1-1-2010

Energy Model Development and Heating Energy Investigation of the Nested Thermal Envelope Design (NTED (tm))

Erin Elizabeth DIxon
Ryerson University

ENERGY MODEL DEVELOPMENT AND HEATING ENERGY INVESTIGATION OF THE NESTED THERMAL ENVELOPE DESIGN (NTED™)

by

Erin Elizabeth Dixon, B.Sc. Mechanical Engineering, Queen's University, 1998

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in the Program of

Building Science

Toronto, Ontario, Canada 2010

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

ABSTRACT

Energy Model Development and Heating Energy Investigation of the Nested Thermal Envelope Design (NTED™)
M.A.Sc. 2010
Erin Elizabeth Dixon, Building Science, Ryerson University

Space heating accounts for approximately 60% of residential energy use in Canada. Minimizing envelope heat losses is one approach to reducing this percentage. Preliminary research investigated the energy-saving potential of an innovative design, referred to as Nested Thermal Envelope Design (NTED™). The concept involves one insulated building inside another with dual thermal zones. Conservative modeling results from this work showed heating energy reductions of 74%.

This research developed a new NTED™ simulation model to provide increased accuracy and gain a more complete understanding of the potential heating energy savings. The working performance was also investigated by modeling occupied-building operation. The resulting model has shown that the NTED™ design yields savings of 85% relative to a benchmark R-2000 building. These results improve on the preliminary values and reinforce the merit of the design as a means of achieving significant reductions in residential energy use.

ACKNOWLEDGEMENTS

Thank you to Dr. Russell Richman at Ryerson University for his dynamic introduction to the field of Building Science. Dr. Richman's continued encouragement and interest in the diversity of the discipline allowed this work to tell a compelling story.

Dr. Kim Pressnail at the University of Toronto was also a great support and source of knowledge – his enthusiasm for Building Science is contagious and much appreciated, especially during challenging research moments.

In addition, the author gratefully acknowledges the contribution of Richard Raustad, Senior Research Engineer with the Florida Solar Energy Center during EnergyPlus module modification and for model consultation.

DEDICATION

For Gord, whose support made this work possible, and Kate who I hope will only know low-energy buildings.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1.0 INTRODUCTION

A significant amount of research and development in the areas of renewable energy technology and energy efficiency occurred in North America in the 1970s as a result of the 1973 oil crisis. In fact the origins of much of the solar-based energy technology used today can be traced back to this time period. Unfortunately, given our current situation, the end of the oil crisis and a shift in focus in the 1980s put much of this renewable energy research on hold.

Today we realize a critical need to reduce and eventually eliminate our reliance on non-renewable energy sources not only because of dwindling fuel supplies but also to reduce greenhouse gas emissions and minimize our impact on the environment. Many current trends in sustainable building construction are harkening back to times before intensive energy use where concepts such as site orientation, cross ventilation, solar shading and landscaping played key roles in achieving home comfort. As an example, speaking of a century-old Ontario farmhouse, architect John Hix (1988) states that “life in this house was an experience of seasonal rhythm”.

Enter NTED™ (Nested Thermal Envelope Design), a modern design that will allow occupants to experience the benefits of seasonal rhythm through improved thermal comfort and drastic reductions in energy use. This proposed construction method incorporates many of the early passive design principles and improves upon a novel design developed in the 1970s known as the ‘thermal envelope house’.

NTED™ (Figure 1) employs one insulated building inside another to control heat, air and moisture transfer while allowing varied heating, ventilation and air conditioning (HVAC) settings within the space. The interior, or core, area serves as the main living space that is operated at the desired living conditions year-round. The perimeter area, typically operated for 3-season occupation, also acts as a thermal buffer and heat recovery zone, helping to mitigate losses from the core. Preliminary modeling with an NTED™ house located in Toronto, Canada have shown that reductions in heating energy of up to 74% are possible (Pressnail, et al., 2008).

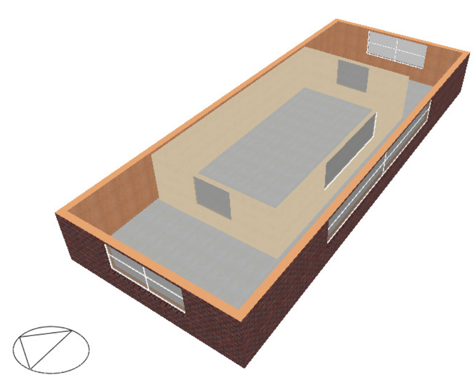


Figure 1: Schematic of NTED™ design showing core and perimeter areas.

1.1 OBJECTIVES

This research is intended to address the following objectives.

(i) A new NTED™ energy simulation model will be developed to provide increased accuracy of the results, and allowing a more complete understanding of the heating energy savings potential of the design.

(ii) The heating energy use of an NTED™ building in energy-savings mode will be compared to that of an NTED™ building operating according to the R-2000 benchmark. This will be done for a variety building geometries and insulation levels to determine how each configuration affects the heating energy use.

(iii) The working performance of the NTED™ design will be evaluated by modeling occupied-building operation.

(iv) The effects of passive, energy-saving devices will be investigated by modeling the use of insulated shutters on the core windows.

1.2 THESIS ORGANIZATION

This document is divided into nine main sections, and a summary is provided here.

Section 1.0 The research topic is introduced, including a brief summary of the building design and a statement of the research objectives.

Section 2.0 A summary of the approaches to create low-energy houses in cold climates is provided. This is useful to understand how NTED™ compares to existing design concepts and construction techniques.

Section 3.0 The NTED™ design is described in detail including a description of the operating principles, construction methods and HVAC system.

Section 4.0 The preliminary modeling work, performed to obtain an initial estimate of the heating energy savings potential of the NTED™ design, is summarized.

Section 5.0 A detailed description of the considerations taken into account and the methods used to create the advanced energy model is provided.

Section 6.0 The building setup process for the advanced energy model is described. In addition, the simulation parameters that were varied to determine how heating energy use is affected by the building configuration and occupant behaviour are outlined.

Section 7.0 The simulation results are presented and discussed.

Section 8.0 The items to be addressed in future research are outlined including the model limitations and areas for improvement for the current work, as well as items that will advance the overall research agenda.

Section 9.0 The conclusions drawn as a result of this research work are summarized.

2.0 REVIEW OF CONSTRUCTION TECHNIQUES FOR LOW-ENERGY HOUSES

An important preliminary element of this research phase was to gain an understanding of the current practice and existing state of research on construction techniques for low-energy houses in cold climates. In general, these practices involve increased insulation and better control of air and moisture movement through careful implementation of air barrier systems and vapour diffusion retarders. The decreased air exchange caused by reduced infiltration due to 'tighter construction', is typically addressed by standards that outline the requirement for mechanical ventilation.

The following describes the benchmark low-energy residential construction program used in Ontario, and hence for this study. In addition, alternative construction standards and techniques are reviewed, some of which relate to the evolution of the NTED™ design.

2.1 R-2000 PROGRAM

R-2000 is a pass/fail residential home construction program developed by Natural Resources Canada's (NRCan) Office of Energy Efficiency in partnership with the residential construction industry. Launched in 1982, the main goal of the R-2000 program was to set benchmarks for Canadian home building in the areas of energy efficiency, comfort (interior air quality) and environmental impact. Participation is voluntary, and to receive certification homes must meet specifications and performance standards as well as have been constructed by licensed homebuilders who have received R-2000 training. According to NRCan (2009), the R-2000 standard is approximately 40% more rigorous than Canadian building codes and results in homes that use 30% less energy than their conventionally-built counterparts. As of 2009, approximately 10,000 homes have been certified to R-2000 standards since the program began.

Table 1 shows details from the current R-2000 specification (NRCan, 2005). Sources for each component guideline are listed, as some are outlined in the R-2000 documentation while others refer to external standards. For example, insulation levels must meet or exceed provincial building code specifications and values are listed for Toronto, Ontario.

Table 1: R-2000 assembly specification.

Component	Standard	Specification
insulation: ceiling (attic / roof)	OBC, 2006	RSI 7.00
insulation: wall	OBC, 2006	RSI 3.34
insulation: foundation wall	OBC, 2006	RSI 2.11
insulation: slab-on-grade	OBC, 2006	RSI 1.41
windows: operable or fixed with sash	R-2000	ER: -13
windows: fixed without sash	R-2000	ER: -3
airtightness	R-2000	1.5 ACH @ 50 Pa / NLA_{10} 0.7 cm^2/m^2
ventilation	CSA F326	
energy use target	HOT2000	
heating & cooling appliances	CAN/CSA F280	

2.2 FACTOR 5 HOUSE / FACTOR 9 HOUSE

Lstiburek (2008) summarizes Canadian efforts to build advanced low-energy homes, which have been ongoing in Canada since the oil crisis of the 1970s. Dumont, who figures prominently in these efforts, designed and built a very low-energy home in Saskatoon, Canada in the early 1990s. Results showed that the incremental cost of building the home that reduced energy use by a factor of 5 compared to a home built to the building code was less than $15,000 CAD. Very thick walls and increased airtightness, among other measures, were used to achieve this result (Dumont, 2000).

In 2007 Dumont extended his efforts to construct a Factor 9 Home in Regina, Canada. This home is intended to use 9 times less energy on a per unit area basis as compared to a typical home (CMHC, 2007). 'Factor 9' was derived from a multiplication of an expected increase in world population of 1.5, a projected worldwide material consumption increase of 3 and a necessary reduction of current greenhouse gas emissions by a factor of 2 to yield: 1.5 x 3 x 2 = 9. The energy use and indoor air quality of the home are to be monitored for a period of one year post-occupancy and will be reported in future publications.

2.3 ENERGUIDE

The EnerGuide program intends that new homes be constructed using techniques that will result in approximately 30% less energy use than those built to standard building codes. Homes are rated on a scale of 0-100 and must achieve a score above 80 to be labeled an EnerGuide-qualified home (NRCan, 2010).

2.4 2030 CHALLENGE

The Royal Architectural Institute of Canada (RAIC) has endorsed The 2030 Challenge. The program is built around a series of targets for new and renovated buildings to reduce fossil fuel use and greenhouse gas emissions by 60% in 2010 up to 100% by 2030 (RAIC, 2009).

2.5 PASSIVE HOUSE

Wolfgang Feist was a major contributor to development of the Passive House concept in Germany in the 1980s and 1990s. The requirements to meet certification are straightforward, although they require rigorous construction and assembly details. The goal is to achieve a highly insulated building that does not require a conventional heating system (PHPP, 2007). The main requirements for Passive House certification are:

1. annual space-heating demand of no more than 15 kWh/m^2;
2. annual total primary energy use of 120 kWh/m^2;
3. airtightness value of 0.6 ACH at a 50 Pa pressure difference.

Preliminary analysis for a 5-unit town house located in Toronto, Canada shows insulation values of RSI 12.3 (R70) for the walls, RSI 17.6 (R100) for the roof and RSI 5.3 (R30) for the slab are required to achieve the Passive House standard.

2.6 NREL/HABITAT ZEH

As part of the U.S. Department of Energy's Building America Program (USDOE, 2010), a 119 m^2 (1280 ft^2), 3-bedroom home (Figure 2) was built in Denver, Colorado to investigate the feasibility of building affordable zero-energy homes for cold climates. The home was built by Habitat for Humanity of Metro Denver in collaboration with the National Renewable Energy Laboratory (NREL) (Christensen & Norton, 2006). Typically known as 'net zero energy' in Canada, a 'zero energy' home is intended to produce as much energy as it consumes over the course of a year. In many cases, as with this home, the power grid is used for energy storage by delivering excess electricity to the grid and drawing energy from the grid when in-house energy sources are unable to meet demands. The house is referred to as the NREL/Habitat ZEH.

Figure 2: Denver NREL/Habitat ZEH (Source: Christensen & Norton, 2006).

The selected envelope design was based on the Habitat for Humanity goal of straightforward and repeatable construction methods with low to moderate material costs and moderate to high labour costs (ibid.). Walls are a nominal RSI 7.0 (R40) with an outer structural 0.038 m x 0.089 m (2 in x 4 in) stud wall on 0.400 m (16 in) centres with RSI 2.3 (R13) fibreglass batt in the cavities. A second 0.038 m x 0.089 m (2 in x 4 in) stud wall was built leaving a 0.089 m (3.5 in) cavity between the walls to accommodate horizontal RSI 2.3 (R13) fibreglass batt. The interior stud wall is also insulated with RSI 2.3 (R13) batt between studs, which are spaced at 0.600 m (24 in) on centre. Figure 3 shows the wall construction.

Figure 3: Double stud wall construction (Source: Christensen & Norton, 2006).

The ceiling is insulated with 0.600 m (24 in) of blown-in fiberglass insulation under raised-heel trusses (Figure 4) to provide an RSI 10.6 (R60) insulating value, and the floor is insulated to nominal RSI 5.3 (R30). The house design incorporates the largest glazing area on the south elevation with reduced glazing on the remaining elevations. Space heating is accomplished via a point-source direct vent natural gas furnace in the main living space and electric baseboard heaters in the bedrooms.

Figure 4: Raised heel trusses to accommodate additional insulation (Source: Christensen & Norton, 2006).

The energy production and consumption of the NREL/Habitat ZEH was monitored post-occupancy from April 2006 – March 2007 and the totals can be seen in Table 2 (Christensen & Norton, 2007). For comparison, the home location in Colorado has 3327 HDD (18^{o}C base) compared to 4000 HDD for Toronto, Ontario (Straube & Burnett, 2005).

Table 2: Annual energy use for NREL/Habitat ZEH.

Energy Type	Total [kWh]
electricity consumption	3585
natural gas consumption	1665
PV electricity production	5127

The results of the study showed that the home produced 24% more energy than was used on a source-energy basis over the 1-year monitoring period. One of the key conclusions of the performance study is (ibid):

> *This case study demonstrates that it is possible to build efficient affordable zero energy homes in cold climates with standard building techniques and materials, simple mechanical systems, and off-the-shelf equipment.*

2.7 THERMAL ENVELOPE HOUSE

Origins of the thermal envelope house (also known as the double envelope, double shell or continuous thermal envelope) can be traced to the United States in the 1970s. Lee Porter Butler and Tom Smith constructed one of the first examples in Lake Tahoe, California in 1977 (OTA, 1981). The University of Nebraska Passive Solar Energy Test Facility built a double shell test room for monitoring in 1979 (Chen, 1982) and according to published studies, various other examples were constructed and monitored around the same time.

Although there appears to be a consensus that these houses are examples of energy-efficient design, there remains a debate as to whether this is due to the operating principles or the double envelope construction.

2.7.1 Design and Construction

Similar to NTED™, these dwellings are described as a 'house within a house'. In the case of a thermal envelope house, the space between the interior and exterior shells forms a thermal buffer and solar collector on the north and south walls, respectively (Figure 5).

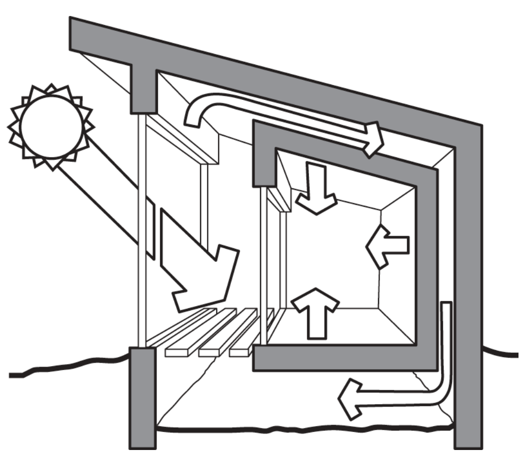


Figure 5: Thermal envelope house construction (Source: Chen, 1983).

Specific construction details include a more-heavily-insulated exterior envelope (typically 0.038 m x 0.15 m (2 in x 6 in) stud walls) and a lesser-insulated interior envelope (0.038 m x 0.089 m (2 in x 4 in) stud walls). The solar collector area is a sunspace along the south exterior envelope. The northern thermal buffer is formed by minimizing windows and providing a cavity (approximately 0.305 m (12 in)) between the inner and outer envelopes. The east and west walls are single shell at the higher insulation values and a lesser number of windows. Of particular note is the fact that the cavity is continuous as the south and north zones are joined through both the attic and basement/crawlspace areas. Continuous air barrier/vapour diffusion retarder membranes are included in both the interior and exterior envelopes to minimize air and moisture transfer between the living space and the air cavity as well as from the air cavity to the exterior.

2.7.2 Operating Principles

The operating principles of a thermal envelope house are based on the generation of a convective air loop around the continuous air cavity (Figure 6). This airflow is intended to reduce heat loss and help maintain a comfortable environment through increased radiant temperatures of interior walls (Chown, 1982).

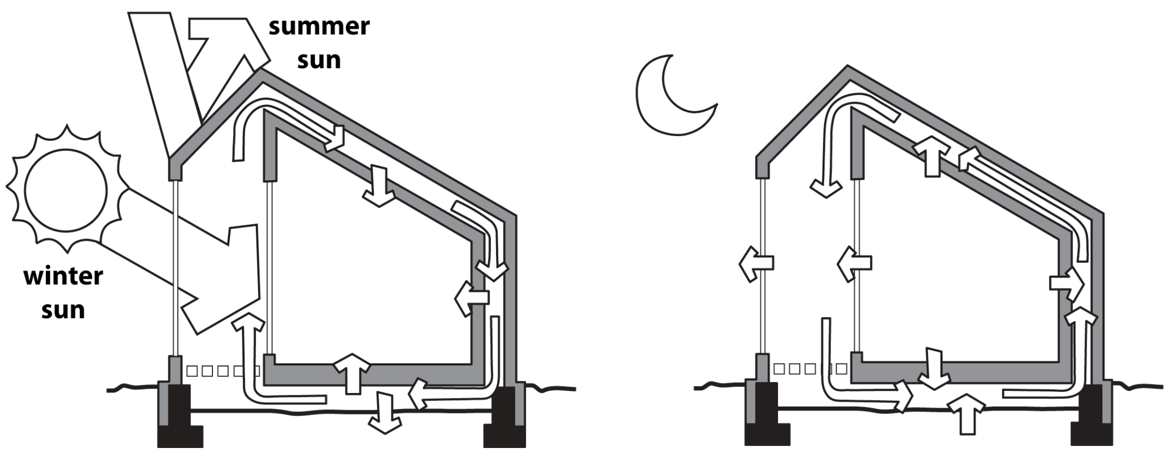


Figure 6: Day and night operation of the thermal envelope house (Source: Chen, 1982).

The theory is that on days when heating is required, sunlight enters the sunspace and warms the air, causing it to rise through the attic. As the heat transfers to the living space and the house exterior, it cools and falls down the north cavity to the basement. At this point, any remaining heat is transferred to the ground and the cooled air is drawn back into the sunspace through openings in the floorboards.

At night, heat loss through the south glazing is intended to reverse the convective loop. Cool air then enters the basement from the sunspace, gains heat from the ground and rises through the north cavity, again transferring heat to the living space and the exterior.

Finally, when cooling is desired, vents at the top of the attic space are intended to allow heated air to escape while cooler replacement air is drawn in through basement vent pipes.

2.7.3 Criticisms, Problems and Recommended Solutions

The previously mentioned, debate as to the explanation for improved efficiencies demonstrated by thermal envelope houses relates to whether it is due mainly to the increased insulation and thermal buffer effects or as a result of the passive solar and convective heat transfer. This distinction is relevant as it could help determine whether a simplified and more economical construction technique could result in comparable thermal performance.

The following is a brief summary of the main criticisms for double envelope houses (Chown, 1982).

1. Because heat transfer to the interior and exterior of the cavity depends on the temperature difference and R-value of the envelopes, low outside temperatures will result in greater heat losses to the exterior.
2. The temperature differences between north and south air spaces may not be sufficient to generate a full convective loop, resulting in localized currents (Figure 7).
3. The warmest air entering the basement area will pass highest in the space, thus minimizing transfer to floor and reducing the thermal storage effect.
4. The single-shell end walls may reduce the radiant temperature and therefore thermal comfort.
5. The material quantities and design complexity can result in increased construction costs.

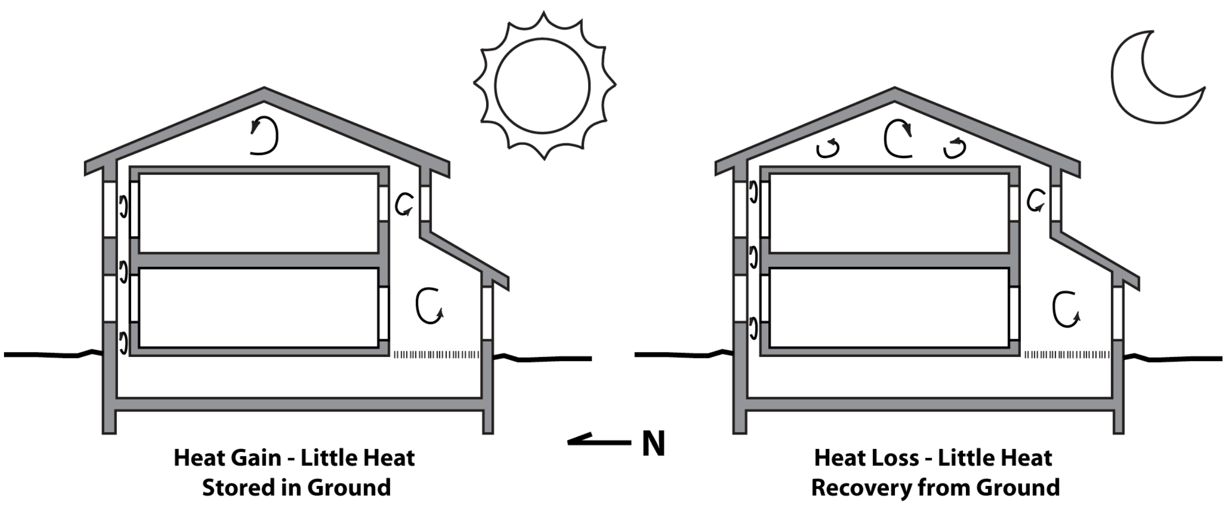


Figure 7: Localized convective loops causing ineffective ground storage and heat recovery (Source: Chown, 1982).

A series of case studies was reviewed to gain an understanding of some of the issues encountered with thermal envelope house design. Table 3 provides a summary of these issues as well as recommended solutions to improve the design.

Table 3: Summary of problems and solutions for thermal envelope case study houses.

Problem	Recommended Solution	Reference
Moisture transfer from crawlspace.	Add vapour diffusion retarder, finish floor.	Chown, 1982
Condensation on sunspace windows.	Add drip pans or dehumidification.	Chen, 1982
Difficulty cooling (upper floor overheating).	Localized air conditioning.	Chen, 1982, 1983
Excessive SHG from angled south windows.	Vertical glazing only.	Chen, 1982, 1983
Insufficient convective loop.	Install fans to drive air movement.	Chown, 1982
Rooms not joined to sunspace can be cold.	Localized heating (i.e. electric baseboard).	Chen, 1982
Risk of fire spread through north cavity.	Drywall cavity, install automatic dampers.	Chown, 1982

2.7.4 Current Status

It appears that somewhere in the neighbourhood of hundreds (perhaps even low thousands) of thermal envelope houses have been built, mainly in the United States, over the past 30 years. While a reasonable list of relevant literature titles has been reviewed, virtually all were published between the late 1970s and early 1980s. The lack of design uptake and apparent cessation of research on thermal envelope houses after the 1980s provides some cause for concern. Specifically, was the lack of continued research due to poor operating performance, or are other factors at play? A talk by Denis Hayes (Green Energy Act Alliance, 2009), Director of the US Solar Energy Research Institute from 1979-1981 (now the US National Renewable Energy Laboratory) revealed a possible contributing factor to the halted research. With Ronald Reagan's election in 1981 came drastic cuts to the budget and staffing of the Solar Energy Research Institute and other programs with an environmental focus. In other words, the lack of support for technologies designed to increase building energy efficiency, rather than proven poor performance, likely contributed to the reduced focus on thermal envelope houses.

2.8 ALPHA HOUSE

In Canada, the first thermal envelope house was built in 1979. Alpha House (Figure 8), as it is known, is located in New Tecumseth, Ontario and was built by architect John Hix (Lane-Moore, 2007).

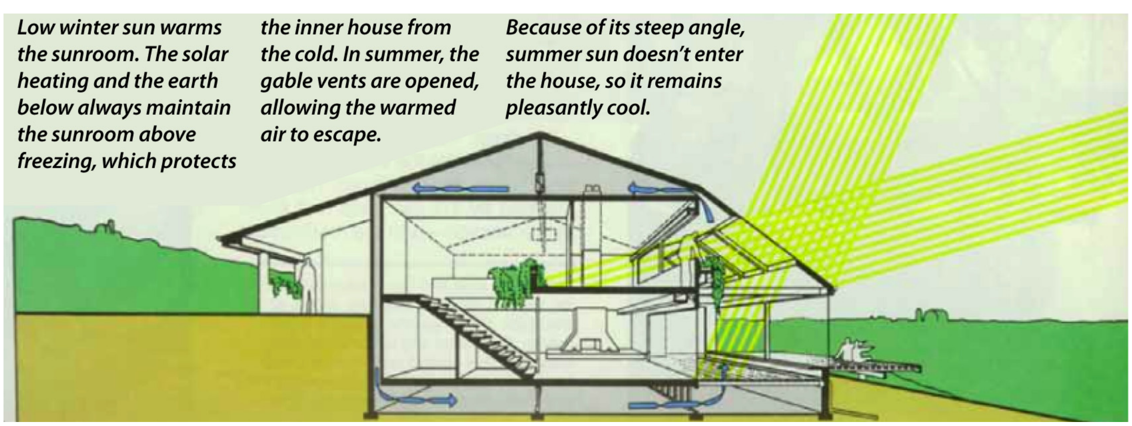


Figure 8: Layout and operation of the Alpha House by John Hix (Source: Hix, 1983).

2.8.1 Design Inspiration

According to Hix (1988):

> *Alpha House… responds to its Ontario climate by combining the lessons of local vernacular buildings with those of traditional Bavarian farmhouses to create a contemporary, regionally and climatically responsive architecture.*

Functional inspiration for Alpha House is taken from Bavarian farmhouses where Hix uses the concept of building into a hill on the north side and exposing the south to the sun. Also, from the local Ontario vernacular, he buffers the remaining northern exposure by unheated utility areas that parallel traditional farmhouse summer kitchens. The aesthetic inspiration is provided by the local 19^{th} century agricultural barns and is reflected by a simple exterior form.

Hix (ibid) speaks of the traditional Ontario farmhouse form as a compact cube shape surrounded by large porch overhangs and an unheated wood and food storage shed addition located on the north side. He describes the farmhouse seasonal operation as follows:

Winter:

1. The wood/food storage shed shelters the house from the cold winter winds.
2. The cooking stove is centrally located and surrounded by eating and living areas.
3. The stove was lit throughout the winter, with a radiant flue and dampers to heat the second floor.
4. Parlour and formal dining room areas were heated only on Sundays and holidays.

Summer:

1. The kitchen stove was moved to the shed to keep the cooking heat out of the house.
2. Screened windows and doors were opened to cool the house with cross ventilation.

In summary, Hix states:

> *Summer, markedly different from winter, life in this house was an experience of seasonal rhythm.*

2.8.2 Alpha House Features

Alpha House employs many of the previously outlined design principles of a typical thermal envelope house, as well as some of the suggested features for improvement, as listed in Table 4.

Table 4: Alpha House standard thermal envelope features.

Standard Features	Reference
Fan-assisted convective loop (when sunroom temperature is higher than crawlspace).	Hix 1988
Exterior-insulated concrete block crawlspace with earthen floor.	Hix 1983
Minimized east and west windows.	Hix 1983
Vents to release summer heat at attic gable ends.	Hix 1983, 1988

Alpha House also exhibits some non-standard design features (Table 5) that could result in improved the energy efficiency over the typical design.

Table 5: Alpha House non-standard thermal envelope features.

Non-Standard Features	Reference
North-facing lower floor is buried in a hillside.	Hix 1983, 1988
North-facing upper floor houses unconditioned utility area outside the double envelope.	Hix 1988
North-facing entry space has interior and exterior doors to minimize air transfer.	Hix 1983
Insulated shutters on east and west windows (not clear whether interior or exterior).	Hix 1983
Insulated electric roller blinds separates the sunroom from the lower level living space.	Hix 1983
Sunspace proportions prevent summer sun from entering the interior space.	Hix 1988

2.8.3 Questions and Areas for Further Investigation

While the Alpha House documentation provides a preliminary understanding of the design details, an investigation of the topics outlined to follow would be beneficial to address the operating performance. Because this house was built in 1979 and has been lived in since then, an account of any problems or maintenance throughout its life could provide useful insight.

The existence of earth floor crawlspace areas was presented as a performance issue in some of the thermal envelope case studies (Chen, 1983) due to moisture migration in the convective air loop as well as the potential for animal and insect penetration into the wall cavities and living space (Chown, 1982). Has this been the case for Alpha House?

The documentation refers to ‘well insulated’ and ‘heavily insulated’ construction (Hix, 1988) with no specific details on thermal resistance values. In addition, the existence and placement of vapour diffusion retarder and air barrier systems is not addressed.

In the summer when the dampers are opened to allow heated sunroom air to escape, no mention is made of how this air is replaced. Several potential scenarios can be hypothesized including infiltration, crawlspace openings or lower-level windows, each of which would have a different effect on the intended airflow.

The insulated shutters would seem to be advantageous in reducing winter energy losses. It would be interesting to investigate the use of these devices on the exterior sunroom glazing as well. Because the stored heat from the crawlspace thermal mass is intended to form a blanket of warm air around the interior envelope, it would seem that reducing the direct heat loss through the sunroom glazing could help provide an improved distribution of the crawlspace air. Although this may affect the natural convective loop formation (as outlined under the thermal envelope house operating principles), Alpha House does have auxiliary fans that could also be activated at night.

Several of the reviewed articles (Hix, 1983; Lane-Moore, 2007) provide heating season energy costs with no explanation or further details. Because the Alpha House supplementary heating system includes a propane furnace and a fireplace, there is the potential that site-sourced wood fuel is not accounted for in the quoted costs.

2.9 ENERTIA® HOUSE

Michael Sykes, an engineer from North Carolina, developed a house design he has labeled 'Enertia®'. According to an article on the company website (Barkley, 1999), development work began in the 1980s with early construction in the 1990s. Approximately 80 homes have been constructed in 22 years (Roberts, 2007). More recently, Enertia® houses have been receiving media attention as the design won the 2007 History Channel Invent Now Challenge.

2.9.1 Operating Principles

Although the Enertia® website makes no mention of the thermal envelope houses, the operating principles are similar. Enertia® homes are double-walled structures and Figure 9 shows a convective air loop in the cavity that operates based on solar heat gain and basement thermal storage. During winter, heated air is contained within the structure and in summer, windows are opened to remove warm air from the cavity.

Figure 9: Enertia® house seasonal operating principles (Source: Enertia®, 2009).

2.9.2 Construction Details

The main difference between the Enertia® design and more traditional thermal envelope houses is that these are built of solid wood with no insulation in either the interior or exterior walls (Figure 10), although the roof is constructed using structural insulated panels. According to the Enertia® website (2009), the thermal mass offered by the 0.150 m x 0.150 m (6 in x 6 in) southern yellow pine glue-laminated lumber (Figure 10) provides sufficient storage capacity to mitigate the daily temperature swings during summer and winter seasons.

Figure 10: Enertia® house construction and southern yellow pine glue-laminated lumber (Source: Enertia®, 2009).

Figure 11 shows a sample house assembly including the 0.190 m (7.5 in) wide north cavity (Barkley, 1999) and the gaskets used to create an air seal between the stacked timbers (Roberts, 2007). The Enertia® website describes the walls as 'permeable' which presumably refers to the absence of a vapour diffusion retarding membrane although no details are provided as to a recommended finish on the interior or exterior of the pine.

Plans offered by Enertia® are for large homes ranging from 186-557 m^2 (2000-6000 ft^2) and kits comprise the main structural components including the southern yellow pine timbers cut to size. Customers provide elements such as windows, doors and finish materials.

Figure 11: Enertia® house assembly showing north cavity and gasket air seal (Source: Enertia®, 2009).

2.9.3 Performance and Criticisms

Although the Enertia® company website does speak to the theory behind the home operating principles, actual performance data are not made available. Additional searching has not located performance results, and a Product Review from Environmental Building News (ibid.) says that no such data are available at this point.

Among the concerns of the published performance claims outlined in the Environmental Building News article (ibid.) are the fact that the energy savings over a traditional home (66%, in one case) do not take into account the fact that Enertia® homes typically operate at elevated summer conditions, for example 27°C and humid versus 23°C with dehumidification for air-conditioned counterparts.

In addition, claims that the home design eliminates the need for supplementary heating and cooling have been called into question. In fact, homeowners in Maryland, New Hampshire and Vermont use radiant floor heating systems, and other homes use wood-burning fireplaces for heating and small air conditioners for cooling.

Finally, of the limited testing that has been done, a blower door test performed on an Enertia® home in Durham, North Carolina revealed an ACH_{nat} of 0.3 (ibid.). For reference, the Energy Star home rating system requires an ACH_{nat} less than 0.5 for infiltration, and ventilation must be at least 0.35 ACH by mechanical or natural means (USEPA, 2001). In other words if this example case is typical of the airtightness achieved by an Enertia® home, supplementary mechanical ventilation should be provided.

2.10 THE SANTA CLAUS METHOD OF SUPPLYING SUPPLEMENTARY HEAT

William Shurcliff, an American physicist who helped develop the atomic bomb, became interested in solar energy in the 1970s as a result of the oil crisis. After his death in 2006 at the age of 97, one of his sons explained that his interest in solar energy (and other positive pursuits) was “a sort of atonement” for the horrifying result of Hiroshima and Nagasaki (Wald, 2006). Shurcliff wrote dozens of books and hundreds of articles to explain the theories and practice of solar energy use in buildings (Bernstein, 2006).

In one book, Shurcliff (1981) describes “a radically new method of supplying supplementary solar heat to super-insulated houses”. Termed the ‘Santa Claus Method’ it involves three main components:

1. a large thermal mass (the basement) maintained at 16-24°C;
2. an air conditioning unit;
3. an air-type solar collector.

The concept described by Shurcliff involves use of the basement thermal mass to store heat for use in the remainder of the house. An air conditioning unit is situated between the basement and main floor living space and acts to deliver basement heat to the primary living areas. An air-type solar collector replenishes the basement heat via a small fan, as necessary (Figure 12).

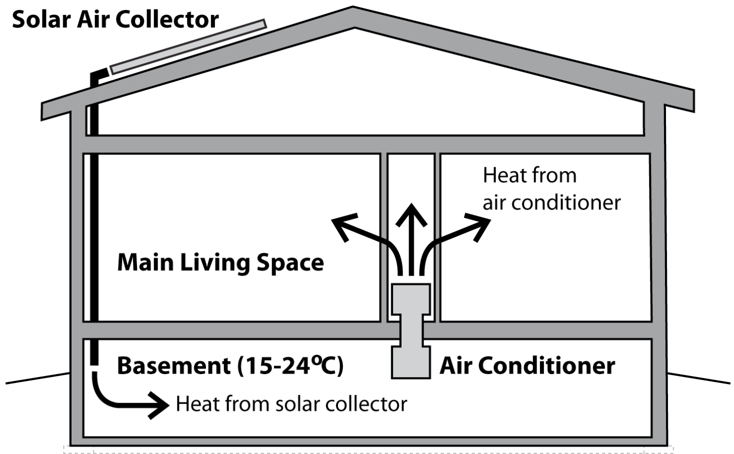


Figure 12: William Shurcliff's Santa Claus Method.

The coefficient of performance (COP) of a heat pump is a ratio of the heat output to the electrical energy input. Shurcliff describes how the COP of the air conditioner acting to deliver heat exceeds that of the unit acting to remove heat because of the additional contribution from the compressor and fans. He also points out that locating the unit completely indoors eliminates the typical heat pump performance issues that occur when outdoor temperatures drop below 0°C. At a COP of 4, the unit delivers four times more energy than is required to operate the device, and hence the output energy appears to be a gift from Santa Claus.

This description is one of the many concepts proposed by Shurcliff as a means to utilize solar energy in houses. Further searching has not resulted in any references to suggest that the concept has been taken further and implemented in a trial installation.

3.0 NTED™ DESIGN CONCEPT

NTED™ is an innovative design technique that proposes to extend the Alpha House concept by employing a double envelope on all elevations and at the ceiling interface. While Alpha House relies on a fan-driven convective loop for heat transfer between the zones, NTED™ employs a heat pump to maximize recovery of interior-zone heat losses and exterior-zone solar heat gains. An energy recovery ventilator (ERV) is also used to reduce heat loss in the mechanical ventilation system, a necessary component of the highly-sealed design.

At the time of the initial NTED™ concept development, the documentation describing the Shurcliff 'Santa Claus Method' had not yet been discovered. Although the NTED™ details are slightly different, this work may be the first investigation and application of a building that is closely related to the early concept by the well-known solar-energy advocate.

Dr. Russell Richman and Dr. Kim Pressnail initiated the NTED™ design concept at the University of Toronto in 2007. After completing his PhD studies, Dr. Richman took a faculty position at Ryerson University in 2008 and students at both institutions began working on various aspects of the project. A summary of the initial NTED™ design and principles of operation is provided to follow.

3.1 INITIAL DESIGN AND PRINCIPLES OF OPERATION

An NTED™ house consists of an insulated interior envelope defined as the 'core' area that contains the primary living spaces including the bedrooms, kitchen, bathroom and family room. Surrounding the core is an insulated exterior envelope termed the 'perimeter' area that includes secondary living spaces such as a dining room and additional bedrooms. The exterior envelope is constructed in a manner typical of residential construction with structural and finishing elements, operable windows, insulation, an air barrier and vapour retarding system. The interior envelope differs somewhat from typical partition walls in that it also contains insulation, operable windows, an air barrier and vapour retarding system.

3.1.1 Operating Principles

Throughout most of the year when temperatures are moderate, occupants inhabit the entire building using a single temperature setpoint. This operation is referred to as 'Traditional' mode. During times of extreme outdoor temperatures, occupants can choose to inhabit only the core and condition this space to a comfortable temperature. In this case, the perimeter is maintained at an intermediate setpoint between the core and exterior temperatures – referred to as the 'Gemini' operating mode. Essentially, this mode creates a thermal buffer around the core, helping to reduce heat transfer between both the core and perimeter and perimeter and exterior due to smaller thermal gradients across each envelope. In addition, heat losses are reduced in Gemini mode due to a decreased surface area of the conditioned space as well as reduced effects of gross air movement from wind, as the exterior envelope shields the interior envelope.

One of the most significant energy efficiency improvements while operating in Gemini mode is the fact that core heating energy is obtained through the use of a heat pump operating between the core and perimeter spaces, as shown in Figure 13. Due to the intermediate perimeter temperature, the heat pump evaporator can see temperatures of 5°C or greater, allowing operation at a COP of 3 or more. This heat pump recovers both core heat losses and solar heat gains admitted through the perimeter glazing as it operates to heat the core living space.

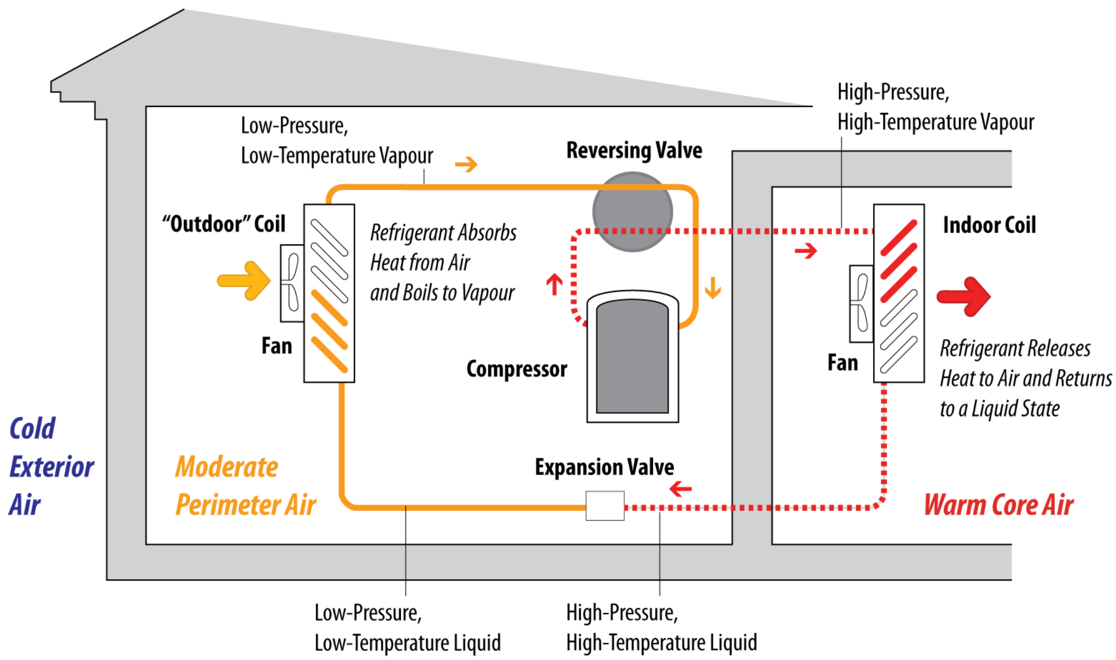


Figure 13: NTED™ core heating in Gemini mode.

The NTED™ system includes additional energy-saving devices such as an energy recovery ventilator (ERV) and insulated window shutters. The ERV is a key component of the HVAC system to ensure that the living spaces are adequately ventilated while minimizing energy cost. Insulated shutters may be installed on the core windows, which has several advantages over traditional externally-applied versions. In this case, the shutters are easily accessible and less subject to freezing, thus encouraging regular use by occupants.

A final proposed energy saving concept in the NTED™ system is the use of an underground thermal storage bed. During the summer, excess heat removed from the core by the air conditioning system can be fed to the thermal storage area. In the winter this heat would be made available to help offset the heating energy demand. Figure 14 provides a schematic of the NTED™ systems and their intended function throughout the year.

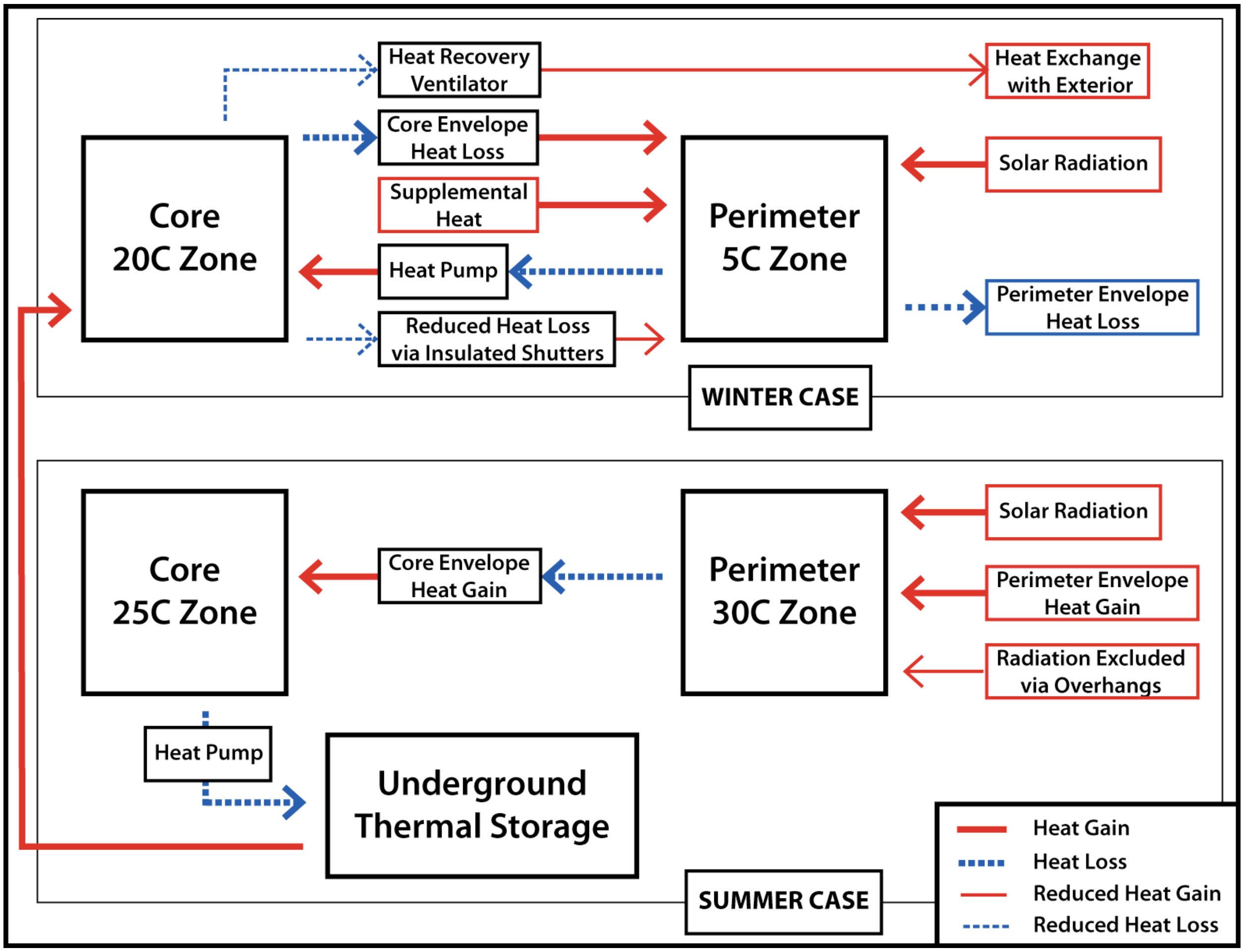


Figure 14: NTED™ seasonal heat flows.

3.1.2 Design Applicability and Potential Building Configurations

A significant advantage of the NTED™ concept is its adaptability. In fact, NTED™ can be applied to virtually all types of buildings from new to retrofit residential construction, commercial and multi-unit residential applications. Simply stated, the perimeter zone can expand or contract to accommodate the spatial constraints of most applications.

