

**Evaluation of the passive cooling potential of mass inherent  
in medium to large commercial buildings**

by

**John Nelson**

B.S., Colorado State University, 2006

M.E., University of Colorado, 2015

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written by John Nelson  
has been approved for the Department of Civil, Environmental, and Architectural Engineering

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Prof. Gregor P. Henze

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Prof. Moncef Krarti

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Prof. Wangda Zuo

Date \_\_\_\_\_

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Nelson, John (M.S. Architectural Engineering)

Evaluation of the passive cooling potential of mass inherent in medium to large commercial buildings

Thesis directed by Prof. Gregor P. Henze

While the literature on thermal mass and passive cooling is rich, what it means for a building to be thermally massive is not well defined or consistently applied. Most research has been conducted with mass depths far greater than would be seen in typical construction. Meanwhile, some research suggests that because the heat transfer rate at the surface is limited, the focus should be on surface area of exposed mass. Since even lightweight commercial construction typically has large surface areas of mass in the floor slabs, this research investigates how effective that mass is for passive cooling, relative to other mass depths. In all climates analyzed it was found that there was a pronounced shoulder where energy savings from passive cooling of increasing mass depths was steep until roughly 7.5 cm to 10 cm, and thereafter the energy savings diminished rapidly. When considering the embodied energy of concrete, the incremental benefit of added mass beyond a typical topping slab of 10 cm does not justify the incremental embodied energy cost from an energy standpoint alone, unless a very long embodied energy payback period was adopted.

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## Chapter 1

### Introduction

Thermal mass can shift loads and provide a dampening effect on internal temperatures, which can be exploited for energy savings, load reduction and improved comfort. Sometimes referred to as the thermal flywheel concept, the basic principle is that thermal mass absorbs excess heat during the day, and stores it until it can be discharged later [11], or in some cases used to reduce subsequent heating loads [4, 7]. As mass is tempered passively, it can provide more comfortable mean radiant temperatures as well as more consistent temperatures, both with the potential to improve comfort while also saving energy. For commercial buildings, the primary strategy with thermal mass is passive cooling through a night flush. When night time air temperatures are sufficiently cold, air is brought in to ‘cool’ the exposed thermal mass, which in turn provides a heat sink for the following day [2]. Since most internal gains have a significant radiant fraction, if exposed mass is pre-cooled the effect is to prevent those internal gains from ever becoming convective loads through directly absorbing the radiant component [9], and either controlling the release of its heat at night or retaining it for benefit [8]. This is a contrast to a thermally light weight building without passive cooling, in which a larger portion of the internal and other gains more quickly become convective cooling load contributions.

The terms thermally heavy and thermally light are not applied consistently throughout research. Most of the literature on thermal mass has been conducted with mass levels that are far greater than would be found in typical construction. The same can be said about most of the publicized buildings that have implemented passive cooling. However, some research utilizes thin-

ner levels of mass and places more emphasis on the surface area of exposed mass. The Building Research Establishment's (BRE) digest on thermal mass in office buildings makes the point that "For most floor construction types the ability of the slab to conduct and store the thermal energy is superior to the rate of surface heat transfer. It is therefore the surface heat transfer characteristics that determine or limit the thermal storage performance of the slab" [4].

This view of thermal mass as surface area of exposed mass rather than mass depth has implications towards reducing the barriers of implementing passive cooling, because most commercial buildings have large surface areas of mass located in the floor slabs. This is true of even steel framed buildings, which could be considered lightweight construction. There is a certain frugality to better utilization of the mass which is inherent in these buildings, both from a first cost standpoint, and a life-cycle standpoint given the embodied energy in concrete. Better utilization of the mass located in the floor slabs requires exposing it, either as the floor or ceiling, as carpets and dropped ceilings effectively insulate the structure from the interior environment [7].

The motivation of this research is therefore to investigate how applicable passive cooling can be to more typical commercial buildings, which consistently have internal loads and large surface areas of mass hidden in the floor slabs, or to determine if passive cooling is only applicable to the structurally massive and highly passive projects that it is most commonly applied to. For this investigation, this research analyzes how effective the typical 10 cm floor slab could be at passive cooling for energy savings, relative to other mass depths. It is important to caveat that this research is being analyzed for buildings with active cooling. Deeper mass levels have the benefit of improved comfort in fully passive buildings over multiday warm periods [34], as well as applicability to other passive strategies. While fully passive buildings are applaudable, they are also very rare for commercial construction in the United States.

## Chapter 2

### Literature Review

#### 2.1 Impacts of Thermal Mass with Passive Cooling

Energy and cost savings reported for thermally massive buildings utilizing passive cooling have ranged greatly. Modeling techniques, optimization of controls, and different climate zones are among the factors leading to a wide range. A 2017 literature review noted energy savings of 12-40% from night cooling [31]. A 2013 literature review which was more focused on load reduction noted an 8.5% to 29% energy cost savings [38]. A recent study focusing on energy cost savings and utilizing building energy simulations (BES) with optimized controls indicated cooling and reheating energy savings from 15-40% for six commercial buildings in Boston, Chicago, and Miami during typical summer conditions [25]. Measured results for energy cost savings have been limited because it is difficult to isolate the effects of thermal inertia [41].

Load reductions similarly show a large range in performance. The 2017 literature review discussed multiple studies in the range of 30-80% sensible cooling load reduction for properly performed passive cooling and commented on two studies with only 10-20% cooling load reduction, which was attributable to rudimentary control strategies [31]. The 2013 literature review focused on load reduction indicated that over 30% peak cooling load reduction can be achieved through thermal mass for load shifting. Measured results are more available for load reduction, although they are still few. A NIST experimental test facility showed 15% reduction in peak sensible cooling load [18]. Braun et al. found 30% reduction in peak sensible cooling load for a real building in Iowa where model-based controls were implemented [22].

## 2.2 Sensitivity to Influential Parameters

Artmann et al. performed a parameter study on passive cooling with night air with respect to reducing overheating hours in a fully passive scenario [2]. Sensitivity to both surface heat transfer and air flow rates were found up to a certain point. For surface heat transfer, significant sensitivity was found only for total heat transfer coefficients below  $4 \text{ W/m}^2 \text{ K}$ . For airflow, it was found that there was a critical value of airflow, beyond which no significant improvement in overheating hours occurred. This critical value started at 4 ACH and “in most cases, applying a higher air change rate than 8 ACH did not improve thermal comfort significantly” [2]. Thermal mass and heat gains were also noted to have a significant effect on achievable comfort through passive cooling alone. To analyze the effects of thermal mass, three cases of different amounts of exposed mass surface area were studied, rather than the varying the depth of the mass, which is an interesting study and aligns with the concept of thermal mass as surface area. 180 mm of mass was used in the floor slab, which is far deeper than a typical topping slab. It was found that “a 180 mm thick concrete ceiling in direct contact with the room air reduced overheating by a factor of two compared to a suspended ceiling.” By also including thermally massive brick exterior walls, overheating was reduced by a factor of 3 [2]. It is notable that this study used the same control strategy across 8 climates.

Another study supported Artmann et al.’s finding on the diminishing returns of increasing air changes during a night flush. In a sensitivity study to pressure coefficients for passive cooling of office buildings in a natural ventilation setting, Ramponi et. al, indicated that all climates studied showed a sharp increase in energy savings up to 3 ACH, and thereafter experienced a shoulder, generally between 4-6 ACH [35]. This study also investigated the convective heat transfer coefficient (CHTC) and found that it had a larger effect than the discharge coefficients of the natural ventilation openings which was a primary topic of the study. In their analysis, enhanced CHTCs increased savings from 30 to 37% [35].

