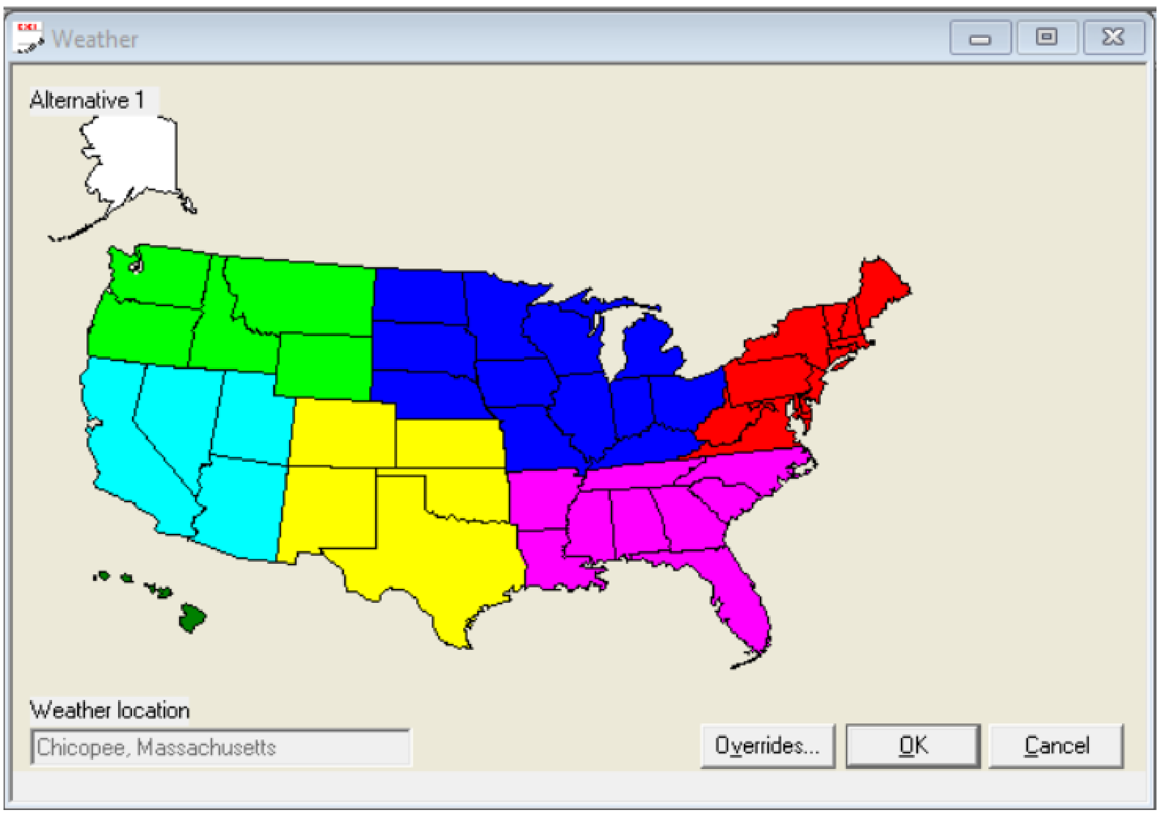
Finally, as analyzed in Chapter 4, a deep level retrofit has the potential in reducing both system cost and energy demand. Future work is recommended to study the benefits of a deep retrofit at a more detailed level. For instance, studies can be done to identify the most optimal framework in devising a retrofit plan and selecting building attributes to retrofit. Life cycle cost analysis can also be conducted to compare more retrofit options, such as area-specific retrofits focusing on only the mechanical or the ventilation system, or a complete rebuild of a facility.

Appendices

Appendix A

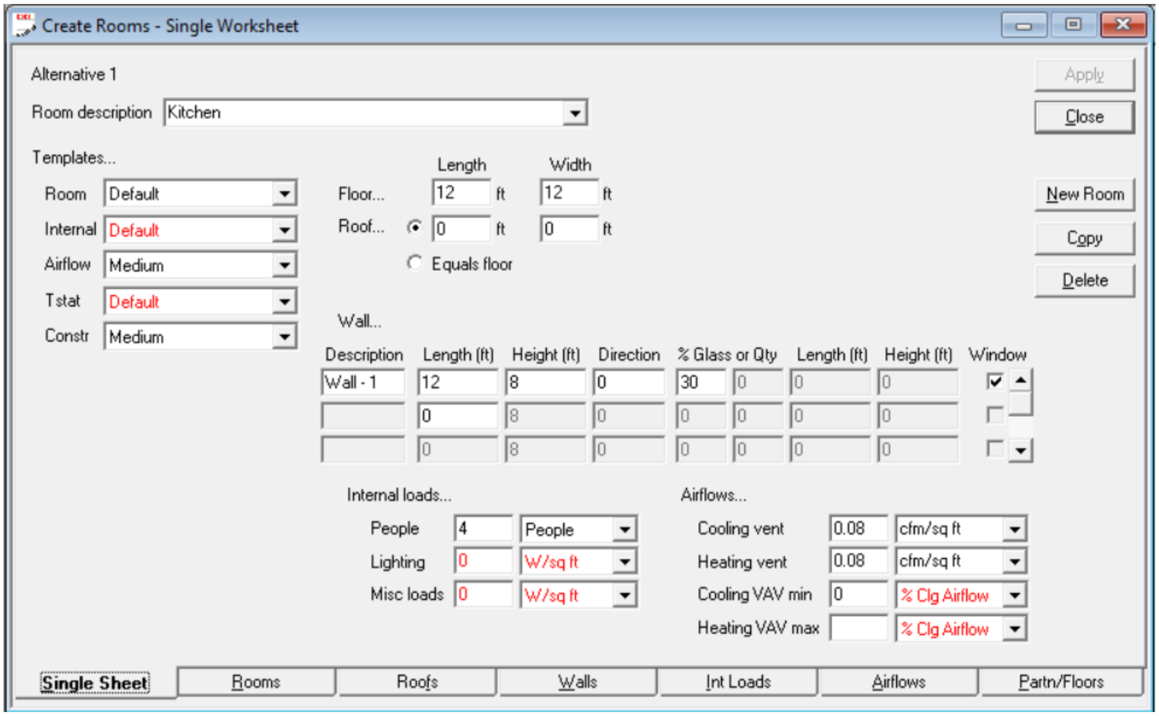
Trace 700 Model Inputs

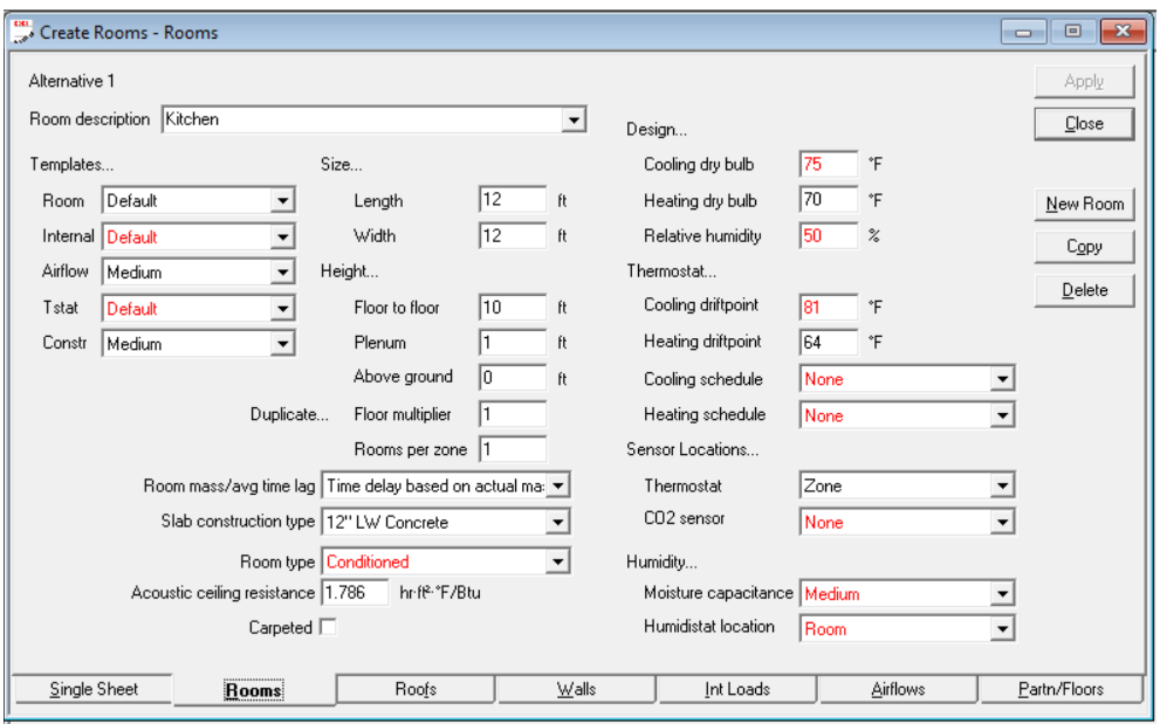
A.1 Weather Information

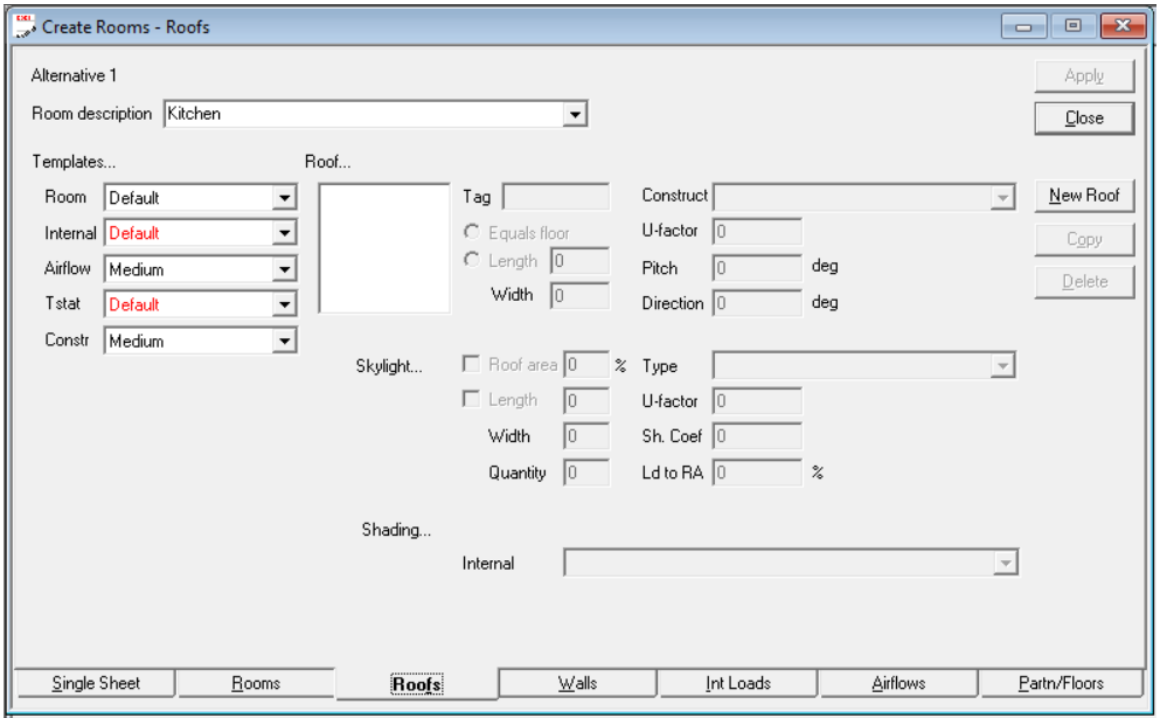


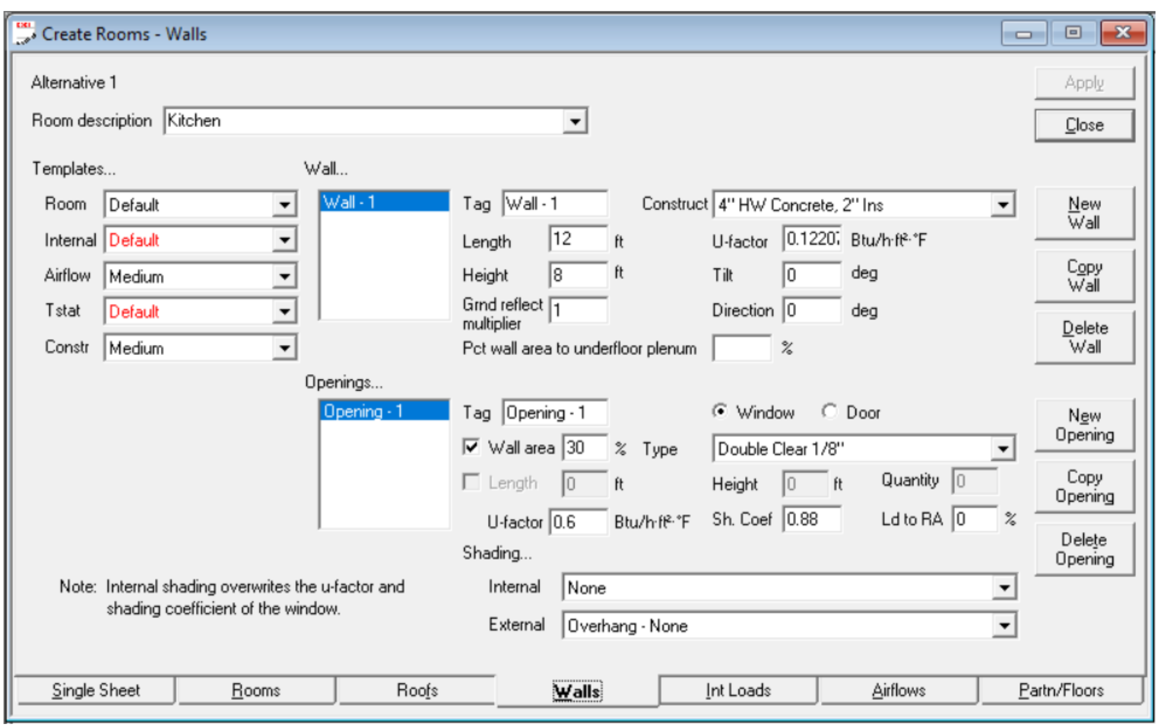
A.2 Rooms

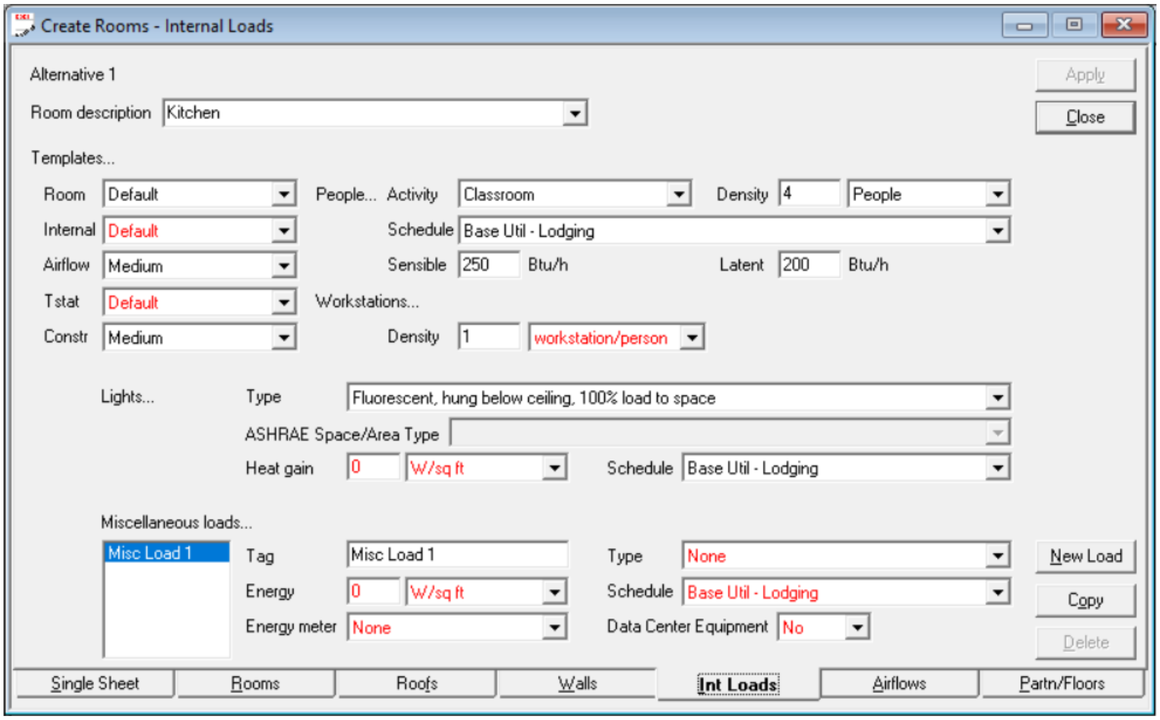
A.2.1 Kitchen

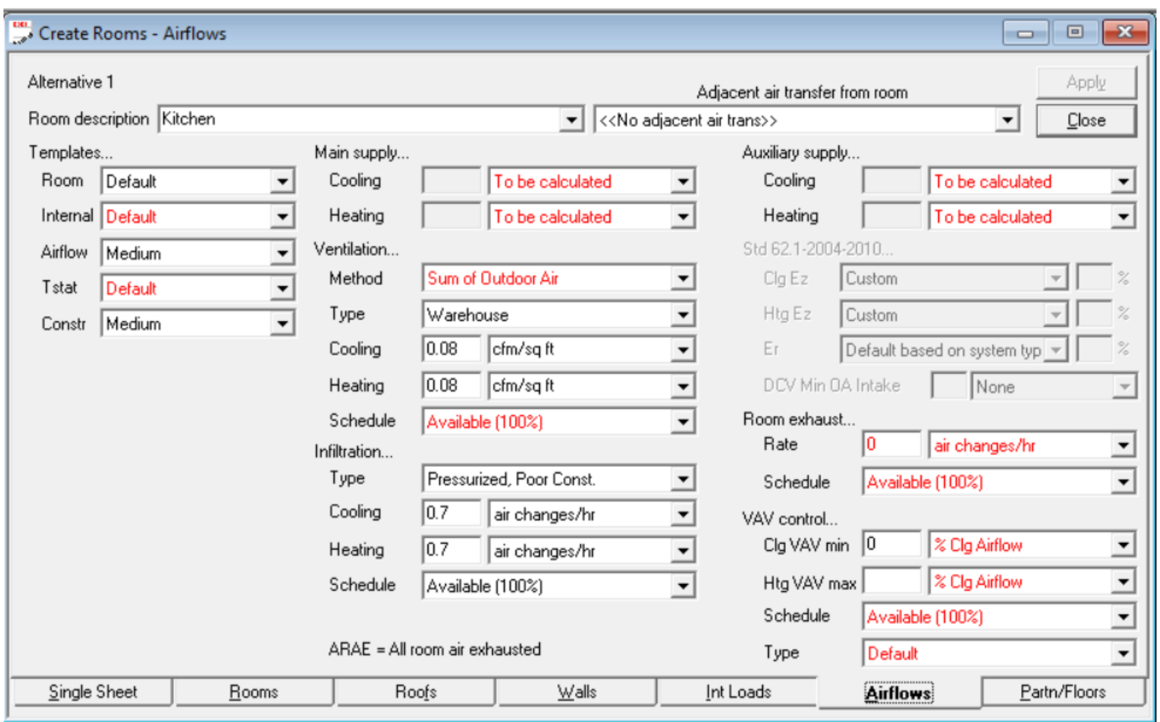

Create Rooms - Single Worksheet
Alternative 1
Room description Kitchen
Apply
Close
New Room
Copy
Delete
Templates...
Room Default
Internal Default
Airflow Medium
Tstat Default
Constr Medium
Length Width
Floor... 12 ft 12 ft
Roof... 0 ft 0 ft
Equals floor
Wall...
Description Length (ft) Height (ft) Direction % Glass or Qty Length (ft) Height (ft) Window
Wall - 1 12 8 0 30 0 0 0
Internal loads...
People 4 People
Lighting 0 W/sq ft
Misc loads 0 W/sq ft
Airflows...
Cooling vent 0.08 cfm/sq ft
Heating vent 0.08 cfm/sq ft
Cooling VAV min 0 % Clg Airflow
Heating VAV max % Clg Airflow
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

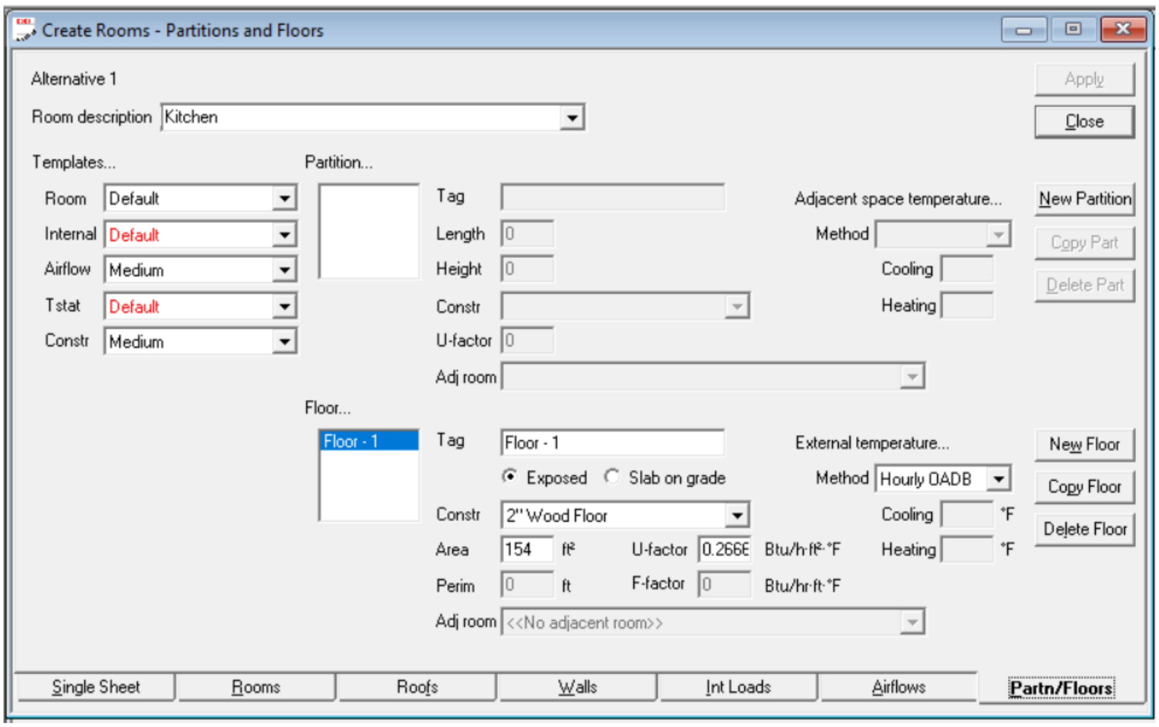

Create Rooms - Rooms
Alternative 1
Room description Kitchen
Apply
Close
New Room
Copy
Delete
Templates...
Room Default
Internal Default
Airflow Medium
Tstat Default
Constr Medium
Size...
Length 12 ft
Width 12 ft
Height...
Floor to floor 10 ft
Plenum 1 ft
Above ground 0 ft
Duplicate...
Floor multiplier 1
Rooms per zone 1
Room mass/avg time lag Time delay based on actual ma:
Slab construction type 12" LW Concrete
Room type Conditioned
Acoustic ceiling resistance 1.786 hr·ft²·°F/Btu
Carpeted
Design...
Cooling dry bulb 75 °F
Heating dry bulb 70 °F
Relative humidity 50 %
Thermostat...
Cooling driftpoint 81 °F
Heating driftpoint 64 °F
Cooling schedule None
Heating schedule None
Sensor Locations...
Thermostat Zone
CO2 sensor None
Humidity...
Moisture capacitance Medium
Humidistat location Room
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Roofs
Alternative 1
Apply
Room description
Kitchen
Close
Templates...
Roof...
Room
Default
Internal
Default
Airflow
Medium
Tstat
Default
Constr
Medium
Tag
Equals floor
Length
Width
Construct
U-factor
Pitch
Direction
deg
deg
New Roof
Copy
Delete
Skylight...
Roof area
%
Type
U-factor
Sh. Coef
Ld to RA
Quantity
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

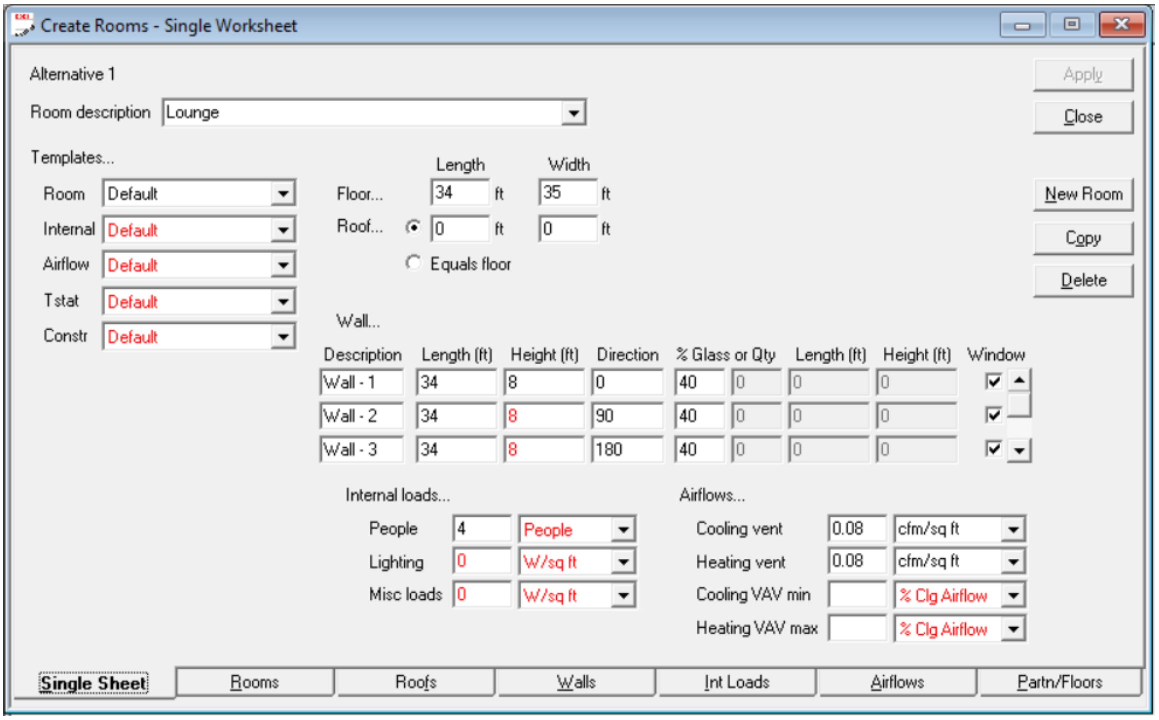

Create Rooms - Walls
Alternative 1
Apply
Room description
Kitchen
Close
Templates...
Wall...
Room
Default
Internal
Default
Airflow
Medium
Tstat
Default
Constr
Medium
Wall - 1
Tag
Wall - 1
Construct
4" HW Concrete, 2" Ins
New Wall
Length
12
ft
U-factor
0.1220
Btu/h·ft²·°F
Height
8
ft
Tilt
0
deg
Copy Wall
Grnd reflect multiplier
1
Direction
0
deg
Delete Wall
Pct wall area to underfloor plenum
%
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
New Opening
Wall area
30
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
Copy Opening
U-factor
0.6
Btu/h·ft²·°F
Sh. Coef
0.88
Ld to RA
0
%
Delete Opening
Shading...
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Internal
None
External
Overhang - None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

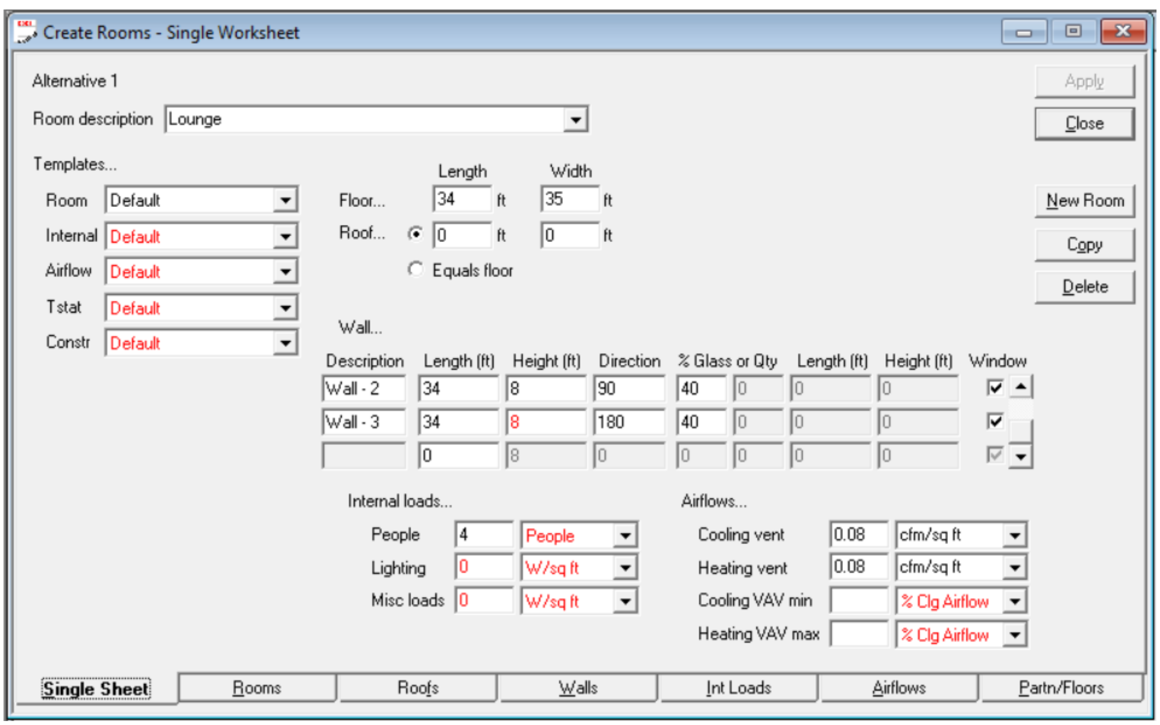

Create Rooms - Internal Loads
Alternative 1
Apply
Close
Room description Kitchen
Templates...
Room Default
Internal Default
Airflow Medium
Tstat Default
Constr Medium
People... Activity Classroom
Density 4 People
Schedule Base Util - Lodging
Sensible 250 Btu/h
Latent 200 Btu/h
Workstations...
Density 1 workstation/person
Lights... Type Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain 0 W/sq ft
Schedule Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag Misc Load 1
Type None
New Load
Energy 0 W/sq ft
Schedule Base Util - Lodging
Copy
Energy meter None
Data Center Equipment No
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

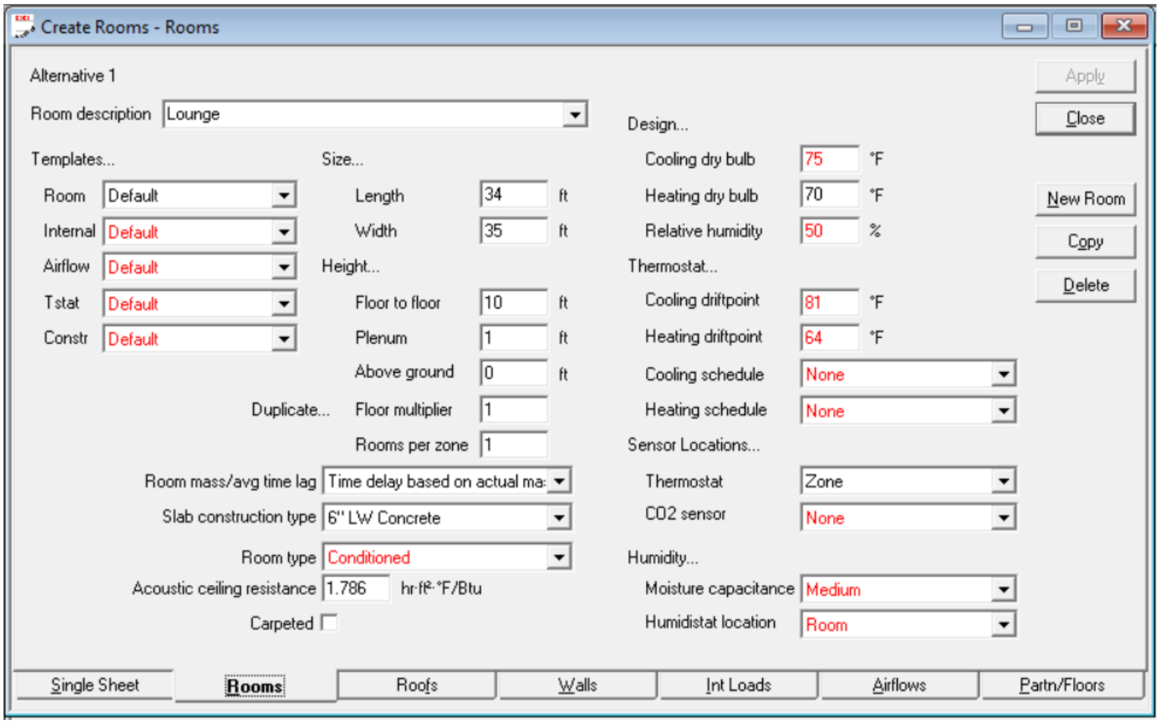

Create Rooms - Airflows
Alternative 1
Adjacent air transfer from room
Apply
Room description Kitchen
<<No adjacent air trans>>
Close
Templates...
Room Default
Internal Default
Airflow Medium
Tstat Default
Constr Medium
Main supply...
Cooling To be calculated
Heating To be calculated
Ventilation...
Method Sum of Outdoor Air
Type Warehouse
Cooling 0.08 cfm/sq ft
Heating 0.08 cfm/sq ft
Schedule Available (100%)
Infiltration...
Type Pressurized, Poor Const.
Cooling 0.7 air changes/hr
Heating 0.7 air changes/hr
Schedule Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling To be calculated
Heating To be calculated
Std 62.1-2004-2010...
Clg Ez Custom
Htg Ez Custom
Er Default based on system typ
DCV Min OA Intake None
Room exhaust...
Rate 0 air changes/hr
Schedule Available (100%)
VAV control...
Clg VAV min 0 % Clg Airflow
Htg VAV max % Clg Airflow
Schedule Available (100%)
Type Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

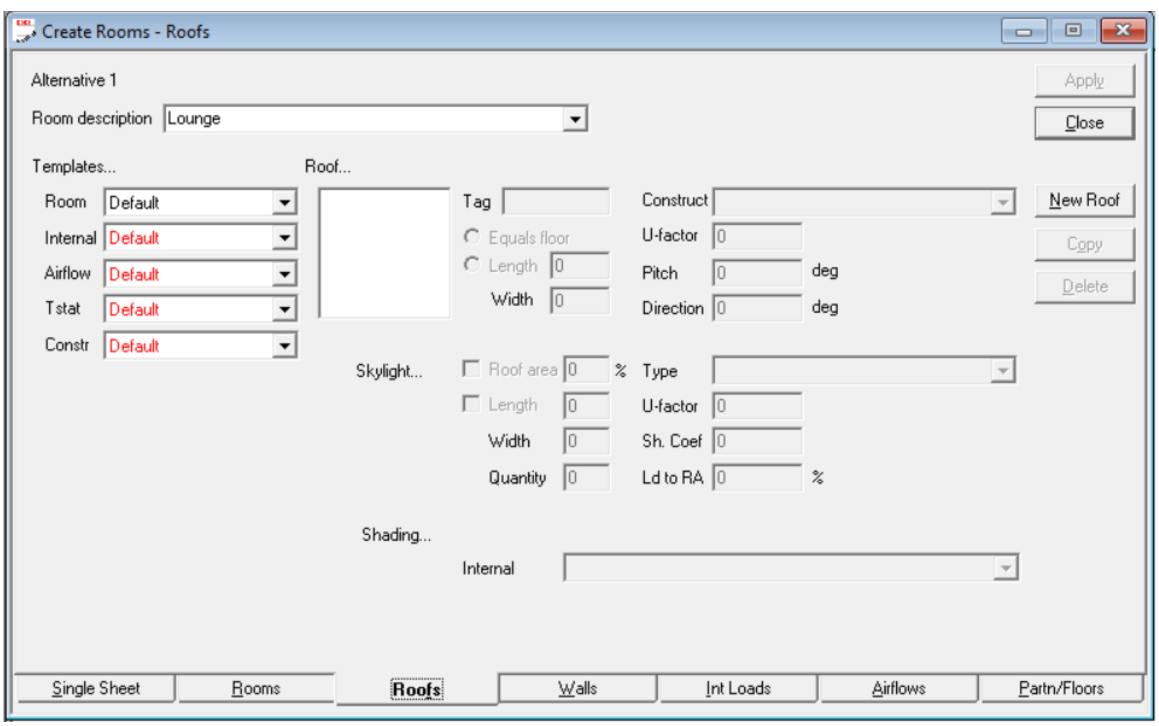

Create Rooms - Partitions and Floors
Alternative 1
Room description
Kitchen
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Medium
Tstat
Default
Constr
Medium
Partition...
Tag
Length
Height
Constr
U-factor
Adj room
Adjacent space temperature...
Method
Cooling
Heating
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" Wood Floor
Area
154
ft²
U-factor
0.2666
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Hourly OADB
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

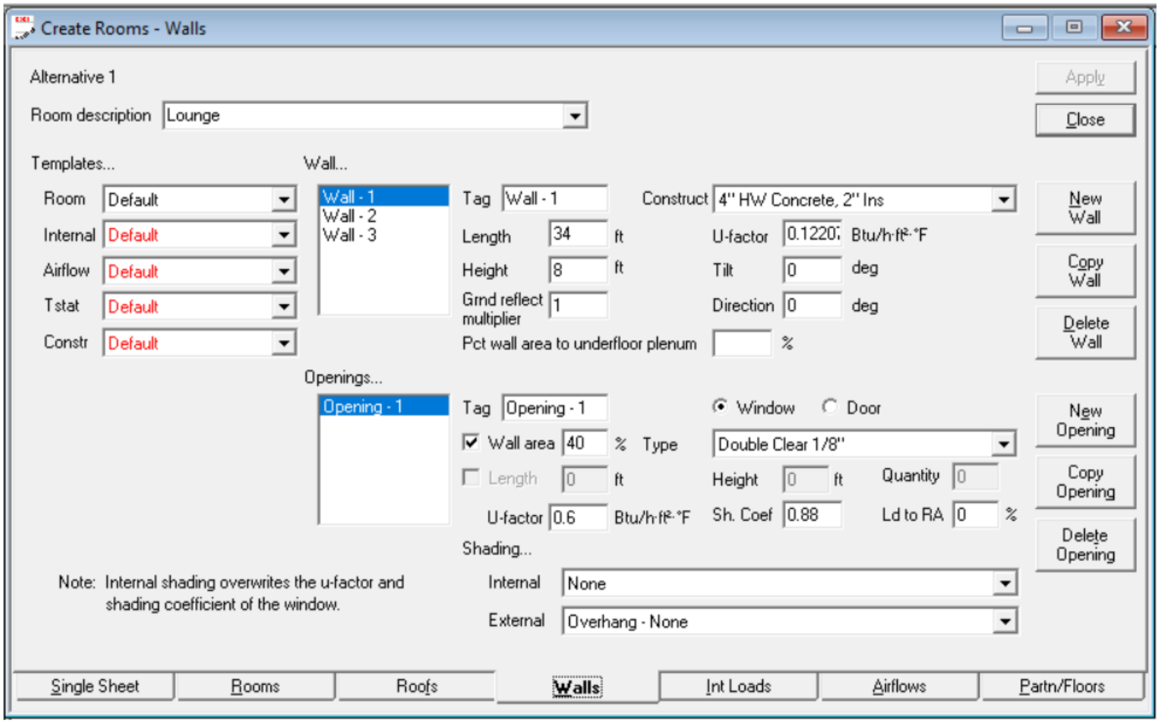
A.2.2 Lounge

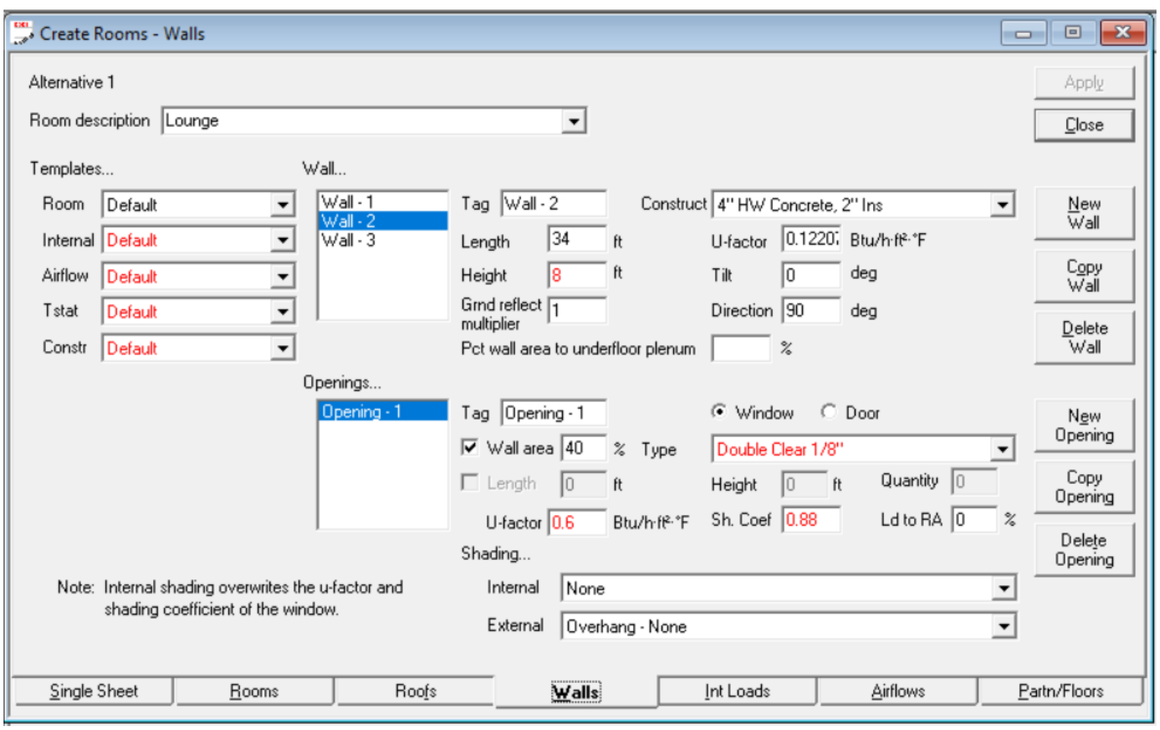

Create Rooms - Single Worksheet
Alternative 1
Room description
Lounge
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Length
Width
Floor...
34
ft
35
ft
Roof...
0
ft
0
ft
Equals floor
New Room
Copy
Delete
Wall...
Description
Length (ft)
Height (ft)
Direction
% Glass or Qty
Length (ft)
Height (ft)
Window
Wall - 1
34
8
0
40
Wall - 2
34
8
90
40
Wall - 3
34
8
180
40
Internal loads...
People
4
People
Lighting
0
W/sq ft
Misc loads
0
W/sq ft
Airflows...
Cooling vent
0.08
cfm/sq ft
Heating vent
0.08
cfm/sq ft
Cooling VAV min
% Clg Airflow
Heating VAV max
% Clg Airflow
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

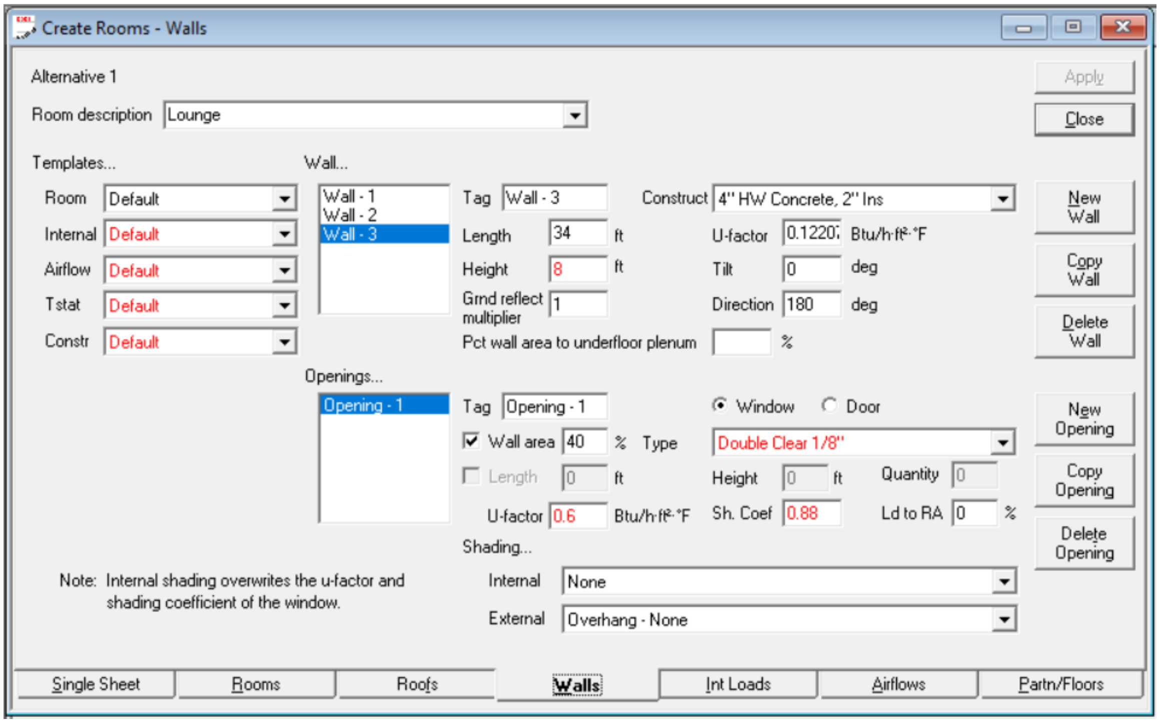

Create Rooms - Single Worksheet
Alternative 1
Room description
Lounge
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Length
Width
Floor...
34
ft
35
ft
Roof...
0
ft
0
ft
Equals floor
New Room
Copy
Delete
Wall...
Description
Length (ft)
Height (ft)
Direction
% Glass or Qty
Length (ft)
Height (ft)
Window
Wall - 2
34
8
90
40
Wall - 3
34
8
180
40
Internal loads...
People
4
People
Lighting
0
W/sq ft
Misc loads
0
W/sq ft
Airflows...
Cooling vent
0.08
cfm/sq ft
Heating vent
0.08
cfm/sq ft
Cooling VAV min
% Clg Airflow
Heating VAV max
% Clg Airflow
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