In the single-family residential application, single-storey design is straightforward with the core isolated from the perimeter via an insulated interior envelope on the north, east, south and west sides as well as at the ceiling interface. The perimeter area is adjustable and can be large enough to accommodate living spaces, reduced in size to accommodate only storage areas, or further reduced to an airspace that would allow space for service routing.

In multiple-storey applications and/or where a basement is desired, several designs are possible. The first option is to include these areas within the double envelope. A second option is to locate the additional storeys and basement only above and below the core living space. In this case, the second storey would implement double stud wall construction to minimize heat loss and the basement configuration would allow gravel-based thermal storage to be located under the perimeter area.

The examples outlined previously reinforce the flexibility of the NTED™ system and shows the potential for significant reductions in building conditioning energy use, which can occur across all building types.

3.2 DESIGN BENEFITS

Key benefits of the NTED™ design are summarized as follows.

1. Reduced temperature gradient (and therefore heat loss) across the exterior wall assembly.
2. Core heat losses can be recovered from the perimeter via a heat pump operating at a high COP.
3. The surface area for heat loss is reduced, as the core is much smaller than a typical house perimeter.
4. Heat loss from gross air movement, i.e. wind, is decreased.
5. Perimeter losses occur at 5°C rather than 20°C, therefore the same volume loss involves less energy.
6. Less heat loss occurs when residents enter and leave the building.
7. Concept is applicable to all building types including multi-unit residential, commercial and historical.
8. Flexible operating modes allow usage to be adjusted based on space needs or energy prices.

3.3 COMMON CRITICISMS

There are several considerations that must be addressed for the NTED™ concept to gain wide acceptance and these can be categorized under lifestyle, architectural and technical headings. Table 6 provides a summary of some anticipated issues related both to performance and design. Potential means to address the issues are also provided.

From a lifestyle perspective, while the proposed solution offers great potential for energy savings, it requires an adjustment to current typical living conditions. Occupants must understand that in times of extreme temperatures and/or when energy prices are high, living in a smaller area can result in significant energy savings.

Architecturally, challenges exist to ensure that the buildings are attractive, functional and do not feel like a box inside a box – allowing light penetration and natural airflow through core windows is an important factor in this regard.

Finally, technically, achieving an effective balance between incremental costs for envelope and HVAC upgrades while designing a flexible system that can accommodate both single-zone (whole-building) temperature and ventilation as well as multi-zone operation is key. While operational savings have the potential to be significant, initial costs and material use should be minimized to ensure a sustainable design.

Table 6: NTED™ anticipated design and performance issues and potential solutions.

Residential Design Acceptance Issue	Proposed Solution
1. Reluctance to purchase underutilized space.	1. Education on design benefits and seasonal lifestyle.
2. Incremental construction costs.	2. Shift in thinking to life-cycle from initial capital cost.
3. Feeling of living in a box.	3. Designs must maximize core light & openness.
Inter-Zone Moisture Transfer Control Issue	**Proposed Solution**
1. Gross air movement from interior door opening.	1. Provide entry vestibule to minimize transfer.
2. General air leakage.	2a. Depressurize the core relative to the perimeter.
	2b. Air barrier/vapour retarder in each envelope.
	2c. Dehumidify the perimeter to recover latent energy.

4.0 PRELIMINARY MODEL SUMMARY

Initial energy modeling (Pressnail et al., 2009) was performed considering heating loads in Toronto, Canada. At the time of this work, energy simulation programs had limitations that did not allow modeling of nested envelopes with a heat pump operating between zones. As a result, a heating-degree-day calculation, in conjunction with results from HOT2000 10.31 (a whole-house energy analysis program published by Natural Resources Canada (NRCan, 2008)), was used to estimate the heating energy use.

The goal of the preliminary work was to compare the heating energy requirement for an unoccupied single-family home operating in Gemini and Traditional modes. Building construction was modeled to meet R-2000 standards and operating the home in Traditional mode represented an R-2000 base case.

4.1 BUILDING CONFIGURATION

Table 7 provides a summary of the construction details for the preliminary NTED™ model shown in Figure 15. The building is a single-storey residential dwelling with the long elevation along the east-west axis and the core centred between the east and west perimeter elevations.

Table 7: Construction summary of initial NTED™ model.

Component	Details
Perimeter dimension	14.5 m x 9.5 m
Core dimension	8.0 m x 6.5 m
Ceiling height	2.5 m
Airtightness	1.5 ACH @ 50 Pa (R-2000)
Minimum ventilation	ACH = 0.41 (CSA F326: 2 bed, 1 bath, 1 utility, 1 kitchen, 1 living, 1 dining)
Perimeter-only heating fuel	Natural gas
Core-only heating fuel	Electricity
Whole-building heating fuel	Natural gas
Perimeter south glazing	Slightly less than 20%
Perimeter east, west glazing	Slightly less than 15%
Core south, east, west glazing	20%
Perimeter north glazing	None
Core north glazing	None
Glazing	Double-glazed / 13 mm argon / low-E coating / insulated metal spacer
Exterior walls	Effective RSI 3.1 (brick / air / wood stud / glass fibre / poly / drywall)
Interior walls	Effective RSI 3.2 (drywall / wood stud / glass fibre / poly / drywall)
Roof	Effective RSI 9.7 (glass fibre)
Slab	Concrete (assumed negligible losses due to thermal storage)

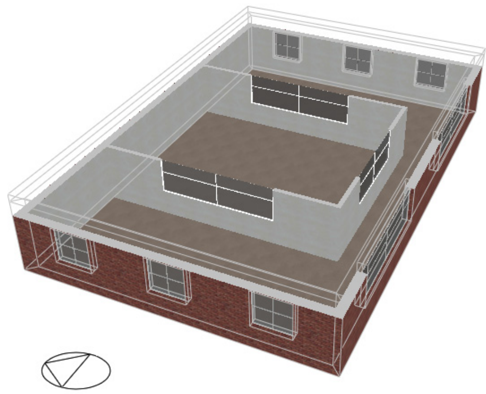


Figure 15: Preliminary NTED™ design showing core and perimeter areas (Source: Pressnail, et al., 2008).

4.2 SIMULATION METHOD

In Traditional mode, modeling was carried out using a 20°C temperature setpoint for the entire building (core and perimeter areas). In Gemini mode, the core temperature was set at 20°C and the perimeter temperature was the greater of 5°C or the average monthly exterior temperature. The various HOT2000 model scenarios and associated spreadsheet calculations necessary for this preliminary work are outlined to follow.

The Traditional mode scenario was straightforward and HOT2000 was used to calculate the heating energy required for the base case.

In Gemini mode, HOT2000 was used to calculate the perimeter heat losses by running the entire building at a 5°C setpoint. HOT2000 was then used to run a core-only building with a 20°C setpoint and the exterior temperature set to the greater of 5°C or the average monthly exterior temperature. At this point, supplementary calculations were carried out to determine the total heating energy requirement for Gemini mode. This was done by first reducing the core heat losses from the 20°C case by 2/3 to reflect the heat pump operating at an assumed COP of 3 and second, this value was added to the perimeter heat losses obtained from the 5°C case.

Because of the limitations and assumptions associated with this modeling method, it is considered to provide a conservative estimate of the heating energy use. The main factors that impact the accuracy of the results and act to overestimate the heating demand are as follows.

1. Reliance on average monthly temperature data.
2. Lack of accounting for solar heat gains.
3. An assumed heat pump COP of 3 throughout the heating period.

4.3 PRELIMINARY RESULTS

Table 8 shows the annual total heating load (kWh) for the NTED™ home operated in Gemini mode to be 2950 kWh/year. This value is obtained by adding the perimeter heating load of 1780 kWh to the heat pump energy requirement of 1170 kWh used to heat the core to 20°C. This value is the difference between the core heat losses of 3511 kWh and the useful contribution from the heat pump operating at a COP of 3 of 2341 kWh.

By comparison, the calculated value for the building operating in Traditional mode is 11420 kWh/year. Given these values, Gemini mode operation represents a 74% reduction in heating energy use. Accounting for the change in habitable area, 83 kWh/m^2 is required when heating the entire 138 m^2 house compared to 57 kWh/m^2 when heating only the 52 m^2 core. This represents a 31% savings per unit of habitable area.

Table 8: Preliminary energy model results for NTED™ Gemini mode operation.

Heating Load Categories	[kWh]
Heating load to heat whole-building to 5°C	1780
Additional load to heat core-only to 20°C	3511
Heat pump contribution (66.7% of core load)	-2341
Total Heating Load:	2950

Figure 16 shows the cost of annual heating energy use for the Gemini and Traditional mode scenarios and includes a building constructed to Ontario Building Code (OBC) standards (1997 energy provisions with 2006 amendments) and operated in Traditional mode for order-of-magnitude comparison. Costs are calculated based on natural gas prices of \$0.40/m^3 with a season energy output of 32 MJ/m^3 and electricity prices of \$0.08/kWh. It should be noted that the houses operated in Traditional mode uses only natural gas for heating while the house operated in Gemini mode uses a combination of electricity (for the core heat pump) and natural gas (for the perimeter) and hence results in a higher cost per kWh.

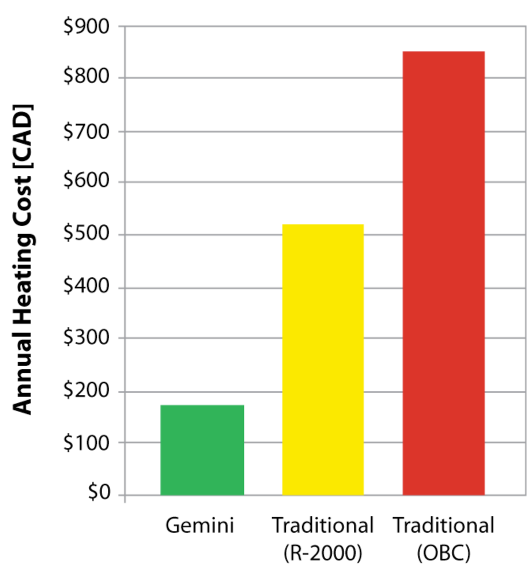


Figure 16: Annual energy costs for preliminary NTED™ modeling results.

4.4 AREAS FOR FURTHER STUDY

As previously mentioned, the preliminary modeling provided a conservative estimate of the energy savings anticipated from the NTED™ system. Even with the model limitations and conservative assumptions, the predicted energy savings were shown to be significant, thereby warranting further study to provide a more accurate forecast of the energy saving potential. The following areas represent key items that would contribute to improved accuracy of the simulation model.

1. Account for solar heat gains.
2. Include nested thermal envelope construction and an inter-zone heat pump.
3. Consider the summer cooling case.
4. Model underground thermal storage.

Accounting for perimeter solar heat gains should result in increased energy savings as these gains act to increase the perimeter temperature, thereby decreasing both the perimeter heating load and the core heat losses due to a reduced temperature difference between the zones.

Modeling nested envelopes should also result in increased perimeter temperatures as the heat losses from the core act to heat the perimeter. In addition, use of an inter-zone heat pump will more-accurately reflect the temperatures and overall heating energy requirement. As the heat pump takes heat from the perimeter for delivery to the core, the perimeter temperature will decrease and, in some cases, the perimeter may require heating to maintain the 5^{o}C setpoint. Another important component of the NTED™ design is the ventilation and ERV system. While these elements will result in an increase in energy use, they are especially important with the double-envelope construction and must be accounted for in the energy use totals.

To this point, NTED™ research has focused on the winter (heating) case. This is to be expected with the building located in the heating-dominated climate of Toronto, Canada. However, the significant seasonal variation of this location also warrants consideration of summer conditions where cooling may be desired. Future modeling efforts could also help determine the applicability of the double-envelope design in mixed as well as cooling-dominated climates.

Modeling the thermal storage concept is an extension of the summer cooling case and would provide a whole-year picture of the system's ability to decrease energy use. This system involves excess summer heat being stored for use during the winter to offset the heating energy requirement.

5.0 ADVANCED MODEL DESIGN

The current research phase extended the preliminary work by addressing the first two components of the previously-outlined areas for further study (accounting for solar heat gains and modeling nested thermal envelope construction with an inter-zone heat pump). This portion of the work involved creation of a more accurate energy model to represent the building layout and HVAC setup of the NTED™ system, allowing simulation using a sub-hourly modeling program.

An additional study area was also incorporated to determine the effects of building geometry, construction and occupant behaviour on heating energy use. In keeping with the preliminary research, these studies also focused on the heating season with the building located in Toronto, Canada. Figure 17 shows the NTED™ heat flow diagram, highlighting the elements covered by this research phase.

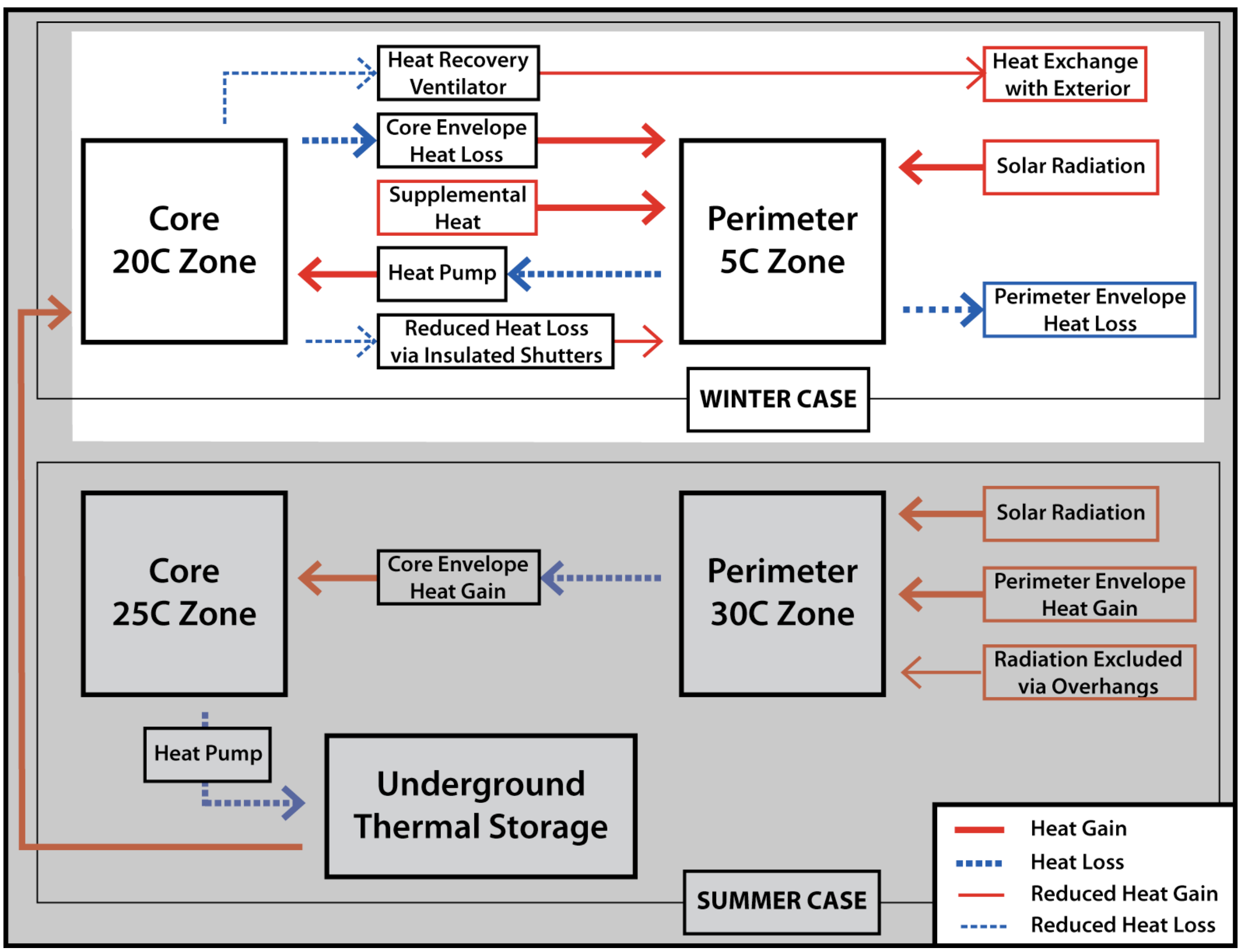


Figure 17: Area of focus for current NTED™ research phase.

The simulation model setup was performed in five stages and the details will be discussed in subsequent sections.

Stage 1: Construction

1. The building proportions were adjusted to reflect appropriate core and perimeter living spaces for a home located in Toronto, Ontario.
2. A thermally-isolated, double-envelope model was created, specifically addressing the core ceiling and the north wall.
3. The core and perimeter insulation levels were defined.
4. Infiltration rates were calculated for the core and perimeter zones.

Stage 2: Primary Equipment

1. An inter-zone heat pump model was created.
2. A ventilation system including an energy recovery ventilator (ERV) was implemented.
3. Ventilation rates were established according to the appropriate standard.
4. A heat source strategy for the perimeter zone was determined.

Stage 3: Occupants

1. Internal gains were established according to Canadian averages.
2. The number of building occupants was set to an appropriate level for the home size.
3. An occupant schedule was created.
4. The building operating modes were established to provide a range of cases.

Stage 4: Passive Systems

1. An operating schedule and construction detail was established for the insulated shutters.

Stage 5: Comparison to Existing Low-Energy Designs

1. An R-2000 building model was created to evaluate the benchmark energy use values.
2. An additional model, representing the LBNL/Habitat ZEH, was created for further comparison.

5.1 CONSIDERATIONS FOR MODEL LOCATION

For the purposes of this research, the NTED™ model is located in Toronto, Ontario. As such, an understanding of certain local characteristics such as climate and energy supply mix provides a context for the design principles and energy targets.

5.1.1 Ontario Energy Supply and Residential Usage

In order to understand the impact of home energy savings, a summary of the available Ontario energy supply mix (OEB, 2009) and Canadian residential usage (NRCan, 2006) is presented in Table 9. Of particular note, the current electricity supply yields 22% from renewable sources including hydroelectric, wind and solar (OEB, 2009).

Table 9: Ontario energy supply mix and residential use breakdown.

Electricity Supply Mix		Residential Energy Use by Source		Residential Energy End-Use	
1. Nuclear	52%	1. Natural Gas	46%	1. Space Heating	60%
2. Renewables	22%	2. Electricity	38%	2. Water Heating	25%
3. Coal	18%	3. Wood	8%	3. Appliances	13%
4. Natural Gas / Other	8%	4. Heating Oil	7%	4. Lighting	5%
		5. Other (Propane, Coal)	1%	5. Space Cooling	1%

5.1.2 Toronto Climate and Weather

Toronto, Canada, like much of the central and northern United States, is located in what is considered to be a 'cold' thermal region as illustrated in Figure 18.

Figure 18: North American thermal climate regions (Source: Lstiburek, 2007).

One of the main challenges with this climate from a building science perspective is the fact that temperature extremes occur seasonally rather than daily. In many ways, climates exhibiting daily temperature variations are easier to manage as techniques that mitigate daytime solar heat gain but utilize thermal mass for overnight heating can be implemented. Further complicating the Toronto climate is the fact that although it is heating-dominated with winter temperatures below 0°C (Table 10), the hot, humid summer conditions can also require cooling to maintain a comfortable interior environment.

Table 10: Canadian climate normals from 1971-2000 for Toronto, Ontario.

	Temperature			Bright Sunshine		Precipitation	
Month	Avg. Daily [°C]	Max [°C]	Min [°C]	Total [hr]	% of Possible	Rain [mm]	Snow [mm]
Jan	-4.2	-1.1	-7.3	88.3	30.5	29.1	382
Feb	-3.2	-0.2	-6.3	110.3	37.3	26.2	266
Mar	1.3	4.6	-2	156.3	42.3	42.0	220
Apr	7.6	11.3	3.8	185.4	46.1	63.2	60
May	14.2	18.5	9.9	229.1	50.3	73.3	0
Jun	19.2	23.5	14.8	256.2	55.5	71.5	0
Jul	22.2	26.4	17.9	276.2	59.1	67.5	0
Aug	21.3	25.3	17.3	241.3	55.7	79.6	0
Sept	17	20.7	13.2	188	50.0	83.4	0
Oct	10.6	13.8	7.3	148.4	43.3	64.7	1
Nov	4.8	7.4	2.2	83.6	28.7	75.7	81
Dec	-0.9	1.8	-3.7	74.7	26.8	71.0	322

In comparison with other Canadian cities, Toronto exhibits one of the highest sunshine exposure levels with a mean annual percentage of daylight hours with bright sunshine of 45% (Figure 19) and a mean annual total hours with bright sunshine of 2000 (Figure 20) and is therefore well-positioned to take advantage of solar gains. However, because the majority of these hours occur during the summer (Table 10), seasonal thermal storage would help gain the maximum benefit from the available solar energy.

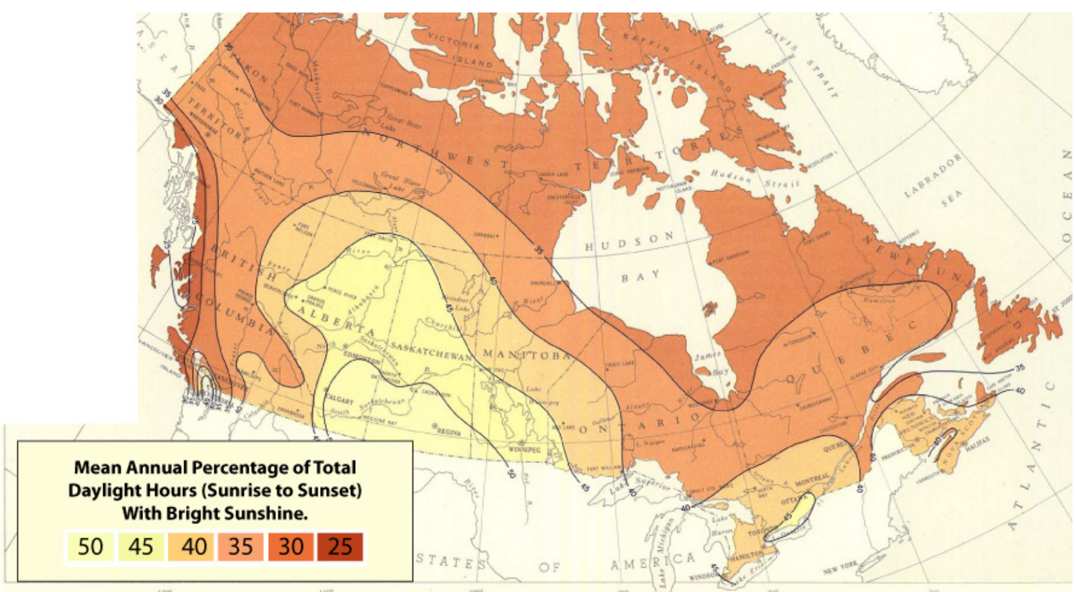


Figure 19: Mean annual percentage of daylight hours with bright sunshine (Source: NRCan, 2008).

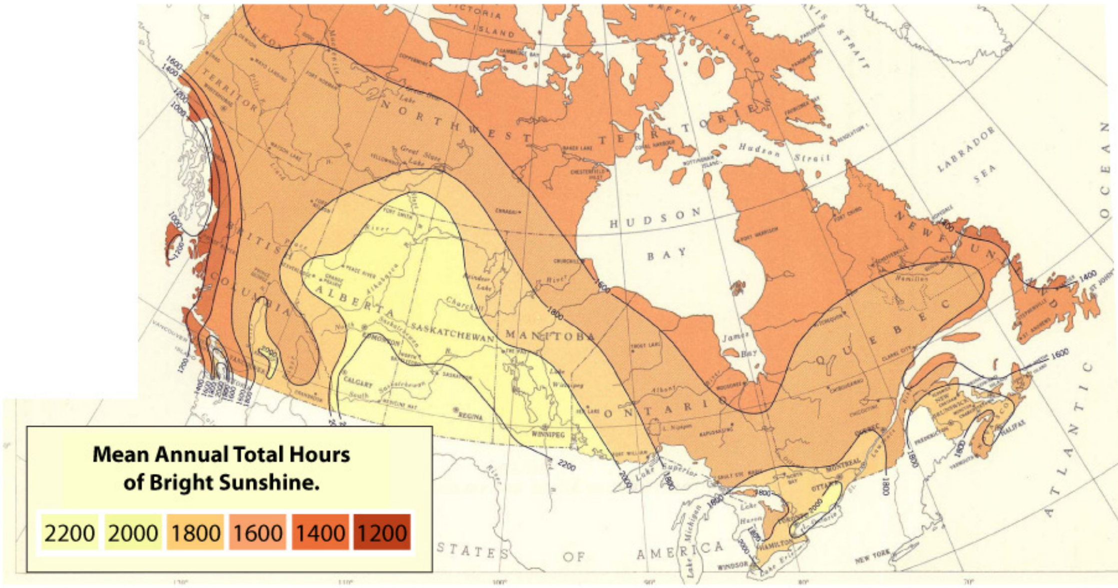


Figure 20: Mean annual total hours of bright sunshine (Source: NRCan, 2008).

5.2 AIR-SOURCE HEAT PUMP OPERATION

An air-source heat pump is a critical component of the NTED™ design. The following provides a review of the general operating principles of a heat pump as well as a review of their applicability in cold climates.

A heat pump uses electricity to move heat from one place to another, typically through a vapour-compression cycle. Air-source heat pumps, common in residential space heating and cooling applications, take heat from outdoor air for delivery indoors in winter and remove heat from indoor air for delivery outdoors in summer. Another type of heat pump that can be used for residential conditioning is a ground-source unit. These devices operate in a similar manner except that the indoor air heat exchange occurs with ground water or soil. The general operating principles of the air-source heat pump, as used in the NTED™ design, will be discussed here.

The vapour-compression cycle circulates a refrigerant that absorbs and releases heat based on its thermal conditions. Figure 21 shows the components of a heat pump as well as the thermal conditions of the refrigerant at various points along the cycle. Heat is absorbed by the low-temperature, low-pressure liquid in the evaporator coil and is released from the high-pressure, high-temperature vapour in the condenser coil. Electricity is provided to the compressor to activate the process and drive the change of state of the refrigerant from a low-pressure, low-temperature vapour to a high-pressure, high-temperature vapour.

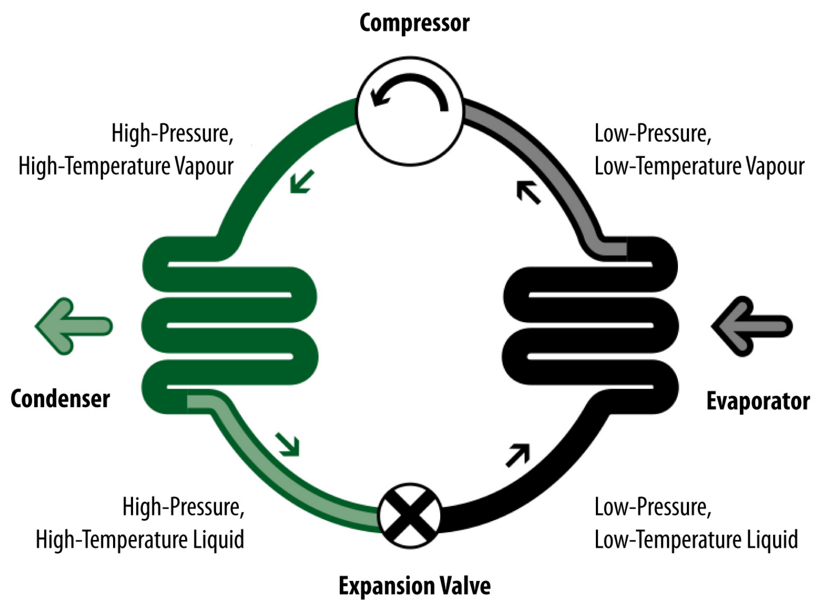


Figure 21: Heat pump cycle (Source: NRCan, 2004).

Figure 22 shows the components of an air-source heat pump in heating mode where the indoor coil is acting as a condenser and the outdoor coil is acting as an evaporator.

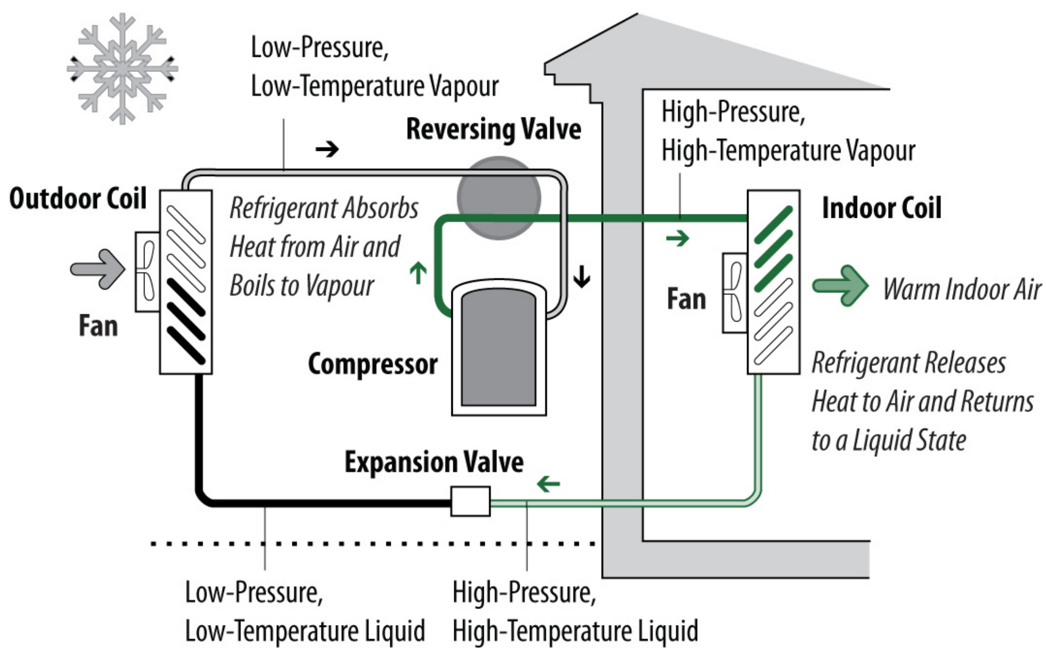


Figure 22: Air-source heat pump heating cycle (Source: NRCan, 2004).

Figure 23 shows the heat pump in cooling mode where the indoor coil is acting as an evaporator and the outdoor coil is acting as a condenser.

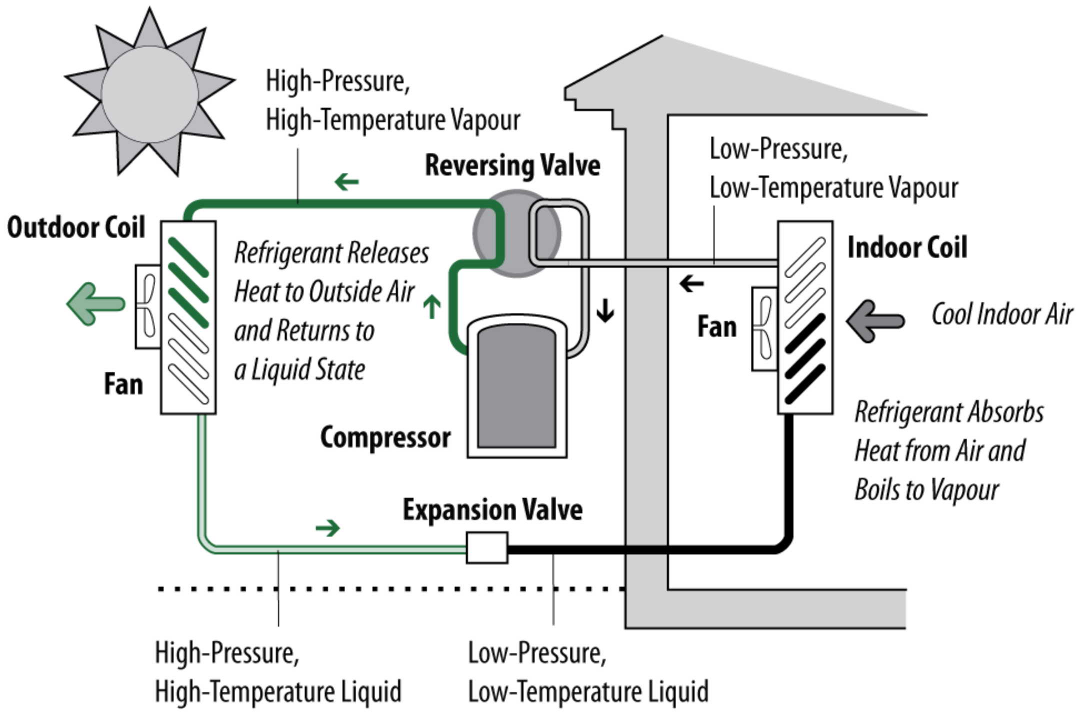


Figure 23: Air-source heat pump cooling cycle (Source: adapted from NRCan, 2004).

5.2.1 General Heat Pump Relationships

The relationships used to describe a heat pump system when operating in heating or cooling mode are useful to determine the energy transfer between the evaporator and condenser coils. For a vapour-compression cycle, the associated energies can be defined as follows.

Energy Inputs:	Compressor Q_{comp} (energy consumption)
	Evaporator Q_{evap} (cooling capacity)
Energy Output:	Condenser Q_{cond} (heating capacity)

Considering the unit operating in heating mode, the heating capacity or the energy released by the condenser is given by:

$$Q_{cond} = Q_{evap} + Q_{comp} \qquad (1)$$

Rearranging equation (1) shows the energy absorbed by the evaporator is expressed according to:

$$Q_{evap} = Q_{cond} - Q_{comp} \qquad (2)$$

As previously stated, the coefficient of performance (COP) is a ratio of the energy output to the energy consumption, given by:

$$COP = Q_{cond} / Q_{comp} \qquad (3)$$

Manipulating equation (3) yields:

$$Q_{comp} = Q_{cond} / COP \qquad (3a)$$

Substituting equation (3a) into (2) yields:

$$Q_{evap} = Q_{cond} - Q_{cond} / COP \qquad (2a)$$

Simplifying (2a) provides an alternate relationship between the energy taken from the heat source by the evaporator and delivered to the heat sink by the condenser.

$$Q_{evap} = (1\text{-}1/COP)Q_{cond} \qquad (4)$$

Considering the heat pump in cooling mode where the evaporator is removing heat from the source zone, the cooling capacity is given by equation (2). In this situation, the condenser is releasing heat according to equation (1). The COP is then given by the ratio of the cooling capacity to the energy consumption as:

$$COP = Q_{evap} / Q_{comp} \qquad (5)$$

Manipulating equation (5) yields:

$$Q_{comp} = Q_{evap} / COP \qquad (5a)$$

Substituting (5a) into equation (1) results in:

$$Q_{cond} = Q_{evap}/COP + Q_{evap} \qquad (1a)$$

Simplifying (1a) provides an alternate relationship between the energy released to the heat sink by the condenser and removed from the heat source by the evaporator.

$$Q_{cond} = (1 + 1/COP)Q_{evap} \qquad (6)$$

5.2.2 Cold Weather Heat Pump Operation

The coefficient of performance of a heat pump varies with the exterior temperature and, for high efficiency units, can be as high as 4 in moderate (above 5^{o}C) outdoor temperatures. When compared to electrical resistance heating, which has a coefficient of performance of 1, this is a significant improvement. However, as the outdoor temperature declines, so too does the performance of the heat pump. Figure 24 shows the relationship between the coefficient of performance and outdoor temperature for a typical air-source heat pump.

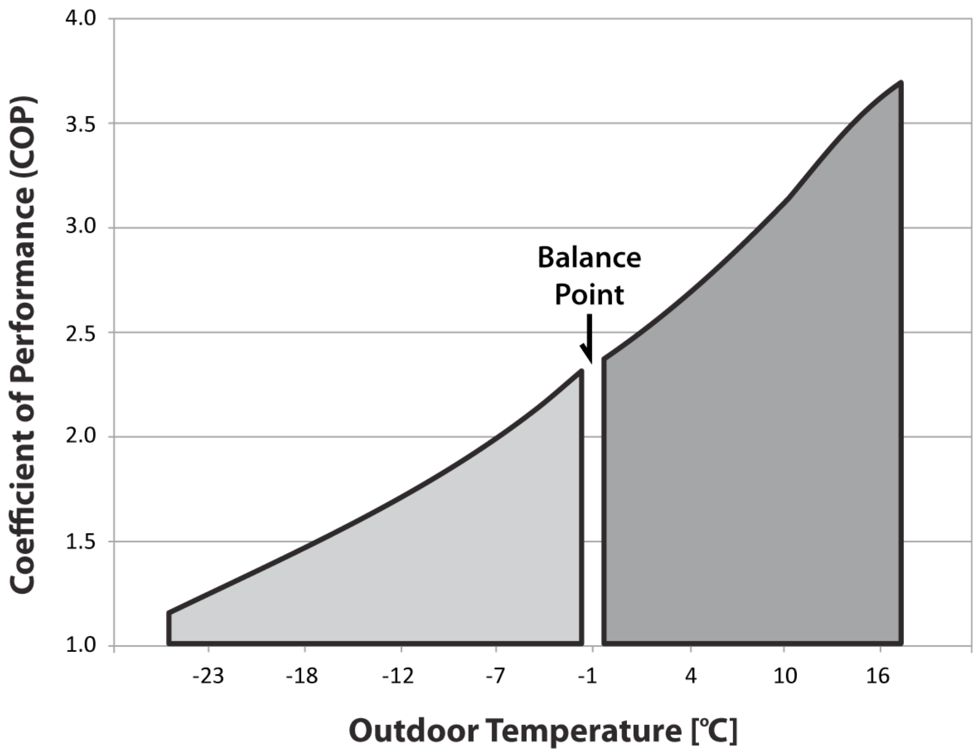


Figure 24: Performance of an air-source heat pump according to outdoor air temperature (Source: NRCan, 2004).

The ability of a heat pump to extract heat decreases with reduced exterior temperatures, which results in lower heating capacities (Mitsubishi, 2008). This is a significant issue in heating-dominated climates because as the heat load increases, the available capacity decreases and the additional heat must be supplied by other means. In the case of a typical air-source heat pump, this occurs by supplementary electric resistance heating coils that, as previously mentioned, operate at a COP of 1. An additional energy draw with low temperature heat pump operation occurs as a result of the defrost cycle that must be initiated to remove the frozen condensate from the evaporator coil.

A publication by the Natural Resources Canada EnerGuide program (NRCan, 2004) describes the process for sizing heat pump systems. According to the guide, the combined need for heating and cooling in many regions of Canada results in trade-offs for system sizing. Current design practices recommend sizing the heat pump to meet no more than 125% of the cooling load, which corresponds to approximately 80-90% of the heating load. This helps ensure that neither the performance during heating at moderate outdoor temperatures nor cooling and dehumidification are adversely affected and also minimizes unit cost. However, the result of this sizing technique is that a secondary heating system is required in colder regions of Canada during the coldest weather periods.

In an effort to increase the applicability of air-source heat pumps in cold climates, several modified designs are now available that provide improved performance at lower ambient temperatures. Table 11 lists the two main suppliers for low-temperature air-source heat pumps in North America.

Table 11: Low-temperature heat pump manufacturers.

Low-Temperature Heat Pump	Process Features Different from Standard Heat Pump
Hallowell Acadia	dual compression, cooling economizer, 4 operating modes
Mitsubishi Zuba Central	variable speed compressor, 'hyper-heat inverter' injection circuit

These low-temperature heat pump units use additional refrigerant circuits and alternative compression methods to produce refrigerant thermal properties that are better suited to heat absorption than occurs with standard designs.

5.2.3 Comparison of Standard and Low-Temperature Air-Source Heat Pumps

The following provides a brief summary of key comparison points for standard versus low-temperature heat pump units. The categories to be addressed are: performance, physical dimensions and cost.

Table 12 lists three air-source heat pump models with similar heating capacities. The first two are low-temperature units and the last is a standard model. The HSPF (Heating Seasonal Performance Factor) is used to define the performance of air-source heat pumps and is obtained by dividing the heating season output [Btu] by the heating season electricity use [W-h]. It can be seen that the low-temperature versions (example 1 and 2) have a higher HSPF value with smaller outdoor units than the standard Carrier model (example 3).

Table 12: Air-source heat pump model comparison.

Heat Pump Model	Capacity	HSPF	Outdoor Unit Dimensions
1.Hallowell Acadia	13.2 kW (45,000 Btu/h)	9.73	0.75 m^3 (49" L x 31" D x 28" H = 26.6 ft^3)
2. Mitsubishi Zuba Central	11.7 kW (40,000 Btu/h)	9.4	0.43 m^3 (38" L x 13" D x 53" H = 15.2 ft^3)
3. Carrier 25HPA5	12.3 kW (42,000 Btu/h)	8	0.87 m^3 (40" L x 36" W x 37" H = 30.8 ft^3)

Figure 25 provides an illustration of how heat pump heating capacities can vary with ambient temperature and how standard models compare to low-temperature versions in this regard. It should be noted that Figure 24 is an example case and does not represent the heat pump units listed in Table 12.

As a final comparison point, pricing information is not readily available for these devices and as such, it is difficult to compare low-temperature with standard heat pumps on a unit cost basis. Suppliers will provide a total cost for system installation (including ducting) and a 2007 Hallowell Acadia installation price range of $8000-$12000 CAD is said to be approximately $3000-$4000 CAD more than a standard heat pump (EnergyIdeas, 2007).

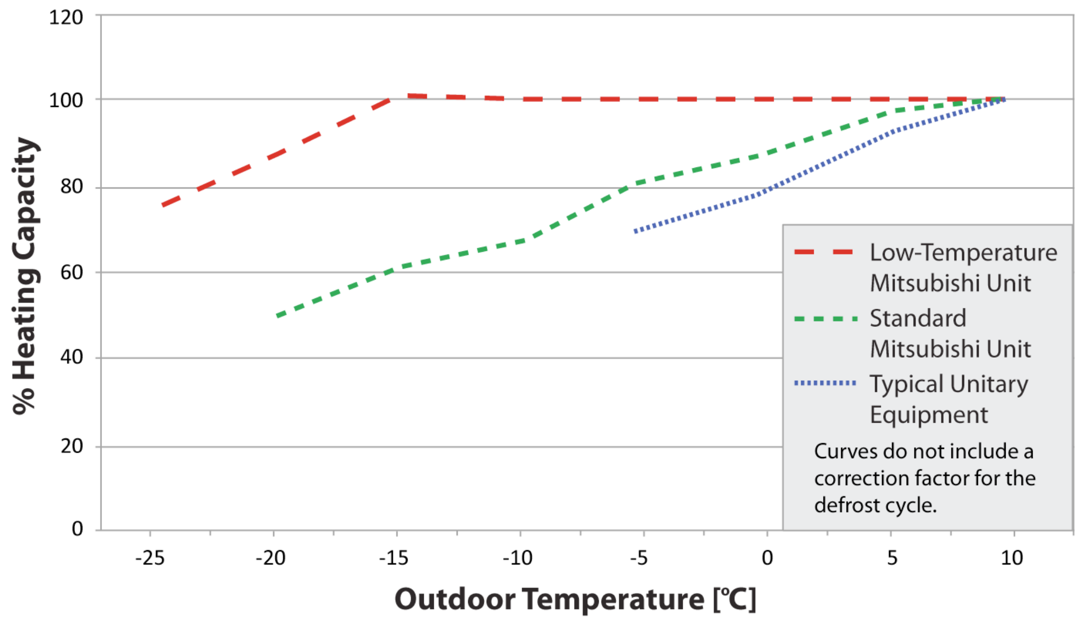


Figure 25: Air-source heat pump heating capacity variation with outdoor temperature (Source: Mitsubishi, 2008).

5.3 ENERGY MODELING SOFTWARE SELECTION

Software limitations in the preliminary research phase and the desire to advance the simulation model with this work necessitated selection of a different modeling application. A building thermal simulation tool that would allow detailed model setup, control and output management was required.

Programs in the building thermal simulation genre offer varying degrees of user-friendliness, simulation accuracy, level of input detail as well as ability to customize for a specific application. For example, HOT2000, the program used for the initial work, is a spreadsheet-based application designed to analyze buildings that intend to receive R-2000 certification. A list of four programs that were thought to meet the required input precision and simulation control was compiled and reviewed at the start of this research phase.

1. DesignBuilder (DBS, 2009)
2. EnergyPlus (USDOE, 2009)
3. TRNSYS (TESS, 2009)
4. ESP-r (ESRU, 2009)

Initial review was carried out using the Building Energy Software Tools Directory (USDOE, 2010). Additional investigation was completed through general inquiry to professionals and researchers in the Building Science field. While at the conclusion of this process it appeared that all of the titles had potential for use in the second phase of NTED™ modeling, a decision was made to proceed, at least initially, with the combination of DesignBuilder and EnergyPlus. The primary reason for the use of DesignBuilder and EnergyPlus is integration of the two titles, which allows flexibility of input and user control.

5.3.1 DesignBuilder and EnergyPlus

EnergyPlus is a thermal simulation program developed by the US Department of Energy (USDOE, 2009), which is intended to be paired with a user interface to facilitate data input and analysis. DesignBuilder, created by DesignBuilder Software Ltd. of the UK (DBS, 2009), is one such user interface. Figure 26 shows the EnergyPlus engine (left side) and its relationship with third-party user interface applications (right side).