Breesch et al. conducted a sensitivity analysis on passive cooling in office buildings with respect to controlling comfort in a natural ventilation setting, and found that internal heat gains,

air tightness, solar heat gain coefficient of the sunblinds, and CHTC were the most impactful four parameters. CHTC was ahead of factors including mass depth, mass thermal properties, and discharge and wind pressure coefficients [10]. Since internal gains and sunblind characteristics are BES inputs rather than factors the simulation calculates, it could be concluded that with respect to BES prediction accuracy, CHTC is among the most important factors tested. It was also found that performance is highly dependent on outdoor temperatures [10].

The above parameter studies all indicate that the CHTC has importance for the accurate prediction of passive cooling. The state of modeling convection is in general not as accurate as radiation or conduction [14, 33]. Specifically, assumptions of isothermal surfaces, perfectly mixed zone air, and simplified convection correlations developed for specific instances are all problematic for accuracy [23]. Goethals et al. indicated that in a typical situation without night cooling, “the low temperature differences between the surfaces and the air result in the choice of convection coefficients having only a minor impact. On the other hand, in the case where the office is night cooled, a larger scatter is noticeable, just because the larger temperature differences occur” [14]. Yet correlations have not been developed for passive cooling specifically, and two recent studies investigating convection correlations with respect to passive cooling both indicated that it is not clear which correlations are best suited to passive cooling, and that further research is necessary [23, 14].

### **2.3 Mass Depth**

The concept that there is a point in which increasing the depth of mass will have diminishing returns has been observed in literature [44, 18, 34, 43]. How pronounced the diminishing returns are, or where the shoulder exists, has not been a primary source of study to the best of the author’s knowledge, but has been alluded to in the following research.

Henze et al. conducted a sensitivity analysis of optimal control of thermal mass and concluded that doubling the mass, in depth and not surface area which already included walls, showed only weak returns with respect to cooling load reduction [18]. The starting point for the mass was 10

cm of interior brick for walls and 20 cm for the floor slab, which is already double that of a typical topping slab. With respect to energy cost savings “savings relative to the reference case appear to be maximized (29%) not for the heaviest mass construction but rather for half and regular building thermal mass” [18]. This is a very interesting finding and raises the question as to if thinner mass levels may in some cases outperform thicker mass levels.

Pfafferott et al. performed a parameter analysis on night cooling utilizing the Fraunhofer ISE building for comparison. Two rooms were modeled in the ESP-r simulation program and used to test parameters. The parameter analysis includes stepping mass and surface heat transfer coefficient (radiant and convection combined) jointly. The 10 cm and 15 cm mass depth behave nearly identically under the 8 W/m<sup>2</sup> K scenario, indicating that the extra 5 cm of mass did not lead to more savings. The 15 cm case was then modeled with 12 W/m<sup>2</sup> K and it outperformed both other cases, but the analysis was not repeated for the 10 cm [34].

Hajiah and Krarti performed an analysis of optimized controls for simultaneously using building thermal mass and ice storage and noted “the simulation results indicate that even with little mass, significant savings can be achieved using the optimal controls” [15]. 16.3% savings was achieved with 186 kg/m<sup>2</sup> of mass at the floor, which works out to be roughly 84 mm of normal weight concrete. While mass depths were not varied in the study, the results lead to a hopeful outlook that the mass depths of typical topping slabs can be effective for passive cooling.

In *Nonlinear Coupling Between Thermal Mass and Natural Ventilation in Buildings*, Yam et al. comments on the relationship between convective heat transfer and the depth of thermal mass and notes that when the convective heat transfer coefficient is small, “further increase of thermal mass has no effect at all” [43]. The authors suggest a new dimensionless number to measure thermal mass based on the capacity of heat storage rather than the amount of thermal mass. While this is a highly intriguing concept, the ‘thermal mass number’ presented is a dimensionless ratio between the maximum heat stored and the total heat gain in the building. This is not a complete metric of thermal mass because it would result in the same thermal mass number in a climate with excellent passive cooling potential as one with poor passive cooling potential, and it is also difficult to

translate this thermal mass number back into a mass depth for practitioners.

Slee et al. raised the question of how much thermal mass is needed, but their analysis is of a concept and cannot be used to determine depth of thermal mass in building design by the authors' own statements [37]. The analysis included measurements of steel drums of water for thermal mass in an enclosure in Australia, and modeling of the steel drums, which is a very different surface heat transfer interaction than buildings experience and limits the applicability of the results. None the less, their conclusion seems correct. "There comes a point at which adding additional thermal capacity to the space no longer influences the internal temperature range. The general view that 'mass is good, therefore more mass must be better' is shown to be erroneous."

All of the above studies have indicated that there is a point at which additional mass depth provides only diminishing returns, if any, or that notable savings have been demonstrated with thin mass levels. These studies have motivated this research, because if the mass which is inherent in most commercial buildings is adequate for passive cooling, then there is a frugality case to be made, as well as a lower barrier to adoption.

## Chapter 3

### Methodology and Modeling

To investigate how suitable typical floor slabs are for use as thermal mass, BES were performed for six different climate zones using EnergyPlus v8.8.0. For each climate zone, both a passive night flush and a mechanical night flush for passive cooling were analyzed. Optimizations using GenOpt v3.1.1 were performed to select appropriate night flush settings, and then parametric analyses were performed to determine the relationship between energy savings and mass depth between 0.1 cm and 30 cm. Several sensitivity tests were also conducted on Climate Zone 5b, which is a climate that has both strong diurnal swings for a complete night flush, but also times where a night flush is not adequate.

#### 3.1 DOE Reference Building used for simulation analysis

The Department of Energy (DOE) creates Commercial Reference Building models as a part of weighing the effects of each new version of ANSI/ASHRAE/IES Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings [16]. There are 16 prototype buildings across 15 climate zones which collectively represent 70% of the building stock in the United States [12]. Built in EnergyPlus, they are available to the public and were chosen for use in this research because they have been heavily analyzed with the intention of representing typical buildings, and are also transparent and well documented for further analysis.

The Medium Office prototype was used, which is a three story 4,982 square meter (53,628 square feet) office building. The Medium Office prototype is additionally applicable to weighing

the question of thermal mass with large office buildings, because it has the same floor slab mass characteristics and internal load densities as the Large Office prototype, with the exception excluding the data center. The ASHRAE Standard 90.1-2013 version of the DOE Reference Building model was used in the analysis, representing where many codes are with relation to envelope and system efficiencies.

### **3.1.1 Exposing Mass of the DOE Reference Building**

The DOE Reference model has 10 cm (4 inch) deep floor slabs, accurately representing a typical topping slab over a ribbed metal pan which steps between 7.5 and 12.5 cm. This mass was exposed as a ceiling by removing the acoustical ceiling tile and the plenum zone, extending the height of the occupied zone up. There is a 15 cm concrete floor at the ground level which was left covered by carpet. 10 cm of concrete was added to the roof beneath the insulation, which is not uncommon in commercial buildings, although it could also be argued that this is added mass because it is not always present. Buildings can utilize exposed mass as floors instead of ceilings to definitively avoid added mass, although care would need to be taken to make sure the ground exchange does not lead to discomfort in winters of cooler climates. There is additionally 8" of concrete in the walls, on the outside of the insulation, which was left unchanged in the model. While this mass has an effect of dampening conduction through the walls with diurnal swings, it is isolated from the night flush and the internal load cycle because of the insulation on the inside. The DOE Reference Buildings also contains thermal properties for interior furnishings, which were left unchanged.