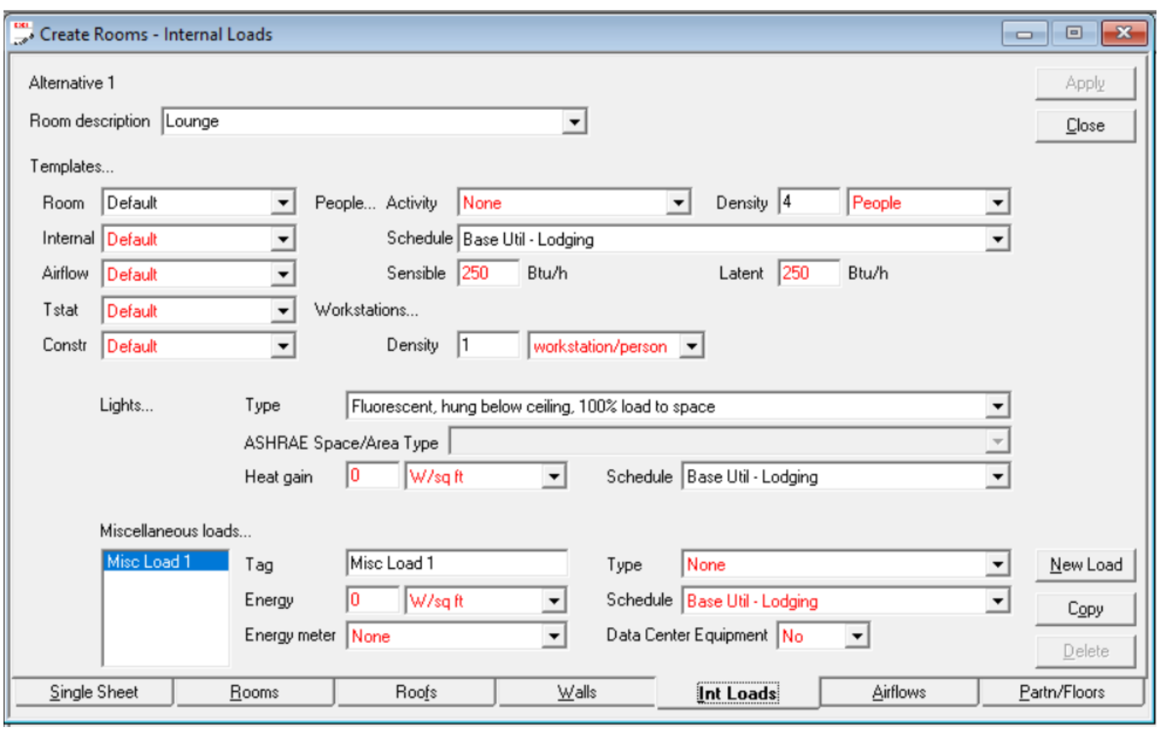

Create Rooms - Rooms
Alternative 1
Room description Lounge
Apply
Close
Design...
Templates...
Size...
Cooling dry bulb 75 °F
Room Default
Length 34 ft
Heating dry bulb 70 °F
New Room
Internal Default
Width 35 ft
Relative humidity 50 %
Copy
Airflow Default
Height...
Thermostat...
Tstat Default
Floor to floor 10 ft
Cooling driftpoint 81 °F
Delete
Constr Default
Plenum 1 ft
Heating driftpoint 64 °F
Above ground 0 ft
Cooling schedule None
Duplicate...
Floor multiplier 1
Heating schedule None
Rooms per zone 1
Sensor Locations...
Room mass/avg time lag Time delay based on actual ma
Thermostat Zone
Slab construction type 6" LW Concrete
CO2 sensor None
Room type Conditioned
Humidity...
Acoustic ceiling resistance 1.786 hr·ft²·°F/Btu
Moisture capacitance Medium
Carpeted
Humidistat location Room
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

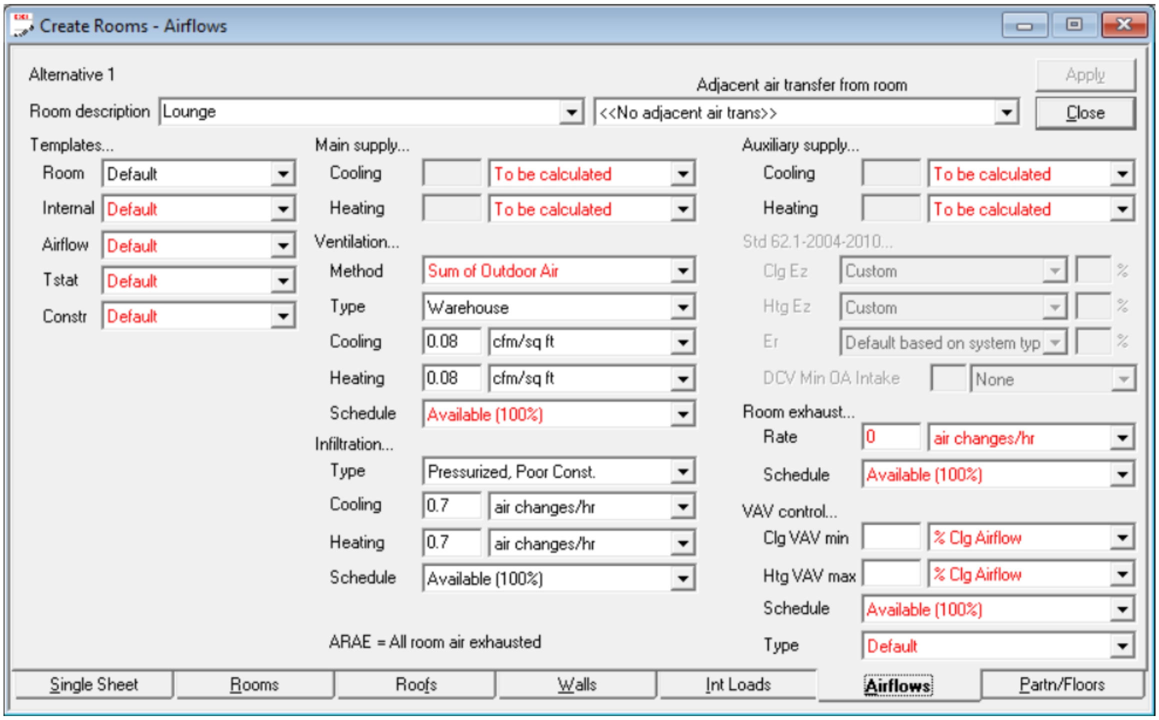

Create Rooms - Roofs
Alternative 1
Room description Lounge
Apply
Close
Templates...
Roof...
Room Default
Tag
Construct
New Roof
Internal Default
Equals floor
U-factor 0
Copy
Airflow Default
Length 0
Pitch 0 deg
Delete
Tstat Default
Width 0
Direction 0 deg
Constr Default
Skylight...
Roof area 0 %
Type
Length 0
U-factor 0
Width 0
Sh. Coef 0
Quantity 0
Ld to RA 0 %
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

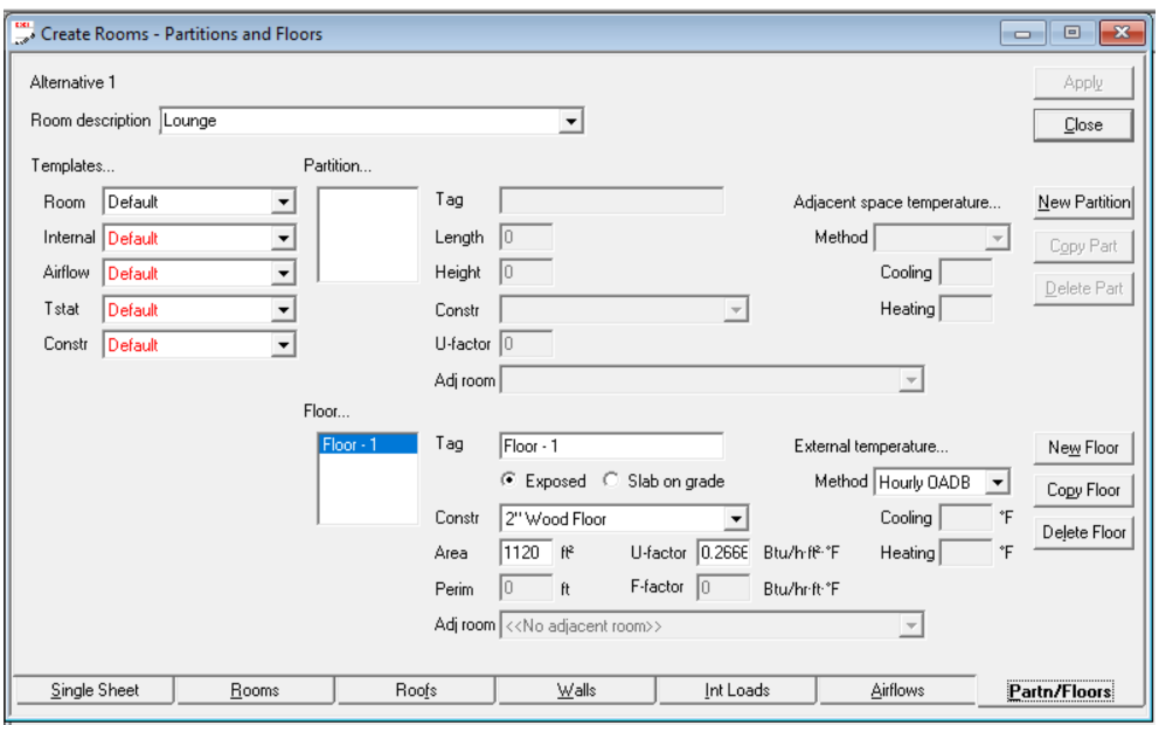

Create Rooms - Walls
Alternative 1
Room description Lounge
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Wall...
Wall - 1
Wall - 2
Wall - 3
Tag Wall - 1
Construct 4" HW Concrete, 2" Ins
Length 34 ft
U-factor 0.1220 Btu/h·ft²·°F
Height 8 ft
Tilt 0 deg
Grnd reflect multiplier 1
Direction 0 deg
Pct wall area to underfloor plenum %
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag Opening - 1
Window Door
Wall area 40 % Type Double Clear 1/8"
Length 0 ft
Height 0 ft
Quantity 0
U-factor 0.6 Btu/h·ft²·°F
Sh. Coef 0.88
Ld to RA 0 %
Shading...
Internal None
External Overhang - None
New Opening
Copy Opening
Delete Opening
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Walls
Alternative 1
Room description Lounge
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Wall...
Wall - 1
Wall - 2
Wall - 3
Tag Wall - 2
Construct 4" HW Concrete, 2" Ins
Length 34 ft
U-factor 0.1220 Btu/h·ft²·°F
Height 8 ft
Tilt 0 deg
Grnd reflect multiplier 1
Direction 90 deg
Pct wall area to underfloor plenum %
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag Opening - 1
Window Door
Wall area 40 % Type Double Clear 1/8"
Length 0 ft
Height 0 ft
Quantity 0
U-factor 0.6 Btu/h·ft²·°F
Sh. Coef 0.88
Ld to RA 0 %
Shading...
Internal None
External Overhang - None
New Opening
Copy Opening
Delete Opening
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

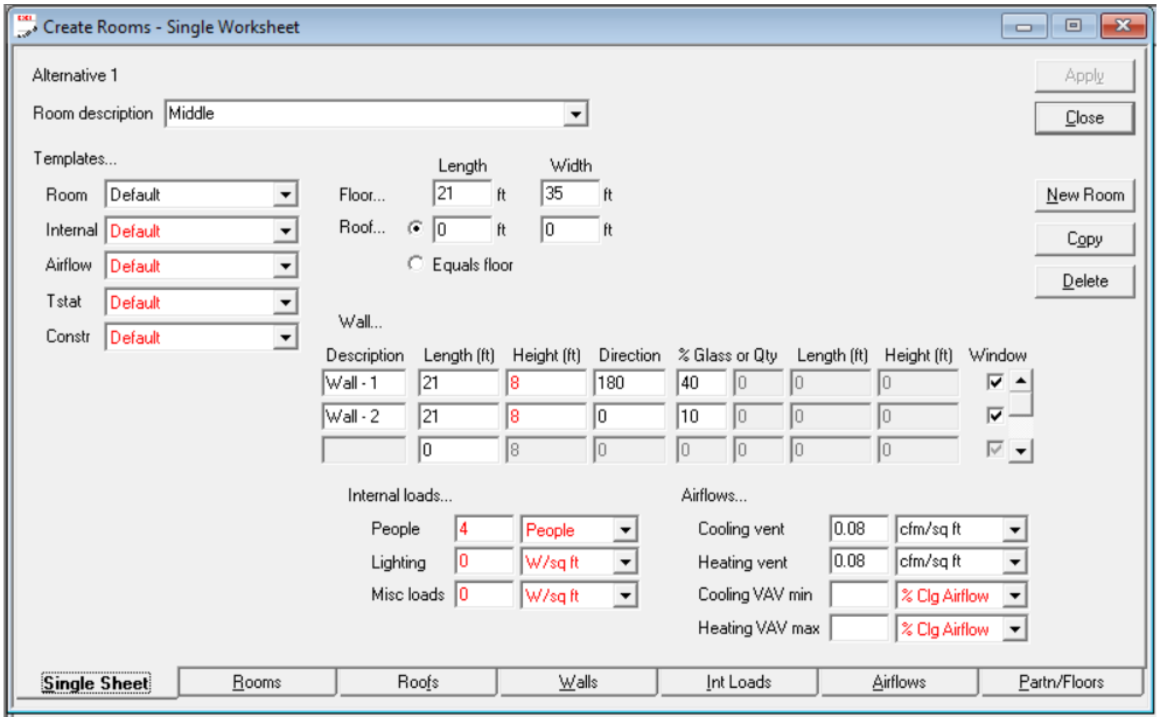

Create Rooms - Walls
Alternative 1
Room description
Lounge
Apply
Close
Templates...
Wall...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Wall - 1
Wall - 2
Wall - 3
Tag
Wall - 3
Construct
4" HW Concrete, 2" Ins
Length
34
ft
U-factor
Height
8
ft
Tilt
0
deg
Grnd reflect multiplier
1
Direction
180
deg
Pct wall area to underfloor plenum
%
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
Wall area
40
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
U-factor
0.6
Sh. Coef
0.88
Ld to RA
0
%
New Opening
Copy Opening
Delete Opening
Shading...
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Internal
None
External
Overhang - None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

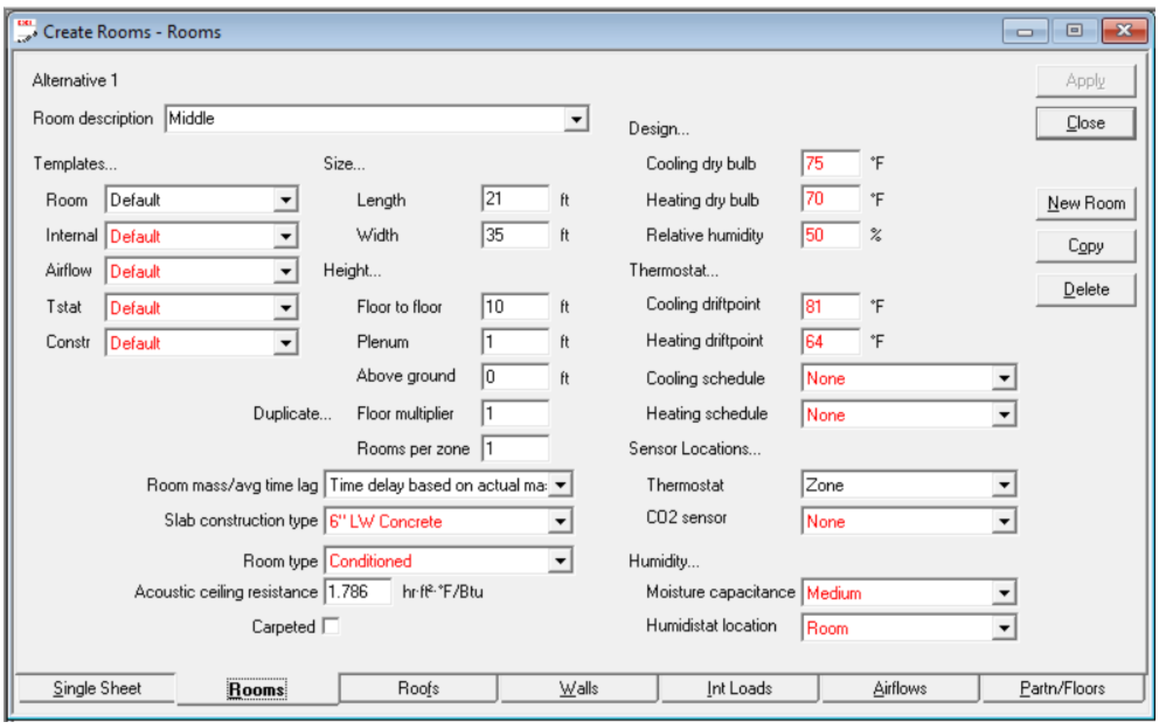

Create Rooms - Internal Loads
Alternative 1
Room description
Lounge
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
People...
Activity
None
Density
4
People
Schedule
Base Util - Lodging
Sensible
250
Btu/h
Latent
250
Btu/h
Workstations...
Density
1
workstation/person
Lights...
Type
Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain
0
W/sq ft
Schedule
Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag
Misc Load 1
Type
None
New Load
Energy
0
W/sq ft
Schedule
Base Util - Lodging
Copy
Energy meter
None
Data Center Equipment
No
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

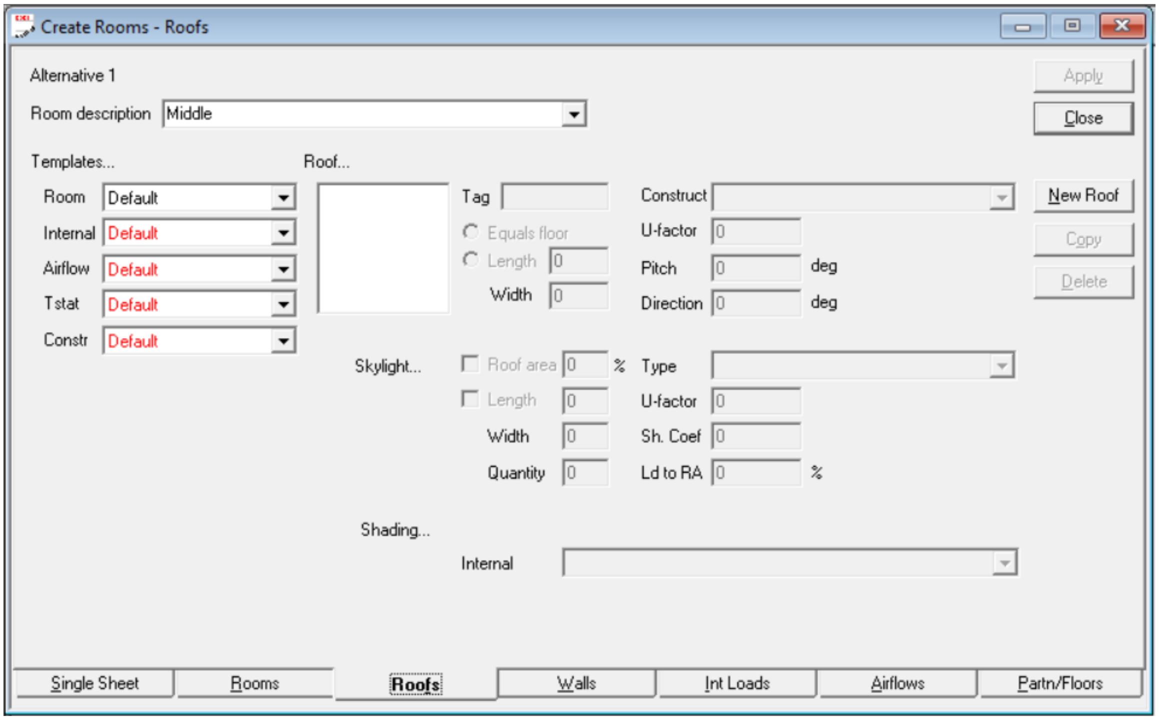

Create Rooms - Airflows
Alternative 1
Adjacent air transfer from room
Apply
Room description
Lounge
<<No adjacent air trans>>
Close
Templates...
Room
Default
Internal
Airflow
Tstat
Constr
Main supply...
Cooling
Heating
To be calculated
Ventilation...
Method
Sum of Outdoor Air
Type
Warehouse
0.08
cfm/sq ft
Schedule
Available (100%)
Infiltration...
Pressurized, Poor Const.
0.7
air changes/hr
Auxiliary supply...
Std 62.1-2004-2010...
Clg Ez
Custom
Htg Ez
Er
Default based on system typ
DCV Min OA Intake
None
Room exhaust...
Rate
0
VAV control...
Clg VAV min
% Clg Airflow
Htg VAV max
ARAE = All room air exhausted
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

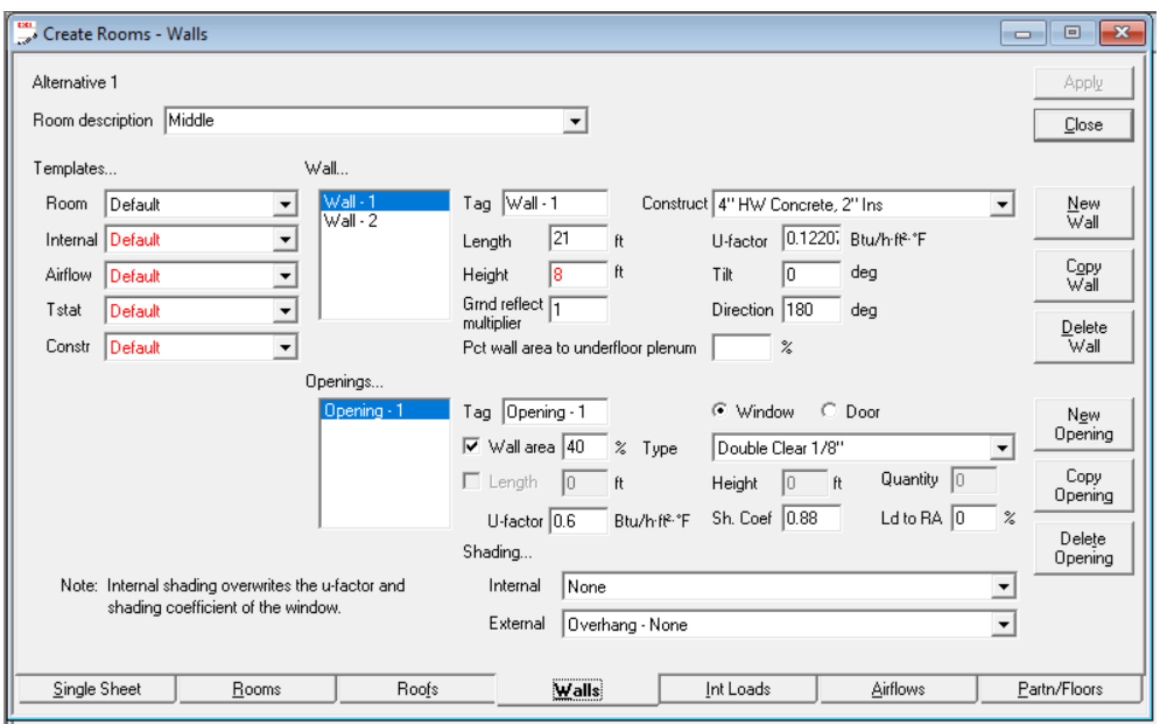

Create Rooms - Partitions and Floors
Alternative 1
Apply
Room description
Lounge
Close
Templates...
Partition...
Room
Default
Tag
Adjacent space temperature...
New Partition
Internal
Length
Method
Copy Part
Airflow
Height
Cooling
Delete Part
Tstat
Constr
Heating
U-factor
Adj room
Floor...
Floor - 1
External temperature...
New Floor
Exposed
Slab on grade
Hourly OADB
Copy Floor
2" Wood Floor
°F
Delete Floor
Area
1120
ft²
0.266E
Btu/h·ft²·°F
Perim
ft
F-factor
Btu/hr·ft·°F
<<No adjacent room>>
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

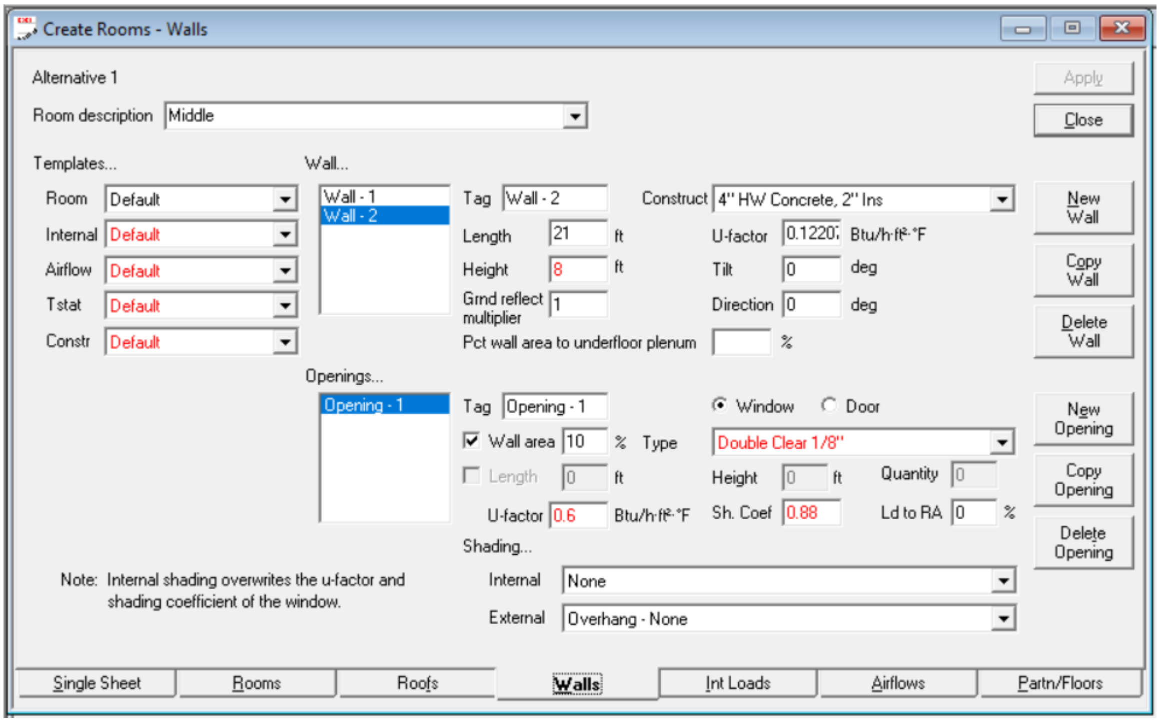
A.2.3 Middle

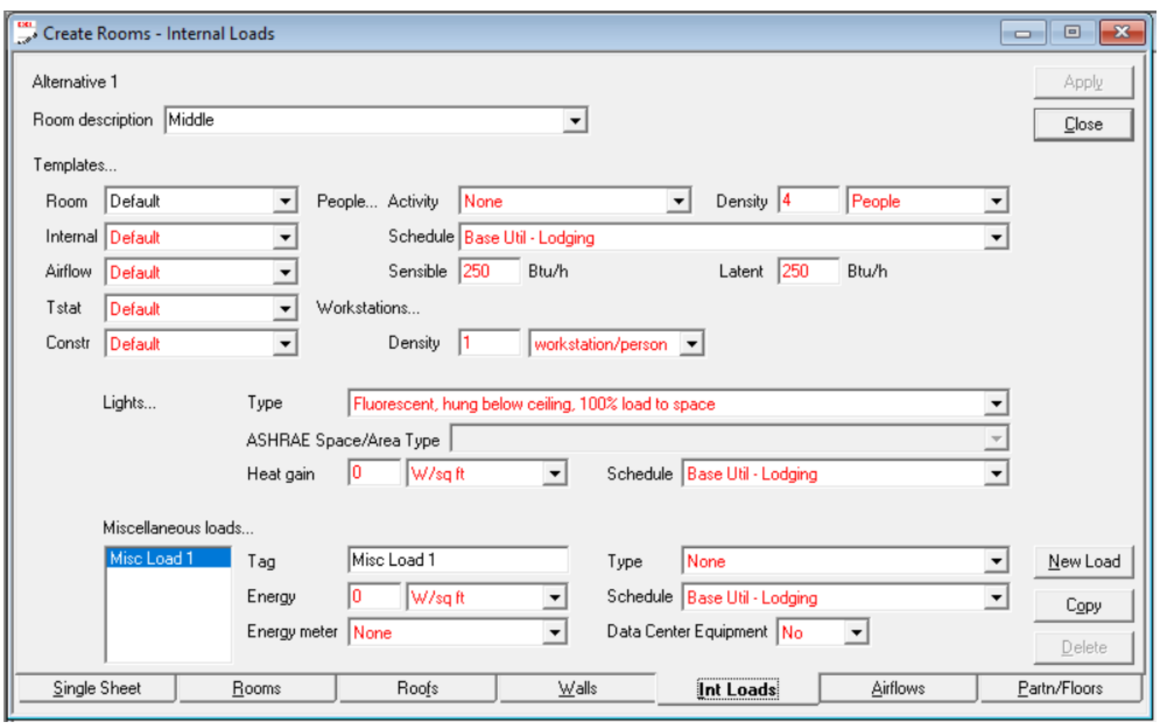

Create Rooms - Single Worksheet
Alternative 1
Room description
Middle
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Length
Width
Floor...
21
ft
35
ft
Roof...
0
ft
0
ft
Equals floor
New Room
Copy
Delete
Wall...
Description
Length (ft)
Height (ft)
Direction
% Glass or Qty
Length (ft)
Height (ft)
Window
Wall - 1
21
8
180
40
0
0
0
Wall - 2
21
8
0
10
0
0
0
0
8
0
0
0
0
0
Internal loads...
People
4
People
Lighting
0
W/sq ft
Misc loads
0
W/sq ft
Airflows...
Cooling vent
0.08
cfm/sq ft
Heating vent
0.08
cfm/sq ft
Cooling VAV min
% Clg Airflow
Heating VAV max
% Clg Airflow
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

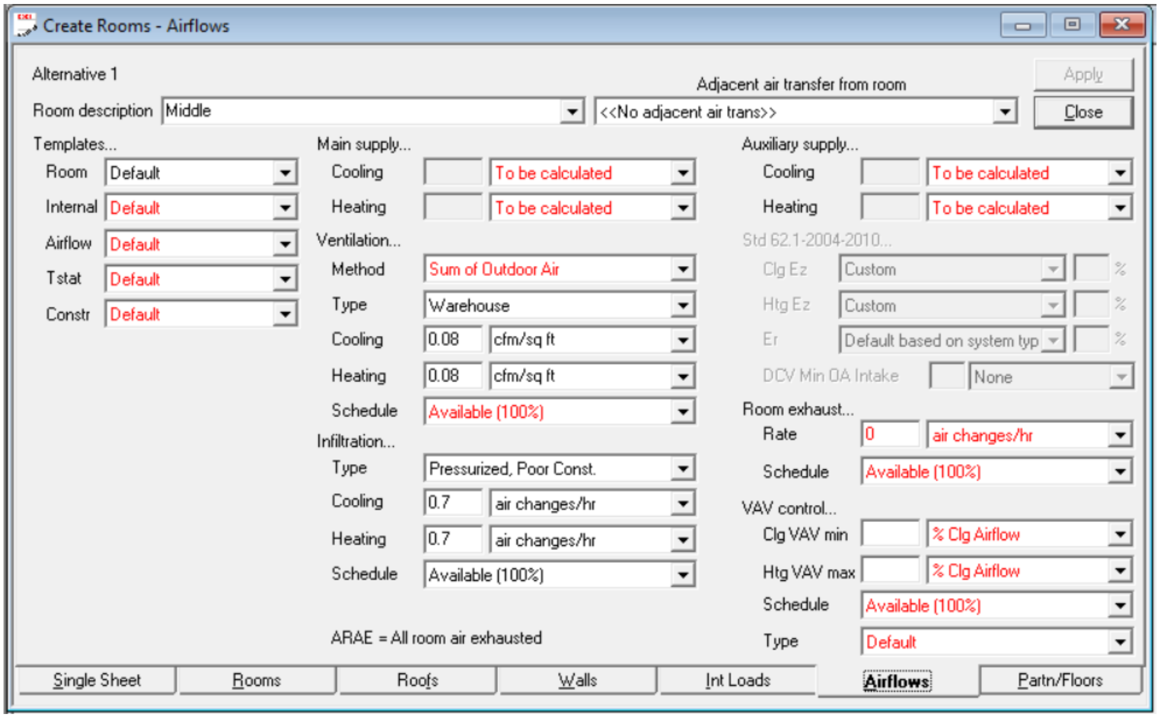

Create Rooms - Rooms
Alternative 1
Room description
Middle
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Size...
Length
21
ft
Width
35
ft
Height...
Floor to floor
10
ft
Plenum
1
ft
Above ground
0
ft
Duplicate...
Floor multiplier
1
Rooms per zone
1
Room mass/avg time lag
Time delay based on actual ma:
Slab construction type
6" LW Concrete
Room type
Conditioned
Acoustic ceiling resistance
1.786
hr·ft²·°F/Btu
Carpeted
Design...
Cooling dry bulb
75
°F
Heating dry bulb
70
°F
Relative humidity
50
%
Thermostat...
Cooling driftpoint
81
°F
Heating driftpoint
64
°F
Cooling schedule
None
Heating schedule
None
Sensor Locations...
Thermostat
Zone
CO2 sensor
None
Humidity...
Moisture capacitance
Medium
Humidistat location
Room
New Room
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

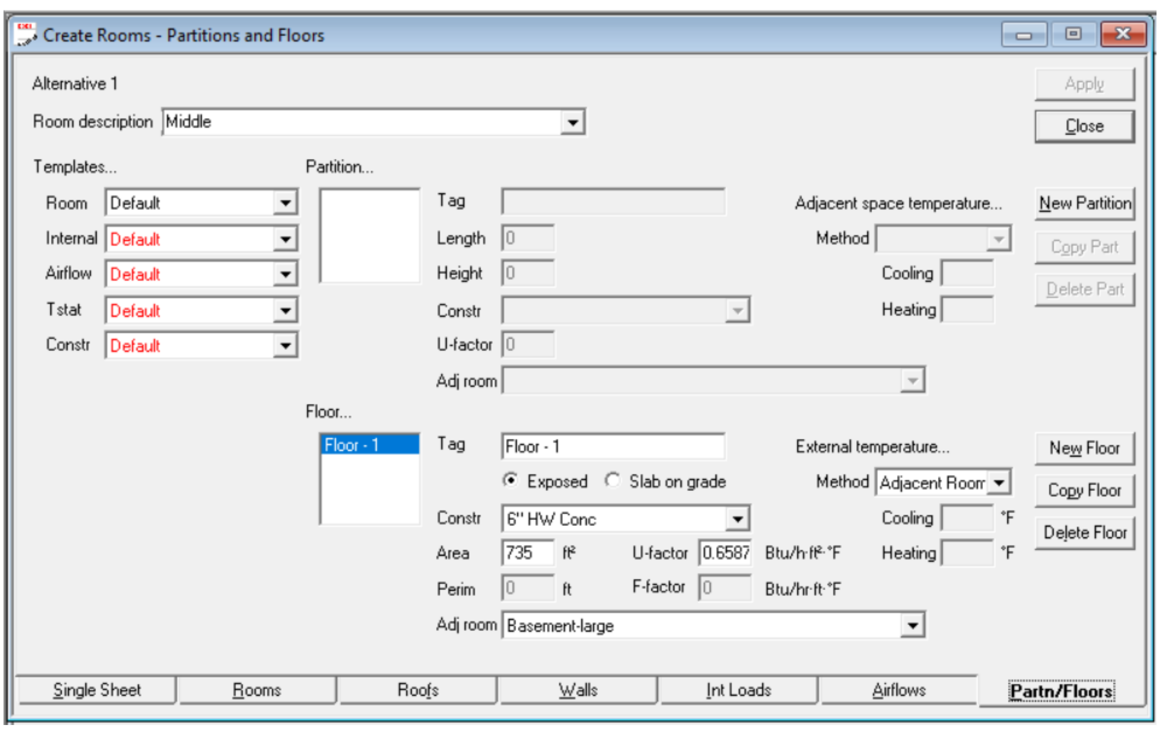

Create Rooms - Roofs
Alternative 1
Room description
Middle
Apply
Close
Templates...
Roof...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Tag
Equals floor
Length
Width
Construct
U-factor
Pitch
deg
Direction
deg
New Roof
Copy
Delete
Skylight...
Roof area
%
Type
Length
U-factor
Width
Sh. Coef
Quantity
Ld to RA
%
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Walls
Alternative 1
Room description
Middle
Apply
Close
Templates...
Wall...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Wall - 1
Wall - 2
Tag
Wall - 1
Construct
4" HW Concrete, 2" Ins
Length
21
ft
U-factor
0.1220
Btu/h·ft²·°F
Height
8
ft
Tilt
0
deg
Grnd reflect multiplier
1
Direction
180
deg
Pct wall area to underfloor plenum
%
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
Wall area
40
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
U-factor
0.6
Btu/h·ft²·°F
Sh. Coef
0.88
Ld to RA
0
%
New Opening
Copy Opening
Delete Opening
Shading...
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Internal
None
External
Overhang - None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

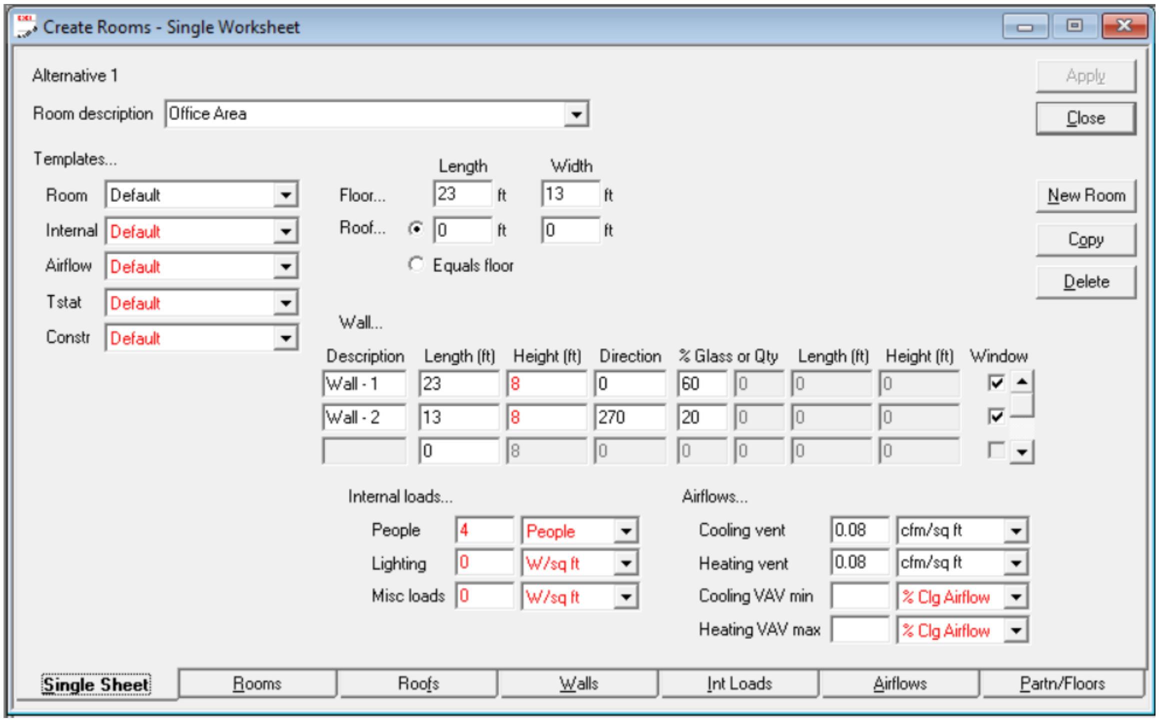

Create Rooms - Walls
Alternative 1
Room description
Middle
Apply
Close
Templates...
Room
Default
Internal
Airflow
Tstat
Constr
Wall...
Wall - 1
Wall - 2
Tag
Length
21
ft
Height
8
Grnd reflect multiplier
1
Construct
4" HW Concrete, 2" Ins
U-factor
Btu/h·ft²·°F
Tilt
0
deg
Direction
Pct wall area to underfloor plenum
%
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Window
Door
Wall area
10
Type
Double Clear 1/8"
Length
Quantity
U-factor
0.6
Sh. Coef
0.88
Ld to RA
New Opening
Copy Opening
Delete Opening
Shading...
Internal
None
External
Overhang - None
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

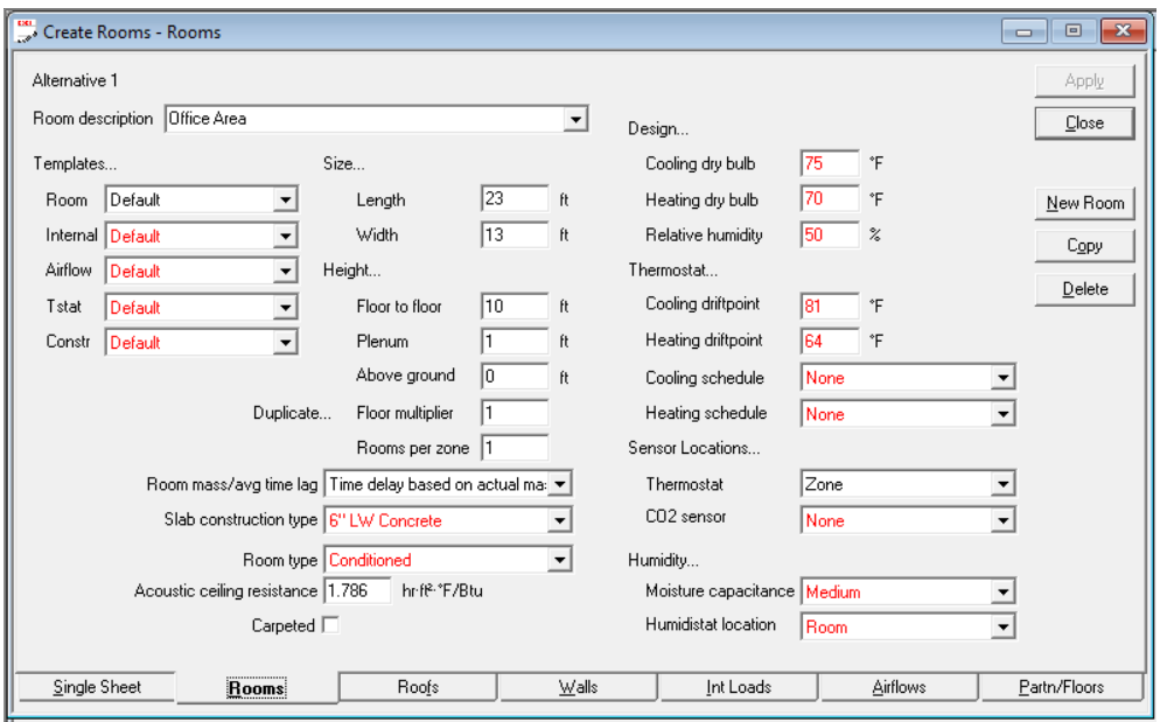

Create Rooms - Internal Loads
Alternative 1
Room description
Middle
Apply
Close
Templates...
Room
Default
Internal
Airflow
Tstat
Constr
People...
Activity
None
Density
4
People
Schedule
Base Util - Lodging
Sensible
250
Btu/h
Latent
Workstations...
1
workstation/person
Lights...
Type
Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain
0
W/sq ft
Miscellaneous loads...
Misc Load 1
Tag
Energy
Energy meter
Data Center Equipment
No
New Load
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

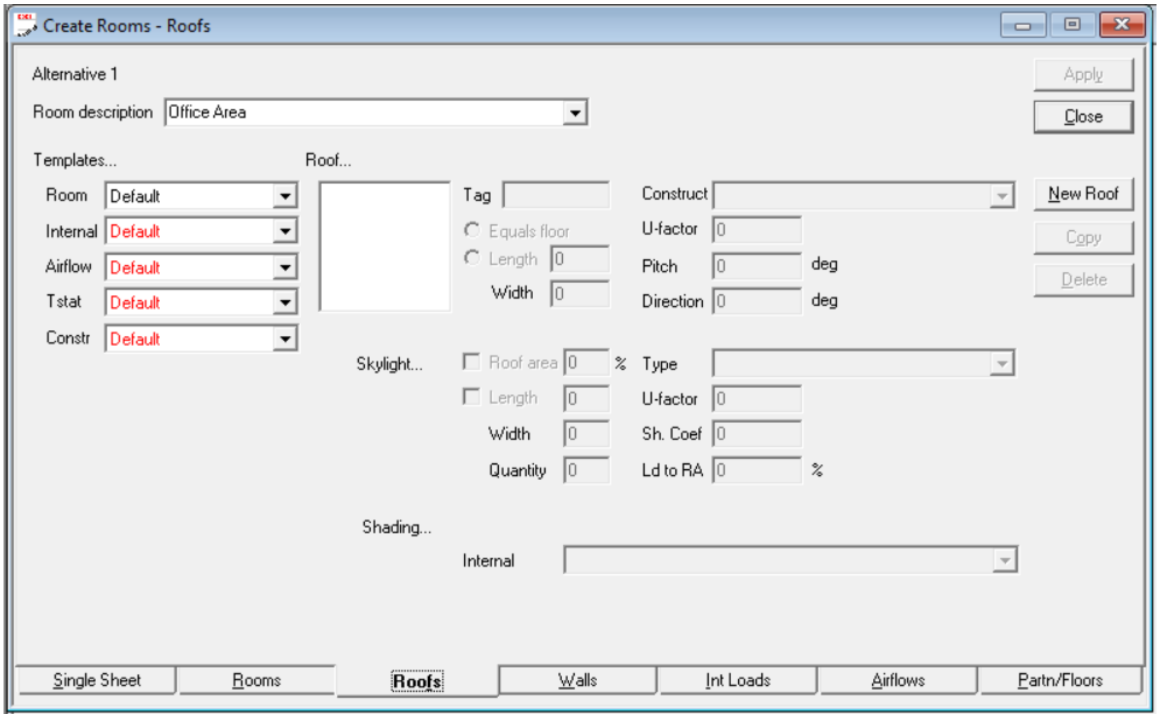

Create Rooms - Airflows
Alternative 1
Adjacent air transfer from room
Apply
Room description
Middle
<<No adjacent air trans>>
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Main supply...
Cooling
To be calculated
Heating
To be calculated
Ventilation...
Method
Sum of Outdoor Air
Type
Warehouse
Cooling
0.08
cfm/sq ft
Heating
0.08
cfm/sq ft
Schedule
Available (100%)
Infiltration...
Type
Pressurized, Poor Const.
Cooling
0.7
air changes/hr
Heating
0.7
air changes/hr
Schedule
Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling
To be calculated
Heating
To be calculated
Std 62.1-2004-2010...
Clg Ez
Custom
Htg Ez
Custom
Er
Default based on system typ
DCV Min OA Intake
None
Room exhaust...
Rate
0
air changes/hr
Schedule
Available (100%)
VAV control...
Clg VAV min
% Clg Airflow
Htg VAV max
% Clg Airflow
Schedule
Available (100%)
Type
Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

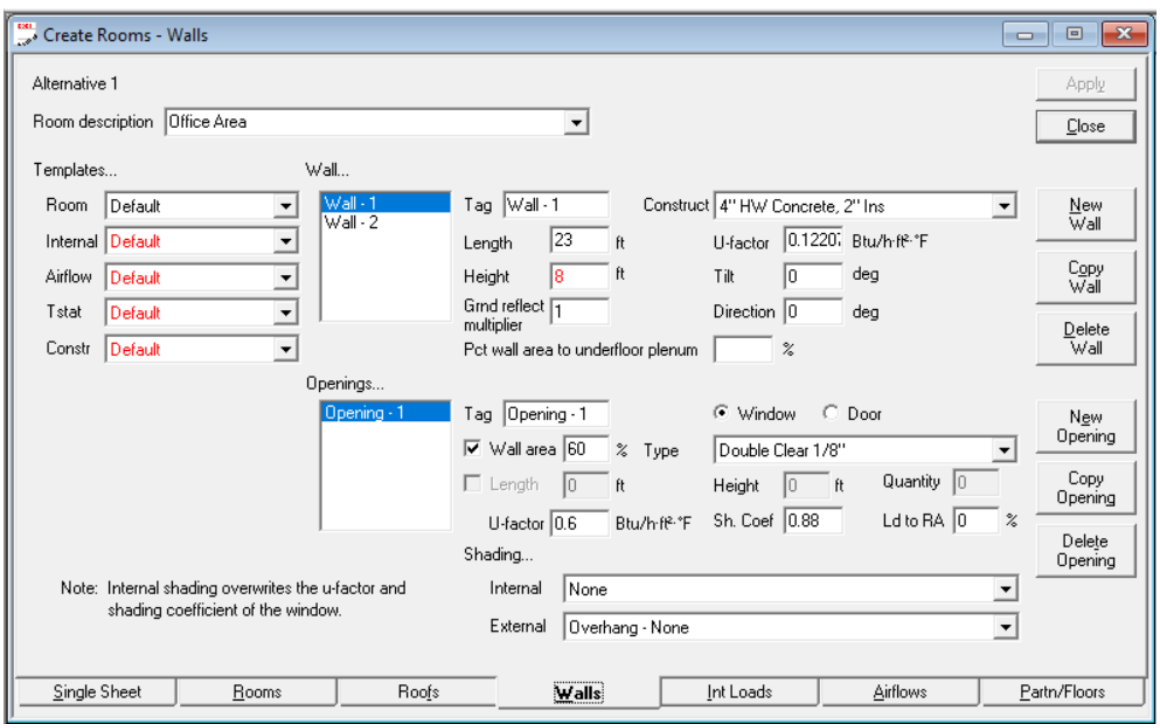

Create Rooms - Partitions and Floors
Alternative 1
Apply
Room description
Middle
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition...
Tag
Length
0
Height
0
Constr
U-factor
0
Adj room
Adjacent space temperature...
Method
Cooling
Heating
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
6" HW Conc
Area
735
ft²
U-factor
0.6587
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
Basement-large
External temperature...
Method
Adjacent Room
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