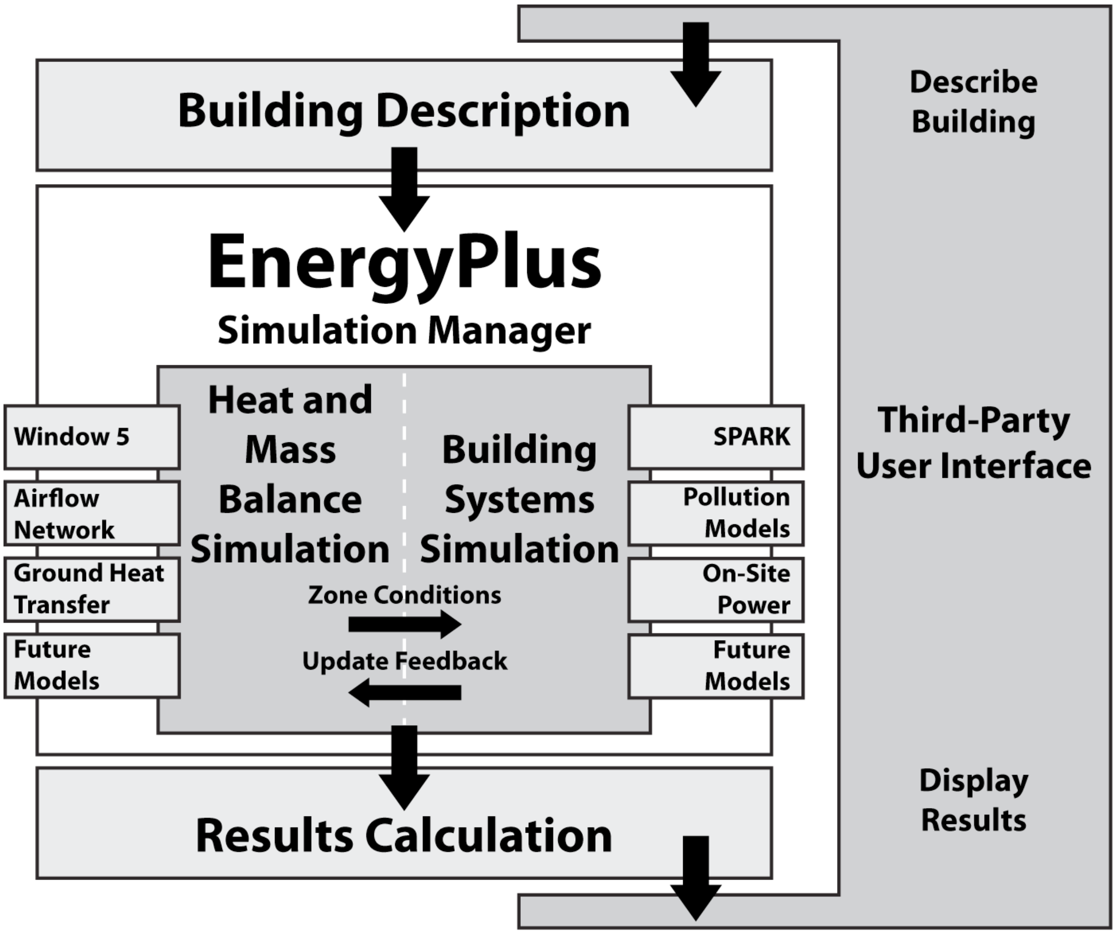


Figure 26: EnergyPlus and the user-interface (Source: LBNL, 2009b).

Testing and validation of the EnergyPlus application is carried out using a selection of industry standards to ensure that the simulation methods are accurate. Testing is completed for major releases and is categorized in three main areas: analytical tests, comparative tests and release & executable tests (USDOE, 2010). Test reports for the current software release are available for review and download on the EnergyPlus website. Among the comparative tests are the following:

1. ANSI/ASHRAE Standard 140-2007: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs
2. Building Energy Simulation Test (BESTest) methods

EnergyPlus model information can be entered using a text editor or through the IDF Editor, a basic tool which provides an unpopulated template for data entry. Files created by these methods are referred to as Input Data Files (IDF) and can also be created using the DesignBuilder interface and run in the DesignBuilder environment or exported for modification and simulation using the EnergyPlus tool directly.

DesignBuilder is a relatively new application (v1.0 December, 2005) that is constantly evolving to provide greater integration with the EnergyPlus engine. As such, there are situations where program limitations may require basic model construction and settings to be entered in the DesignBuilder environment and the resulting data imported into EnergyPlus for greater control and more-advanced modeling. The intention for this research was to complete the geometry and construction input and, where possible, the HVAC setup in DesignBuilder and move to EnergyPlus for model refinement and simulation, if necessary.

Considering that this research is intended to extend the preliminary work in several pre-defined areas, it is important that the modeling software is able to accommodate these requirements. With the combination of DesignBuilder and EnergyPlus there are two main concerns for software capability. The first is the input ability of DesignBuilder – is the required option available for selection in the DesignBuilder user menus? The second issue is the simulation abilities of EnergyPlus – does the modeling software account for the topic in question?

The first item to be addressed with this phase of the modeling work is to account for solar heat gains through the perimeter windows. As this is a simulation item, the EnergyPlus documentation can be seen to describe the process in detail (LBNL, 2008a). The model accounts for the sunlit areas as they change throughout the day, accounting for sunlit and shaded windows and opaque building elements as illustrated in Figure 27.

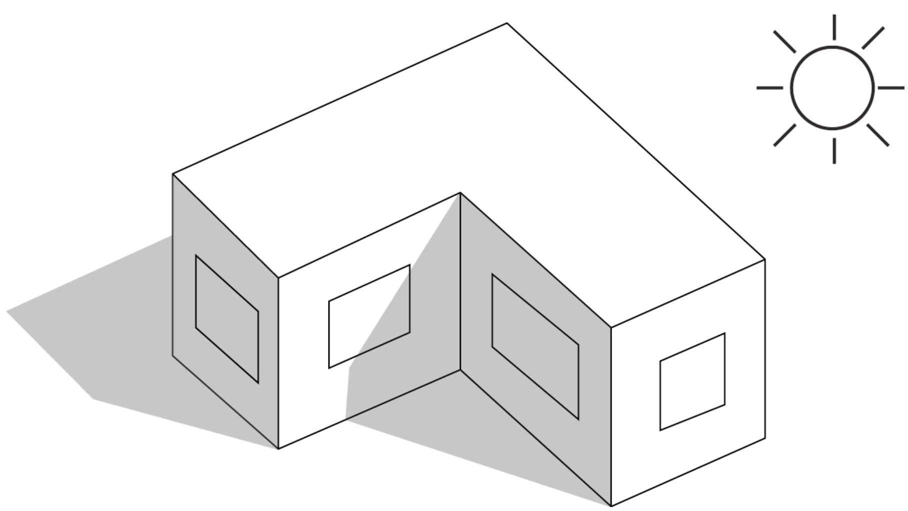


Figure 27: EnergyPlus accounting for surface shading (Source: LBNL, 2008a).

EnergyPlus calculates the total solar gain on exterior building surfaces as a combination of direct and diffuse solar radiation, according to the equation in Figure 28.

$$Q_{so} = \alpha \bullet \left(I_b \bullet \cos\theta \bullet \frac{S_s}{S} + I_s \bullet F_{ss} + I_g \bullet F_{sg} \right)$$

Figure 28: EnergyPlus solar heat gain equation (Source: LBNL, 2008a).

Where: α = solar absorptance of the surface
ϑ = angle of incidence of the sun's rays
S = area of the surface
S_s = sunlit area of the surface
I_b = intensity of the beam (direct) radiation
I_s = intensity of the sky diffuse radiation
I_g = intensity of the ground reflected diffuse radiation
F_{ss} = angle factor between the surface and the sky
F_{sg} = angle factor between the surface and the ground

The second aspect to be addressed with this research phase is modeling the nested envelope configuration, which is predominantly a geometry input issue. Investigation into the DesignBuilder support material revealed that nested envelopes could be entered using the DesignBuilder interface. In fact, the DesignBuilder support website contains a "Warehouse With Office" tutorial (DBS, 2009) explaining how to input a dual-zone warehouse building containing an office that is thermally isolated at the ceiling and along two exterior walls, as shown in Figure 29.

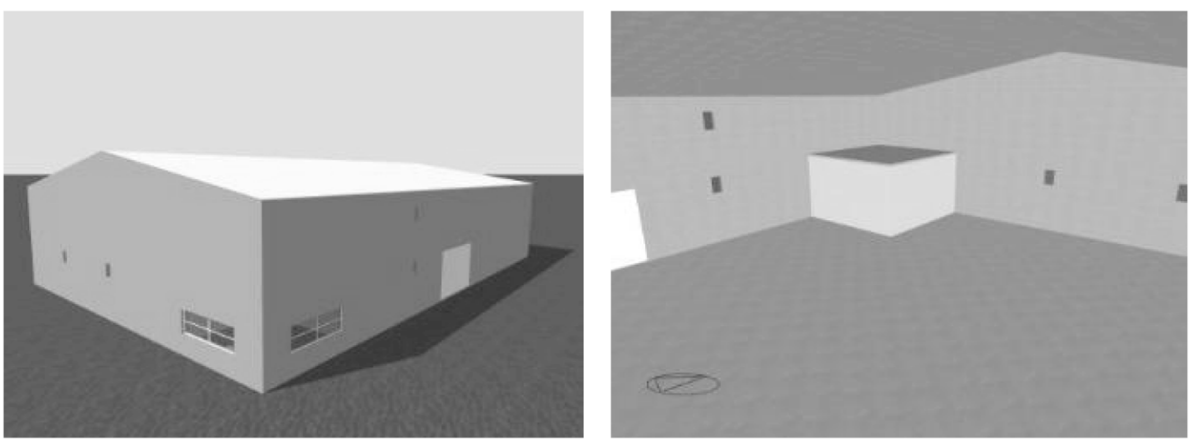


Figure 29: DesignBuilder warehouse with office tutorial (Source: DesignBuilder website, 2009).

The final aspect to be addressed in this work is the impact of an inter-zone heat pump. A first review of the DesignBuilder software revealed that while heat pump elements were not available with the then-current version of the software (v1.8), they were expected to be included in the subsequent release (v2.0) due in March, 2009. Initially, this was thought to be a straightforward solution. In the meantime however, a review of the EnergyPlus support documentation was carried out to provide an understanding of how the heat pump model operates. From this investigation, the ability of EnergyPlus to model a heat pump as an inter-zone unit was not apparent. At this point, a dialogue with the EnergyPlus support team revealed that this was not possible with the existing software. Two potential avenues to obtain the upgrade were suggested.

1. Complete an EnergyPlus upgrade request – not likely to be addressed until late 2010.
2. Obtain a developer license to gain access to the source code for module development.

As option 1 did not fit within the timeline for this research phase, option 2 was chosen and an EnergyPlus Collaborative Developer's License Agreement (CDLA) was obtained. This license allows research and non-commercial institutions to develop custom versions of the EnergyPlus software. Under this agreement, modifications must be provided royalty-free to Lawrence Berkeley National Laboratory, University of Illinois and the U.S. Government (including the Department of Energy) for potential use, alteration and incorporation into future EnergyPlus releases.

Once this course of action was selected, it became necessary to determine the HVAC setup details to understand the required source code modifications and establish a plan to complete the work.

5.4 PROPOSED AND SELECTED HVAC CONFIGURATIONS

The NTED™ HVAC setup must be able to accommodate multiple zones and temperature setpoints. The additional criteria for heat to be provided either from an external source or within an interior zone, depending on the building operating mode, is a unique situation and very different from what occurs in a typical residential setup. In an ideal case, a single heating system would allow individual core and perimeter setpoints as well as a whole-house setpoint, however as mentioned, this setup is complicated by the inter-zone nature of the Gemini operating mode where heat is taken from the perimeter zone for delivery to the core zone. An additional consideration is the energy-modeling component of the project. The chosen software must be able to represent the system being studied accurately. As a result, several HVAC configurations were proposed and considered both from real-life and modeling perspectives before the final selection was made.

Because this modeling phase focused on the heating season, HVAC scenarios were developed with a primary concern for this case. Considering the building operating in Gemini mode (20^{o}C core setpoint and 5^{o}C perimeter setpoint) with a core heat pump, several potential situations were assessed.

A. The first case occurs when the perimeter remains sufficiently above the 5^{o}C setpoint that removing heat for delivery to the core does not decrease the perimeter temperature below 5^{o}C. In this situation, perimeter heating is not required. It should be noted that the perimeter setpoint is a minimum value established to reduce the chances of condensation in the building components as well as to provide a moderate temperature for heat pump operation. As a result, situations where the perimeter is above the setpoint are desirable and zone cooling would not be implemented to maintain the 5^{o}C temperature.

B. A second case occurs when the perimeter temperature is below the 5°C setpoint or is close enough to 5°C that removing heat for delivery to the core will reduce the perimeter temperature below the setpoint. In this situation, perimeter heating is required.

Case A is straightforward and an inter-zone heat pump would be sufficient to provide the necessary building heat. Several potential strategies can be used to address case B.

i. Use an inter-zone heat pump to take heat from the perimeter only when it is above the 5°C setpoint (or some margin above the setpoint). If the perimeter temperature is at or below 5°C, have the heat pump take heat from the building exterior (as would occur with a standard heat pump installation).
ii. Implement an inter-zone heat pump to take heat from the perimeter and, when necessary, heat the perimeter with a supplementary system.

As discussed previously, modification of the EnergyPlus source code was necessary to incorporate an inter-zone heat pump and represent the Gemini operating mode according to either of cases (i) and (ii). The EnergyPlus documentation was reviewed to determine whether existing program objects could be modified to model the desired situation as well as what code modifications would be required.

5.4.1 Inter-Zone Heat Pump Based on the Hot Water Model

In keeping with the preferred option of a single HVAC system, case (i) was considered to provide the necessary multi-zone and operating mode flexibility. This situation requires a heat pump that can take heat either from an interior zone or the building exterior depending on a source zone temperature limit. The proposed inter-zone heat pump for this case was to be based on the EnergyPlus heat pump water heater model, shown in Figure 30. This object includes an air-to-water heat pump that has the ability to take heat from zone air, outdoor air or a combination of the two.

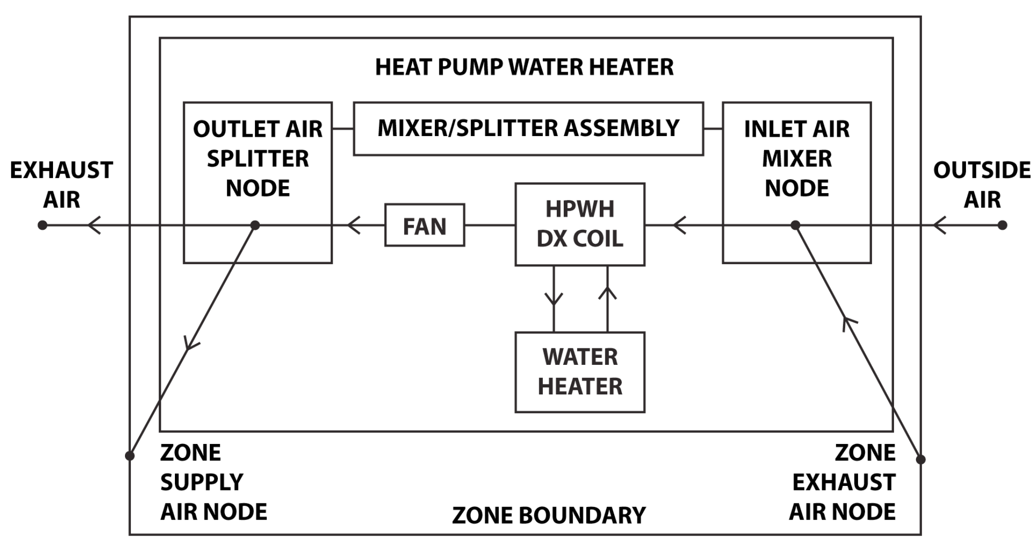


Figure 30: EnergyPlus heat pump water heater schematic (Source: LBNL, 2008a).

While it was initially thought that this model would provide a solid basis for the airflow logic, further analysis yielded several potential problems and revealed that significantly more code modification would be required than was originally anticipated. From a system operation perspective, the air-to-water components would need to be replaced with air-to-air components and the heat sink conditions linked to a building zone rather than a water tank. For the desired NTED™ logic, the system would need to be able to switch between air modes (full interior zone, full exterior zone, or mixture) based on the source zone temperature condition rather than an input-specified ratio. Finally, because of the Canadian climate, the ability to incorporate either a supplemental heater or a low-temperature heat pump would be necessary to allow operation at exterior temperatures below the 5ºC limit dictated by the EnergyPlus software.

Although this model has the potential to simulate a single HVAC system that meets NTED™ requirements, sufficient modeling had yet to be performed to understand whether the perimeter is an adequate source for core heating in the Toronto climate without requiring supplemental heat. If this were the case, then the significant programming investment that would enable the heat pump to use outdoor air to heat the core would not be necessary. As a result, the more straightforward approach proposed by case (ii) was thought to be a beneficial step to help understand the behaviour of the NTED™ system in the climate of interest.

5.4.2 Inter-Zone Heat Pump Based on the Air-Source Model

The case (ii) solution requires a heat pump that can operate between zones in a building. In this situation, the proposed inter-zone heat pump model would be based on the EnergyPlus air-source heat pump. In standard operation, the air-source heat pump functions between a specified zone and the building exterior. Figure 31 shows the components of the standard EnergyPlus air-source heat pump and its interaction with the exterior, which is considered to be an unlimited heat source/sink. In other words, the heat pump takes heat from the building exterior, as necessary, with no impact on the ambient temperature of the heat source.

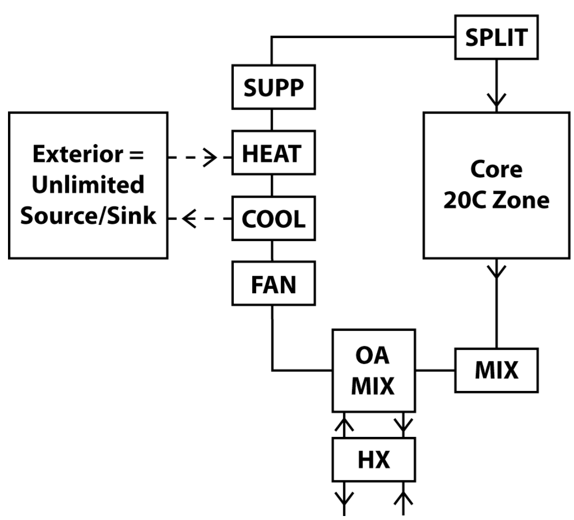


Figure 31: EnergyPlus air-source heat pump components.

In order for the heat pump to operate between two zones in a building, the EnergyPlus source code would be modified to account for the source zone air conditions and apply an appropriate cooling load to the source zone to reflect the heat removed. Figure 32 shows how the modified heat pump would function in an inter-zone configuration. In the case of core heating, the heat pump would apply a cooling load to the perimeter zone through the evaporator component and a heating load would be applied to the core through the condenser component.

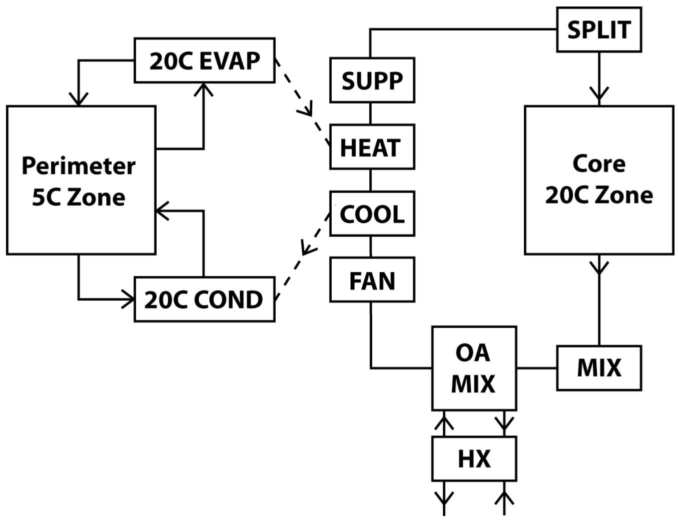


Figure 32: Modified EnergyPlus inter-zone air-source heat pump.

In this configuration, the heat pump is only able to operate between zones in the building. As a result, if the perimeter is not an adequate heat source for the core and the temperature drops below the 5°C setpoint, it will require supplementary heating. It was decided to use electric resistance heat for this purpose for several reasons. First, it is an inexpensive system that requires minimal setup and maintenance. Second, it is similar in some respects to the previously-described case (i). In that situation, if the perimeter is not an adequate heat source for the core and outdoor air is used, the electric resistance supplementary heating coil will be activated due to the low ambient temperatures.

Low-temperature heat pumps (introduced previously) are a potential option for NTED™. However, there is some advantage to using a standard air-source unit in the interest of design simplicity and lower cost. As a result, it was decided to assess the NTED™ model operation using a standard heat pump and consider moving to a low-temperature unit if the perimeter temperature conditions precluded operation of the standard unit at a desirable COP.

For future consideration, modeling a low-temperature heat pump in EnergyPlus is not a straightforward exercise because the dual or multi-speed compressors and auxiliary refrigerant loops need to be accounted for. Although EnergyPlus does contain an object representing a multi-speed air-source heat pump that allows two to four discrete compressor speeds, multiple compressors with different specifications would require customization. In addition, the current multi-stage compressor object does not incorporate some of the necessary code extensions that were available in the single-speed model and used during the modification process, as will be discussed.

5.4.3 Traditional Mode HVAC Strategies

HVAC strategies discussed to this point address the Gemini operating mode. It is also necessary to account for the Traditional mode condition, where the whole house is operated at a 20^{o}C temperature setpoint, to provide a benchmark for heating energy use.

Many potential real-life HVAC scenarios, each with pros and cons, can be theorized for the Traditional operating mode. Possibilities include the use of a heat pump as in the previously-outlined case (i) that can not only heat the core using perimeter or outdoor air, but can also heat the entire building using outdoor air, or as outlined in case (ii), use of an inter-zone heat pump to heat the core and electric baseboards to heat the perimeter.

Because the NTED™ system is a new design concept, energy modeling could be a useful approach to evaluate the performance of the system and compare the configuration options. However, the intent of this research is to focus on the performance of the Gemini operating mode. Specifically, the goal is to compare the heating energy use of an NTED™ building operating in Gemini mode using an inter-zone heat pump to that of an NTED™ building operating in Traditional mode according to the R-2000 benchmark. In order to reflect typical low-energy home construction and the R-2000 specification in Ontario, a forced-air gas furnace was chosen as the heating system. This results from the fact that the hot-air furnace is the most common type of heating system found in Ontario as shown in Table 13 (NRCan, 2005) and natural gas is the most common fuel type as shown in Table 14 (ibid.).

Table 13: Heating system use in Canada by region.

Region	Heating System	Penetration Rate
Atlantic	Electric baseboards	33%
	Hot-air furnace	31%
Quebec	Electric baseboards	61%
Ontario	Hot-air furnace	76%
Praries	Hot-air furnace	82%
British Columbia	Hot-air furnace	50%

Table 14: Heating energy source in Canada by region.

Region	Energy Source	Penetration Rate
Atlantic	Oil	39%
	Electricity	38%
Quebec	Electricity	73%
Ontario	Natural gas	68%
Praries	Natural gas	78%
British Columbia	Natural gas	52%

5.4.4 Ventilation Strategies

Ventilation is an important component of highly-sealed construction to ensure that occupants receive adequate fresh air and that odours and other pollutants are removed from the living space. While both mechanical and natural ventilation can play a role, mechanical ventilation is especially important in the case of the NTED™ system where the constantly-occupied core living space is isolated from the building exterior and natural ventilation is difficult. Another aspect particular to the NTED™ design is the fact that perimeter ventilation can be intermittent according to occupation (when the building is operated in Traditional mode) and, at least in warmer months, obtained by natural means.

According to standards such as CSA Standard F326 Residential Mechanical Ventilation Systems (CSA, 1991) mechanical ventilation rates are dictated by room programming. Constant baseline rates are provided for most rooms with a higher rate for the master bedroom, assuming occupation by 2 people. Table 15 provides a summary of the CSA F326 values. It should be noted that the additional elevated rates listed for the bathroom and kitchen accommodate the exhaust needs from cooking and bathing. These requirements can be met by an intermittent system that would be turned on by the occupants as necessary and have not been incorporated into the NTED™ model.

Table 15: CSA F326 mechanical ventilation rates according to room programming.

Room	Minimum Ventilation Rate [L/s]	Intermittent Exhaust Rate [L/s]
Master Bedroom	10	
Bedroom	5	
Living Room	5	
Dining Room	5	
Family Room	5	
Kitchen	5	30
Bathroom	5	10
Utility Room	5	

Several ventilation strategies were investigated and a key building programming criterion is proposed that would avoid including water-based services i.e. laundry and bathrooms in the perimeter zone. This guideline would help minimize moisture generation and therefore reduce the chances of condensation resulting from the low Gemini-mode perimeter temperature setpoint.

One of the ventilation strategies suggested in the preliminary research phase involved exhausting air from the core through an ERV and routing the return air to the perimeter zone. The intention is to depressurize the core slightly with respect to the perimeter thereby creating conditions where infiltration to the core would occur in order to minimize the transfer of moist core air into the perimeter. This situation also allows the potential for dynamic heat recovery where cold infiltrating air picks up heat that is migrating out through the wall cavity by conduction (Timusk, 1987). While this solution could prove beneficial in the Gemini operating mode, issues arise when trying to quantify the effects through modeling. In the first place, the typical setup for EnergyPlus does not account for building pressures. Further investigation revealed that it is possible to model building pressure, air distribution system leaks, and inter-zone airflow due to wind and HVAC system operation using the AirflowNetwork model (LBNL, 2008a). However, consultation with the EnergyPlus support team and review of sample input files revealed that this is a highly complex model requiring detailed setup information and it does not appear that it will allow air to be passed between zones using an ERV. As a result, it was decided to focus on a working model and leave this enhancement as an option for further study if more detailed analysis is desired.

A second ventilation technique proposed from the early work was to employ two separate systems that allow the core and perimeter air to be conditioned and ventilated separately. It was decided not to explore this option further due to the disadvantages associated with added costs and resource use for a system that would only be used intermittently.

In the end, the selected ventilation strategy involved connecting the ERV to the heating system ductwork and having the system exhaust and replace the air from the occupied zones. It is assumed that the building is occupied according to the operating mode with core-only occupation for Gemini mode and whole-building occupation for Traditional mode. Given these conditions, only the core exhausts and receives fresh air in Gemini mode, while both the core and perimeter receive fresh air in Traditional mode.

5.5 MODIFICATIONS TO THE ENERGYPLUS SOURCE CODE

As described previously, modifications to the EnergyPlus source code were necessary in order to model an inter-zone heat pump. EnergyPlus is a modular application that was designed to allow informed users to contribute to program development. Written in Fortran 90, updates can be carried using either the Fortran 90 or the newer Fortran 95 language.

The EnergyPlus source code is divided into just over 200 individual modules to help streamline the development process. Modules allow developers to focus on their area of interest without having to learn the entire program structure. Standards exist for the programming style to ensure naming conventions are followed, and emphasis is placed on development ease rather than optimized program speed and minimal size (LBNL, 2009a).

5.5.1 Software Used for Source Code Modifications

Research was carried out to determine the best software setup to complete the code modification process, which involves several steps and various tools are available for each. The first stage of the work is code editing. Although EnergyPlus Fortran modules can be modified with basic text editing programs, these applications do not include much of the functionality of a dedicated programming environment such as the ability to manage code modules as well as display various aspects of the code text in unique colours and formats. The second stage of the work is code debugging and program compiling. Applications that accomplish these tasks check the program source code for errors and combine the individual modules into a program executable file.

The EnergyPlus developers, as well as other professionals who carry out Fortran programming, were consulted to determine their preferred software tools. In all cases, Intel Visual Fortran and Microsoft Visual Studio were recommended. Intel Visual Fortran is a compiling and debugging tool that is installed to run within a development environment, and Microsoft Visual Studio is one such example. In addition, the WinDiff application was recommended by the EnergyPlus developers to allow visual comparison of the differences between individual text files and entire directories. Table 16 provides a summary of the selected software tools and the versions installed for the code modification work.

Table 16: Software for EnergyPlus source code modification.

Software Title	Version	Description
Intel Visual Fortran	11.1	Fortran compiling and debugging application.
Microsoft Visual Studio	2008 Professional	Integrated development environment (IDE).
Microsoft WinDiff	5.1	File and directory comparison tool.

5.5.2 Source Code Modification Summary

In order to address the conditions of the heat-pump entering air and the source-zone heat load, changes were made to several different program modules and input files.

Early review of the EnergyPlus software documentation and discussions with the program developers revealed that the heat-pump object was an optional field that would allow the input air conditions to be defined. The Input Output Reference Manual (LBNL, 2008b) defines the Condenser Air Inlet Node Name field as follows. It should be noted that EnergyPlus considers the 'condenser' to be the outdoor coil as the terminology is based on a cooling-dominated climate.

> *Field: Condenser Air Inlet Node Name*
> *This optional alpha field specifies the outdoor air node name used to define the conditions of the air entering the outdoor condenser. If this field is left blank, the outdoor air temperature entering the condenser (dry-bulb or wet-bulb) is taken directly from the weather data. If this field is not blank, the node name specified must also be specified in an OutdoorAir:Node object where the height of the node is taken into consideration when calculating outdoor air temperature from the weather data.*

In other words, the logic was already present to have condenser (outdoor coil) inlet air conditions differ from the standard climate data for the specified location. In the case of the inter-zone heat pump, the condenser outlet node also required definition. To that end, inclusion of a field in the EnergyPlus input data directory – the file used by the EP-Launch tool to list the available data input fields – was the first step in the modification process. Appendix A, Figure A1 shows an excerpt from the Energy+.idd file which includes the added field: Condenser Air Outlet Node Name. This field was added to the Coil:Heating:DX:SingleSpeed and

Coil:Cooling:DX:SingleSpeed objects. In some cases, modified code is marked with a comment labeled '!**NTED' allowing the changes to be located easily using search tools.

The next step was to add a new object to define the unit located in the perimeter zone (acting as an evaporator for the heating case and a condenser for the cooling case). Again, because the EnergyPlus naming conventions are based on the cooling case, the new object added to the IDD is labeled Coil:DX:Condenser. Appendix A, Figure A2 shows the code modifications to include the new condenser component.

A total of three Fortran modules were edited during the code modification process, as shown in Table 17. The main editing relating to the heat pump function occurs in the dxcoil.f90 module while the remaining module updates relate to the equipment definition and general program function.

Table 17: Modified EnergyPlus code modules.

Code Module	Description of Changes
dxcoil.f90	Main functional edits for inter-zone heat pump.
datazoneequipment.f90	Equipment definition.
zoneequipmentmanager.f90	Equipment association with functional code.

A WinDiff comparison of the original and modified dxcoil.f90 files reveals changes to approximately 25 different areas. A significant number of these code changes relate to input data processing, variable definition, error communication, and interaction with the zone heat balance. The main functional changes relating to the inter-zone heat pump occur in the three areas outlined in Table 18.

Table 18: Main inter-zone heat pump functional edits to the dxcoil.f90 subroutine.

dxcoil.f90 Subroutine	Description
CalcDXHeatingCoil	Defines the source zone unit outlet conditions during core heating.
CalcDoe2DXCoil	Defines the source zone unit outlet conditions during core cooling.
SimDXCondenser	New subroutine added to simulate the source zone unit.

In changing the standard heat pump to an inter-zone model, the 'outdoor' unit is moved inside a building zone. Instead of using exterior conditions for inlet values, the unit now obtains inlet conditions from the zone air. Previously, the outlet conditions were ignored, as their impact on the exterior was not considered. In the NTED™ case, the outlet conditions must be quantified to pass the energy impact to the zone heat balance.

EnergyPlus calculates the core-zone load based on the amount of energy needed to meet the zone setpoint. In the heating case, this energy is Q_{cond} and in the cooling case it is Q_{evap}. The associated load that is imposed on the perimeter zone is calculated according to the general heat pump relationships outlined previously. When the core is being heated, the cooling load applied to the perimeter is given by equation (2).

$$Q_{evap} = Q_{cond} - Q_{comp} \tag{2}$$

For the case where the core is being cooled, the perimeter receives a heating load, according to equation (1).

$$Q_{cond} = Q_{evap} + Q_{comp} \quad (1)$$

The EnergyPlus program is written such that it uses equations (7) and (8) to provide energy loads to the zone heat balance. In other words, the heating and cooling loads defined in equations (1) and (2) must be calculated using equations (7) or (8) and cannot be provided as energy (Q) values. The use of equation (7) or (8) is dictated by whether there is a sensible-only (heating/cooling) load or a sensible plus latent (moisture) load on the zone.

Sensible-only load: $$Q = m_{dot}\, c_p\, \Delta T \quad (7)$$

Sensible + latent load: $$Q = m_{dot}\, \Delta h \quad (8)$$

Where:
- Q = energy load [J/s]
- c_p = heat capacity [J/kg K]
- m_{dot} = mass flow [kg/s]
- ΔT = air temperature difference [K]
- h = enthalpy [J/kg]
- W = humidity ratio [kg_{water}/kg_{air}]

As can be seen, to solve equations (7) and (8) for the heat load, the associated mass flow, air temperatures and moisture ratio values are required. One of the key code updates in the dxcoil.f90 module involved providing a means for the program to obtain these values. It should be noted that the actual numerical values resulting from the processes outlined to follow, in fact do not matter, as they are only used to re-calculate a known heat load. That is, the intermediate values are only necessary in order to follow the zone heat balance process as it is laid out in the EnergyPlus program. In any case, rather than choosing random placeholders, some effort was made to incorporate reasonable numbers.

The values used to calculate the energy load in the zone heat balance were entered in the CalcDXHeatingCoil subroutine for the core heating (perimeter cooling) case and the CalcDoe2DXCoil subroutine for the core cooling (perimeter heating) case. The relationships used to obtain the values to solve equations (7) and (8) are outlined to follow. These code changes can be seen in Appendix A for both the CalcDXHeatingCoil (Figure A3) and CalcDoe2DCoil (Figure A4) updates. The code excerpts were created using the WinDiff tool and show the comparison between the original and modified Energy+.idd files. Yellow highlighted content represents additions to the original file included in the modified file. For reference, exclusions from the original file that are no longer found in the modified version would be marked in red.

As reversible heat pumps are sized according to the cooling case, the mass flow rate was derived from the cooling energy relationship (6) defined previously.

$$Q_{cond} = (1 + 1/COP)\, Q_{evap} \quad (6)$$

Assuming a COP of 3 in equation (6) yields relationship (6a), which shows the rate of heat delivery (Q_{cond}) to be larger than the rate of heat removal (Q_{evap}).

$$Q_{cond} = 1.3\ (Q_{evap}) \qquad (6a)$$

The same relationship was assumed for the mass flow rates. In this case, the relationship expresses the outdoor coil mass flow as a multiple of the rated (or indoor) coil mass flow.

$$m_{dot/cond} = 1.3\ (m_{dot/rated}) \qquad (6c)$$

As a further point to this relationship, it was later learned that the EnergyPlus developer team had carried out air conditioner performance measurements, which included coil mass flow rates. The results of these tests showed an indoor flow rate that was half of the value of the outdoor flow rate. Although it does not matter for the function of the program, a more accurate relationship in that case would have been:

$$m_{dot/cond} = 2\ (m_{dot/rated})$$

The specific heat of air is obtained from an EnergyPlus function that calculates the value based on the inlet air humidity ratio and dry bulb temperature.

The outlet enthalpy is obtained from an EnergyPlus function that determines the value based on the outlet air humidity ratio and dry bulb temperature.

In the CalcDXHeatingCoil subroutine (core heating mode), the outlet temperature is calculated by manipulating equation (7) to yield (7a) as shown to follow.

$$T_{out} = T_{in} - Q_{evap} / m_{dot}\ c_p \qquad (7a)$$

In the CalcDoe2DXCoil subroutine (core cooling mode), the outlet temperature is calculated by manipulating equation (7) to yield (7b).

$$T_{out} = T_{in} + Q_{cond} / m_{dot}\ c_p \qquad (7b)$$

Once these values are obtained, they are passed to the zone heat balance in order to calculate the new energy load on the perimeter zone. The calculation methods for the heating and cooling cases are discussed to follow.

In core cooling mode, the heat pump evaporator (core unit) operates according to the standard program and removes a latent and sensible heat component from the zone as dictated by the entered performance curves. The code modification deals with delivery of the heat removed form the core to the perimeter zone. This is straightforward as it is a sensible-only load delivered through the condenser component (perimeter unit).

In heating mode, the situation is more complex as the evaporator (perimeter unit) removes a total heat from the zone that is made up of sensible and latent components. Because it is not clear how to account for the proportion of each, a simplification was made. In this model, the moisture ratio for the evaporator exiting air was set to equal that of the incoming air, indicating no change in moisture level. While this is correct in core cooling mode, as the condenser does not remove moisture, the result of this assumption in core heating mode is that the energy delivered to the perimeter zone is provided entirely as a sensible load. Because the latent component is ignored, the perimeter is over-cooled causing a reduced temperature value and the unchanged moisture level would not reflect the actual decrease in moisture content.

It is not currently known how to account for this simplification. Perhaps it could be done through consideration of equipment performance data to determine how moisture removal is affected by the entering air conditions. However, it is reassuring to know that the end result will be overestimated heating energy values due to artificially low perimeter temperatures when the building is operating in Gemini mode. It is also worth noting that the latent load impact should be less in heating mode than it would be if this case occurred in cooling mode as the amount of moisture that can be available in the air at cooler temperatures is significantly less than at higher temperatures. For example, in core heating mode with the perimeter at a generous 10°C and 80% relative humidity, the amount of moisture available to be removed is one third of what would be available in core cooling mode were the source zone at 28°C and 80% relative humidity.

Once the zone heat balance was addressed for situations when the unit was in operation, values were also defined in the heating and cooling subroutines for situations were the perimeter coil was not operating. In this case, the values required for the zone heat balance were set to pass-through conditions, in other words, the temperature, enthalpy and humidity ratio outlet conditions equaled the zone air conditions and the mass flow rate was set to zero.

The final update to be addressed in the dxcoil.f90 module is the addition of the SimDXCondenser subroutine. This code reads the condenser input and calculates and reports the sensible heating and cooling energy loads (Appendix A, Figure A5).

Updates to the remaining two modules outlined in Table 17 are summarized briefly here, and WinDiff summaries are provided in Appendix A. The datazoneequipment.f90 module (Figure A6) defines the new DX Condenser Coil equipment component as: Coil:DX:SingleSpeed:Condenser. The zoneequipmentmanager.f90 module (Figure A7) associates this Coil:DX:SingleSpeed:Condenser object with the newly-created SimDXCondenser subroutine (located in the dxcoil.f90 module).

5.5.3 Modified EnergyPlus Software Setup

Once the code updates were completed, the modules were compiled to create an executable file. This process was carried out several times as the code revisions were performed and trial simulations were run to test the software changes.

In order to set up a functioning version of EnergyPlus that uses the NTED™ code modifications, the USDOE-issued installer for EnergyPlus version 4.0 must be initiated. It is important to note that the code modifications were carried out using the master version 4.0 module files and they are not compatible with other releases of EnergyPlus. Once the installation is complete, the user must replace the installed EnergyPlus executable and input data directory files with the modified versions. This is best accomplished by copying the original files to a safe place and copying the modified files to the EnergyPlus root directory. The file locations are specified to follow.

C:\EnergyPlusV4-0-0\EnergyPlus.exe

C:\EnergyPlusV4-0-0\Energy+.idd

It should be noted that the file names for the original and modified versions are the same, which is required for the program to recognize the files.

5.5.4 EnergyPlus Zone Load Verification

Several verifications were carried out to ensure that the code modifications were functioning as expected and the desired loads were being applied to the perimeter zone for both the core heating and cooling cases.

A quick check was done by calculating the capacity delivered to a given zone using equation (8) in order to see if the calculated value was the same as the reported heating or cooling rate for the new condenser object (perimeter zone unit).

$$Q = m_{dot}\, \Delta h \qquad (8)$$

A more-detailed verification was carried out by applying the heat pump relationships to the trial simulation results. This process revealed that in fact the code modifications were performing as expected and the desired loads were applied to the perimeter zone. During this process several sample cases for heating and cooling were evaluated. The COP was calculated using equations (3) and (5), and the raw data file can be reviewed in Appendix B.

$$COP_{heating} = Q_{cond} / Q_{comp} \qquad (3)$$

$$COP_{cooling} = Q_{evap} / Q_{cond} \qquad (5)$$

Equations (4) and (6) were manipulated, yielding equations (4a) and (6a).

$$Q_{evap} = (1\text{-}1/COP)Q_{cond} \qquad (4)$$

$$Q_{evap} / Q_{cond} = 1\text{-}1/COP \qquad (4a)$$

$$Q_{cond} = (1 + 1/COP)Q_{evap} \qquad (6)$$

$$Q_{cond} / Q_{evap} = 1 + 1/COP \qquad (6a)$$

Equations (4a) and (6a) were then solved to ensure that the left side equaled the right side.

For the core heating (perimeter cooling) case, the EnergyPlus output files define the following values:

Energy Inputs: Compressor Q_{comp} (energy consumption) = DX Heating Coil Electric Power

Evaporator Q_{evap} (cooling capacity) = Evaporator Sensible Cooling Rate

Energy Output: Condenser Q_{cond} (heating capacity) = DX Coil Total Heating Rate

The equations are defined in relation to the EnergyPlus output files, and Table 19 shows the sample simulation values and the calculated load relationship.

$$COP_{heating} = \text{(DX Coil Total Heating Rate) / (DX Heating Coil Electric Power)} \quad (3)$$

$$\text{(Evaporator Sensible Cooling Rate) / (DX Total Heating Rate)} = (1- 1/COP) \quad (4a)$$

Table 19: Verification of the perimeter-zone load for the core heating case.

Date/ Time	DX Coil Total Heating Rate	DX Heating Coil Electric Power	COP	Evaporator Sensible Cooling Rate	Q_{evap} / Q_{cond}	1-1/COP
01/01 00:15	796.7	399.63	1.99	396.84	0.498	0.498
01/01 12:00	623.23	279.62	2.23	343.61	0.551	0.551

It can be seen that the ratio of the cooling rate to the total heating rate is in good agreement with the calculated COP ratio. Therefore it can be concluded that the code modifications are applying the desired cooling load to the perimeter zone when the core is being heated with the inter-zone heat pump.

For the core cooling (perimeter heating) case, the EnergyPlus output files define the following values:

Energy Inputs: Compressor Q_{comp} (energy consumption) = DX Cooling Coil Electric Power

Evaporator Q_{evap} (cooling capacity) = DX Coil Total Cooling Rate

Energy Output: Condenser Q_{cond} (heating capacity) = Condenser Sensible Heating Rate

The equations are defined to follow are in relation to the EnergyPlus output files, and Table 20 shows the sample simulation values and the calculated load relationship.

$$COP_{cooling} = \text{(DX Total Cooling Rate) / (DX Cooling Coil Electric Power)} \quad (5)$$

$$\text{(Condenser Sensible Heating Rate) / (DX Total Cooling Rate)} = (1+1/COP) \quad (6a)$$

Table 20: Verification of the perimeter-zone load for the core cooling case.

Date/ Time	DX Coil Total Cooling Rate	DX Cooling Coil Electric Power	COP	Condenser Sensible Heating Rate	Q_{evap} / Q_{cond}	1+1/COP
07/01 00:15	82.65	26.99	3.06	109.64	1.33	1.33
07/01 12:00	57.49	18.49	3.05	76.34	1.33	1.33

Again, the ratios are in good agreement and it can be concluded that the code modifications are applying the desired heating load to the perimeter zone when the core is being cooled with the inter-zone heat pump.

6.0 ADVANCED MODEL SETUP

Once the simulation details were established and the software was configured according to the NTED™ operating principles, the building model and simulation matrix could be created to reflect the desired criteria for investigations of the heating energy use.

6.1 MODEL AND SIMULATION PARAMETERS

Model parameters refer to the building design and simulation software inputs used to establish the NTED™ model. Parameters were established through a variety of means – review and adoption of preliminary model details, research into typical Canadian residential designs as well as decisions based on the desired study areas for this research phase.

Simulation parameters are details that will be varied in order to investigate the effects of different building and equipment configurations on the heating energy use. Parameters include model geometry, construction elements and system setpoints.

The following provides a description of the model and simulation parameters as well as any relevant justifications for selection to the final simulation matrix.

6.1.1 Simulation Period

As with the preliminary research work, this phase covers the heating season in Toronto, Canada. The simulation period was chosen to span a single heating season from October 1 through May 31 to ensure that all potential heating load conditions were captured.

6.1.2 Review and Modification of the Initial DesignBuilder Model

As part of the preliminary modeling work, a building model was created using DesignBuilder. In the end software limitations prevented the model from being used and the work was carried out using HOT2000, as previously discussed. The original DesignBuilder model was reviewed to evaluate its usability as a first step in the current research phase.

As a result of this assessment, several improvement areas were noted and addressed in subsequent models. Figure 33 shows the initial DesignBuilder model with a gross building dimension of 10 m x 15 m (150 m^2) and a core area of 6.5 m x 8 m (52 m^2).

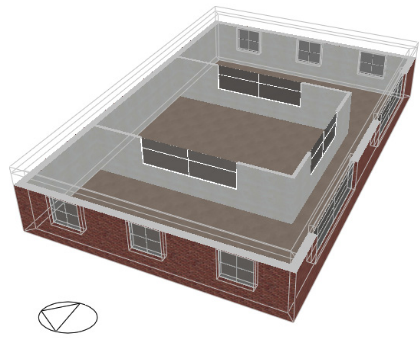


Figure 33: NTED™ model created for preliminary research using DesignBuilder software (Source: Pressnail, et al., 2008).

Although the building simulation process was completed in EnergyPlus, model construction was entered using DesignBuider for display and evaluation purposes. Figure 34 shows the second iteration of the NTED™ building model. Key updates included thermal isolation of the core from the perimeter area along the north wall and at the ceiling intersection as well as adjustment of the building dimensions to reflect typical house sizes for the region of interest. The building dimension selection process will be discussed in a subsequent section.

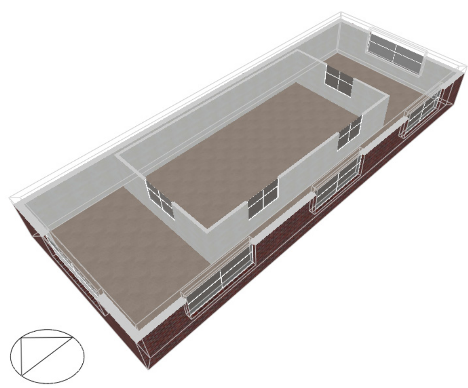


Figure 34: Updated NTED™ model including dimension changes and thermal isolation of core.

Figure 35 shows the final NTED™ model. In this version, windows were simplified to a single opening for each elevation. To maximize light penetration, core and perimeter window openings were aligned.