### **3.1.2 Thermal Properties of Concrete**

Thermal properties of the concrete were reviewed and left unchanged for the energy analysis, and a sensitivity analysis was performed for the conductivity of concrete. As simulated, the concrete has a density of 2,322 kg/m<sup>3</sup> (145 lbs/ft<sup>3</sup>), which is typical for normal weight concrete [4], specific heat of 832 J/kg K and conductivity of 2.31 W/m K. Conductivity can vary in concrete. A

study showed the use of quaritized aggregates leads to conductivities of 2.29 W/m K to 2.77 W/m K depending on sand type I or II (quartz vs mica), while limestone aggregates lead to lower conductivities of 1.6 W/m K to 2.03 W/m K for dry concrete. Meanwhile, moisture content of the concrete can have a 70% effect on conductivity [21]. A sensitivity analysis was performed varying the conductivity from 1.3 to 2.7 W/m K and was found to have very little effect. Results for the conductivity sensitivity analysis are included as Figure B.1 in Appendix B.

### 3.1.3 Internal Loads

Primary internal loads in the DOE Reference Building model include an occupant density of 0.054 people/m<sup>2</sup> (0.005 people/ft<sup>2</sup> or 200 ft<sup>2</sup>/person), lighting power density of 8.83 W/m<sup>2</sup> (0.82 W/ft<sup>2</sup>), and plug load density of 8.07 W/m<sup>2</sup> (0.75 W/ft<sup>2</sup>). Radiant fractions of the people, lights and plugs are 0.3, 0.7, and 0.5 respectively. As a sensitivity test, densities for people, lights and plugs were varied by plus or minus 30% on 10% increments steps, which is included in the Results and Discussion section.

Two parameters which seemed likely to vary from the DOE Reference Building were also changed in another internal load sensitivity test. Lighting power density was reduced by 35% to 5.74 W/m<sup>2</sup> (0.533 W/ft<sup>2</sup>) and the radiant fraction was reduced from 0.7 to 0.1 to represent LED lighting. Additionally, the radiant fraction of people was changed from 0.3 to 0.6. The ASHRAE Handbook of Fundamentals notes that the radiant fraction from people can vary between 0.19 to 0.6 depending on people's activity and the air speed around them [3], with the low airspeeds of a dedicated outdoor air system leading to a higher radiant fraction. The results showed very little effect however, with slightly less heat moving in and out of the mass. Results are included as Figure B.2 in Appendix B.

## 3.2 Night Flush Cases

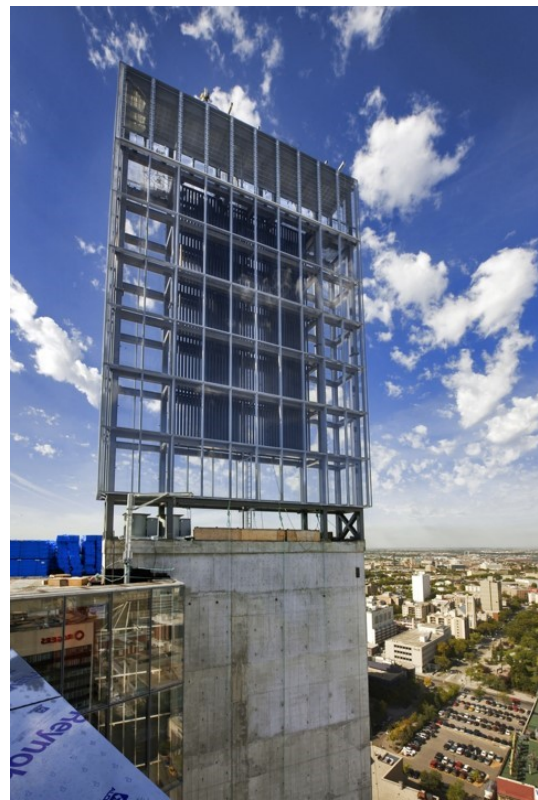
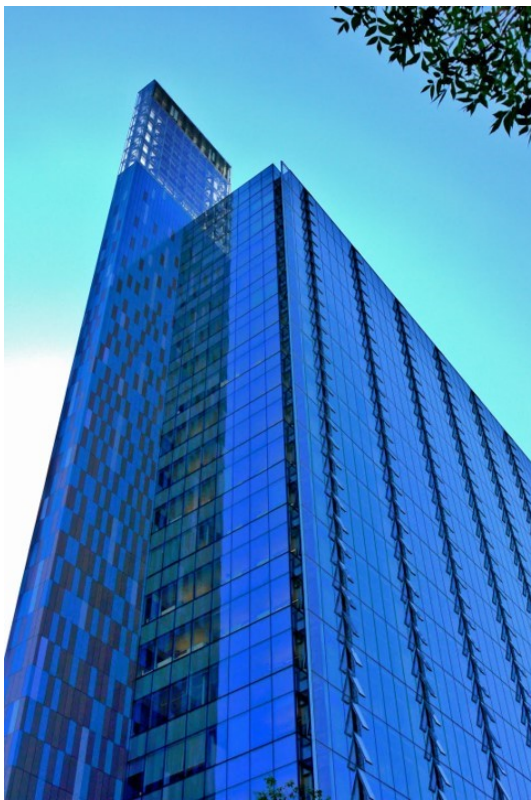
Two scenarios were analyzed for each of the six locations, one with a mechanical night flush and another with a passive night flush. EnergyPlus ZoneVentilation objects were used as a simple

way to include the night flush in the model. HVAC Availability Managers were set to control the HVAC system off during the night flush in all cases, which was allowed to be between 18:00 and 06:00. The VAV system in the DOE Reference model is allowed to cycle on at night to meet heating or cooling setpoints. This was not changed, to preserve function in colder months, but during months with a night flush the heating setpoint was repressed to 10°C to prevent heating during a flush. ZoneVentilation objects were set to off during the winter and summer design days so that the parametric analyses results are not influenced by equipment sizing.

For the mechanical night flush cases, the ZoneVentilation objects were set to Intake to capture the heat of the fan energy into the air stream. Relevant settings such as fan efficiency were included to make this object match the VAV parameters, as addressed further in the Optimization section.

For the passive night flush cases, natural ventilation was not modeled directly. Instead, parametric analyses were conducted for 2, 4 and 6 ACH. 4 ACH was the most heavily analyzed case, as well as the case which the night flush optimization was conducted for. The intention with 4 ACH was to ensure that air change rates during the night flush was not a limiting factor, which could bias results towards lower mass levels by not fully exercising the mass. 3 to 4 ACH has been demonstrated to capture the majority of savings available from a night flush [35, 2]. Further, air changes available through natural ventilation are highly dependent on design parameters such as the depth of space, operable window sizes, the use of a solar chimney, etc. The Manitoba Hydro building is a creative example of a 21-story office building using a solar chimney to not only induce stack effect during the day, but mass was added to the solar chimney so that at night the temperature differences continue to induce more airflow (Figure 3.1). Thus, the achievable air flow during a night flush is variable, and to model it only for the DOE Commercial Reference buildings would limit the applicability of the results. For this reason, multiple air changes rates were included, and these cases have been labeled Passive Night Flush since natural ventilation is not directly modeled. Additionally, air changes rates up to 20 ACH were conducted as a sensitivity test and are included in the Results and Discussion section.