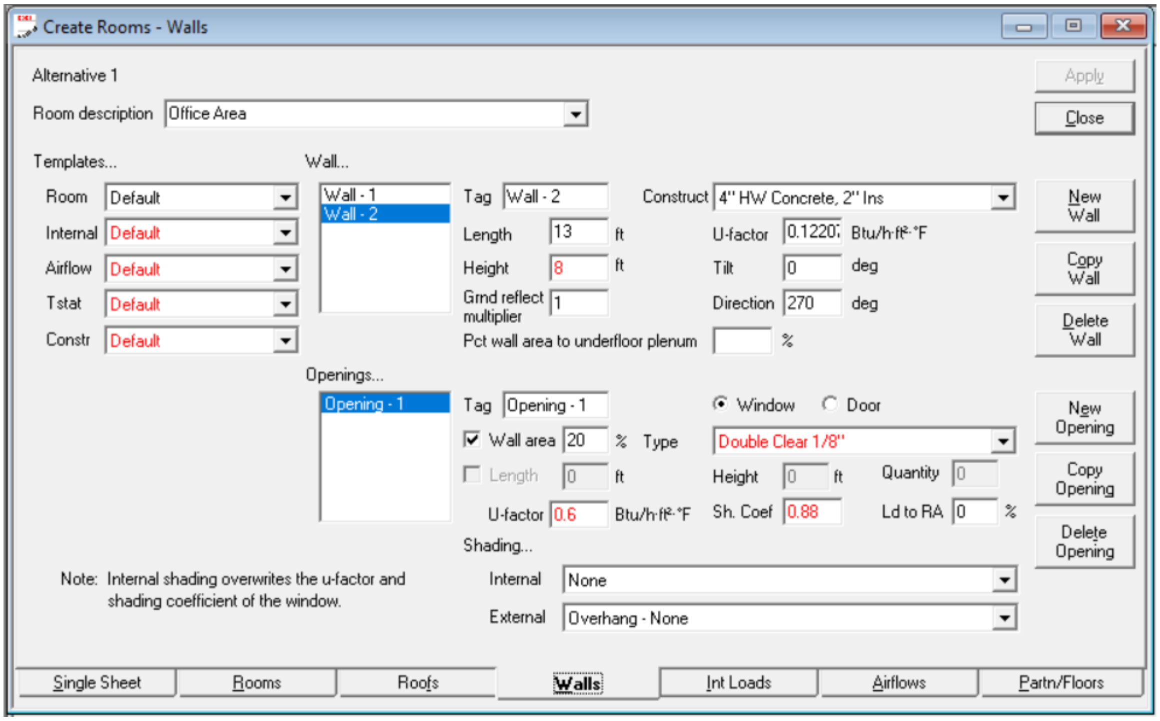
A.2.4 Office Area

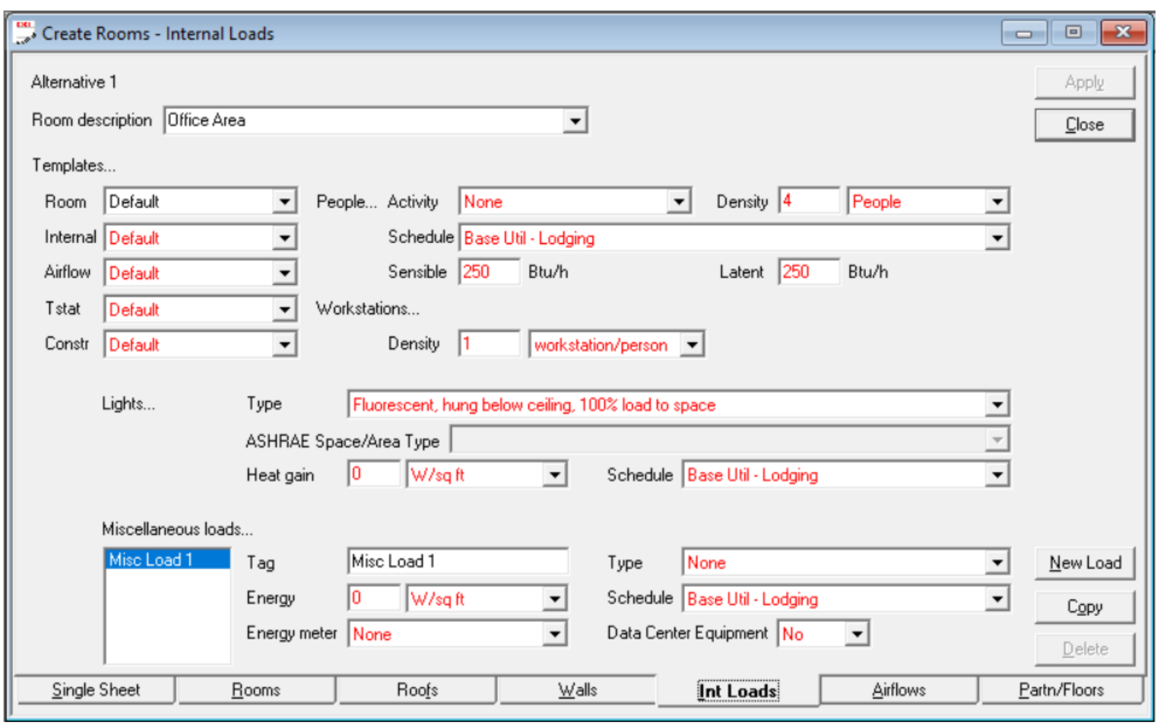


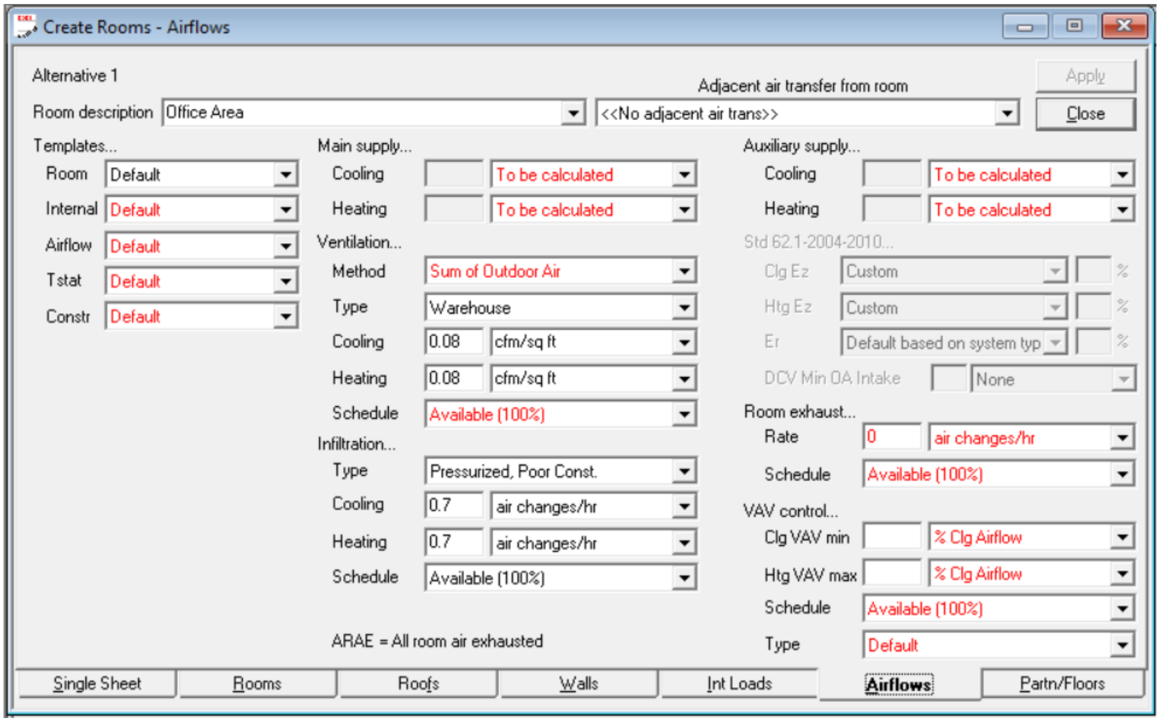


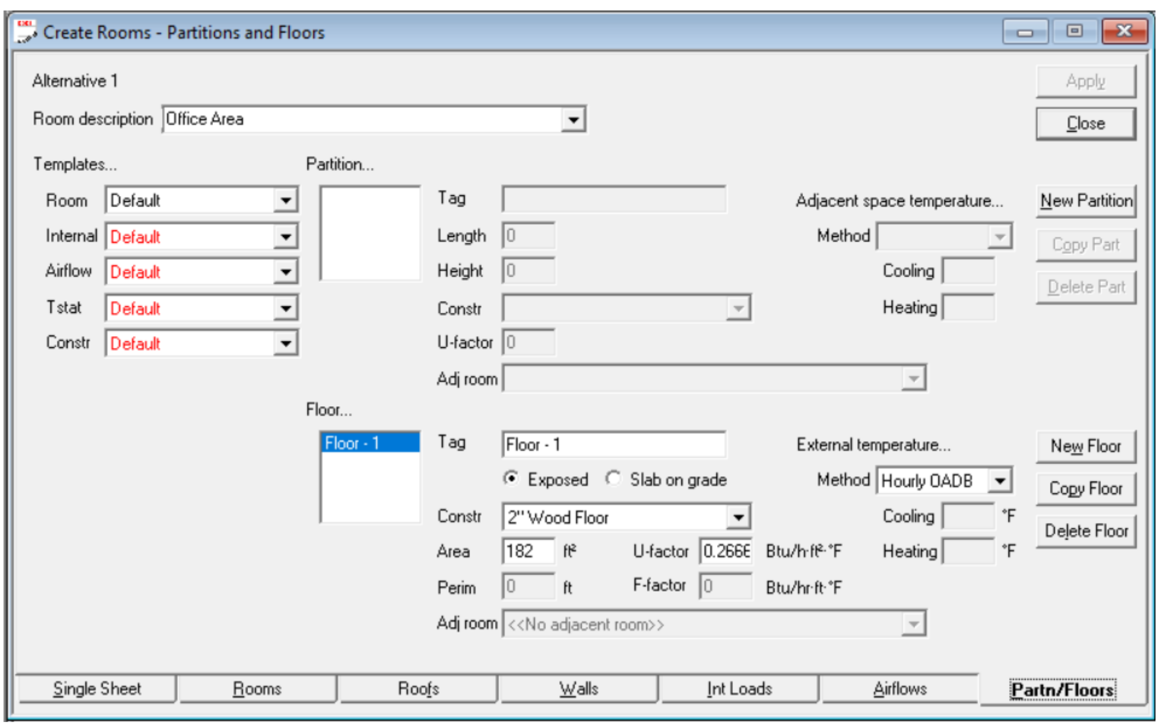

Create Rooms - Roofs
Alternative 1
Room description
Office Area
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Roof...
Tag
Equals floor
Length
Width
Construct
U-factor
Pitch
Direction
deg
deg
New Roof
Copy
Delete
Skylight...
Roof area
%
Type
Length
U-factor
Width
Sh. Coef
Quantity
Ld to RA
%
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Walls
Alternative 1
Room description
Office Area
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Wall...
Wall - 1
Wall - 2
Tag
Wall - 1
Construct
4" HW Concrete, 2" Ins
Length
23
ft
U-factor
0.1220
Btu/h·ft²·°F
Height
8
ft
Tilt
0
deg
Grnd reflect multiplier
1
Direction
0
deg
Pct wall area to underfloor plenum
%
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
Wall area
60
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
U-factor
0.6
Btu/h·ft²·°F
Sh. Coef
0.88
Ld to RA
0
%
New Opening
Copy Opening
Delete Opening
Shading...
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Internal
None
External
Overhang - None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

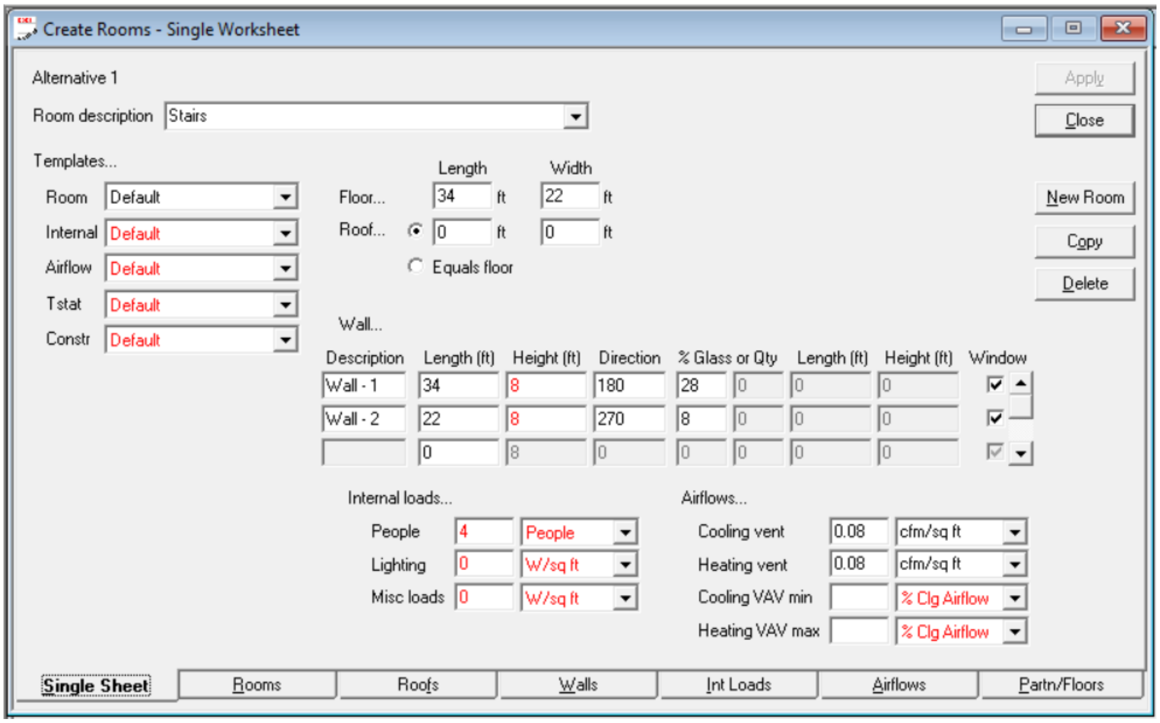

Create Rooms - Walls
Alternative 1
Room description
Office Area
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Wall...
Wall - 1
Wall - 2
Tag
Wall - 2
Length
13
ft
Height
8
ft
Grnd reflect multiplier
1
Pct wall area to underfloor plenum
%
Construct
4" HW Concrete, 2" Ins
U-factor
0.1220
Btu/h·ft²·°F
Tilt
0
deg
Direction
270
deg
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
Wall area
20
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
U-factor
0.6
Btu/h·ft²·°F
Sh. Coef
0.88
Ld to RA
0
%
New Opening
Copy Opening
Delete Opening
Shading...
Internal
None
External
Overhang - None
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

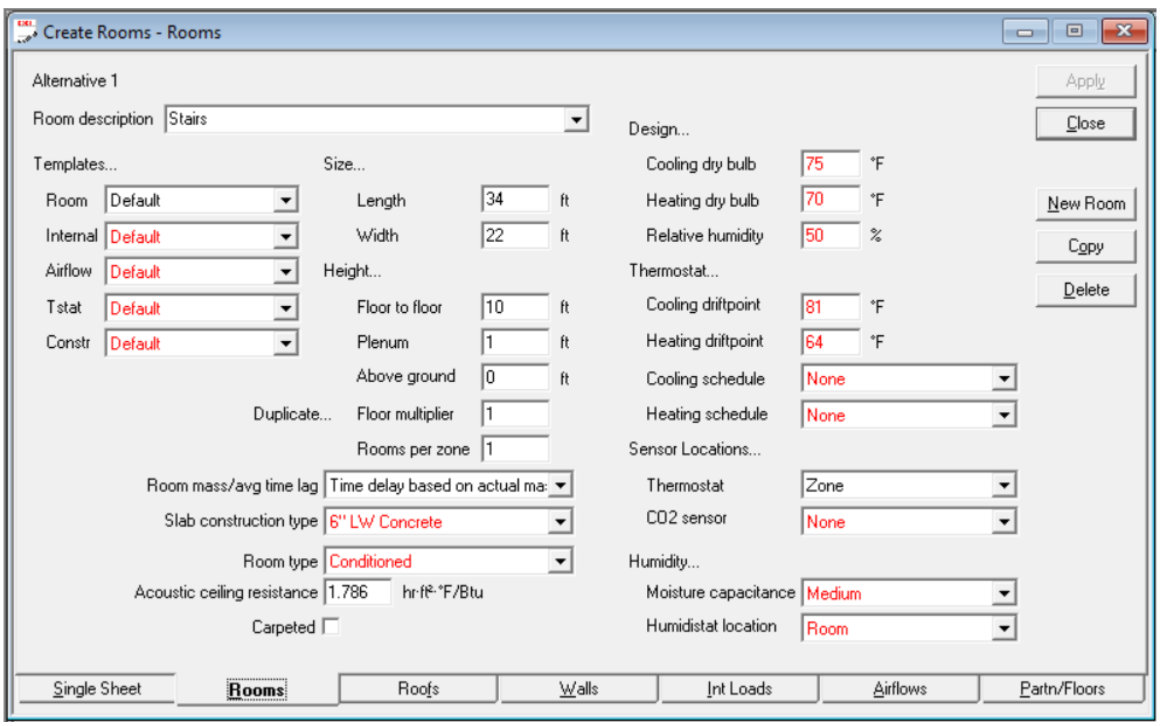

Create Rooms - Internal Loads
Alternative 1
Room description
Office Area
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
People...
Activity
None
Density
4
People
Schedule
Base Util - Lodging
Sensible
250
Btu/h
Latent
250
Btu/h
Workstations...
Density
1
workstation/person
Lights...
Type
Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain
0
W/sq ft
Schedule
Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag
Misc Load 1
Energy
0
W/sq ft
Energy meter
None
Type
None
Schedule
Base Util - Lodging
Data Center Equipment
No
New Load
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

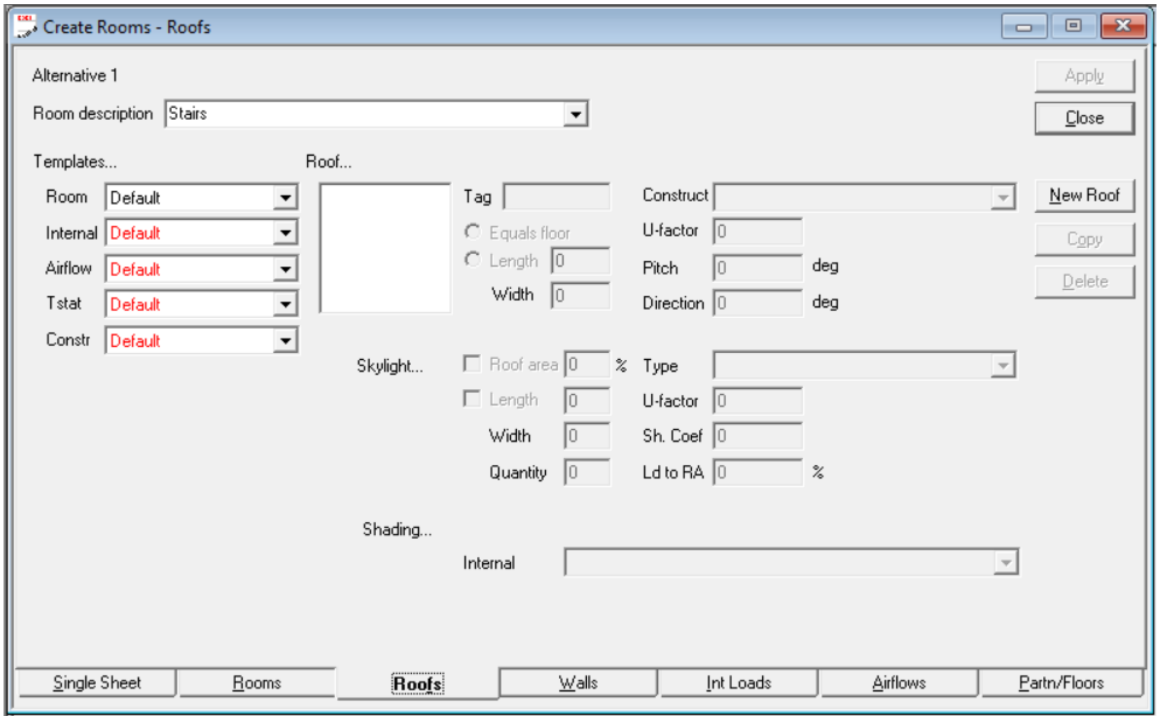

Create Rooms - Airflows
Alternative 1
Room description
Office Area
Adjacent air transfer from room
<<No adjacent air trans>>
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Main supply...
Cooling
To be calculated
Heating
To be calculated
Ventilation...
Method
Sum of Outdoor Air
Type
Warehouse
Cooling
0.08
cfm/sq ft
Heating
0.08
cfm/sq ft
Schedule
Available (100%)
Infiltration...
Type
Pressurized, Poor Const.
Cooling
0.7
air changes/hr
Heating
0.7
air changes/hr
Schedule
Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling
To be calculated
Heating
To be calculated
Std 62.1-2004-2010...
Clg Ez
Custom
Htg Ez
Custom
Er
Default based on system typ
DCV Min OA Intake
None
Room exhaust...
Rate
0
air changes/hr
Schedule
Available (100%)
VAV control...
Clg VAV min
% Clg Airflow
Htg VAV max
% Clg Airflow
Schedule
Available (100%)
Type
Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

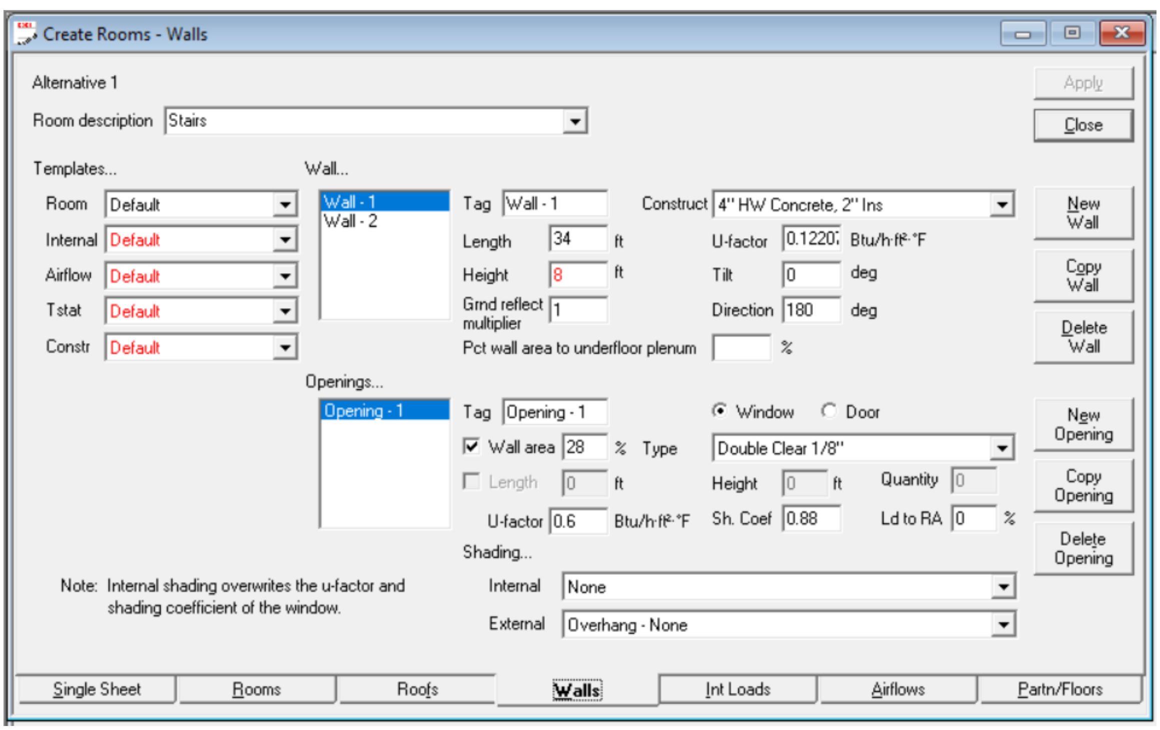

Create Rooms - Partitions and Floors
Alternative 1
Room description
Office Area
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition...
Tag
Length
0
Height
0
Constr
U-factor
0
Adj room
Adjacent space temperature...
Method
Cooling
Heating
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" Wood Floor
Area
182
ft²
U-factor
0.2666
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Hourly OADB
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

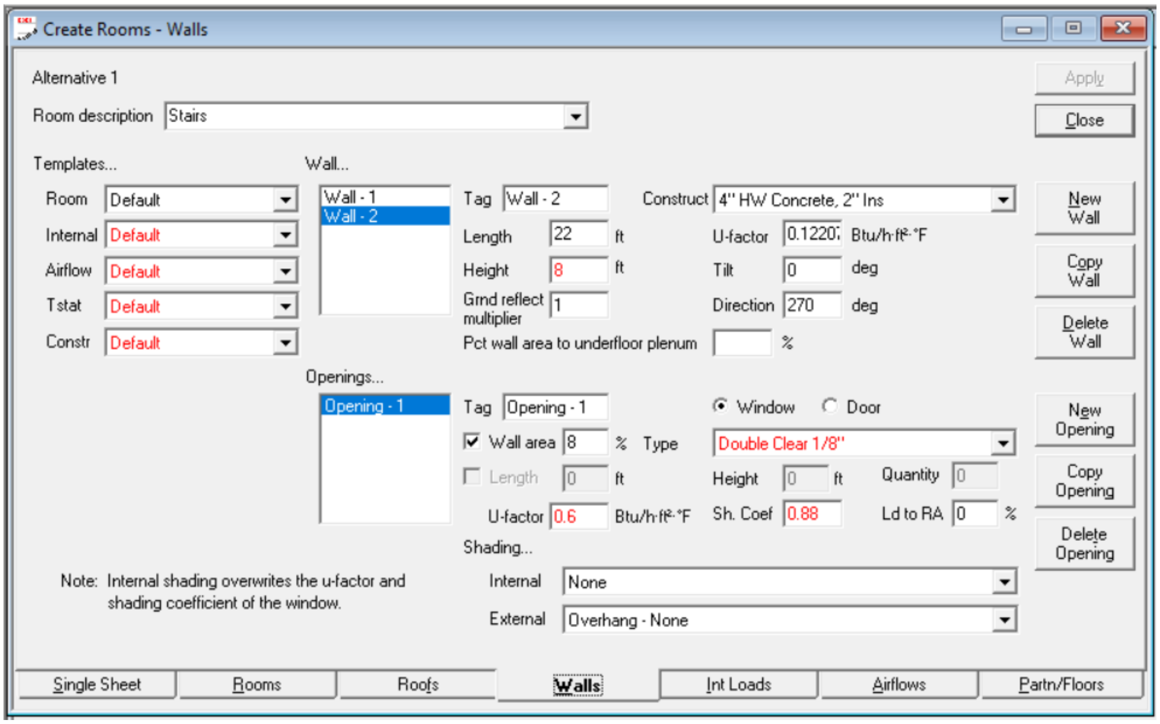
A.2.5 Stairs

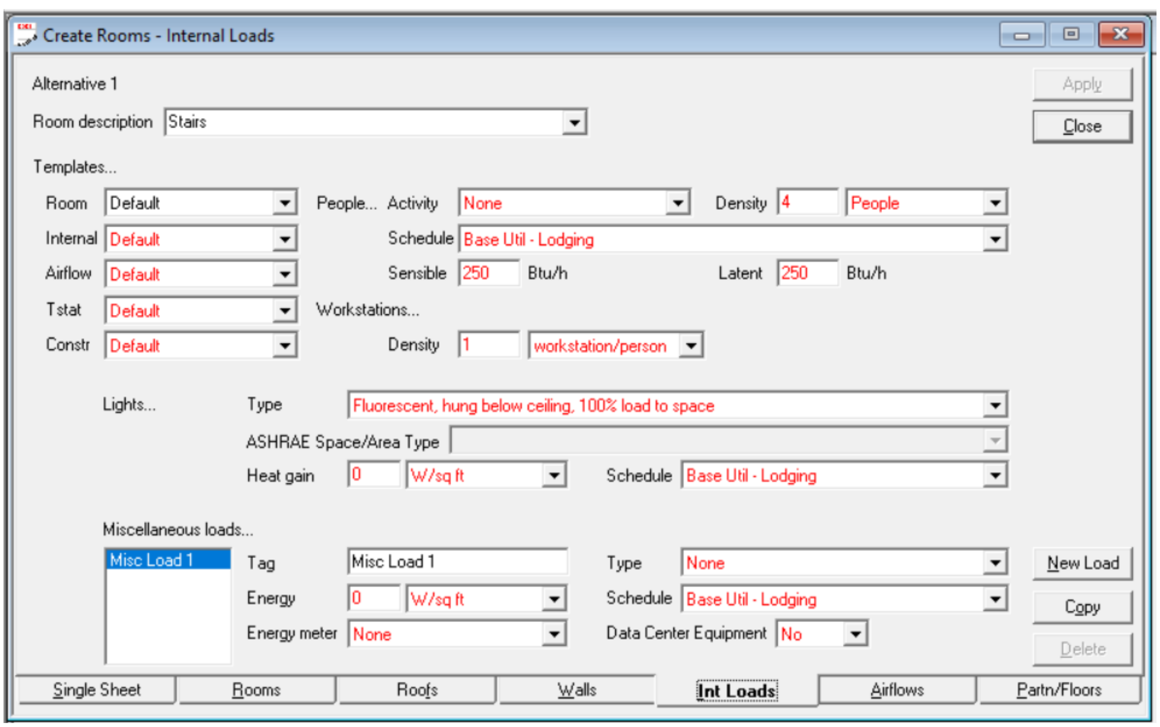

Create Rooms - Single Worksheet
Alternative 1
Room description Stairs
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Length Width
Floor... 34 ft 22 ft
Roof... 0 ft 0 ft
Equals floor
New Room
Copy
Delete
Wall...
Description Length (ft) Height (ft) Direction % Glass or Qty Length (ft) Height (ft) Window
Wall - 1 34 8 180 28 0 0 0
Wall - 2 22 8 270 8 0 0 0
0 8 0 0 0 0 0
Internal loads...
People 4 People
Lighting 0 W/sq ft
Misc loads 0 W/sq ft
Airflows...
Cooling vent 0.08 cfm/sq ft
Heating vent 0.08 cfm/sq ft
Cooling VAV min % Clg Airflow
Heating VAV max % Clg Airflow
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

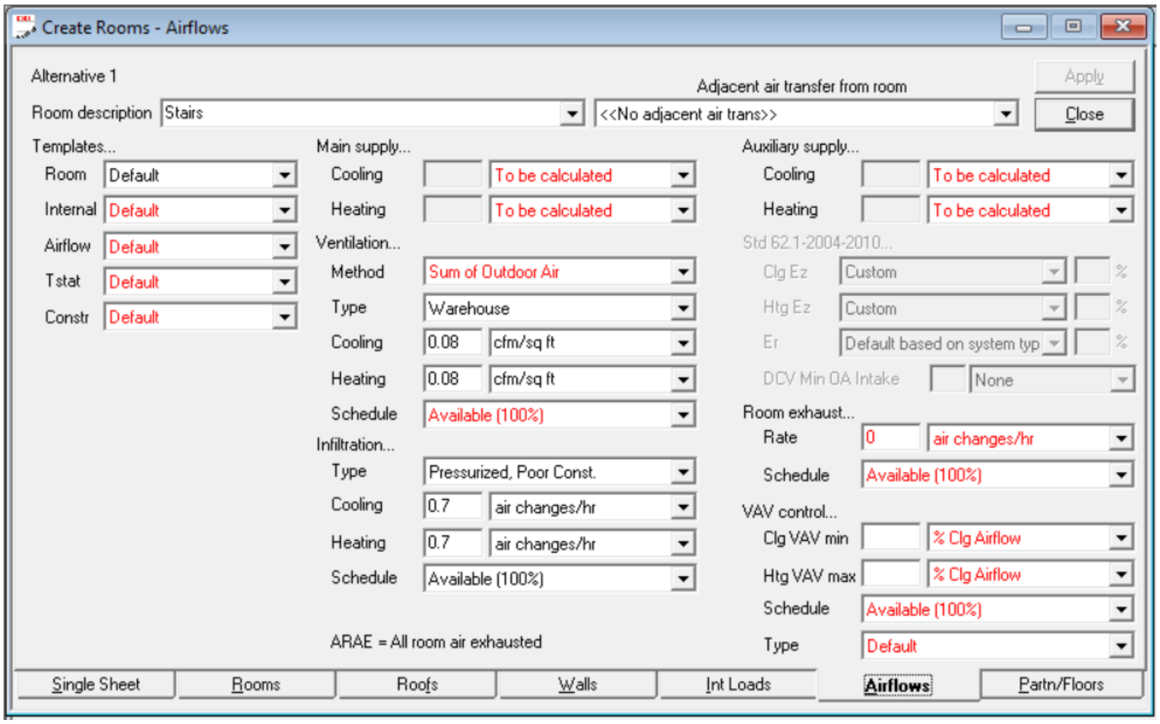

Create Rooms - Rooms
Alternative 1
Room description Stairs
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Size...
Length 34 ft
Width 22 ft
Height...
Floor to floor 10 ft
Plenum 1 ft
Above ground 0 ft
Duplicate...
Floor multiplier 1
Rooms per zone 1
Room mass/avg time lag Time delay based on actual ma:
Slab construction type 6" LW Concrete
Room type Conditioned
Acoustic ceiling resistance 1.786 hr·ft²·°F/Btu
Carpeted
Design...
Cooling dry bulb 75 °F
Heating dry bulb 70 °F
Relative humidity 50 %
Thermostat...
Cooling driftpoint 81 °F
Heating driftpoint 64 °F
Cooling schedule None
Heating schedule None
Sensor Locations...
Thermostat Zone
CO2 sensor None
Humidity...
Moisture capacitance Medium
Humidistat location Room
New Room
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

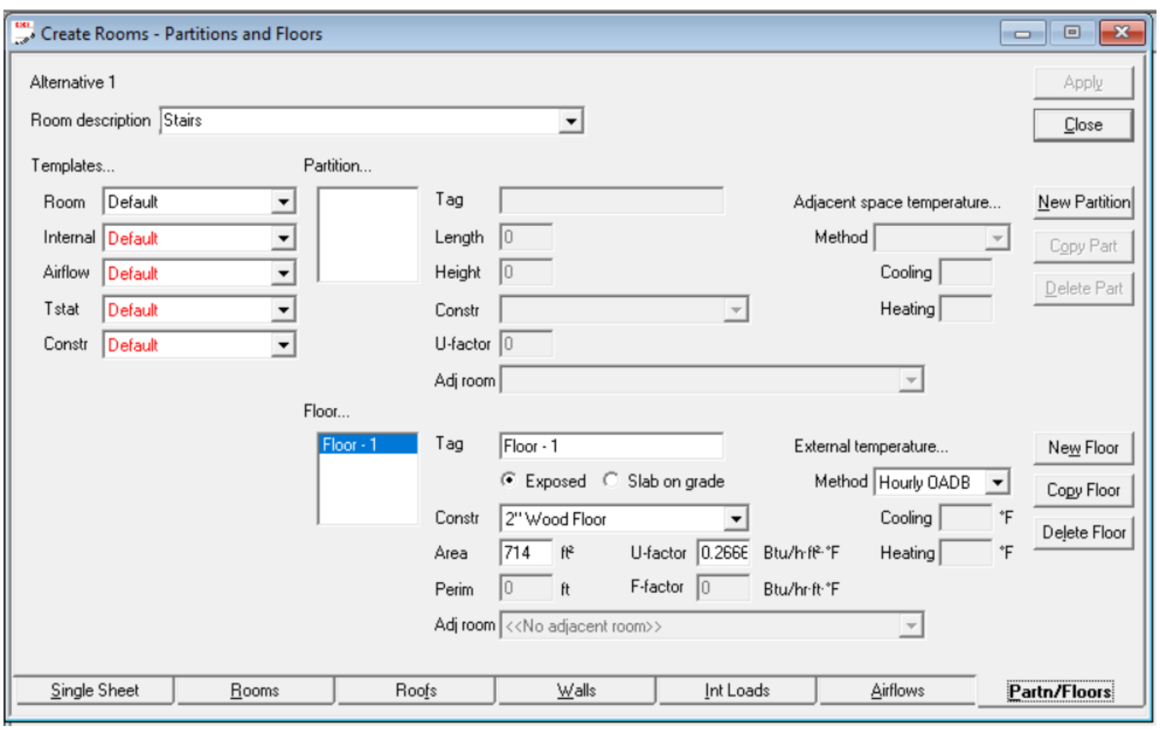

Create Rooms - Roofs
Alternative 1
Room description
Stairs
Apply
Close
Templates...
Roof...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Tag
Equals floor
Length
Width
Construct
U-factor
Pitch
deg
Direction
deg
New Roof
Copy
Delete
Skylight...
Roof area
%
Type
Length
U-factor
Width
Sh. Coef
Quantity
Ld to RA
%
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Walls
Alternative 1
Room description
Stairs
Apply
Close
Templates...
Wall...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Wall - 1
Wall - 2
Tag
Wall - 1
Construct
4" HW Concrete, 2" Ins
Length
34
ft
U-factor
0.1220
Btu/h·ft²·°F
Height
8
ft
Tilt
0
deg
Grnd reflect multiplier
1
Direction
180
deg
Pct wall area to underfloor plenum
%
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
Wall area
28
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
U-factor
0.6
Btu/h·ft²·°F
Sh. Coef
0.88
Ld to RA
0
%
New Opening
Copy Opening
Delete Opening
Shading...
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Internal
None
External
Overhang - None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

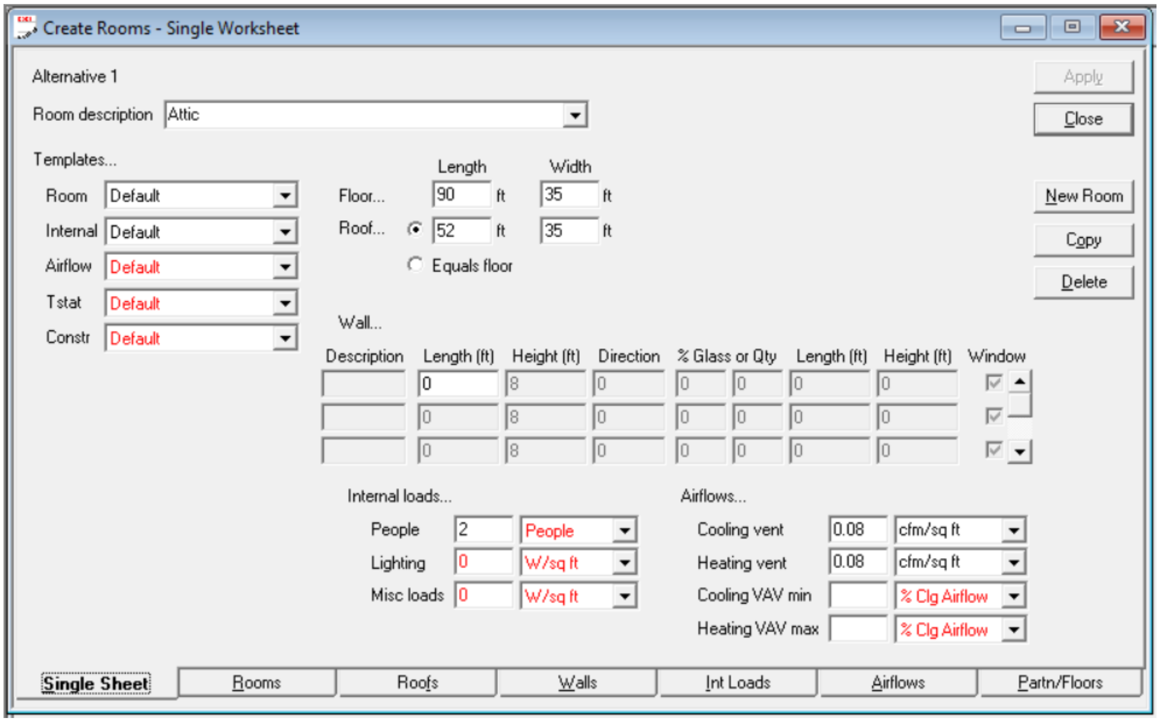

Create Rooms - Walls
Alternative 1
Room description
Stairs
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Wall...
Wall - 1
Wall - 2
Tag
Wall - 2
Length
22
ft
Height
8
ft
Grnd reflect multiplier
1
Pct wall area to underfloor plenum
%
Construct
4" HW Concrete, 2" Ins
U-factor
0.1220
Btu/h·ft²·°F
Tilt
0
deg
Direction
270
deg
New Wall
Copy Wall
Delete Wall
Openings...
Opening - 1
Tag
Opening - 1
Window
Door
Wall area
8
%
Type
Double Clear 1/8"
Length
0
ft
Height
0
ft
Quantity
0
U-factor
0.6
Btu/h·ft²·°F
Sh. Coef
0.88
Ld to RA
0
%
New Opening
Copy Opening
Delete Opening
Shading...
Internal
None
External
Overhang - None
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

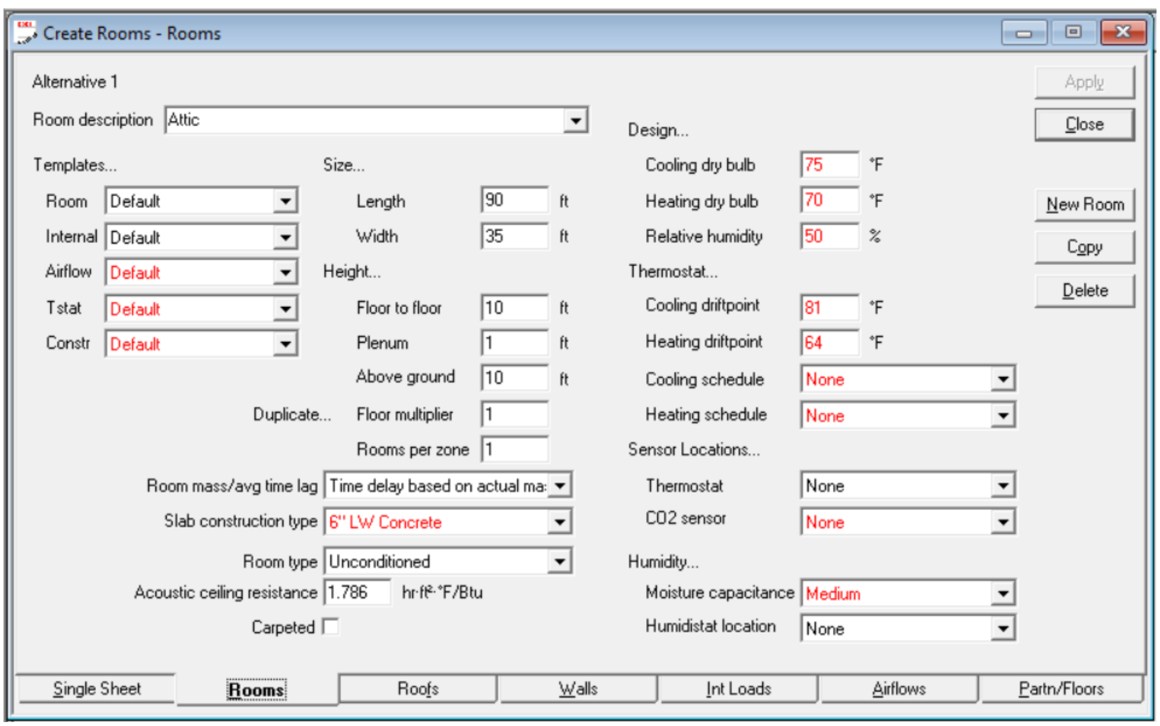

Create Rooms - Internal Loads
Alternative 1
Room description
Stairs
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
People...
Activity
None
Density
4
People
Schedule
Base Util - Lodging
Sensible
250
Btu/h
Latent
250
Btu/h
Workstations...
Density
1
workstation/person
Lights...
Type
Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain
0
W/sq ft
Schedule
Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag
Misc Load 1
Energy
0
W/sq ft
Energy meter
None
Type
None
Schedule
Base Util - Lodging
Data Center Equipment
No
New Load
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

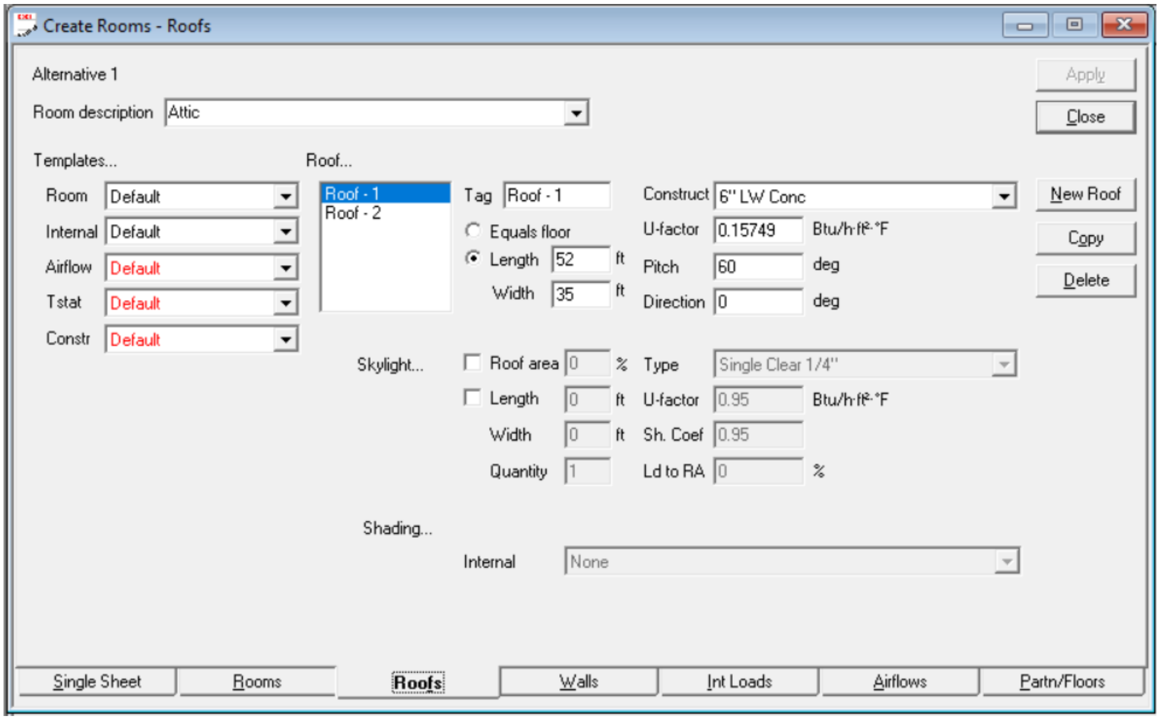

Create Rooms - Airflows
Alternative 1
Room description Stairs
Adjacent air transfer from room
<<No adjacent air trans>>
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Main supply...
Cooling To be calculated
Heating To be calculated
Ventilation...
Method Sum of Outdoor Air
Type Warehouse
Cooling 0.08 cfm/sq ft
Heating 0.08 cfm/sq ft
Schedule Available (100%)
Infiltration...
Type Pressurized, Poor Const.
Cooling 0.7 air changes/hr
Heating 0.7 air changes/hr
Schedule Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling To be calculated
Heating To be calculated
Std 62.1-2004-2010...
Clg Ez Custom %
Htg Ez Custom %
Er Default based on system typ %
DCV Min OA Intake None
Room exhaust...
Rate 0 air changes/hr
Schedule Available (100%)
VAV control...
Clg VAV min % Clg Airflow
Htg VAV max % Clg Airflow
Schedule Available (100%)
Type Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