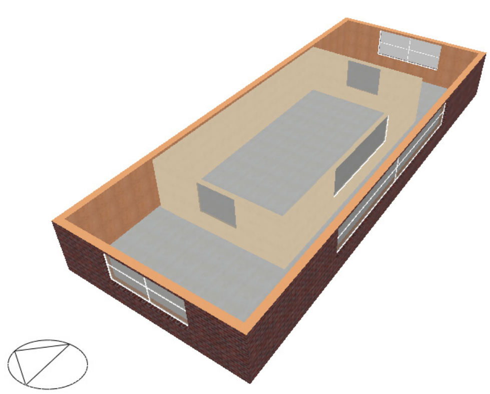


Figure 35: Final NTED™ model with aligned single window openings.

6.1.3 Building Geometry

Data from the Natural Resources Canada Survey of Home Energy Use (NRCan, 2005) were used to establish the NTED™ perimeter and core areas for modeling. The gross building area (combined perimeter and core) was selected based on the typical heated dwelling area in Ontario. At 144 m^2 this size is 3.5% larger than the 139 m^2 shown for Ontario in Figure 36.

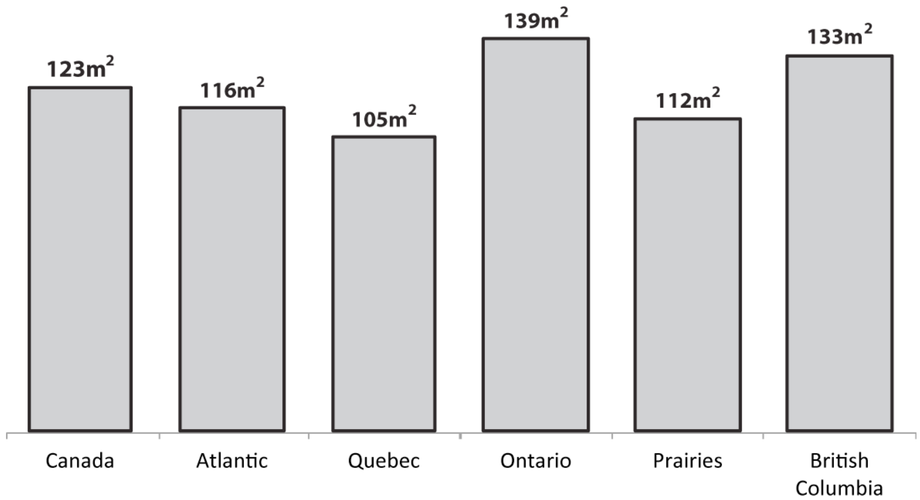


Figure 36: Average heated dwelling area in Canada by region (Source: NRCan, 2005).

The perimeter and core areas of 72 m^2 each were chosen to fall within the second largest category of heated dwelling area in Canada. Figure 37 shows that 28% of the heated dwellings in Canada have areas that fall in the range of 56 m^2 – 93 m^2. The goal for the building areas was to establish a representative model that accurately reflects the foundation principles of NTED™ – namely, a conservative dwelling designed to achieve a high level of energy efficiency and hence possessing a moderate floor area.

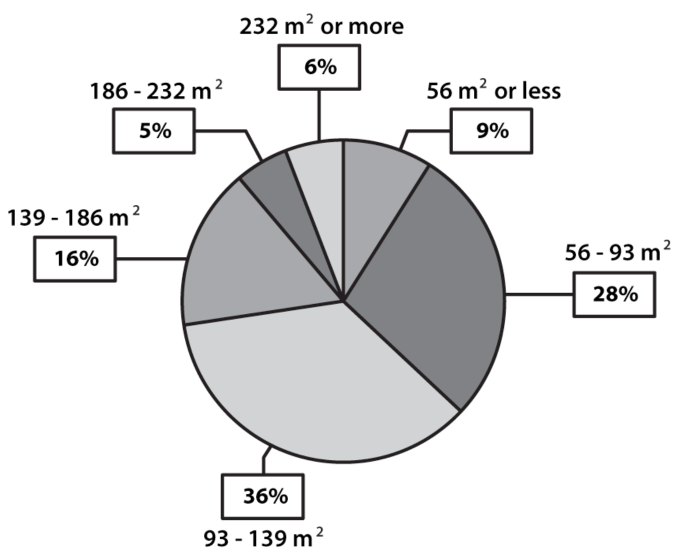


Figure 37: Breakdown of heated dwelling area in Canada (Source: NRCan, 2005).

Data in Figures 37 and 38 include single detached houses, double/row houses, low-rise apartments (fewer than 5 stories) and mobile homes. Areas refer to the total floor space excluding any basement and garage. The Baseline NTED™ building, according to the floor areas described, is shown in Figure 38.

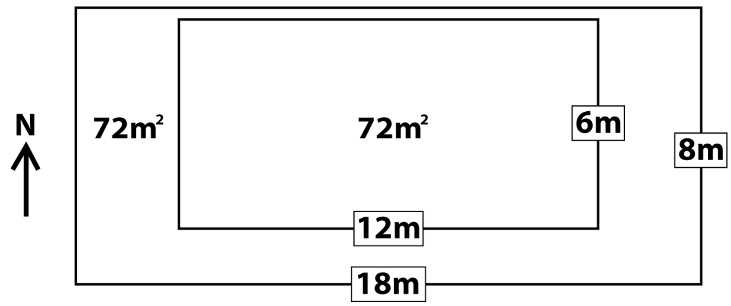


Figure 38: NTED™ Baseline building configuration.

The initial research proposal for this project suggested a study to vary the space between the core and perimeter envelopes along all elevations, in other words, to investigate the effects of larger or smaller spaces as well as the impact of different core and perimeter surface areas by modeling square and rectangular footprints. The idea being to maximize perimeter solar heat gains, minimize heat losses and exclude summer solar gains directly to the core.

As a first step towards a detailed study in this area, two additional building configurations were established by varying the wall dimensions while maintaining the areas at 72 m^2 for both the perimeter and core zones. The intent was to determine the sensitivity of the building design to solar access. Figure 39 shows the additional layouts – Square and 90^o Baseline.

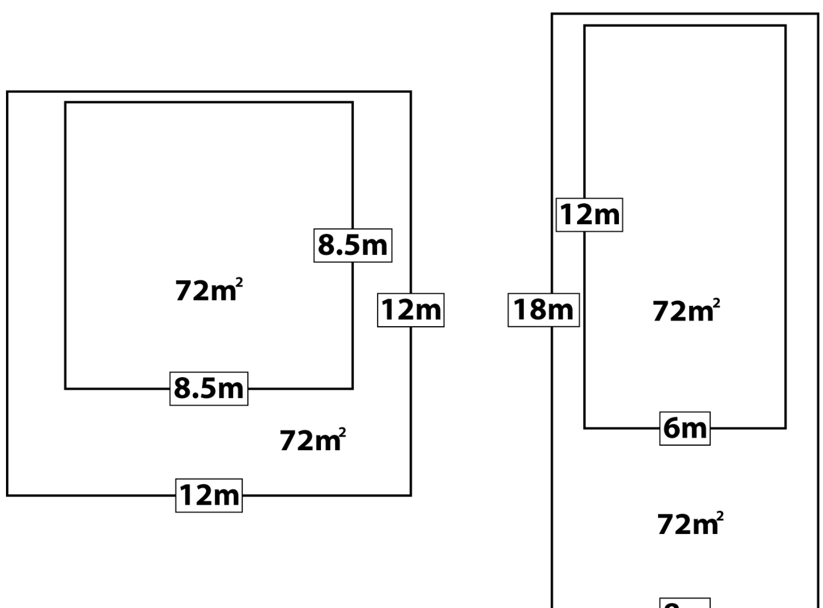


Figure 39: Square and 90^o Baseline building configurations.

It should be noted that Figures 38 and 39 represent the enclosed thermal zones for the EnergyPlus simulation. The diagrams show the floor area from the interior wall surface for each zone and the core and perimeter walls have no thickness in this case. In other words, the diagrams represent the thermal boundaries for the simulation rather than the actual building construction, which would take the wall thicknesses into account. Given that the configurations are independent of the wall thickness, they do not need to be adjusted to maintain the zone floor area and volume when changes are made to the construction details i.e. insulation thickness.

Table 21 shows the relative proportions and dimensions of key core and perimeter elements, consistent for each of the three building configurations. It should be noted that there is no glazing on the core and perimeter north elevations.

Table 21: NTED™ energy modeling building parameters.

Perimeter Area	Perimeter Ceiling Height	Perimeter South Glazing	Perimeter East/West Glazing	Core Area	Core Ceiling Height	Core South Glazing	Core East/West Glazing	North Wall Cavity
72 m^2	3 m	20%	15%	72 m^2	2.5 m	20%	20%	0.15 m

The different ceiling heights between the core and perimeter areas allow thermal isolation of the zones with space for an insulated core ceiling. The north cavity was set at 0.15 m to create a small thermal buffer and minimize the non-livable space. While it was proposed that a larger area could be used for storage, allow maintenance and perhaps have a greater impact as a thermal buffer, potential issues could result from tight storage causing inadequate airflow and resulting in cold spots and moisture problems. In the end, it was determined that this level of detail would be more appropriate for a future study once the overall energy impacts were assessed.

6.1.4 Glazing and Light Penetration

Because of the unique building configuration of NTED™, where the core is isolated from the exterior, building geometry has a greater impact on solar access compared to a typical residential design. The desire for winter solar heat gain and year-round daylighting provides a large number of potential study areas including the following.

1. The optimal percentage glazing coverage in the core and perimeter zones. For example, larger core than perimeter windows allows greater light penetration and interior windows facilitate insulated shutter use.
2. Evaluation of the effects of the alignment and elevation of the core and perimeter windows.
3. The depth of the perimeter zone affecting direct solar access to the core.

   a. South: while a smaller space could allow sun directly into the core minimizing the core heat load, it may be shown that the optimal space would be just large enough to prevent summer sun access to the core (larger roof overhangs could have an impact here as well).
   b. East / west: these are predicted to be the most logical supplementary living areas as deeper spaces will help minimize direct solar gains to the core in the summer.
4. Assessing the energy impact of direct light access to core via clerestory windows or light tubes.

It was decided that several of the window considerations would be accounted for in the model geometry but a specific study would be postponed as a potential topic for later work.

As mentioned previously, window layout was simplified by modeling the desired area as a single opening on each elevation. Glazing percentages by elevation, shown in Table 21, were maintained from the preliminary model. Windows are centred horizontally and are 1.2 m high above the sill, which is 0.8 m from the floor. In other words, the top of the windows is 2.0 m from the floor.

From a building geometry perspective, the minimum required perimeter depth to exclude sunlight from entering the south core windows directly between April and September was determined. Figure 40 shows the sun angles and penetration for four dates of interest in Toronto, Canada throughout the year.

In order to prevent direct warm-season sun access to the core, dimension E in Figure 40 must be at least 1.2 m. Case B, occurring during the month of April, is the lowest sun angle to be excluded from the core.

Using trigonometry, the relationship to solve for the distance E, is given by the following.

$$\tan \beta = \text{opposite} / \text{adjacent}$$

$$\tan \beta = h / E$$

Where: $\beta = 46^o$
$h = 1.2$ m
$E = ?$ m

Solving for the perimeter depth yields:

$$E = h / \tan \beta = (1.2 \text{ m}) / \tan 46^o$$

$$E = 1.2 \text{ m}$$

All of the building configurations were chosen with south cavity dimensions that exceeded the calculated minimum value of 1.2 m.

1. Baseline south cavity = 2 m
2. Square south cavity = 3.5 m
3. 90^o Baseline south cavity = 6 m

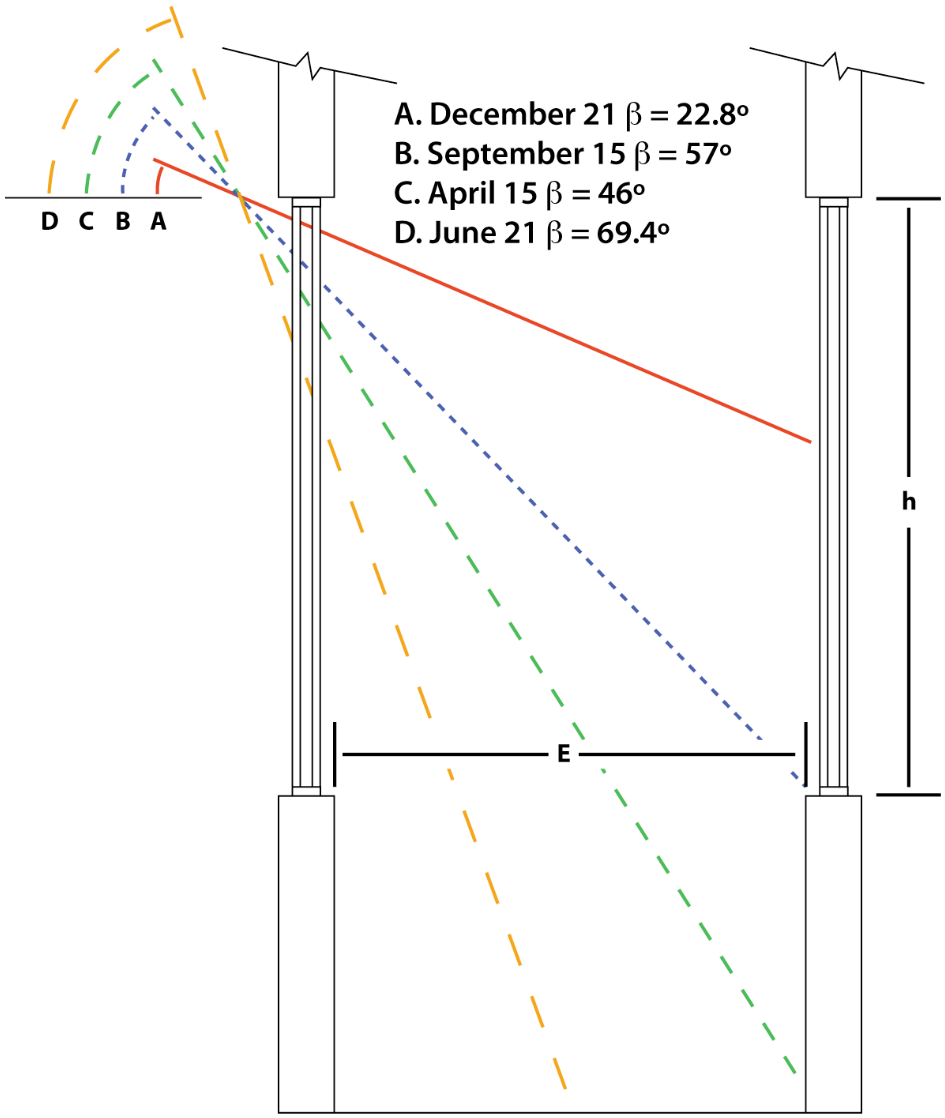


Figure 40: Perimeter dimensions to exclude warm-season sun in Toronto, Ontario.

6.1.5 Building Construction

The following provides a summary of the building construction details including materials, order of construction as well as the thickness and conductivity values used to create the simulation model.

Conductivity values for the building materials used in the NTED™ model are listed in Table 22. The DesignBuilder values were used after a comparison to the ASHRAE Fundamentals tables (ASHRAE, 2005) yielded reasonable agreement for the majority of materials, as shown.

Table 22: Material conductivity values.

Material	DesignBuilder Conductivity [W/m K]	DesignBuilder Density [kg / m3]	ASHRAE Fundamentals Conductivity [W/m K]	ASHRAE Fundamentals Density [kg / m3]
gypsum wall board	0.25	900	0.16	800
polyethylene sheet	0.5	980	n/a	n/a
glass fibre insulation	0.04	12	0.0378	10-16
wood framing member	n/a	n/a	0.12	450
OSB sheathing	0.13	650	0.135	800
air space	0.14	n/a	0.12	n/a
brick	0.84	1700	0.71-0.85	1760
poured concrete	1.13	2000	1.14	1920
XPS	0.034	35	0.029	29-56
gravel	0.41	1200	n/a	n/a
plywood sheathing	0.15	700	0.116	1100
asphalt shingles	0.7	2100	0.0645	1100

A variety of insulation levels were selected to investigate the effect of varying the core and perimeter wall thicknesses on heating energy use. Proposed potential thermal resistance configurations included:

1. equal perimeter and core R-2000 envelopes i.e. 0.14 m stud cavities;
2. reduced perimeter envelope compared to the core;
3. reduced core envelope compared to the perimeter;
4. lesser perimeter and core envelopes that that sum to approximately R-2000 i.e. 0.089 m stud cavities.

While it is predicted that there may be performance benefits to double R-2000 envelopes, it is also conceivable that benefits of lesser core insulation, including reduced construction costs and increased light penetration in the core from narrower doorways and window wells, would offset some of the benefits. In addition, while core heat loss can be recovered from the perimeter via the inter-zone heat pump, it would seem to be highly desirable to reduce heat loss from the perimeter to the exterior where the heat is not recoverable and the potential for loss is greatest due to the larger temperature gradient.

An effective thermal conductivity value was calculated for each of the wall and ceiling areas to account for the framing elements that penetrate the insulation layer. An on-centre stud spacing of 0.400 m was assumed and the window areas were not included in the wall calculation. The effective conductivity values were calculated using a weighted average, as follows.

$$U_{avg} = U_1(A_1/(A_1+A_2) + U_2(A_2/(A_1+A_2)$$

Table 23 lists the composition of the framing and insulation elements for each area as well as the resulting conductivity value. A summary of the calculations is provided in Appendix C. It should be noted that the perimeter ceiling composition was taken to be 100% insulation as it is assumed that the joists will not penetrate the insulation layer.

Table 23: Composition and effective thermal conductivity values of core and perimeter walls.

Area	Framing [%]	Insulation [%]	Effective Conductivity [W/m K]
core walls	14	86	0.05
core ceiling	11	89	0.05
perimeter walls	14	86	0.05
perimeter ceiling	0	100	0.04

Table 24 shows the selected wall insulation thicknesses and designations used in the results analysis. The effective thermal resistance of the stud-insulation cavity was calculated using the previously described conductivity values.

Table 24: Insulation levels of core and perimeter walls.

Core Wall Designation	Perimeter Wall Designation	Insulation Thickness [m]	Effective (Stud-Insulation) Thermal Resistance [m^2K/W]
c4	p4	0.089	1.78
c6	p6	0.140	2.80
c12	p12	0.292	5.84

Table 25 shows the core construction details with materials listed from inside to outside and Table 26 shows the perimeter details. The roof details are provided in Table 27 and the core and perimeter window construction details in Table 28.

Table 25: Core construction details.

	Core Wall Construction	Core Ceiling Construction	Core Slab Construction
Inside	0.0125 m gypsum wall board	0.0125 m gypsum wall board	0.15 m poured concrete
	0.0002 m polyethylene	0.0002 m polyethylene	0.0002 m polyethylene
	c4, c6, c12 glass fibre insulation	0.140 m glass fibre insulation	0.050 m XPS insulation
Outside	0.0125 m gypsum wall board	0.0125 m gypsum wall board	0.10 m crushed gravel

Table 26: Perimeter construction details.

	Perimeter Wall Construction	Perimeter Ceiling Construction	Perimeter Slab Construction
Inside	0.0125 m gypsum wall board	0.0125 m gypsum wall board	0.15 m poured concrete
	0.0002 m polyethylene	0.0002 m polyethylene	0.0002 m polyethylene
	p4, p6, p12 glass fibre insulation	0.305 m glass fibre insulation	0.050 m XPS insulation
	0.016 m OSB sheathing		0.10 m crushed gravel
	0.025 m air space		
Outside	0.100 m brick		

Table 27: Roof construction details.

	Roof Construction
Inside	roof air space
	0.019 m plywood
Outside	0.005 m asphalt shingles

Table 28: Core and perimeter window construction details.

	Window Construction		Conductivity [W/m K]
Inside	0.003 m	low-e glass	0.9
	0.013 m	argon	0.0177
Outside	0.003 m	clear glass	0.9

6.1.6 Core and Perimeter Setpoint Temperatures

The preliminary modeling study was performed with a 20°C core and 5°C perimeter setpoint temperature. A review of these temperatures was carried out in order to determine whether they would be maintained going forward or if adjustments would be made for this modeling phase.

The 5°C perimeter setpoint provides a sufficiently moderate temperature to allow the heat pump to operate at a COP of at least 3. However, it is questioned whether this provides adequate protection of the building materials from damage due to condensation. While the NTED™ operating principles are designed to minimize energy use, this must occur under conditions that ensure safe building operation.

The dew point temperature of the core air, assuming 20°C and 50% relative humidity is approximately 9°C. Given this, and depending on the building design, it may be preferable to set the perimeter temperature to a higher value, for example 10°C. Building design can also play a role, as inclusion of an entry vestibule would help minimize transfer of warm, moist core air to the perimeter.

A preliminary evaluation of the perimeter setpoint can be completed during the simulation runs by assessing the zone temperature. It has yet to be determined whether the initial 5°C setpoint requires supplementary heat to be applied to the perimeter zone. As this is assessed, the results will show whether the alternate suggestion of a 10°C setpoint would also require additional heat for the perimeter, thereby increasing the overall heating load.

Although the core setpoint of 20°C may be considered low by today's standards it is appropriate for a building design that is developed around the principles of energy conservation. In addition, the increased radiant temperatures provided by the intermediate core envelope will allow occupant comfort at lower than typical room air temperatures. For example, the German Passive House standard requires windows that will have an interior surface temperature of no less than 17°C in all climates and the interior design temperature is 20°C (PHPP, 2007).

A study of the impact of the perimeter thermal buffer on the window surface temperatures for the NTED™ building shows that in Traditional mode, the interior surface of the exterior windows is 15.6°C. In Gemini mode, the interior surface of the core windows is at least 18.3°C (Table 29). According to the Passive House standard, at this temperature, occupants can be comfortable in the space without requiring a heat source located under the window (ibid.). The calculations for the window study can be seen in Appendix C.

Table 29: Results of the window surface temperature study.

Window	Operating Mode	Air Temperature Outside Window	Air Temperature Inside Zone	Interior Glass Surface Temperature
Perimeter	Traditional	-15°C	20°C	15.6°C
Core	Gemini	5°C	20°C	18.3°C

6.1.7 Ventilation

As previously discussed, the ventilation rates for the NTED™ building were to be established according to the base rates in the CSA Standard F326 Residential Mechanical Ventilation Systems (CSA, 1991). Table 30 shows the room layout and the associated mechanical ventilation rates required for the core and perimeter zones.

Table 30: NTED™ building zone mechanical ventilation rates.

Room	Core Ventilation [L/s]	Perimeter Ventilation [L/s]
Living Room	5	
Kitchen	5	
Bathroom	5	
Master Bedroom	10	
Bedroom	5	2 x 5
Dining Room		5
Total	30	15

The ventilation rates for the NTED™ building are activated according to the operating mode. In Gemini mode the core ventilation rate is used and in Traditional mode, the building is operated using a total rate given by the sum of the perimeter and core ventilation rates, or 45 L/s.

The EnergyPlus input requires volumetric ventilation rates per zone in [m^3/s] and the values in Table 30 were converted as outlined to follow.

$$[m^3/s] = [L/s][m^3/L]$$

Core ventilation: $(30\ L/s)(1/1000\ m^3/L) = 0.03\ m^3/s$

Perimeter ventilation: $(15\ L/s)(1/1000\ m^3/L) = 0.015\ m^3/s$

These values were also converted to an ACH rate for summary purposes.

$$ACH = [m^3/s][s/hr][m^3]^{-1}$$

For the core: $V_c = (6\ m)(12\ m)(2.5\ m) = 180\ m^3$

$$ACH_c = (0.03\ m^3/s)(3600\ s/hr) / (180\ m^3) = 0.6$$

For the perimeter: $V_p = (8\ m)(18\ m)(3\ m) - (180\ m^3) = 252\ m^3$

$$ACH_p = (0.015\ m^3/s)(3600\ s/hr) / (252\ m^3) = 0.21$$

6.1.8 Infiltration

Infiltration is the uncontrolled flow of air into a building through leakage openings. As with typical buildings, perimeter infiltration would occur in the NTED™ model based on the leakage rate of the construction. When the building is operated in Gemini mode, core infiltration could also occur due to the moisture-management strategy that involved depressurizing the core slightly with respect to the perimeter. This was intended to prevent exfiltration of moist core air into the perimeter zone. A leakage rate for the core zone would quantify the energy impact of the cooler perimeter air penetrating the core envelope.

As mentioned, representing perimeter zone infiltration in EnergyPlus is straightforward as the zone represents a typical house configuration exposed to the exterior elements. The perimeter rate was set based on the R-2000 standard air leakage rate of 1.5 ACH at a pressure difference of 50 Pa. This ensures comparison accuracy between the building operating modes. A review of the EnergyPlus documentation (LBNL, 2008b) reveals that the infiltration input is provided at design conditions, in other words a natural infiltration rate is required.

Two methods to convert the 50 Pa pressurization specification to ambient conditions were reviewed – the K-P model, developed by Kronvall and Persily (Meier, 1994) and the LBL infiltration model, developed by Sherman (1986). The straightforward K-P method is said to provide a good estimate of the average air change rate and simply divides the ACH_{50} rate by 20. In order to better account for factors such as the building location and construction details, Sherman developed the LBL infiltration model which divides the ACH_{50} by a correction factor N, given by the following.

$$N = C \times H \times S \times L$$

Where:
- C = climate factor (function of temperature and wind)
- H = building height correction factor
- S = wind shielding correction factor
- L = leakiness correction factor

For the NTED™ model in the Toronto, Canada climate the LBL method was used and the natural infiltration rate for the perimeter zone was derived as follows.

$$ACH_{NAT} = ACH_{50} / N$$

Where:
- C = 18 (average value for climate)
- H = 1.0 (1 storey building)
- S = 1.0 (normal wind shielding)
- L = 1.4 (small cracks, tight construction)

$$ACH_{NAT} = ACH_{50} / (C \times H \times S \times L)$$

$$ACH_{NAT} = 1.5 / (18 \times 1.0 \times 1.0 \times 1.4)$$

$$ACH_{NAT} = 0.06$$

This air change value must be converted to a volumetric flow rate for entry into EnergyPlus. This was done according to the following.

$$Q_p = [m^3/s] = [AC/h][h/s][m^3/AC]$$

The perimeter volume is equal to the gross volume minus the core volume and is given by:

$$V_p = (3\ m \times 18\ m \times 8\ m) – (2.5\ m \times 6\ m \times 12\ m)$$

$$V_p = 432\ m^3 – 180\ m^3 = 252\ m^3$$

The volumetric infiltration flow rate is:

$$Q_p = (0.06\ AC/h)(1/3600\ s/h)(252\ m^3)$$

$$Q_p = 0.0042\ m^3/s$$

For core infiltration when the building is operated in Gemini mode, the leakage rate was established assuming that the construction techniques would be consistent for the core and perimeter envelopes and hence would result in equivalent openings per unit of surface area.

The equation (9) for airflow through an equivalent leakage area according to the air density and pressure difference is as follows (Hutcheon & Handegord, 1995).

$$Q = C\ A\ [(2/\rho)(\Delta P)]^{1/2} \qquad (9)$$

Where:	Q_p =	$0.0042\ m^3/s$	infiltration rate
	C =	0.6	orifice coefficient
	A =	? $[m^2]$	leakage area
	ρ =	$1.33\ kg/m^3$	infiltrating air density, assuming air at -10°C, 50% RH
	ΔP =	4 Pa	interior and exterior pressure difference

A pressure difference of 4 Pa was chosen, as it is the reference pressure from ASTM E779-03 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (ASTM, 2003).

Solving the infiltration equation for 'A' yields the following perimeter equivalent leakage area (ELA):

$$A_{pELA} = Q / (C\ [(2/\rho)(\Delta P)]^{1/2})$$

$$A_{pELA} = 0.0042 / (0.6\ [(2/1.33)(4)]^{1/2})$$

$$A_{pELA} = 0.00285\ m^2$$

Calculating the perimeter surface area, considering the walls and ceiling provides the following:

$$A_p = 2\ (8\ m \times 3\ m) + 2\ (18\ m \times 3\ m) + (18\ m \times 8\ m)$$

$$A_p = 300\ m^2$$

The leakage openings per square meter of surface area is:

$$A_L = (\text{total leakage opening [m}^2\text{]}) / (\text{total surface area [m}^2\text{]})$$

$$A_L = (0.00285 \text{ m}^2) / (300 \text{ m}^2)$$

$$A_L = 9.50 \times 10^{-6} \text{ m}^2/\text{m}^2$$

Calculating the core surface area, again considering the walls and ceiling provides:

$$A_c = 2\ (6 \text{ m} \times 2.5 \text{ m}) + 2\ (12 \text{ m} \times 2.5 \text{ m}) + (6 \text{ m} \times 12 \text{ m})$$

$$A_c = 162 \text{ m}^2$$

Assuming the same leakage openings per square meter of construction between the core and perimeter results in the following core ELA:

$$A_{cELA} = (162 \text{ m}^2)(9.50 \times 10^{-6} \text{ m}^2/\text{m}^2)$$

$$A_{cELA} = 0.00154 \text{ m}^2$$

Calculating the core infiltration rate using the infiltration equation (9).

Where:	Q_c =	? m^3/s	infiltration rate
	C =	0.6	orifice coefficient
	A =	0.00154 m^2	leakage area
	ρ =	1.23 kg/m^3	infiltrating air density, assuming air at 5^{o}C, 50% RH
	ΔP =	2 Pa	core and perimeter pressure difference

The 2 Pa pressure difference was selected by assuming that it would be lower than the perimeter/exterior difference (from ASTM, 2003) due to the absence of wind effects.

$$Q_c = (0.6)(0.00154 \text{ m}^2)\ [(2/1.23 \text{ kg/m}^3)(2\text{Pa})]^{1/2}$$

$$Q_c = 0.00167 \text{ m}^3/\text{s}$$

With the core and perimeter infiltration rates calculated, the EnergyPlus documentation was reviewed to understand how the model functions. The Input Output Reference manual (LBNL, 2008b) states:

> *Zone Infiltration is the unintended flow of air from the outdoor environment directly into a thermal zone. Infiltration is generally caused by the opening and closing of exterior doors, cracks around windows, and even in very small amounts through building elements.*

In other words, on first review, it appears that the infiltration model considers the supply air to be the exterior, according to the traditional definition. While this is correct for the perimeter case, it means that the core would have a larger heating load resulting from infiltration of cold exterior air instead of intermediate perimeter air.

Further investigation was carried out by reviewing the EnergyPlus source code module that handles infiltration. The HeatBalanceManager.f90 code shows that the initial interpretation is correct and the infiltration object calls the exterior-air conditions as shown in Figure 41.

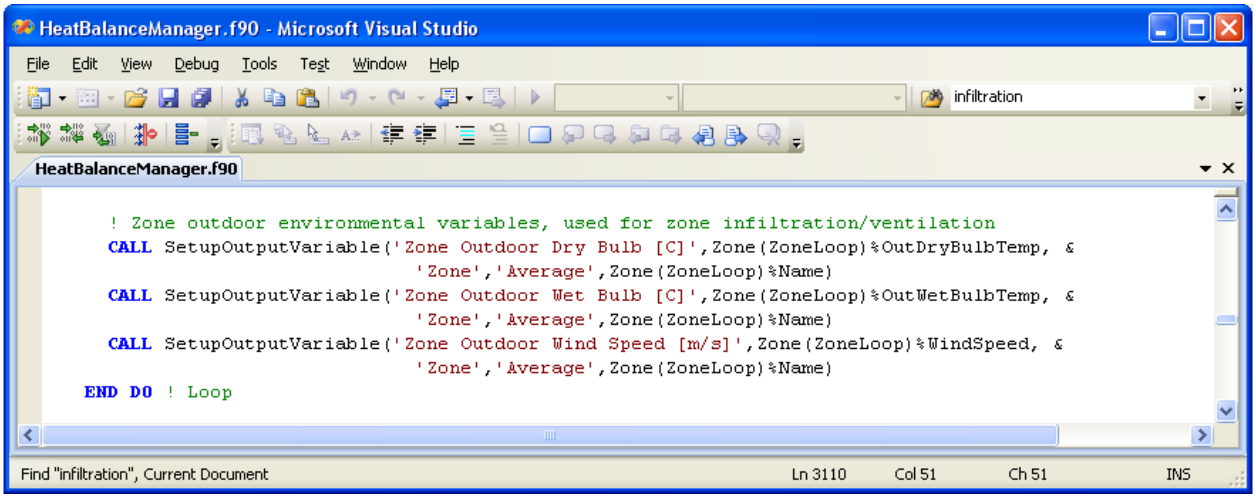


Figure 41: Infiltration object calling the outdoor environment air conditions.

Because the core infiltration conditions will result in an overestimated heating energy use, it was decided to set up the model to include both core and perimeter infiltration when the building is operating in Gemini mode. An additional trial was also completed to assess the energy implications of the core infiltration load. This was accomplished by removing the core infiltration object from the Gemini-operated test case.

It should be noted that only the perimeter infiltration is active when the building is operating in Traditional mode. This reflects the single temperature setpoint situation where only exterior air is penetrating the building envelope.

6.1.9 HVAC Configuration

The two operating modes and corresponding HVAC configurations used for simulation purposes are outlined in Table 31 for Traditional mode (representative of a typical R-2000 home) and Table 32 for Gemini mode.

Table 31: Operating conditions for NTED™ in Traditional mode.

Core Temperature Setpoint	Perimeter Temperature Setpoint	Whole-Building HVAC	Whole-Building Ventilation	Mechanical Ventilation Rate
20°C	20°C	forced-air gas furnace	heat recovery ventilator	0.045 m^3/s

Table 32: Operating conditions for NTED™ in Gemini mode.

Core Temperature Setpoint	Core Heating	Core Ventilation	Mechanical Ventilation Rate	Perimeter Temperature Setpoint	Perimeter Heating	Perimeter Ventilation
20°C	air-source heat pump	heat recovery ventilator	0.03 m^3/s	5°C	electric baseboard	n/a (non-occupied)

6.1.10 HVAC System Specification and Performance

HVAC equipment objects are defined in EnergyPlus through input fields in the IDF file. In some cases, more detailed information can be entered to further define the equipment through a series of performance curves. Table 33 provides a summary of the individual EnergyPlus objects used to model the HVAC equipment. In some cases, input data were based on standard EnergyPlus settings. Because the main focus of this work is to achieve a functional model of the inter-zone heat pump, equipment manufacturer data were used as the basis for the direct expansion (DX) coils, to represent the performance of a specific heat pump unit.

Table 33: HVAC equipment summary.

Equipment	EnegyPlus Objects	Data Source	Performance Curves Available / Used	
air-source heat pump	Fan:OnOff	EnergyPlus	Yes	Yes
	Coil:Cooling:DX:SingleSpeed	Carrier	Yes	Yes
	Coil:Heating:DX:SingleSpeed	Carrier	Yes	Yes
	Coil:Heating:Electric	EnergyPlus	No	No
electric baseboard heater	ZoneHVAC:Baseboard:Convective:Electric	EnergyPlus	No	No
forced-air gas furnace	Fan:OnOff	EnergyPlus	Yes	Yes
	Coil:Heating:Gas	OBC, 2006	Yes	No
	Coil:Cooling:DX:SingleSpeed	EnergyPlus	Yes	No
energy recovery ventilator	HeatExchanger:AirtoAir:SensibleAndLatent	EnergyPlus	No	No

Selection of the air-source heat pump unit to be modeled was based on availability of complete manufacturer data. This was done in order to ensure the most accurate performance curves possible for these trials. Table 34 provides a summary of the selected heat pump model. Appendix D contains the raw heating and cooling performance data used to create the EnergyPlus performance curves.

The efficiency column in Table 34 shows the unit performance rating. The Seasonal Energy Efficiency Ratio (SEER) defines the performance of the unit operating in air-conditioning mode. Similar to the HSPF calculation, it is given by the cooling season output [Btu] divided by the electric energy use [W-h] for the same time period. For both the SEER and HSPF, higher values mean greater energy efficiency of the unit. The ENERGY STAR program requires that central air conditioning systems have a SEER of at least 14 and air-source heat pumps have an HSPF of at least 8 (USEPA, 2010).

The size column in Table 34 refers to the cooling capacity of the air conditioning unit. One ton of refrigeration capacity is equal to the amount of energy required to melt one ton (907 kg) of ice in a 24-hour period.

Table 34: Heat pump model specification summary.

Manufacturer	Model	Efficiency	Size
Carrier	25HPA5	15 SEER / 8 HSPF	1.5 – 5 nominal tons

Typically, the performance of HVAC equipment varies according to the operating conditions. This is to say that while equipment may display its highest efficiency at a given set of conditions, these are not always present and the equipment often operates at off-optimal conditions. Manufacturers generally provide information in the form of data points or curves to define their equipment performance. EnergyPlus can accept this performance data as a series of equations to define the curves. An example performance curve for the Carrier 25HPA5 unit is provided in Figure 42 where the COP is shown as a function of the outdoor temperature.

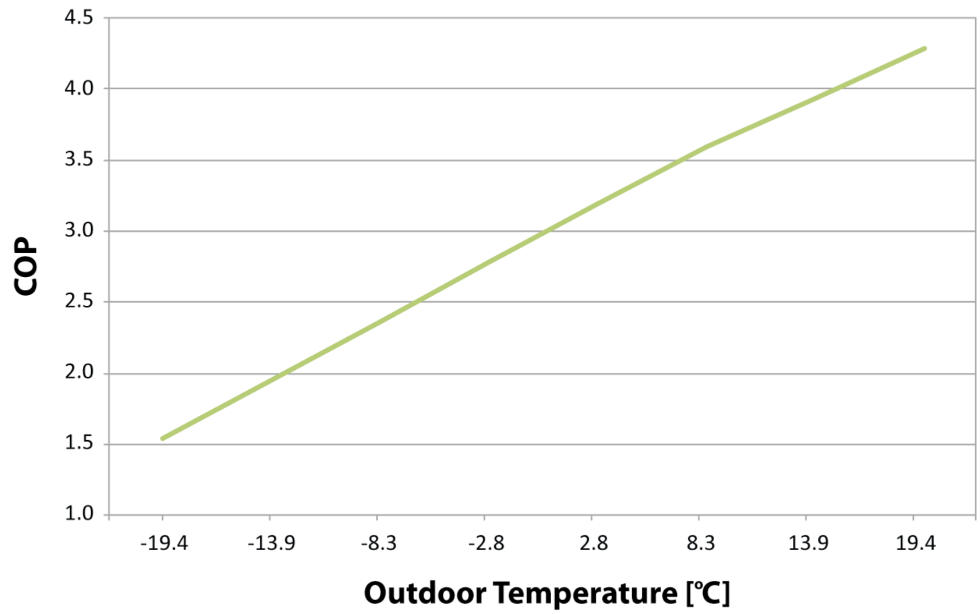


Figure 42: Sample performance curve for the Carrier 25HPA5 heat pump unit.

In most cases, EnergyPlus performance curves are created by carrying out a regression exercise using the manufacturer performance data. The IDF input information is a series of coefficients used in an equation that is solved to determine a factor relating the rated equipment conditions to the actual conditions at which the unit is operating for a given simulation time step. The rated temperature conditions for the regression process were selected based on ANSI/AHRI Standard 210/240 (AHRI, 2008) and are listed in Table 35.

Table 35: Standard temperature rating conditions for heat pumps.

Condition	Indoor Dry Bulb	Indoor Wet Bulb	Outdoor Dry Bulb	Outdoor Wet Bulb
Heating	21°C (70°F)	15.6°C (60°F)	8°C (47°F)	6°C (43°F)
Cooling	27°C (80°F)	19°C (67°F)	35°C (95°F)	n/a

Because the core zone has a relatively small floor area, one of the lowest possible flow rates for the Carrier unit was selected as the rating point. According to heat pump and air conditioning sizing guidelines (Rudd, 2006 & Falke, 2006), units should generally be operated at 400 cfm/ton (0.189 m^3/s / 3.5 kW) over the indoor coil. This provides an appropriate flow rate for heating capacity delivery and for latent and sensible heat removal in most cooling applications (this rate may be adjusted in very humid or dry climates to balance the latent and sensible loads). The chosen 600 cfm (0.283 m^3/s) flow rate provides the recommended 400 cfm/ton in heating and cooling modes at the rated temperature conditions as shown.

[cfm] / [Btuh] x 12000 Btuh/ton = [cfm/ton]

In cooling mode: (600 cfm) / (17800 Btuh) x (12000 Btuh/ton) = 404 cfm/ton

In heating mode: (600 cfm) / (18000 Btuh) x (12000 Btuh/ton) = 400 cfm/ton

The performance curves created for the DX cooling and heating coils are listed in Table 36. The associated equations and detailed steps to describe the regression analysis can be found in Appendix E.

Table 36: Summary of DX coil performance curves.

DX Coil	Curve Name
Heating	1. Total Heating Capacity as a Function of Temperature
	2. Total Heating Capacity as a Function of Flow Fraction
	3. Energy Input Ratio as a Function of Temperature
	4. Energy Input Ratio as a Function of Flow Fraction
	5. Part Load Fraction as a Function of Part Load Ratio
Cooling	6. Total Cooling Capacity as a Function of Temperature
	7. Total Cooling Capacity as a Function of Flow Fraction
	8. Energy Input Ratio as a Function of Temperature
	9. Energy Input Ratio as a Function of Flow Fraction
	10. Part Load Fraction as a Function of Part Load Ratio

An example equation, case 1 from Table 36, is shown below. The letter coefficients for the equation are determined by regression and entered into the EnergyPlus IDF file. During the simulation, the equation is solved based on the simulation step temperature conditions and the entered coefficients. The resulting factor is then multiplied by the rated total heating capacity to yield the total heating capacity at the operating temperature conditions.

$$1.\ TotCapTempModFac = a + b(T_{db,i}) + c(T_{db,i})^2 + d(T_{db,o}) + e(T_{db,o})^2 + f(T_{db,i})(T_{db,o})$$

In regards to the forced-air gas furnace equipment, EnergyPlus models a standard system with a default efficiency of 80%, rather than a high-efficiency condensing unit. An enquiry was made to the EnergyPlus support team regarding the best way to address this issue, as it is desired to model the highest possible efficiency for the Traditional operating mode case. The response explained that although the efficiency value for the unit can be changed in the input file, the performance data required to modify the standard performance curve relationship is not readily available. As a result, the forced-air gas furnace efficiency was set to 90% without implementing the performance curve feature. This efficiency was chosen to meet the minimum required level specified in the Ontario Building Code (OBC, 2006) and hence required by the R-2000 standard. Although there are obvious implications of using a lower efficiency unit, namely larger heating energy use for the benchmark case, the importance of carrying out accurate simulations with known input data was deemed more important at this point.

6.1.11 HVAC System Sizing

HVAC equipment should be sized to meet building heating and cooling loads in order to maximize the operating efficiency and minimize energy use. This was done in several different ways based on the equipment type.

As previously discussed, the air-source heat-pump model was created using the performance data from a 1.5–5 ton capacity Carrier unit. Due to the relatively small footprint of the core zone and the intermediate perimeter zone temperatures, the heating and cooling loads in Gemini mode are small. As a result, the heat pump model was modified to create a 0.5-ton unit by adjusting the heating and cooling coil capacity and flow rate values. The corresponding SI units for the 400 cfm/ton performance rating point are shown in Table 37 and the smaller system is obtained by dividing the values in half to yield the flow rate and capacity for a 0.5-ton unit.

Table 37: Modified heat pump airflow and capacity values.

Heat Pump	Flow Rate	Capacity
Rating Point	400 cfm = 0.189 m^3/s	1 ton = 3517 W
Scaled System	200 cfm = 0.0945 m^3/s	0.5 ton = 1760 W

The effect of this adjustment is that a smaller air-source heat pump operating according to the performance of the larger unit is modeled. This is a reasonable approach for this phase of the work as the intent is to assess the building design rather than the performance of specific equipment.

The forced-air gas furnace components were sized using the EnergyPlus autosizing feature. This allows unit capacities and flow rates to be assessed based on winter and summer design day simulations. After several trials, the model was set up with the thermostat located in the perimeter zone to ensure that it reached the 20^{o}C setpoint, which did not occur with the thermostat located in the core zone.

6.1.12 Occupant Behaviour

Occupants can have a significant impact on the energy use of a home. For example, a study by the Canadian Centre for Housing Technology (CCHT) showed that energy savings of 12% (combined gas and electricity) are possible with a day and night thermostat setback of 4^{o}C in a home built to R-2000 standards (CMHC, 2005). The NTED™ system provides occupants with operating mode options that are intended to allow greater reductions of heating energy than is possible with typical home designs.

Occupants can impact building heating energy use directly, through intentional adjustments to the building operating mode, and indirectly, by the heat gains resulting from their presence and their use of equipment. In order to quantify the effect of the operating mode on NTED™ heating energy use, an occupant profile was created and applied in three different scenarios. The gains are set to reflect the occupied floor space by adjusting the lighting loads but maintain constant occupation and usage rates for appliances and domestic hot water across all operating scenarios. The intention of this setup is to isolate the heating loads and determine how the heating energy use is affected by the operating mode when the building is occupied.

The occupant schedule (Table 38) was based on 3 people with full occupation at night and on holidays, no occupation during the day from Monday to Friday and partial occupation on weekend days. Appendix F, Figure F1 shows the IDF entry for the occupant schedule.

Table 38: Occupant schedule details.

Days	Occupation	Time
Week nights	100%	5:00 pm – 8:00 am
Week days	0%	8:00 am – 5:00 pm
Holidays	100%	8:00 am – 5:00 pm
Weekend nights	100%	5:00 pm – 10:00 am
Weekend days	50%	10:00 am – 5:00 pm

Appliance, lighting and domestic hot water loads were based on average Canadian household usage (NRCan, 2004). Table 39 shows the total residential floor area for the Canadian housing stock and includes the composite percentage of single-family attached and detached homes.

Table 39: Residential floor area for Canadian housing stock.

Canadian Residential Stock	Floor Area [m2]
Total residential	1.545×10^9
Single family attached & detached	1.197×10^9
% Single-family (SF) homes	77%

The information in Table 39 was used in conjunction with the total Canadian energy use by residential end use as shown in Table 40 to calculate the various loads per unit of single-family dwelling floor area. The calculated rates were activated at all times according to the schedules shown in Appendix F, Figure F2 to yield the total annual usage values. Appendix F, Figure F3 shows the calculations to obtain these results including an adjustment to the appliance load to remove the freezer unit from the total as well as a back-calculation to verify that the calculated rate would yield the correct annual total usage. The resulting lighting load of 1.31 W/m^2 was applied to the core and occupied perimeter zones. The domestic hot water load of 7.14 W/m^2 and net appliance load of 3.57 W/m^2 were applied to the core zone only.