Figure 3.1: Solar chimney with mass for greater night flush at the Manitoba Hydro building. Images courtesy of Manitobahydroplace.com



### 3.3 Comfort

Care was taken to ensure that the night flush did not result in excessively cool temperatures. Comfort was reviewed using Predicted Mean Vote (PMV) and Percent People Dissatisfied (PPD), and targeted bounds between a PMV of  $\pm 0.5$  during occupied hours. While heating was prevented during the night flush, it was allowed to resume at 06:00, giving one potential hour of reheat before the building reaches 20% occupancy at 07:00, and two hours before the building reaches full occupancy at 08:00. This morning reheat to maintain comfort differs from past literature but was done to further exercise the thermal mass because the research question is on thermal mass depth and a more conservative night flush could bias results towards thinner mass levels. Further, since the night flush settings are building wide in this research, but the largest core zones typically had the warmest observed minimum temperatures during the flush, this reheat method allows a more aggressive flush to capture further passive cooling in the core zones while not causing excessive discomfort in other zones. Additional research could optimize zones independently in the mechanical case, which would likely lead to additional energy savings.

### 3.4 Optimization and Parametric Analysis

Optimization was performed with the objective function as minimum total site energy using GenOpt v3.1.1. The Hybrid Generalized Pattern Search Algorithm with Particle Swarm Optimization Algorithm was used. This hybrid algorithm starts with Particle Swarm Optimization (PSO). Then, discrete variables (start/stop time) become fixed at the value determined by the PSO, and the continuous variables are optimized further with the Hooke-Jeeves Generalized Pattern Search (GPS) algorithm. The GPS implementation of Hooke-Jeeves is specifically recommended for finding the lowest of multiple local minima [42]. An optimization was repeated for Climate Zone 5b using only Particle Swarm Optimization without the Hooke-Jeeves GPS algorithm, and while similar results were found, the Hybrid implementation found a lower minima energy, with slightly more bounds on the flush.

### 3.4.1 Site versus Source Energy Optimization

Site energy was chosen as the objective function in lieu of the more commonly used Source energy for two reasons. The first has to do with Source energy being in a dynamic period, making an optimization based on Source energy today difficult to interpret in the future. Source energy gained popularity at a time when the grid makeup was relatively stable, and heavily reliant on coal. Now for economic reasons, many coal plants are being converted to combined cycle natural gas, and renewables are providing a larger portion of the electricity, all changing the conversions between Source and Site energy. Additionally, Public Utility Commissions and utilities are acting on explicit renewable energy goals which stretch into the future and will continue change the conversion factors between Site and Source energy, adding complication to the future interpretation of optimizations based on Source energy at current conversion factors. The second reason Site energy was used is a more aspirational reason, in placing our goals at a point when we no longer use combustion of fossil fuels in buildings. This is required in The Living Building Challenge's Net Positive Energy Imperative, in which no combustion onsite is allowed.

However, in recognition that source energy is the preferred metric to many, Appendix D contains a breakout of gas versus electric heat in the results of all climate zones analyzed. Gas is used at the air handlers, whereas reheat is all electric in the DOE Reference models. It was found that the heating energy savings was entirely in electric reheat for each of the climate zones analyzed. The gas heating at the air handlers range from no change to increasing slightly, depending upon the climate zone. It is expected that this was due to the Supply Air Temperature (SAT) reset, in which the warmer deck temperature is allowed because the warmest zone does not need as much cooling. With the heating savings being in electricity and not gas, this indicates that optimization based on Site Energy is nearly equivalent to optimization based on Source Energy for this situation.

Table 3.1: Optimized Variables

Night Flush Case	$T_{outside}$ Min	$T_{outside}$ Max	$T_{inside}$ Min	Start/Stop Time	ACH	Pressure
Passive	X	-	X	X	-	-
Mechanical	X	X	X	X	X	X*

X: variable optimized.

\*Dependent variable on ACH.

### 3.4.2 Optimization Variables

Start time and stop time were variables for the optimizer, with time increments of one hour and an allowable flush period between 18:00 and 06:00. The minimum inside temperature and minimum outside temperature were also optimized variables to put bounds on the flush and prevent overcooling. Mass depth was allowed to be a free variable so as to not bias around a certain mass depth. The limits for this variable were between 0.1 cm and 30 cm. For the mechanical night flush, minimum outside temperature and air changes per hour were included as variables to reduce fan energy. The maximum air change rate was set to 4.25 ACH, which was the maximum observed flow rate in the DOE Reference model for Climate Zone 5b. Pressure was set as a dependent variable based on the air change rate through Equation 3.1, whereas pressure 1 and ACH 1 are both from the VAV system.

$$pressure_2 = pressure_1 * \left(\frac{ACH_2}{ACH_1}\right)^2 \quad (3.1)$$

Once the optimization was complete, the optimized variables were updated in the respective models and a parametric analysis was performed using JEPlus v1.6.4, stepping only the mass depth between 0.1 cm and 30 cm.

### 3.4.3 Optimization Period

The process to use GenOpt v3.1.1 to determine optimal setpoints for the night flushes was repeated on a monthly basis for applicable months, which varies by climate. Shoulder seasons were included. Peter May-Ostendorp's dissertation on offline Model Predictive Control for near-optimal supervisory control in mixed-mode buildings distinguishes between swing and cooling seasons when

developing ‘improved heuristics’ based on rule extraction from Model Predictive Control (MPC) solutions [26]. In investigating seasonality, May-Ostendorp notes “it might be necessary to develop multiple rules for different seasons or even months of the year” which could be implemented as ‘seasonal setpoint reset schedules’. In commenting on the balance between the best performance and a parsimonious model, May-Ostendorp notes “it is therefore reasonable to assume that extracted rules might vary on these longer time scales of months or weeks, but certainly not days.” Tanner’s dissertation on optimized controls in Mixed Mode buildings builds on May-Ostendorp’s research and similarly notes that “rules generated for a single season or location do not transfer well to other seasons or locations” [40]. Their collective work drove the decision to optimize the night flush setpoints for different seasons (months) and for each different climate zone as the appropriate level of optimization refinement for addressing the research question of mass depth. This represents good control, although it must be noted that this is not the maximum achievable energy savings available if hourly optimization was performed.

To further understand the implications of this level of optimization, optimizations were repeated for both daily and annual periods as a sensitivity test in Boulder, CO on the passive night flush case. The daily optimization was performed for a one-week period in the shoulder season of May. May 15th through May 21st was selected for being particularly dynamic week in temperature, based on review of the weather file. Temperatures range from 2°C to 29°C in this week. At 10 cm mass depth, the daily optimization was able to reduce building energy use by an additional 4.3%, which is a 23.5% increase in the available savings through passive cooling, when compared to applying the setpoints from the entire month of May to this week. The additional energy savings was in reduced reheat by placing additional bounds on the flush when beneficial, while not significantly limiting passive cooling. No additional cooling energy was found through daily optimization in this time-period. Meanwhile the annual optimization, with a single heuristic schedule for the entire passive cooling period, resulted in only a 6% reduction in available energy savings through passive cooling when compared to monthly optimized case. This suggests that simple heuristics with settings determined through optimization obtain reasonable performance, although certainly

not the academic maximum. The reason appears to be that throughout the summer when the majority of cooling is occurring, clear patterns exist in the optimal setpoints which are based on maximizing cooling, and it is the climate and not the setpoints which limit the extent of passive cooling. Results for both cases are included in Appendix E.