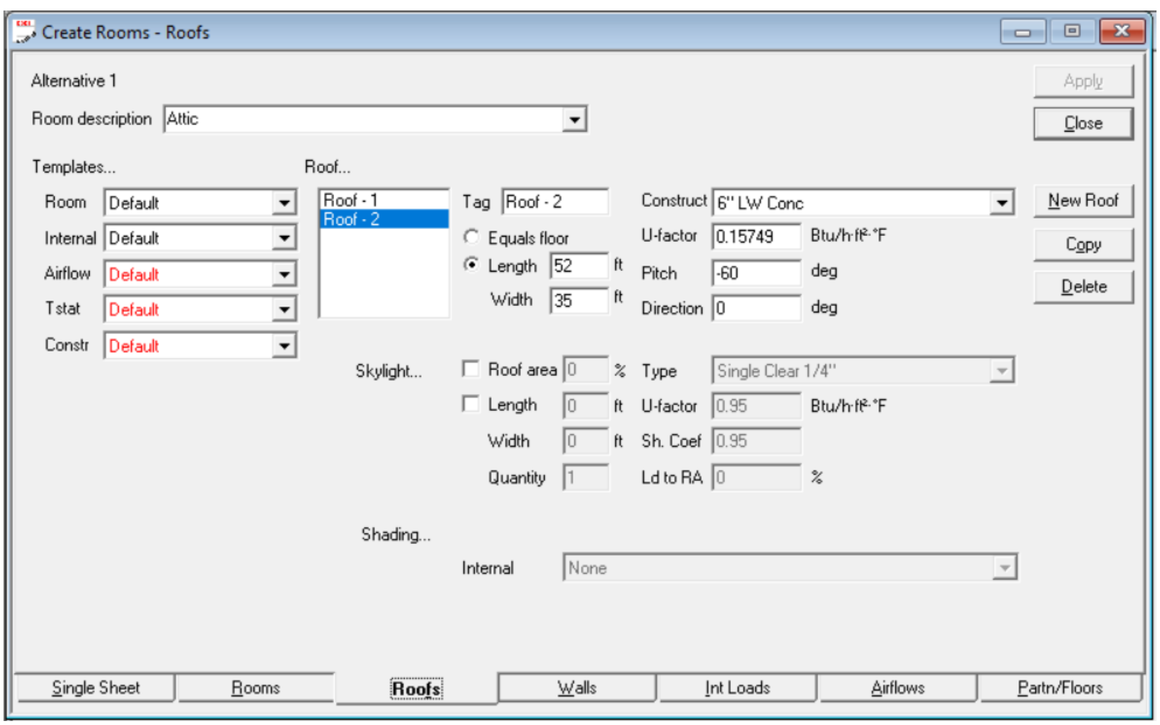

Create Rooms - Partitions and Floors
Alternative 1
Room description Stairs
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Tag
Length 0
Height 0
Constr
U-factor 0
Adj room
Adjacent space temperature...
Method
Cooling
Heating
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed Slab on grade
Constr 2" Wood Floor
Area 714 ft²
U-factor 0.266E Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Hourly OADB
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

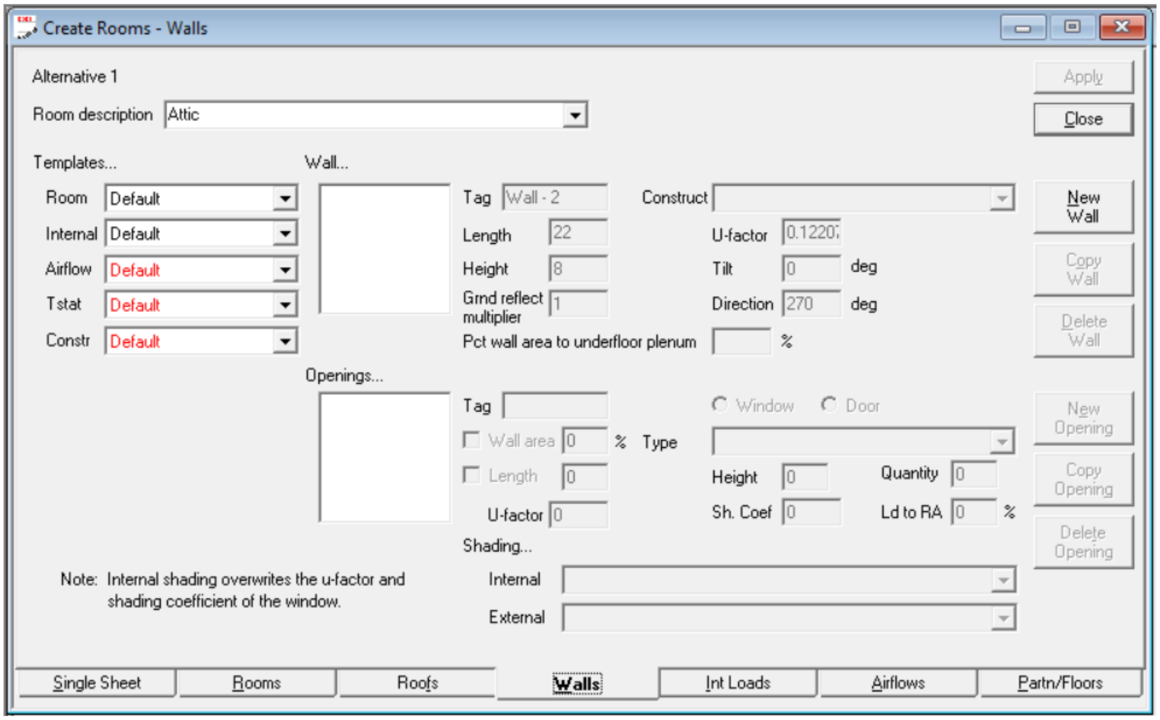
A.2.6 Attic

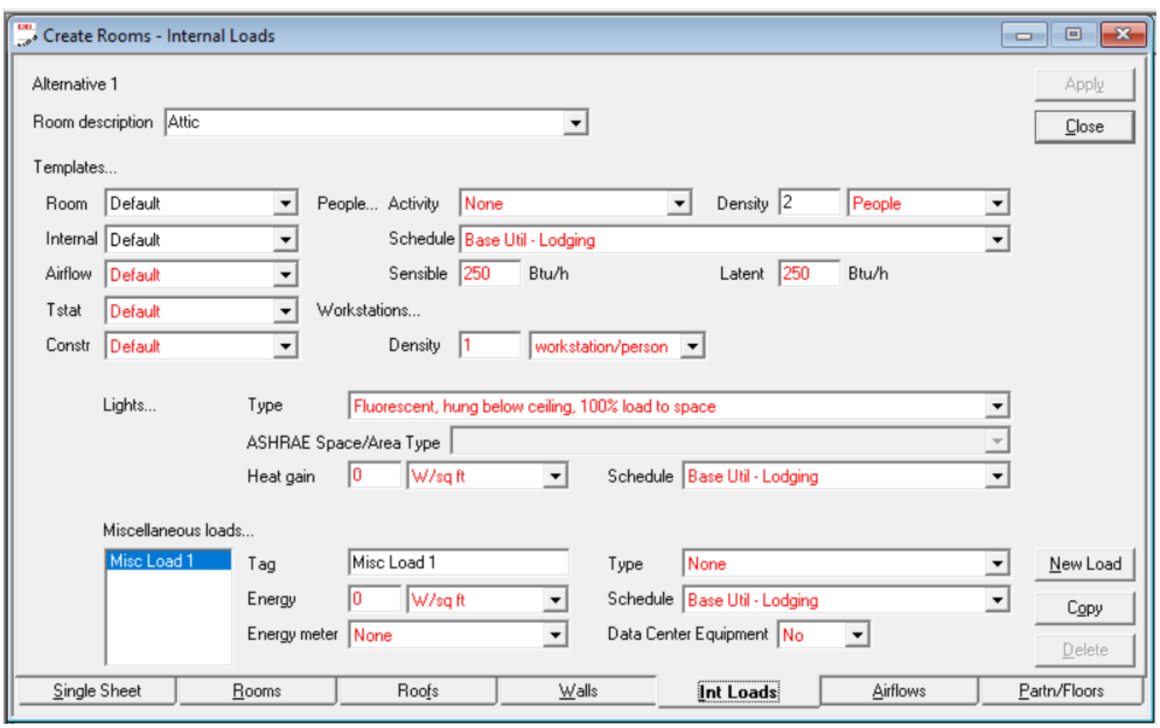

Create Rooms - Single Worksheet
Alternative 1
Room description Attic
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Length
Width
Floor... 90 ft 35 ft
Roof... 52 ft 35 ft
Equals floor
New Room
Copy
Delete
Wall...
Description Length (ft) Height (ft) Direction % Glass or Qty Length (ft) Height (ft) Window
0 8 0 0 0 0 0
0 8 0 0 0 0 0
0 8 0 0 0 0 0
Internal loads...
People 2 People
Lighting 0 W/sq ft
Misc loads 0 W/sq ft
Airflows...
Cooling vent 0.08 cfm/sq ft
Heating vent 0.08 cfm/sq ft
Cooling VAV min % Clg Airflow
Heating VAV max % Clg Airflow
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

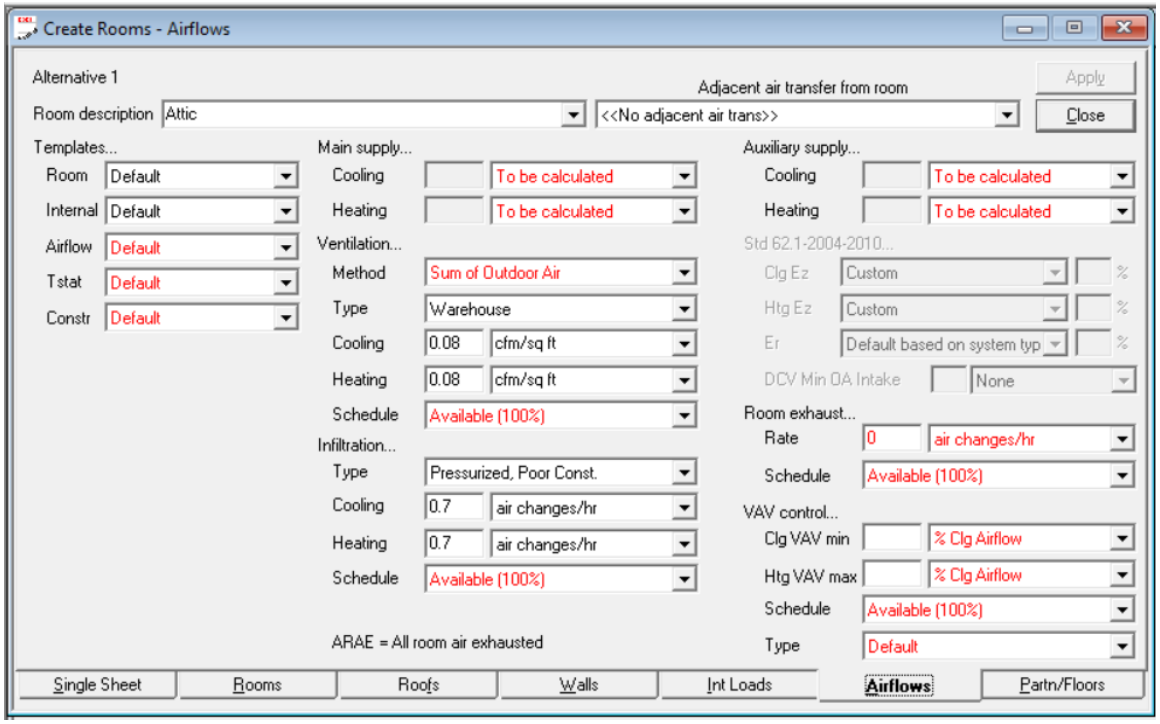

Create Rooms - Rooms
Alternative 1
Room description Attic
Apply
Close
Design...
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Size...
Length 90 ft
Width 35 ft
Height...
Floor to floor 10 ft
Plenum 1 ft
Above ground 10 ft
Duplicate...
Floor multiplier 1
Rooms per zone 1
Room mass/avg time lag Time delay based on actual ma:
Slab construction type 6" LW Concrete
Room type Unconditioned
Acoustic ceiling resistance 1.786 hr·ft²·°F/Btu
Carpeted
Cooling dry bulb 75 °F
Heating dry bulb 70 °F
Relative humidity 50 %
Thermostat...
Cooling driftpoint 81 °F
Heating driftpoint 64 °F
Cooling schedule None
Heating schedule None
Sensor Locations...
Thermostat None
CO2 sensor None
Humidity...
Moisture capacitance Medium
Humidistat location None
New Room
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

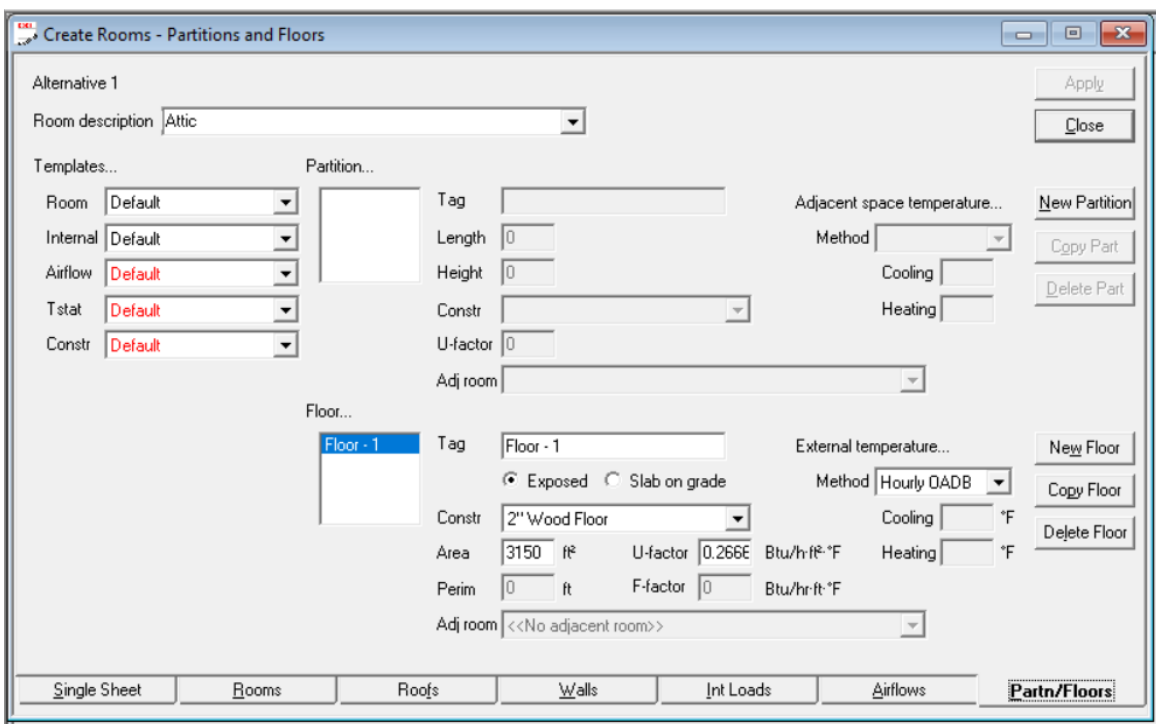

Create Rooms - Roofs
Alternative 1
Room description
Attic
Apply
Close
Templates...
Roof...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Roof - 1
Roof - 2
Tag
Roof - 1
Equals floor
Length
52
ft
Width
35
ft
Construct
6" LW Conc
U-factor
0.15749
Btu/h·ft²·°F
Pitch
60
deg
Direction
0
deg
New Roof
Copy
Delete
Skylight...
Roof area
0
%
Type
Single Clear 1/4"
Length
0
ft
U-factor
0.95
Btu/h·ft²·°F
Width
0
ft
Sh. Coef
0.95
Quantity
1
Ld to RA
0
%
Shading...
Internal
None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Roofs
Alternative 1
Room description
Attic
Apply
Close
Templates...
Roof...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Roof - 1
Roof - 2
Tag
Roof - 2
Equals floor
Length
52
ft
Width
35
ft
Construct
6" LW Conc
U-factor
0.15749
Btu/h·ft²·°F
Pitch
-60
deg
Direction
0
deg
New Roof
Copy
Delete
Skylight...
Roof area
0
%
Type
Single Clear 1/4"
Length
0
ft
U-factor
0.95
Btu/h·ft²·°F
Width
0
ft
Sh. Coef
0.95
Quantity
1
Ld to RA
0
%
Shading...
Internal
None
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

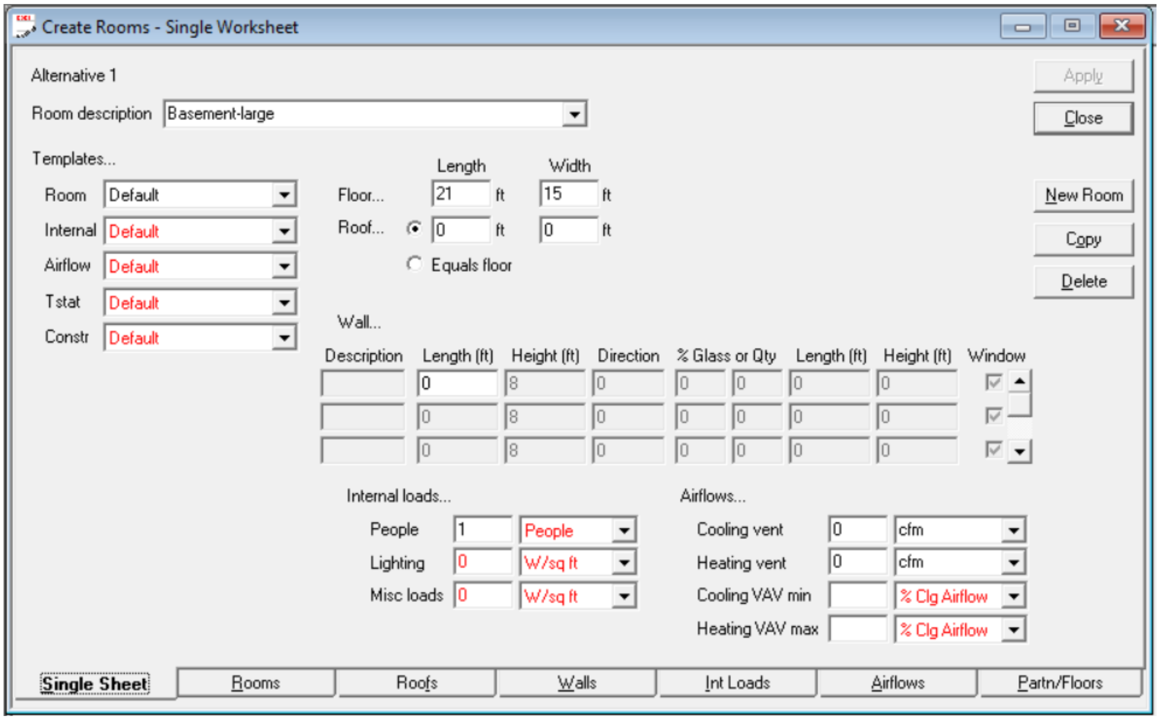

Create Rooms - Walls
Alternative 1
Room description Attic
Apply
Close
Templates...
Wall...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Tag Wall - 2
Length 22
Height 8
Grnd reflect multiplier 1
Construct
U-factor 0.1220
Tilt 0 deg
Direction 270 deg
Pct wall area to underfloor plenum %
New Wall
Copy Wall
Delete Wall
Openings...
Tag
Window
Door
Wall area 0 %
Type
Length 0
Height 0
Quantity 0
U-factor 0
Sh. Coef 0
Ld to RA 0 %
New Opening
Copy Opening
Delete Opening
Shading...
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Internal
External
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

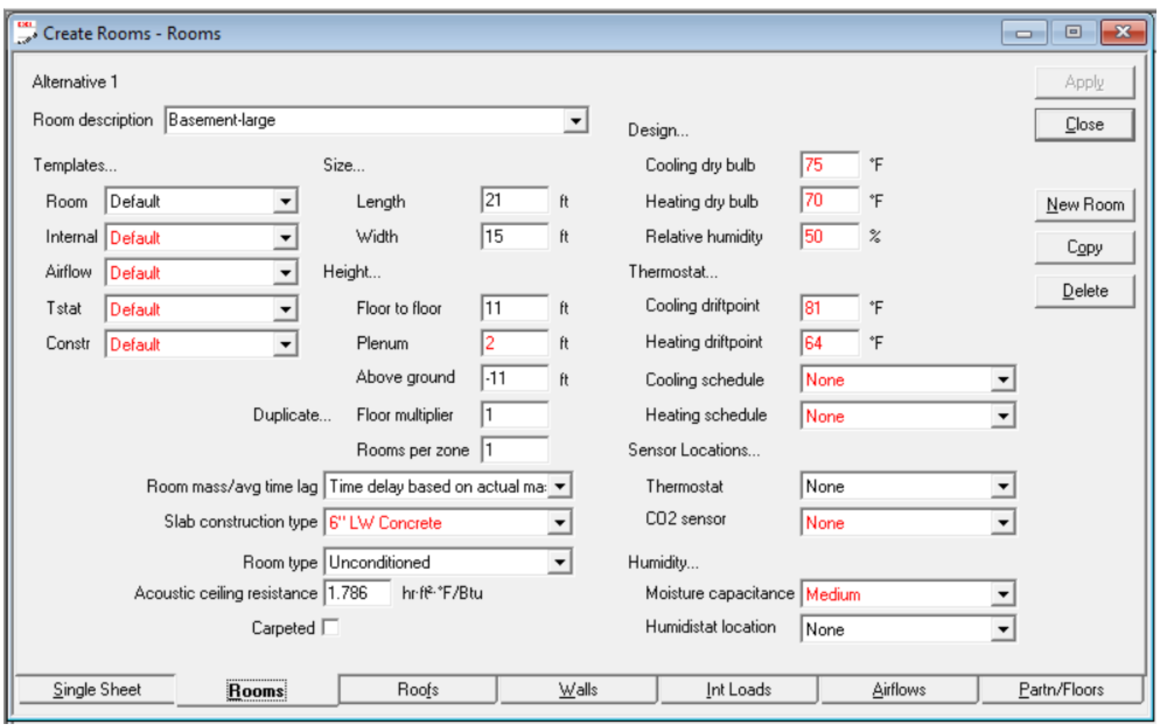

Create Rooms - Internal Loads
Alternative 1
Room description Attic
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
People... Activity None
Density 2 People
Schedule Base Util - Lodging
Sensible 250 Btu/h
Latent 250 Btu/h
Workstations...
Density 1 workstation/person
Lights...
Type Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain 0 W/sq ft
Schedule Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag Misc Load 1
Energy 0 W/sq ft
Energy meter None
Type None
Schedule Base Util - Lodging
Data Center Equipment No
New Load
Copy
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

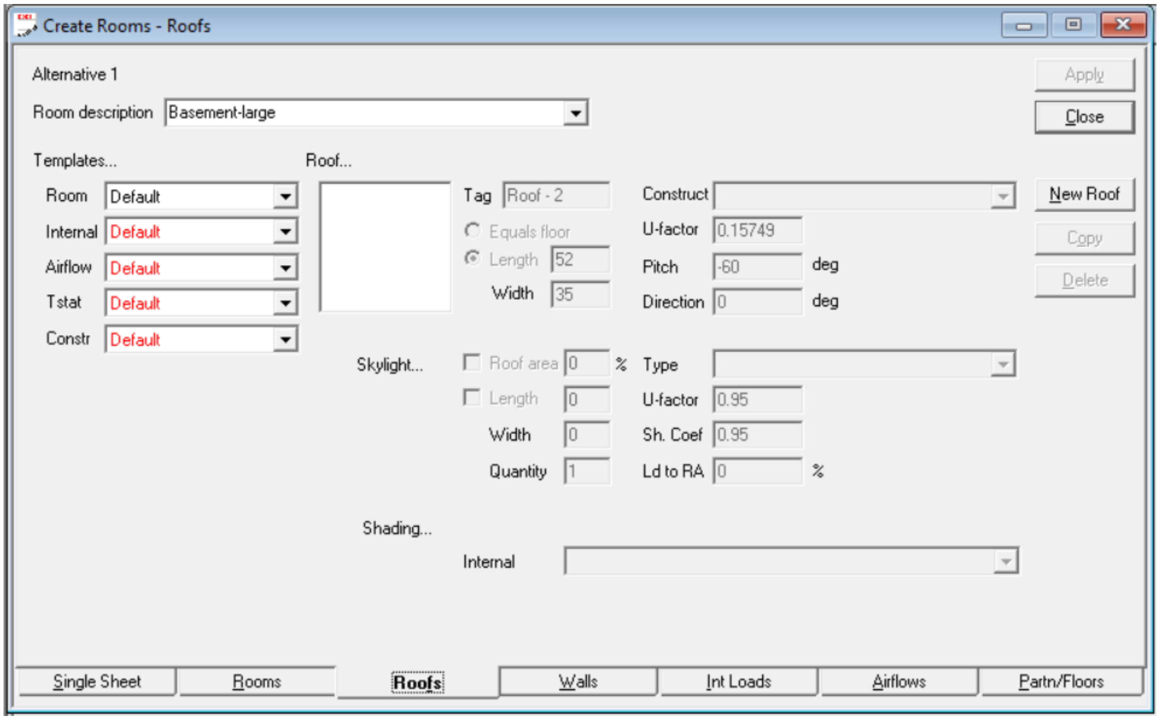

Create Rooms - Airflows
Alternative 1
Room description Attic
Adjacent air transfer from room
<<No adjacent air trans>>
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Main supply...
Cooling To be calculated
Heating To be calculated
Ventilation...
Method Sum of Outdoor Air
Type Warehouse
Cooling 0.08 cfm/sq ft
Heating 0.08 cfm/sq ft
Schedule Available (100%)
Infiltration...
Type Pressurized, Poor Const.
Cooling 0.7 air changes/hr
Heating 0.7 air changes/hr
Schedule Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling To be calculated
Heating To be calculated
Std 62.1-2004-2010...
Clg Ez Custom %
Htg Ez Custom %
Er Default based on system typ %
DCV Min OA Intake None
Room exhaust...
Rate 0 air changes/hr
Schedule Available (100%)
VAV control...
Clg VAV min % Clg Airflow
Htg VAV max % Clg Airflow
Schedule Available (100%)
Type Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

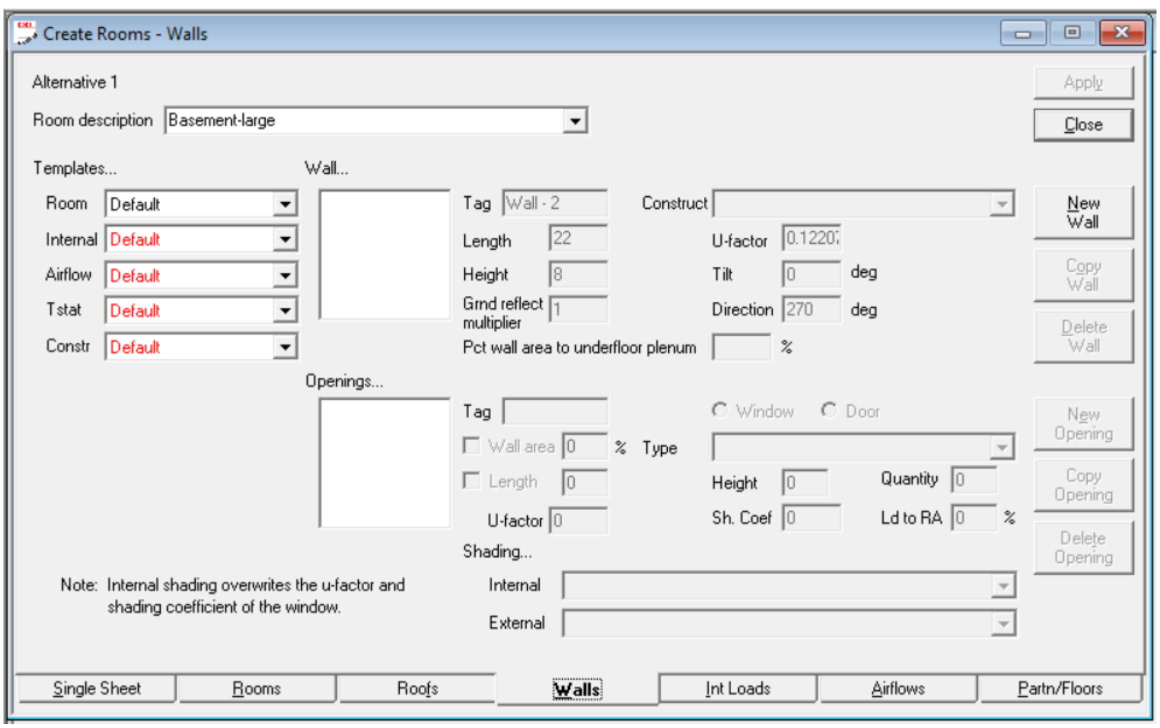

Create Rooms - Partitions and Floors
Alternative 1
Room description Attic
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Tag
Length 0
Height 0
Constr
U-factor 0
Adj room
Adjacent space temperature...
Method
Cooling
Heating
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" Wood Floor
Area 3150 ft²
U-factor 0.266E Btu/hr·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Hourly OADB
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

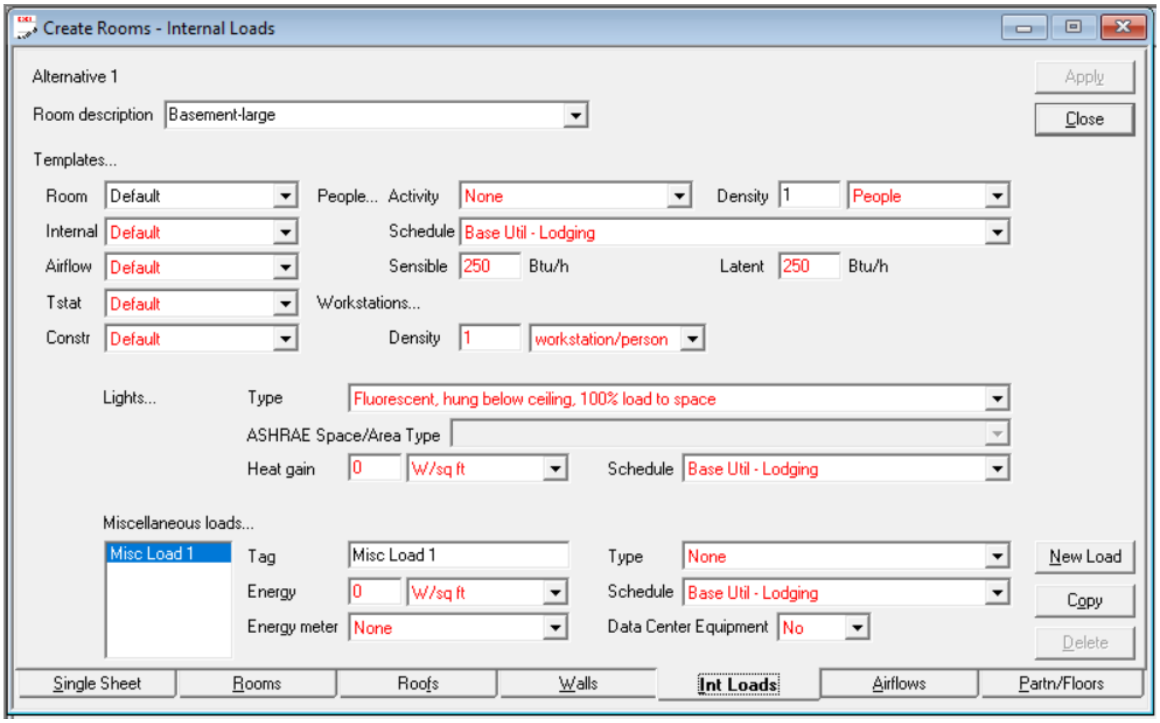
A.2.7 Basement-Large

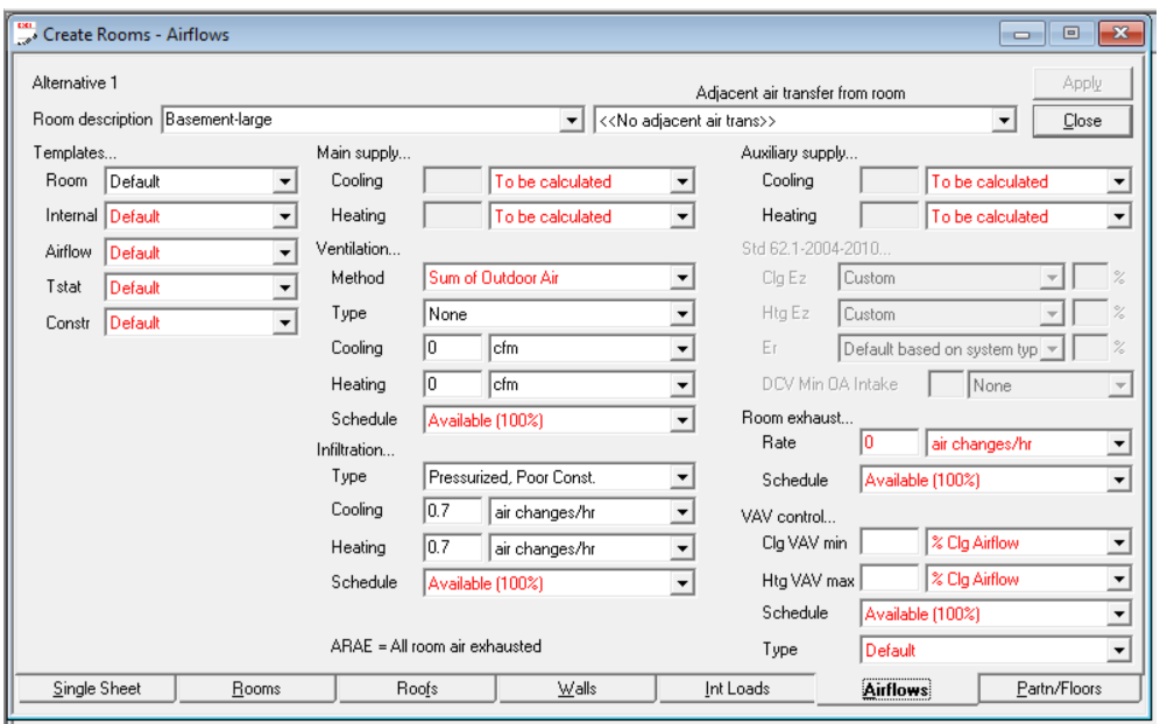


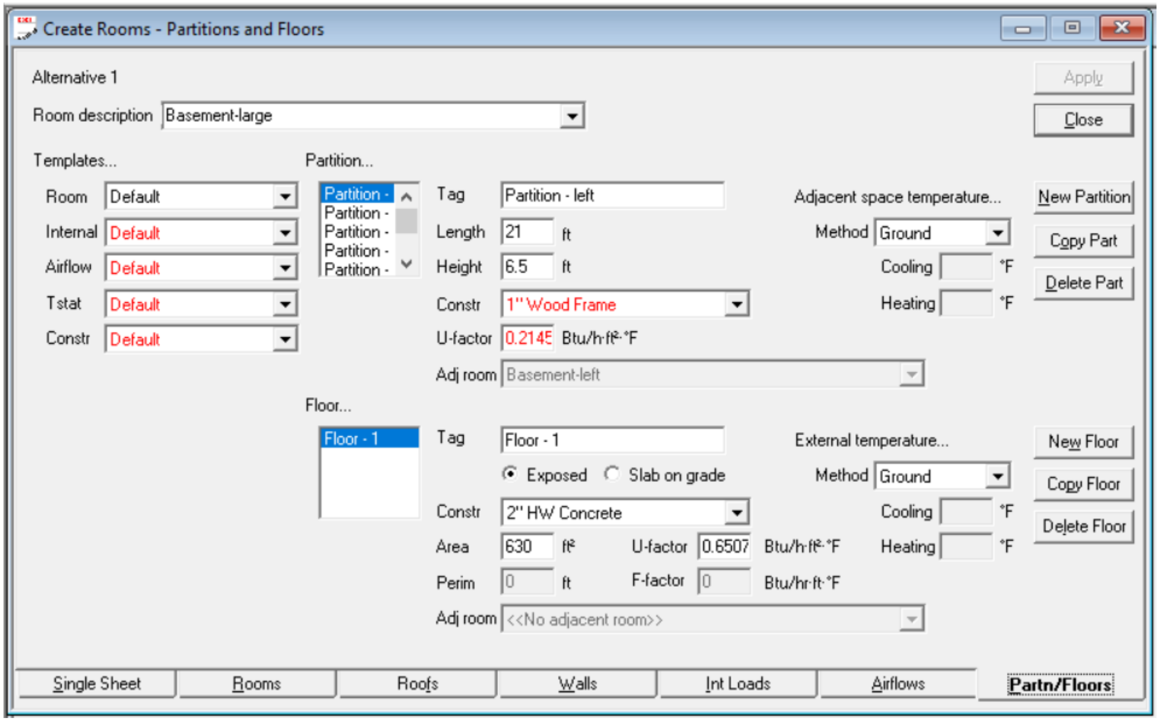


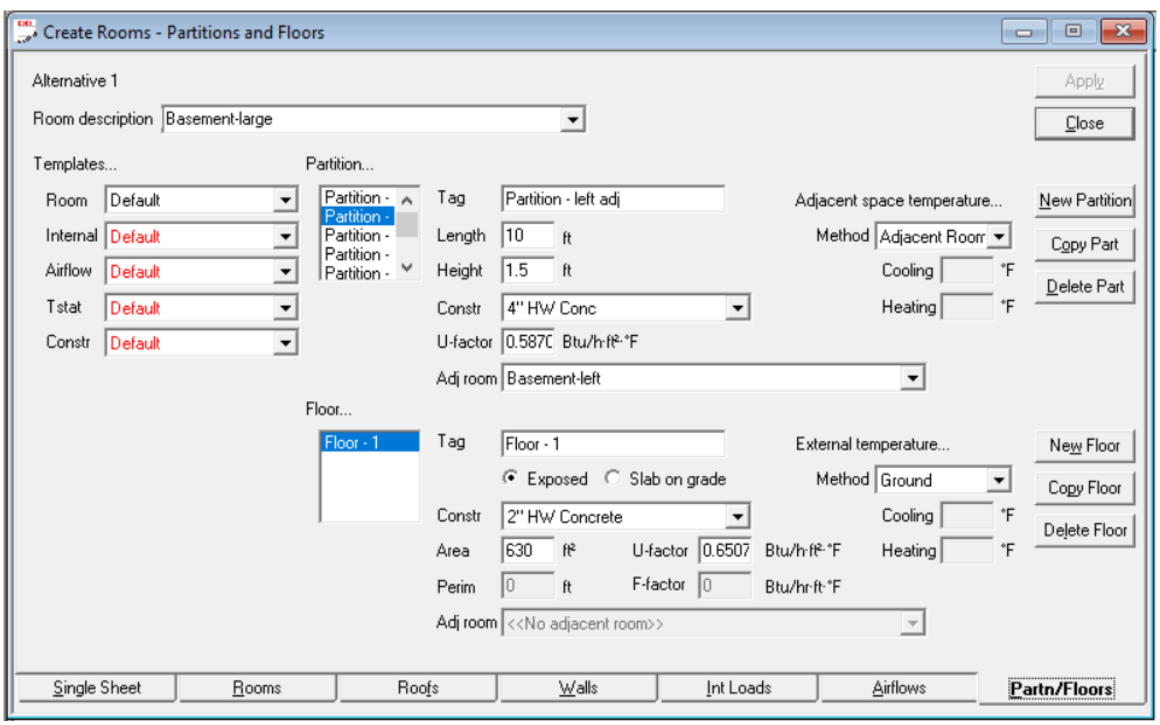

Create Rooms - Roofs
Alternative 1
Room description
Basement-large
Apply
Close
Templates...
Room
Internal
Airflow
Tstat
Constr
Default
Roof...
Tag
Roof - 2
Equals floor
Length
52
Width
35
Construct
U-factor
0.15749
Pitch
-60
deg
Direction
0
New Roof
Copy
Delete
Skylight...
Roof area
%
Type
U-factor
0.95
Sh. Coef
Ld to RA
Quantity
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

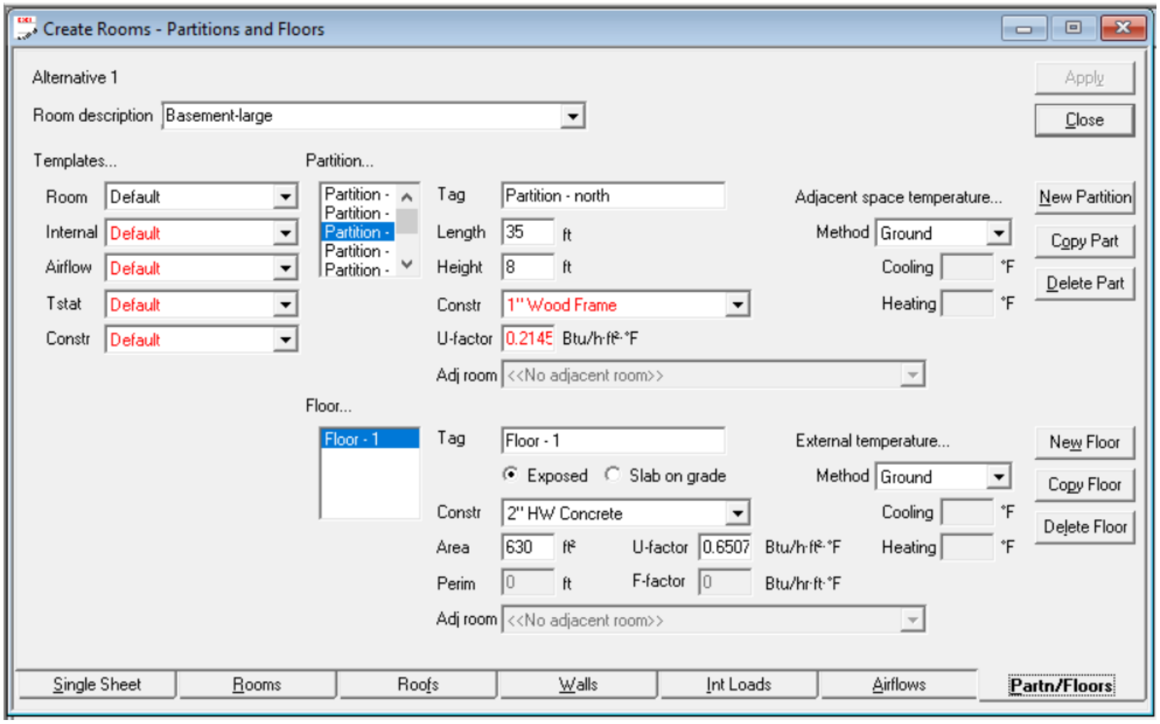

Create Rooms - Walls
Alternative 1
Room description
Basement-large
Apply
Close
Templates...
Room
Internal
Airflow
Tstat
Constr
Default
Wall...
Tag
Wall - 2
Length
22
Height
8
Grnd reflect multiplier
Construct
U-factor
0.1220
Tilt
deg
Direction
270
Pct wall area to underfloor plenum
New Wall
Copy Wall
Delete Wall
Openings...
Window
Door
Wall area
Type
Quantity
Sh. Coef
Ld to RA
New Opening
Copy Opening
Delete Opening
Shading...
External
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

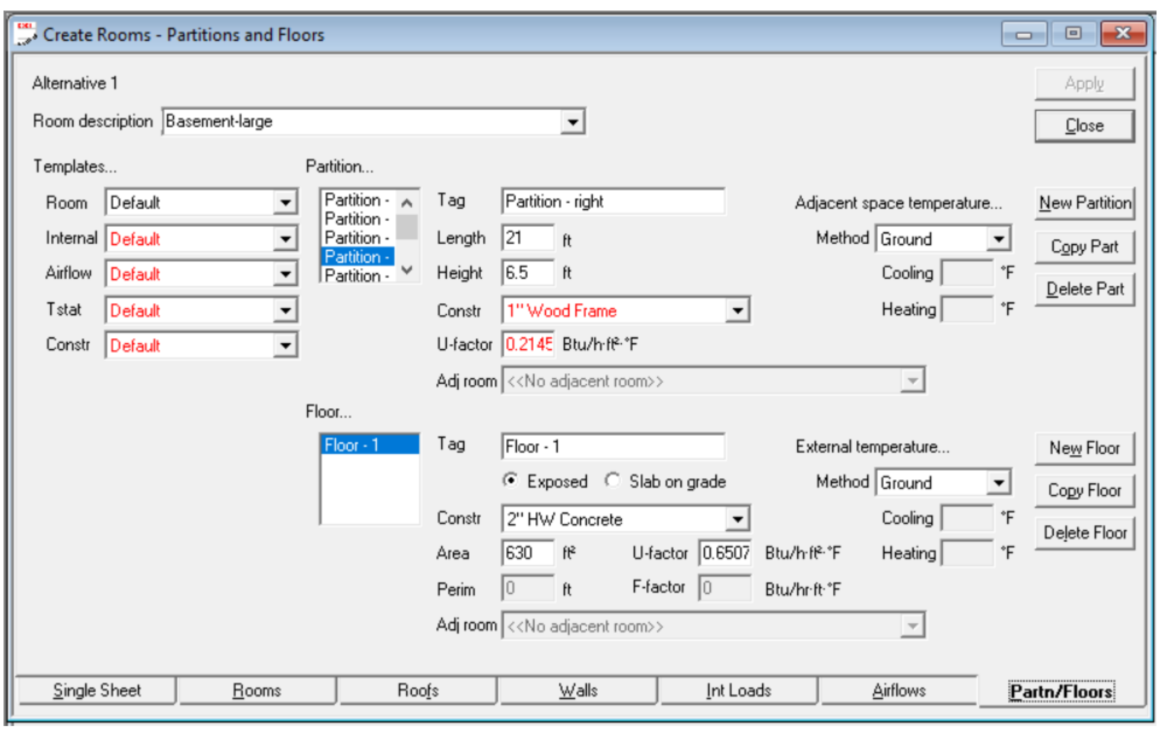

Create Rooms - Internal Loads
Alternative 1
Apply
Close
Room description
Basement-large
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
People...
Activity
None
Density
1
People
Schedule
Base Util - Lodging
Sensible
250
Btu/h
Latent
250
Btu/h
Workstations...
Density
1
workstation/person
Lights...
Type
Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain
0
W/sq ft
Schedule
Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag
Misc Load 1
Type
None
New Load
Energy
0
W/sq ft
Schedule
Base Util - Lodging
Copy
Energy meter
None
Data Center Equipment
No
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

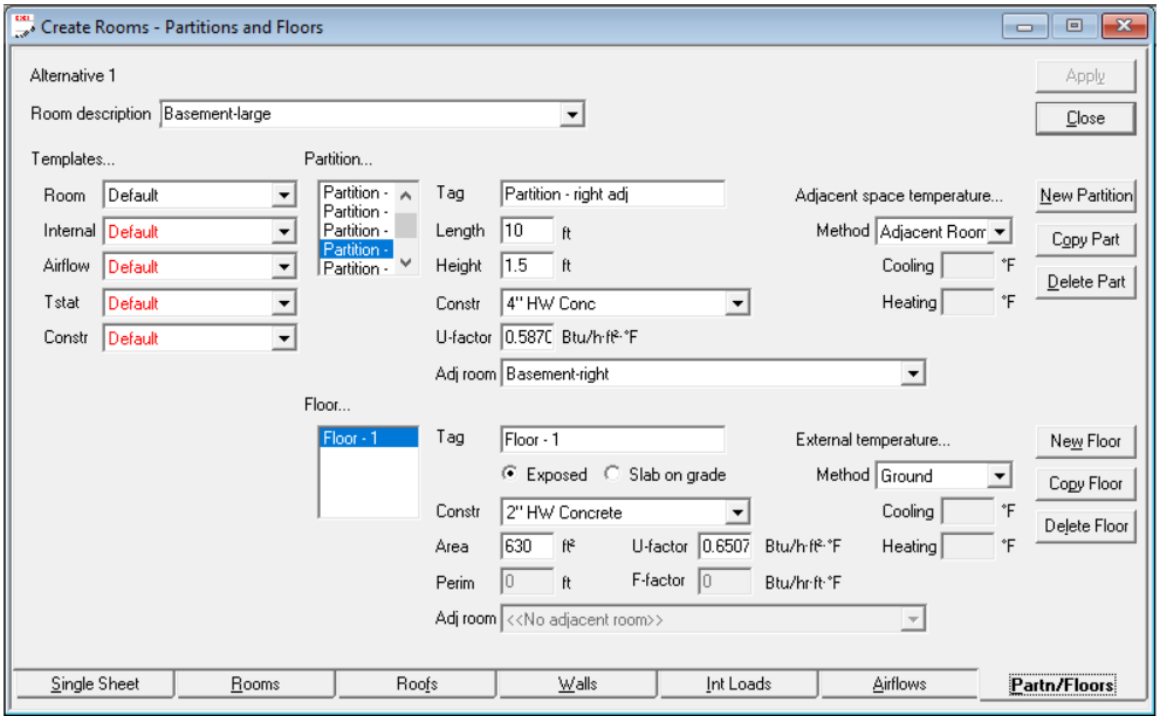

Create Rooms - Airflows
Alternative 1
Adjacent air transfer from room
Apply
Room description
Basement-large
<<No adjacent air trans>>
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Main supply...
Cooling
To be calculated
Heating
To be calculated
Ventilation...
Method
Sum of Outdoor Air
Type
None
Cooling
0
cfm
Heating
0
cfm
Schedule
Available (100%)
Infiltration...
Type
Pressurized, Poor Const.
Cooling
0.7
air changes/hr
Heating
0.7
air changes/hr
Schedule
Available (100%)
Auxiliary supply...
Cooling
To be calculated
Heating
To be calculated
Std 62.1-2004-2010...
Clg Ez
Custom
Htg Ez
Custom
Er
Default based on system typ
DCV Min OA Intake
None
Room exhaust...
Rate
0
air changes/hr
Schedule
Available (100%)
VAV control...
Clg VAV min
% Clg Airflow
Htg VAV max
% Clg Airflow
Schedule
Available (100%)
Type
Default
ARAE = All room air exhausted
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