Table 40: Average equipment energy use for Canadian single-family homes.

Equipment	Energy Use by End Use [W]	Single-Family Home Energy Use [W]	Single-Family Energy Use Per Unit Area [W/m^2]
Appliances	5.882×10^9	4.557×10^9	3.57
Lighting	2.023×10^9	1.567×10^9	1.31
Domestic hot water	1.1025×10^{10}	8.542×10^9	7.14

The occupant activity schedule (Appendix F, Figure F4) was set by assuming an average value of 125 W/person at all times. This schedule is combined with the occupancy schedule to apply the gains when people are in the building. The EnergyPlus Input Output Manual (LBNL, 2008b) provides a table to relate the input [W/person] to the ASHRAE Fundamentals (2005) heat generation values for a variety of activities. The chosen value represents a standing, relaxed person and corresponds to the ASHRAE value of 70 W/m^2.

A clothing schedule (Appendix F, Figure F5) was also set to reflect the level of dress that would be likely for occupants based on the climate in Toronto, Canada, as shown in Table 41. The schedule uses [clo] values, which provide an estimate of the insulation level of clothing (ASHRAE, 2005).

Table 41: Occupant clothing schedule details.

Date	[clo]	Equivalent Clothing
January 1 – April 30	1.0	pants, long-sleeved shirt, sweater
May 1 – September 30	0.5	pants, short-sleeved shirt
October 1 – December 31	1.0	pants, long-sleeved shirt, sweater

The occupant schedules and equipment loads are applied in the three occupant scenarios outlined to follow.

Best Case: Gemini-Occupied

1. Building operating in Gemini mode for the entire simulation period.
2. 20^{o}C core and 5^{o}C perimeter temperature setpoint.
3. Core-only appliance, lighting, domestic hot water and ventilation loads.

Medium Case: Moderate-Occupied

1. Building operating in Gemini mode on weekdays and Traditional mode on weekends and holidays according to Table 42.

Table 42: Moderate-Occupied operating mode accounting for 2009-2010 calendar year.

Month	# Days	# Weekdays (Excluding Holidays)	# Weekend Days	# Holidays
October	31	21	9	1
November	30	21	9	0
December	31	21	8	2
January	31	20	10	1
February	28	19	8	1
March	31	23	8	0
April	30	20	8	2
May	31	20	10	1
Total	243	165	70	8
Percent of Total		68%	32%	

2. The Moderate case energy use is calculated from the Gemini and Traditional mode simulation results using a weighted average according to: $Q_{Moderate} = 0.32Q_{Traditional} + 0.68Q_{Gemini}$
3. Appliance, lighting, domestic hot water and ventilation loads are according to the composite Gemini and Traditional mode cases.

Worst Case: Traditional-Occupied

1. Building operating in Traditional mode for the entire simulation period.
2. 20°C core and perimeter temperature setpoint.
3. Core-only appliance and domestic hot water loads, core and perimeter lighting and ventilation loads.

6.1.13 Insulated Shutters

The NTED™ building configuration lends itself well to the use of passive devices such as insulated window shutters. The intended use for the shutters is to reduce core heat losses at night when solar gains are not available and views to the exterior are not necessary. In order to assess the maximum benefit, a basic schedule was implemented that would apply the shutters every day between 10:00pm and 7:00am.

The insulating value for the shutters was established assuming the equivalent protection that would be provided by approximately 0.073 m of XPS insulation with a conductivity of 0.034 W/m K applied over the defined core window construction. This configuration was set to achieve an RSI 2.1 (R12) insulating value, which is almost two-and-a-half times greater than an example RSI 0.9 (R5) shutter described in a paper from the National Research Council of Canada (Quirouette, 1980).

6.1.14 Summary Simulation Matrix

The final simulation matrix for energy use comparison, shown in Table 43, is divided into three main categories – geometry, wall construction and occupant behaviour. The geometry and wall construction simulations were completed without occupants to isolate the effect of building configuration on heating energy use.

The geometry category involves the operating modes (1-2) with the standard R-2000 insulation levels (9) simulated against each of the house orientations (3-5).

The wall construction variations see the Gemini operating mode (2) in Baseline orientation (3) simulated against all of the insulation thickness combinations (6-11). Because the building is operated at a single temperature setpoint in Traditional mode (1), the Baseline orientation (3) is simulated only against each of the perimeter insulation levels (8, 9, 10).

The occupant behaviour category involves the Baseline geometry (3) and R-2000 wall construction (9) simulated against each of the occupant behaviour variations (12-14).

The energy-saving devices category investigates the insulated shutters applied to the core windows of the Baseline building (3) with R-2000 wall construction (9) and the Gemini-Occupied building (15).

Table 43: Simulation matrix.

Operating Mode	Geometry	Wall Construction	Occupant Behaviour	Energy-Saving Devices
1. Traditional 2. Gemini	3. Baseline 4. Square 5. 90^o Baseline	6. c4-p4 7. c4-p6 8. c6-p4 9. c6-p6 10. c6-p12 11. c12-p6	12. Traditional-Occupied 13. Gemini-Occupied 14. Moderate-Occupied	15. Gemini-Occupied Shutters

6.2 ANTICIPATED RESULTS AND COMPARISON METHOD

It is anticipated that questions will arise regarding the validity of the energy use comparisons chosen for this study. Specifically, the fact that fuel sources and equipment, as well as the occupied floor areas, are different between the Gemini and Traditional operating modes, may be areas of concern.

It should be understood that the NTED™ concept is not to be considered a typical residential design that would be compared in the same way as traditional homes. The proposed design involves a flexible living space that can expand or contract in response to operating needs, weather conditions and/or energy prices. As a result, unlike typical studies where the building design and construction would be fixed in order to evaluate different HVAC systems, the NTED™ principles link the HVAC system and building envelope configuration to form integral parts of the building's heating energy strategy.

Several considerations will be made in order to account as well as possible for the changes in comparison to a typical study. First, when considering a comparison of an air-source heat pump operating at a COP of 3 or more and a forced-air gas furnace operating at a 90% efficiency, it is to be expected that a minimum energy savings of slightly more than a factor of 3 should be demonstrated. Second, the heating energy use values will be presented both as overall seasonal totals as well as per unit of habitable floor area, to accommodate the change in footprint between the total-building and core-only areas. In some respects this will provide a more accurate representation of the energy use, as it will be related to the occupied space.

6.3 INITIAL SIMULATION RESULTS – MODEL TROUBLESHOOTING

A variety of trials were performed with the chosen software and simulation settings to evaluate the results and determine the best setup to run the final simulation matrix.

6.3.1 DesignBuilder Issues and Resolution

For the first round of simulation runs, the model was created using DesignBuilder for the geometry and materials definition and EnergyPlus for the HVAC setup. It would have been preferred to use DesignBuilder for all HVAC setup other than the modified heat pump but this proved not to be possible. An investigation into the DesignBuilder HVAC templates was carried out by selecting several systems in DesignBuilder and inspecting the resulting IDF files in EnergyPlus. The templates proved to define complex commercial systems and neither a residential forced-air gas furnace nor electric baseboard heaters were available in the then-current version of DesignBuilder.

An additional review of the DesignBuilder IDF file was carried out to assess the geometry and materials definitions. This process revealed some issues that make modification of the file within the EnergyPlus environment somewhat challenging. From an identification perspective, in DesignBuilder, materials are listed by logical names and zones are labeled by the user. However, these names are linked to numeric values that populate the IDF file. In other words, it can be difficult to identify the materials and zones in the EnergyPlus file. In addition, although it appears that the user can define the zone geometry based on the coordinate origin of (0, 0, 0), in actual fact, clicking on the origin in DesignBuilder results in an origin with up to ten decimal places. Figure 43 shows an example of the DesignBuilder origin issue where the Vertex 3 point is given by (0.7518261394, -0.345, 0). This makes geometry modification in EnergyPlus more complicated than necessary, as the coordinates must be adjusted using the same level of accuracy to ensure that all of the zones are enclosed and no gaps or voids remain between adjacent vertices.

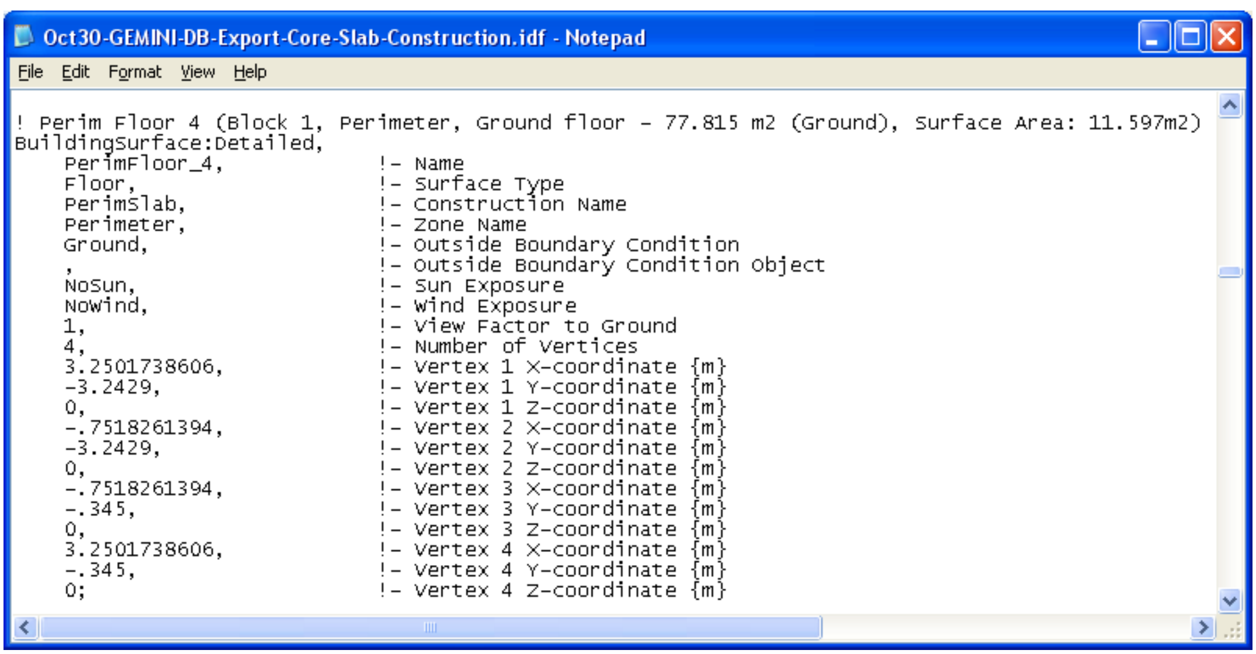


Figure 43: Building origin coordinates in exported DesignBuilder IDF.

Because of the input geometry issues and difficulties editing the exported DesignBuilder information in the EnergyPlus environment, it was decided to attempt input of geometry directly into EnergyPlus. Two test simulation files were created and run for comparison purposes. The first file used the EnergyPlus HVAC setup with the DesignBuilder geometry and the second file used EnergyPlus-entered HVAC and geometry. Upon comparison of the heating energy demand, it was somewhat unexpected to find that the result from the DesignBuilder geometry file (Table 44, case 1) was more than double that of the EnergyPlus geometry version (Table 44, case 2).

Table 44: Heating demand from initial-stage slab construction study.

Slab Construction Configuration	Simulation Heating Demand [W]
1. DesignBuilder perimeter slab void	1494
2. EnergyPlus full perimeter slab	732

Careful comparison of the two input files revealed that the data were consistent for all areas except for the geometry. As with the previously described material and zone naming changes, the DesignBuilder geometry was unclear and required more detailed study for clarification. It was discovered that the perimeter floor slab construction was defined as a series of rectangles rather than as one individual rectangle for the entire area. A plot of the coordinates revealed the geometry shown in Figure 44.

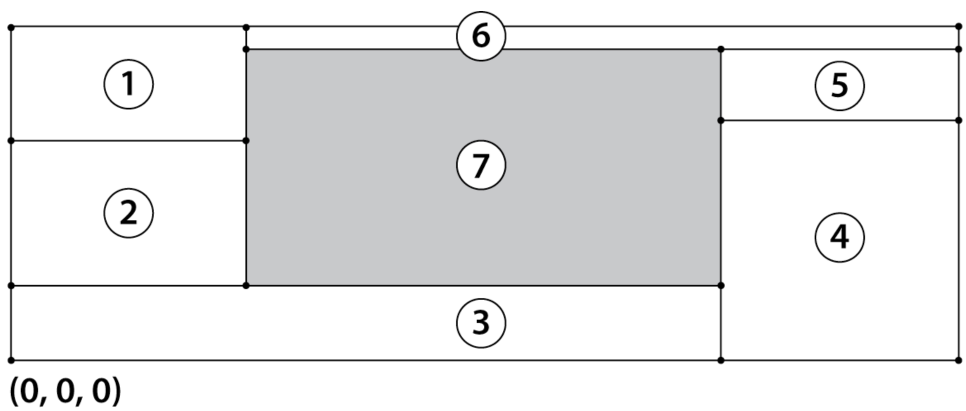


Figure 44: DesignBuilder NTED™ floor slab definition.

Table 45 shows a simplified example of the coordinates that defined both the perimeter and core zone floor slab in the DesignBuilder version of the IDF file. It can be seen that area 7 is represented as the core zone floor slab but is not included as part of the perimeter zone. In order to explain the resulting heating energy demand difference it was theorized that entered geometry is not treated as an entire building, rather individual zones are considered separately. This would occur when the EnergyPlus simulation describes the system as a series of equations that are solved to obtain the energy results. The end effect of area 7 being omitted from the perimeter floor slab is a void equal to the core area creating a direct path for heat loss to the ground and resulting in resulting in a significant increase in heating load for the zone.

Table 45: DesignBuilder floor slab coordinates.

Rectangle	Zone	Upper Left	Lower Left	Lower Right	Upper Right
1	Perimeter	(0, 8, 0)	(0, 5.5, 0)	(4, 5.5, 0)	(4, 8, 0)
2	Perimeter	(0, 5.5, 0)	(0, 2, 0)	(4, 2, 0)	(4, 5.5, 0)
3	Perimeter	(0, 2, 0)	(0, 0, 0)	(16, 0, 0)	(16, 2, 0)
4	Perimeter	(16, 6, 0)	(16, 0, 0)	(20, 0, 0)	(20, 6, 0)
5	Perimeter	(16, 7.5, 0)	(16, 6, 0)	(20, 6, 0)	(20, 7.5, 0)
6	Perimeter	(4, 8, 0)	(4, 7.5, 0)	(20, 7.5, 0)	(20, 8, 0)
7	Perimeter	not defined	not defined	not defined	not defined
7	Core	(4, 7.5, 0)	(4, 2, 0)	(16, 2, 0)	(16, 7.5, 0)

In order to verify this theory, a third model was created in which the floor slab construction was added to the DesignBuilder geometry version to fill in the area 7 void. The result of this trial showed good agreement between the heating demand values for the EnergyPlus geometry (Table 46, case 2) and the modified DesignBuilder geometry (Table 46, case 3), which are within 3%. Conversely, the EnergyPlus geometry (Table 46, case 2) is only 49% of the DesignBuilder initial heat loss (Table 46, case 1).

Table 46: Heating demand from final-stage slab construction study.

Slab Construction Configuration	Simulation Heating Demand [W]
1. DesignBuilder perimeter slab void	1494
2. EnergyPlus full perimeter slab	732
3. DesignBuilder slab void filled in	757

Due to the uncertainty of the translation between DesignBuilder input and the EnergyPlus IDF, it was decided to use EnergyPlus exclusively for the model setup and simulation work. DesignBuilder did prove useful in some instances, for example to assess how a particular feature is populated in EnergyPlus. Glazing systems can be created in DesignBuilder where the inputs are well-defined and described with logical names. Also, activation of a feature such as infiltration in DesignBuilder allows review of the necessary inputs in the EnergyPlus environment. Finally, the general simulation settings, as populated by DesignBuilder, provide a helpful starting point for creating an EnergyPlus model file. Once the fields that should be populated are revealed, the EnergyPlus Input Output Reference Manual (LBNL, 2008b) can be consulted for details.

6.3.2 Impact of Core Infiltration With Outdoor Air

Once the model input process was determined and the IDF files were created according to the NTED™ simulation matrix, the core infiltration study was performed. As described previously, it was determined that the infiltration object uses outdoor air, rather than perimeter zone air as would be the case for the NTED™ building operating in Gemini mode. As a result, two trial simulations were performed to determine the difference in heating energy use that occurs in the Gemini-operated building with active core infiltration according to the defined settings and with the core infiltration set to zero. As can be seen in Table 47, the core infiltration case shows a 5% increase in the heating load over the zero infiltration scenario.

Table 47: Impact of core infiltration on Gemini mode heating energy use.

	Matrix Combination				Heating Energy Use [kWh]	Energy Savings
(a)	2. Gemini	3. Baseline	9. C6-P6	Core infiltration	1253	5%
(b)	2. Gemini	3. Baseline	9. C6-P6	No core infiltration	1186	

Because the NTED™ design is intended to be operated with the core slightly depressurized with respect to the perimeter, there will be an energy impact from infiltrating perimeter air. Since the trial simulations showed a relatively small effect of the overestimated energy use, the choice was made to complete the simulation matrix with the core infiltration active while the building is operating in Gemini mode. This will provide a conservative estimate for the Gemini mode heating energy use.

The energy use values were obtained by setting the relevant Output:Meter objects to report monthly and run period totals as shown in Appendix G. The meter files provide the energy use for each selected category in Joules [J] and these values were totaled and converted to a kilowatt hour [kWh] value for the run period. Appendix H provides the calculations to obtain the [kWh] values for all presented simulation results.

7.0 RESULTS AND DISCUSSION OF ADVANCED MODEL SIMULATIONS

After correcting the model errors and verifying the input data, the simulation matrix was run and the results analyzed. The following provides a summary and discussion of the results.

7.1 FINAL SIMULATION RESULTS

The final results confirm the preliminary modeling work and show that the NTED™ design has a significant potential for heating energy reductions as compared to the benchmark R-2000 building.

7.1.1 Comparison to Preliminary Modeling

The first analysis point was to evaluate the EnergyPlus simulation results with the same configurations used in the conservative initial HOT2000 calculations. This involves a comparison of the heating energy use with the building operating in Gemini and Traditional modes. It can be seen that the EnergyPlus model results in larger heating energy differences than were calculated with the HOT2000 model. Table 48 shows the heating energy use and demonstrates a savings of 85% when operating in Gemini versus Traditional mode.

Table 48: Comparison to preliminary simulation results.

	Matrix Combination			Heating Energy Use [kWh]	Energy Savings
(i)	1. Traditional	3. Baseline	9. C6-P6	8133	85%
(ii)	2. Gemini	3. Baseline	9. C6-P6	1253	

As was previously discussed, the total heating energy use is also considered on a per-unit-area basis (Table 49). In this case, taking into account the change in habitable area from 144 m^2 for Traditional mode to 72 m^2 for Gemini mode, the Traditional heating energy use is 56 kWh/m^2 compared to 17 kWh/m^2 in Gemini mode. This difference represents a savings of 70%.

Table 49: Energy use per unit of floor area.

	Matrix Combination			Heating Energy Use [kWh]	Heated Floor Area	Area-Based Energy Use	Energy Savings
(i)	1. Traditional	3. Baseline	9. C6-P6	8133	144 m2	56 kWh/m2	70%
(ii)	2. Gemini	3. Baseline	9. C6-P6	1253	72 m2	17 kWh/m2	

The initial simulation results demonstrated an overall savings of 74% and a per unit area savings of 31%. The increase in efficiency demonstrated by the EnergyPlus model can be attributed to the improved accuracy of the model input details and the simulation tool. For example, the sub-hourly EnergyPlus model is able to account for solar gains through the perimeter glazing. Also, the inter-zone heat pump operates based on equipment performance data and operating temperature conditions, which result in a COP varying from 3.5

to 4.0. This was verified by using a database program (FileMaker, 2010) to calculate and sort the COP values for the over 23,000 time steps from the Gemini simulation.

The zone temperature distributions for the Gemini and Traditional operating mode simulations were also evaluated using FileMaker Pro. Table 50 shows the Gemini mode case where it can be seen that the core zone temperature was maintained with a high level of accuracy throughout the simulation period. This means that the inter-zone heat pump was functioning as desired and delivering the necessary heating load. The largest temperature deviation occurred in the perimeter zone where the temperature dropped below the 5^{o}C setpoint by a maximum of 0.6^{o}C for 1% of the simulated time. This represents a combined total of 2.43 days of the 243-day period. A check of the perimeter zone heating energy use revealed that this minimal decrease was not sufficient to activate the electric baseboard heaters. In other words, the core heat losses and perimeter solar heat gains are sufficient to maintain the perimeter temperature such that supplementary heat is not required even with the heat pump removing heat for delivery to the core.

Table 50: Gemini mode heating season zone temperature distribution.

Zone	Setpoint	Temperature Below Setpoint	Zone Minimum Temperature
Core	20^{o}C	< 19.9^{o}C = 0%	19.9^{o}C
Perimeter	5^{o}C	< 4.9^{o}C = 1%	4.4^{o}C

A sample single-day (January 21st) temperature distribution with the building operating in Gemini mode is provided in Figure 45. The outdoor temperature can be seen to stay below 0^{o}C for approximately 8 hours of the 24-hour period. In addition, it is approximately 10^{o}C in the perimeter zone, while the core maintains the 20^{o}C setpoint throughout the day.

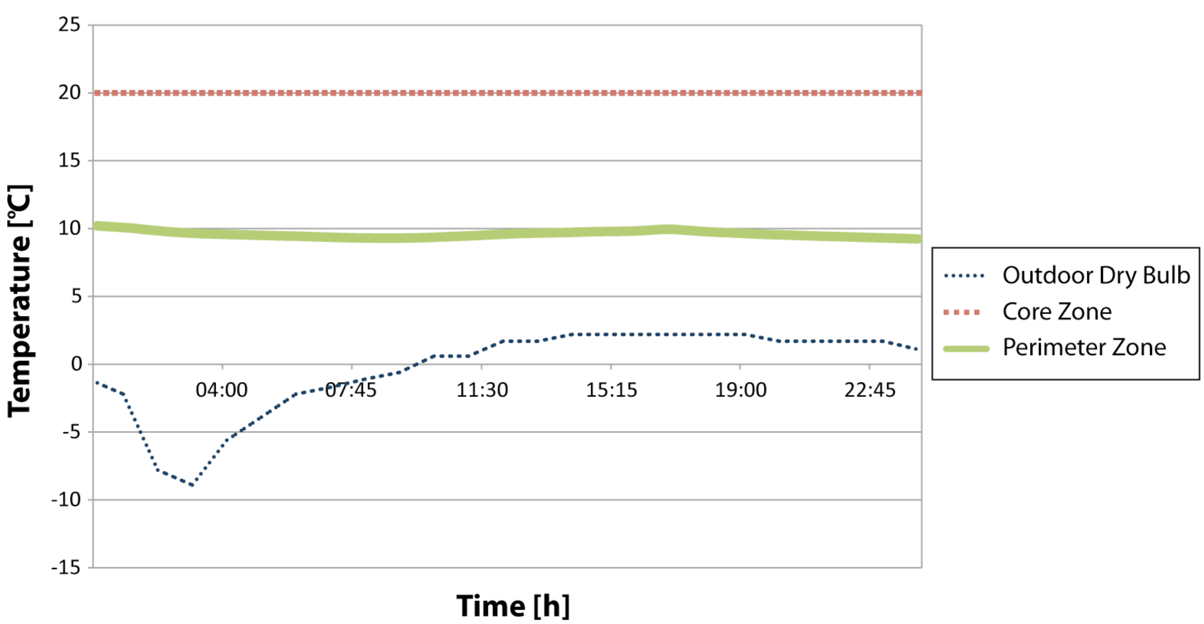


Figure 45: NTED™ Gemini mode temperature distribution for January 21.

Table 51 shows the results of the temperature distribution analysis with the building operating in Traditional mode. In this case, the perimeter zone temperature (the thermostat location) maintains the temperature setpoint throughout the simulation period. The setpoint is not maintained as well in the core zone however, where it is under-achieved for the majority of the simulation period. The end result is that the total reported heating energy for the benchmark Traditional operating mode is actually somewhat less than it should be which causes underestimated energy differences between the Gemini and Traditional mode cases.

Table 51: Traditional mode heating season zone temperature distribution.

Zone	Setpoint	Temperature Below Setpoint	Zone Minimum Temperature
Core	20°C	< 19.9°C = 99%	18.5°C
Perimeter	20°C	< 19.9°C = 0%	19.9°C

The sample single-day (January 21st) temperature distribution for the building operating in Traditional mode is provided in Figure 46. In this case, the perimeter zone maintains the 20°C setpoint while the core can be seen to remain slightly below the 20°C setpoint throughout the day.

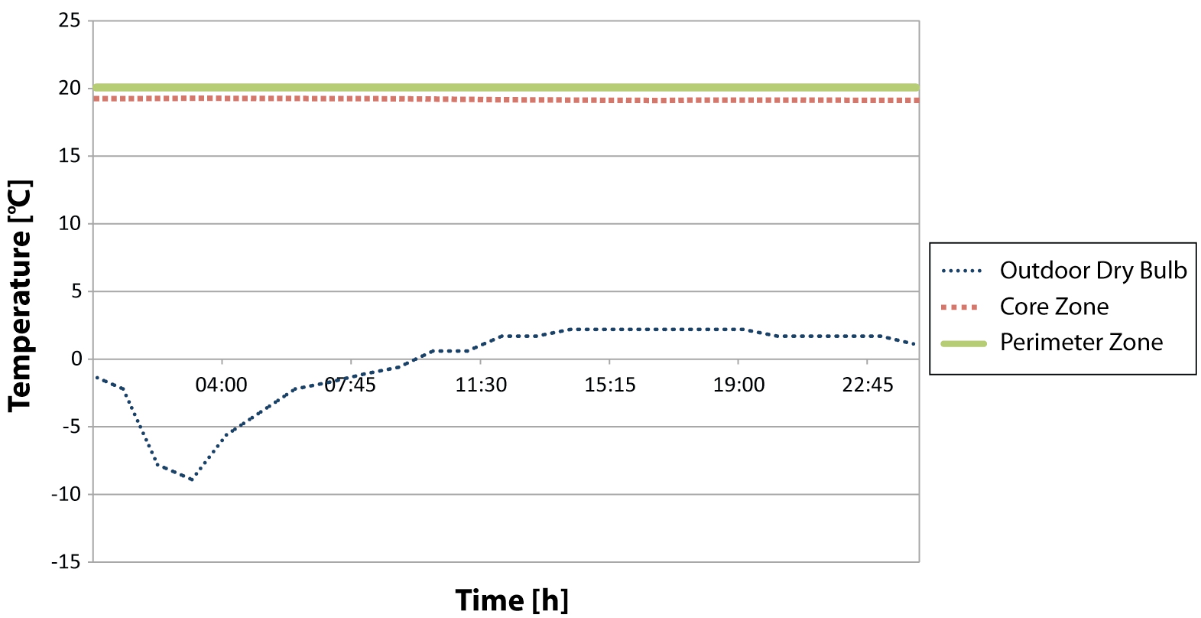


Figure 46: NTED™ Traditional mode temperature distribution for January 21.

7.1.2 Geometry

Table 52 shows the results of the geometry simulation category where the effect of three different building configurations on the heating energy use is investigated when operating in Gemini and Traditional modes.

Table 52: Geometry simulation results.

Matrix Combination				Heating Energy Use [kWh]
(i)	1. Traditional	3. Baseline	9. C6-P6	8133
(iii)	1. Traditional	4. Square	9. C6-P6	8331
(iv)	1. Traditional	5. 90° Baseline	9. C6-P6	8783
(ii)	2. Gemini	3. Baseline	9. C6-P6	1253
(v)	2. Gemini	4. Square	9. C6-P6	1313
(vi)	2. Gemini	5. 90° Baseline	9. C6-P6	1348

Comparing the Baseline (i) & (ii) to the Square (iii) & (v) configurations shows a difference of 5% or less in heating energy requirement when operating in both Gemini and Traditional modes. A Baseline (i) & (ii) to 90° Baseline (iv) & (vi) configuration comparison shows less than a 10% difference in heating energy requirement in Gemini and Traditional modes. These results are shown in Table 53.

Table 53: Geometry simulation relationships.

Matrix Combination				Heating Energy Use [kWh]	Energy Savings
(i)	1. Traditional	3. Baseline	9. C6-P6	8133	2%
(iii)	1. Traditional	4. Square	9. C6-P6	8331	
(ii)	2. Gemini	3. Baseline	9. C6-P6	1253	5%
(v)	2. Gemini	4. Square	9. C6-P6	1313	
(i)	1. Traditional	3. Baseline	9. C6-P6	8133	7%
(iv)	1. Traditional	5. 90° Baseline	9. C6-P6	8783	
(ii)	2. Gemini	3. Baseline	9. C6-P6	1253	7%
(vi)	2. Gemini	5. 90° Baseline	9. C6-P6	1348	

These results suggest that the building design is not highly sensitive to orientation, making it appropriate for urban and retrofit applications where solar access is limited and/or building orientation is predetermined.

7.1.3 Wall Construction

Table 54 shows the results of the wall construction study. This work was intended to determine how the wall insulation values affected the heating energy use. When comparing the Gemini operating modes it can be seen that the perimeter insulation has a greater effect on reducing heating energy use than does core insulation. This is illustrated by the greater energy use in scenarios (xi) C6-P4 & (xiii) C12-P6 compared to the opposite configurations (x) C4-P6 & (xii) C6-P12.

Table 54: Wall construction simulation results.

Matrix Combination				Heating Energy Use [kWh]
(vii)	1. Traditional	3. Baseline	8. C6-P4	9533
(i)	1. Traditional	3. Baseline	9. C6-P6	8133
(viii)	1. Traditional	3. Baseline	10. C6-P12	6550
(ix)	2. Gemini	3. Baseline	6. C4-P4	1412
(x)	2. Gemini	3. Baseline	7. C4-P6	1294
(xi)	2. Gemini	3. Baseline	8. C6-P4	1375
(ii)	2. Gemini	3. Baseline	9. C6-P6	1253
(xii)	2. Gemini	3. Baseline	10. C6-P12	1121
(xiii)	2. Gemini	3. Baseline	11. C12-P6	1209

This difference can be anticipated due to the greater temperature difference between the perimeter and exterior than between the core and perimeter areas, the larger perimeter surface area compared to that of the core, as well as the impact of wind and pressure differences on the exterior envelope. Table 55 shows the difference in surface area between the core and perimeter envelope. Note that the perimeter envelope is calculated with the building operating in Traditional mode and hence represents the whole-building exterior surface area i.e. including the slab area under the core.

Table 55: NTED™ core and perimeter surface areas.

	Wall Area [m²]	Slab Area [m²]	Ceiling Area [m²]	Total Area [m²]
Core	90	72	72	234
Perimeter	156	144	144	444
Reduction	42%	50%	50%	47%

Of additional interest from this phase is the impact of the perimeter insulation on the operating modes. Comparing the C6-P4 to C6-P12 cases for both the Traditional and Gemini modes shows a 31% decrease in energy use between the Traditional mode configurations (vii) & (viii) as compared to only a 18% decrease between the Gemini mode configurations (xi) & (xii). These results are shown in Table 56. Again this difference is supported by the smaller temperature difference between the interior and exterior conditions and the reduced exposed surface area in Gemini versus Traditional modes. This suggests that the thermal buffer that occurs when the NTED™ double-envelope is operating in Gemini mode decreases the reliance on a highly-insulated exterior envelope that would be necessary in a single-envelope building operating with one thermal zone.

Table 56: Impact of perimeter insulation on operating mode.

Matrix Combination				Heating Energy Use [kWh]	Energy Savings
(vii)	1. Traditional	3. Baseline	8. C6-P4	9533	31%
(viii)	1. Traditional	3. Baseline	10. C6-P12	6550	
(xi)	2. Gemini	3. Baseline	8. C6-P4	1375	18%
(xii)	2. Gemini	3. Baseline	10. C6-P12	1121	

7.1.4 Occupant Behaviour

The results of the occupant behaviour study are presented as total-heating-season energy-use values in Table 57, representing the combined internal gains and heating energy use.

Table 57: Heating season energy use simulation results including occupant gains and heating energy.

Matrix Combination				Heating Season Energy Use [kWh]
(xiv)	3. Baseline	9. C6-P6	12. Traditional-Occupied	10342
(xvi)	3. Baseline	9. C6-P6	14. Moderate-Occupied	6820
(xv)	3. Baseline	9. C6-P6	13. Gemini-Occupied	5156

These results are also presented graphically in Figure 47 where it can be seen that occupants operating the building in Gemini mode cause a 50% reduction in energy use for the total heating season relative to the benchmark Traditional case. The Moderate occupant mode, where the building uses Gemini mode during the week and Traditional mode on weekends and holidays, represents a 34% savings in total heating season energy use relative to the Traditional mode case.

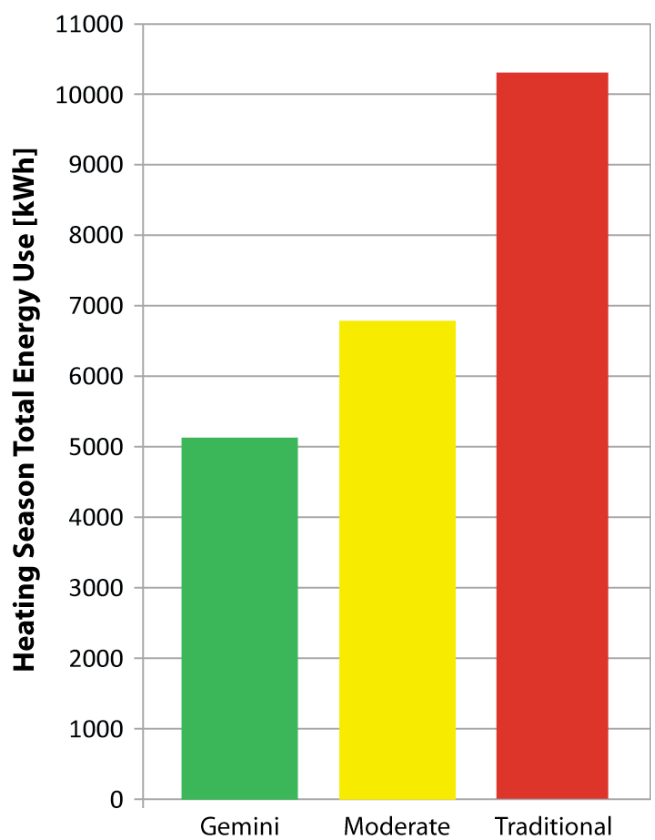


Figure 47: Comparison of energy use over the heating season for occupied-building operating modes.

Because the gains are set to similar levels, with changes only for the occupied-perimeter lighting load, the difference in total energy use between the three scenarios can be attributed largely to the heating loads. This can be seen in Table 58 where the heating energy use values for the occupied building are presented. In this case, the occupant internal gains are sufficient to maintain the temperature setpoint in Gemini mode and the very small heating energy value represents only the ventilation component.

Table 58: Simulation results showing occupant behaviour heating energy use.

Matrix Combination				Heating Energy Use [kWh]
(xiv)	3. Baseline	9. C6-P6	12. Traditional-Occupied	3644
(xvi)	3. Baseline	9. C6-P6	14. Moderate-Occupied	1243
(xv)	3. Baseline	9. C6-P6	13. Gemini-Occupied	109

Again, these values are presented graphically in Figure 48. The Gemini operating mode displays a 97% savings in heating energy use from the Traditional mode while the Moderate case represents a 66% savings over the Traditional benchmark. Evaluating the Gemini and Traditional mode heating energy use on a per unit area basis shows a 1.5 kWh/m^2 load for the Gemini case and a 25 kWh/m^2 for the Traditional case which represents a savings of 94%.

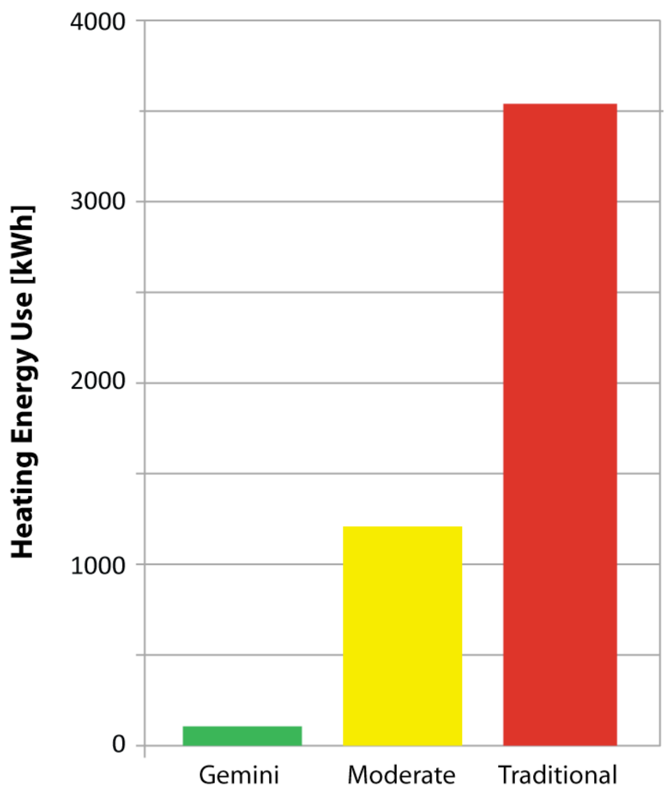


Figure 48: Isolated heating season energy use comparison for occupied-building operating modes.

This study demonstrates that the flexibility offered by the NTED™ design provides the potential for occupants to achieve significant energy savings during the heating season through varied space use.

7.1.5 Insulated Shutters

During the EnergyPlus model setup process, it was discovered that a software limitation would prevent a straightforward study of insulated shutters on the core windows. Specifically, while EnergyPlus allows insulated shutters to be activated and deactivated based on a usage schedule, they cannot be installed on interior windows. As a result, several other trials were attempted in an effort to quantify the shutter impact.

The intention was to take the thermal resistance value for the window with the insulated shutter installed and apply it in several different window-opening constructions. Three different scenarios (Table 59, cases 15b, 15c, 15d) were established and simulated as full shutter activation. In other words, the shutters were in place throughout the entire simulation period.

Table 59: Core window configurations used to simulate insulated shutters.

Scenario		Details
15a.	Standard Glazing	No changes to the core windows.
15b.	Conductivity	Modified glazing conductivity values.
15c.	Core Doors	Door sub-surface implementation.
15d.	No Windows	Elimination of core windows.

The energy savings (Q_{total}) resulting from the shutter use was to be calculated using a weighted average for the 37.5% shutter utilization rate with the 62.5% no-shutter base case (15a) as follows.

$$Q_{total} = 0.625(Q_{15a}) + 0.375(Q_{15b,c,d})$$

For the first modified trail (15b), the EnergyPlus glazing conductivity values were increased to reflect the applied shutters. Table 60 shows the original and adjusted conductivity values for each of the window layers. Glass layers in the modified case are adjusted to include half of the shutter insulating value, derived as outlined to follow.

$k_{XPS} = 0.034$ W/m K $k_{glass} = 0.9$ W/m K

$t_{XPS} = 0.0734$ m $t_{glass} = 0.003$ m

$R_{XPS} = 2.16$ m^2 K/W $R_{glass} = 0.003333$ m^2 K/W

Divide R_{XPS} in half to apply value to each glass layer.

$$\tfrac{1}{2} R_{XPS} = 1.08 \text{ m}^2 \text{ K/W}$$

Add ½ R_{XPS} to R_{glass} and calculate resulting conductivity value.

$$R_{modified} = 1.08 + 0.003333 = 1.083333 \text{ m}^2 \text{ K/W}$$

$$k_{modified} = (1/R_{modified})(t_{glass})$$

$$k_{modified} = (1/1.083333 \text{ m}^2 \text{ K/W})(0.003\text{m}) = 0.002267 \text{ W/m K}$$

Table 60: Modified glass conductivity values to incorporate shutter insulating value.

Window Component	Original Conductivity [W/m K]	Modified Conductivity [W/m K]
glass	0.9	0.00277
argon	0.0177	0.0177
glass	0.9	0.00277

The second scenario (15c) involved replacing the core windows with a door sub-surface. The opaque door construction was considered to more accurately reflect the insulated shutter format, unlike the first trial that maintained the window transparency. In this situation, the door was modeled as a single XPS layer with a thickness calculated to yield the same thermal resistance as that provided by the shutter applied over the glazing from the first case. The XPS thickness was calculated as follows.

$$R_{window} = 0.003333 + 0.734463 + 0.003333 = 0.741129 \text{ m}^2 \text{ K/W}$$

$$R_{shutter} = 2.16 \text{ m}^2 \text{ K/W}$$

$$R_{total} = 0.741129 + 2.16 = 2.9011 \text{ m}^2 \text{ K/W}$$

$$t_{XPS} = (k_{XPS})(R_{total}) = 0.034 \times 2.9011 = 0.0986 \text{ m}$$

The third trial was intended to compare the energy use values for a building with and without core windows. In this situation, the standard construction was compared to a modified building where the core windows were replaced with the R-2000 interior wall construction over the entire surface area.

It should be noted that for ease of comparison, each of the modified window opening cases was configured to have the same thermal resistance value – equal to the desired impact of the shutter applied over the core window unit. This thermal resistance value is 2.9 m^2K/W as shown in Table 61.

In the end, compared to the baseline Gemini-Occupied case where the heating energy use was 109 kWh, each of the modified insulated shutter cases demonstrated increased energy use (Table 61). However, there is less than a 10% difference between the base case lowest energy use and the highest energy use scenario.

Table 61: Insulated shutter simulation results.

Matrix Combination				Opening Detail	Opening RSI [m^2K/W]	Heating Energy [kWh]
(xv)	3. Baseline	9. C6-P6	13. Gemini-Occupied	15a. Standard Glazing	0.74	109
(xvii)	3. Baseline	9. C6-P6	13. Gemini-Occupied	15b. Conductivity	2.9	121
(xviii)	3. Baseline	9. C6-P6	13. Gemini-Occupied	15c. Core Doors	2.9	112
(xix)	3. Baseline	9. C6-P6	13. Gemini-Occupied	15d. No Windows	2.9	118

Because of the small differences in heating energy use and the ranking of the scenarios, an explanation for the results is not clear. It would be expected that cases 15c (xvii) and 15d (xix) would exhibit the same heating energy use given that the thermal resistance value of the construction was the same and both were opaque elements. It could also be anticipated that the 15b (xvii) case would exhibit a lower energy use, as the transparent nature of the construction should allow solar gains to enter the zone.

In any case, ignoring the ranking differences for the moment, the fact that the modified insulated window cases result in greater heating energy use than the base case could suggest that the core window heat gain is greater than the heat loss over the heating season. If this were the case, the overnight use of insulated shutters on the core windows would be beneficial. Because this study has proven to be inconclusive, further investigation is warranted to quantify the level of energy savings that would result.

A further point is that this study may suggest that improper building operation can have a negative outcome on the building energy use. Specifically, the use of insulated shutters during the day when solar gains are available could result in increased energy use. This suggests that occupant training and/or automated systems would be beneficial to help ensure energy-efficient operation.

7.1.6 Preliminary Comparison to the NREL/Habitat ZEH

The NREL/Habitat ZEH design principles are similar to that of the NTED™ concept. Because the occupied performance of the NREL/Habitat ZEH has been proven, it is of interest to determine how the home design compares to NTED™. The study described in this section provides a preliminary investigation into the performance of the NTED™ design when compared to an equivalent building constructed according the insulation levels used in the NREL/Habitat ZEH building.

While the performance results for the NREL/Habitat ZEH building are available (Christensen & Norton, 2007), a direct comparison to the EnergyPlus simulation results for the NTED™ is not ideal. In the first place, the study authors point out that the occupant energy load is a significant portion of the overall energy use, as was also found in the NTED™ case. As a result, the occupant schedules and appliance and lighting loads in the NTED™ model would need to be adjusted to reflect the NREL/Habitat ZEH operating conditions. In addition, the buildings are located in different climates with differing solar exposure and heating degree-day values. Finally, the total energy use numbers for the NREL/Habitat ZEH are for a full year of occupancy and hence also include cooling loads and occupant energy-use during the summer months, which were not considered for the NTED™ simulations in this research phase.

In order to perform a preliminary comparison between the NREL/Habitat ZEH and NTED™ designs, a new model was created in EnergyPlus to determine how the NREL/Habitat ZEH insulation levels compare to the baseline NTED™ design. The new building is referred to as the HFH model and was created using the Traditional-mode NTED™ building as a starting point. The NTED™ perimeter floor area, windows and construction materials were maintained in the HFH model with the only changes having been made to the perimeter ceiling height and the insulation RSI values. The HFH ceiling height was adjusted from the NTED™ perimeter value of 3 m (which accommodates the core envelope) to 2.5 m according to standard construction practices and the insulation RSI values were adjusted to represent the NREL/Habitat ZEH values. A summary comparison of the HFH building and the NTED™ perimeter is provided in Table 62.

Table 62: Comparison of HFH and NTED™ model parameters.

Building	Floor Area	Ceiling Height	Wall Insulation	Ceiling Insulation	Slab Insulation
NTED™ Perimeter	8 m x 18 m	3.0 m	0.140 m / RSI 3.5	0.305 m / RSI 7.6	0.05 m / RSI 1.5
HFH	8 m x 18 m	2.5 m	0.267 m / RSI 6.7	0.423 m / RSI 10.6	0.18 m / RSI 5.3

The simulations were performed with the building located in Toronto, Canada and the HFH version was run with and without building occupants. The occupancy schedules were set according to the NTED™ building. The lighting load was kept at a consistent unit area level to reflect the change in floor area while the appliance and domestic hot water loads for the HFH case were adjusted to yield the same overall usage to allow a direct comparison with the NTED™ cases. In other words, it is assumed that the occupants use appliances and domestic hot water at the same rate for each building. This requires an adjustment to provide the same total usage value because the appliance and domestic hot water loads for the NTED™ building are applied to an area of 72 m^2 compared to an area of 144 m^2 for the HFH building. A sample calculation for the modified appliance load is shown and the values are summarized in Table 63.