### 3.5 Heat Balance Algorithm

By default, EnergyPlus uses conduction transfer functions (CTF) for transient heat transfer in its heat balance algorithm. Previous research has indicated issues with the CTF at higher mass levels [36, 28, 13, 41]. Early simulations for this research using the CTF encountered these issues as inconsistent results at greater mass depths. Overall, the CTF produced generally correct patterns with respect to mass depth and energy savings, but the inconsistent results produced jagged steps in the parametric curve beginning at 17.5 cm for Climate Zone 5b.

As an alternative, the Conduction Finite Difference (CondFD) heat balance algorithm is the appropriate method for modeling deeper mass levels [27, 13, 36]. This method also adds considerable modeling time however, which has been suggested to limit its applicability in annual whole building simulations [28]. EnergyPlus does give the ability to assign heat balance algorithms for selected surfaces in lieu of global settings however, reducing the impact of selecting this algorithm in annual simulations. This research was conducted with CondFD assigned for each of the ceiling and floor surfaces only and was found to produce the same results as applying CondFD as a global parameter.

NREL completed a validation of the Conduction Finite Difference method and recommended a time step of two to three minutes, noting that a time step of four minutes leads to differences in heating or cooling that were not observed in smaller times steps [39]. A timestep of three minutes was therefore used in this research. Other settings used in NREL's validation were used in this research; difference scheme of Crank Nicholson 2nd order, space discretization constant of 3, relaxation factor of 1, inside face surface temperature convergence criteria of 0.002. Giuliani et al. and Mazzarella et al. also indicated the Crank Nicholson implementation of CondFD was preferable for simulations of deeper mass [13, 27]. Some instability was still observed at higher mass

levels with CondFD, which was resolved by changing the temperature convergence from 0.2°C to 0.1°C, changing the minimum warmup days from 6 to 15, and increasing the maximum warmup days to 120.

### **3.6 Convection Coefficient**

Research identified in the Literature Review section establishes that modeling of convection is in general not as accurate as radiation or conduction, that predicated energy results for passive cooling are sensitive to the parameter, and that no convection correlations have been developed specifically for this rather unique scenario. This research is not intended to answer the open question of the best convection correlations for passive cooling, but a good representation of heat flux into and out of the mass is a critical aspect to understanding the appropriate depth of mass. The aim is therefore to use the most appropriate correlations available, and then also run sensitivity analyses to test the influence of convection on the research question of mass depth.

The Adaptive Convection Algorithm (ACA) was selected as a global setting for interior convection, with the default settings for natural convection correlations at the ceiling overridden from Alamdari Hammond Stable Horizontal and Alamdari Hammond Unstable Horizontal to Walton Stable Horizontal and Walton Unstable Horizontal, for reasons discussed in the Surface Heat Transfer Investigation section. All other default correlations used in the ACA were kept. It is notable that the results are nearly indistinguishable from the TARP algorithm, which is EnergyPlus' default global convection algorithm and is based on Walton's correlations [29].

## Chapter 4

### Surface Heat Transfer Investigations in EnergyPlus

#### 4.0.1 Available Convection Correlations in EnergyPlus

EnergyPlus has four global settings for convective heat transfer algorithms, as well as another 29 convection correlations from research which can be assigned by surface type or implemented through the ACA [30]. The ACA allows BES software to select appropriate convection correlations “on a time-dependent basis during a simulation” [33]. In particular for this research, the ACA changes the ceiling convection correlation for stable and unstable conditions. Stable and unstable refers to the direction of heat flow and whether buoyancy induces (unstable) or slows (stable) heat transfer [29]. With respect to an exposed mass ceiling and a night flush, unstable is the daytime condition where air being ‘cooled’ by the ceiling is able to freely drop away. Stable refers to the night condition of warm air rising and being trapped by the ceiling, which limits the heat transfer.

Of the 10 convection correlations which could be assignable to ceilings, the following 9 correlations are applicable for further discussion, with the Fisher Ceiling Diffuser Correlation being dismissed.

#### 4.0.2 Alamdari Hammond Horizontal (Stable and Unstable)

These are the default natural convection correlations for ceiling stable and ceiling unstable conditions when the ACA is selected. Roughly a decade after the ACA was introduced, Beausoleil-Morrison et al.’s continued work on convection concluded that Alamdari and Hammond’s correlations shows convincing agreement with data reported for vertical plates, but that there is a large

scattering of data for horizontal plates [33]. Meanwhile, Goethals et al.’s sensitivity analysis on CHTCs during night cooling concluded that the Alamdari and Hammond correlations result in significantly lower CHTCs at higher temperature differences, which is a critical condition of a night flush [14]. Our own sensitivity analysis agreed that this correlation produces the lowest CHTC during a night flush of any correlation studied.

#### 4.0.3 Beausoleil-Morrison Mixed (Stable and Unstable)

This ‘mixed’ correlation refers to a mixture of buoyancy and momentum forces. As pointed out by Artmann et al. there is a potential for both forces to exist in a night flush, leading to increased convection, “but the magnitude of these effects is hard to predict.” [1]. The use of a momentum component is therefore highly intriguing. However, the momentum component of the Beausoleil-Morrison Mixed correlations (Stable correlation included as Equation 3.2) was based on the Fisher Pedersen Ceiling Diffuser Ceiling correlation which was developed for higher airflows and has a lower airflow validity limit of 3 ACH [14]. As discussed later in the results section, the optimizer consistently chose air change rates under 3 ACH for the mechanical night flush case, which limits the applicability of this correlation. This correlation was also developed for ceiling diffusers flush with the ceiling, which would not be the case with an exposed mass ceiling.

$$h = \left( (0.6 * \left( \frac{|\Delta T|}{D_h} \right)^{\frac{1}{5}})^3 + \left( \left[ \frac{T_s - T_a}{|\Delta T|} \right] * [-0.166 + 0.484ACH^{0.8}] \right)^3 \right)^{\frac{1}{3}} \quad (4.1)$$

At low temperature differences, the Fisher component (right side of Equation 3.2) is dominant, which leads to significantly higher CHTCs than other correlations as demonstrated by Goethals et al. [14]. At high temperature differences, more emphasis is shifted to the natural convection component, which was based on Alamdari and Hammond’s, and underestimates the CHTC for high temperature differences found in night flush scenarios. So, while a mixed correlation is highly intriguing for a night flush scenario, neither of the correlations used in the Beausoleil-Morrison Mixed correlation are well suited for the unique situation of a night flush for passive cooling.

#### **4.0.4 Karadag Chilled Ceiling (Unstable)**

The use of a chilled ceiling correlation for the unstable (daytime) condition is intriguing because the passively cooled mass ceiling is in effect a chilled ceiling. However, the original research for this correlation only includes results for temperature differences of 5°C and higher [19], and no validations could be found for lower temperature differences. The correlation did produce very good daytime convective heat transfer, roughly double that of the selected Walton Unstable correlation, but without validation it is considered too aggressive.