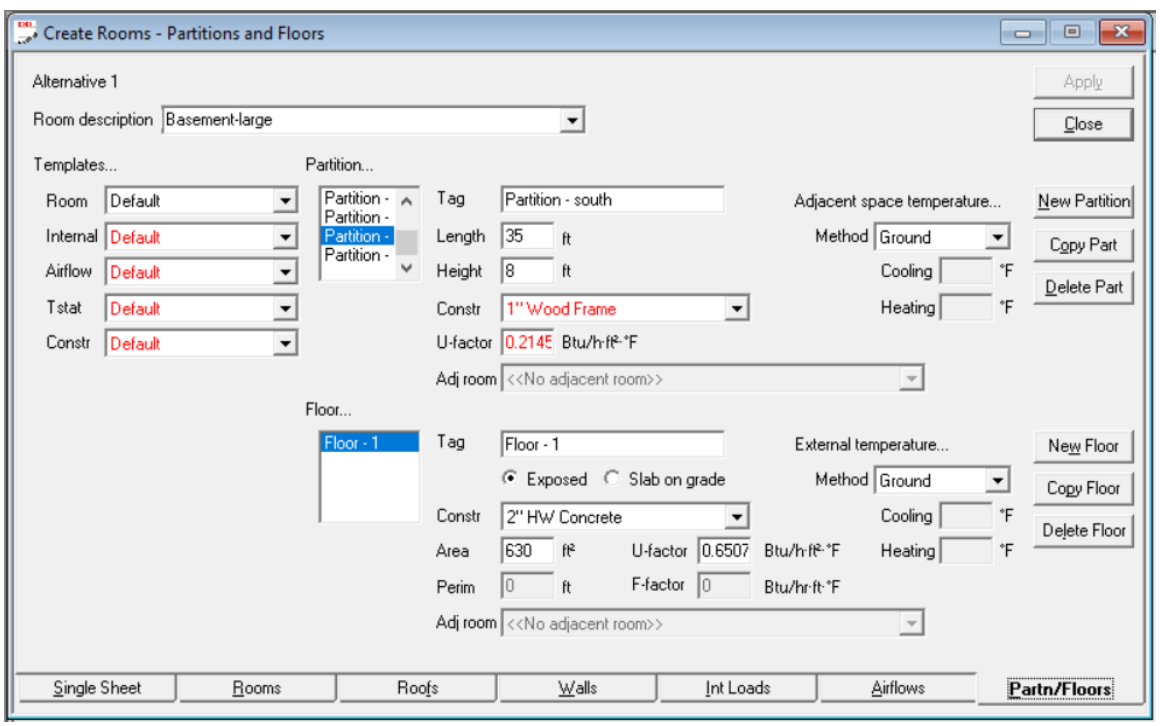

Create Rooms - Partitions and Floors
Alternative 1
Apply
Room description
Basement-large
Close
Templates...
Partition...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Tag
Partition - left
Length
21
ft
Height
6.5
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
Basement-left
Adjacent space temperature...
Method
Ground
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
630
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Ground
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

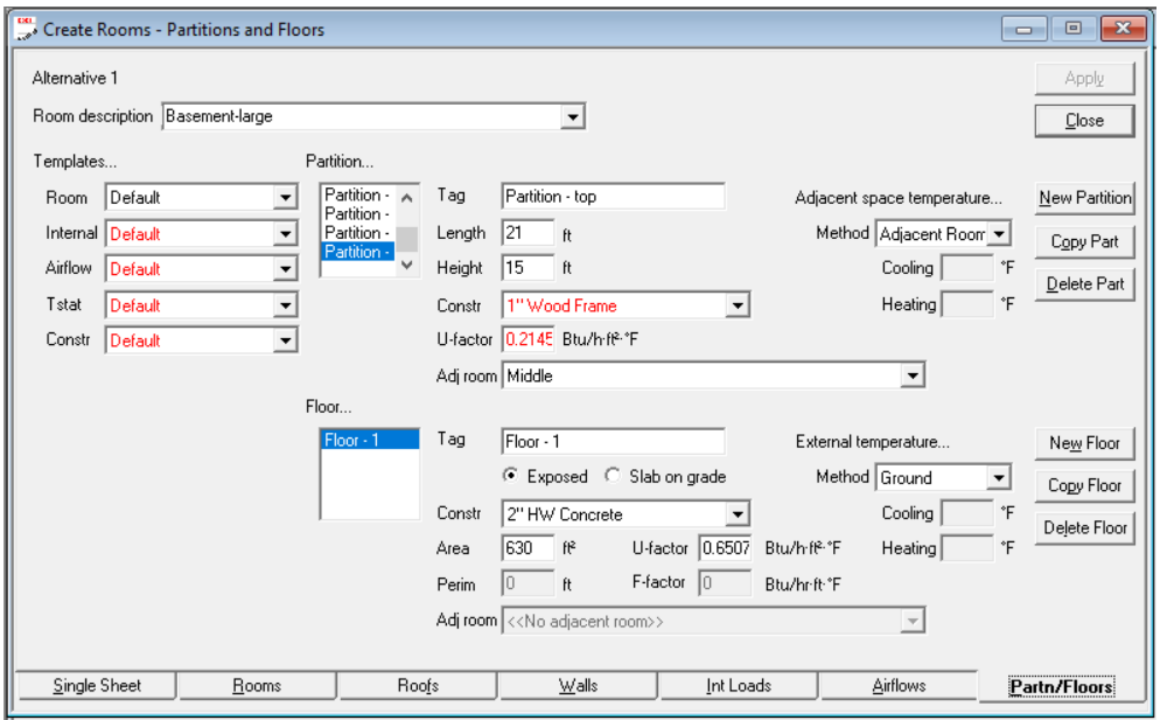

Create Rooms - Partitions and Floors
Alternative 1
Apply
Room description
Basement-large
Close
Templates...
Partition...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Tag
Partition - left adj
Length
10
ft
Height
1.5
ft
Constr
4" HW Conc
U-factor
0.5870
Btu/h·ft²·°F
Adj room
Basement-left
Adjacent space temperature...
Method
Adjacent Room
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
630
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Ground
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Partitions and Floors
Alternative 1
Room description
Basement-large
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition...
Partition -
Partition -
Partition -
Partition -
Partition -
Tag
Partition - north
Length
35
ft
Height
8
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
<<No adjacent room>>
Adjacent space temperature...
Method
Ground
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
630
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Ground
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

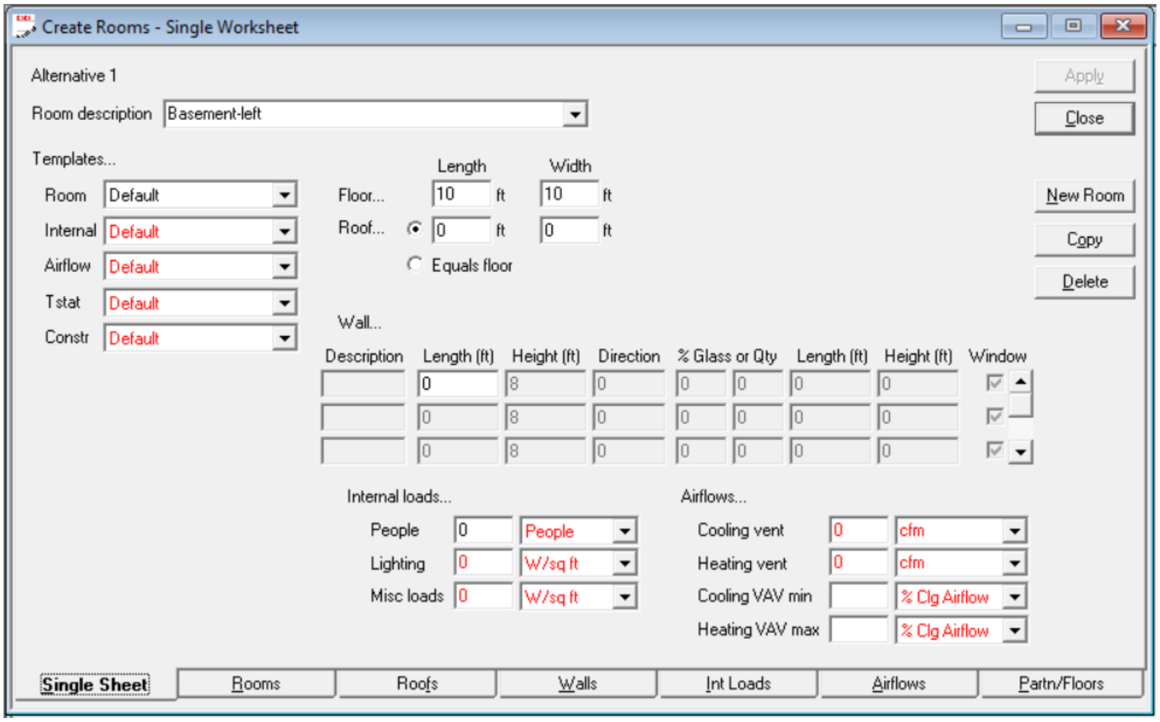

Create Rooms - Partitions and Floors
Alternative 1
Room description
Basement-large
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition...
Partition -
Partition -
Partition -
Partition -
Partition -
Tag
Partition - right
Length
21
ft
Height
6.5
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
<<No adjacent room>>
Adjacent space temperature...
Method
Ground
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
630
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Ground
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

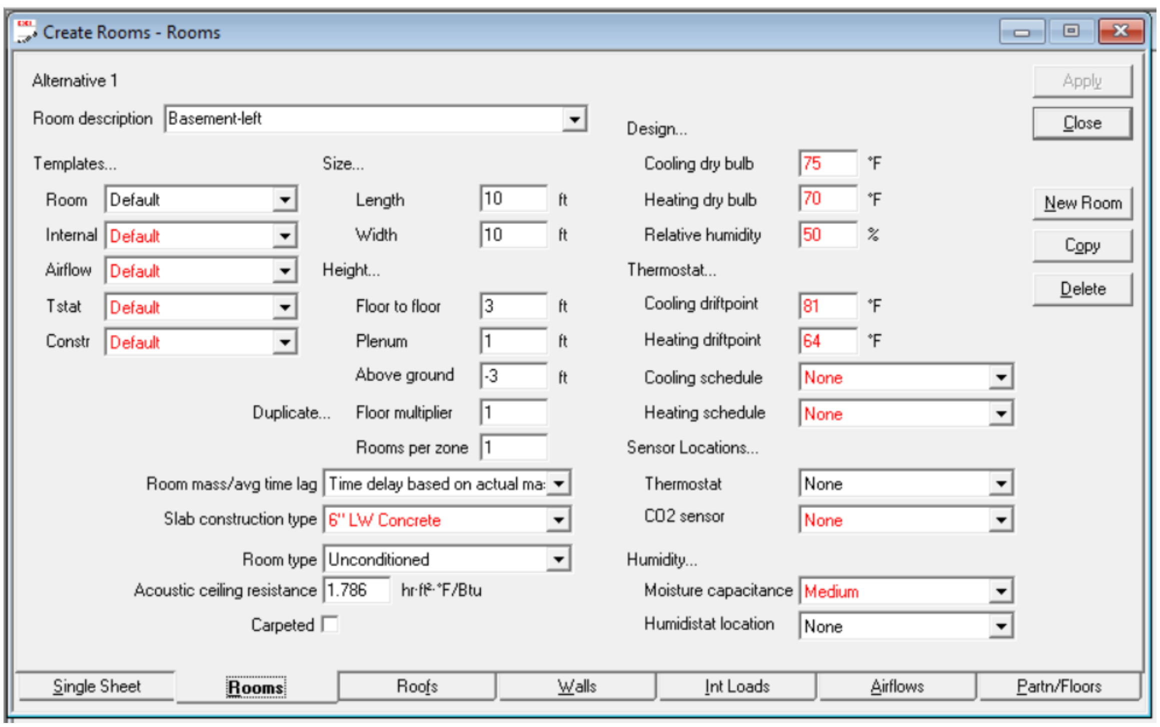

Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-large
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Tag Partition - right adj
Length 10 ft
Height 1.5 ft
Constr 4" HW Conc
U-factor 0.587 Btu/h·ft²·°F
Adj room Basement-right
Adjacent space temperature...
Method Adjacent Room
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 630 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Ground
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

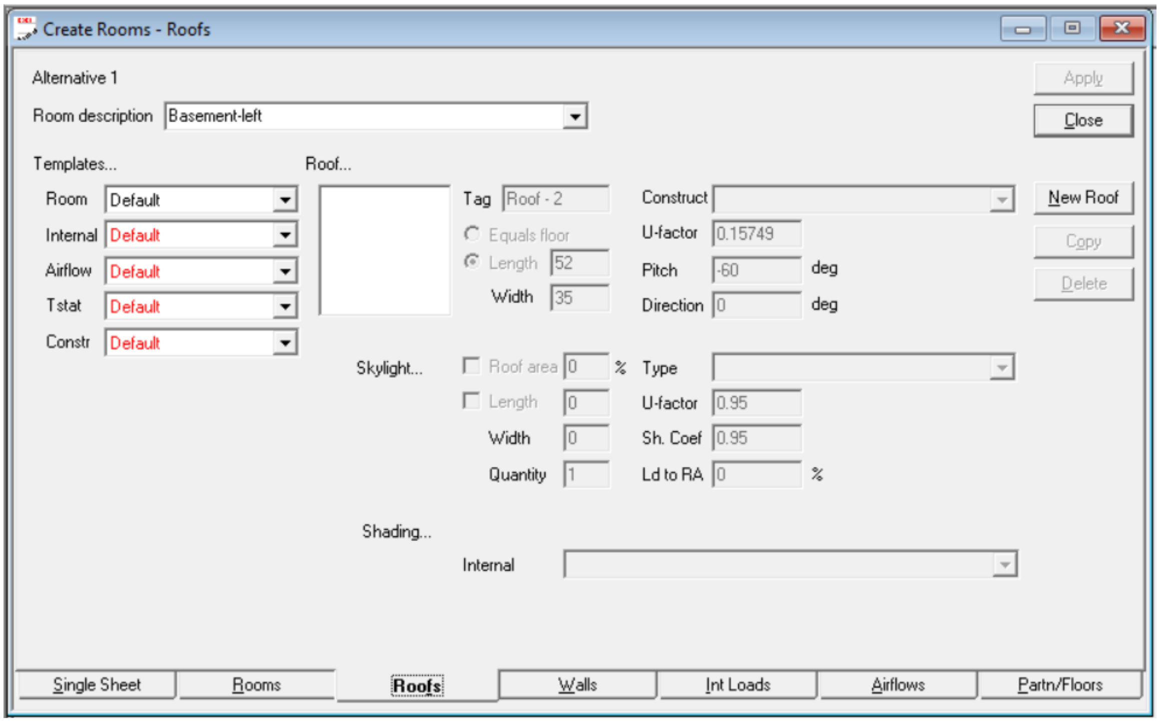

Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-large
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Tag Partition - south
Length 35 ft
Height 8 ft
Constr 1" Wood Frame
U-factor 0.2145 Btu/h·ft²·°F
Adj room <<No adjacent room>>
Adjacent space temperature...
Method Ground
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 630 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Ground
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

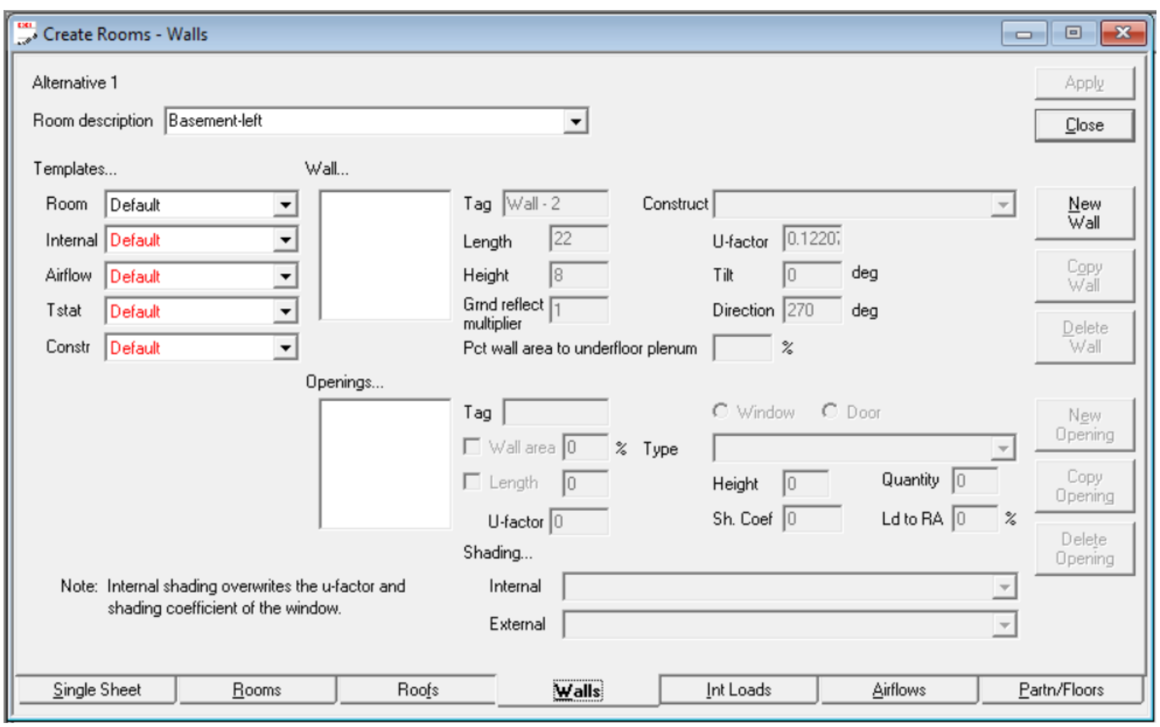

Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-large
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Partition -
Partition -
Partition -
Partition -
Tag Partition - top
Length 21 ft
Height 15 ft
Constr 1" Wood Frame
U-factor 0.2145 Btu/h·ft²·°F
Adj room Middle
Adjacent space temperature...
Method Adjacent Room
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 630 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Ground
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

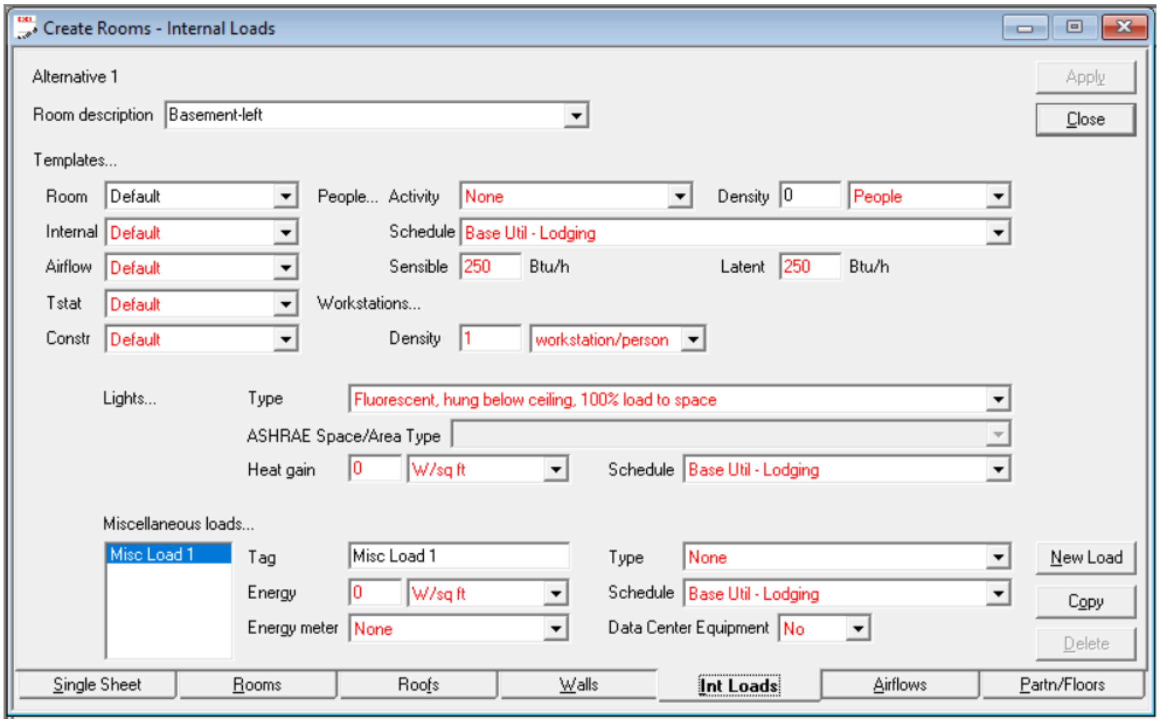
A.2.8 Basement-Left

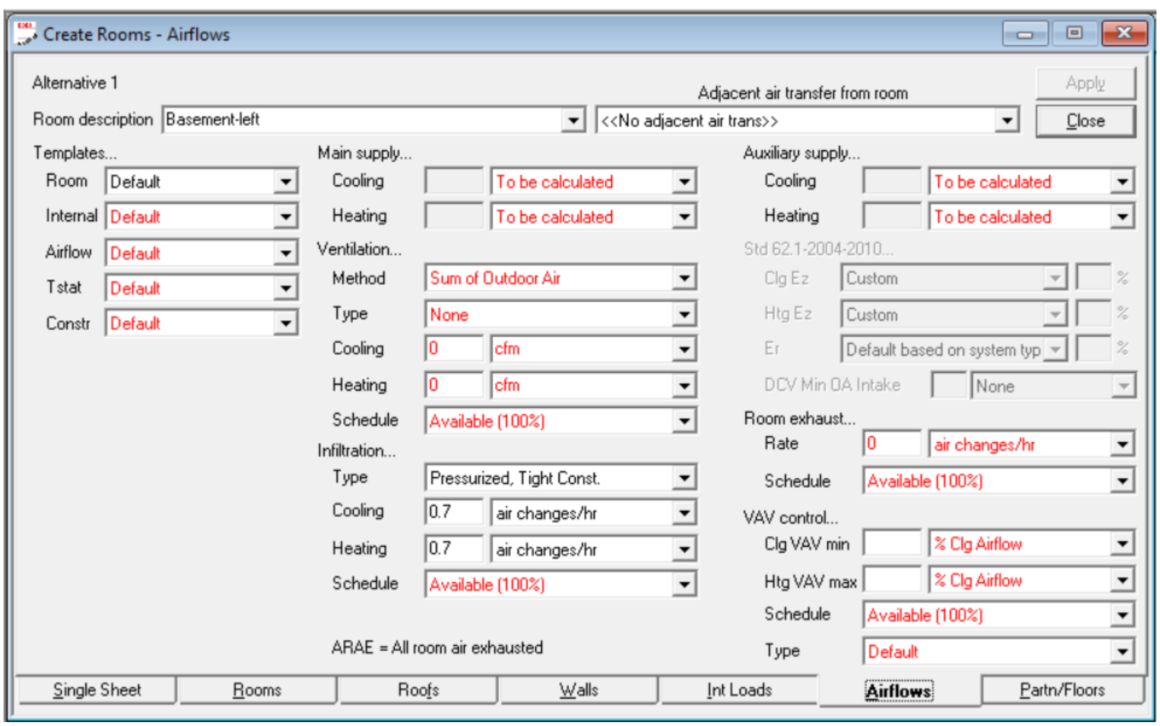


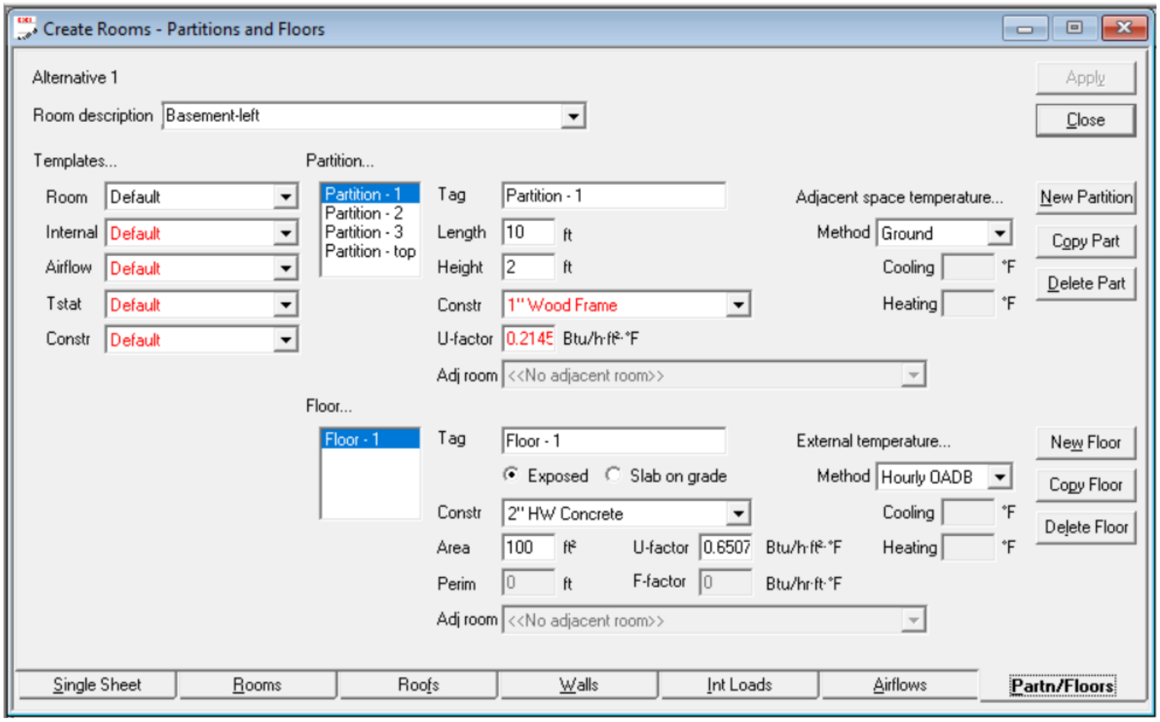


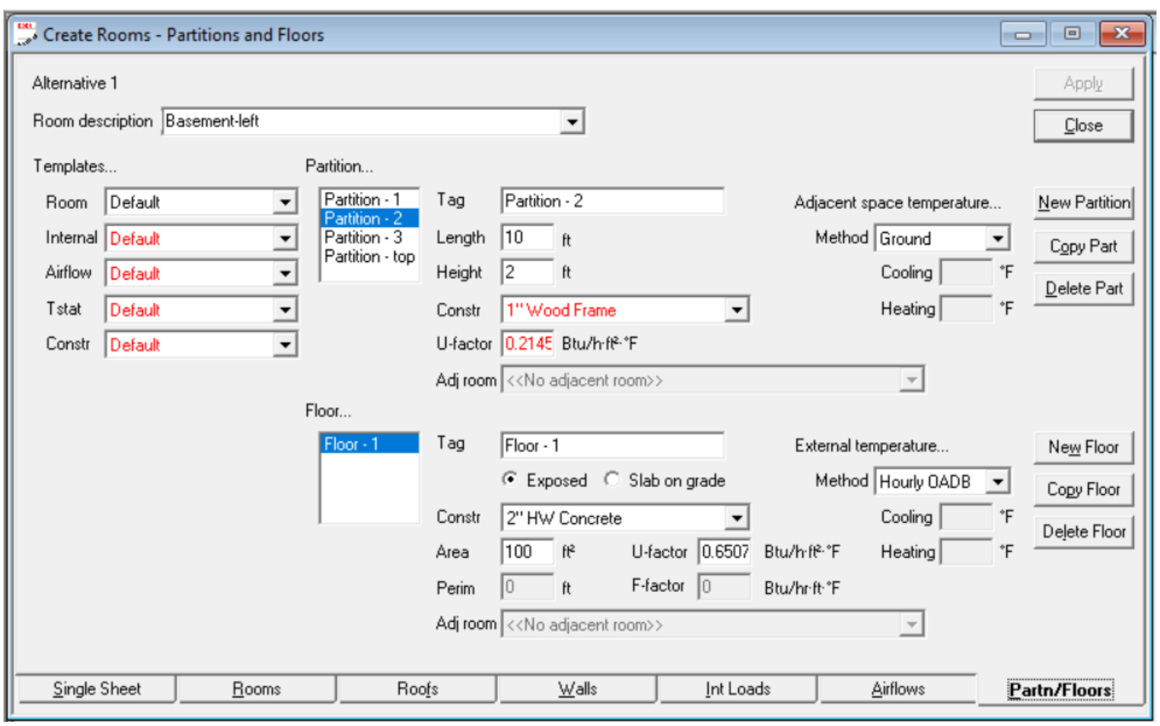

Create Rooms - Roofs
Alternative 1
Room description Basement-left
Apply
Close
Templates...
Roof...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Tag Roof - 2
Equals floor
Length 52
Width 35
Construct
U-factor 0.15749
Pitch -60 deg
Direction 0 deg
New Roof
Copy
Delete
Skylight...
Roof area 0 %
Length 0
Width 0
Quantity 1
Type
U-factor 0.95
Sh. Coef 0.95
Ld to RA 0 %
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

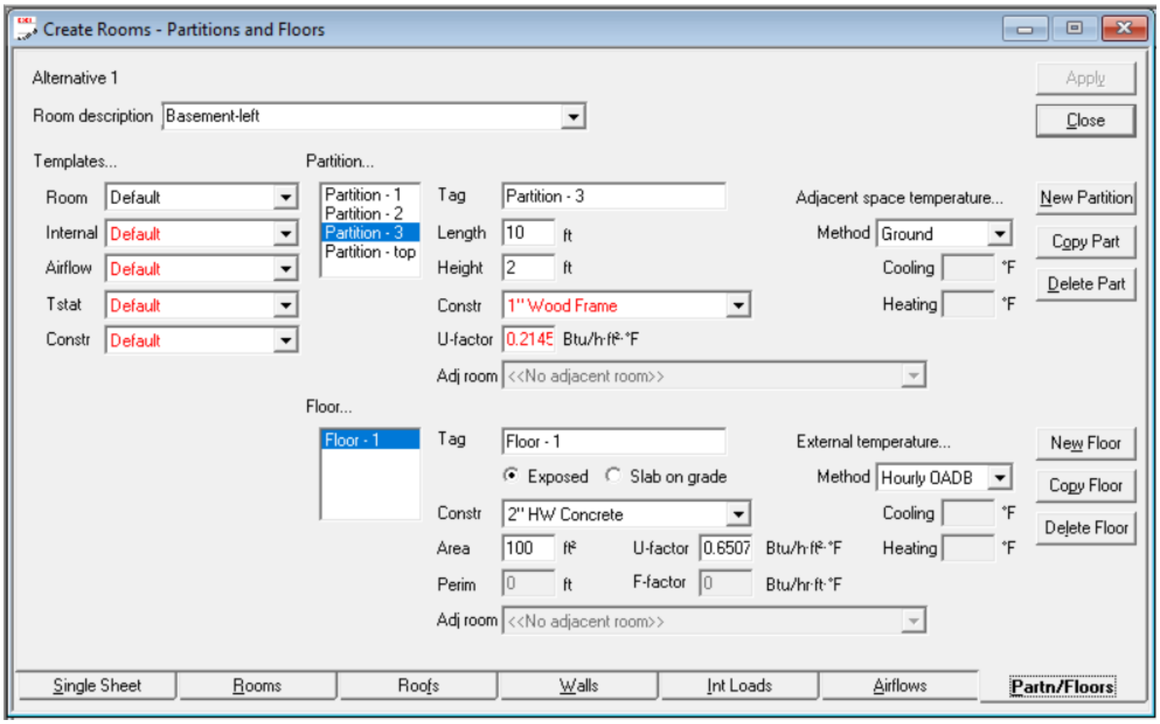

Create Rooms - Walls
Alternative 1
Room description Basement-left
Apply
Close
Templates...
Wall...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Tag Wall - 2
Length 22
Height 8
Grnd reflect multiplier 1
Pct wall area to underfloor plenum %
Construct
U-factor 0.1220
Tilt 0 deg
Direction 270 deg
New Wall
Copy Wall
Delete Wall
Openings...
Tag
Wall area 0 %
Length 0
U-factor 0
Window
Door
Type
Height 0
Sh. Coef 0
Quantity 0
Ld to RA 0 %
New Opening
Copy Opening
Delete Opening
Shading...
Internal
External
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Internal Loads
Alternative 1
Apply
Close
Room description
Basement-left
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
People...
Activity
None
Density
0
People
Schedule
Base Util - Lodging
Sensible
250
Btu/h
Latent
250
Btu/h
Workstations...
Density
1
workstation/person
Lights...
Type
Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain
0
W/sq ft
Schedule
Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag
Misc Load 1
Type
None
New Load
Energy
0
W/sq ft
Schedule
Base Util - Lodging
Copy
Energy meter
None
Data Center Equipment
No
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

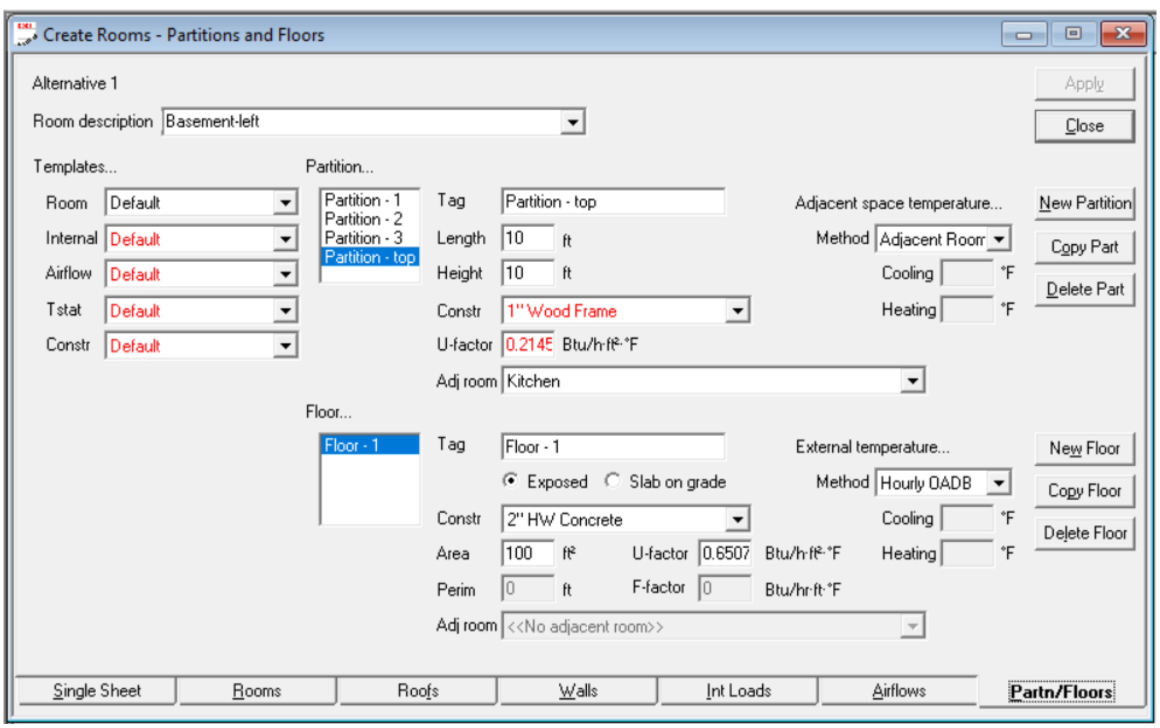

Create Rooms - Airflows
Alternative 1
Adjacent air transfer from room
Apply
Room description
Basement-left
<<No adjacent air trans>>
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Main supply...
Cooling
To be calculated
Heating
To be calculated
Ventilation...
Method
Sum of Outdoor Air
Type
None
Cooling
0
cfm
Heating
0
cfm
Schedule
Available (100%)
Infiltration...
Type
Pressurized, Tight Const.
Cooling
0.7
air changes/hr
Heating
0.7
air changes/hr
Schedule
Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling
To be calculated
Heating
To be calculated
Std 62.1-2004-2010...
Clg Ez
Custom
%
Htg Ez
Custom
%
Er
Default based on system typ
%
DCV Min OA Intake
None
Room exhaust...
Rate
0
air changes/hr
Schedule
Available (100%)
VAV control...
Clg VAV min
% Clg Airflow
Htg VAV max
% Clg Airflow
Schedule
Available (100%)
Type
Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-left
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag Partition - 1
Length 10 ft
Height 2 ft
Constr 1" Wood Frame
U-factor 0.2145 Btu/h·ft²·°F
Adj room <<No adjacent room>>
Adjacent space temperature...
Method Ground
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 100 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Hourly OADB
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-left
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag Partition - 2
Length 10 ft
Height 2 ft
Constr 1" Wood Frame
U-factor 0.2145 Btu/h·ft²·°F
Adj room <<No adjacent room>>
Adjacent space temperature...
Method Ground
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 100 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Hourly OADB
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

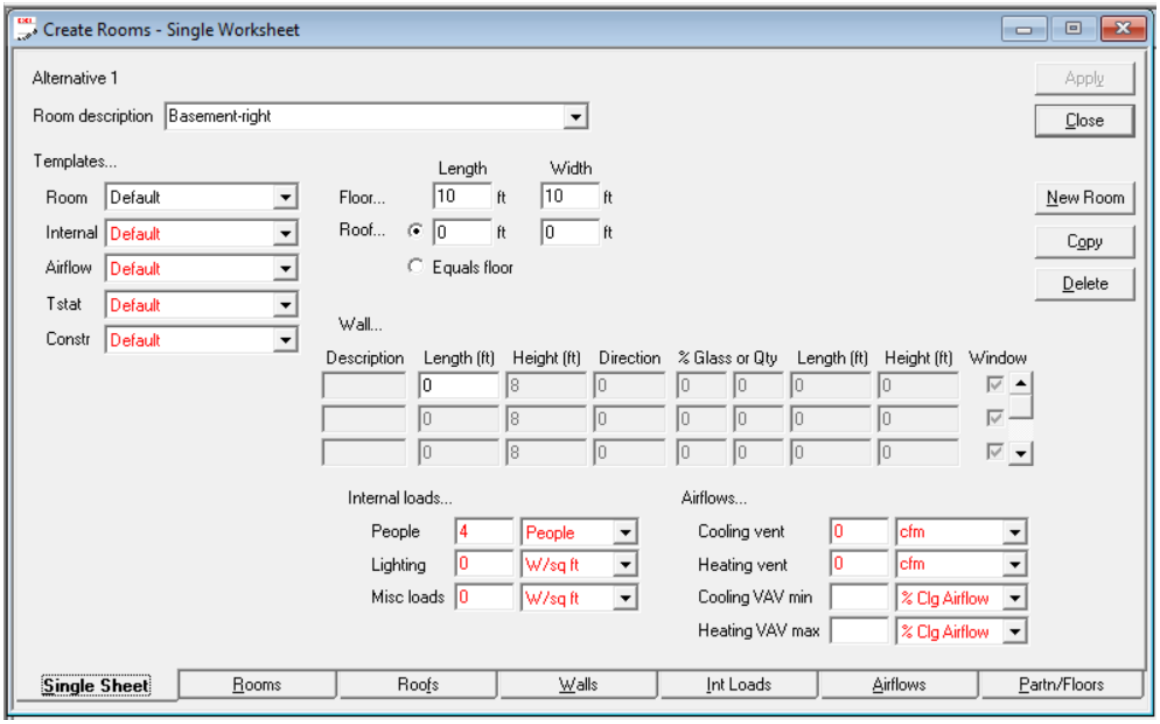


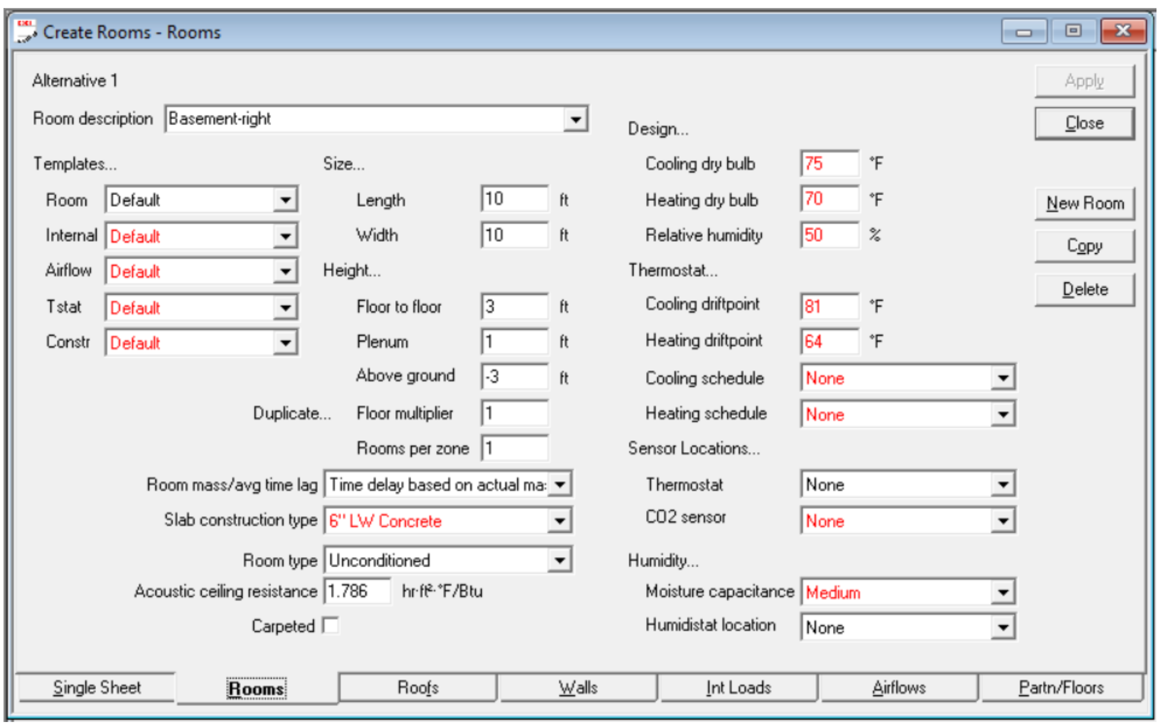
Create Rooms - Partitions and Floors
Alternative 1
Room description
Basement-left
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition...
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag
Partition - 3
Length
10
ft
Height
2
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
<<No adjacent room>>
Adjacent space temperature...
Method
Ground
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
100
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Hourly OADB
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

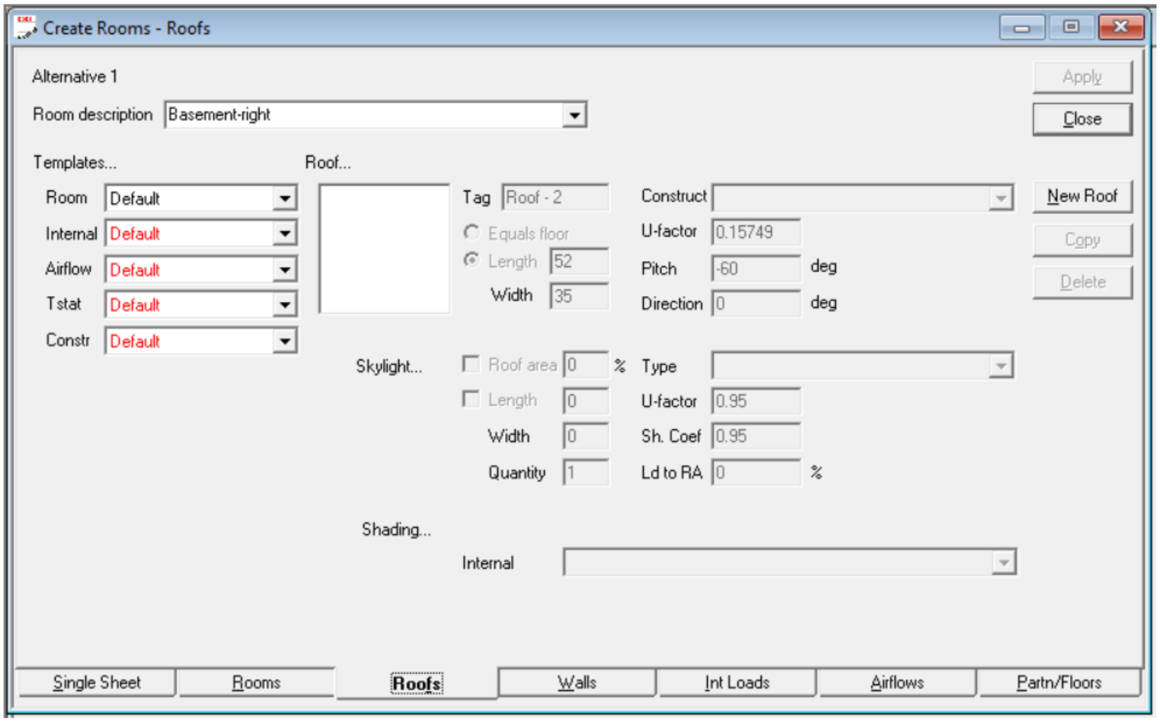


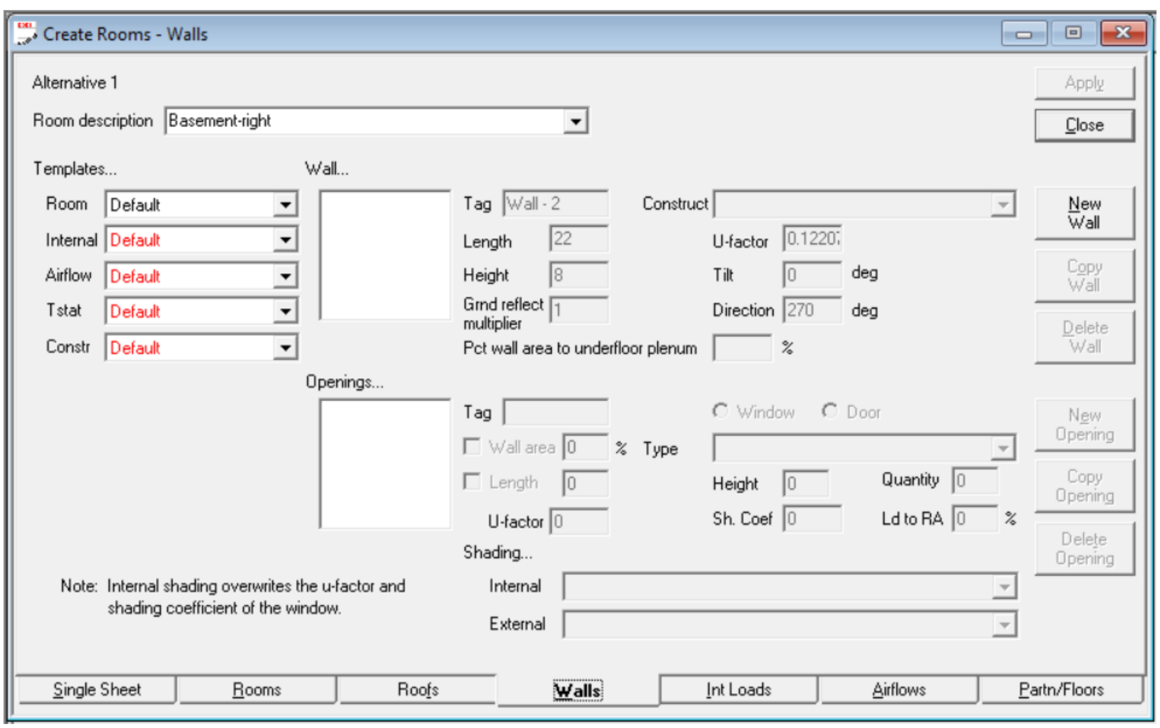
Create Rooms - Partitions and Floors
Alternative 1
Room description
Basement-left
Apply
Close
Templates...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition...
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag
Partition - top
Length
10
ft
Height
10
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
Kitchen
Adjacent space temperature...
Method
Adjacent Room
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
100
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Hourly OADB
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