NTED™ appliance load: $(3.57\ W/m^2) \times (72\ m^2) = 257\ W$

HFH appliance load: $(257\ W) / (144\ m^2) = 1.79\ W/m^2$

Table 63: Equipment loads for HFH and NTED™ models.

Building	Appliance Load [W/m²]	Lighting Load [W/m²]	Domestic Hot Water Load [W/m²]
NTED™	3.57	1.31	7.14
HFH	1.79	1.31	3.57

The HFH home was operated with the same HVAC setup as the NTED™ Traditional mode. A forced-air gas furnace was used for heating and an ERV was operated at the same ventilation rate as the NTED™ Traditional mode. The HFH infiltration rates were also set to the NTED™ Traditional mode values.

The simulation results for the HFH cases are shown in Table 64 along with the corresponding NTED™ results. The NTED™ construction and building geometry can be determined by referencing the simulation numbers to the previously described results. Appendix I contains the summary input data and simulation results. With the unoccupied NTED™ building operating in Gemini mode throughout the heating season, an energy savings of 65% is observed over the HFH case. This energy usage expressed on a per unit area basis is 17 kWh/m^2 for Gemini NTED™ and 25 kWh//m^2 for the HFH case which is a savings of 32%. When the buildings are simulated with occupants, the total NTED™ savings are reduced to 12%. Of additional interest is that when the NTED™ building is operated in Moderate mode (weekday Gemini, weekend and holiday Traditional), the total energy use increases above the HFH energy usage case.

Table 64: Simulation results comparing NTED™ to HFH.

Building	Unoccupied Heating Energy Use [kWh]	Energy Savings	Occupied Total Energy Use [kWh]	Energy Savings
(xiv) NTED™ Traditional	8133		10342	
(xvi) NTED™ Moderate	n/a		6820	
(xv) NTED™ Gemini	1253	65%	5156	12%
HFH	3589		5891	

A further comparison point for the buildings is the amount of insulating material used in each case. While operational energy is an important component of sustainable building design, material selection and use also play a role in the environmental impact. Table 65 shows the HFH and NTED™ insulation volumes [m^3] for the wall, ceiling and floor areas. In the case of the NTED™ building, the wall and ceiling insulation is split between the core and perimeter areas. If the gross building volume were the same in both cases, this would result in a reduced insulation level for the NTED™ case. However, since the ceiling height is lower by 0.5 m in the HFH building than in the NTED™ perimeter, the net effect is the same insulation volume for both buildings. In the case of the ceiling and floor insulation levels, a savings of 11% and 73% respectively is demonstrated for the NTED™ building over the HFH design.

Table 65: Insulation material savings.

Building	Wall Insulation Fibreglass Batt [m^3]	Ceiling Insulation Fibreglass Batt [m^3]	Floor Insulation XPS [m^3]
NTED™	34	54	7
HFH	34	61	26
savings	0%	11%	73%

This insulation information could be used in one of two ways. The NTED™ building could be constructed as described resulting in a lower embodied energy impact due to the insulation material, or the NTED™ building insulation could be increased to equal that of the HFH building, resulting in an even greater energy savings.

8.0 FUTURE RESEARCH

As the results of this research phase reinforce the preliminary work and show that the NTED™ concept is promising, several additional areas remain to be investigated that would help gain a complete understanding of the overall energy saving benefits resulting from the NTED™ system.

8.1 ADVANCED MODEL LIMITATIONS AND AREAS FOR IMPROVEMENT

Building energy modeling is a complex process. As has been shown, there are many variables and inputs required to create a simulation input file. The intent of this research was to further the initial energy modeling performed to assess the potential of the NTED™ building design. While several important tasks have been completed with this work, primarily creation of a functioning inter-zone heat pump model, additional items have come to light that, with modification or refinement, could improve the accuracy of the NTED™ energy model. Several of the potential improvement areas are discussed to follow.

When carrying out comparative energy use analyses, the accuracy of the benchmark model is important to ensure that the calculated savings are true. To this end, further investigation into the forced-air gas furnace efficiency could be completed. Accurate representation of a condensing furnace would allow the Traditional-mode efficiency to be increased from the current 90% to 95% or higher according to units available in the local market. As an intermediate step, the forced-air gas heating energy use values could be decreased to represent the condensing model efficiency being considered.

As a further improvement to the occupied-building scenarios, air mixing between zones can be used to represent door and window openings. This information could be used to gain a more complete understanding of the impact of occupants on heating energy use.

A core infiltration value was established in an attempt to quantify the heating energy impact of operating the building with the core slightly depressurized with respect to the perimeter. As has been pointed out, the ability to model this situation accurately requires modification of the EnergyPlus source code to allow the infiltration object to use zone air rather than exterior air conditions.

The newly created inter-zone heat-pump model has been verified to ensure that it is applying the expected heating and cooling loads on the perimeter zone. However, while the current model calculates the correct total cooling load for the perimeter zone, this value is not being separated into its composite latent and sensible loads. Rather, the entire value is being applied to the perimeter as a sensible load. Establishing a means of breaking the total energy into the latent and sensible components would increase the core temperature and provide a more accurate representation of the energy available to heat the core.

For cases where it is intended to model an actual NTED™ building design, HVAC equipment details should be adjusted to represent the specified equipment. This is particularly true for the air-source heat pump and the ERV used when the building is operated in Gemini mode.

Extending to the real-life NTED™ building design scenario should also involve refinement of the internal gains loads. A custom model should move from the current average values, used to isolate the heating loads for operating mode comparison, to values based on energy-efficient equipment specifications and projected or actual usage rates for the particular home design.

Finally, as discussed, the impact of the core window insulated shutters was not quantifiable with the current version of EnergyPlus. This could be addressed through further source code modification to allow the insulated shutter object to be applied to interior windows. Other potential means to quantify their impact could also be proposed in an attempt to provide a more complete understanding for the heating energy savings potential of the NTED™ design.

8.2 CONSTRUCTION, MONITORING AND VALIDATION

The next phase of work for the NTED™ project is to apply the concept to an existing residential building allowing both performance measurements and simulation model validation. The building, shown in Figure 49, is located in Toronto, Canada. It is a University of Toronto property that will be inhabited and monitored by students to advance the NTED™ research agenda. A preliminary concept sketch of the proposed core (inner hatched area) and perimeter (outer hatched area) is also shown.

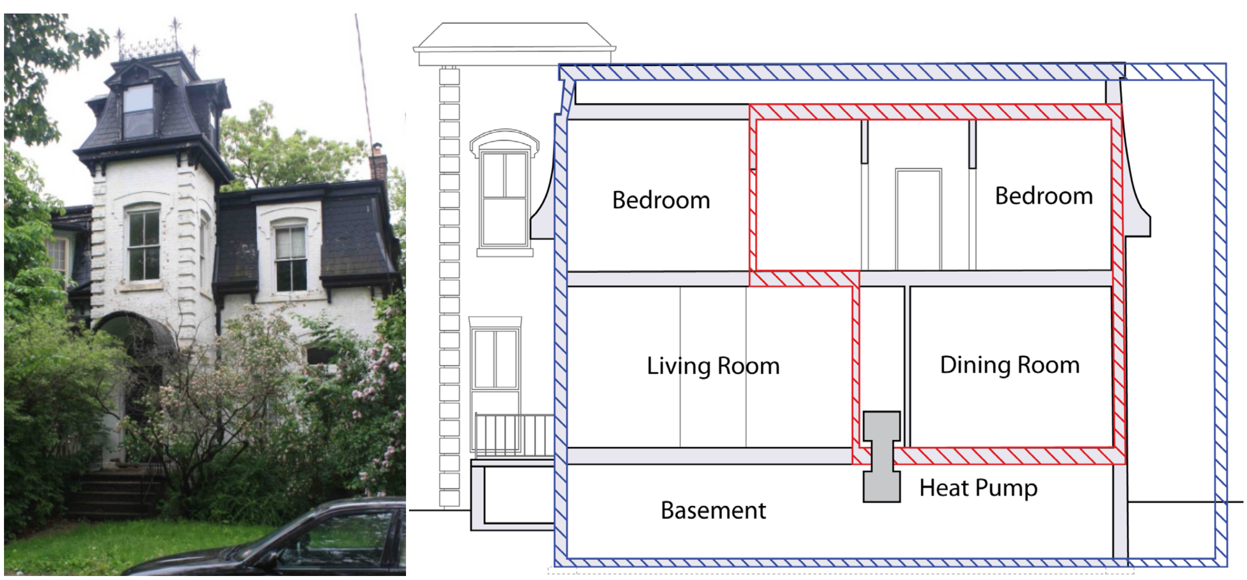


Figure 49: Toronto, Ontario house and initial design sketch for NTED™ retrofit.

8.3 SUMMER COOLING CASE

To this point, NTED™ research has focused on the winter heating case. This is understandable given the building's location in the heating-dominated climate of Toronto, Canada. However, the significant seasonal variation of the climate in this location also warrants consideration of the summer season where cooling may be desired. Figure 50 shows some of the aspects that could be included in a summer study of the NTED™ design.

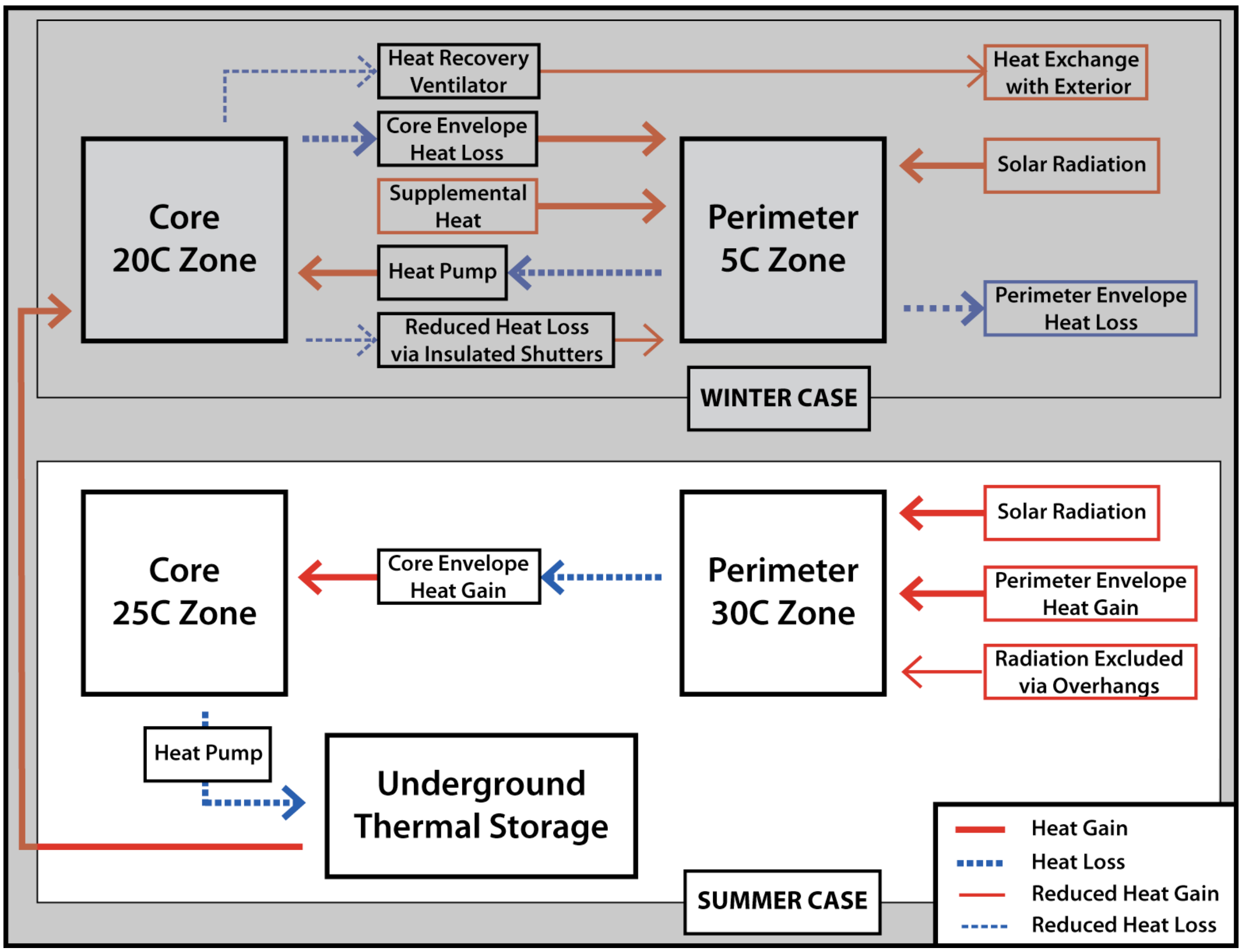


Figure 50: NTED™ heat flow schematic summer model considerations.

In core cooling mode, the current heat pump modification applies the heat removed from the core by the evaporator component to the perimeter zone through the condenser component, as shown in Figure 51.

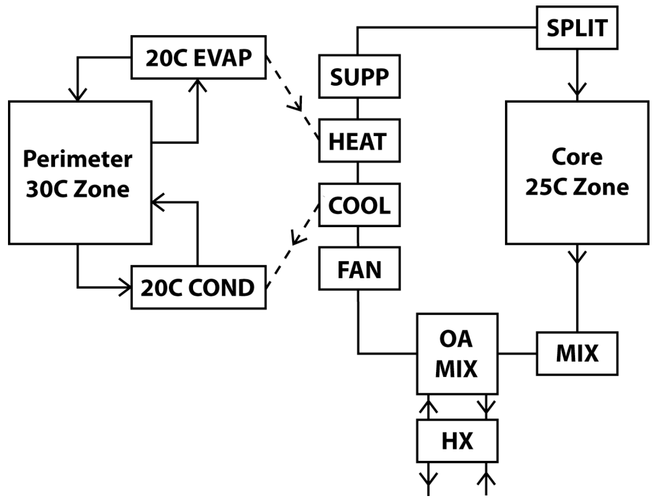


Figure 51: Inter-zone heat pump applying heating load to the perimeter during core cooling.

Future modeling efforts can include modification to allow one of two options. In the first case, the model could expel excess heat from the core to the exterior as is done with a traditional air conditioning unit as shown in Figure 52.

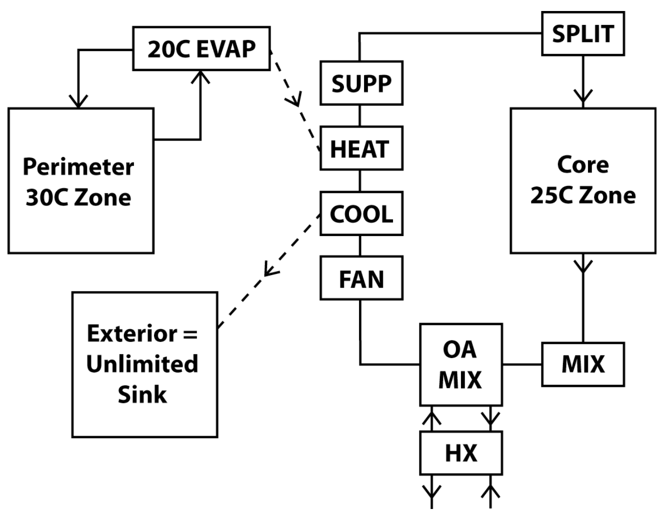


Figure 52:Inter-zone heat pump and exterior air conditioning system.

In the second potential scenario, the excess heat could be directed to an underground thermal storage area to offset the heating load during the winter months as shown in Figure 53.

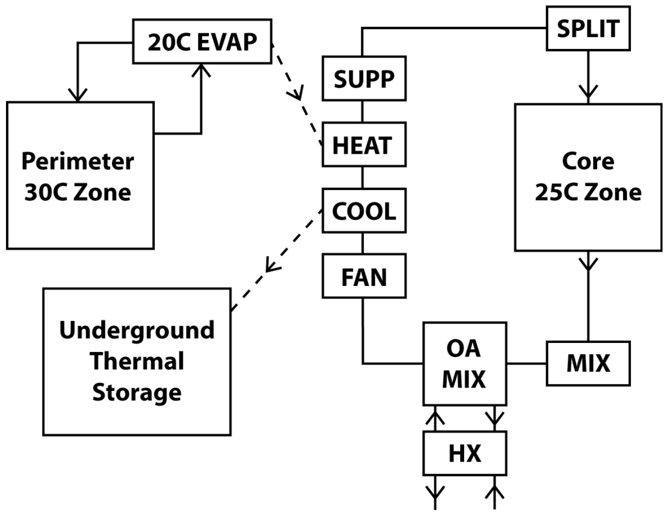


Figure 53: Inter-zone heat pump tied to an underground thermal storage bed.

8.4 SPACE USE AND BUILDING CONFIGURATION

The NTED™ building configuration and intended method of operation differs from traditional buildings such that particular attention should be paid to ensure the occupants experience a pleasing and healthy space. In particular, access to natural light in the core and overall space programming are important elements to be considered during the design process.

The three building configurations investigated as part of this research are intended to be preliminary concepts only. Many potential options exist and Figure 54 shows three such examples that could be considered both from an energy model and an architectural space-use perspective.

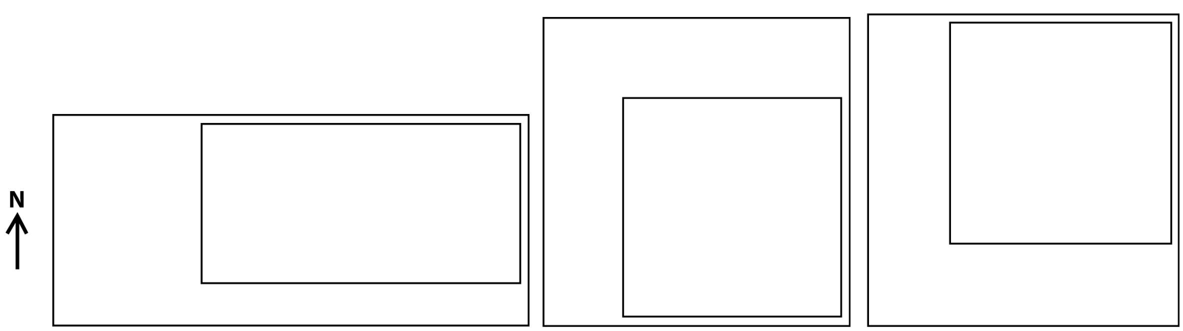


Figure 54: Additional potential building configurations for space use and energy modeling studies.

As mentioned previously, an additional potential building configuration involves expansion of the core area to virtually fill the perimeter envelope where instead of a habitable perimeter space, only a thermal buffer would be provided (Figure 55). This scenario would be useful in cases where a limited available footprint requires the maximum possible interior core area, and the building would be operated exclusively in Gemini mode. A study of this situation would involve determining the smallest possible buffer space that would allow sufficient air volume, and therefore heat capacity, to ensure the perimeter setpoint is maintained for the heat pump to operate at a desirable COP.

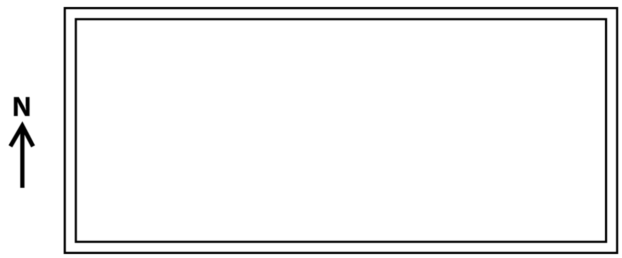


Figure 55: NTED™ core expansion to fill the perimeter envelope.

8.5 CLIMATE SENSITIVITY STUDY

The preliminary and advanced NTED™ modeling was completed with the building located in Toronto, Ontario. Because Canada is a large country with a wide range of climates from the more moderate coastal regions to the extreme northern areas, it would be beneficial to perform further studies to determine the applicability of the design in additional representative locations.

8.6 DAILY OPERATING MODE VARIATIONS

The current research included a Moderate operating mode case where the building switched between Gemini and Traditional mode based on whether it was a weekday or weekend/holiday. Another potential study could investigate the impact of varying the operating mode according to the time of day. Similar to a thermostat setback used in homes today, the NTED™ building could be operated in Gemini mode during the day and Traditional mode in the evening and/or overnight.

9.0 CONCLUSION

Residential space heating makes up the largest component of home energy use in Canada at 60% of the total. An innovative concept in building design, termed 'Nested Thermal Envelope Design' (NTED™), was proposed that would enable dual thermal zones and create a thermal buffer around a core living space through the use of nested thermal envelopes. Preliminary modeling predicted that heating energy savings of 74% were possible in Toronto, Canada.

The goal of this research was to quantify the heating energy savings potential of the NTED™ design and determine how it is affected by the building configuration as well as by occupant behaviour. Successful NTED™ proof-of-concept serves to reinforce a residential heating theory by William Shurcliff as well as some of the principles of the 1970s thermal envelope houses, and solidifies their value in the evolution of low-energy home design.

This research has extended the preliminary work and confirmed that the NTED™ design has the potential to achieve significant reductions in household heating energy use by showing savings of 85% between the NTED™ building and the benchmark R-2000 standard. The increased savings occur because the advanced model accounts for solar heat gains and models inter-zone heat pump operation according to the equipment performance curves. As a result, in an efficient use of electricity, the COP varies from 3.5-4 over the heating season in Toronto, Canada.

Design flexibility allows NTED™ to be applied both to new and existing buildings and this research has demonstrated a lack of reliance on southern exposure, making it appropriate for the vast majority of building designs and lot configurations. This was demonstrated through a less than 8% difference in heating energy use between three building configurations that varied the southern exposure and window areas on the south, east and west elevations. Of additional benefit to the NTED™ design is the fact that conventional building methods reduce the barriers for adoption by contractors and building owners.

In Gemini mode, perimeter insulation was shown to have a greater impact than core insulation on reducing heating energy use. This is somewhat expected as the perimeter envelope surface area is larger, it is exposed to the effects of gross air movement from wind and the temperature gradient between the perimeter and exterior is often greater than between the core and perimeter. In other words, NTED™ building designs should incorporate higher levels of insulation in the perimeter envelope than the core envelope to maximize the heating energy savings.

Because of the demonstrated importance of perimeter insulation, a further investigation was carried out to determine whether it has a greater impact with the building operating in Gemini or Traditional mode. A 31% reduction in heating energy use for Traditional mode compared to an 18% reduction in Gemini mode between the highly-insulated and minimally-insulated envelopes demonstrated that perimeter insulation is more significant for traditional building construction (i.e. Traditional mode) and the thermal buffer provided in Gemini mode is an effective means of reducing heating energy use.

In the occupied-building scenarios, internal gains were shown to have a significant impact on the heating energy use. In fact, the Gemini-operated building demonstrated levels of heating energy efficiency equivalent to those required by the rigorous Passive House standard as a ventilation-only load was observed in the Baseline building configuration.

While this research shows improved model accuracy over the preliminary work, the unique building configuration and operating principles of the NTED™ design requires an iterative approach to achieve a complete model. As a result, at the conclusion of this research additional areas remain to be addressed with future work. In particular, several items act to increase the heating energy use values for the building operating in Gemini mode, specifically, infiltration of exterior air and lack of accounting for the latent load on the perimeter. Conversely, the lower forced-air gas furnace efficiency resulting from the absence of a condensing model acts to increase the heating energy use for the Traditional mode case. While these aspects do impact the resulting energy values, it is estimated that the reported energy savings are accurate as the conservative Gemini items offset the over-estimated Traditional case.

As the need for low-energy buildings increases, NTED™ is proving to be an option that will allow occupants to control their energy use through dual thermal zones and the ability to expand or contract their conditioned living space.

10.0 REFERENCES

Air-Conditioning, Heating, and Refrigeration Institute (AHRI). (2008). *ANSI/AHRI Standard 210/240: Performance rating of unitary air-conditioning & air-source heat pump equipment*. Arlington, VA: Air-Conditioning, Heating, and Refrigeration Institute, Inc.

American Society of Heating, Refrigerating and Air- Conditioning Engineers (ASHRAE). (2005). *2005 ASHRAE handbook: fundamentals In (Ed.), (I-P and SI eds. ed.)*. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASTM. (2003). ASTM International: *E779-03 Standard test method for determining air leakage rate by fan pressurization*. West Conshohocken, PA: ASTM International.

Barkley, M. (1999). Greensboro News, Local Business 12-19-99: *Innovative solar system "envelopes" house*. Retrieved May 1, 2009 from http://enertia.com/PressKit/Publicty/FullReprints/GreensboroNewsRecord/tabid/83/Default.aspx

Bernstein, A. (2006). The Washington Post, June 28, 2006: *Physicist William Shurcliff; advocated for public interest*.

Canada Mortgage and Housing Corporation (CMHC). (2005). Research Highlight, Technical Series 05-100: *Effects of thermostat setting on energy consumption*. Retrieved April 28, 2009 from http://www.cmhc-schl.gc.ca/odpub/pdf/63816.pdf

Canada Mortgage and Housing Corporation (CMHC). (2007). Innovative Buildings: *Factor 9 home: a new prairie approach*. Retrieved July 20, 2010 from http://www.cmhc-schl.gc.ca/en/inpr/bude/himu/inbu/upload/65664EnW.pdf

Canadian Standards Association (CSA). (1991). *CAN/CSA-F326-M91 (R2005) Residential mechanical ventilation systems*.

Chen, B. et al. (1982). *Path to passive: Nebraska's passive solar primer*. Solar Energy Associates: Omaha, NE.

Chen, B. (1983). *Nebraska residential solar architecture: A representative inventory*. Solar Energy Associates: Omaha, NE.

Christensen, C. & Norton, P. (2006). *A cold-climate case study for affordable zero energy homes*. 2006 Solar Conference, Denver, Colorado. Conference Paper NREL/CP-550-39678.

Christensen, C. & Norton, P. (2007). *Performance results from a cold climate case study for affordable zero energy homes*. ASHRAE Winter Conference, New York, New York. Conference Paper NREL/CP-550-42339.

Chown, G.A. (1982). Building Practice Note: *Thermal envelope houses*. Division of Building Research, National Research Council of Canada: Ottawa, ON.

DesignBuilder Software (DBS). (2009). DesignBuilder Software Ltd. Stroud, Gloucestershire, United Kingdom. Retrieved March 20, 2009 from http://www.designbuilder.co.uk

DesignBuilder Software (DBS). (2009). *Warehouse with office tutorial*. DesignBuilder Software Program Help. Retrieved May 18, 2009 from http://www.designbuilder.co.uk/helpv2/

EnergyIdeas Clearinghouse. PTR #19, December, 2007. *Product & technology review: Acadia™ heat pump*. Retrieved July 26, 2010 from http://www.energyideas.org/documents/Factsheets/PTR/AcadiaHeatPump.pdf

Environment Canada. (2004). *Canadian climate normals 1971-2000: Toronto, Ontario*. Retrieved December 7, 2008 from http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html?Province=ALL&StationName=toronto&SearchType=BeginsWith&LocateBy=Province&Proximity=25&ProximityFrom=City&StationNumber=&IDType=MSC&CityName=&ParkName=&LatitudeDegrees=&LatitudeMinutes=&LongitudeDegrees=&LongitudeMinutes=&NormalsClass=A&SelNormals=&StnId=5051&

ESP-r Software (ESRU). (2009). Department of Mechanical Engineering, University of Strathclyde, Glasgow Scotland. http://www.esru.strath.ac.uk/Programs/ESP-r

Falke, R. (2006). ContractingBusiness.com, *Calculating heating system airflow*. Retrieved July 27, 2010, from http://contractingbusiness.com/enewsletters/cb_imp_43580/

FileMaker, Inc. (2010). FileMaker Pro 11, www.filemaker.com

Green Energy Act Alliance (2009). Hosted event: *Why green energy? – with David Suzuki and Hermann Scheer*. April 23, 2009, University of Toronto, Toronto, Canada.

Hix, J. (1983). *1001 Decorating ideas: seasonal living, fall 1983*. 1001 Publications Inc.: Montreal, QC.

Hix, J. (1988). *Buildings in nature*. Retrieved April 29, 2009 from http://www.johnhixarchitect.com/author.html

Hutcheon, N. & Handegord, G. (1995) *Building science for a cold climate*. Institute for Research in Construction.

Lane-Moore, L. (2007). The Barrie Examiner, Fall 2007, 21-27: *The sun king: when it comes to passive solar design, architect John Hix rules*.

Lawrence Berkeley National Laboratory (LBNL). (2008a). *EnergyPlus engineering reference, the reference to EnergyPlus calculations*, November 11, 2008, Copyright University of Illinois, University of California and Lawrence Berkeley National Laboratory.

Lawrence Berkeley National Laboratory (LBNL). (2009a). *EnergyPlus guide for module developers, everything you need to know about developing for EnergyPlus*, March 24, 2009, Copyright University of Illinois, University of California and Lawrence Berkeley National Laboratory.

Lawrence Berkeley National Laboratory (LBNL). (2008b). *EnergyPlus input output reference, the encyclopedic reference to EnergyPlus input and output*, November 11, 2008, Copyright University of Illinois, University of California and Lawrence Berkeley National Laboratory.

Lawrence Berkeley National Laboratory (LBNL). (2009b). *Getting started with EnergyPlus: basic concepts manual – essential information you need about running EnergyPlus*, April 5, 2009, Copyright University of Illinois, University of California and Lawrence Berkeley National Laboratory.

Legalett. (2008). Form No. 0545: *HRV/ERV operation with Legalett*. Retrieved February 16, 2009 from http://www.legalett.com

Lstiburek, J.W. 2008. *Building America*. *ASHRAE Journal*, December 2008, 60-64.

Lstiburek, J. (2007) *Building science digest 146: EIFS – problems and solutions*. Westford, MA: Building Science Press. Retrieved September 15, 2008 from www.buildingscience.com

Meier, A. (1994). Home Energy Magazine Online January/February 1994, *Infiltration: just ACH_{50} divided by 20?* Retrieved March 24, 2009 from http://www.homeenergy.org/archive/hem.dis.anl.gov/eehem/94/940111.html#94011143

Mitsubishi Electric HVAC Advanced Products Division. (2008). *Hyper-Heating Inverter: bringing year-round comfort solutions to extreme climates*. Retrieved July 26, 2010 from http://www.mehvac.com/UploadedFiles/Resource/H2i_brochure.pdf

Natural Resources Canada (NRCan). (2008). Atlas of Canada: *Wind and sunshine*. Retrieved December 4, 2008 from http://atlas.nrcan.gc.ca/site/english/maps/archives/3rdedition/environment/climate/020

Natural Resources Canada (NRCan). (2004). Office of Energy Efficiency, EnerGuide: *Heating and cooling with a heat pump*. Retrieved June 6, 2009 from http://oee.nrcan.gc.ca/publications/infosource/pub/home/heating-heat-pump/booklet.pdf

Natural Resources Canada (NRCan). *R-2000 guideline: April 1, 2005*. Retrieved March 24, 2009 from http://oee.nrcan.gc.ca/residential/personal/new-homes/r-2000/standard/current/purpose.cfm?attr=4

Natural Resources Canada (NRCan). August, 2006: *Energy use data handbook 1990 and 1998 to 2004*. Energy Publications Office of Energy Efficiency Natural Resources Canada.

Natural Resources Canada (NRCan). Office of Energy Efficiency R-2000 program website. Last accessed March 24, 2009 http://oee.nrcan.gc.ca/residential/personal/new-homes/r-2000/About-r-2000.cfm

Natural Resources Canada (NRCan). (2005). *2003 Survey of household energy use (SHEU) summary report*. Energy Publications: Office of Energy Efficiency.

Natural Resources Canada (NRCan). (2010). Office of Energy Efficiency EnerGuide program. Last accessed July 20, 2010 http://oee.nrcan.gc.ca/residential/personal/new-homes/upgrade-packages/energuide-service.cfm?attr=0

Office of Technology Assessment (OTA). (1981). *An Assessment of technology for local development*. Retrieved March 23, 2009 from http://www.princeton.edu/~ota/

Ontario Building Code (OBC). 2006. *Ontario building code 2006: containing the building code act and O. Reg. 350/06 amended to O. Reg 205/08*. Toronto, ON: Queen's Printer for Ontario.

Ontario Energy Board (OEB) website. Last accessed March 18, 2009 http://www.oeb.gov.on.ca/OEB/For+Consumers/About+the+Energy+Sector/Ontarios+Energy+Marketplace+-+The+Big+Picture

PHPP 2007. *Passive House Planning Package 2007, requirements for quality approved passive houses*. Passive Haus Institut, Technical Information PHI-2007/1(E).

Pressnail, K.D., Richman, R., Kirsch, A.M. (2008). *An innovative approach to low-energy building performance using nested thermal envelopes.* 12th Canadian Conference on Building Science and Technology, Montreal, QC, 2009.

Quirouette, R.L. (1980). Building Practice Note: Insulated Window Shutters, Division of Building Research, National Research Council of Canada, Ottawa.

Roberts, T. (2007). Environmental Building News Product Review: *Enertia double-envelope home still has problems*. BuildingGreen.com – EBN: 16:7.

Royal Architectural Institute of Canada (RAIC). 2009. 2030 Challenge program. Last accessed December 14, 2009 http://www.raic.org/architecture_architects/green_architecture/2030_about_e.htm

Rudd, A. (2006). *Design process for sizing: cooling and heating system capacity, room air flows, trunk and runout ducts, and transfer air ducts*. Building Science Corporation: Westford, MA.

Sherman, M. (1986). Energy and Buildings 10 (1987) 81-86: *Estimation of infiltration from leakage and climate indicators*.

Shurcliff, W.A. (1981). *Super insulated houses and double envelope houses – a survey of principles and practice*, Andover, MA: Brick House Publishing Company.

Straube, J. & Burnett, E. (2005). *Building science for building enclosures*. Westford, MA: Building Science Press.

TRYNSYS software (TESS). 2009. Thermal Energy Systems Specialists. http://www.trynsys.com

Timusk, J. (1987). Ventilation Technology – Research and Application, 8th AIVC Conference: *Design, construction and performance of a dynamic wall house*.

US Environmental Protection Agency (USEPA), US Department of Energy. (2001). *Energy Star home sealing specification version 1.0*. Retrieved May 1, 2009 from http://www.energystar.gov/ia/home_improvement/home_sealing/ES_HS_Spec_v1_0b.pdf

USDOE. 2009. EnergyPlus, Version 4.0, U.S. Department of Energy. Last accessed June 4, 2009 http://apps1.eere.energy.gov/buildings/energyplus/

USDOE. 2010. Building Energy Software Tools Directory. Last accessed June 22, 2010 http://apps1.eere.energy.gov/buildings/tools_directory/

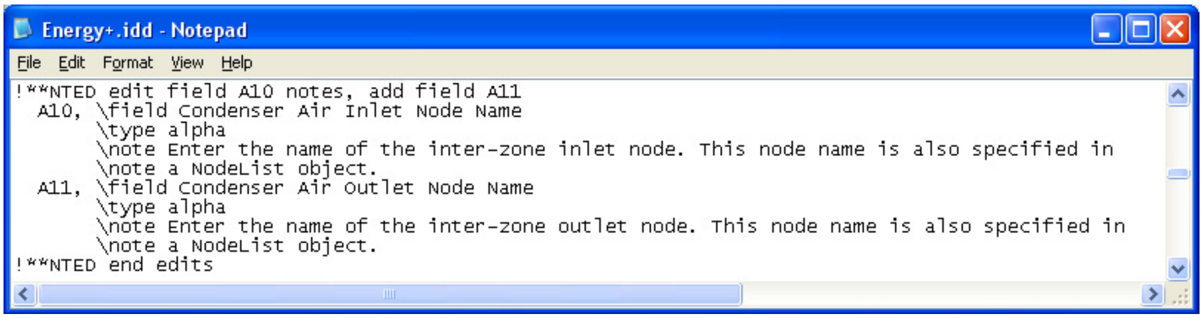
USDOE. 2010. Building America Program website. Last accessed August 2, 2010 http://www1.eere.energy.gov/buildings/building_america/

USEPA. 2010. Energy Star program website: *Air-source heat pumps and central air conditioners key product criteria*. Retrieved July 23, 2010 from http://www.energystar.gov/index.cfm?c=airsrc_heat.pr_crit_as_heat_pumps

Wald, M.L. (2006). The New York Times, June 28, 2006: *William A. Shurcliff, who helped develop atomic bomb, dies at 97*.

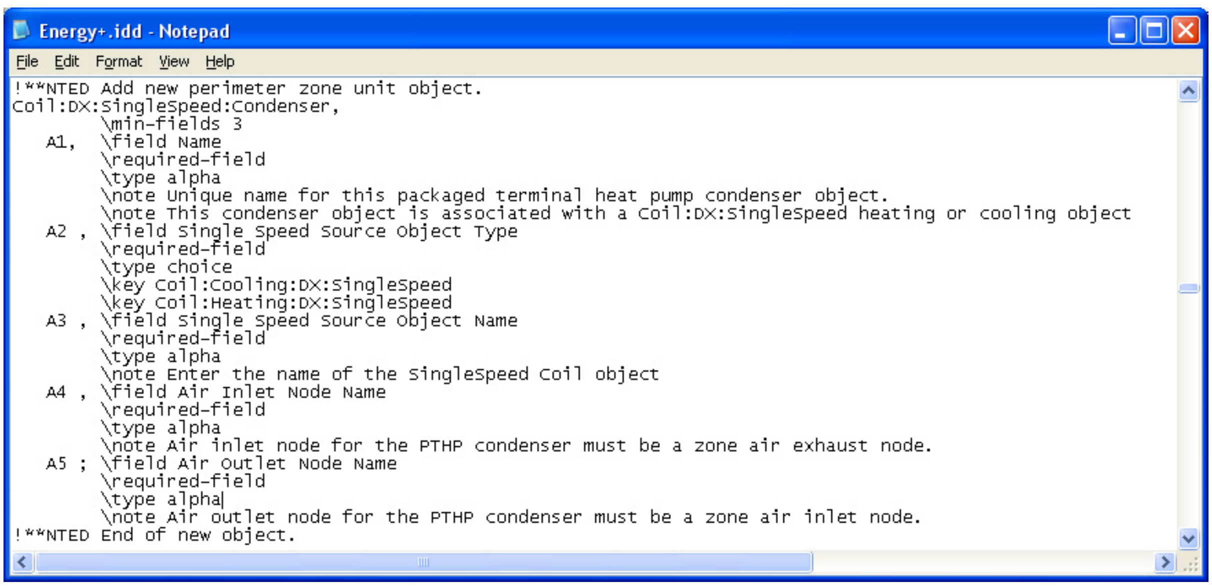
APPENDIX A – CODE MODIFICATIONS

This appendix contains samples of the modifications made to the EnergyPlus source code to create an inter-zone air-source heat pump to allow the NTED™ design to be modeled.



```
!**NTED edit field A10 notes, add field A11
  A10, \field Condenser Air Inlet Node Name
       \type alpha
       \note Enter the name of the inter-zone inlet node. This node name is also specified in
       \note a NodeList object.
  A11, \field Condenser Air Outlet Node Name
       \type alpha
       \note Enter the name of the inter-zone outlet node. This node name is also specified in
       \note a NodeList object.
!**NTED end edits
```

Figure A1: Condenser node inlet and outlet addition to the Energy+.idd file.



```
!**NTED Add new perimeter zone unit object.
Coil:DX:SingleSpeed:Condenser,
        \min-fields 3
   A1,  \field Name
        \required-field
        \type alpha
        \note Unique name for this packaged terminal heat pump condenser object.
        \note This condenser object is associated with a Coil:DX:SingleSpeed heating or cooling object
   A2 , \field Single Speed Source Object Type
        \required-field
        \type choice
        \key Coil:Cooling:DX:SingleSpeed
        \key Coil:Heating:DX:SingleSpeed
   A3 , \field Single Speed Source Object Name
        \required-field
        \type alpha
        \note Enter the name of the SingleSpeed Coil object
   A4 , \field Air Inlet Node Name
        \required-field
        \type alpha
        \note Air inlet node for the PTHP condenser must be a zone air exhaust node.
   A5 ; \field Air Outlet Node Name
        \required-field
        \type alpha
        \note Air outlet node for the PTHP condenser must be a zone air inlet node.
!**NTED End of new object.
```

Figure A2: Condenser object (perimeter zone unit) addition to Energy+.idd file.

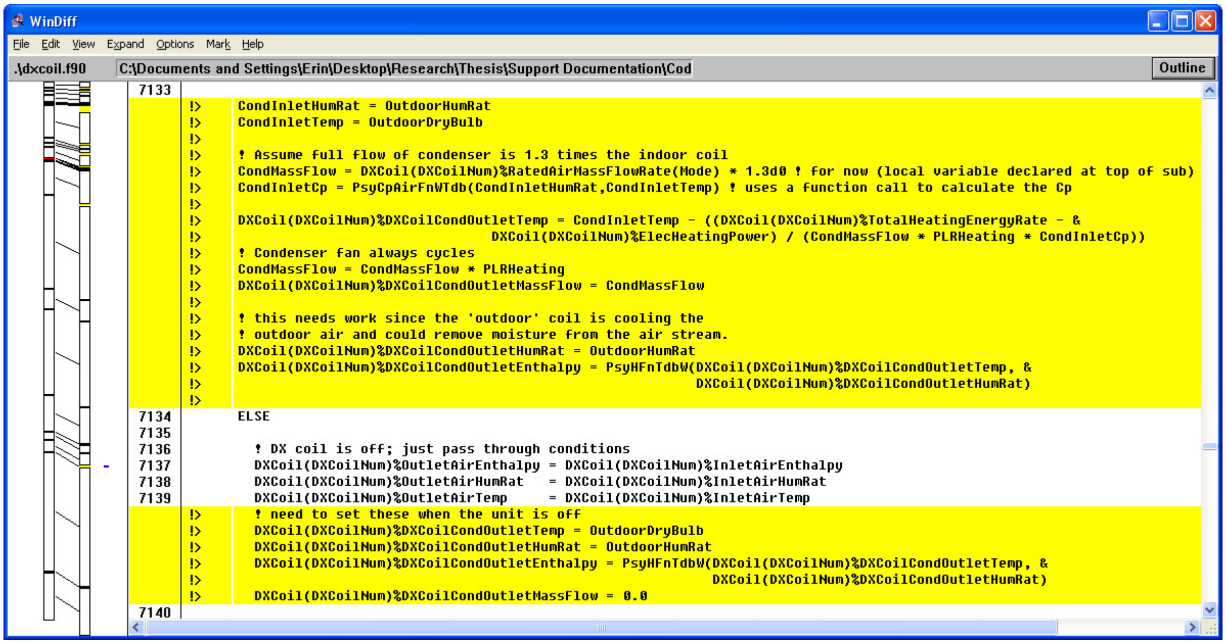


Figure A3: Calculating the cooling load to be applied to the perimeter during the core heating case.

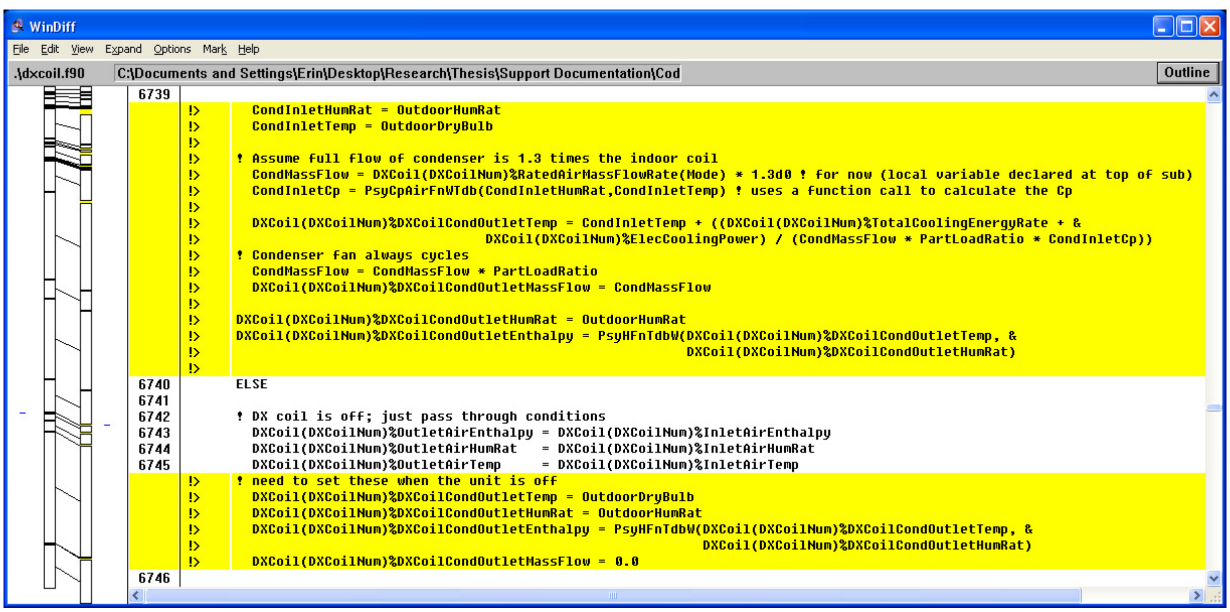


Figure A4: Calculating the heating load to be applied to the perimeter during the core cooling case.