#### **4.0.5 Khalifa Eq7 Ceiling and Khalifa Eq4 Ceiling Away from Heat**

Khalifa created two convection correlations for ceilings that are available in EnergyPlus. Neither has been labeled as unstable or stable, but Khalifa's research indicates both correlations are valid for rooms with heating elements and up to a 5°C temperature difference [20]. This would limit the applicability of both to the unstable condition, where the ceiling is cooler than the air. The EnergyPlus Engineering Reference Guide additionally lists both correlations for certain unstable conditions and neither are noted to be for stable conditions [29]. When applied to the unstable (daytime) condition in the night flush, the results of both are very similar to the Karadag Chilled Ceiling correlation, with Eq7 Ceiling being slightly above Karadag's chilled ceiling correlation, and Eq4 being slightly below. Both correlations are roughly double that of the Walton Unstable Horizontal correlation.

#### **4.0.6 Walton Horizontal (Unstable and Stable)**

The Walton Unstable Horizontal correlation is the only unstable correlation listed in the EnergyPlus Engineering Reference guide for both chilled ceiling and simple buoyancy applications [29]. The Walton Unstable Horizontal correlation produced roughly half the CHTC as the Karadag Chilled Ceiling or Khalifa correlations, and roughly 50% higher than that of the Alamdari Hammond unstable correlation.

While choosing a correlation made specifically for passive cooling would have been ideal if

it existed, this middle ground spot of being above correlations which have been demonstrated to be too low for this unique situation, but below correlations which were suspected to be too high, was the driving factor in selecting the Walton Unstable correlation. Similarly, the Walton Stable correlation was also a middle ground.

Implementing the Walton correlations through the Adaptive Convection Algorithm produced nearly indistinguishable results from the TARP algorithm, which is EnergyPlus' default and is based on the Walton correlations. This method allows other convection correlations for walls and floors to be dynamically selected during the simulation however. If future work leads to a development of a new convection correlation for night flushing, implementing it through the ACA would likely be the preferred path for EnergyPlus. The ability to implement new correlations into the ACA was specifically noted as an intention in Beausoleil-Morrison's original ACA work [5].

#### **4.0.7 Results from Convection Correlations**

Figure 4.1 shows the convective heat transfer coefficient (CHTC) for various combinations of the convection correlations applied for stable and unstable conditions, at the thermal mass ceiling. The date displayed is May 16th in Climate Zone 5b, in which cool night temperatures are available for passive cooling. There is roughly a 250% difference in the CHTC based on the choice of the convection correlation.

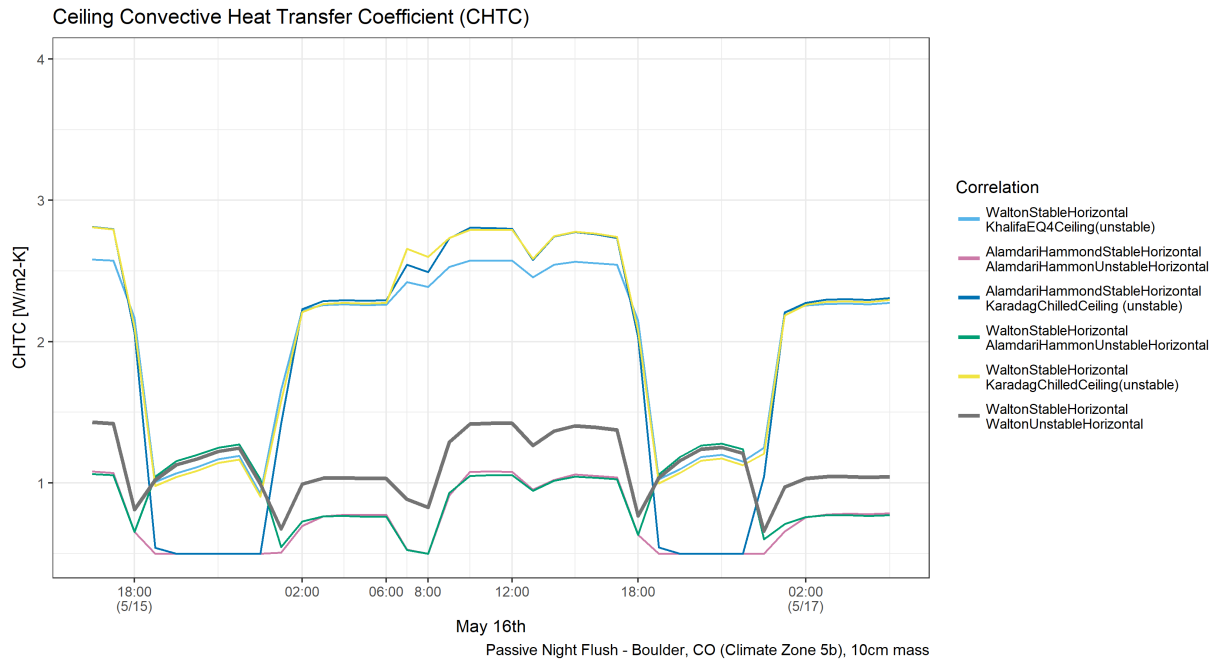


Figure 4.1: Convection Coefficient During Night Flush

Figure 4.2 shows the actual convective heat transfer over the same period. During the day, low temperature differences lead to a lower spread of results than the CHTC. Meanwhile at night, the larger temperature differences lead to a larger spread in results. Even with the same correlation applied to the stable condition (night), there is a spread in results based on the correlation used in the unstable condition (daytime), which would lead to different concrete surface temperatures. This would be difficult to conceptualize from CHTCs alone.