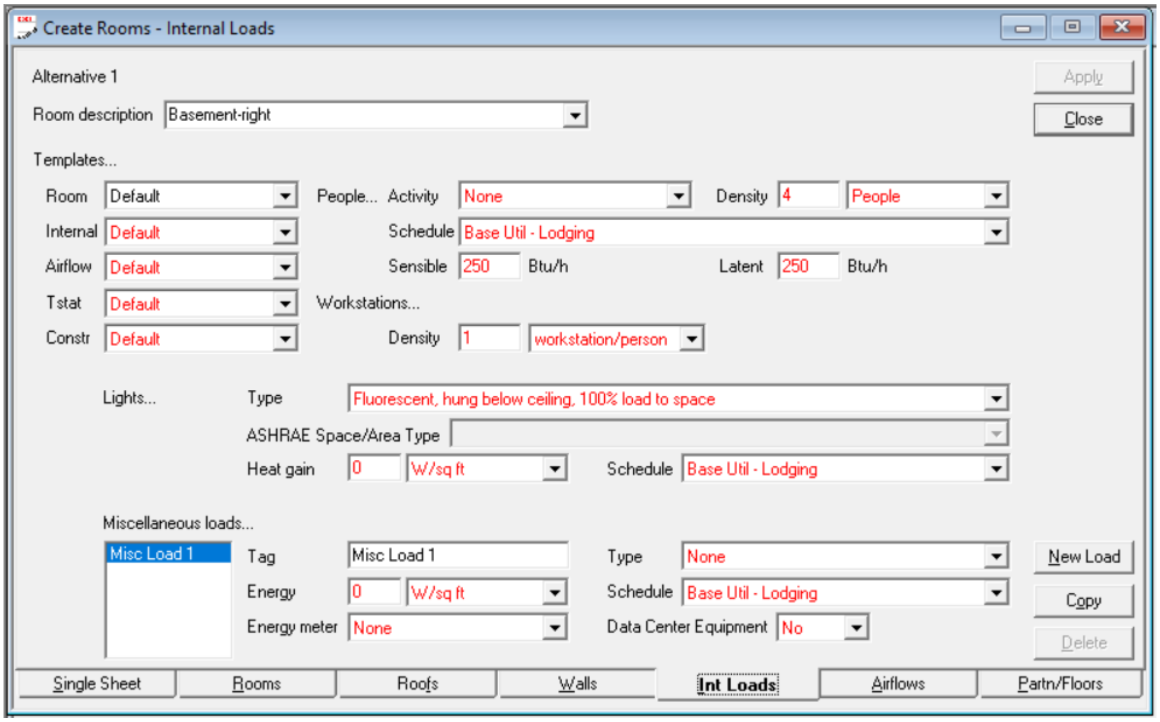
A.2.9 Basement-Right

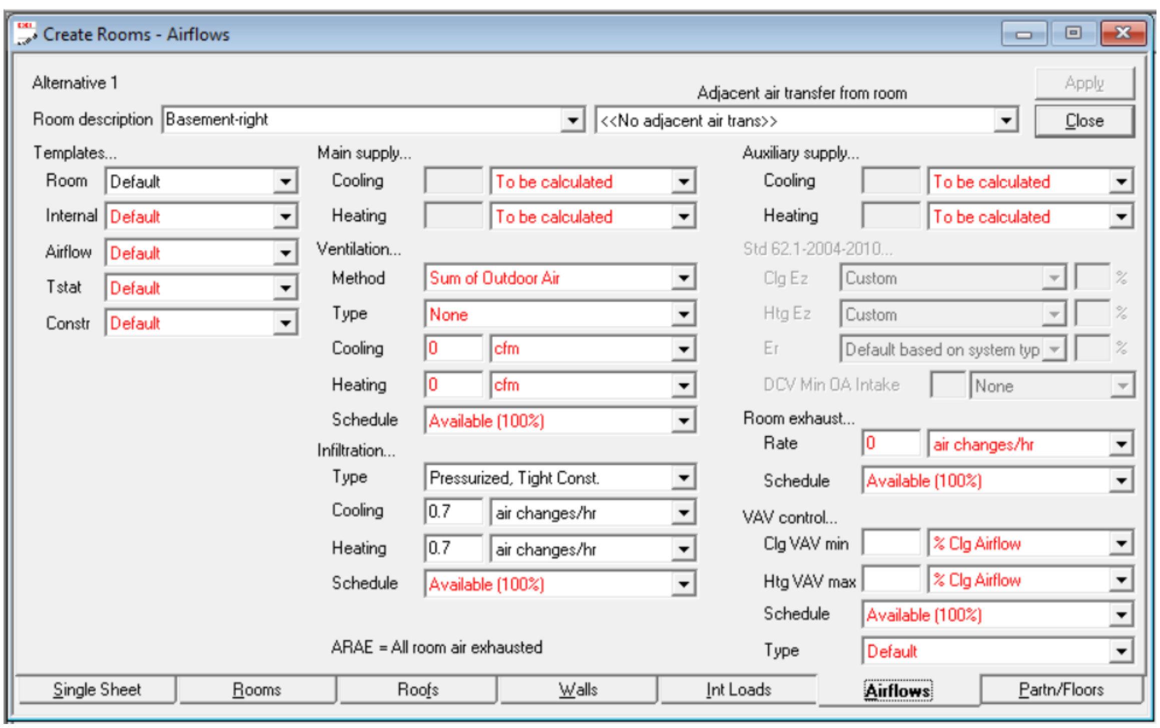


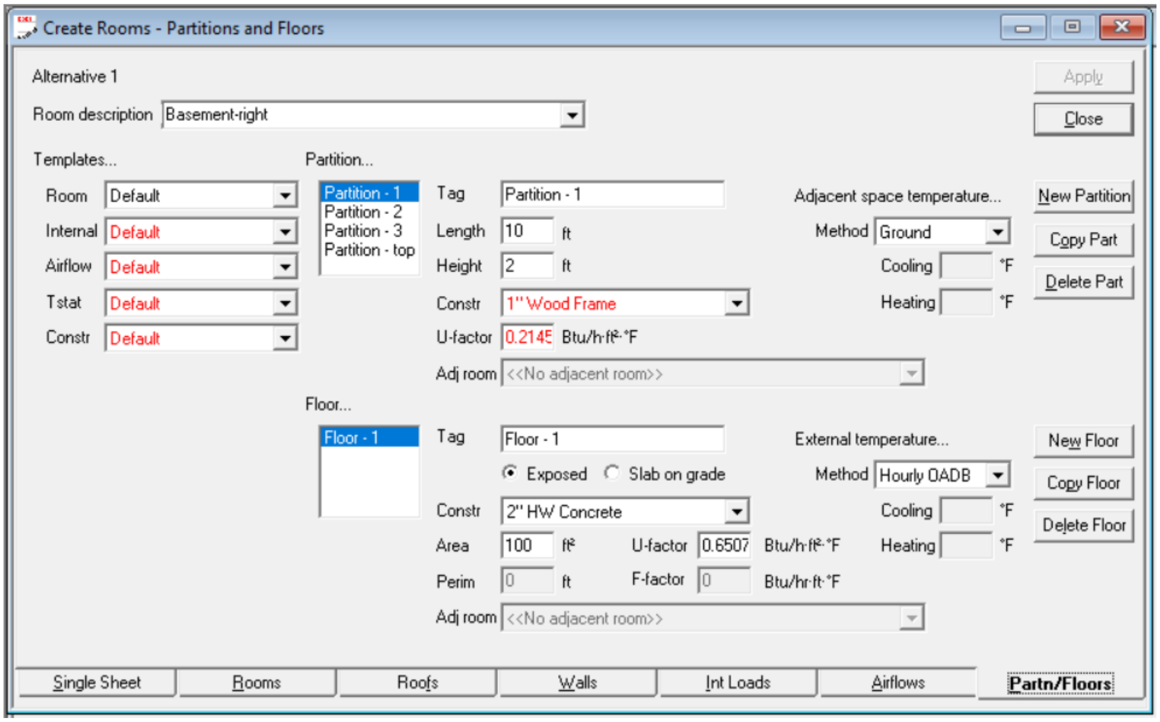


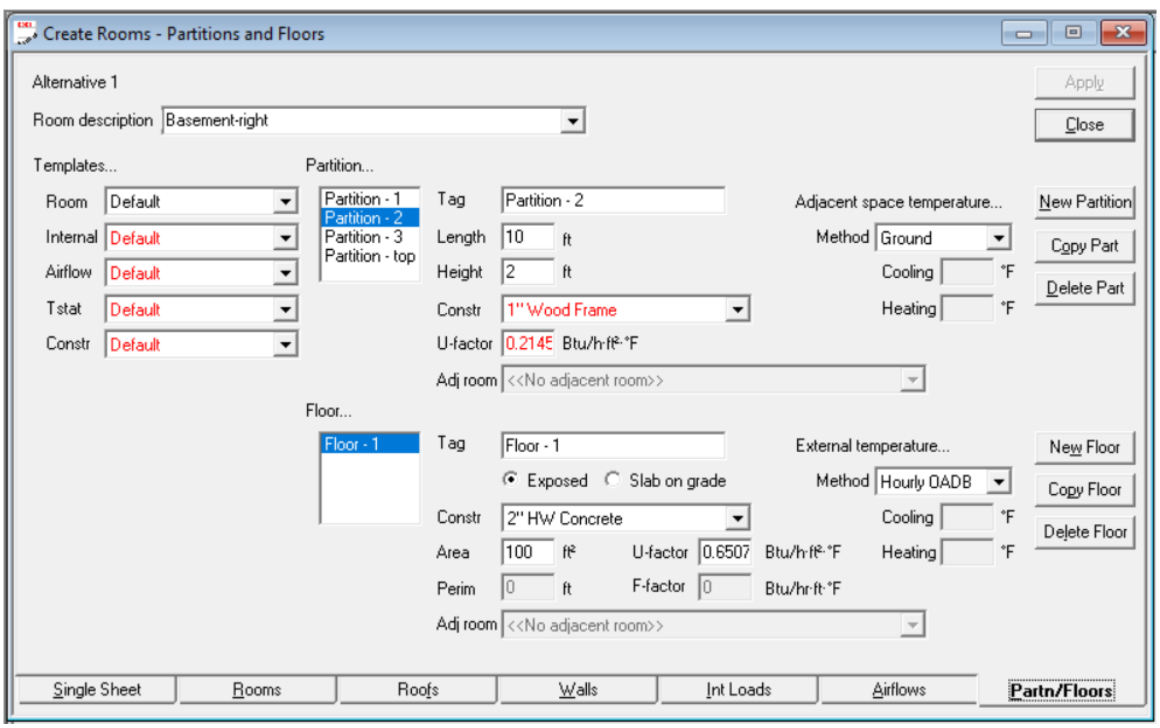

Create Rooms - Roofs
Alternative 1
Room description Basement-right
Apply
Close
Templates...
Roof...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Tag Roof - 2
Equals floor
Length 52
Width 35
Construct
U-factor 0.15749
Pitch -60 deg
Direction 0 deg
New Roof
Copy
Delete
Skylight...
Roof area 0 %
Length 0
Width 0
Quantity 1
Type
U-factor 0.95
Sh. Coef 0.95
Ld to RA 0 %
Shading...
Internal
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

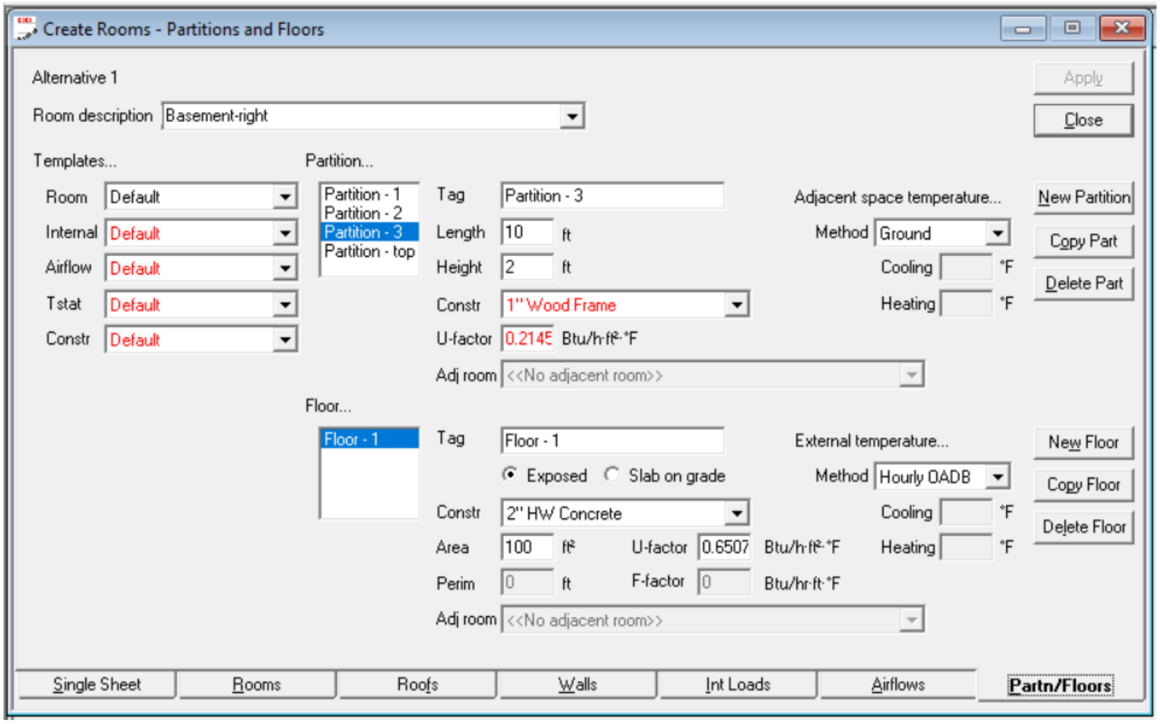

Create Rooms - Walls
Alternative 1
Room description Basement-right
Apply
Close
Templates...
Wall...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Tag Wall - 2
Length 22
Height 8
Grnd reflect multiplier 1
Pct wall area to underfloor plenum
Construct
U-factor 0.1220
Tilt 0 deg
Direction 270 deg
New Wall
Copy Wall
Delete Wall
Openings...
Tag
Window
Door
Wall area 0 %
Type
Length 0
Height 0
Quantity 0
U-factor 0
Sh. Coef 0
Ld to RA 0 %
New Opening
Copy Opening
Delete Opening
Shading...
Internal
External
Note: Internal shading overwrites the u-factor and shading coefficient of the window.
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

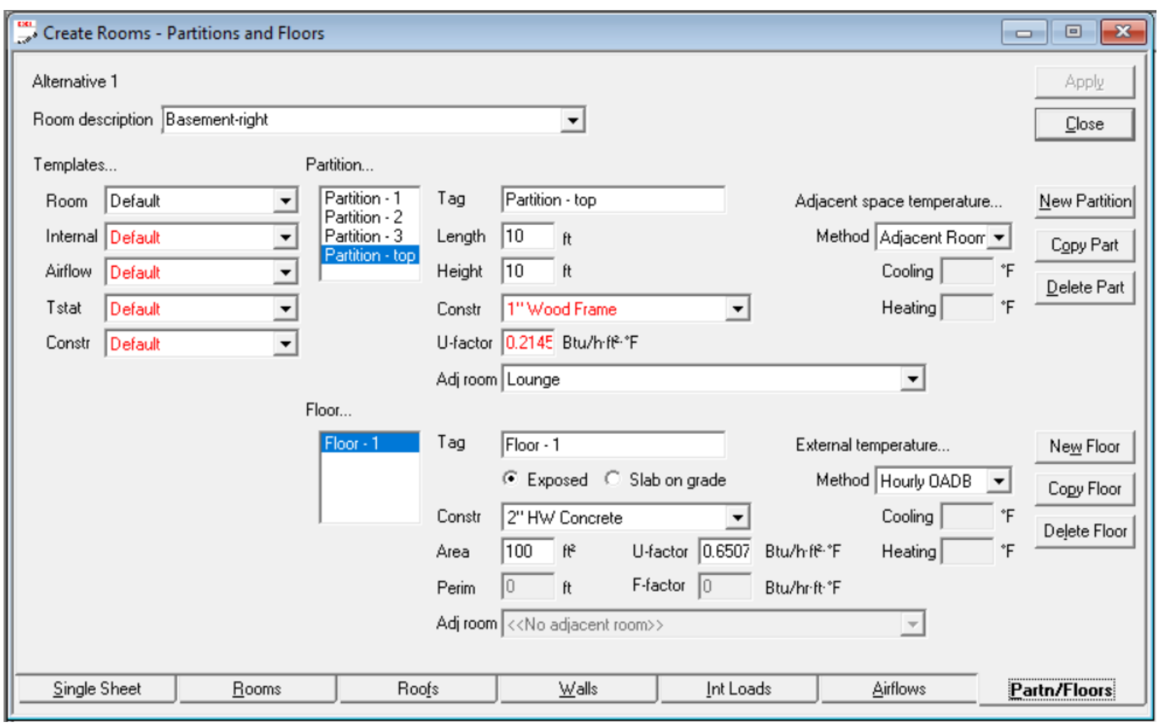

Create Rooms - Internal Loads
Alternative 1
Room description Basement-right
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
People... Activity None
Density 4 People
Schedule Base Util - Lodging
Sensible 250 Btu/h
Latent 250 Btu/h
Workstations...
Density 1 workstation/person
Lights...
Type Fluorescent, hung below ceiling, 100% load to space
ASHRAE Space/Area Type
Heat gain 0 W/sq ft
Schedule Base Util - Lodging
Miscellaneous loads...
Misc Load 1
Tag Misc Load 1
Type None
New Load
Energy 0 W/sq ft
Schedule Base Util - Lodging
Copy
Energy meter None
Data Center Equipment No
Delete
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors


Create Rooms - Airflows
Alternative 1
Adjacent air transfer from room
Apply
Room description Basement-right
<<No adjacent air trans>>
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Main supply...
Cooling To be calculated
Heating To be calculated
Ventilation...
Method Sum of Outdoor Air
Type None
Cooling 0 cfm
Heating 0 cfm
Schedule Available (100%)
Infiltration...
Type Pressurized, Tight Const.
Cooling 0.7 air changes/hr
Heating 0.7 air changes/hr
Schedule Available (100%)
ARAE = All room air exhausted
Auxiliary supply...
Cooling To be calculated
Heating To be calculated
Std 62.1-2004-2010...
Clg Ez Custom %
Htg Ez Custom %
Er Default based on system typ %
DCV Min OA Intake None
Room exhaust...
Rate 0 air changes/hr
Schedule Available (100%)
VAV control...
Clg VAV min % Clg Airflow
Htg VAV max % Clg Airflow
Schedule Available (100%)
Type Default
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

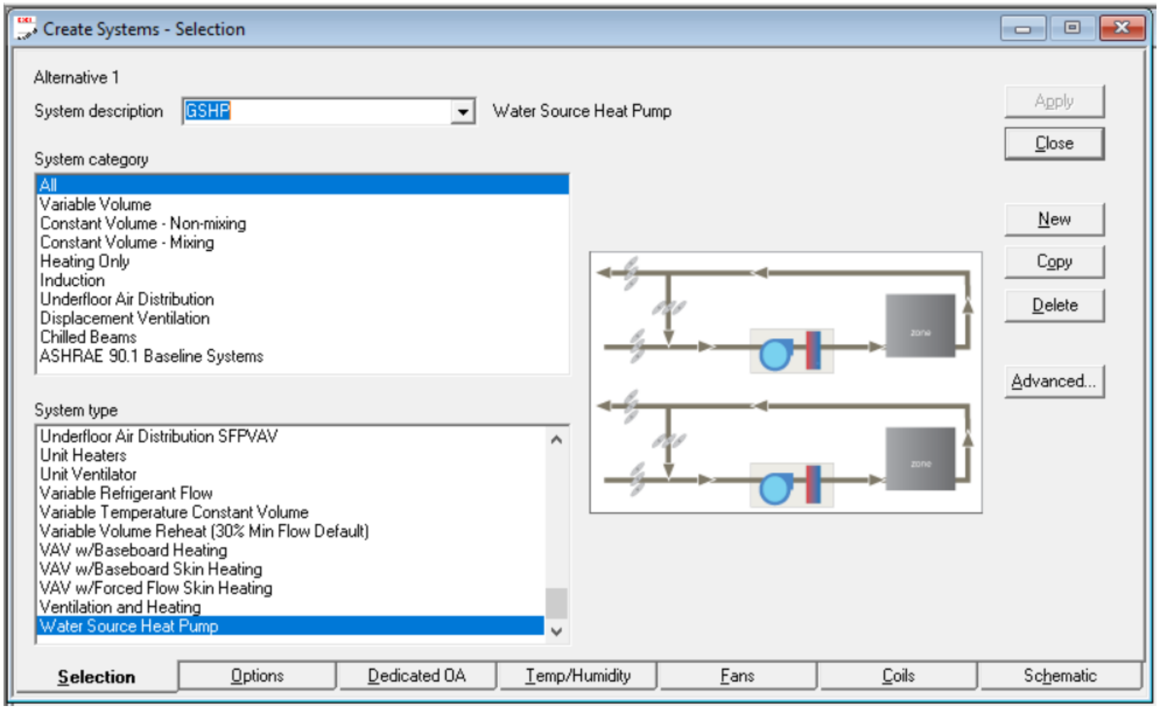

Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-right
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag Partition - 1
Length 10 ft
Height 2 ft
Constr 1" Wood Frame
U-factor 0.2145 Btu/h·ft²·°F
Adj room <<No adjacent room>>
Adjacent space temperature...
Method Ground
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 100 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Hourly OADB
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

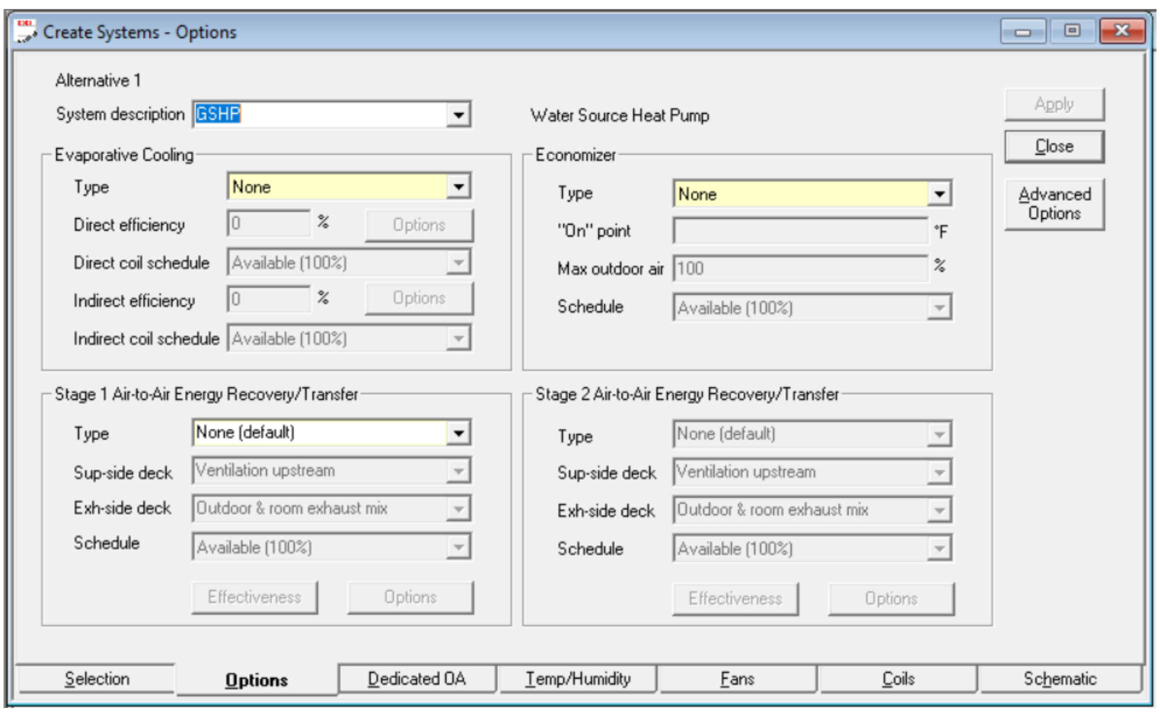

Create Rooms - Partitions and Floors
Alternative 1
Room description Basement-right
Apply
Close
Templates...
Room Default
Internal Default
Airflow Default
Tstat Default
Constr Default
Partition...
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag Partition - 2
Length 10 ft
Height 2 ft
Constr 1" Wood Frame
U-factor 0.2145 Btu/h·ft²·°F
Adj room <<No adjacent room>>
Adjacent space temperature...
Method Ground
Cooling °F
Heating °F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag Floor - 1
Exposed
Slab on grade
Constr 2" HW Concrete
Area 100 ft²
U-factor 0.6507 Btu/h·ft²·°F
Perim 0 ft
F-factor 0 Btu/hr·ft·°F
Adj room <<No adjacent room>>
External temperature...
Method Hourly OADB
Cooling °F
Heating °F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

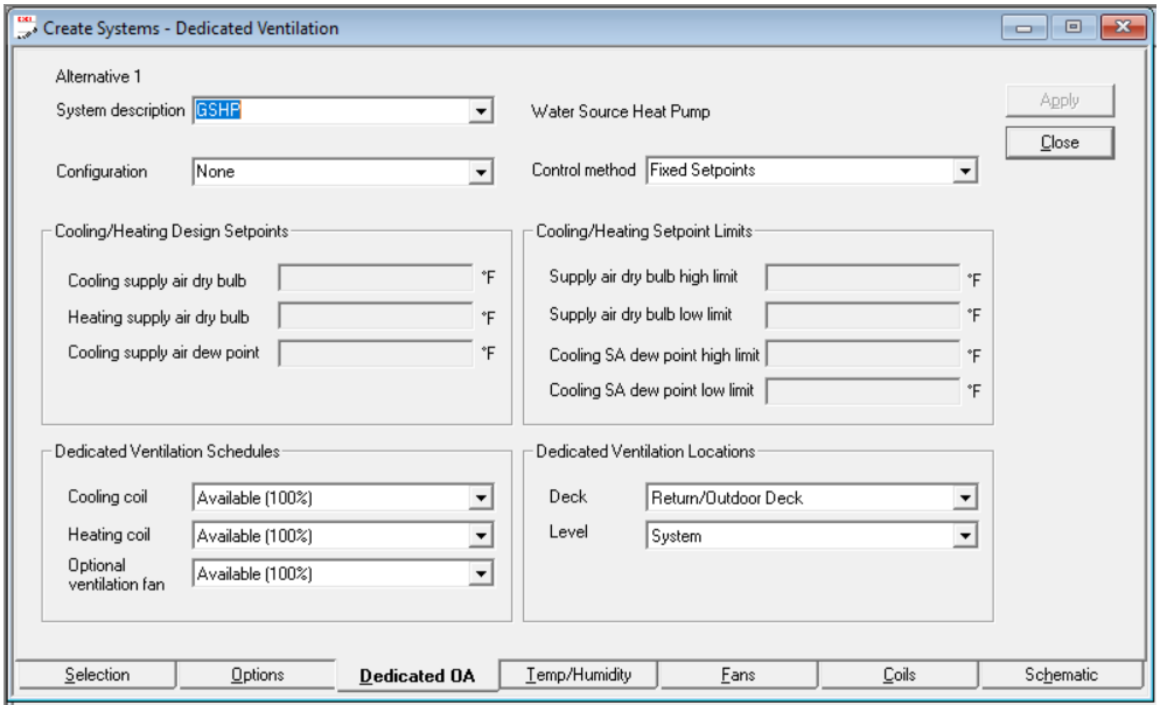

Create Rooms - Partitions and Floors
Alternative 1
Apply
Room description
Basement-right
Close
Templates...
Partition...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag
Partition - 3
Length
10
ft
Height
2
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
<<No adjacent room>>
Adjacent space temperature...
Method
Ground
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
100
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Hourly OADB
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

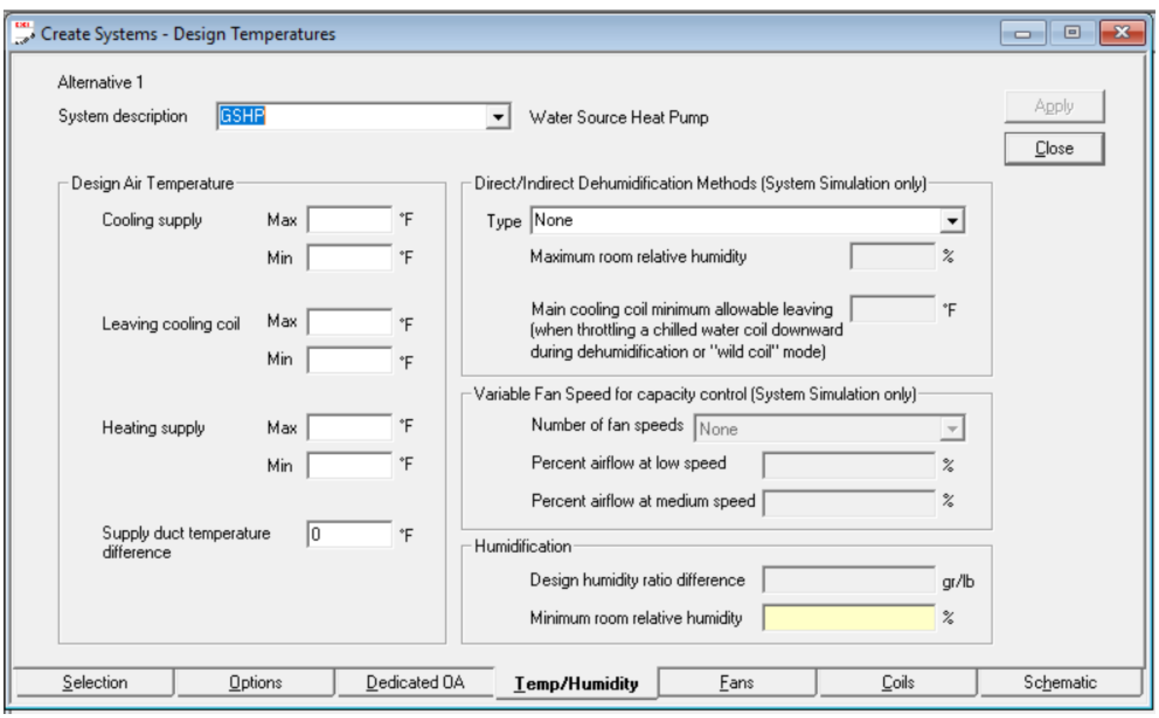

Create Rooms - Partitions and Floors
Alternative 1
Apply
Room description
Basement-right
Close
Templates...
Partition...
Room
Default
Internal
Default
Airflow
Default
Tstat
Default
Constr
Default
Partition - 1
Partition - 2
Partition - 3
Partition - top
Tag
Partition - top
Length
10
ft
Height
10
ft
Constr
1" Wood Frame
U-factor
0.2145
Btu/h·ft²·°F
Adj room
Lounge
Adjacent space temperature...
Method
Adjacent Room
Cooling
°F
Heating
°F
New Partition
Copy Part
Delete Part
Floor...
Floor - 1
Tag
Floor - 1
Exposed
Slab on grade
Constr
2" HW Concrete
Area
100
ft²
U-factor
0.6507
Btu/h·ft²·°F
Perim
0
ft
F-factor
0
Btu/hr·ft·°F
Adj room
<<No adjacent room>>
External temperature...
Method
Hourly OADB
Cooling
°F
Heating
°F
New Floor
Copy Floor
Delete Floor
Single Sheet
Rooms
Roofs
Walls
Int Loads
Airflows
Partn/Floors

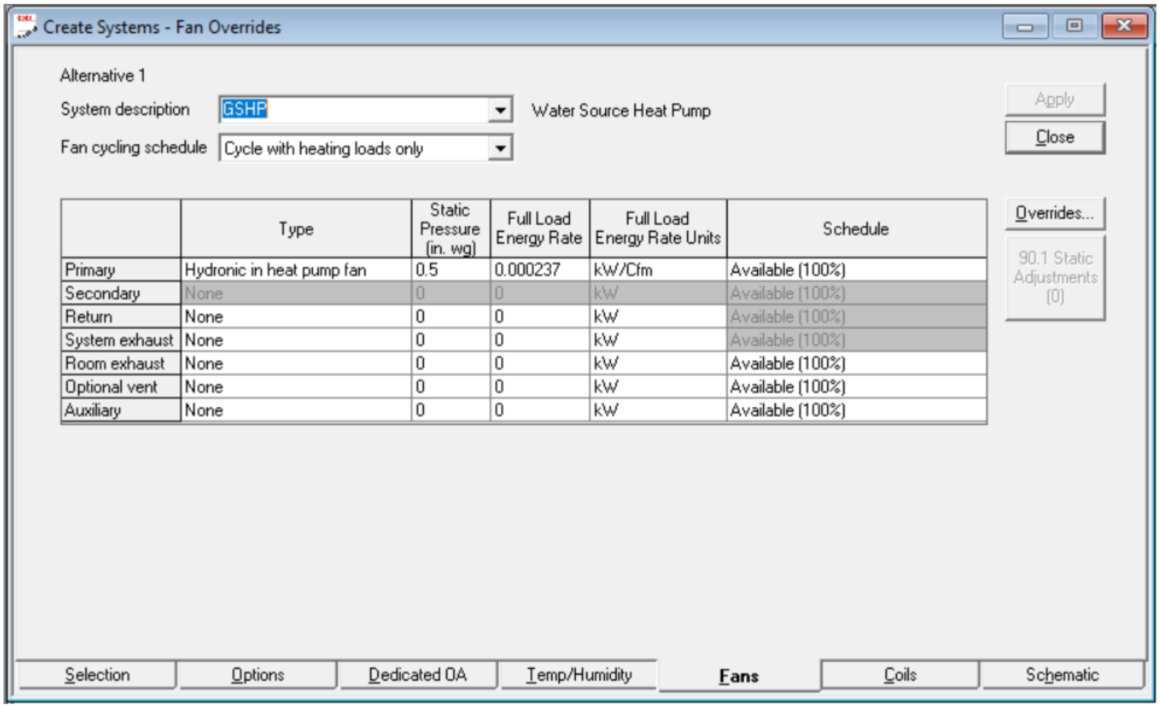
A.3 Systems

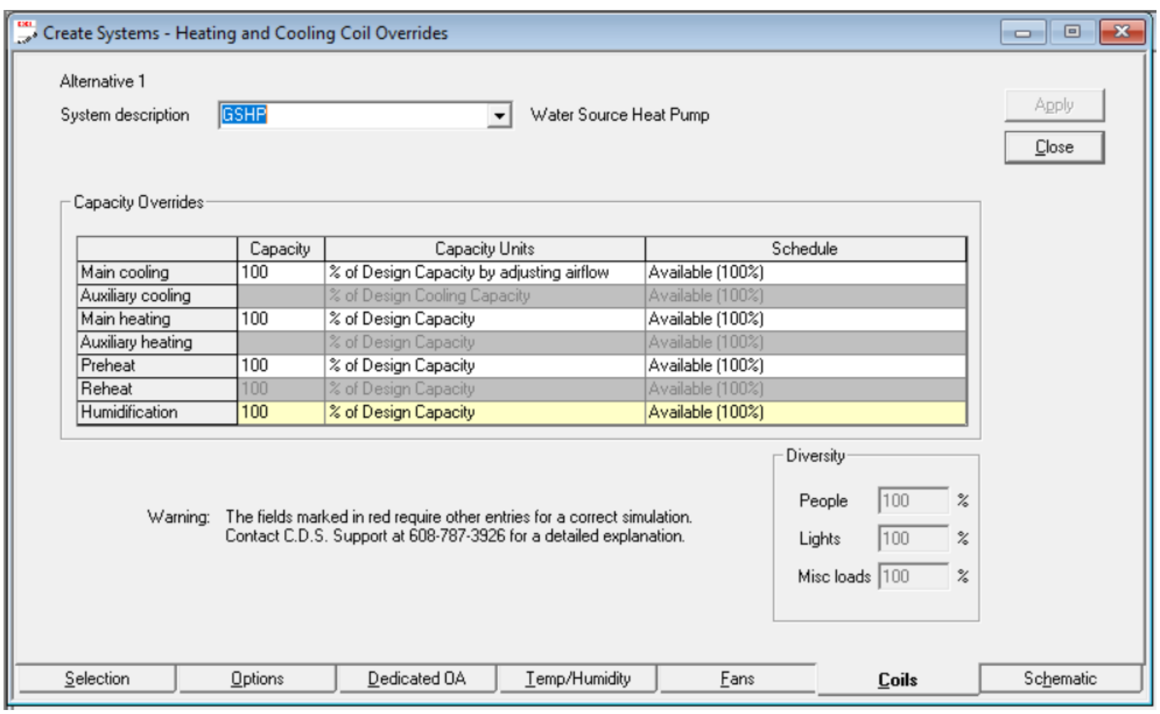

Create Systems - Selection
Alternative 1
System description
GSHP
Water Source Heat Pump
Apply
Close
New
Copy
Delete
Advanced...
System category
All
Variable Volume
Constant Volume - Non-mixing
Constant Volume - Mixing
Heating Only
Induction
Underfloor Air Distribution
Displacement Ventilation
Chilled Beams
ASHRAE 90.1 Baseline Systems
System type
Underfloor Air Distribution SFPVAV
Unit Heaters
Unit Ventilator
Variable Refrigerant Flow
Variable Temperature Constant Volume
Variable Volume Reheat (30% Min Flow Default)
VAV w/Baseboard Heating
VAV w/Baseboard Skin Heating
VAV w/Forced Flow Skin Heating
Ventilation and Heating
Water Source Heat Pump
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic

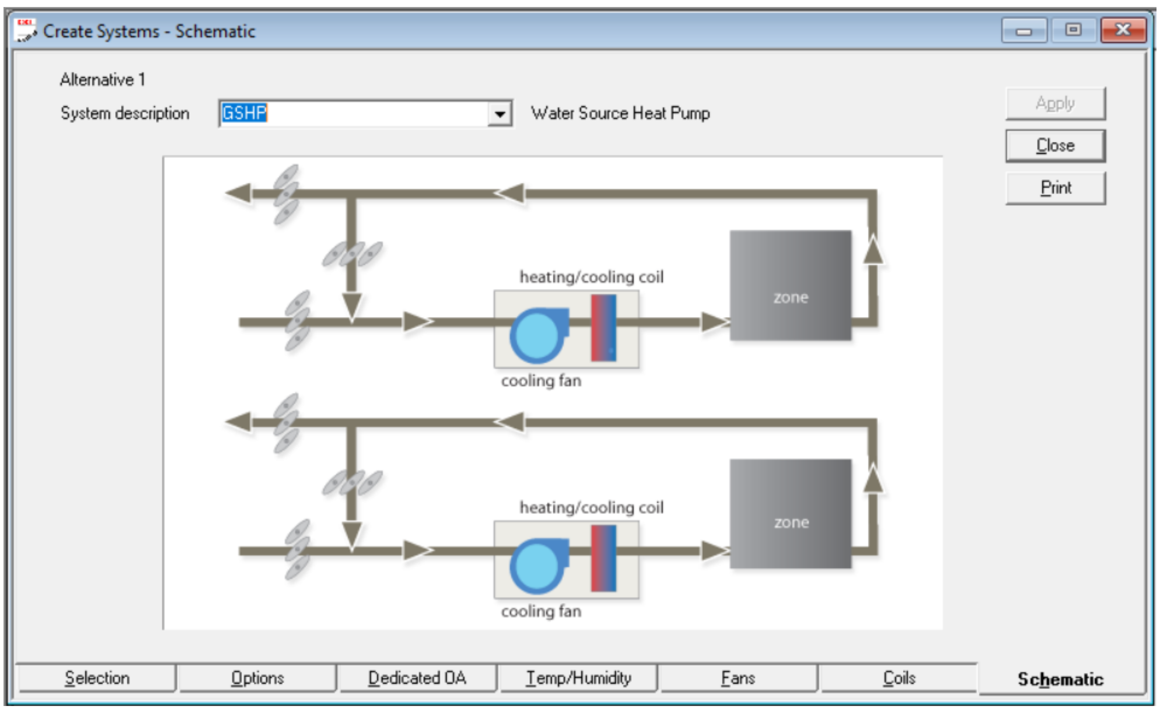

Create Systems - Options
Alternative 1
System description
GSHP
Water Source Heat Pump
Apply
Close
Advanced Options
Evaporative Cooling
Type
None
Direct efficiency
0
%
Options
Direct coil schedule
Available (100%)
Indirect efficiency
0
%
Options
Indirect coil schedule
Available (100%)
Economizer
Type
None
"On" point
°F
Max outdoor air
100
%
Schedule
Available (100%)
Stage 1 Air-to-Air Energy Recovery/Transfer
Type
None (default)
Sup-side deck
Ventilation upstream
Exh-side deck
Outdoor & room exhaust mix
Schedule
Available (100%)
Effectiveness
Options
Stage 2 Air-to-Air Energy Recovery/Transfer
Type
None (default)
Sup-side deck
Ventilation upstream
Exh-side deck
Outdoor & room exhaust mix
Schedule
Available (100%)
Effectiveness
Options
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic


Create Systems - Dedicated Ventilation
Alternative 1
System description
GSHP
Water Source Heat Pump
Apply
Close
Configuration
None
Control method
Fixed Setpoints
Cooling/Heating Design Setpoints
Cooling supply air dry bulb
Heating supply air dry bulb
Cooling supply air dew point
°F
Cooling/Heating Setpoint Limits
Supply air dry bulb high limit
Supply air dry bulb low limit
Cooling SA dew point high limit
Cooling SA dew point low limit
Dedicated Ventilation Schedules
Cooling coil
Heating coil
Optional ventilation fan
Available (100%)
Dedicated Ventilation Locations
Deck
Return/Outdoor Deck
Level
System
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic

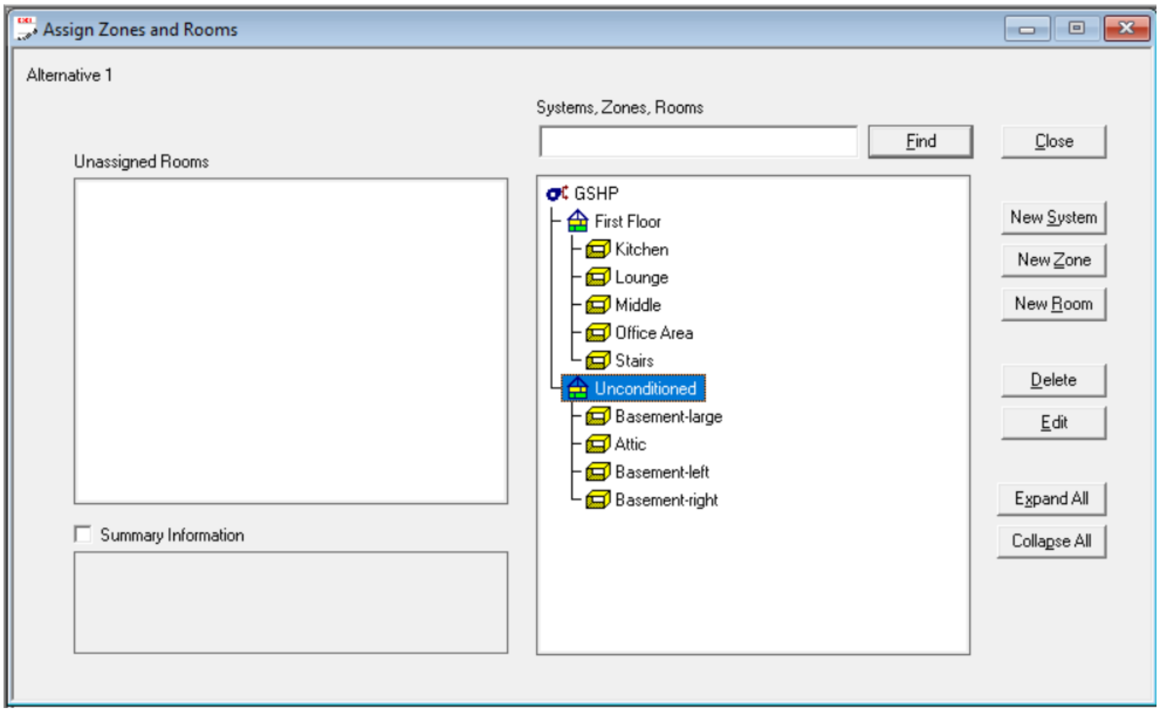

Create Systems - Design Temperatures
Alternative 1
System description
GSHP
Water Source Heat Pump
Apply
Close
Design Air Temperature
Cooling supply
Leaving cooling coil
Heating supply
Max
Min
°F
Supply duct temperature difference
0
Direct/Indirect Dehumidification Methods (System Simulation only)
Type
None
Maximum room relative humidity
%
Main cooling coil minimum allowable leaving (when throttling a chilled water coil downward during dehumidification or "wild coil" mode)
Variable Fan Speed for capacity control (System Simulation only)
Number of fan speeds
None
Percent airflow at low speed
Percent airflow at medium speed
Humidification
Design humidity ratio difference
gr/lb
Minimum room relative humidity
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic


Create Systems - Fan Overrides
Alternative 1
System description GSHP
Water Source Heat Pump
Fan cycling schedule Cycle with heating loads only
Apply
Close
Overrides...
90.1 Static Adjustments (0)
Type
Static Pressure (in. wg)
Full Load Energy Rate
Full Load Energy Rate Units
Schedule
Primary Hydronic in heat pump fan 0.5 0.000237 kW/Cfm Available (100%)
Secondary None 0 0 kW Available (100%)
Return None 0 0 kW Available (100%)
System exhaust None 0 0 kW Available (100%)
Room exhaust None 0 0 kW Available (100%)
Optional vent None 0 0 kW Available (100%)
Auxiliary None 0 0 kW Available (100%)
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic

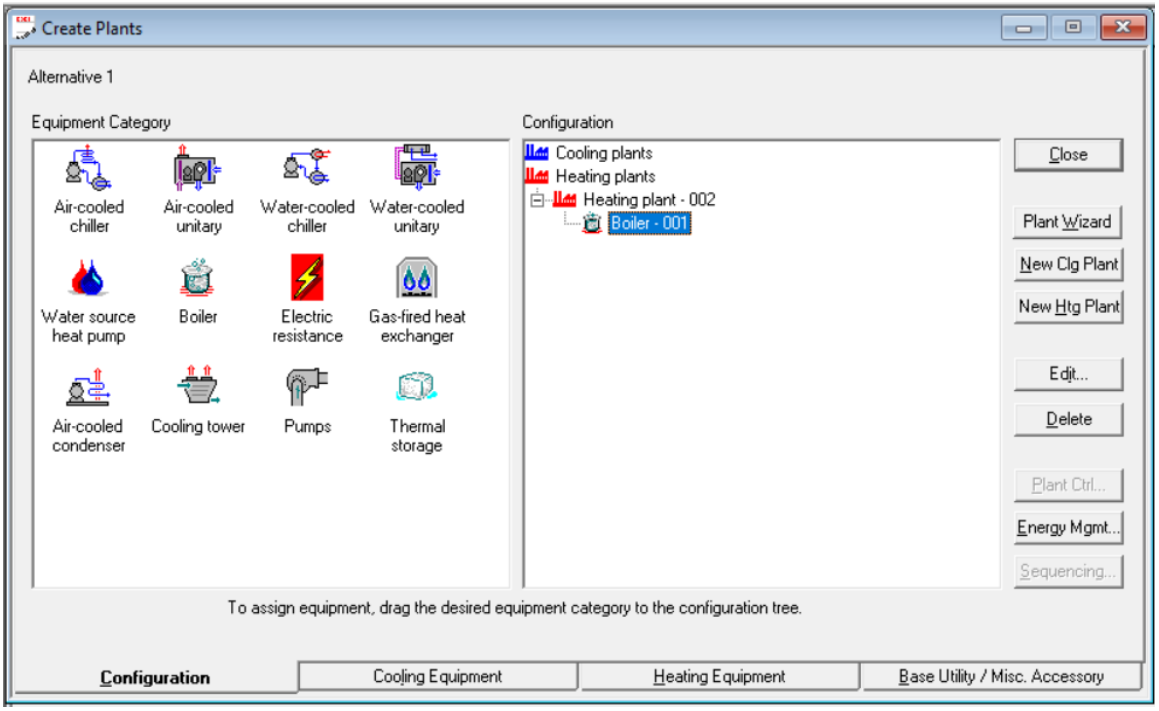

Create Systems - Heating and Cooling Coil Overrides
Alternative 1
System description GSHP
Water Source Heat Pump
Apply
Close
Capacity Overrides
Capacity
Capacity Units
Schedule
Main cooling 100 % of Design Capacity by adjusting airflow Available (100%)
Auxiliary cooling % of Design Cooling Capacity Available (100%)
Main heating 100 % of Design Capacity Available (100%)
Auxiliary heating % of Design Capacity Available (100%)
Preheat 100 % of Design Capacity Available (100%)
Reheat 100 % of Design Capacity Available (100%)
Humidification 100 % of Design Capacity Available (100%)
Diversity
People 100 %
Lights 100 %
Misc loads 100 %
Warning: The fields marked in red require other entries for a correct simulation.
Contact C.D.S. Support at 608-787-3926 for a detailed explanation.
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic