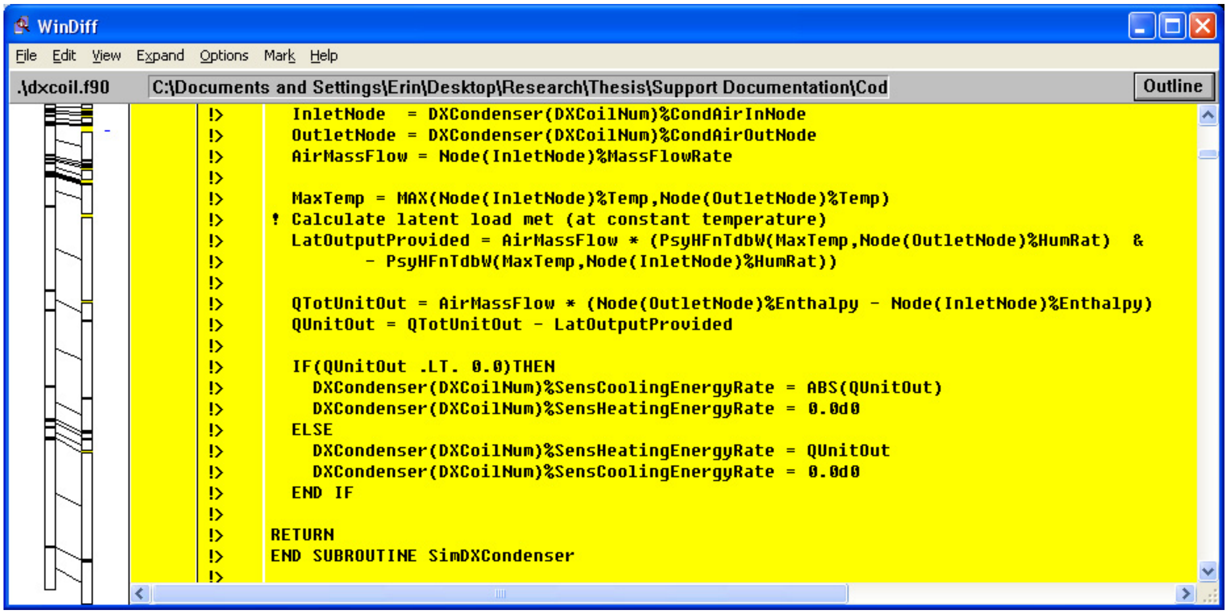


Figure A5: Excerpt from the SimDXCondenser subroutine.

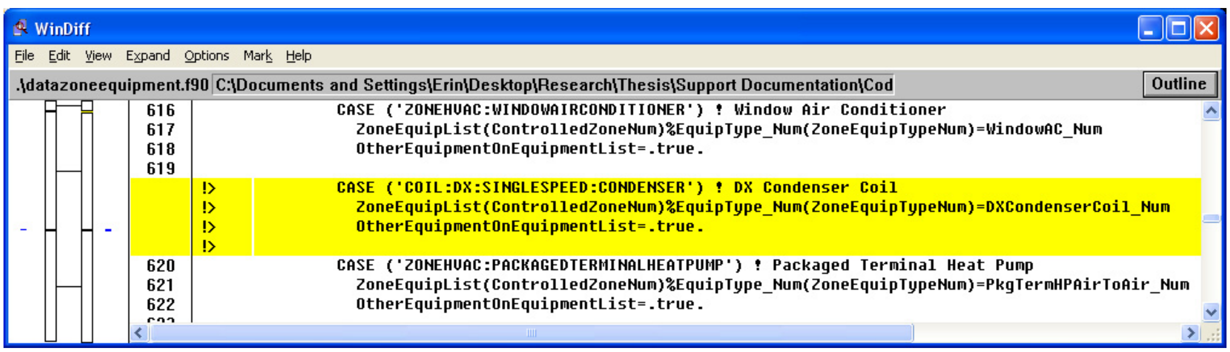


Figure A6: DX Condenser definition in datazoneequipment.f90 module.

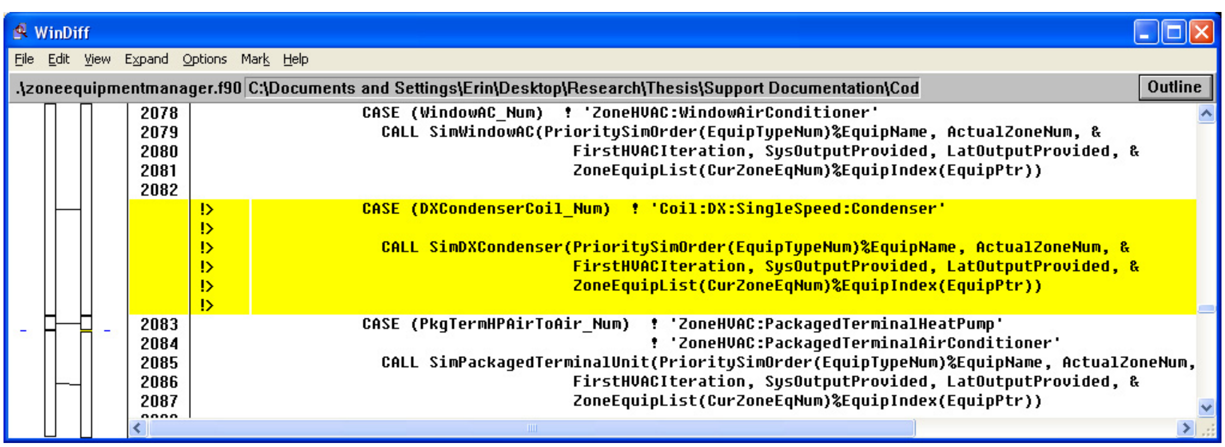


Figure A7: DX Condenser association with SimDXCondenser subroutine in zoneequipmentmanager.f90 module.

APPENDIX B – ZONE LOAD VERIFICATION

This appendix contains the raw data and calculations performed to determine that the newly-created inter-zone heat pump was applying the desired heating and cooling loads to the perimeter zone.

Date/Time	Environment:Outdoor Dry Bulb [C](Each Call)	687:Zone Mean Air Temperature [C](Each Call)	674:Zone Mean Air Temperature [C](Each Call)	756:Zone Mean Air Temperature [C](Each Call)	**20CZONEPTHPCOOLINGCONDENSER:DX Condenser Sensible Heating Rate[W] (Each Call)**	**20CZONECOOLCOIL:DX Coil Total Cooling Rate[W](Each Call)**	**20CZONECOOLCOIL:DX Cooling Coil Electric Power[W] (Each Call)**	**20CZONEPTHPHEATINGEVAPORATOR:DX Condenser Sensible Cooling Rate[W] (Each Call)**	**20CZONEHEATCOIL:DX Coil Total Heating Rate[W] (Each Call)**	**20CZONEHEATCOIL:DX Heating Coil Electric Power[W] (Each Call)**
01/01 00:15:00	-15.05	20.00329	5.0001771	-17.53728	0	0	0	396.8403362	796.4734434	399.6331072
01/01 00:30:00	-14	20.003292	5.0000567	-17.56837	0	0	0	397.138128	797.0592147	399.9210867
01/01 00:45:00	-12.95	20.003292	5.0000103	-17.50868	0	0	0	397.331148	797.4375737	400.1064257
01/01 01:00:00	-11.9	20.003292	4.9999915	-17.35068	0	0	0	397.4211157	797.6137796	400.1926639
01/01 01:15:00	-12.5	20.003594	4.9999865	-17.1147	0	0	0	445.4659453	809.9918887	364.5259434
01/01 01:30:00	-13.1	20.003635	4.9999871	-16.84811	0	0	0	447.9577142	814.4071391	366.4494249
01/01 01:45:00	-13.7	20.003654	4.9999898	-16.60145	0	0	0	450.5446594	818.9897148	368.4450554
01/01 02:00:00	-14.3	20.003672	4.9999933	-16.4131	0	0	0	453.0338145	823.3978362	370.3640217
01/01 02:15:00	-14.775	20.003689	4.9999965	-16.2994	0	0	0	455.279998	827.3746482	372.0946502
01/01 02:30:00	-15.25	20.003705	4.9999993	-16.26052	0	0	0	457.4803528	831.2693964	373.7890436
01/01 02:45:00	-15.725	20.00372	5.0000017	-16.29005	0	0	0	459.6578713	835.1228247	375.4649534
01/01 11:30:00	-17.5	20.001137	11.214044	-11.57649	0	0	0	355.5776946	650.010383	294.4326884
01/01 11:35:00					0	0	0	347.5348855	635.7589647	288.2240792
01/01 11:40:00					0	0	0	348.9778098	635.092439	286.1146292
01/01 11:45:00	-17.35	20.001094	11.78362	-10.96187	0	0	0	349.6482368	634.7723793	285.1241425
01/01 11:52:30					0	0	0	343.4608095	623.8730666	280.4122571
01/01 12:00:00	-17.2	20.001439	12.056043	-10.63229	0	0	0	343.6104595	623.2324337	279.6219742
01/01 12:07:30					0	0	0	339.6228575	614.8960366	275.2731791
01/01 12:15:00	-17.475	20.001414	12.522264	-10.06154	0	0	0	340.9378051	614.2335638	273.2957587
01/01 12:22:30					0	0	0	337.8515609	608.2066741	270.3551132
01/01 12:30:00	-17.75	20.001389	12.727313	-9.817703	0	0	0	338.4293462	607.9369688	269.5076226
01/01 12:45:00	-18.025	20.002092	12.900914	-9.743512	0	0	0	335.5109848	602.2976526	266.7866678
01/01 13:00:00	-18.3	20.002103	13.115203	-9.788062	0	0	0	332.069247	595.1689624	263.0997155
01/01 13:15:00	-17.05	20.002062	13.373971	-9.881206	0	0	0	327.87512	586.2190531	258.3439331
01/01 13:30:00	-15.8	20.002017	13.650873	-9.900144	0	0	0	323.5724448	576.8134416	253.2409968
01/01 13:45:00	-14.55	20.00198	13.848498	-9.767984	0	0	0	320.4654347	569.4407235	248.9752888
01/01 14:00:00	-13.3	20.001954	13.932951	-9.494072	0	0	0	318.297671	564.2961737	245.9985027
01/02 23:00:00	-8.9	20.003433	5.0001999	-10.59783	0	0	0	422.5585367	846.5621811	424.0036444
01/02 23:15:00	-8.625	20.003435	5.0000607	-10.58845	0	0	0	422.9747185	847.3772073	424.4024888
01/02 23:30:00	-8.35	20.003437	5.0000083	-10.55337	0	0	0	423.3485421	848.1061925	424.7576504
01/02 23:45:00	-8.075	20.003439	4.9999885	-10.49339	0	0	0	423.6787909	848.7490606	425.0702698
01/02 24:00:00	-7.8	20.003731	5.0024875	-10.4097	0	0	0	471.6335607	856.2998412	384.6662806
07/01 00:15:00	19.4	20.500074	24.124426	19.384244	109.6369142	82.644935	26.99197878	0	0	0
07/01 00:30:00	18.8	20.500069	24.003482	19.216118	106.8231042	80.568428	26.25467651	0	0	0
07/01 00:45:00	18.2	20.500064	23.880264	19.033169	103.9779725	78.468321	25.50965162	0	0	0
07/01 01:00:00	17.6	20.50006	23.758006	18.82688	101.1085713	76.344781	24.76379002	0	0	0
07/01 01:15:00	17.625	20.500059	23.596468	18.53587	98.47161051	74.352878	24.11873227	0	0	0
07/01 01:22:30					95.50311499	72.110592	23.39252311	0	0	0
07/01 01:30:00	17.65	20.500034	23.506791	18.255399	95.4578544	72.076404	23.3814502	0	0	0
07/01 01:37:30					92.64299078	69.950216	22.69277484	0	0	0
07/01 01:45:00	17.675	20.500033	23.315136	17.751844	92.6258171	69.937244	22.68857304	0	0	0
07/01 01:52:30					89.71115858	67.735728	21.97543085	0	0	0
07/01 02:00:00	17.7	20.500032	23.171694	17.441414	89.69994808	67.72726	21.97268783	0	0	0
07/01 11:30:00	20.35	20.500011	23.593771	29.39633	62.59957243	47.260139	15.33943295	0	0	0
07/01 11:45:00	20.725	20.500011	23.878929	30.830894	69.42520145	52.378796	17.04640533	0	0	0
07/01 12:00:00	21.1	20.50001	24.224465	32.747045	76.33496391	57.486526	18.84843793	0	0	0
07/01 12:15:00	21.525	20.50001	24.581678	34.787641	83.35859434	62.660322	20.69827247	0	0	0
07/01 12:30:00	21.95	20.500011	24.981748	37.692502	91.6220941	68.795227	22.82686735	0	0	0
07/01 12:45:00	22.375	20.500012	25.000017	40.072785	100.0580548	75.132066	24.92598922	0	0	0
07/01 13:00:00	22.8	20.500015	25.000048	41.844837	108.0547283	81.139331	26.91539765	0	0	0
07/01 13:15:00	23.225	20.500016	25.000064	44.332976	115.8804584	87.018565	28.86189294	0	0	0
07/01 13:30:00	23.65	20.500019	25.000087	45.57045	123.4988591	92.742401	30.75645773	0	0	0
07/01 13:45:00	24.075	20.500027	25.000133	46.874474	130.9814084	98.364508	32.6169	0	0	0
07/01 14:00:00	24.5	20.500029	25.000146	48.343517	138.3157084	103.87558	34.44013005	0	0	0

1.

$$COP = \frac{\text{DX Coil Total Heating Rate}}{\text{DX Heating Coil Electric Power}} = \frac{796.47344}{399.63311}$$

$$COP = 1.9930117$$

$$\frac{\text{Evaporator Sensible Cooling Rate}}{\text{DX Total Heating Rate}} = 1-1/COP$$

$$\frac{396.84034}{796.47344} = 1-1/(1.993)$$

$$0.4982468 = 0.4982468$$

2.

$$COP = \frac{\text{DX Coil Total Heating Rate}}{\text{DX Heating Coil Electric Power}} = \frac{623.23243}{279.62197}$$

$$COP = 2.2288393$$

$$\frac{\text{Evaporator Sensible Cooling Rate}}{\text{DX Total Heating Rate}} = 1-1/COP$$

$$\frac{343.61046}{623.23243} = 1-1/(2.23)$$

$$0.551336 = 0.551336$$

3.

$$COP = \frac{\text{DX Coil Total Cooling Rate}}{\text{DX Cooling Coil Electric Power}} = \frac{82.644935}{26.991979}$$

$$COP = 3.0618331$$

$$\frac{\text{Condenser Sensible Heating Rate}}{\text{DX Total Cooling Rate}} = 1+1/COP$$

$$\frac{109.63691}{82.644935} = 1+1/(3.06)$$

$$1.3266017 = 1.3266017$$

4.

$$COP = \frac{\text{DX Coil Total Cooling Rate}}{\text{DX Cooling Coil Electric Power}} = \frac{57.486526}{18.848438}$$

$$COP = 3.0499358$$

$$\frac{\text{Condenser Sensible Heating Rate}}{\text{DX Total Cooling Rate}} = 1+1/COP$$

$$\frac{76.334964}{57.486526} = 1+1/(3.05)$$

$$1.3278758 = 1.3278758$$

APPENDIX C – MATERIAL CALCULATIONS

This appendix contains the data and calculations used to adjust the wall conductivity values to account for the thermal bridging of the framing elements as well as the window surface temperature study details.

Baseline Building Geometry

	height [m]	width [m]	length [m]	slab [m2]	wall [m2]	ceiling [m2]	window [m2]	net wall [m2]	wall [%]
Core	2.5	6	12	72	90	72	12	78	0.8666667
Perimeter	3	8	18	144	156	144	18	138	0.8846154

on-centre stud spacing

	16" oc	2x width	2x6 depth	8"depth	12" depth
[in]	16	1.5	5.5	8	12
[m]	0.4	0.0381	0.14	0.203	0.305

	k conductivity [W/mK]	U conductance [W/m2K]	R resistance [m2K/W]
5.5" spf	0.12	0.857142857	1.2
5.5" batt	0.04	0.285714286	3.5
12" batt	0.04	0.131147541	7.6

Uavg = U1(A1/(A1+A2)) + U2(A2/(A1+A2))

Core Wall	**length of studs in full wall area**				**stud**	**insulation**			
2x6"	**16" oc**	297	m	**wall + window**	11.3157	78.6843	m2	**Uavg**	0.37 W/m2K
				wall-only area	9.80694	68.19306	m2	**kavg**	0.05 W/mK
				% component	0.143811408	0.856188592		**Ravg**	2.72 m2K/W
Perimeter Wall	**length of studs in full wall area**				**stud**	**insulation**			
2x6"	**16" oc**	494	m	**wall + window**	18.8214	137.1786	m2	**Uavg**	0.36 W/m2K
				wall-only area	16.6497	121.3503	m2	**kavg**	0.05 W/mK
				% component	0.137203616	0.862796384		**Ravg**	2.75 m2K/W
Core Ceiling	**length of joists in ceiling area**				**joist**	**insulation**			
2x6"	**16" oc**	204	m	**ceiling area**	7.7724	64.2276	m2	**Uavg**	0.35 W/m2K
				% component	0.10795	0.89205		**kavg**	0.05 W/mK
								Ravg	2.88 m2K/W
Perim Ceiling	**length of joists in ceiling area**				**joist**	**insulation**			
12" batt	**16" oc**	396	m	**ceiling area**	0	144	m2	**Uavg**	0.13 W/m2K
				% component	0	1		**kavg**	0.04 W/mK
								Ravg	7.63 m2K/W

Window Surface Temperature Study

Core Window: Gemini Mode

	exterior	perimeter	core
T [°C]	-15	5	20

Material	Thickness l [m]	Conductivity k [W/m°C]	Conductance C=k/l [W/m²°C]	Thermal Resistance R_T=1/C [m²°C/W]	Temperature Drop Across Layer $\Delta T = q_T R_T$ [°C]	Temperature at Interface T [°C]
						20
Indoor surface coefficient			8.29	0.12	1.73	
						18.27
Glass	0.03	0.9	30	0.03	0.48	
						17.79
Argon	0.013	0.018	1.36	0.73	10.58	
						7.21
Glass	0.03	0.9	30	0.03	0.48	
						6.73
Indoor Surface Coefficient				0.12	1.73	
						5

Σ R_T = 1.041129944 **m²°C/W**

U = 0.960494899 **W/m²°C**

q_T = 14.40742349 **W/m²**

Perimeter Window: Traditional Mode

Material	Thickness l [m]	Conductivity k [W/m°C]	Conductance C=k/l [W/m²°C]	Thermal Resistance R_T=1/C [m²°C/W]	Temperature Drop Across Layer $\Delta T = q_T R_T$ [°C]	Temperature at Interface T [°C]
						20
Indoor surface coefficient				0.12	4.42	
						15.58
Glass	0.03	0.9	30	0.03	1.23	
						14.36
Argon	0.01	0.02	1.36	0.73	27.03	
						-12.67
Glass	0.03	0.9	30	0.03	1.23	
						-13.90
Outdoor air film coefficient				0.03	1.10	
						-15

Σ R_T = 0.951129944 **m²°C/W**

U = 1.051381051 **W/m²°C**

q_T = 36.7983368 **W/m²**

APPENDIX D – AIR-SOURCE HEAT PUMP MANUFACTURER PERFORMANCE DATA

This appendix contains the raw heating and cooling performance data used to create the EnergyPlus performance curves.

HEAT PUMP HEATING PERFORMANCE

INDOOR AIR		OUTDOOR COIL ENTERING AIR TEMPERATURES °F (°C)																							
		−3 (−19.4)			7 (−13.9)			17 (−8.3)			27 (−2.8)			37 (2.8)			47 (8.3)			57 (13.9)			67 (19.4)		
EDB °F (°C)	CFM	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†	Capacity MBtuh		Total Sys. KW†
		Total	Integ*		Total	Integ*		Total	Integ*		Total	Integ*		Total	Integ*		Total	Integ*		Total	Integ*		Total	Integ*	
25HPA518A30 Outdoor Section With FX4CNF018 Indoor Section																									
65 (18.3)	525	6.33	5.82	1.12	8.28	7.61	1.17	10.37	9.45	1.22	12.63	11.22	1.28	15.24	13.87	1.35	18.07	18.07	1.44	21.23	21.23	1.55	24.72	24.72	1.69
	600	6.44	5.93	1.12	8.41	7.73	1.16	10.52	9.59	1.21	12.84	11.40	1.26	15.49	14.10	1.33	18.38	18.38	1.41	21.63	21.63	1.51	25.07	25.07	1.61
	675	6.54	6.02	1.12	8.50	7.81	1.16	10.65	9.71	1.20	13.01	11.56	1.25	15.69	14.28	1.31	18.63	18.63	1.38	21.94	21.94	1.48	25.07	25.07	1.56
70 (21.1)	525	5.99	5.51	1.16	7.97	7.33	1.22	10.07	9.18	1.28	12.32	10.95	1.34	14.85	13.51	1.42	17.69	17.69	1.51	20.80	20.80	1.62	24.25	24.25	1.77
	600	6.10	5.62	1.16	8.11	7.45	1.22	10.23	9.33	1.27	12.51	11.11	1.32	15.11	13.75	1.39	18.00	18.00	1.47	21.19	21.19	1.58	24.69	24.69	1.69
	675	6.19	5.69	1.17	8.22	7.56	1.21	10.36	9.45	1.26	12.68	11.26	1.31	15.35	13.97	1.37	18.25	18.25	1.45	21.52	21.52	1.55	24.88	24.88	1.64
75 (23.9)	525	5.64	5.19	1.21	7.65	7.03	1.27	9.76	8.90	1.34	12.02	10.68	1.40	14.49	13.19	1.48	17.31	17.31	1.58	20.37	20.37	1.70	23.77	23.77	1.84
	600	5.75	5.29	1.21	7.76	7.13	1.27	9.92	9.05	1.33	12.21	10.84	1.38	14.75	13.42	1.45	17.62	17.62	1.54	20.76	20.76	1.65	24.26	24.26	1.78
	675	5.85	5.38	1.22	7.90	7.26	1.27	10.03	9.15	1.32	12.34	10.96	1.37	14.95	13.61	1.44	17.86	17.86	1.52	21.06	21.06	1.62	24.53	24.53	1.72

HEATING INDOOR MODEL	CAPACITY	POWER	FURNACE MODEL
*FX4CNF018	1.00	1.00	
FE4ANF002	0.99	0.97	
FF1ENP018	1.00	1.06	
FF1ENP024	1.00	1.05	
FV4BNF002	0.99	0.97	
FX4CNF024	1.00	0.99	
FY4ANF018	1.00	1.07	
FY4ANF024	1.00	1.06	
CAP**1814A**	1.00	1.08	
CAP**2414A**	1.00	1.04	
CAP**2417A**	1.00	1.04	
CNPF*2418A**	1.00	1.02	
CNPH*2417A**	1.00	1.02	
CNPV*1814A**	1.00	1.03	
CNPV*2414A**	1.00	1.02	
CNPV*2417A**	1.00	1.02	
CSPH*2412A**	1.00	1.02	
CAP**1814A**	0.97	1.04	58CV(A,X)070−12
CAP**2414A**	0.98	1.01	58CV(A,X)070−12
CNPH*2417A**	0.98	0.99	58CV(A,X)070−12
CNPV*1814A**	0.97	1.00	58CV(A,X)070−12
CNPV*2414A**	0.98	0.99	58CV(A,X)070−12
CSPH*2412A**	0.98	1.00	58CV(A,X)070−12
CAP**2417A**	0.98	1.00	58CV(A,X)090−16
CNPH*2417A**	0.98	0.98	58CV(A,X)090−16
CNPV*2417A**	0.98	0.98	58CV(A,X)090−16
CSPH*2412A**	0.98	0.99	58CV(A,X)090−16
CAP**2417A**	1.00	0.94	58MEB040−12
CNPH*2417A**	1.00	0.95	58MEB040−12
CNPV*2417A**	1.00	0.95	58MEB040−12
CSPH*2412A**	1.00	0.97	58MEB040−12
CAP**2417A**	0.99	0.96	58MEB060−12
CNPH*2417A**	0.99	0.97	58MEB060−12
CNPV*2417A**	0.99	0.97	58MEB060−12
CSPH*2412A**	0.98	0.99	58MEB060−12
CNPH*2417A**	0.98	0.99	58MVB040−14
CSPH*2412A**	0.98	0.99	58MVB040−14
CAP**2417A**	0.98	1.00	58MVB060−14
CNPH*2417A**	0.98	0.99	58MVB060−14
CNPV*2417A**	0.98	0.99	58MVB060−14
CSPH*2412A**	0.98	0.99	58MVB060−14
CNPH*2417A**	0.98	0.98	58MVB080−14
CSPH*2412A**	0.98	0.99	58MVB080−14
CAP**1814A**	0.98	1.02	58PH*045−08

HEATING INDOOR MODEL	CAPACITY	POWER	FURNACE MODEL
CAP**2414A**	0.99	0.98	58PH*045−08
CNPH*2417A**	1.00	0.98	58PH*045−08
CNPV*1814A**	0.99	1.00	58PH*045−08
CNPV*2414A**	1.00	0.98	58PH*045−08
CSPH*2412A**	0.99	0.98	58PH*045−08

See notes on pg. 42

DETAILED COOLING CAPACITIES#

EVAPORATOR AIR		CONDENSER ENTERING AIR TEMPERATURES °F (°C)																	
		75 (23.9)			85 (29.4)			95 (35)			105 (40.6)			115 (46.1)			125 (51.7)		
CFM	EWB °F (°C)	Capacity MBtuh		Total Sys. KW**	Capacity MBtuh		Total Sys. KW**	Capacity MBtuh		Total Sys. KW**	Capacity MBtuh		Total Sys. KW**	Capacity MBtuh		Total Sys. KW**	Capacity MBtuh		Total Sys. KW**
		Total	Sens‡		Total	Sens‡		Total	Sens‡		Total	Sens‡		Total	Sens‡		Total	Sens‡	
25HPA518A30 Outdoor Section With FX4CNF018 Indoor Section																			
525	72 (22.2)	21.38	11.04	1.16	20.36	10.65	1.30	19.30	10.24	1.46	18.17	9.81	1.65	16.96	9.35	1.85	15.66	8.87	2.07
	67 (19.4)	19.39	13.53	1.16	18.44	13.12	1.31	17.45	12.70	1.47	16.40	12.26	1.65	15.28	11.79	1.85	14.07	11.29	2.07
	63 (17.2)††	17.97	13.07	1.17	17.08	12.65	1.32	16.14	12.22	1.48	15.14	11.78	1.66	14.08	11.30	1.86	12.95	10.80	2.08
	62 (16.7)	17.61	16.02	1.17	16.74	15.59	1.32	15.83	15.13	1.48	14.89	14.63	1.66	13.95	13.95	1.86	13.04	13.04	2.08
	57 (13.9)	16.98	16.98	1.17	16.29	16.29	1.32	15.56	15.56	1.48	14.79	14.79	1.66	13.95	13.95	1.86	13.04	13.04	2.08
600	72 (22.2)	21.85	11.59	1.17	20.79	11.18	1.31	19.68	10.77	1.48	18.51	10.33	1.66	17.26	9.87	1.86	15.91	9.38	2.08
	67 (19.4)	19.82	14.40	1.17	18.83	13.98	1.32	17.80	13.55	1.48	16.71	13.10	1.66	15.54	12.62	1.87	14.30	12.11	2.09
	63 (17.2)††	18.37	13.88	1.18	17.44	13.46	1.33	16.47	13.02	1.49	15.43	12.56	1.67	14.34	12.08	1.87	13.16	11.56	2.09
	62 (16.7)	18.04	17.17	1.18	17.15	16.70	1.33	16.22	16.22	1.49	15.38	15.38	1.67	14.50	14.50	1.87	13.54	13.54	2.09
	57 (13.9)	17.71	17.71	1.18	16.98	16.98	1.33	16.21	16.21	1.49	15.39	15.39	1.67	14.50	14.50	1.87	13.54	13.54	2.09
675	72 (22.2)	22.22	12.10	1.18	21.12	11.69	1.32	19.98	11.27	1.49	18.77	10.83	1.67	17.48	10.37	1.87	16.10	9.87	2.09
	67 (19.4)	20.16	15.23	1.18	19.14	14.80	1.33	18.07	14.36	1.49	16.95	13.90	1.68	15.75	13.41	1.88	14.48	12.88	2.10
	63 (17.2)††	18.69	14.65	1.19	17.73	14.23	1.34	16.72	13.78	1.50	15.66	13.31	1.68	14.54	12.81	1.88	13.34	12.27	2.10
	62 (16.7)	18.42	18.18	1.19	17.56	17.56	1.34	16.75	16.75	1.50	15.89	15.89	1.68	14.96	14.96	1.88	13.96	13.96	2.10
	57 (13.9)	18.33	18.33	1.19	17.56	17.56	1.34	16.75	16.75	1.50	15.89	15.89	1.68	14.96	14.96	1.88	13.96	13.96	2.10

COOLING INDOOR MODEL	CAPACITY	POWER	FURNACE MODEL
*FX4CNF018	1.00	1.00	
FE4ANF002	1.01	0.97	
FF1ENP018	0.98	1.08	
FF1ENP024	0.99	1.08	
FV4BNF002	1.01	0.97	
FX4CNF024	1.01	0.98	
FY4ANF018	0.98	1.09	
FY4ANF024	0.99	1.09	
CAP**1814A**	0.98	1.09	
CAP**2414A**	1.00	1.09	
CAP**2417A**	1.00	1.09	
CNPF*2418A**	0.99	1.10	
CNPH*2417A**	0.99	1.10	
CNPV*1814A**	0.98	1.09	
CNPV*2414A**	0.99	1.10	
CNPV*2417A**	0.99	1.10	
CSPH*2412A**	0.99	1.10	
CAP**1814A**	0.97	0.97	58CV(A,X)070−12
CAP**2414A**	0.99	0.99	58CV(A,X)070−12
CNPH*2417A**	0.99	0.99	58CV(A,X)070−12
CNPV*1814A**	0.97	0.97	58CV(A,X)070−12
CNPV*2414A**	0.99	0.99	58CV(A,X)070−12
CSPH*2412A**	0.99	0.99	58CV(A,X)070−12
CAP**2417A**	0.99	0.99	58CV(A,X)090−16
CNPH*2417A**	0.99	0.99	58CV(A,X)090−16
CNPV*2417A**	0.99	0.99	58CV(A,X)090−16
CSPH*2412A**	0.99	0.99	58CV(A,X)090−16
CAP**2417A**	1.01	0.97	58MEB040−12
CNPH*2417A**	1.01	0.97	58MEB040−12
CNPV*2417A**	1.01	0.97	58MEB040−12
CSPH*2412A**	1.01	0.97	58MEB040−12
CAP**2417A**	1.01	0.97	58MEB060−12
CNPH*2417A**	1.01	1.01	58MEB060−12
CNPV*2417A**	1.01	1.01	58MEB060−12
CSPH*2412A**	1.01	1.01	58MEB060−12
CNPH*2417A**	0.99	0.99	58MVB040−14
CSPH*2412A**	0.99	0.99	58MVB040−14
CAP**2417A**	0.99	0.99	58MVB060−14
CNPH*2417A**	0.99	0.99	58MVB060−14

COOLING INDOOR MODEL	CAPACITY	POWER	FURNACE MODEL
CNPV*2417A**	0.99	0.99	58MVB060−14
CSPH*2412A**	0.99	0.99	58MVB060−14
CNPH*2417A**	0.99	0.99	58MVB080−14
CSPH*2412A**	0.99	0.99	58MVB080−14
CAP**1814A**	0.99	0.99	58PH*045−08
CAP**2414A**	1.01	1.01	58PH*045−08
CNPH*2417A**	1.01	1.01	58PH*045−08
CNPV*1814A**	0.99	0.99	58PH*045−08
CNPV*2414A**	1.01	1.01	58PH*045−08
CSPH*2412A**	1.01	1.01	58PH*045−08

See notes on pg. 32

APPENDIX E – PERFORMANCE CURVE REGRESSION ANALYSIS

This appendix contains the data and calculations used to create the EnergyPlus heat pump performance curves.

DX Heating Coil Performance Curve Regression

Carrier	25HPA5	Performance 15 Series Heat Pump with Puron Refrigerant (1 1/2 - 5 Nominal Tons)		
Rated Airflow	600	cfm	0.248	m^3/s
Rated Capacity	18.00	Mbtuh	5276	W
Rated COP	3.59			
Flow Ratio	400	cfm/ton		

1	2	3	4	5	6	7	8	9	
Performance Data (Manual Page 33)									
entering $T_{db,i}$	entering $T_{db,o}$	capacity [MBtuh]	power [KW]	capacity [KW]	CapTFac	EIR	EIRTFac	COP	
18.3	-19.4	6.44	1.12	1.887	0.36	0.59	2.13	1.68	
18.3	-13.9	8.41	1.16	2.464	0.47	0.47	1.69	2.12	
18.3	-8.3	10.52	1.21	3.082	0.58	0.39	1.41	2.55	
18.3	-2.8	12.84	1.26	3.762	0.71	0.33	1.20	2.99	
18.3	2.8	15.49	1.33	4.539	0.86	0.29	1.05	3.41	
18.3	8.3	18.38	1.41	5.385	1.02	0.26	0.94	3.82	
18.3	13.9	21.63	1.51	6.338	1.20	0.24	0.85	4.20	
18.3	19.4	25.07	1.61	7.346	1.39	0.22	0.79	4.56	
21.1	-19.4	6.10	1.16	1.787	0.34	0.65	2.33	1.54	
21.1	-13.9	8.11	1.22	2.376	0.45	0.51	1.84	1.95	
21.1	-8.3	10.23	1.27	2.997	0.57	0.42	1.52	2.36	
21.1	-2.8	12.51	1.32	3.665	0.70	0.36	1.29	2.78	
21.1	2.8	15.11	1.39	4.427	0.84	0.31	1.13	3.19	
21.1	8.3	18.00	1.47	5.274	1.00	0.28	1.00	3.59	**Rated Conditions**
21.1	13.9	21.19	1.58	6.209	1.18	0.25	0.91	3.93	
21.1	19.4	24.69	1.69	7.234	1.37	0.23	0.84	4.28	
23.9	-19.4	5.75	1.21	1.685	0.32	0.72	2.58	1.39	
23.9	-13.9	7.78	1.27	2.280	0.43	0.56	2.00	1.79	
23.9	-8.3	9.92	1.33	2.907	0.55	0.46	1.64	2.19	
23.9	-2.8	12.21	1.38	3.578	0.68	0.39	1.38	2.59	
23.9	2.8	14.75	1.45	4.322	0.82	0.34	1.20	2.98	
23.9	8.3	17.62	1.54	5.163	0.98	0.30	1.07	3.35	
23.9	13.9	20.76	1.65	6.083	1.15	0.27	0.97	3.69	
23.9	19.4	24.26	1.78	7.108	1.35	0.25	0.90	3.99	

Regression Steps

1. Carrier manual 'EDB' column
2. Carrier manual 'Outdoor Coil Entering Air Temperatures' column
3. Carrier manual 'Total Capacity' values for the specified temperatures
4. Carrier manual 'Total Sys. kW' values for the specified temperatures
5. Convert [MBtuh] capacity to [kW]
6. Normalize the capacity to the rated reference point
   CapTFac = capaciy / rated capacity
7. EIR = power / capacity = inverse of COP
8. Express EIR as a ratio to the rated conditions i.e. normalize the EIR
   EIRTFac = EIR / rated EIR
9. COP = capacity / power

10	11	12	13	14	15	19
Total Heating Capacity as a Function of Temperature						
CapTFac	$T_{db,i}$	$T_{db,i}^2$	$T_{db,o}$	$T_{db,o}^2$	$T_i \times T_o$	Test Cap
0.36	18.3	334.89	-19.4	376.36	355.02	0.36
0.47	18.3	334.89	-13.9	193.21	254.37	0.47
0.58	18.3	334.89	-8.3	68.89	151.89	0.58
0.71	18.3	334.89	-2.8	7.84	51.24	0.71
0.86	18.3	334.89	2.8	7.84	51.24	0.86
1.02	18.3	334.89	8.3	68.89	151.89	1.02
1.20	18.3	334.89	13.9	193.21	254.37	1.20
1.39	18.3	334.89	19.4	376.36	355.02	1.39
0.34	21.1	445.21	-19.4	376.36	409.34	0.34
0.45	21.1	445.21	-13.9	193.21	293.29	0.45
0.57	21.1	445.21	-8.3	68.89	175.13	0.56
0.70	21.1	445.21	-2.8	7.84	59.08	0.69
0.84	21.1	445.21	2.8	7.84	59.08	0.84
1.00	21.1	445.21	8.3	68.89	175.13	1.00
1.18	21.1	445.21	13.9	193.21	293.29	1.18
1.37	21.1	445.21	19.4	376.36	409.34	1.37
0.32	23.9	571.21	-19.4	376.36	463.66	0.32
0.43	23.9	571.21	-13.9	193.21	332.21	0.43
0.55	23.9	571.21	-8.3	68.89	198.37	0.54
0.68	23.9	571.21	-2.8	7.84	66.92	0.67
0.82	23.9	571.21	2.8	7.84	66.92	0.82
0.98	23.9	571.21	8.3	68.89	198.37	0.98
1.15	23.9	571.21	13.9	193.21	332.21	1.16
1.35	23.9	571.21	19.4	376.36	463.66	1.35

10. From column 6
11. From column 1
12. Column 11 squared
13. From column 2
14. Column 13 squared
15. Absolute value of column 11 times column 13

16. Perform regression with:
    Input Y-Range: column 10
    Input X-Range: columns 11-15

17. Regression output displayed
18. EnergyPlus IDF inputs

19. Back-check of analysis using TotCapTempModFac equation

TotCapTempModFac = a + b $(T_{db,i})$ + c $(T_{db,i})^2$ + d $(T_{db,o})$ + e $(T_{db,o})^2$ + f $(T_{db,i})(T_{db,o})$

17 SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999936
R Square	0.999873
Adjusted R Square	0.999838
Standard Error	0.004393
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	2.734914	0.546983	28341.46	2.121E-34
Residual	18	0.0003474	1.93E-05		
Total	23	2.7352614			

18	Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0%
	a	0.910056	0.107166	8.4919997	1.04E-07	0.684908	1.1352037	0.684908	1.135204
	b	-0.006383	0.010252	-0.622658	0.541318	-0.027921	0.0151547	-0.027921	0.015155
	c	-2.21E-05	0.000243	-0.091264	0.928291	-0.000532	0.0004876	-0.000532	0.000488
	d	0.026398	7.05E-05	374.18925	1.78E-36	0.02625	0.0265464	0.02625	0.026546
	e	0.000218	2.64E-05	8.2318155	1.63E-07	0.000162	0.0002731	0.000162	0.000273
	f	1.91E-05	2.83E-05	0.674845	0.508351	-4.04E-05	7.861E-05	-4.04E-05	7.86E-05

20	21		22	23	24
Total Heating Capacity as a Function of Flow Fraction					
Flow	**Capacity**		**CapFFac**	**ff**	**ff^2**
525	17.69		0.98	0.88	0.77
600	18.00		1.00	1.00	1.00
675	18.25		1.01	1.13	1.27

28
Test Cap
0.98
1.00
1.01

20 Carrier manual 'CFM' column
21 Carrier manual 'Total Capacity' at rated temperature conditions
22 Normalized capacity: CapFFac = capacity / rated capacity
23 Flow fraction = actual flow rate / rated flow rate
24 Column 23 squared

TotCapFlowModFac = a + b (ff) + c (ff)^2

25 Perform regression with:
Input Y-Range: column 22
Input X-Range: columns 23-24

26 Regression output displayed
27 EnergyPlus IDF inputs

28 Back-check of analysis using TotCapFlowModFac equation

26 SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.0004858	0.000243	#NUM!	#NUM!
Residual	0	0	65535		
Total	2	0.0004858			

27	Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0%
	a	0.768889	0	65535	#NUM!	0.768889	0.7688889	0.768889	0.768889
	b	0.337778	0	65535	#NUM!	0.337778	0.3377778	0.337778	0.337778
	c	-0.106667	0	65535	#NUM!	-0.106667	-0.106667	-0.106667	-0.106667

29	30	31	32	33	34
EIR as a Function of Temperature					
EIRTFac	**$T_{db,i}$**	**$T_{db,i}^2$**	**$T_{db,o}$**	**$T_{db,o}^2$**	**T_i x T_o**
2.13	18.3	334.89	-19.4	376.36	355.02
1.69	18.3	334.89	-13.9	193.21	254.37
1.41	18.3	334.89	-8.3	68.89	151.89
1.20	18.3	334.89	-2.8	7.84	51.24
1.05	18.3	334.89	2.8	7.84	51.24
0.94	18.3	334.89	8.3	68.89	151.89
0.85	18.3	334.89	13.9	193.21	254.37
0.79	18.3	334.89	19.4	376.36	355.02
2.33	21.1	445.21	-19.4	376.36	409.34
1.84	21.1	445.21	-13.9	193.21	293.29
1.52	21.1	445.21	-8.3	68.89	175.13
1.29	21.1	445.21	-2.8	7.84	59.08
1.13	21.1	445.21	2.8	7.84	59.08
1.00	21.1	445.21	8.3	68.89	175.13
0.91	21.1	445.21	13.9	193.21	293.29
0.84	21.1	445.21	19.4	376.36	409.34
2.58	23.9	571.21	-19.4	376.36	463.66
2.00	23.9	571.21	-13.9	193.21	332.21
1.64	23.9	571.21	-8.3	68.89	198.37
1.38	23.9	571.21	-2.8	7.84	66.92
1.20	23.9	571.21	2.8	7.84	66.92
1.07	23.9	571.21	8.3	68.89	198.37
0.97	23.9	571.21	13.9	193.21	332.21
0.90	23.9	571.21	19.4	376.36	463.66

38
Test EIR
2.19
1.79
1.46
1.20
1.00
0.86
0.79
0.78
2.29
1.89
1.56
1.30
1.10
0.96
0.89
0.88
2.40
2.01
1.67
1.41
1.21
1.07
1.00
0.99

29 From column 8
30 From column 1
31 Column 30 squared
32 From column 2
33 Column 32 squared
34 Absolute value of column 30 times column 32

35 Perform regression with:
Input Y-Range: column 29
Input X-Range: columns 30-34

36 Regression output displayed
37 EnergyPlus IDF inputs

38 Back-check of analysis using EIRTempModFac equation

EIRTempModFac = a + b ($T_{db,i}$) + c ($T_{db,i}$)^2 + d ($T_{db,o}$) + e ($T_{db,o}$)^2 + f ($T_{db,i}$)($T_{db,o}$)

36 SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.992687
R Square	0.985428
Adjusted R Square	0.98138
Standard Error	0.068999
Observations	24

ANOVA

	df	SS	MS	F	Significance F
Regression	5	5.7950961	1.159019	243.4455	7.166E-16
Residual	18	0.0856962	0.004761		
Total	23	5.8807923			

		Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0%
37									
	a	0.701288	1.683165	0.4166483	0.681862	-2.834911	4.2374868	-2.834911	4.237487
	b	0.008587	0.161014	0.053331	0.958056	-0.329691	0.3468653	-0.329691	0.346865
	c	0.00069	0.003811	0.1811647	0.858263	-0.007316	0.0086968	-0.007316	0.008697
	d	-0.036267	0.001108	-32.73119	1.72E-17	-0.038595	-0.033939	-0.038595	-0.033939
	e	0.001048	0.000415	2.5248269	0.021184	0.000176	0.0019202	0.000176	0.00192
	f	-7.06E-06	0.000445	-0.015874	0.987509	-0.000942	0.0009274	-0.000942	0.000927

EIR as a Function of Flow Fraction

39	40	41	42	43		44	45	46		50
Flow	**MBtuh**	**total KW**	**capacity**	**EIR**		**EIRFFac**	**ff**	**ff^2**		**Test EIR**
525	17.69	1.51	5.18	0.29		1.05	0.88	0.77		1.05
600	18.00	1.47	5.27	0.28		1.00	1.00	1.00		1.00
675	18.25	1.45	5.35	0.27		0.97	1.13	1.27		0.97

EIRFlowModFac = a + b (ff) + c $(ff)^2$

48 SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	3

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.0026703	0.001335	#NUM!	#NUM!
Residual	0	0	65535		
Total	2	0.0026703			

		Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0
49									
	a	1.868328	0	65535	#NUM!	1.868328	1.8683276	1.868328	1.868328
	b	-1.447337	0	65535	#NUM!	-1.447337	-1.447337	-1.447337	-1.447337
	c	0.57901	0	65535	#NUM!	0.57901	0.5790098	0.57901	0.57901

Part Load Fraction as a Function of PLR

PartLoadFrac = 0.85 + 0.15(PLR)

PLR = sensible heating load / steady-state sensible heating load

39 Carrier manual 'CFM' column
40 Carrier manual 'Total Capacity' at rated temperature conditions
41 Carrier manual 'Total Sys. kW' at rated temperatures
42 Convert [MBtuh] capacity to [kW]
43 EIR = power / capacity = inverse of COP
44 Normalized EIR: EIRFFac = EIR / rated EIR
45 Flow fraction = actual flow rate / rated flow rate
46 Column 45 squared

47 Perform regression with:
Input Y-Range: column 44
Input X-Range: columns 45-46

48 Regression output displayed
49 EnergyPlus IDF inputs

50 Back-check of analysis using EIRFlowModFac equation

DX Cooling Coil Performance Curve Regression

Carrier	25HPA5	Performance 15 Series Heat Pump with Puron Refrigerant (1 1/2 - 5 Nominal Tons)		
Rated Airflow	600	cfm	0.248	m^3/s
Rated Capacity	17.80	Mbtuh	5217	W
Rated COP	3.52			
Flow Ratio	404	cfm/ton		

1	2	3	4	5	6	7	8	9	10	11	
Performance Data (Manual Page 23)											
$T_{wb,i}$	$T_{db,o}$	capacity [MBtuh]	power [KW]	sensible [MBtuh]	capacity [KW]	CapTFac	EIR	EIRTFac	COP	SHR	
22.2	23.9	21.85	1.17		6.40	1.23	0.18	0.64	5.47		
22.2	29.4	20.79	1.31		6.09	1.17	0.22	0.76	4.65		
22.2	35	19.68	1.48		5.77	1.11	0.26	0.90	3.90		
22.2	40.6	18.51	1.66		5.42	1.04	0.31	1.08	3.27		
22.2	46.1	17.26	1.86		5.06	0.97	0.37	1.30	2.72		
22.2	51.7	15.91	2.08		4.66	0.89	0.45	1.57	2.24		
19.4	23.9	19.82	1.17		5.81	1.11	0.20	0.71	4.96		
19.4	29.4	18.83	1.32		5.52	1.06	0.24	0.84	4.18		
19.4	35	17.80	1.48	12.70	5.22	1.00	0.28	1.00	3.52	0.713	**Rated Conditions**
19.4	40.6	16.71	1.66		4.90	0.94	0.34	1.19	2.95		
19.4	46.1	15.54	1.87		4.55	0.87	0.41	1.45	2.43		
19.4	51.7	14.30	2.09		4.19	0.80	0.50	1.76	2.00		
17.2	23.9	18.37	1.18		5.38	1.03	0.22	0.77	4.56		
17.2	29.4	17.44	1.33		5.11	0.98	0.26	0.92	3.84		
17.2	35	16.22	1.49		4.75	0.91	0.31	1.10	3.19		
17.2	40.6	15.38	1.67		4.51	0.86	0.37	1.31	2.70		
17.2	46.1	14.50	1.87		4.25	0.81	0.44	1.55	2.27		
17.2	51.7	13.54	2.09		3.97	0.76	0.53	1.86	1.90		
16.7	23.9	18.04	1.18		5.29	1.01	0.22	0.79	4.48		
16.7	29.4	17.15	1.33		5.02	0.96	0.26	0.93	3.78		
16.7	35	16.22	1.49		4.75	0.91	0.31	1.10	3.19		
16.7	40.6	15.38	1.67		4.51	0.86	0.37	1.31	2.70		
16.7	46.1	14.50	1.87		4.25	0.81	0.44	1.55	2.27		
16.7	51.7	13.54	2.09		3.97	0.76	0.53	1.86	1.90		
13.9	23.9	17.71	1.18		5.19	0.99	0.23	0.80	4.40		
13.9	29.4	16.98	1.33		4.98	0.95	0.27	0.94	3.74		
13.9	35	16.21	1.49		4.75	0.91	0.31	1.11	3.19		
13.9	40.6	15.39	1.67		4.51	0.86	0.37	1.31	2.70		
13.9	46.1	14.50	1.87		4.25	0.81	0.44	1.55	2.27		
13.9	51.7	13.54	2.09		3.97	0.76	0.53	1.86	1.90		