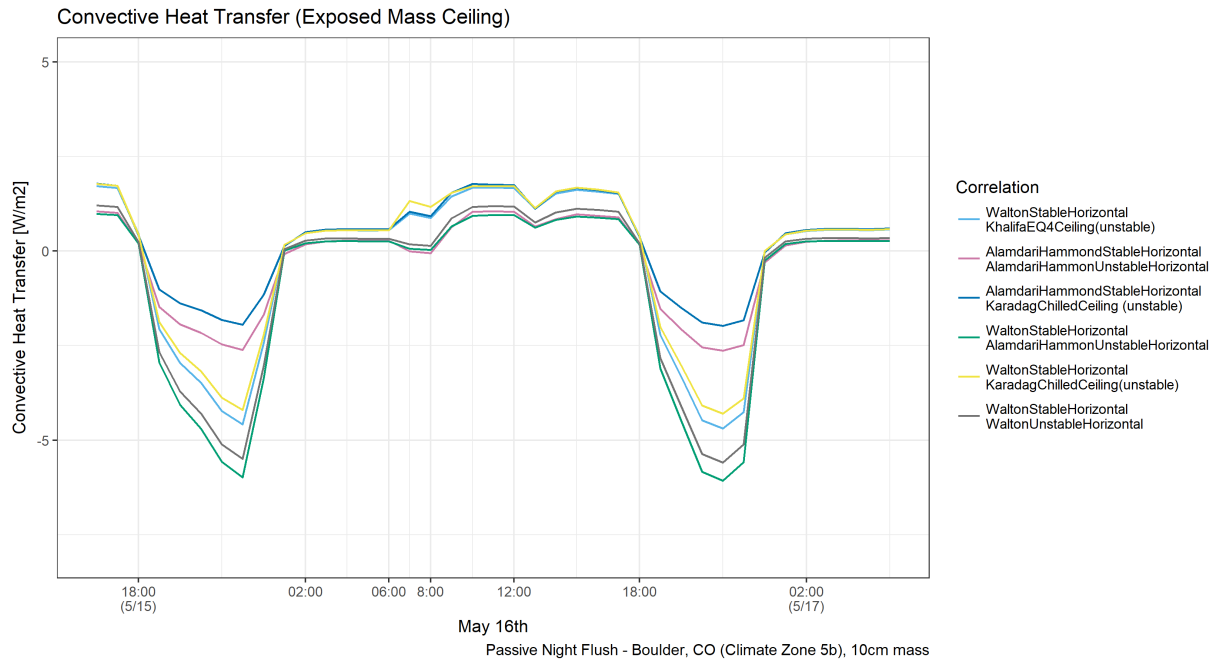


Figure 4.2: Convective Heat Transfer During Night Flush

Figure 4.3 introduces radiant heat transfer over the same period. There are two notable conclusions from this figure, one of which was unexpected. The first is that the correlations which produce the highest convective heat transfer also lead to the lowest radiant heat transfer, and likewise lowest convective heat transfer options lead to highest radiant heat transfer. In this sense, radiant heat transfer partially offsets the differences between the total predicted surface heat transfer for the various convection correlation options. Some of the literature on night cooling has utilized combined radiant and convective heat transfer which would not have accounted for this relationship. However, this self-corrective behavior has already been noted in literature through experimental tests demonstrating that displacement ventilation leads to a lower CHTC at the ceiling, which leads to greater radiative heat exchange between the ceiling and the other surfaces [1]. The study suggested that total heat transfer scales linearly with temperature difference.

The other finding is that radiant heat exchange commonly matches or exceeds that of convection at the ceiling during the night flush. In analyzing heat exchange of other surfaces which are thermally light, they are simultaneously rejecting heat by convection and accepting radiant heat

during the night flush. This was not expected. The reason appears to be that all surfaces are cooled by the night flush, and while surfaces such as carpet lack the thermal capacity for passive cooling the next day, they do at least cool quickly, providing radiant cooling for the exposed ceiling. The floor is additionally in an unstable convection regime (buoyancy inducing heat transfer) during the night flush, which leads to further cooling of the floor which has a great radiant form factor with the ceiling.

Similarly, radiant heat exchange plays a larger role than convection during the days where temperature differences are too low for significant convective heat transfer, but the mass is still able to absorb radiant heat from warm bodies and objects.

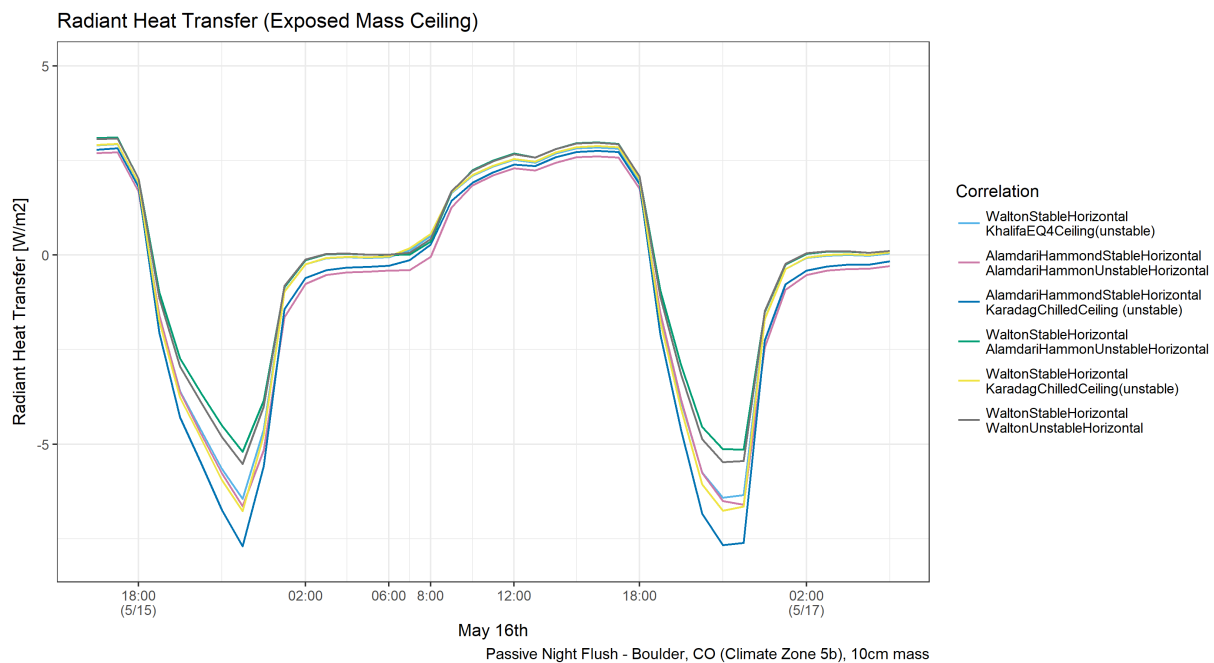


Figure 4.3: Radiant Heat Transfer During Night Flush

#### 4.0.8 Additional Convection Sensitivity Tests

The choice of convection correlations remains important even though the total surface heat transfer in thermal mass does not vary as widely as the convection coefficients. To understand the impact that the choice of the convection correlation has the underlying relationship between mass

depth and energy savings, parametric analysis were performed for various correlation choices in Climate Zone 5b. Additionally, hard set convection coefficients at 2, 4, 6, 10, 20 and 50 W/m<sup>2</sup> K were tested on the ceilings to investigate the overall relationship between convection on mass depth. See the Results and Discussion section.

## Chapter 5

### Results and Discussion

#### 5.1 Parametric Analysis on Optimized Energy Savings

Figure 5.1 illustrates the results of the parametric analyzes for the mechanical night flush cases, and Figure 5.2 illustrates the same for the passive night flush cases. In all cases, there is a clear shoulder where additional mass does not lead to more meaningful energy savings. 10 cm of exposed mass, the level inherent in most commercial buildings, captures the majority of the energy savings across each of the six climate zones studied.