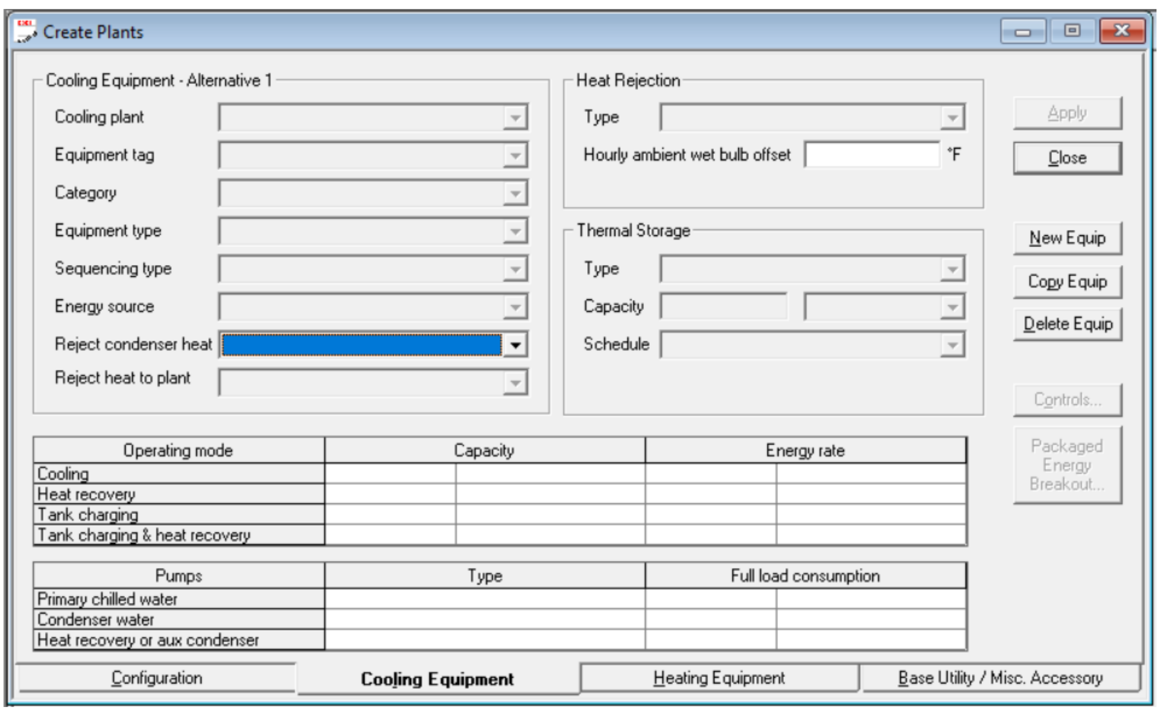

Create Systems - Schematic
Alternative 1
System description
GSHP
Water Source Heat Pump
Apply
Close
Print
heating/cooling coil
zone
cooling fan
heating/cooling coil
zone
cooling fan
Selection
Options
Dedicated OA
Temp/Humidity
Fans
Coils
Schematic

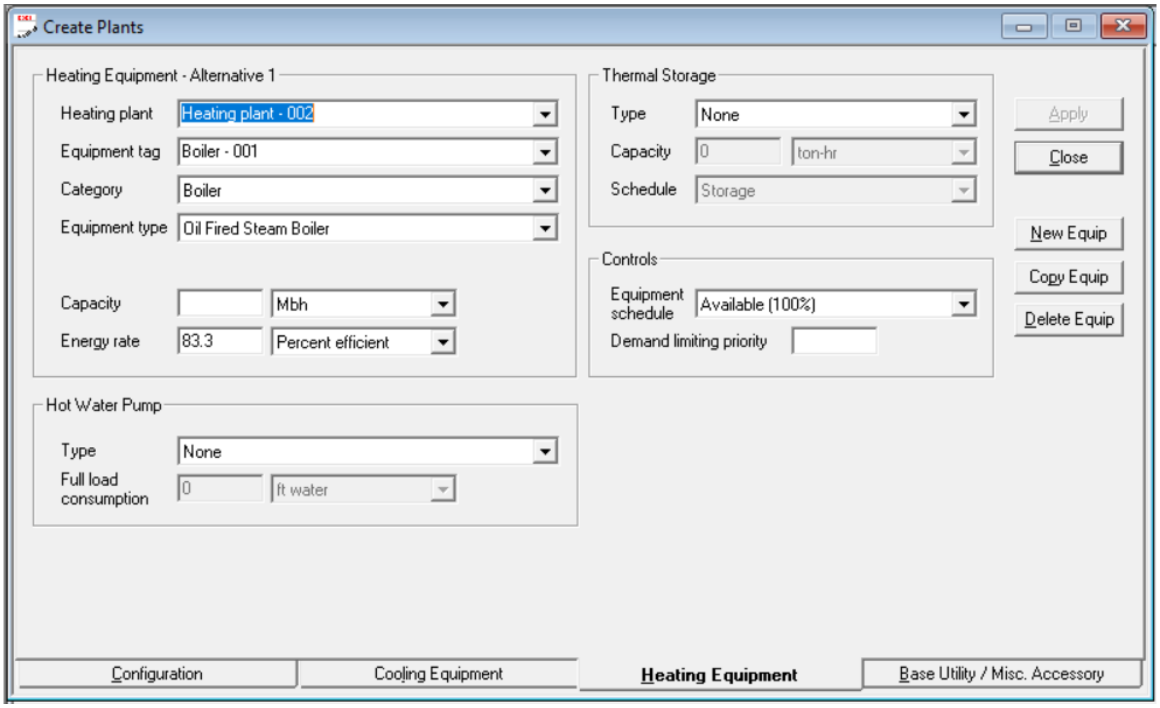
A.4 Assign Rooms to Systems

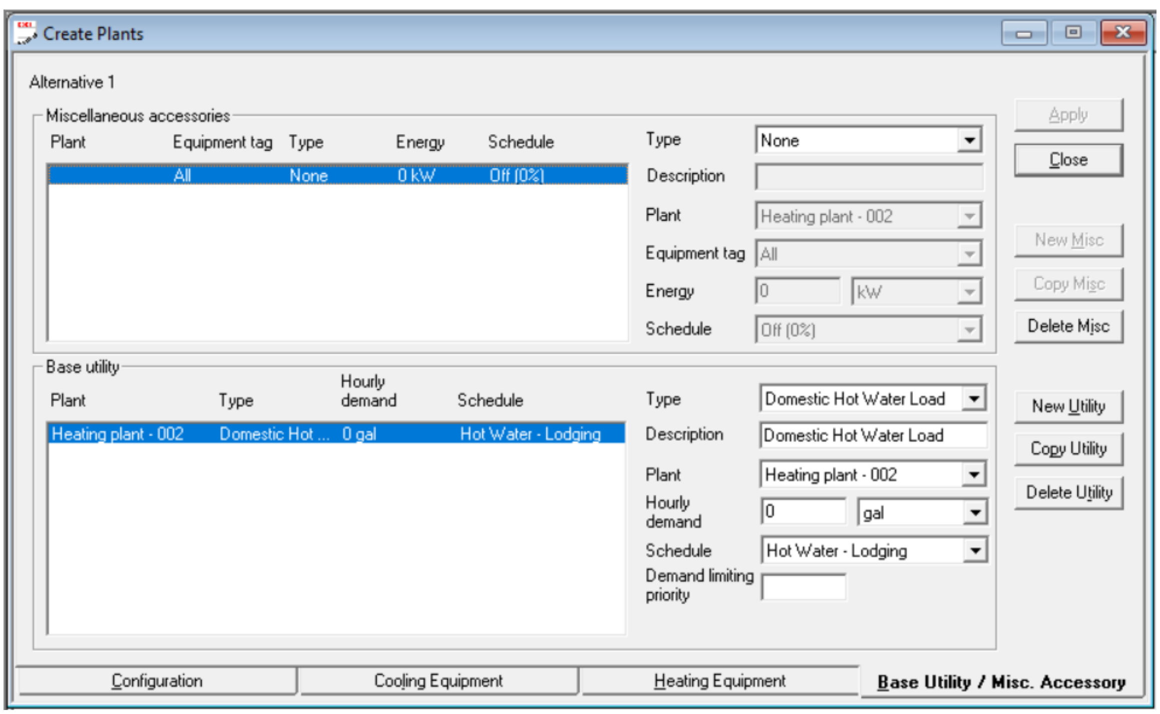


A.5 Plants

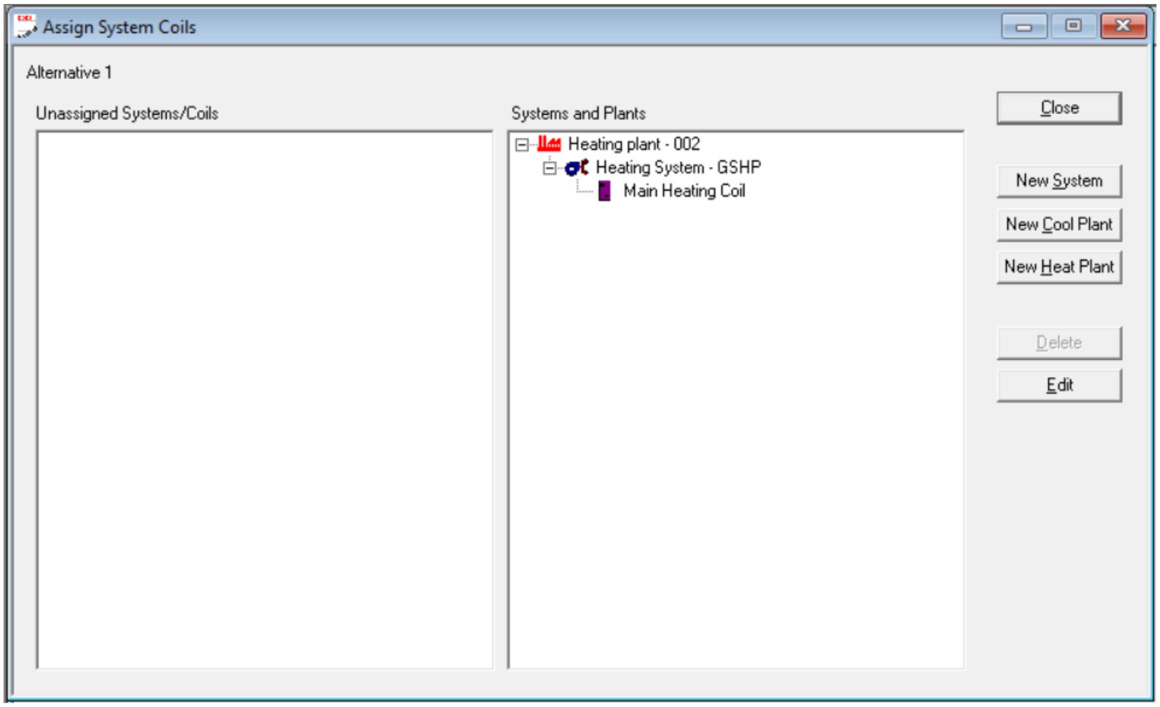

Create Plants
Alternative 1
Equipment Category
Air-cooled chiller
Air-cooled unitary
Water-cooled chiller
Water-cooled unitary
Water source heat pump
Boiler
Electric resistance
Gas-fired heat exchanger
Air-cooled condenser
Cooling tower
Pumps
Thermal storage
Configuration
Cooling plants
Heating plants
Heating plant - 002
Boiler - 001
Close
Plant Wizard
New Clg Plant
New Htg Plant
Edit...
Delete
Plant Ctrl...
Energy Mgmt...
Sequencing...
To assign equipment, drag the desired equipment category to the configuration tree.
Configuration
Cooling Equipment
Heating Equipment
Base Utility / Misc. Accessory


Create Plants
Cooling Equipment - Alternative 1
Cooling plant
Equipment tag
Category
Equipment type
Sequencing type
Energy source
Reject condenser heat
Reject heat to plant
Heat Rejection
Type
Hourly ambient wet bulb offset
°F
Thermal Storage
Type
Capacity
Schedule
Apply
Close
New Equip
Copy Equip
Delete Equip
Controls...
Packaged Energy Breakout...
Operating mode
Capacity
Energy rate
Cooling
Heat recovery
Tank charging
Tank charging & heat recovery
Pumps
Type
Full load consumption
Primary chilled water
Condenser water
Heat recovery or aux condenser
Configuration
Cooling Equipment
Heating Equipment
Base Utility / Misc. Accessory


Create Plants
Heating Equipment - Alternative 1
Heating plant
Heating plant - 002
Equipment tag
Boiler - 001
Category
Boiler
Equipment type
Oil Fired Steam Boiler
Capacity
Mbh
Energy rate
83.3
Percent efficient
Hot Water Pump
Type
None
Full load consumption
0
ft water
Thermal Storage
Type
None
Capacity
0
ton-hr
Schedule
Storage
Controls
Equipment schedule
Available (100%)
Demand limiting priority
Apply
Close
New Equip
Copy Equip
Delete Equip
Configuration
Cooling Equipment
Heating Equipment
Base Utility / Misc. Accessory


Create Plants
Alternative 1
Miscellaneous accessories
Plant
Equipment tag
Type
Energy
Schedule
All
None
0 kW
Off (0%)
Type
None
Description
Plant
Heating plant - 002
Equipment tag
All
Energy
0
kW
Schedule
Off (0%)
Base utility
Plant
Type
Hourly demand
Schedule
Heating plant - 002
Domestic Hot ...
0 gal
Hot Water - Lodging
Type
Domestic Hot Water Load
Description
Domestic Hot Water Load
Plant
Heating plant - 002
Hourly demand
0
gal
Schedule
Hot Water - Lodging
Demand limiting priority
Apply
Close
New Misc
Copy Misc
Delete Misc
New Utility
Copy Utility
Delete Utility
Configuration
Cooling Equipment
Heating Equipment
Base Utility / Misc. Accessory

A.6 Assign Systems to Plants



Appendix B

Trace Manual

B.1 Room Definition

Overview of Create Rooms

Overview of Rooms, Zones, and Systems

Create Rooms tabs:

Single Sheet tab

Rooms tab

Roofs tab

Walls tab

Int Loads tab

Airflows tab

Partn/Floors tab

TRACE performs cooling and heating load calculations for each individual room, so a "room" is the smallest space for which you can calculate loads. A room can be a single office surrounded by walls or can be the perimeter portion of a large open-plan office area. In other areas of the program, you have the option of grouping rooms into zones and/or systems for higher level design calculations (i.e. design airflows, coil capacities, design temperatures, etc.).

When creating rooms, you essentially "assign" to it all of the components that contribute to or affect its cooling and heating loads. These load components include, but are not limited to:

- Size and mass of room
- Room design thermostat settings
- Size, construction, and direction of external walls and roofs
- Size, properties, and direction of external windows and skylights
- Internal loads, such as people, lights, and miscellaneous equipment
- Infiltration
- Ventilation requirements
- Partition walls and exposed or slab-on-grade floors

The Create Rooms screen is comprised of seven tabs. The first tab, named Single Sheet, is intended to allow you to enter the basic information about a room on a single screen. It also contains most of the information you might find on typical building blueprints. You may be able to use this tab only (along with the Templates) to enter room information for the majority of the rooms in your project. The remaining tabs can be used to enter more detailed information about the rooms. These tabs are simply a means of viewing the same information that you enter on the Single Sheet tab, plus a few more details.

The top area of the Create Rooms screen, displaying the Room Description and the Templates, remains in view for all of the tabs. This allows you to select Templates from any of the tabs or to switch between rooms by using the Room Description drop-down list.

B.2 Partition Definition

Create Rooms - Partn/Floors

Overview of Create Rooms

On this tab, you can "assign" partition walls, exposed floors, and slab-on-grade floors to each room.

A **partition** is a wall that is not exposed to the outdoor environment, but affects the cooling or heating load on the room because of a "significant" temperature difference between the two rooms it separates. (It is not necessary to model a partition if there is not a significant thermal difference between the spaces adjacent to it, since partition loads are strictly based on conduction.)

An **exposed floor** is very similar to a partition wall, and may or may not be exposed to the outdoor environment. It affects the cooling or heating load on the room because of a "significant" temperature difference between the two rooms it separates.

A **slab-on-grade** is used to account for heating losses through the actual floor slab to the outdoor environment. Slab-on-grade losses are calculated for heating design calculations only.

Field Explanations

Room Description

Templates	**Partition**	**Adjacent space temperature**
Room	Tag	Method
Internal	Length	Cooling
Airflow	Height	Heating
Tstat	Constr	
Constr	U-factor	
	Adj room	
	Floor	**External temperature**
	Tag	Method
	Slab-On-Grade	Cooling
	Perimeter (length)	Heating
	Loss coeff	
	Exposed Floor	
	Constr	
	Area	
	U-factor	
	Adj room	

Appendix C

Blower Door Test Reports for Lawrence and Morris House from 2010

C.1 Morris House

BUILDING LEAKAGE TEST COMPARISON

COZY HOME PERFORMANCE, LLC
74 Lyman Road
Northamptoon, MA 01060
Phone: 413.320.7611

	Test #1		Test #2
Test File:	Morris Hall Pre	Test File:	Morris Hall Post
Date of Test:	12.28.10	Date of Test:	
Customer:	Smith College Morris Hall - Post Test Contact: Todd Holland Northampton, MA 01063	Customer:	

Test Results

	Test #1	Test #2	Change	Percent
1. Airflow at 50 Pascals:	25525 CFM	13936 CFM	-11589 CFM	-45.4 %
	7.12 ACH	3.89 ACH	-3.23 ACH	-45.4 %
2. CFM50 per ft2 Floor Area	1.10 CFM/ft2	0.60 CFM/ft2	-0.50 CFM/ft2	-45.4 %
3. Leakage Areas:				
Canadian EqLA @ 10 Pa:	3041.5 in2	1766.1 in2	-1275.4 in2	-41.9 %
LBL ELA @ 4 Pa:	1754.8 in2	1055.3 in2	-699.5 in2	-39.9 %
4. Minneapolis Leakage Ratio: (CFM50 per ft2 Surface Area)	0.94	0.51	-0.43	-45.4 %

Infiltration Estimates

	Test #1	Test #2	Change	Percent
1. Estimated Annual Average	2245.3 CFM	1350.3 CFM	-895.0 CFM	-39.9 %
Infiltration Rate:	0.63 ACH	0.38 ACH	-0.25 ACH	-39.9 %
2. Estimated Design Infiltration Rate:				
Winter:	3265.2 CFM	1963.7 CFM	-1301.5 CFM	-39.9 %
	0.91 ACH	0.55 ACH	-0.36 ACH	-39.9 %
Summer:	1846.5 CFM	1110.5 CFM	-736.0 CFM	-39.9 %
	0.52 ACH	0.31 ACH	-0.21 ACH	-39.9 %

Cost Estimates

1. Estimated Costs of Air Leakage for Heating:
2. Estimated Costs of Air Leakage for Cooling:

C.2 Lawrence House

BUILDING LEAKAGE TEST COMPARISON

COZY HOME PERFORMANCE, LLC
74 Lyman Road
Northampton, MA 01060
Phone: 413.320.7611

Test #1		Test #2	
Test File:	Lawrence Hall Pre Test	Test File:	Lawrence Hall Post Test
Date of Test:	12/28/10	Date of Test:	
Customer:	Smith College Lawrence Hall - Post Test Contact: Todd Holland Northampton, MA 01063	Customer:	

Test Results

	Test #1	Test #2	Change	Percent
1. Airflow at 50 Pascals:	21458 CFM	12604 CFM	-8854 CFM	-41.3 %
	5.99 ACH	3.52 ACH	-2.47 ACH	-41.3 %
2. CFM50 per ft2 Floor Area	0.92 CFM/ft2	0.54 CFM/ft2	-0.38 CFM/ft2	-41.3 %
3. Leakage Areas:				
Canadian EqLA @ 10 Pa:	2579.9 in2	1479.6 in2	-1100.3 in2	-42.6 %
LBL ELA @ 4 Pa:	1496.1 in2	846.4 in2	-649.7 in2	-43.4 %
4. Minneapolis Leakage Ratio: (CFM50 per ft2 Surface Area)	0.79	0.47	-0.33	-41.3 %

Infiltration Estimates

	Test #1	Test #2	Change	Percent
1. Estimated Annual Average Infiltration Rate:	1914.2 CFM	1083.0 CFM	-831.3 CFM	-43.4 %
	0.53 ACH	0.30 ACH	-0.23 ACH	-43.4 %
2. Estimated Design Infiltration Rate:				
Winter:	2783.7 CFM	1574.9 CFM	-1208.9 CFM	-43.4 %
	0.78 ACH	0.44 ACH	-0.34 ACH	-43.4 %
Summer:	1574.2 CFM	890.6 CFM	-683.6 CFM	-43.4 %
	0.44 ACH	0.25 ACH	-0.19 ACH	-43.4 %

Cost Estimates

1. Estimated Costs of Air Leakage for Heating:
2. Estimated Costs of Air Leakage for Cooling:

Appendix D

Heat Pump Sizing Spreadsheet

Geothermal System Parameters				
	SI		IP	
L	182.88	m	600	ft
rho_w	1000	kg/m3		
v_w	0.234044295	m/s		
V_w	0.00012618	m3/s	2	gpm
m_dot	0.12618000	kg/s		
r_pi	0.0131	m		
d_p	0.03175	m	1.25	in
r_po	0.015875	m	0.625	in
d_b	0.1524	m	6	in
r_b	0.0762	m	3	in
u_w	0.001307	Ns/m2		
A_p	0.000539129	m2		
Re_current	6898.892381			
Re_medium	8638.167828			
Re_deep	9473.065294			
T_in	4	C	277.15	K
T_out	14	C		
T_avg	9	C		
delT	6	C		
Depth per Bore	182.88	m	600	ft
T_ground	15	C	59	F
c_p	4180	J/kgK		
k_grout	1.73	m-ºC/W		
k_p	0.46	m-ºC/W		
k_ground	3	m-ºC/W		
R_bore	0.138	m-ºC/W	0.1922	h-ft-ºF/Btu
R_conv	0.010009745	m-ºC/W		
R_pipe	0.015625708	m-ºC/W		
R_grount	0.088046459	m-ºC/W		
R_6h	0.05	m-ºC/W		
R_1m	0.088	m-ºC/W		
R_10y	0.095	m-ºC/W		
Calculated Variables				
m_dot_current	0.459330144	kg/s		
m_dot_medium	0.383421053	kg/s		
m_dot_deep	0.346889952	kg/s		
Current				
V_total	0.00045933	m3/s	7.280554	gpm
V_well	0.00015311	m3/s	2.426851	gpm
v_well	0.283995349	m/s		
Medium				
V_total	0.0003834211	m3/s	6.077367	gpm
V_well	0.000191711	m3/s	3.038683	gpm
v_well	0.355593239	m/s		
Deep				
V_total	0.0003468900	m3/s	5.498335	gpm
V_well	0.000173445	m3/s	2.749167	gpm
v_well	0.321713482	m/s		
Convertion				
gpm to m3/s	0.00006309			

HP Sizing (Geothermal only)				
HP_1 (Building)			HP_1	
			93	W
			0.026444094	ton
HP_2 (Main)			HP_2	
Q Annual heating	229198.4	kbtu/yr	11661.70492	W
	39791.39	btu/hr		
	39.79139	kbtu/hr		
	11.6617	kW		
COP	3			
C factor btu/hr to ton	12000			
q_h	19200	W	2133.333333	W/well
q_m	17283	W	6400	W
q_yr	11661.7	W	0.61	ton/well
HP_3 (Geothermal)			HP_3	
f	0.03503		1.026717795	W
del_P	8136.93	Pa	0.000291942	ton
		Total Pump Power	6401.026718	W
# of Wells (fixed delT)				
L_total	441.6	m	1448.818898	ft
# of Wells	3			

HP Sizing (Medium)

HP_1 (Building)			HP_1		
				93	W
				0.026444094	ton

HP_2 (Main)			HP_2		
Q Annual heating	189780	kbtu/yr		9656.081192	W
	32947.91667	btu/hr			
	32.94791667	kbtu/hr			
	9.656081192	kW	Percentage Drop (%)	17.2	
COP	3				
C factor btu/hr to ton	12000				
q_h	16027	W		1780.777778	W/well
q_m	14543	W		5342.333333	W all wells
q_yr	9656.081192	W		0.51	ton/well

HP_3 (Geothermal)			HP_3		
f	0.035030442			1.026717795	W
del_P	8136.929744	Pa		0.000291942	ton
		Total Pump Power		5343.360051	W

# of Wells (fixed delT)				
L_total	368.621	m	1209.386483	ft
# of Wells	3			

Attic (Method 1 average)			
U	0.15749	R	6.349609499
Adding 6/7 of R42	36	U	0.027777778
Final U	0.023612969	U	42.3496095

Attic (Method 2 R42 in series)				
Original U	0.15749	IP	= R (IP)	6.34961
Insulation R	42	IP		
New U	0.181299524	IP	*parallel	
	0.02068269	IP	*series	

HP Sizing (Deep)

HP_1 (Building)			HP_1	
			93	W
			0.026444094	ton

HP_2 (Main)			HP_2		
Q Annual heating	163052	kbtu/yr	8296.150018	W	
	28307.63889	btu/hr			
	28.30763889	kbtu/hr			
	8.296150018	kW	Percentage Drop (%)		28.9
COP	3				
C factor btu/hr to ton	12000				
q_h	14500	W	2416.666667	W/well	
q_m	12391	W	4833.333333	W all wells	
q_yr	8296.150018	W	0.69	ton/well	

HP_3 (Geothermal)			HP_3	
f	0.035030442		1.026717795	W
del_P	8136.929744	Pa	0.000291942	ton
	Total	Pump Power	4834.360051	W

# of Wells (fixed delT)				
L_total	333.5	m	1094.160105	ft
# of Wells	2			

Wall				
Original U	0.12207	IP	= R (IP)	8.192021
False Wall R	21	IP		
New U	0.034255936	IP		

Appendix E

Field House Energy Consumption Reports

Reports follow the order: geothermal only, medium, deep; annual, monthly, hourly.

E.1 Geothermal Only

ENERGY CONSUMPTION SUMMARY

By ACADEMIC

	Elect Cons. (kWh)	Oil Cons. (kBtu)	Water Cons. (1000 gals)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 1						
Primary heating						
Primary heating		262,590		91.7 %	262,590	276,410
Other Htg Accessories	4,180		4	5.0 %	14,265	42,799
Heating Subtotal	**4,180**	**262,590**	**4**	**96.6** %	**276,855**	**319,210**
Primary cooling						
Cooling Compressor				0.0 %	0	0
Tower/Cond Fans				0.0 %	0	0
Condenser Pump				0.0 %	0	0
Other Clg Accessories				0.0 %	0	0
Cooling Subtotal....				**0.0** %	**0**	**0**
Auxiliary						
Supply Fans	2,825			3.4 %	9,643	28,931
Pumps				0.0 %	0	0
Stand-alone Base Utilities				0.0 %	0	0
Aux Subtotal....	2,825			3.4 %	9,643	28,931
Lighting						
Lighting				0.0 %	0	0
Receptacle						
Receptacles				0.0 %	0	0
Cogeneration						
Cogeneration				0.0 %	0	0
Totals						
Totals**	**7,005**	**262,590**	**4**	**100.0** %	**286,498**	**348,141**

* Note: Resource Utilization factors are included in the Total Source Energy value .
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Project Name:
Dataset Name: 44_Current.TRC

TRACE® 700 v6.3.3 calculated at 01:02 AM on 04/09/2019
Alternative - 1 Energy Consumption Summary report page 1

MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**Field House**													
Electric														
	On-Pk Cons. (kWh)	922	892	904	610	269	326	500	345	163	326	842	907	7,005
	On-Pk Demand (kW)	1	1	1	1	1	1	2	1	1	1	1	1	2
Oil														
	Cons. (therms)	464	530	436	220	86	0	0	0	5	99	346	440	2,626
Water														
	Cons. (1000gal)	1	1	1	0	0	0	0	0	0	0	1	1	4

Energy Consumption

Building	42,250	Btu/(ft2-year)
Source	51,341	Btu/(ft2-year)
Floor Area	6,781	ft2

Environmental Impact Analysis

CO2	8,399 lbm/year
SO2	26 gm/year
NOX	7 gm/year

BUILDING COOL HEAT DEMAND

By ACADEMIC

January	Typical Weather (°F)		Design		Weekday		Saturday		Sunday		Monday	
Hour	OADB	OAWB	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)
1	23.3	21.1	-80,851	0.0	-66,144	0.0	-62,314	0.0	-62,098	0.0	-62,848	0.0
2	22.4	20.2	-76,403	0.0	-66,310	0.0	-64,256	0.0	-64,122	0.0	-64,945	0.0
3	22.1	20.0	-76,106	0.0	-67,705	0.0	-65,916	0.0	-65,800	0.0	-66,631	0.0
4	22.3	20.2	-76,480	0.0	-68,483	0.0	-66,806	0.0	-66,703	0.0	-67,539	0.0
5	23.0	20.7	-76,648	0.0	-68,858	0.0	-67,268	0.0	-67,176	0.0	-68,016	0.0
6	24.1	22.0	-76,482	0.0	-68,048	0.0	-66,542	0.0	-66,461	0.0	-67,306	0.0
7	25.5	23.4	-75,822	0.0	-66,585	0.0	-65,151	0.0	-65,079	0.0	-65,927	0.0
8	27.2	25.1	-74,272	0.0	-64,690	0.0	-63,717	0.0	-63,653	0.0	-64,104	0.0
9	29.1	26.9	-61,878	0.0	-58,467	0.0	-58,178	0.0	-58,123	0.0	-57,968	0.0
10	31.0	28.5	-46,005	0.0	-49,910	0.0	-51,314	0.0	-51,274	0.0	-51,536	0.0
11	32.9	30.0	-26,854	0.0	-44,102	0.0	-41,673	0.0	-41,639	0.0	-42,128	0.0
12	34.6	31.3	-3,288	0.0	-36,817	0.0	-35,502	0.0	-35,470	0.0	-36,333	0.0
13	36.0	32.1	0	0.0	-33,200	0.0	-32,015	0.0	-31,985	0.0	-32,894	0.0
14	37.1	32.7	0	0.0	-30,168	0.0	-28,995	0.0	-28,967	0.0	-29,898	0.0
15	37.8	33.1	0	0.0	-29,637	0.0	-28,470	0.0	-28,443	0.0	-29,379	0.0
16	38.1	33.1	0	0.0	-30,984	0.0	-30,247	0.0	-30,223	0.0	-30,741	0.0
17	37.7	33.2	-23,943	0.0	-36,770	0.0	-35,860	0.0	-35,837	0.0	-36,541	0.0
18	36.8	32.9	-38,422	0.0	-43,065	0.0	-42,157	0.0	-42,137	0.0	-42,868	0.0
19	35.3	31.9	-50,449	0.0	-49,282	0.0	-48,219	0.0	-48,202	0.0	-49,117	0.0
20	33.4	30.4	-54,722	0.0	-52,011	0.0	-50,852	0.0	-50,838	0.0	-51,887	0.0
21	31.2	28.3	-58,279	0.0	-50,394	0.0	-52,181	0.0	-52,165	0.0	-50,162	0.0
22	28.9	26.3	-61,264	0.0	-57,408	0.0	-54,292	0.0	-54,276	0.0	-57,291	0.0
23	26.7	24.2	-63,896	0.0	-58,573	0.0	-57,376	0.0	-57,361	0.0	-58,432	0.0
24	24.8	22.5	-66,058	0.0	-61,276	0.0	-60,270	0.0	-60,257	0.0	-61,142	0.0

February	Typical Weather (°F)		Design		Weekday		Saturday		Sunday		Monday	
Hour	OADB	OAWB	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)
1	15.6	13.2	-79,861	0.0	-80,230	0.0	-77,528	0.0	-77,312	0.0	-77,744	0.0
2	14.1	11.9	-82,435	0.0	-80,429	0.0	-78,750	0.0	-78,627	0.0	-79,185	0.0
3	13.1	10.9	-84,053	0.0	-80,983	0.0	-79,673	0.0	-79,583	0.0	-80,185	0.0
4	12.8	10.7	-85,318	0.0	-81,583	0.0	-80,471	0.0	-80,395	0.0	-80,991	0.0
5	13.1	11.2	-86,144	0.0	-82,425	0.0	-81,415	0.0	-81,353	0.0	-81,910	0.0
6	14.1	12.2	-86,416	0.0	-82,090	0.0	-81,124	0.0	-81,071	0.0	-81,643	0.0
7	15.6	13.8	-86,076	0.0	-81,162	0.0	-80,243	0.0	-80,198	0.0	-80,777	0.0
8	17.6	15.9	-81,681	0.0	-78,725	0.0	-78,029	0.0	-77,987	0.0	-78,373	0.0
9	19.9	18.1	-70,989	0.0	-73,050	0.0	-72,537	0.0	-72,472	0.0	-72,504	0.0
10	22.4	20.4	-52,163	0.0	-62,677	0.0	-62,051	0.0	-62,007	0.0	-62,304	0.0
11	24.9	22.1	-37,112	0.0	-54,869	0.0	-53,675	0.0	-53,635	0.0	-54,546	0.0
12	27.2	23.8	-26,775	0.0	-51,680	0.0	-51,047	0.0	-51,020	0.0	-51,430	0.0
13	29.2	25.6	-16,316	0.0	-48,569	0.0	-47,517	0.0	-47,493	0.0	-48,362	0.0
14	30.7	26.8	-4,523	0.0	-46,038	0.0	-44,925	0.0	-44,902	0.0	-45,850	0.0
15	31.7	27.4	-6,703	0.0	-44,462	0.0	-43,348	0.0	-43,328	0.0	-44,291	0.0
16	32.0	27.7	-21,545	0.0	-44,337	0.0	-43,649	0.0	-43,631	0.0	-44,179	0.0
17	31.7	27.3	-26,898	0.0	-47,938	0.0	-47,077	0.0	-47,060	0.0	-47,793	0.0
18	30.7	26.7	-42,141	0.0	-53,617	0.0	-52,749	0.0	-52,731	0.0	-53,456	0.0
19	29.2	25.8	-56,753	0.0	-59,768	0.0	-58,757	0.0	-58,739	0.0	-59,607	0.0
20	27.2	24.1	-67,115	0.0	-64,767	0.0	-63,760	0.0	-63,744	0.0	-64,624	0.0
21	24.9	22.0	-71,897	0.0	-67,620	0.0	-66,622	0.0	-66,608	0.0	-67,493	0.0
22	22.4	19.6	-75,448	0.0	-70,473	0.0	-69,489	0.0	-69,475	0.0	-70,361	0.0
23	19.9	17.3	-77,555	0.0	-72,383	0.0	-71,412	0.0	-71,401	0.0	-72,285	0.0
24	17.6	15.1	-79,548	0.0	-76,145	0.0	-75,501	0.0	-75,490	0.0	-76,092	0.0

E.2 Geothermal + Medium

ENERGY CONSUMPTION SUMMARY

By ACADEMIC

	Elect Cons. (kWh)	Oil Cons. (kBtu)	Water Cons. (1000 gals)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 1						
Primary heating						
Primary heating		214,901		90.6 %	214,901	226,212
Other Htg Accessories	3,549		3	5.1 %	12,112	36,340
Heating Subtotal	**3,549**	**214,901**	**3**	**95.7** %	**227,013**	**262,551**
Primary cooling						
Cooling Compressor				0.0 %	0	0
Tower/Cond Fans				0.0 %	0	0
Condenser Pump				0.0 %	0	0
Other Clg Accessories				0.0 %	0	0
Cooling Subtotal....				**0.0** %	**0**	**0**
Auxiliary						
Supply Fans	2,992			4.3 %	10,212	30,638
Pumps				0.0 %	0	0
Stand-alone Base Utilities				0.0 %	0	0
Aux Subtotal....	2,992			4.3 %	10,212	30,638
Lighting						
Lighting				0.0 %	0	0
Receptacle						
Receptacles				0.0 %	0	0
Cogeneration						
Cogeneration				0.0 %	0	0
Totals						
Totals**	**6,541**	**214,901**	**3**	**100.0** %	**237,225**	**293,190**

* Note: Resource Utilization factors are included in the Total Source Energy value .
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Project Name:
Dataset Name: 1014_Duplicate_updated.trc

TRACE® 700 v6.3.3 calculated at 08:57 AM on 04/09/2019
Alternative - 1 Energy Consumption Summary report page 1

MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**Field House**													
Electric														
	On-Pk Cons. (kWh)	868	853	846	458	173	379	545	418	171	198	779	852	6,541
	On-Pk Demand (kW)	1	1	1	1	2	2	2	2	2	1	1	1	2
Oil														
	Cons. (therms)	395	446	368	163	51	0	0	0	0	62	288	376	2,149
Water														
	Cons. (1000gal)	1	0	1	0	0	0	0	0	0	0	1	1	3

Energy Consumption		
Building	34,984	Btu/(ft2-year)
Source	43,237	Btu/(ft2-year)
Floor Area	6,781	ft2

Environmental Impact Analysis	
CO_2	7,843 lbm/year
SO_2	25 gm/year
NOX	7 gm/year

BUILDING COOL HEAT DEMAND

By ACADEMIC

January	Typical Weather (°F)		Design		Weekday		Saturday		Sunday		Monday	
Hour	OADB	OAWB	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)
1	23.3	21.1	-66,471	0.0	-57,286	0.0	-53,819	0.0	-53,560	0.0	-54,305	0.0
2	22.4	20.2	-63,151	0.0	-57,147	0.0	-55,551	0.0	-55,385	0.0	-55,988	0.0
3	22.1	20.0	-63,163	0.0	-57,877	0.0	-56,533	0.0	-56,447	0.0	-57,011	0.0
4	22.3	20.2	-63,697	0.0	-58,477	0.0	-57,226	0.0	-57,133	0.0	-57,742	0.0
5	23.0	20.7	-64,012	0.0	-58,826	0.0	-57,682	0.0	-57,593	0.0	-58,222	0.0
6	24.1	22.0	-64,004	0.0	-58,544	0.0	-57,477	0.0	-57,396	0.0	-58,038	0.0
7	25.5	23.4	-63,553	0.0	-57,842	0.0	-56,803	0.0	-56,730	0.0	-57,382	0.0
8	27.2	25.1	-62,295	0.0	-56,822	0.0	-56,024	0.0	-55,957	0.0	-56,382	0.0
9	29.1	26.9	-55,540	0.0	-51,977	0.0	-51,381	0.0	-51,283	0.0	-51,328	0.0
10	31.0	28.5	-38,749	0.0	-43,427	0.0	-42,754	0.0	-42,689	0.0	-42,990	0.0
11	32.9	30.0	-19,035	0.0	-34,609	0.0	-33,841	0.0	-33,796	0.0	-34,308	0.0
12	34.6	31.3	0	0.0	-29,663	0.0	-28,522	0.0	-28,480	0.0	-29,381	0.0
13	36.0	32.1	0	0.0	-26,550	0.0	-25,344	0.0	-25,300	0.0	-26,254	0.0
14	37.1	32.7	0	0.0	-23,795	0.0	-22,426	0.0	-22,377	0.0	-23,503	0.0
15	37.8	33.1	0	0.0	-23,451	0.0	-22,159	0.0	-22,116	0.0	-23,155	0.0
16	38.1	33.1	0	0.0	-24,925	0.0	-24,229	0.0	-24,194	0.0	-24,643	0.0
17	37.7	33.2	0	0.0	-30,751	0.0	-29,794	0.0	-29,758	0.0	-30,485	0.0
18	36.8	32.9	-23,742	0.0	-37,050	0.0	-36,094	0.0	-36,063	0.0	-36,831	0.0
19	35.3	31.9	-43,406	0.0	-41,876	0.0	-40,754	0.0	-40,720	0.0	-41,637	0.0
20	33.4	30.4	-48,581	0.0	-43,324	0.0	-42,217	0.0	-42,185	0.0	-43,095	0.0
21	31.2	28.3	-51,833	0.0	-45,519	0.0	-44,425	0.0	-44,396	0.0	-45,308	0.0
22	28.9	26.3	-54,439	0.0	-47,978	0.0	-46,902	0.0	-46,874	0.0	-47,785	0.0
23	26.7	24.2	-55,869	0.0	-50,603	0.0	-49,543	0.0	-49,519	0.0	-50,427	0.0
24	24.8	22.5	-57,284	0.0	-53,050	0.0	-52,007	0.0	-51,984	0.0	-52,892	0.0

February	Typical Weather (°F)		Design		Weekday		Saturday		Sunday		Monday	
Hour	OADB	OAWB	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)
1	15.6	13.2	-65,771	0.0	-67,106	0.0	-64,504	0.0	-64,294	0.0	-64,714	0.0
2	14.1	11.9	-69,019	0.0	-66,968	0.0	-65,488	0.0	-65,377	0.0	-65,897	0.0
3	13.1	10.9	-70,771	0.0	-67,379	0.0	-66,224	0.0	-66,145	0.0	-66,697	0.0
4	12.8	10.7	-72,040	0.0	-67,947	0.0	-66,907	0.0	-66,842	0.0	-67,408	0.0
5	13.1	11.2	-72,870	0.0	-68,804	0.0	-67,819	0.0	-67,761	0.0	-68,337	0.0
6	14.1	12.2	-73,194	0.0	-68,585	0.0	-67,644	0.0	-67,593	0.0	-68,176	0.0
7	15.6	13.8	-72,980	0.0	-67,854	0.0	-66,954	0.0	-66,909	0.0	-67,498	0.0
8	17.6	15.9	-68,765	0.0	-65,660	0.0	-65,028	0.0	-64,988	0.0	-65,356	0.0
9	19.9	18.1	-60,268	0.0	-61,431	0.0	-61,222	0.0	-61,189	0.0	-61,185	0.0
10	22.4	20.4	-43,591	0.0	-55,624	0.0	-55,023	0.0	-54,974	0.0	-55,272	0.0
11	24.9	22.1	-28,497	0.0	-46,644	0.0	-45,949	0.0	-45,918	0.0	-46,399	0.0
12	27.2	23.8	-14,098	0.0	-42,107	0.0	-40,847	0.0	-40,821	0.0	-41,649	0.0
13	29.2	25.6	0	0.0	-39,647	0.0	-40,409	0.0	-40,390	0.0	-41,367	0.0
14	30.7	26.8	0	0.0	-38,001	0.0	-37,191	0.0	-37,173	0.0	-38,143	0.0
15	31.7	27.4	0	0.0	-36,781	0.0	-35,770	0.0	-35,753	0.0	-36,727	0.0
16	32.0	27.7	0	0.0	-36,780	0.0	-36,172	0.0	-36,157	0.0	-36,708	0.0
17	31.7	27.3	-9,710	0.0	-40,370	0.0	-39,577	0.0	-39,564	0.0	-40,304	0.0
18	30.7	26.7	-39,711	0.0	-46,267	0.0	-45,479	0.0	-45,465	0.0	-46,200	0.0
19	29.2	25.8	-51,606	0.0	-52,397	0.0	-51,471	0.0	-51,458	0.0	-52,339	0.0
20	27.2	24.1	-57,930	0.0	-56,257	0.0	-55,713	0.0	-55,706	0.0	-56,225	0.0
21	24.9	22.0	-60,933	0.0	-58,022	0.0	-57,371	0.0	-57,363	0.0	-57,986	0.0
22	22.4	19.6	-63,428	0.0	-59,788	0.0	-59,137	0.0	-59,130	0.0	-59,754	0.0
23	19.9	17.3	-65,526	0.0	-60,963	0.0	-60,326	0.0	-60,320	0.0	-60,933	0.0
24	17.6	15.1	-67,255	0.0	-63,220	0.0	-62,586	0.0	-62,580	0.0	-63,192	0.0

E.3 Geothermal + Deep

ENERGY CONSUMPTION SUMMARY

By ACADEMIC

	Elect Cons. (kWh)	Oil Cons. (kBtu)	Water Cons. (1000 gals)	% of Total Building Energy	Total Building Energy (kBtu/yr)	Total Source Energy* (kBtu/yr)
Alternative 1						
Primary heating						
Primary heating		181,734		89.2 %	181,734	191,2
Other Htg Accessories	3,189		3	5.3 %	10,886	32,6
Heating Subtotal	**3,189**	**181,734**	**3**	**94.5** %	**192,620**	**223,9**
Primary cooling						
Cooling Compressor				0.0 %	0	
Tower/Cond Fans	222			0.4 %	759	2,2
Condenser Pump				0.0 %	0	
Other Clg Accessories				0.0 %	0	
Cooling Subtotal....	**222**			**0.4** %	**759**	**2,2**
Auxiliary						
Supply Fans	3,058			5.1 %	10,436	31,3
Pumps				0.0 %	0	
Stand-alone Base Utilities				0.0 %	0	
Aux Subtotal....	3,058			5.1 %	10,436	31,3
Lighting						
Lighting				0.0 %	0	
Receptacle						
Receptacles				0.0 %	0	
Cogeneration						
Cogeneration				0.0 %	0	
Totals						
Totals**	**6,470**	**181,734**	**3**	**100.0** %	**203,815**	**257,5**

* Note: Resource Utilization factors are included in the Total Source Energy value .
** Note: This report can display a maximum of 7 utilities. If additional utilities are used, they will be included in the total.