Regression Steps

1 Carrier manual 'EWB' column
2 Carrier manual 'Condenser Entering Air Temperatures' column
3 Carrier manual 'Total Capacity' values for the specified temperatures
4 Carrier manual 'Total Sys. kW' values for the specified temperatures
5 Carrier manual 'Sensible Capacity' value
6 Convert [MBtuh] capacity to [kW]
7 Normalize the capacity to the rated reference point
CapTFac = capaciy / rated capacity
8 EIR = power / capacity = inverse of COP
9 Express EIR as a ratio to the rated conditions i.e. normalize the EIR
EIRTFac = EIR / rated EIR
10 COP = capacity / power
11 Sensible heat ratio = sensible capacity / total capacity

12	13	14	15	16	17	21
Total Cooling Capacity as a Function of Temperature						
CapTFac	T_{wb}	T_{wb}^2	T_{db}	T_{db}^2	$T_{wb} \times T_{db}$	Test Cap
1.23	22.2	492.84	23.9	571.21	530.58	1.24
1.17	22.2	492.84	29.4	864.36	652.68	1.17
1.11	22.2	492.84	35	1225.00	777.00	1.11
1.04	22.2	492.84	40.6	1648.36	901.32	1.04
0.97	22.2	492.84	46.1	2125.21	1023.42	0.97
0.89	22.2	492.84	51.7	2672.89	1147.74	0.90
1.11	19.4	376.36	23.9	571.21	463.66	1.10
1.06	19.4	376.36	29.4	864.36	570.36	1.04
1.00	19.4	376.36	35	1225.00	679.00	0.99
0.94	19.4	376.36	40.6	1648.36	787.64	0.93
0.87	19.4	376.36	46.1	2125.21	894.34	0.87
0.80	19.4	376.36	51.7	2672.89	1002.98	0.80
1.03	17.2	295.84	23.9	571.21	411.08	1.03
0.98	17.2	295.84	29.4	864.36	505.68	0.98
0.91	17.2	295.84	35	1225.00	602.00	0.93
0.86	17.2	295.84	40.6	1648.36	698.32	0.87
0.81	17.2	295.84	46.1	2125.21	792.92	0.82
0.76	17.2	295.84	51.7	2672.89	889.24	0.76
1.01	16.7	278.89	23.9	571.21	399.13	1.02
0.96	16.7	278.89	29.4	864.36	490.98	0.97
0.91	16.7	278.89	35	1225.00	584.50	0.92
0.86	16.7	278.89	40.6	1648.36	678.02	0.87
0.81	16.7	278.89	46.1	2125.21	769.87	0.81
0.76	16.7	278.89	51.7	2672.89	863.39	0.76
0.99	13.9	193.21	23.9	571.21	332.21	0.99
0.95	13.9	193.21	29.4	864.36	408.66	0.95
0.91	13.9	193.21	35	1225.00	486.50	0.91
0.86	13.9	193.21	40.6	1648.36	564.34	0.86
0.81	13.9	193.21	46.1	2125.21	640.79	0.81
0.76	13.9	193.21	51.7	2672.89	718.63	0.76

12 From column 7
13 From column 1
14 Column 13 squared
15 From column 2
16 Column 15 squared
17 Absolute value of column 13 times column 15

18 Perform regression with:
Input Y-Range: column 12
Input X-Range: columns 13-17

19 Regression output displayed
20 EnergyPlus IDF inputs

21 Back-check of analysis using TotCapTempModFac equation

TotCapTempModFac = $a + b (T_{wb}) + c (T_{wb})^2 + d (T_{db}) + e (T_{db})^2 + f (T_{wb})(T_{db})$

19 SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9980206
R Square	0.9960452
Adjusted R Square	0.9952213
Standard Error	0.0084019
Observations	30

ANOVA

	df	SS	MS	F	Significance F
Regression	5	0.4266958	0.0853392	1208.9131	5.28E-28
Residual	24	0.0016942	7.059E-05		
Total	29	0.42839			

20

	Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0%
a	1.6459113	0.0802821	20.501586	1.02E-16	1.4802171	1.8116055	1.4802171	1.8116055
b	-0.082891	0.0075484	-10.981274	7.663E-11	-0.09847	-0.0673118	-0.09847	-0.067312
c	0.0034146	0.0001986	17.190425	5.391E-15	0.0030047	0.0038246	0.0030047	0.0038246
d	0.0003222	0.001835	0.1756017	0.8620801	-0.0034651	0.0041095	-0.003465	0.0041095
e	-2.79E-05	1.991E-05	-1.4036429	0.1732327	-6.903E-05	1.314E-05	-6.9E-05	1.314E-05
f	-0.000462	5.806E-05	-7.9616854	3.436E-08	-0.0005821	-0.0003424	-0.000582	-0.000342

22 23 24 25 26

Total Cooling Capacity as a Function of Flow Fraction

Flow	capacity		CapFFac	ff	ff^2
525	17.45		0.9803	0.88	0.77
600	17.80		1.0000	1.00	1.00
675	18.07		1.0152	1.13	1.27

30

Test Cap
0.9803
1.0000
1.0152

TotCapFlowModFac = a + b (ff) + c (ff)^2

ff = actual air mass flow rate / rated air mass flow rate

22 Carrier manual 'CFM' column
23 Carrier manual 'Total Capacity' at rated temperature conditions
24 Normalized capacity: CapFFac = capacity / rated capacity
25 Flow fraction = actual flow rate / rated flow rate
26 Column 25 squared
27 Perform regression with:
Input Y-Range: column 24
Input X-Range: columns 25-26

28 Regression output displayed
29 EnergyPlus IDF inputs

30 Back-check of analysis using TotCapFlowModFac equation

28 SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	3

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.00061	0.000305	#NUM!	#NUM!
Residual	0	0	65535		
Total	2	0.00061			

29

	Coefficients	Standard E	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0%
a	0.7168539	0	65535	#NUM!	0.7168539	0.7168539	0.7168539	0.7168539
b	0.4269663	0	65535	#NUM!	0.4269663	0.4269663	0.4269663	0.4269663
c	-0.14382	0	65535	#NUM!	-0.1438202	-0.1438202	-0.14382	-0.14382

31 32 33 34 35 36

Energy Input Ratio as a Function of Temperature

EIRTFac	T_{wb}	T_{wb}^2	T_{db}	T_{db}^2	$T_{wb} \times T_{db}$
0.64	22.2	492.84	23.9	571.21	530.58
0.76	22.2	492.84	29.4	864.36	652.68
0.90	22.2	492.84	35	1225.00	777.00
1.08	22.2	492.84	40.6	1648.36	901.32
1.30	22.2	492.84	46.1	2125.21	1023.42
1.57	22.2	492.84	51.7	2672.89	1147.74
0.71	19.4	376.36	23.9	571.21	463.66
0.84	19.4	376.36	29.4	864.36	570.36
1.00	19.4	376.36	35	1225.00	679.00
1.19	19.4	376.36	40.6	1648.36	787.64
1.45	19.4	376.36	46.1	2125.21	894.34
1.76	19.4	376.36	51.7	2672.89	1002.98
0.77	17.2	295.84	23.9	571.21	411.08
0.92	17.2	295.84	29.4	864.36	505.68
1.10	17.2	295.84	35	1225.00	602.00
1.31	17.2	295.84	40.6	1648.36	698.32
1.55	17.2	295.84	46.1	2125.21	792.92
1.86	17.2	295.84	51.7	2672.89	889.24
0.79	16.7	278.89	23.9	571.21	399.13
0.93	16.7	278.89	29.4	864.36	490.98
1.10	16.7	278.89	35	1225.00	584.50
1.31	16.7	278.89	40.6	1648.36	678.02
1.55	16.7	278.89	46.1	2125.21	769.87
1.86	16.7	278.89	51.7	2672.89	863.39
0.80	13.9	193.21	23.9	571.21	332.21
0.94	13.9	193.21	29.4	864.36	408.66
1.11	13.9	193.21	35	1225.00	486.50
1.31	13.9	193.21	40.6	1648.36	564.34
1.55	13.9	193.21	46.1	2125.21	640.79
1.86	13.9	193.21	51.7	2672.89	718.63

40

Test EIR
0.62
0.73
0.89
1.08
1.31
1.58
0.74
0.86
1.02
1.22
1.46
1.74
0.79
0.92
1.08
1.29
1.54
1.83
0.80
0.92
1.09
1.30
1.55
1.84
0.79
0.92
1.10
1.32
1.58
1.88

31 From column 9
32 From column 1
33 Column 32 squared
34 From column 2
35 Column 34 squared
36 Absolute value of column 32 times column 34

37 Perform regression with:
Input Y-Range: column 31
Input X-Range: columns 32-36

38 Regression output displayed
39 EnergyPlus IDF inputs

40 Back-check of analysis using EIRTempModFac equation

EIRTempModFac = a + b (T_{wb}) + c (T_{wb})^2 + d (T_{db}) + e (T_{db})^2 + f (T_{wb})(T_{db})

38 SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9988609
R Square	0.997723
Adjusted R Square	0.9972487
Standard Error	0.0194484
Observations	30

ANOVA

	df	SS	MS	F	Significance F
Regression	5	3.977682	0.7955364	2103.2619	7.021E-31
Residual	24	0.0090777	0.0003782		
Total	29	3.9867598			

39	*Coefficients*	*Standard E*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0*	*Upper 95.0%*
a	-0.494958	0.1858342	-2.6634381	0.0135974	-0.8785009	-0.111415	-0.878501	-0.111415
b	0.1392146	0.0174727	7.9675353	3.391E-08	0.1031527	0.1752766	0.1031527	0.1752766
c	-0.004044	0.0004598	-8.7943857	5.676E-09	-0.0049926	-0.0030946	-0.004993	-0.003095
d	-0.002484	0.0042476	-0.5847878	0.5641482	-0.0112506	0.0062827	-0.011251	0.0062827
e	0.0006504	4.608E-05	14.115129	4.049E-13	0.0005553	0.0007455	0.0005553	0.0007455
f	-0.000547	0.0001344	-4.0728397	0.0004383	-0.0008248	-0.00027	-0.000825	-0.00027

41	42	43	44	45		46	47	48
Energy Input Ratio as a Function of Flow Fraction								
Flow	**MBtuh**	**total KW**	**capacity**	**EIR**		**EIRFFac**	**ff**	**ff^2**
525	17.45	1.47	5.11	0.29		1.01	0.88	0.77
600	17.80	1.48	5.22	0.28		1.00	1.00	1.00
675	18.07	1.49	5.29	0.28		0.99	1.13	1.27

52
Test EIR
1.01
1.00
0.99

41 Carrier manual 'CFM' column
42 Carrier manual 'Total Capacity' at rated temperature conditions
43 Carrier manual 'Total Sys. kW' at rated temperatures
44 Convert [MBtuh] capacity to [kW]
45 EIR = power / capacity = inverse of COP
46 Normalized EIR: EIRFFac = EIR / rated EIR
47 Flow fraction = actual flow rate / rated flow rate
48 Column 47 squared

49 Perform regression with:
Input Y-Range: column 46
Input X-Range: columns 47-48

50 Regression output displayed
51 EnergyPlus IDF inputs

52 Back-check of analysis using EIRFlowModFac equation

EIRFlowModFac = a + b (ff) + c (ff)^2

50 SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	65535
Standard Error	0
Observations	3

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.000234	0.000117	#NUM!	#NUM!
Residual	0	0	65535		
Total	2	0.000234			

51	*Coefficients*	*Standard E*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0*	*Upper 95.0%*
a	1.2419303	0	65535	#NUM!	1.2419303	1.2419303	1.2419303	1.2419303
b	-0.398056	0	65535	#NUM!	-0.3980562	-0.3980562	-0.398056	-0.398056
c	0.1561259	0	65535	#NUM!	0.1561259	0.1561259	0.1561259	0.1561259

Part Load Fraction as a Function of Part Load Ratio

PartLoadFrac = 0.85 + 0.15(PLR)

PLR = sensible cooling load / steady-state sensible cooling load

APPENDIX F – OCCUPANCY SCHEDULES

This appendix contains the schedules to define the building internal gains.

Apr30-A-4-GEMINI-Baseline-Occupied-Window.idf - Notepad

```
Schedule:Compact,
   Occupant Schedule,
   Fraction,
   Through: 12/31,
   For: Weekdays,
   Until: 08:00,
   1,
   Until: 17:00,
   0,
   Until: 24:00,
   1,
   For: Weekends,
   Until: 10:00,
   1,
   Until: 17:00,
   0.5,
   Until: 24:00,
   1,
   For: Holidays,
   Until: 24:00,
   1,
   For: SummerDesignDay WinterDesignDay,
   Until: 24:00,
   0;
```

Figure F1: Occupant schedule.

Apr30-A-4-GEMINI-Baseline-Occupied-Window.idf - Notepad

```
Schedule:Compact,
   Lighting Schedule,                               !- **NTED Average Values
   Fraction,
   Through: 12/31,
   For: AllDays,
   Until: 24:00,
   1;

Schedule:Compact,
   Equipment Schedule,                              !- **NTED Average Values
   Fraction,
   Through: 12/31,
   For: AllDays,
   Until: 24:00,
   1;
```

Figure F2: Appliance and lighting schedule.

Internal Gains Load Calculations for EnergyPlus Input

Calculate floor area of single-family homes and % of total residential floor area.

	Floor Area [m2]
total residential	1545000000
single attached + detached	1197000000
% SF homes	0.774757282

Calculate energy use rate from average Canadian rate for single-family homes.

	Energy Use by End Use [W]	Energy Use by End Use for Homes [W]	Energy Use Per Unit Area for Homes [W/m2]
appliances	5882166413	4557251260	3.81
lighting	2023084729	1567399625	1.31
water heating	11025494673	8542082280	7.14

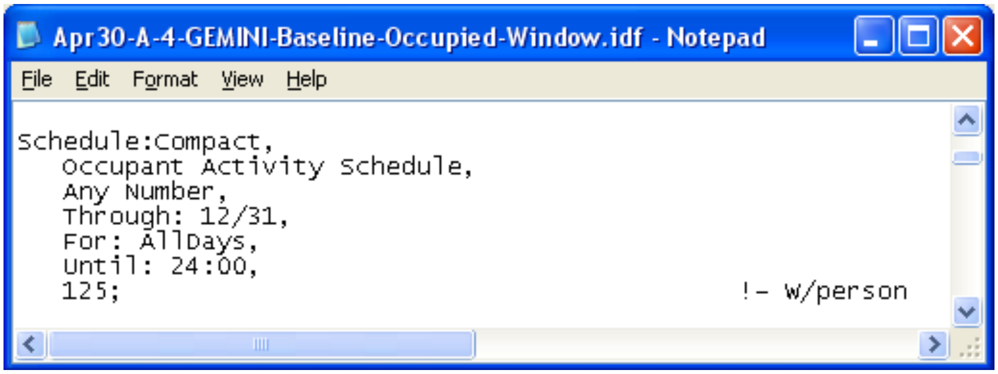
Eliminate freezer from appliance energy use rate.

	Energy Use by End Use [W]	Energy Use by End Use for Homes [W]	Energy Use Per Unit Area for Homes [W/m2]	
refrigerator	1163749366	901623295.1	0.75	
freezer	374175545.4	289895228.4	0.24	
dishwasher	79274479.96	61418480.59	0.05	
clothes washer	69761542.36	54048262.92	0.05	
clothes dryer	957635717.9	741935245.5	0.62	
range	960806697.1	744391984.7	0.62	
other	2279934044	1766395502	1.48	
			3.57	**appliances (adjusted)**

Verify that calculated energy rate yields annual energy use.

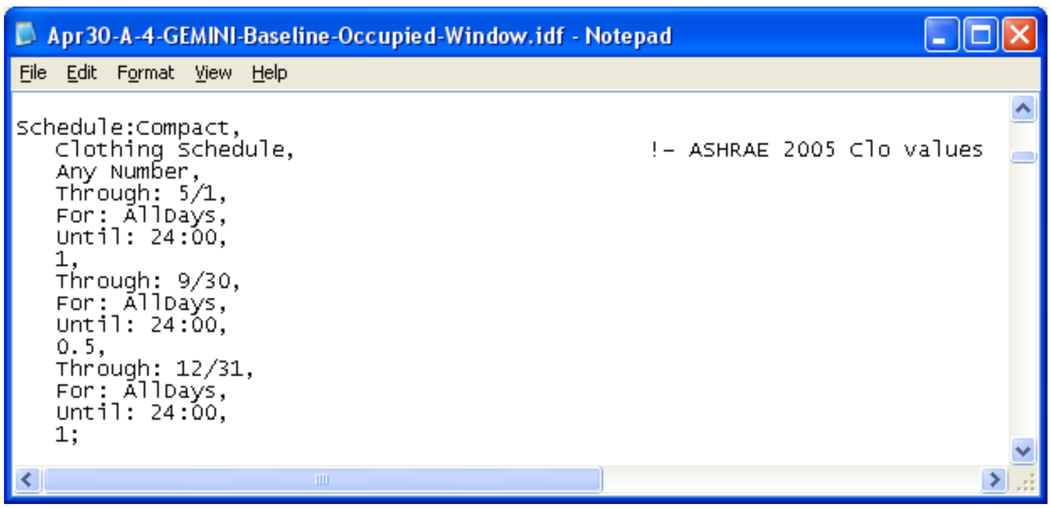
		Energy Use by End Use [J]	Energy Use by End Use for Homes J	Energy Use Per Unit Area for Homes J/m2	Back-Check Annual Energy Use [J/m2]
s/yr	**appliances**	1.855E+17	1.43717E+17	120064724.9	120064725
31536000	**lighting**	6.38E+16	4.94295E+16	41294498.38	41294498
	water heating	3.477E+17	2.69383E+17	225048543.7	225048544

Figure F3: Calculations for appliance, lighting and domestic hot water loads.




```
Schedule:Compact,
   Occupant Activity Schedule,
   Any Number,
   Through: 12/31,
   For: AllDays,
   Until: 24:00,
   125;                                          !- W/person
```

Figure F4: Occupant activity schedule.

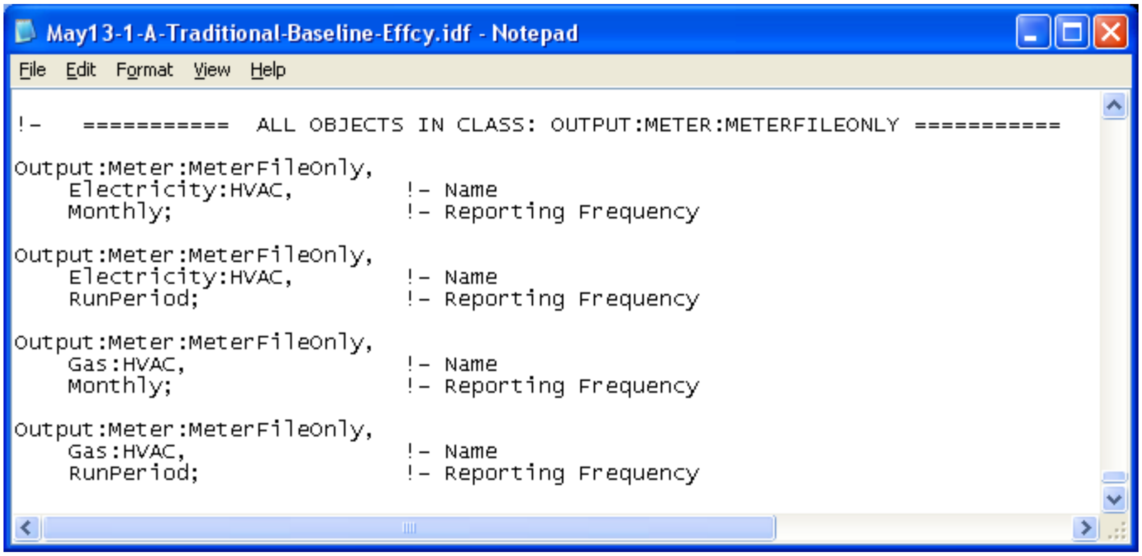



```
Schedule:Compact,
   Clothing Schedule,                            !- ASHRAE 2005 Clo values
   Any Number,
   Through: 5/1,
   For: AllDays,
   Until: 24:00,
   1,
   Through: 9/30,
   For: AllDays,
   Until: 24:00,
   0.5,
   Through: 12/31,
   For: AllDays,
   Until: 24:00,
   1;
```

Figure F5: Clothing schedule.

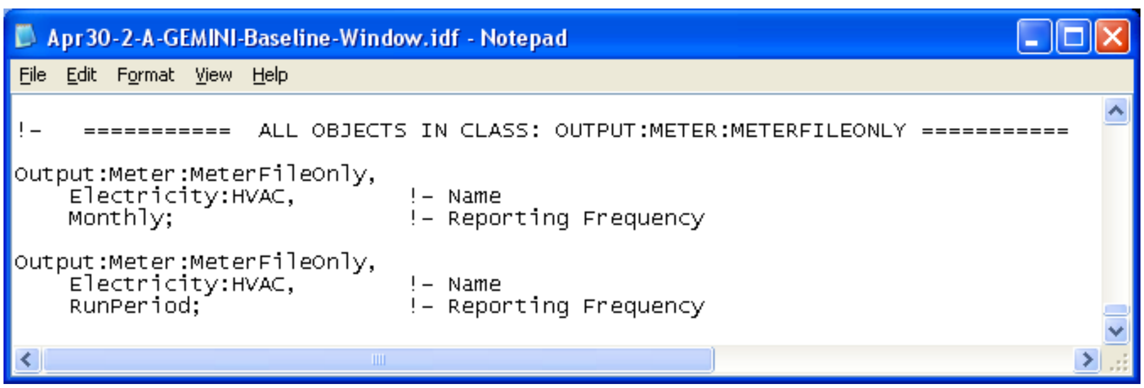
APPENDIX G – ENERGYPLUS OUTPUT METER SETTINGS

This appendix contains the output meters used to obtain the results used for the simulation analysis.



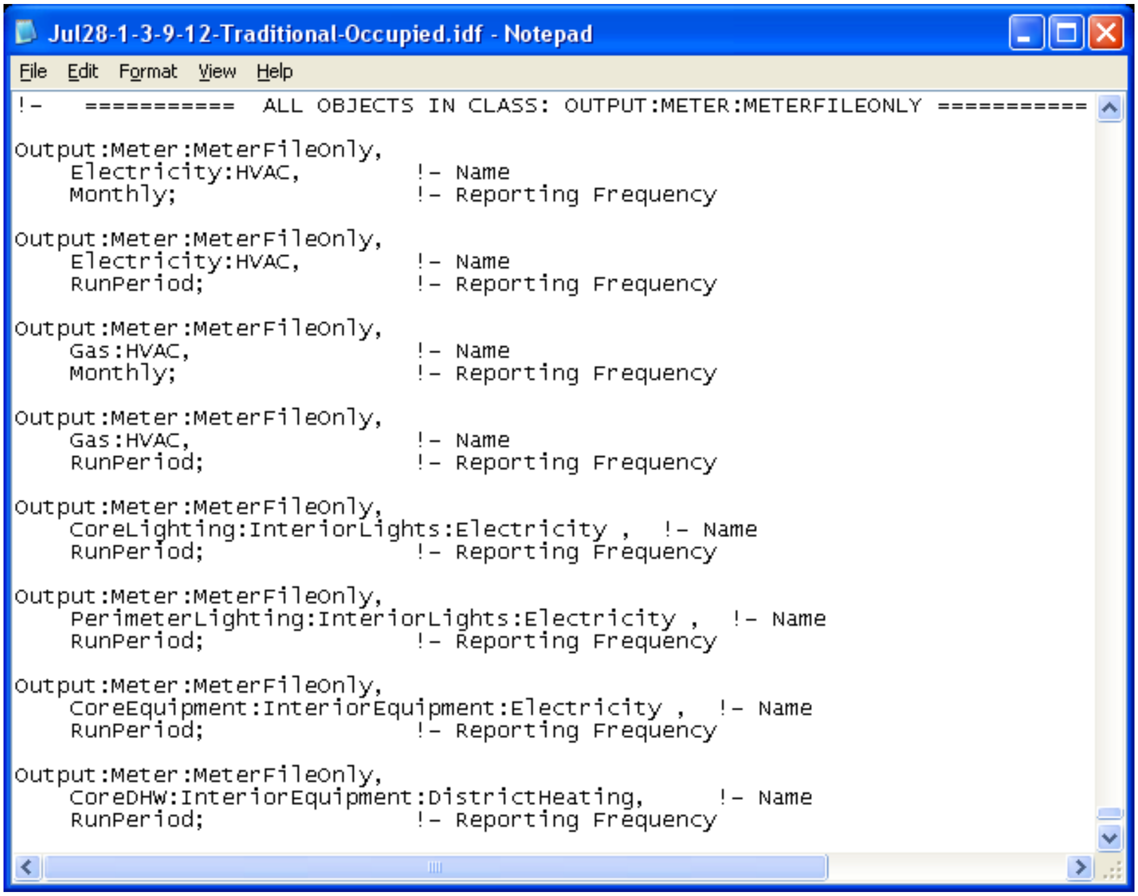

```
!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:METER:METERFILEONLY ===========

Output:Meter:MeterFileOnly,
    Electricity:HVAC,        !- Name
    Monthly;                 !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Electricity:HVAC,        !- Name
    RunPeriod;               !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Gas:HVAC,                !- Name
    Monthly;                 !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Gas:HVAC,                !- Name
    RunPeriod;               !- Reporting Frequency
```

Figure G1: Traditional mode non-occupied meter settings.




```
!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:METER:METERFILEONLY ===========

Output:Meter:MeterFileOnly,
    Electricity:HVAC,        !- Name
    Monthly;                 !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Electricity:HVAC,        !- Name
    RunPeriod;               !- Reporting Frequency
```

Figure G2: Gemini mode non-occupied meter settings.

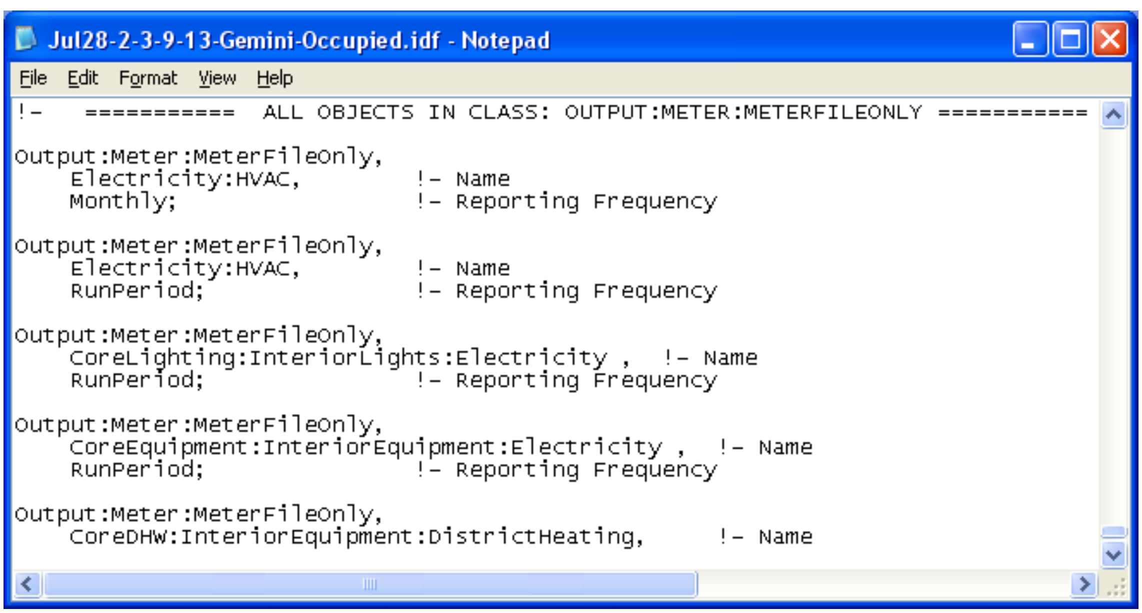


Jul28-1-3-9-12-Traditional-Occupied.idf - Notepad

File Edit Format View Help

```
!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:METER:METERFILEONLY ===========

Output:Meter:MeterFileOnly,
    Electricity:HVAC,         !- Name
    Monthly;                  !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Electricity:HVAC,         !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Gas:HVAC,                 !- Name
    Monthly;                  !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Gas:HVAC,                 !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    CoreLighting:InteriorLights:Electricity ,  !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    PerimeterLighting:InteriorLights:Electricity ,  !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    CoreEquipment:InteriorEquipment:Electricity ,  !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    CoreDHW:InteriorEquipment:DistrictHeating,     !- Name
    RunPeriod;                !- Reporting Frequency
```

Figure G3: Traditional occupied meter settings.



Jul28-2-3-9-13-Gemini-Occupied.idf - Notepad

File Edit Format View Help

```
!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:METER:METERFILEONLY ===========

Output:Meter:MeterFileOnly,
    Electricity:HVAC,         !- Name
    Monthly;                  !- Reporting Frequency

Output:Meter:MeterFileOnly,
    Electricity:HVAC,         !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    CoreLighting:InteriorLights:Electricity ,  !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    CoreEquipment:InteriorEquipment:Electricity ,  !- Name
    RunPeriod;                !- Reporting Frequency

Output:Meter:MeterFileOnly,
    CoreDHW:InteriorEquipment:DistrictHeating,     !- Name
```

Figure G4: Gemini occupied meter settings (note that there is no perimeter lighting to report in this case).

APPENDIX H – SIMULATION RESULTS AND ANALYSIS

This appendix contains the values from the EnergyPlus output files and conversions to the final kWh values.

EnergyPlus NTED Simulation Results

Operating Mode	House Orientation	Wall Construction
1. Traditional	3. Baseline	6. c4 / p4
2. Gemini	4. Square	7. c4 / p6
	5. 90o Base	8. c6 / p4
		9. c6 / p6
		10. c6 / p12
		11. c12 / p6

Time		
	243	days/period
	86400	seconds/day
	20995200	seconds/period
	5832	hours/period

Phase 1: Geometry

Configuration	Energy [J]	[W]	[kW]	[kWh]
1-3-9	29279331076	1394.57262	1.39457262	8133
1-4-9	29991559516	1428.496014	1.42849601	8331
1-5-9	31617648996	1505.946549	1.50594655	8783
2-3-9	4509578404	214.7909238	0.21479092	1253
2-4-9	4727048213	225.1489966	0.225149	1313
2-5-9	4851491504	231.0762224	0.23107622	1348

Phase 2: Construction

Configuration	Energy [J]	[W]	[kW]	[kWh]
1-3-8	34318406431	1634.583449	1.63458345	9533
1-3-9	29279331076	1394.57262	1.39457262	8133
1-3-10	23578806472	1123.057007	1.12305701	6550
2-3-6	5083043092	242.1050093	0.24210501	1412
2-3-7	4658132225	221.8665326	0.22186653	1294
2-3-8	4949539351	235.7462349	0.23574623	1375
2-3-9	4509578404	214.7909238	0.21479092	1253
2-3-10	4034164211	192.146977	0.19214698	1121
2-3-11	4352828979	207.324959	0.20732496	1209

No Core Infiltration

Configuration	Energy [J]	[W]	[kW]	[kWh]
2-3-9	4268379179	203.3026205	0.20330262	1186

EnergyPlus NTED Simulation Results

Geometry	Occupant Behaviour			
3. Baseline	12. Traditional occupied	Time	243	days/period
	13. Gemini occupied		86400	seconds/day
	14. Moderate occupied		20995200	seconds/period
			5832	hours/period

Phase 3: Occupant Behaviour - HVAC Only

Configuration	Energy [J]	[W]	[kW]	[kWh]
3-12	13119261410	624.86956	0.62487	3644
3-13	390763177	18.612025	0.018612	109
3-14	4476453968	213.21321	0.213213	1243

Moderate Operation		
Traditional	78	0.3209877
GEMINI	165	0.6790123

Phase 3: Occupant Behaviour - All Energy Use

Configuration	Energy [J]	[W]	[kW]	[kWh]
3-12	37230149090	1773.2696	1.77327	10342
3-13	18560849065	884.05202	0.884052	5156
3-14	24553463888	1169.4799	1.16948	6820

EnergyPlus NTED Simulation Results

Geometry	Occupant Behaviour			
3. Baseline	13. Gemini occupied	Time	243	days/period
	15. Gemini-occupied + core shutters		86400	seconds/day
	15a. Gemini-occupied core modified glazing shutters		20995200	seconds/period
	15b. Gemini-occupied core door shutters		5832	hours/period
	15c.Gemini-occupied no core windows			
		Shutter Time	0.375	on
			0.625	off

Phase 4: Insulated Shutters - HVAC Only - Heating Season

Configuration	Energy [J]	[W]	[kW]	[kWh]
3-13	390763177.1	18.6120245	0.01861202	109
3-15a	435348748.6	20.7356324	0.02073563	121
3-15b	402914891.4	19.1908099	0.01919081	112
3-15c	425235320	20.2539304	0.02025393	118
3-15	407482766.4	19.4083775	0.01940838	113

APPENDIX I – SIMULATION INPUT AND RESULTS FOR HFH – NTED™ COMPARISON

This appendix contains the values from the EnergyPlus output files and conversions to the final kWh values.

EnergyPlus NTED and HFH Building Comparison

Equivalent insulation thicknesses using EPlus conductivity values RSI to R 5.678

HFH	R	RSI	C	k	t [m]	t [in]
walls	40	7.044734061	0.14195	0.04	0.281789362	11
ceiling	60	10.56710109	0.094633333	0.04	0.422684044	16.7
floor	30	5.283550546	0.189266667	0.034	0.179640719	7

EnergyPlus IDF input values

	k	t [m]	t [in]
walls	0.04	0.267	10.5
ceiling	0.04	0.423	16.7
floor	0.034	0.18	7

	width [m]	length [m]	height [m]
NTED perim	8	18	3
NTED core	6	12	2.5
HFH	8	18	2.5

	wall area [m2]	ceiling area [m2]	floor area [m2]
NTED perim	156	144	144
NTED core	90	72	72
HFH	130	144	144

	wall thickness [m]	ceiling thickness [m]	floor thickness [m]
NTED perim	0.14	0.305	0.05
NTED core	0.14	0.14	0.05
HFH	0.267	0.423	0.18

NTED insulation savings

	NTED	HFH	
wall	34.44	34.71	0.78%
ceiling	54	60.912	11.35%
floor	7.2	25.92	72.22%

Equivalent appliance load for larger building area in HFH case

	NTED W/m2	total W	HFH W/m2
appliances	3.57	257.04	1.79
lighting	1.31		1.31
water heating	7.14	514.08	3.57

EnergyPlus NTED Simulation Results

Operating Mode	House Orientation	Wall Construction	Occupant Behaviour			
1. Traditional	3. Baseline	6. c4 / p4	12. Traditional occupied	Time	243	days/period
2. Gemini	4. Square	7. c4 / p6	13. Gemini occupied		86400	seconds/day
16. HFH	5. 90o Base	8. c6 / p4	14. Moderate occupied		20995200	seconds/period
		9. c6 / p6			5832	hours/period
		10. c6 / p12				
		11. c12 / p6				

Moderate Operation		
Traditional	78	0.32098765
GEMINI	165	0.67901235

Phase 1: Geometry

Configuration	Energy [J]	[W]	[kW]	[kWh]
1-3-9	29279331076	1394.57262	1.3945726	8133
2-3-9	4509578404	214.7909238	0.2147909	1253
16	12921417548	615.446271	0.6154463	3589

Phase 3: Occupant Behaviour - HVAC Only

Configuration	Energy [J]	[W]	[kW]	[kWh]
3-12	13119261410	624.8695611	0.6248696	3644
3-13	390763177	18.61202452	0.018612	109
3-14	4476453968	213.2132091	0.2132132	1243
16	1042022273	49.63145257	0.0496315	289

Phase 3: Occupant Behaviour - All Energy Use

Configuration	Energy [J]	[W]	[kW]	[kWh]
3-12	37230149090	1773.269561	1.7732696	10342
3-13	18560849065	884.0520245	0.884052	5156
3-14	24553463888	1169.479876	1.1694799	6820
16	21207491969	1010.111453	1.0101115	5891

APPENDIX J – CD INDEX FOR ENERGYPLUS CODE MODIFICATION AND SIMULATION FILES

This appendix contains an index of the files located on the data CD that accompanies this thesis document.

EnergyPlus Version 4.0 Modified NTED™ Executable & IDD Files

EnergyPlus.exe
Energy+.idd

EnergyPlus Version 4.0 Source Code – Unmodified Modules

AirflowNetworkBalanceManager.f90
AirflowNetworkSolver.f90
BaseboardRadiator.f90
BaseboardRadiatorWater.f90
BranchInputManager.f90
BranchNodeConnections.f90
ConductionTransferFunctionCalc.f90
CoolTower.f90
CostEstimateManager.f90
CurveManager.f90
DataAirflowNetwork.f90
DataAirLoop.f90
DataAirSystems.f90
DataBranchNodeConnections.f90
DataConvergParams.f90
DataConversions.f90
DataCostEstimate.f90
DataDaylighting.f90
DataDaylightingDevices.f90
Datadefineequip.f90
DataDElight.f90
DataEnvironment.f90
DataErrorTracking.f90
DataGenerators.f90
DataGlobalConstants.f90
DataGlobals.f90
DataHeatBalance.f90
DataHeatBalFanSys.f90
DataHeatBalSurface.f90
DataHVACControllers.f90
DataHVACGlobals.f90
DataIPShortCuts.f90
DataLoopNode.f90
DataMoistureBalance.f90
DataMoistureBalanceEMPD.f90
DataPhotovoltaics.f90
DataPlant.f90
DataPrecisionGlobals.f90
DataReportingFlags.f90
DataRoomAir.f90
DataRootFinder.f90
DataRuntimeLanguage.f90
DataShadowingCombinations.f90
DataSizing.f90

DataStringGlobals.f90
DataSurfaceColors.f90
DataSurfaceLists.f90
DataSurfaces.f90
DataSystemVariables.f90
DataUCSDSharedData.f90
DataVectorTypes.f90
DataViewFactorInformation.f90
DataWater.f90
DataZoneControls.f90
DataZoneEnergyDemands.f90
DataZoneEquipment.f90
DateTime.f90
DaylightingDevices.f90
DaylightingManager.f90
DElightManagerF_NO.f90
DemandManager.f90
DesiccantDehumidifiers.f90
DirectAir.f90
DisplayRoutines.f90
DXCoil.f90
EarthTube.f90
EconomicTariff.f90
EcoRoof.f90
ElectricPowerGenerators.f90
ElectricPowerManager.f90
EMSManager.f90
Energy+.idd
EnergyPlus.f90
ExteriorEnergyUseManager.f90
FanCoilUnits.f90
FluidProperties.f90
General.f90
GeneralRoutines.f90
GlobalNames.f90
HeatBalanceAirManager.f90
HeatBalanceConvectionCoeffs.f90
HeatBalanceHAMTManager.f90
HeatBalanceInternalHeatGains.f90
HeatBalanceIntRadExchange.f90
HeatBalanceManager.f90
HeatBalanceMovableInsulation.f90
HeatBalanceSurfaceManager.f90
HeatBalFiniteDifferenceManager.f90
HeatRecovery.f90
Humidifiers.f90
HVACControllers.f90
HVACCooledBeam.f90
HVACDualDuctSystem.f90
HVACDuct.f90
HVACDXSystem.f90
HVACEvapComponent.f90
HVACFanComponent.f90
HVACFurnace.f90
HVACHeatingCoils.f90

HVACHXAssistedCoolingCoil.f90
HVACInterfaceManager.f90
HVACManager.f90
HVACMixerComponent.f90
HVACMultiSpeedHeatPump.f90
HVACSingleDuctInduc.f90
HVACSingleDuctSystem.f90
HVACSplitterComponent.f90
HVACStandAloneERV.f90
HVACSteamCoilComponent.f90
HVACTranspiredCollector.f90
HVACUnitaryBypassVAV.f90
HVACWaterCoilComponent.f90
HVACWatertoAir.f90
InputProcessor.f90
MixedAir.f90
MoistureBalanceEMPDManager.f90
NodeInputManager.f90
NonZoneEquipmentManager.f90
OutAirNodeManager.f90
OutputProcessor.f90
OutputReportPredefined.f90
OutputReports.f90
OutputReportTabular.f90
PackagedTerminalHeatPump.f90
Photovoltaics.f90
PhotovoltaicThermalCollectors.f90
PlantAbsorptionChillers.f90
PlantBoilers.f90
PlantBoilersSteam.f90
PlantChillers.f90
PlantCondLoopOperation.f90
PlantCondLoopTowers.f90
PlantDemandSideSolvers.f90
PlantEIRChillers.f90
PlantEvapFluidCoolers.f90
PlantFlowResolver.f90
PlantFluidCoolers.f90
PlantFreeCoolingHeatExchanger.f90
PlantGasAbsorptionChiller.f90
PlantGroundHeatExchangers.f90
PlantHeatExchanger.f90
PlantIceThermalStorage.f90
PlantLoadProfile.f90
PlantLoopEquipments.f90
PlantManager.f90
PlantOutsideCoolingSources.f90
PlantOutsideHeatingSources.f90
PlantPipeHeatTransfer.f90
PlantPipes.f90
PlantPlateHeatExchanger.f90
PlantPondGroundHeatExchanger.f90
PlantPressureSystem.f90
PlantPumps.f90
PlantSolarCollectors.f90

PlantSupplySideSolvers.f90
PlantSurfaceGroundHeatExchanger.f90
PlantUtilities.f90
PlantValves.f90
PlantWaterThermalTank.f90
PlantWatertoWaterGSHP.f90
PlantWaterUse.f90
PollutionAnalysisModule.f90
PoweredInductionUnits.f90
PsychRoutines.f90
Purchasedairmanager.f90
RadiantSystemHighTemp.f90
RadiantSystemLowTemp.f90
RefrigeratedCase.f90
ReturnAirPath.f90
RoomAirManager.f90
RoomAirModelCrossVent.f90
RoomAirModelDisplacementVent.f90
RoomAirModelMundt.f90
RoomAirModelUFAD.f90
RoomAirModelUserTempPattern.f90
RootFinder.f90
RuntimeLanguageProcessor.f90
ScheduleManager.f90
SetPointManager.f90
SimAirServingZones.f90
SimulationManager.f90
SizingManager.f90
SolarReflectionManager.f90
SolarShading.f90
SortAndStringUtilities.f90
SQLiteFortranRoutines_NO.f90
SurfaceGeometry.f90
SystemAvailabilityManager.f90
SystemReports.f90
ThermalChimney.f90
ThermalComfort.f90
UnitHeater.f90
UnitVentilator.f90
UtilityRoutines.f90
VectorUtilities.f90
VentilatedSlab.f90
WaterManager.f90
WeatherManager.f90
WindowAC.f90
WindowManager.f90
Zoneairloopequipmentmanager.f90
ZoneDehumidifier.f90
Zoneequipmentmanager.f90
ZonePlenumComponent.f90
ZoneTempPredictorCorrector.f90

EnergyPlus Version 4.0 Source Code – Modified Files

DataZoneEquipment.f90
DXCoil.f90

Zoneequipmentmanager.f90

EnergyPlus NTED™ Simulation Input Data Files

Geometry

Jul28-1-3-9-Traditional-Baseline.idf
Jul28-1-4-9-Traditional-Square.idf
Jul28-1-5-9-Traditional-90Baseline.idf
Jul28-2-3-9-Gemini-Baseline.idf
Jul28-2-4-9-Gemini-Square.idf
Jul28-2-5-9-Gemini-90Baseline.idf

Construction

Jul28-1-3-8-Traditional-c6p4.idf
Jul28-1-3-9-Traditional-c6p6.idf
Jul28-1-3-10-Traditional-c6p12.idf
Jul28-2-3-6-Gemini-c4p4.idf
Jul28-2-3-7-Gemini-c4p6.idf
Jul28-2-3-8-Gemini-c6p4.idf
Jul28-2-3-9-Gemini-c6p6.idf
Jul28-2-3-10-Gemini-c6p12.idf
Jul28-2-3-11-Gemini-c12p6.idf

Occupants

Jul28-1-3-9-12-Traditional-Occupied.idf
Jul28-2-3-9-13-Gemini-Occupied.idf

DesignBuilder/EnergyPlus Comparison

Oct30-GEMINI-DB-Export-Core-Slab-Construction.idf
Oct30-GEMINI-DB-Export-Core-Slab-Void.idf
Oct30-GEMINI-EPlus-Configured-01.idf

Insulated Shutters

Apr20-A-6a-GEMINI-Base-Occ-FullShutters-NoCooling.idf
Apr20-A-6a-GEMINI-Baseline-Occupied-FullShutters-NoCool.idf
Jul13-A-6c-GEMINI-Baseline-Occupied-CoreDoors-NewRSI.idf

No Core Infiltration

Jul28-2-3-9-Gemini-Baseline-NoCInf.idf

HFH

Jul30-HFH-Baseline-NonOccupied.idf
Jul30-HFH-Baseline-Occupied.idf