Project Name:
Dataset Name: 1014_DUPLICATE.TRC

TRACE® 700 v6.3.3 calculated at 06:57 AM on 04/15/201
Alternative - 1 Energy Consumption Summary report page

MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**Field House**													
Electric														
	On-Pk Cons. (kWh)	837	818	815	381	135	468	638	493	210	185	663	827	6,470
	On-Pk Demand (kW)	1	1	1	2	1	2	2	2	2	1	1	1	2
Oil														
	Cons. (therms)	339	380	315	124	37	0	0	0	0	52	243	326	1,817
Water														
	Cons. (1000gal)	0	0	0	0	0	0	0	0	0	0	0	0	3

Energy Consumption		
Building	30,057	Btu/(ft2-year)
Source	37,981	Btu/(ft2-year)
Floor Area	6,781	ft2

Environmental Impact Analysis	
CO_2	7,757 lbm/year
SO_2	24 gm/year
NOX	7 gm/year

BUILDING COOL HEAT DEMAND

By ACADEMIC

January	Typical Weather (°F)		Design		Weekday		Saturday		Sunday		Monday	
Hour	OADB	OAWB	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)
1	23.3	21.1	-57,816	0.0	-50,042	0.0	-47,390	0.0	-47,262	0.0	-47,981	0.0
2	22.4	20.2	-51,257	0.0	-50,337	0.0	-48,937	0.0	-48,857	0.0	-49,620	0.0
3	22.1	20.0	-51,434	0.0	-51,423	0.0	-50,184	0.0	-50,109	0.0	-50,875	0.0
4	22.3	20.2	-52,250	0.0	-52,094	0.0	-50,904	0.0	-50,837	0.0	-51,608	0.0
5	23.0	20.7	-52,629	0.0	-52,339	0.0	-51,193	0.0	-51,133	0.0	-51,910	0.0
6	24.1	22.0	-52,624	0.0	-51,873	0.0	-50,766	0.0	-50,712	0.0	-51,495	0.0
7	25.5	23.4	-52,115	0.0	-50,934	0.0	-49,864	0.0	-49,816	0.0	-50,604	0.0
8	27.2	25.1	-50,548	0.0	-49,463	0.0	-48,810	0.0	-48,768	0.0	-49,176	0.0
9	29.1	26.9	-40,224	0.0	-43,770	0.0	-43,708	0.0	-43,670	0.0	-43,515	0.0
10	31.0	28.5	-25,927	0.0	-36,759	0.0	-36,329	0.0	-36,295	0.0	-36,564	0.0
11	32.9	30.0	0	0.0	-27,657	0.0	-27,051	0.0	-27,020	0.0	-27,476	0.0
12	34.6	31.3	0	0.0	-22,391	0.0	-21,480	0.0	-21,460	0.0	-22,256	0.0
13	36.0	32.1	0	0.0	-19,514	0.0	-18,542	0.0	-18,526	0.0	-19,406	0.0
14	37.1	32.7	0	0.0	-17,269	0.0	-16,156	0.0	-16,147	0.0	-17,156	0.0
15	37.8	33.1	0	0.0	-17,520	0.0	-16,575	0.0	-16,568	0.0	-17,444	0.0
16	38.1	33.1	0	0.0	-19,426	0.0	-19,057	0.0	-19,053	0.0	-19,371	0.0
17	37.7	33.2	0	0.0	-25,386	0.0	-24,714	0.0	-24,708	0.0	-25,331	0.0
18	36.8	32.9	0	0.0	-31,797	0.0	-31,086	0.0	-31,079	0.0	-31,740	0.0
19	35.3	31.9	0	0.0	-37,469	0.0	-36,583	0.0	-36,574	0.0	-37,410	0.0
20	33.4	30.4	-35,531	0.0	-39,668	0.0	-38,688	0.0	-38,677	0.0	-39,605	0.0
21	31.2	28.3	-41,105	0.0	-38,830	0.0	-40,528	0.0	-40,517	0.0	-38,759	0.0
22	28.9	26.3	-43,008	0.0	-43,370	0.0	-40,052	0.0	-40,045	0.0	-43,320	0.0
23	26.7	24.2	-44,819	0.0	-44,383	0.0	-43,609	0.0	-43,603	0.0	-44,334	0.0
24	24.8	22.5	-46,334	0.0	-46,458	0.0	-45,621	0.0	-45,615	0.0	-46,414	0.0

February	Typical Weather (°F)		Design		Weekday		Saturday		Sunday		Monday	
Hour	OADB	OAWB	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)	Htg (Btuh)	Clg (Tons)
1	15.6	13.2	-58,195	0.0	-59,281	0.0	-57,610	0.0	-57,482	0.0	-57,950	0.0
2	14.1	11.9	-59,404	0.0	-59,982	0.0	-58,823	0.0	-58,742	0.0	-59,285	0.0
3	13.1	10.9	-60,433	0.0	-60,847	0.0	-59,824	0.0	-59,755	0.0	-60,320	0.0
4	12.8	10.7	-61,341	0.0	-61,582	0.0	-60,621	0.0	-60,560	0.0	-61,137	0.0
5	13.1	11.2	-61,946	0.0	-62,249	0.0	-61,328	0.0	-61,274	0.0	-61,859	0.0
6	14.1	12.2	-62,146	0.0	-62,140	0.0	-61,252	0.0	-61,203	0.0	-61,795	0.0
7	15.6	13.8	-61,900	0.0	-61,558	0.0	-60,701	0.0	-60,658	0.0	-61,256	0.0
8	17.6	15.9	-57,581	0.0	-58,967	0.0	-58,374	0.0	-58,335	0.0	-58,703	0.0
9	19.9	18.1	-44,545	0.0	-52,854	0.0	-52,569	0.0	-52,516	0.0	-52,491	0.0
10	22.4	20.4	-28,378	0.0	-43,419	0.0	-42,952	0.0	-42,917	0.0	-43,189	0.0
11	24.9	22.1	0	0.0	-36,960	0.0	-36,365	0.0	-36,341	0.0	-36,795	0.0
12	27.2	23.8	0	0.0	-32,831	0.0	-31,909	0.0	-31,888	0.0	-32,689	0.0
13	29.2	25.6	0	0.0	-29,892	0.0	-28,951	0.0	-28,934	0.0	-29,778	0.0
14	30.7	26.8	0	0.0	-27,978	0.0	-27,044	0.0	-27,031	0.0	-27,885	0.0
15	31.7	27.4	0	0.0	-27,064	0.0	-26,137	0.0	-26,127	0.0	-26,985	0.0
16	32.0	27.7	0	0.0	-27,198	0.0	-26,672	0.0	-26,663	0.0	-27,130	0.0
17	31.7	27.3	0	0.0	-30,672	0.0	-29,966	0.0	-29,958	0.0	-30,615	0.0
18	30.7	26.7	0	0.0	-37,860	0.0	-37,141	0.0	-37,134	0.0	-37,806	0.0
19	29.2	25.8	-29,526	0.0	-43,792	0.0	-42,924	0.0	-42,915	0.0	-43,730	0.0
20	27.2	24.1	-47,205	0.0	-48,033	0.0	-47,166	0.0	-47,158	0.0	-47,978	0.0
21	24.9	22.0	-51,347	0.0	-50,086	0.0	-49,217	0.0	-49,209	0.0	-50,032	0.0
22	22.4	19.6	-53,819	0.0	-52,060	0.0	-51,196	0.0	-51,189	0.0	-52,011	0.0
23	19.9	17.3	-55,983	0.0	-53,836	0.0	-52,977	0.0	-52,970	0.0	-53,792	0.0
24	17.6	15.1	-57,214	0.0	-56,543	0.0	-55,745	0.0	-55,739	0.0	-56,518	0.0

Appendix F

Geothermal System Review Spreadsheet

	Skidmore	Ballstate	Princeton	Richard Stockton	Dunbar High School	Oberlin College	University of Ontario Institute of Techn	The Motherhouse	Bates College
Location	Saratoga Springs, NY	Muncie, Indiana	Princeton, New Jersey	Atlantic County, New Jersey	washington DC	Ohio	Oshawa, Ontario, Canada	Michigan	
Orientation	Vertical	Vertical	Vertical	Vertical	Vertical		Vertical		
Thermal Conductivity	2.3 Btu/hr-ft-°F				1.5 Btu/hr-F-ft				
Working Fluid (GHX)		water		water	35% Propylene glycol	water + glycol	glycol solution		
Mass Flow of working fluid GHX				water, 4000 gallons/minute					
Borehole Diameter		4-5 in.		4 in.	5.5-6 in	24			
Number of Boreholes	471	3600	200	400	362	18	384	232	
Notes on # boreholes	Currently 231 - after 2017 - 471 total	3600-4100							
Working fluid in HP		Refrigerant 134a							
Borehole Spacing		15 ft apart		at least 15 ft	Roughly 20 ft				
Diameter of HDPE		1-1/4 inch		1 ¼ inch	1.25 in HDPE				
Number of Heat Pumps		4 Heat Pump Chillers (2500 tons each)		119 roof mounted HPs on buildings					
Depth of Boreholes (ft)	400	400		425	500	300	700		
Notes on depth	between 400-500	400/500 ft							
Soil Type	moist coarse sand and fine grain clay			aquifer, confining bed	Grey Clay, Blue clay				
Rock Type	dolomite						impermeable limestone at 50 - 200 m		
% total heating/cooling provided by geothe	40% of total heating and air-conditioning (58% when fully engaged), meeting 50% of colleges needs after 240 more boreholes installed	.							
COP for Heating		3.8		3.4					
COP for Cooling		2.9							
Cost		70000000		4,004,594	$127,906,735	15500000			
Notes on cost									
Average Subsurface temp					59 F				
Miles of piping		1000 mi		64 mi	68 mi				
Heating/Cooling Load				5.91 MW; cooling: 106 feet/ton	Their cooling load much higher 2,837,907 kBtu		cooling: 7,000 kW.		
Grout Used/ Thermal conductivity				bentonite	Thermal Bentonite 1.2 BTU/hr-F-ft				
Tools used for drilling		Mud rotary			Mud rotary then air rotary after 147 ft				
Surface area for boreholes				4 acres	8.5 acres		7,000 m2 = 1.7 acres		
Company used		MEP Associates	Architects - Studio Ma, Developer - American Campus Communities, Engineering - Dagher Engineering		DGS construction;				
Faculty		Jim Lowe (765) 285-2805 jlowe@bsu.edu					Ken Bright		
Current/Previous Infrastructure		Heat plant, 4 coal fired boilers, 3 natural gas fired boilers - chilled water plant, 5 electrical centrifugal chillers, replace coal boilers with geothermal	Electricity – (1)15 MW Gas Turbine Generator as cogen (certified to run on biodiesel); Steam Generation – (1) Heat Recovery Boiler – (2)Auxiliary Boilers; Chilled Water Production – (3) Steam-Driven Chillers – (5) Electric Chillers – (1) Thermal Storage Tank;	.	482 kW photovoltaic array; two 20,000-gallon cisterns; $0.085 per kWh	.			50% Purchased Electricity, 9,417 MTCDE, 40% On Campus stationary sources,7,502 MTCDE, plan to convert main steam plant to a biomass cogeneration facility by 2020
Configuration	Decentralized; Each area has a GHX with its own HP distributed to multiple buildings	3 GHX fields as energy hubs feeding centralized hot and chilled water to buildings	.	One bore field under 4 acre parking lot. Likely Centralized. Reverse Return - Twenty wells are fed from one 4-inch diameter lateral in a `reverse return' configuration to equalize the pressure drop (and presumably the flow) through each of the 20 wells.	GHX in one bore field under athletic field - unclear about location/configuration of heat pumps	.	Centralized system; Hydronic		
Building Square footage (gsf)			382,000	350,000	280,000				
Notes on square footage			(also see 323,000)	(or 400,000) out of 440,000 SF					
Scale of GSHP system									
Summary Statistics									
$ Cost/well	0	19444.44444	0	10011.485	$353,334	861111.1111	0	0	#DIV/0!
Notes on cost/well:	$5k/well is rule of thumb, most of that cost is to set up rigging, makes phased approach more expensive, there are several good papers on this, Stanford has a decent model								
Wells/1000 gsf	#DIV/0!	#DIV/0!	0.5235602094	1.142857143	1.292857143	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
$ Cost/1000 gsf	#DIV/0!	#DIV/0!	0	11441.69714	$456,810	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

	University of Sherbrooke	Missouri S&T	University of Miami Ohio	Carleton College	Westfield University	Hamilton College	Notre Dame	Western New England University	Middlebury	University of Virginia			
Location			Oxford, Ohio	Minnesota			Notre Dame, Indiana	Springfield, MA					
Orientation			Pond loop	V, H			vertical						
Thermal Conductivity													
Working Fluid (GHX)	15,000 Gallons Propylene Glycol		water				water						
Mass Flow of working fluid GHX	15,000 gallons												
Borehole Diameter													
Number of Boreholes	57	789	315				1303						
Notes on # boreholes			315 bores located under a pond loop field with 113 loops				153 in field 1, 500 in field 2, 650 in field 3						
Working fluid in HP													
Borehole Spacing													
Diameter of HDPE													
Number of Heat Pumps													
Depth of Boreholes (ft)	520	400	600				300						
Notes on depth	520-530	400-440											
Soil Type													
Rock Type													
% total heating/cooling provided by geothe													
COP for Heating													
COP for Cooling													
Cost		32000000	23000000				40000000	900000					
Notes on cost								cost estimate is for GHX system for Southwood Hall					
Average Subsurface temp			56-60 deg F				50-55 degF						
Miles of piping													
Heating/Cooling Load			1,000 tons of cooling, but can be expanded in the future to 2,500 tons				300 ton GHX in field1 and 1000 tons in field 2 and 1350 tons in field 3	3 GHX systems, connections are not clear; Southwood Hall is on one system that is 56,000 gsf with an adjacent athletic field/parking lots					
Grout Used/ Thermal conductivity													
Tools used for drilling													
Surface area for boreholes													
	24F/50F												
Company used		McClure Engineering & CM Engineering	MEP associates; Grote Enterprises provided the HVAC and plumbing coordination, BIM models and installation documents	MEP Associates				Harry Grodsky and Co (Local firm)					
Faculty													
Current/Previous Infrastructure	25% electricity from Hydro-Québec and 75% from free underground thermal energy	.	12 MW power plant, co-gen with steam distribution, their cost of electricity is really inexpensive ($0.04/kWh)										
Configuration	Decentralized heating plant (not GHX)	3 "geothermal plants and a satellite geothermal system" (three halls and a rec center), they mention heat pumps as chillers with backup gas fired boilers, and these plants are connected in some way to neighboring buildings	East quad and west quad have their independent GHX field				south campus (field 1) and central campus (field 2) and the north end of central campus (field 3) have independent GHX fields, central campus and the north end of central campus GHX fields are connected to centralized CW, field 3 is connected to some sort of planned hot water heating distribution						
Building Square footage (gsf)		1000000											
Notes on square footage													
Scale of GSHP system													
Summary Statistics													
$ Cost/well	0	40557.66793	73015.87302	#DIV/0!	#DIV/0!	#DIV/0!	30698.38833					average =	34745.57175
Notes on cost/well:													
Wells/1000 gsf	#DIV/0!	0.789	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!					
$ Cost/1000 gsf	#DIV/0!	32000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!					

Appendix G

Life Cycle Cost Spreadsheet

Field House Paremeters				
	SI		IP	
Gross Area	2066.8488	m^2	6781	ft^2
Roof Area	173.9144909	m^2	1872	ft^2
Roof length		m	52	ft
Wall length		m	92.125	ft
Wall width		m	36.83	ft
Wall height			8	ft
Total Wall Cavity			4126.56	ft^2
Raw oil data			1979.5	gallon
Type 2 oil heating value			139400	btu/gallon
Current oil consumption	80870.7	kwh/yr	275942.3	kbtu/yr
Cost per gallon of oil			2.75	$/gallon
#windows on the first floor	34			

Cost Specifics			
Cost of electricity	0.155	$/kwh	
Cost per well	46000	$	
Cost per window	1500	$	
Cost for sealing (total)	1440	$	3 people, 2 full days, $ 30/
Costs for insulation	4.55	$/ft2	
interest for electricity	0.01		
interest for oil	0.04		
interest for federal fund	0.025		
Geothermal only			
Total Pump	6401.026718	W	
	1.32732E+11	J	
	36869.91389	kWh	
Medium			
Total Pump	5343.360051	W	
	1.108E+11	J	
	30777.75389	kWh	
Deep			
Total Pump	4834.360051	W	
	1.00245E+11	J	
	27845.91389	kWh	

Life Cycle Cost Analysis

	Current	Geothermal	Geothermal + Medium	Geothermal + Deep
Capital Cost				
Installation		$138,000.00	$138,000.00	$92,000.00
Retrofit			$68,035.20	$88,251.05
window replacement			$51,000.00	$51,000.00
attic insulation/sealing			$17,035.20	$17,035.20
envelope insulation				$18,775.85
envelope sealing				$1,440.00
Total Capital Cost	$0.00	$138,000.00	$206,035.20	$180,251.05
Annual Cost				
Oil Purchase	$5,443.63			
Electricity Purchase		$5,714.84	$4,770.55	$4,316.12
Total Annual Cost	$5,443.63	$5,714.84	$4,770.55	$4,316.12
Present Worth at Year 0				
Capital Cost - > Present Worth	$0.00	$138,000.00	$206,035.20	$180,251.05
Annual Cost -> Present Worth	$94,131.16	$147,486.79	$123,116.97	$111,389.04
Discount Rate for Annual	4.00%	1.00%	1.00%	1.00%
Present Worth Factor for Annual	17.29	25.81	25.81	25.81
Total Present Worth	$94,131.16	$285,486.79	$329,152.17	$291,640.09
S.F. Cost	$13.88	$42.10	$48.54	$43.01
Future Worth at Year 30				
Capital Cost -> Future Worth	$0.00	$289,464.33	$432,172.76	$378,088.75
Discount Rate for Capital	2.50%	2.50%	2.50%	2.50%
Future Worth Factor for Capital	2.10	2.10	2.10	2.10
Annual Cost -> Future Worth	$305,305.16	$198,815.74	$165,964.64	$150,155.11
Discount Rate for Annual	4.00%	1.00%	1.00%	1.00%
Future Worth Factor for Annual	56.08	34.78	34.78	34.78
Total Future Worth	$305,305.16	$488,282.19	$598,139.51	$528,245.99
S.F. Cost	$45.02	$72.01	$88.21	$77.90

Appendix H

Scanned Notes

H.1 Field House Field Investigation Notes

commercial - copper pipe
space heater - ~~boiler~~
Water (bathrooms...
~~heating~~

copper

One Boiler 1999 AFUE 80
VBC-63 75 Amp.

copper — ~~yello~~ orange pipes space heating

copper — (DHW) holding water boiler? 130F
↓ copper
? Demand?
~~hold~~
talk to sports team

water meter?

fiberglass, no air-barrier - no air infiltration
ins 16in on center load bear. mason
have gaps: moving air
spider web.

cross section - wall

foundation - basements? How to model?
brick below grid

no wall cavity added concrete

8-20' wide masonary total wall, concrete or brick

faucet 正 正 (4 showers)

shower heads: new.

roof: ins bottom (cellulose) make-up air (Air (a))
no ins space no on top
15' to the rafter. full drop

H.2 Building Insulation Cost Estimation

Spray foaming - 8000 ft^2, just attic

sealing - 3 people, 2 full day, \$30/hr = \$1440

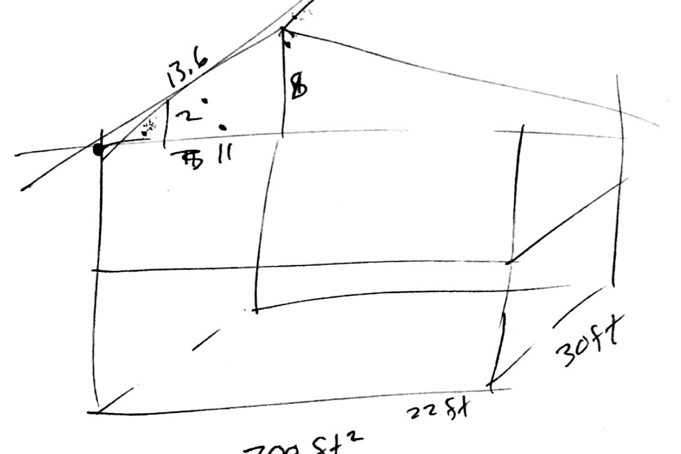
cost is half labor + half materials

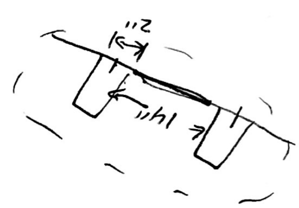
w +\$1,000 for blower door

$\frac{6}{7}(R\text{-}42)$ ∴ you can added

surface area can not be insulated 14% so $\frac{1}{7} = \frac{2}{14}$

\$15,000 to spray foam a 1400 ft^2 house





700 ft^2

faces, stories, twice thickness

$$\left((22\times 8)2 + (30\times 8)2\right)2 + (13.6\times 30)2(2)$$

$$(352 + 480)\times 2$$

= ~~2460~~ ft^2 of cavity

3296 ft^2

3 inches of insulation — gets R-21

we will go to 6"

\$4.55/ft^2 of surface insulated

& remember to double for attics

Appendix I

PV System Design Report

This Appendix presents a design process and framework that could be applied to size a PV array at the Field House. The GSHP design has been updated in this thesis. However, the PV sizing is applicable for this work.

Lily Li
EGR 388-Assignment 2
11/13/2017
Prof. Denise McKahn

PV System Design Report for Field House

Summary

This report details the design of a grid-tied PV system, coupled with a geothermal ground source heat pump for the field house. The main components of this PV system include 72 PV modules and a grid-tied inverter. Initial cost of the system is $30,778.41 and total life cycle cost is $45,422.06, with a life cycle of 30 years.

The motivation and background of the project is summarized in Introduction. Design Criteria describes the specific design requirements that need to be met during the design. Major equations used for the design, load analysis and component sizing are elaborated in Design Process. A list and detailed descriptions of all system components are included in Component Specification and life cycle cost analysis is estimated in the corresponding section.

Introduction

In response to the Smith College Sustainability and Climate Action Plan to reduce carbon emission by 2030, a pilot project to examine the feasibility of transforming to geothermal energy for heating is launched at the field house. A single borehole, geothermal ground source heat pump will be installed for heating the field house and a grid-tied PV system is coupled to the heat pump for electricity supply.

This PV system is grid-tied, in order to best resemble the current and future buildings on Smith campus, as most of the buildings on campus is connected to the grid. Field house is an ideal location for a pilot project, because of its small scale, 4000 square feet in footprint, which lowers the price of both the geothermal and the PV system, and the limited amount of human activities happening inside of it, making the heating and electricity load easier to estimate (i.e. less incidental fluctuation) using Etta's building energy model from 2009.

Overall, the field house stands in plain sight, without much shading. Although there is a tree on the south side of the field house that sometimes shades the target roof by a small amount, shading is not taken into consideration during the design process.

Design Criteria

This section elaborates the design requirements and constraints that must be considered in the design of an adequate system. Overall, these important criteria are 1) the total electricity load for the PV system; 2) the availability of solar insolation for the PV modules; 3) the physical space of the roof that the modules will be mounted on; and 4) economic considerations, for instance, reasonable maintenance fee.

The primary goal of the design is to make sure electricity generated by the PV modules adequately covers the total load required by the geothermal system. To estimate the total load, the coupled system configuration must be understood. A diagram of the geothermal heating system is shown in Figure 1. An entire geothermal heating system consists of a water loop geothermal borehole, a heat pump and a water loop heat distribution. Therefore, the total load for the PV system is the combined electricity inputs:

$$W_{total} = W_1 + W_2 + W_3 \qquad \text{Eqn. 1}$$

in which, W_1 and W_2 are the electricity inputs for water pumps and W_3 is the electricity input for a turbine. Detailed assumptions made to estimate the load will be discussed in Design Process. Final total load is estimated to be 34.5 kWh/day.

The number of PV modules needed for the PV system depends on the annual availability of solar insolation. Based on previous calculations (Appendix A, Table 1.), an annual solar insolation of 1571 kWh/m^2*yr is available to Northampton and is used as the available annual solar insolation on the roof of the field house. An annual average daily solar insolation is calculated by dividing 1571 kWh/m^2*yr with 365 days/year, which equals 4.3 kWh/m^2*day. Therefore, the peak sun hours, which is the number of hours per day for which an equivalent of 1 kW/m2 is generated by the modules, equals 4.3 hours/day. The sun hour is crucial to the calculation for PV system output current, which will also be discussed in detail in Design Process. A total of 72 modules, 24 in series for 3 parallel strings, is the final configuration that harness the most of the available solar energy to power the load of 34.5 kWh/day.

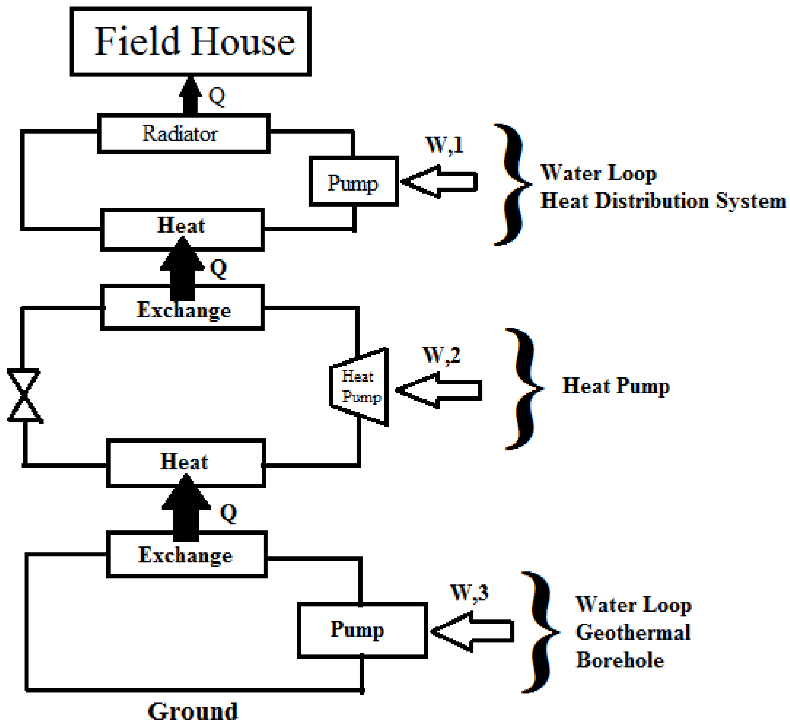


Figure 1. System Diagram for the Geothermal Heating System

The physical space available for the PV modules is the south side of the roof of the field house. The total area is calculated by estimating distance on Google Map and trignometry. The side of the roof is shown in Figure 2. Trignometry is used, demonstrated in Figure 3, assuming the angle $\alpha = 40°$, that gives the width, $b = 21$ ft. Measured with Google Map, the length $l = 90$ ft, which gives a total availabe area $A = 1890$ ft^2.

Figure 2. Side Shot of the Roof of Field House

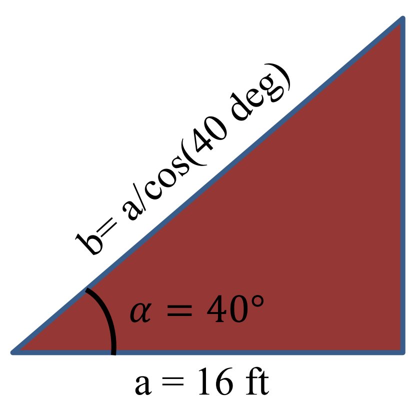


Figure 3. Estimation of the width using Trigonometry

And since the optimal tilt angle $\beta = 41.4°$ (see Appendix A, Table 1.), is almost the same as the roof angle $\alpha = 40°$, and to save the cost for adjustable mounting brackets, the modules will be directly mounted to the roof. Based on calculation, 72 PV modules, 24 in series for 3 parallel strings, is the best configuration. The dimensions of a single panel is 3.9ft by 1.8ft (See specification for Panel RNG-100D in Appendix B). Therefore, the space on the roof is more than sufficient for such a system configuration, with 72 panels adding up to only 1/3 of the surface area, leaving the rest for separation space between the panels.

The entire system consists of PV modules, a inverter and wires, of which the inverter will be replaced once at the 20^{th} year and the modules be cleaned every two weeks in the winter season (from November to March) for snow. The cost for the listed two items above is \$15000, and is approximately 33% of the total life cycle cost. This is a reasonable amount that makes the design economically justifiable.

Design Process

Load analysis

As analyzed in Design Criteria (Eqn 1.), the total load is the sum of the electricity inputs in a geothermal heating system, written as $W_{total} = W_1 + W_2 + W_3$. The following assumptions are made for load calculation:

1. Due to a lack of information on an actual geothermal heat distribution pump, a Taco pump, specific model unknown, that's used in a residential house (Professor McKahn's house) is used to estimate W_1. A power of 93 W is used as the power per pump. There is a total of 4 pumps for the heat distribution system. Therefore a total of 93 W *4 = 372 W is the power of this sub-system.
2. For estimation of W_2, these assumptions are made:
   a) Field house has load bearing masonry exterior walls, concrete substructure and wood superstructure. A wall R-value of 5.5 is used based on Etta Grover-Silva's building model, 2009.
   b) The roof of the field house is asphalt shingles and ceiling is exposed wood, with double wood windows. Based on Etta's model, an attic R-value of 44.5 is used.
   c) Three different gross area are given from different sources: 6910 ft^2, 8133 ft^2 and 9758 ft^2. In this design, the biggest gross area, A = 9758 ft^2 is used, which means W_2 is likely to be an overestimation.
   d) The field house will undergo a retrofit before it is installed with the new system. To find a heat load estimate per square feet, the degree to which this retrofit will go is assumed to be sealing + attic + walls. This gives a heating rate of 30631.15 BTU/ft^2*yr, based on Etta's model and 2a) and 2b).
   e) COP is 3 for the turbine.
3. Also due to a lack of information, the geothermal pump is assumed to be 10 times more powerful than the distribution pump, out of the consideration that a much larger amount of work is required to pump water down to 400-500 ft and back up, in a borehole water loop. Therefore, power for one single pump is 93 W * 10 = 930 W.
4. Overall, based on operating information from Professor McKahn's residential pump, a total of 1/3 of a day, 8 hours, is assumed as the operating duration per day for all three parts of the geothermal system. However, for convenience, the unit will still be "per day".

Detailed calculation is attached in Appendix C. The final load analysis result is shown in Table 1.

Table 1. Load Analysis Results.

Distribution Load (kWh/day)	Heat Pump Load (kWh/day)	Geothermal Load (kWh/day)	Total Load (kWh/day)
2.9783808	24.0568511	7.445952	34.4811839

Inverter Selection

Because the load is in AC and the output of the PV module is in DC, an inverter is required in between to convert the voltage signal. A model, Xantrex GT5.0-NA-240/208 UL-05, is selected with the following specification summary in Table 2 (Detailed specs see Appendix D). This model has a large maximum voltage and current input, to lower the numbers of PV modules needed.

Table 2. Specs Summary of Inverter

Model	Inverter Vmax (V)	Inverter Imax (A)	Inverter Efficiency (%)
Xantrex GT5.0-NA-240/208 UL-05	550 VDC	22 ADC	95.9

PV Modules Configuration

Two criteria are considered when choosing a PV module: efficiency and cost. This design leaned to favor cost than efficiency and used the RNG-100D model, a 100W Monocrystalline Solar Panel, with an efficiency of only 15.47% (See specification for Panel RNG-100D in Appendix B). To find the best configuration of modules, system voltage and current must be determined. Equation 2 relates sun hours, system voltage and inverter efficiency and total load:

$$I_{sys} = \frac{AC\ Load}{V_{DC,sys} \times Derate\ Factor \times \eta_{inverter} \times peak\ sun\ hours} \qquad \text{Eqn. 2}$$

in which AC Load = 34.5 kWh/day, Derate Factor = 0.9, $\eta_{inverter} = 95.9\%$ and peak sun hours = 4.3 hrs/day. System voltage is varied from 0 V to maximum voltage input V_{max} of the inverter to find a good configuration of panels that satisfies the condition that 1) I_{sc} * # Parallel < I_{max} and 2) V_{oc} * # Series < V_{max}, in which # Parallel = I_{sys}/I_{mp}, # Series = V_{sys}/V_{mp}. A summary of the PV module specifications and sizing result is shown in Table 3.

Table 3. Summary of PV Specification and Configuration Calculation

Annual Solar Insolation (kWh/m^2*yr)	Sun hours (hrs/day)		
1570.966791	4.304018604		
I_{mp} (A)	V_{mp} (V)	I_{sc} (A)	V_{oc} (V)
5.29	18.9	5.75	22.5
I_{system} (A)	V_{system} (V)	Theoretical P_{system} (W)	Real P_{system} (W)
20.17850936	460	9282.114305	100W * 72 Panels = 7200
# of Panels in parallel	# of Panels in series	# of Panels Total	
3	24	72	
Check:			
I_{sc} * # Parallel < Imax	V_{oc} * # Series < Vmax		
17.25	540		

And since the number of panels must be an integer, both cells, "# of Panels in Parallel" and "# of Panels in Series" have displayed a rounded down result. Therefore, the real power output of the PV modules is 7200 W rather than 9282 W. Notice that this configuration has passed both current and voltage checks. A detailed wiring diagram will be shown in Component Specification.

Sizing of the Wires

Assuming the connection between each panel in series is 1 ft and that between each string in parallel is 3 ft, 32 ft for one-way connection between PV module and the indoor inverter and another 32 ft for one-way connection between the inverter and the AC load gives a total length of 209 ft. Applied with a factor of safety of 2, the total wire length is 418 ft.

System current is estimated by multiplying the Isys with a general factor of safety of 1.25 and with another 1.25 to account for cloud focusing or reflection, to be 31.5 A. The 8 AWG wire is selected, with an ampacity of 40 A and a total of 488 ft, satisfying all requirements listed above.

Component Specification

The entire system has 72 PV modules, 1 grid-tied inverter and 418 ft long of 8 AWG wire. A summary of component specifications is listed in Table 4. A proposed budget for the PV system is around $ 40,000-$50,000, which is the average price for one geothermal borehole, based on the spreadsheet Rison Naness and I have compiled during the Summer of 2017.

Table 4. Component Specifications for a Grid-Tied PV System for Field House

Component	PV Module	Inverter	Wire
Manufacturer and P/N	Renogy RNG-100D	Xantrex GT5.0-NA-240/208 UL-05	Type THHN/THWN-2 building wire
Dimensions	L: 47.3 in W: 21.3 in H: 1.4 in	L: 15.88 in W: 31.4 in H: 5.39 in	Outside Diamiter = 0.212 inches Weight = 0.069 lbs/ft
Key Design Specs	P_{max} = 100 W V_{mp} = 18.9 V I_{mp} = 5.29 A V_{oc} = 22.5 V I_{sc} = 5.75 A	Max Input Current = 22 ADC Max Input Voltage = 550 VDC	Max Voltage = 600 V
Nominal Voltage (V)	12	240	240
Quantity	72	1	418 ft
Warranty (years)	25	10	Assumed: 30
Unit Price	$140	$3850.41	$ 0.36/ft

A complete wiring diagram is shown in Figure 4.

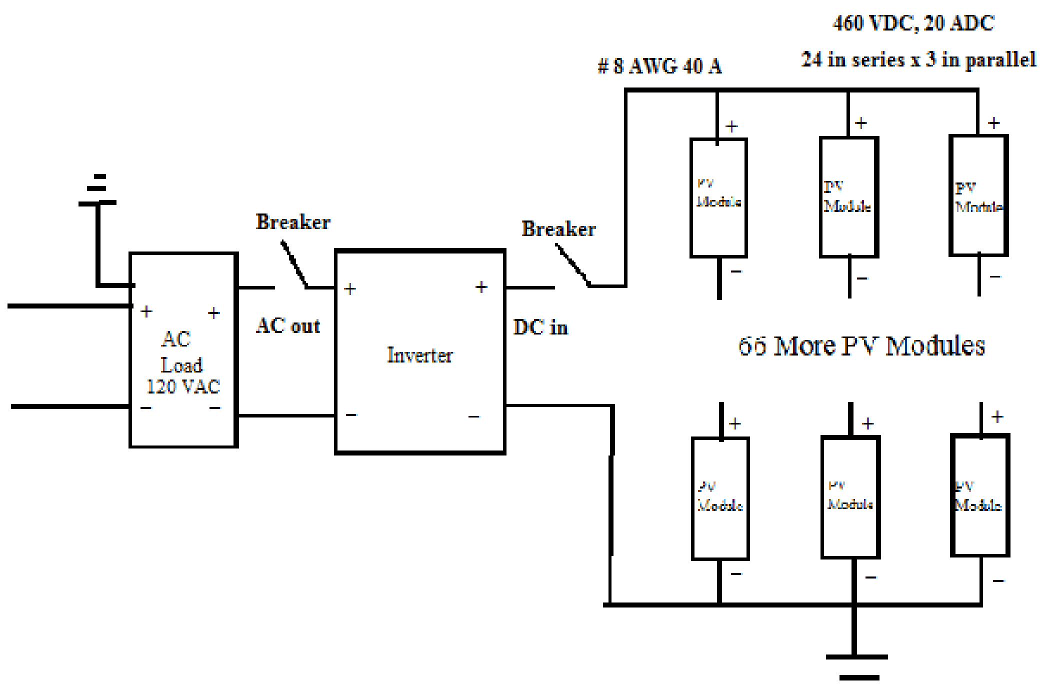


Figure 4. Wiring Diagram for a Grid-Tied PV System

Life Cycle Cost Analysis

The life cycle is assumed to be 30 years, and is justifiable because this is only 5 years more than the warranty of PV module. The replacement cycle for inverter is assumed to be twice the time of the warranty, to be 20 years. The wire is assumed to have a life of 30 years. Installation fee is $2.4/W with an extra $300 of permitting fee. The discount rate is 6%. Salvage rate is assumed to be 20% of the original module cost. Annual maintenance mostly includes removal of snow in the winter (5 month, from November to March), with 4 hours of work every two weeks per month, at a rate of $25/hour.

Based on these assumptions, initial cost = $30820.89, total life cycle cost = $45,464.54. A detailed LCC is attached in Appendix E.

Appendix A: Array Sizing Report from Assignment 1

Plane of Array Design for Field House

Introduction

In response to the Smith College Sustainability and Climate Action Plan to achieve carbon neutrality by 2030, a geothermal energy based heating/cooling system will be installed, replacing the natural gas boilers. As a pilot project, the smith college field house, 4000 square feet in footprint[1] with a stand-alone system, will be equipped with a single borehole, geothermal heat exchanger to test how the system performs on a small scale. A PV system is designed, utilizing solar energy to cover the electricity usage of the heat pump.

This report presents the parameter calculations and optimization for plane of array of the PV system using an excel sheet model. Final results include ideal and actual monthly average insolation, comparisons of monthly insolation on site between different tilt angles of the plane and an optimal tilt angle that yields a maximum annual solar insolation.

The model utilizes the relationship between $\overline{H_T}$ and β described in the following equation:

$$\overline{H_T} = \bar{H}\left(1-\frac{\bar{H}_d}{\bar{H}}\right)\bar{R}_b + \bar{H}_d\left(\frac{1+\cos(\beta)}{2}\right) + \bar{H}\rho_g\left(\frac{1-cob(\beta)}{2}\right)$$

where $\overline{H_T}$ is monthly average daily total insolation on a tilted surface, $\bar{H}$ is horizontal monthly average daily insolation, $\bar{H}_d$ is the diffuse component of the horizontal monthly average daily insolation, $\bar{R}_b$ is the direct beam tilt factor, ρ_g is the ground reflectivity and β is the tilt angle.

Equations that describe the unknown variables above are listed below:

$$\bar{H}_d = (1.391 - 3.56\bar{K}_T + 4.189\bar{K}_T^2 - 2.137\bar{K}_T^3)\times\bar{H} \text{ for } \omega s \le 81.4°$$

$$\bar{H}_d = (1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.821\bar{K}_T^3)\times\bar{H} \text{ for } \omega s > 81.4°$$

where ωs is hour angle, K_T is the clearness index, $K_T = \bar{H}/\bar{H}_o$

$$\bar{R}_b = \frac{\cos(\varphi-\beta)\cos(\delta)\sin(\omega' s) + \frac{\pi}{180}\omega' s\sin(\varphi-\beta)\sin(\delta)}{\cos(\varphi)\cos(\delta)\sin(\omega s) + \frac{\pi}{180}\omega s\sin(\varphi)\sin(\delta)}$$

where φ is the latitude of the site, δ is the declination of the earth on a certain day.

Design Procedure

This model calculates and optimizes monthly average daily solar insolation $\overline{H_T}$ and the annual solar energy received by the PV system on the field house roof for any plane with a tilt angle from 0 to 90 degrees. In the excel, columns are designated for the variables mentioned above and rows are designated for the 12 months. Monthly data are calculated for each of the variables by relating which using the equations listed above.

Some assumptions are made for this model:

1. $\overline{H_T}$ is the insolation of the most representative day of the month, and is assumed to be that of the midday of a month (the 15th).
2. The monthly average solar insolation on a horizontal surface, $\bar{H}$ (kWh/m^2*day), is obtained from the NASA Atmospheric Science Data Center[2], for Northampton (latitude = 42.3 deg, longitude= -72.6 deg), based on which $\bar{H}_d$ (kWh/m^2*day) is calculated.
3. The surface reflectivity ρ_g depends on ground conditions in Northampton which is assumed as: from November to April the ground is covered by snow (0.75), from May to August is green grass (0.26), September is dry grass (0.2) and October is dead leaves (0.3).

Results and Discussion

Performing an optimization using the Solver module in excel to maximize the annual solar energy production

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1 Etta's spreadsheet, 2009

2 It is an average of 22 years' monthly daily insolation, from 1983-2005.

at the field house, by altering the variable tilt angle β within the constraint $0° \leq \beta \leq 90°$, yields a maximum annual solar production =1570.966791 kWh/m^2*month at an optimal tilt angle of $\beta = 41.43032396°$. Corresponding monthly average daily solar insolation and total annual solar energy are listed below:

Table 1. Ideal $\overline{H_T}$ and maximum annual solar energy collected at Optimal β at Field House

Month	$\overline{H_T}$ (kWh/m^2*day)	Tilt Angle β =
January	3.350021437	41.43032396 °
February	4.345347741	
March	4.697309677	Annual Solar Production =
April	4.766856629	1570.966791 kWh/m^2*yr
May	4.761721426	
June	4.960265786	
July	5.087690991	
August	4.914465915	
September	4.60334629	
October	4.057430634	
November	3.188133155	
December	2.929392112	

To visualize the change of monthly average daily insolation with the change of tilt angle, three angles, the angle of the site roof, horizontal and optimal tilt, are selected and their corresponding solar insolation are calculated using the model and graphed below. Estimated by eye, the rooftop of the field house is at an angle of approximately 40°. Roof angle is very close to the optimal angle (41.4°), therefore their insolation curves almost overlap (yellow and black). The horizontal insolation curve, compared with a much bigger tilt angle (both the roof and the optimal angle), is considerably steeper, starting at a lower value in the winter and rising quickly to a higher value in the summer. This is explained by the fact that the sun is less normal to a horizontal plane in the winter and more normal to it in the summer comparing with a tilted plane.

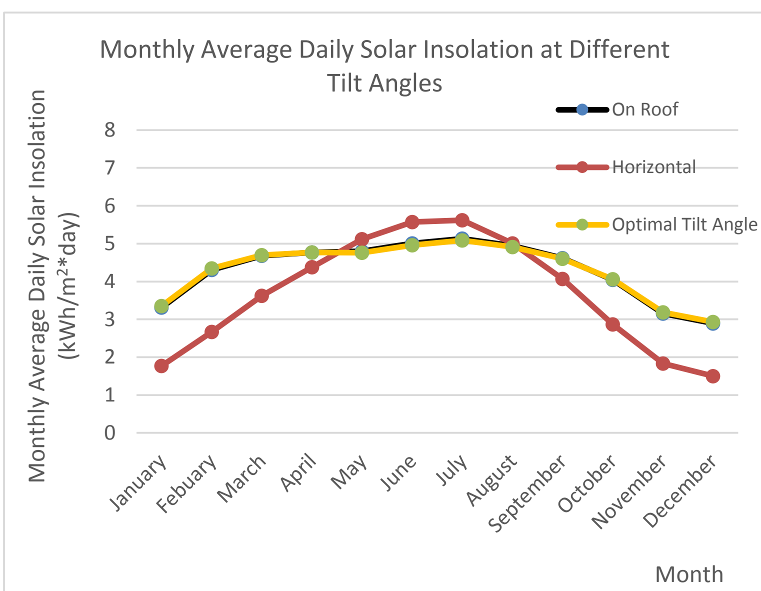


Figure 1. Comparisons between Monthly Average Daily Solar Insolation at Different Angles

However, in reality, it is unlikely to achieve the entire amount of the calculated annual energy production, due to system efficiency limits. To get a more realistic prediction, the three sets of insolation data from the above comparison is multiplied with a 18% efficiency rate and with the area of the south side of the roof of the field house, to get the actual monthly average daily and annual total energy production (listed below). The area is estimated by walking stride length (1m/stride) and trigonometry, to be approximately 40m*10m = 400 m^2. At the bottom row, a rate of $0.2/kWh is multiplied with the annual energy production to get corresponding profits.

Table 2. Actual Monthly Average Daily and Annual Energy Production at Different Angles

Month	Roof Tilt (kWh/day)	Horizontal (kWh/day)	Optimal Tilt (kWh/day)
January	7391.297736	3950.64	7477.247738
February	8684.991176	5382.72	8760.22095
March	10445.84424	8079.84	10484.39515
April	10303.73724	9460.8	10296.41033
May	10708.10935	11427.84	10628.16233
June	10808.62635	12031.2	10714.17422
July	11450.98279	12543.84	11355.72642
August	11035.57994	11182.32	10969.08801
September	9965.075098	8791.2	9943.228018
October	9018.11157	6405.84	9056.185127
November	6816.815202	3952.8	6886.367524
December	6459.355766	3348	6538.403091
Annual (kWh/yr)	113088.5265	96557.04	113109.6089
Profit ($/yr)	22617.70529	19311.408	22621.92178

<u>Conclusion</u>

In summary, a model predicting annual solar energy production of PV system of the smith college field house is established to facilitate the sizing of the plane of array. Calculations of ideal and realistic situations are conducted and presented. For the next step, shading factors should be examined and included in the model. Geothermal borehole sizing and modeling should also be conducted.

Appendix B: Specification for the PV Module

RNG-100D

100W Monocrystalline Solar Panel

Electrical Data

Maximum Power at STC*	100 W
Optimum Operating Voltage (V_{mp})	18.9 V
Optimum Operating Current (I_{mp})	5.29 A
Open Circuit Voltage (V_{oc})	22.5 V
Short Circuit Voltage (I_{sc})	5.75 A
Module Efficiency	15.47%
Maximum System Voltage	600 VDC UL
Maximum Series Fuse Rating	15 A

Mechanical Data

Solar Cell Type	Monocrystalline (4.92 x 4.92 in)
Number of Cells	36 (4 x 9)
Dimensions	47.3 x 21.3 x 1.4in (1202 x 541 x 35mm)
Weight	16.5 lbs (7.5 kg)
Front Glass	Tempered Glass 0.13 in (3.2 mm)
Frame	Anodized Aluminium Alloy
Connectors	MC4 Connectors
Fire Rating	Class C

Thermal Characteristics

Operating Module Temperature	-40°C to +80°C
Nominal Operating Cell Temerature (NOCT)	47±2°C
Temperature Coefficient of Pmax	-0.44%/°C
Temperature Coefficient of Voc	-0.30%/°C
Temperature Coefficient of Isc	0.04%/°C

MC4 Connectors

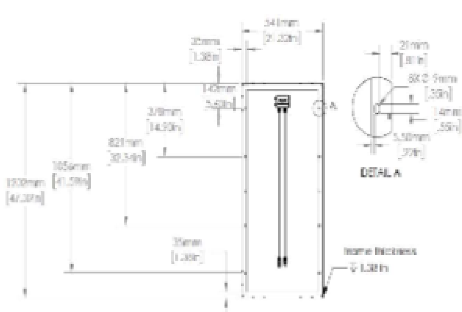
Rated Current	30A
Maximum Voltage	1000VDC
Maximum AWG Size Range	10 AWG
Temperature Range	-40°F to 194°F
IP Rating	IP 67

Junction Box

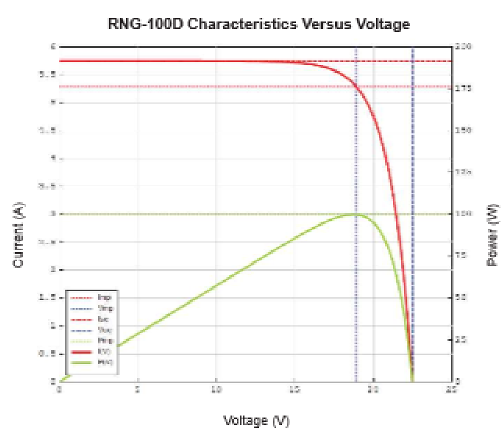
IP Rating	IP 65
Diode Type	HY 10SQ050
Number of Diodes	2 Diode(s)
Output Cables	12 AWG (2.10 ft long)

Certifications

Module Diagram



IV-Curve



*All specifications and data described in this data sheet are tested under Standard Test Conditions (STC - Irradiance: 1000W/m² , Temperature: 25°C, Air Mass: 1.5) and may deviate marginally from actual values. Renogy and any of its affiliates has reserved the right to make any modifications to the information on this data sheet without notice. It is our goal to supply our customers with the most recent information regarding our products. These data sheets can be found in the downloads section of our website, www.renogy.com

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Appendix D: Specification for Inverter

A Specifications

Appendix A contains specifications for the Xantrex Grid Tie Solar Inverter.

The topics in this appendix are organized as follows:

Electrical Specifications

GT5.0

Input

	GT5.0-NA-240/208 UL-05	GT5.0-NA-240/208-POS UL-05
Model number	864-1009-02	864-1011-02
Input voltage, Maximum Power Point range	Certified operating range: 240–550 VDC. (Unit is operable as low as 235 VDC.)	
Absolute maximum array open circuit voltage	600 VDC	
Maximum input current	22.0 ADC (240 V), 20.0 ADC (208 V)	
Maximum array short circuit current	24 ADC	
Reverse polarity protection	Short circuit diode	
Ground fault protection	GF detection, $I_{DIF} > 1$ A	

Output

Nominal output voltage	**240 V**	**208 V**
Maximum output power	5000 W	4500 W
Operating range, utility voltage (phase to phase)*	212–263 VAC	184–228 VAC
Operating range, utility voltage (phase to neutral)*	106.1–131.5 VAC	
Nominal output frequency	60 Hz	
Operating range, utility frequency*	59.3–60.5 Hz	
Startup current	0 Aac	
Maximum continuous output current	21 A	22 A
Maximum output fault current	30 A	
Maximum output overcurrent protection	30 A RMS	
Maximum utility backfeed current	0 A	
Total Harmonic Distortion	<3%	
Power factor	>0.99% (at rated power), >0.95% (full power range)	
Utility monitoring	AC voltage, AC frequency, and anti-islanding protection	
Output characteristics	Current source	
Output current waveform	Sine wave	

*Factory settings can be adjusted with the approval of the utility. This unit is provided with adjustable trip limits and may be aggregated above 30 kW on a single Point of Common Coupling. See "Adjustable Voltage, Frequency, and Reconnection Settings" on page A–12.

Efficiency

	240 V	**208 V**
Maximum peak efficiency	95.9%	95.5%
CEC efficiency	95.5%	95.0%
Night-time tare loss	1 W	

Appendix E: Life Cycle Cost Analysis

Table 1. Life Cycle Cost for a 30-Year System with PV Modules and One Inverter.

Item	Single Present Worth Year	Uniform Present Worth Year	Cost	Present Worth Factor	Present Worth Amount
Initial Costs					
Solar PV Equipment	0		$9,240.00	1	$9,240.00
Installation Cost	0		$17,580.00	1	$17,580.00
Inverter	0		$3,850.41	1	$3,850.41
Wires	0		$150.48	1	$150.48
Total Initial Cost					$30,820.89
Annual Costs					
Annual Maintenance		30	$1,000.00	13.76483115	$13,764.83
Repair & Replacement					
Inverter Replacement	20		$3,850.41	0.311804727	$1,200.58
Salvage Value					
Salvage is 20% of Initial Equipment Cost	30		-$1,848.00	0.174110131	-$321.76
Total Life Cycle Cost					$45,464.54

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