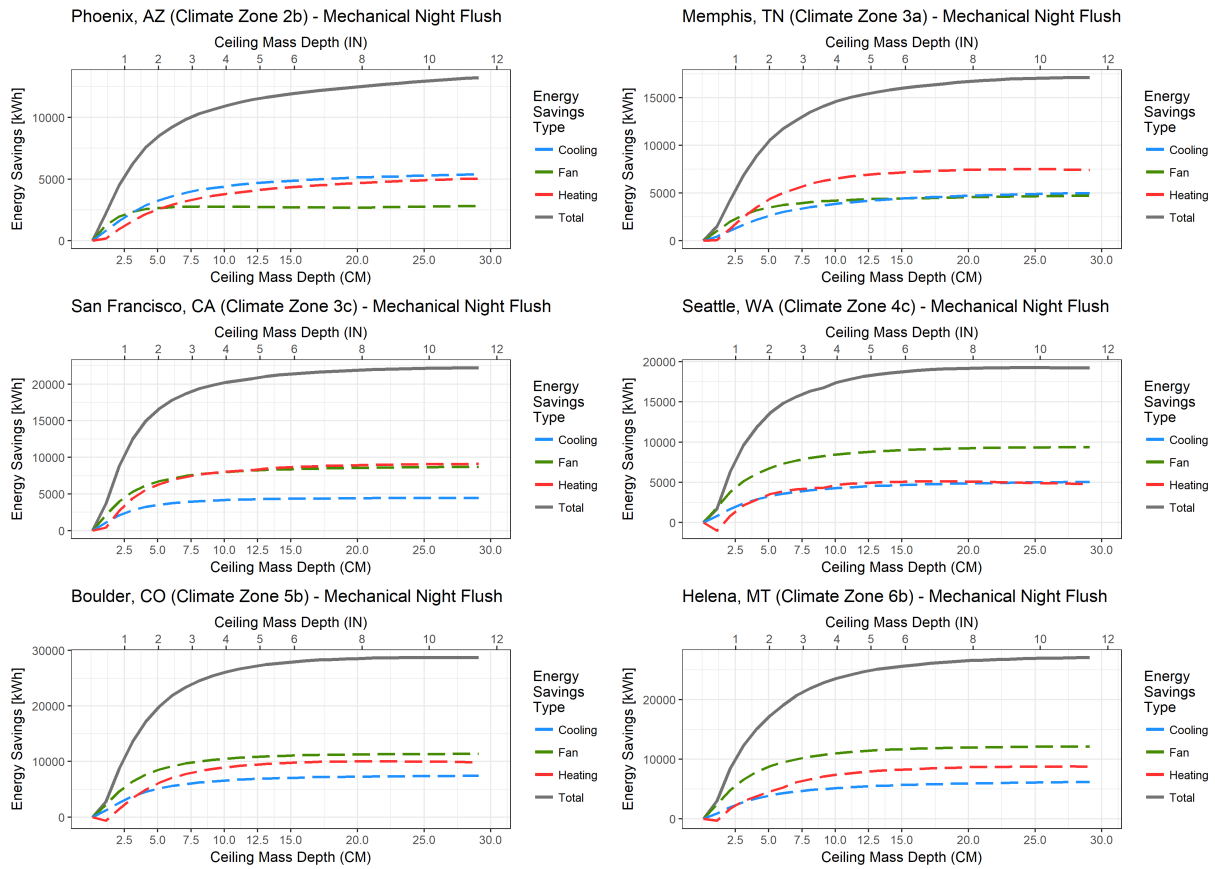


Figure 5.1: Parametric Study on Mass Depth and Energy Savings, Mechanical Night Flush

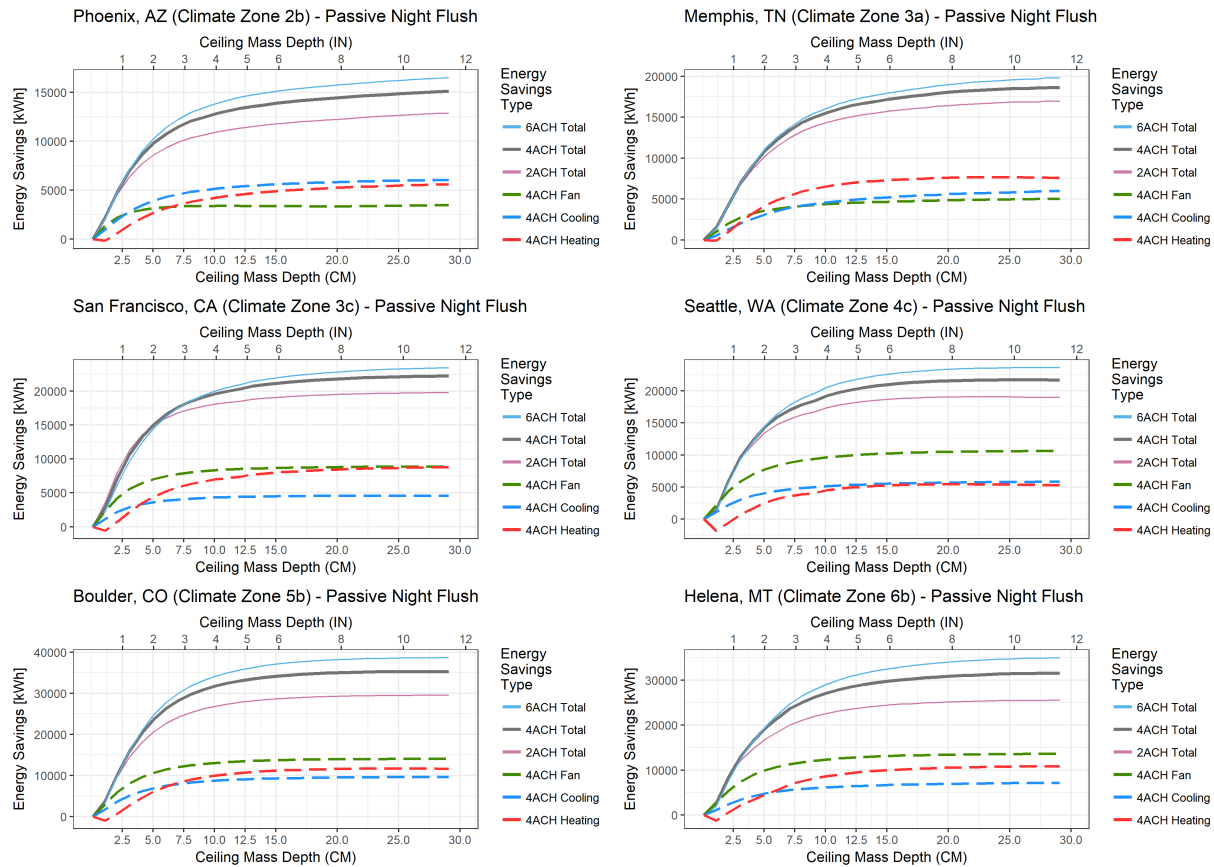


Figure 5.2: Parametric Study on Mass Depth and Energy Savings, Passive Night Flush

In hot climates the shoulder appears to be slightly less pronounced, and greater mass depths continue to save more energy although at diminishing returns. For mechanical night flush cases in Phoenix, AZ and Memphis, TN, the hottest two climates studied, 10 cm captures 83% and 85% of the savings that is available, which was maximized at the peak mass depth analyzed of 30 cm. In more mixed climates, the shoulder is more pronounced. For the mechanical night flush case in Boulder, CO, 10cm captures 91% of the savings that is available at the peak of 30 cm, and 15 cm captures 97%. The savings for the passive cases also shows the same pattern with the pronounced shoulder. Table 5.1 shows energy savings at different mass depths as a percentage of total available savings for the passive cases.

An unexpected finding was that fan energy was actually saved in the mechanical night flush cases, and in some instances the fan energy savings even exceeded the cooling energy savings. Both

Table 5.1: Passive Night Flush, 4ACH - Energy savings of mass depths compared to maximum.

Mass Depth	Climate Zone 2a	Climate Zone 3a	Climate Zone 3c	Climate Zone 4c	Climate Zone 5b	Climate Zone 6b
10 cm	85%	88%	88%	88%	90%	90%
15 cm	92%	96%	95%	97%	97%	97%
20 cm	96%	99%	98%	100%	99%	99%
30 cm	100%	100%	100%	100%	100%	100%

the fan energy of the VAV system and the fan providing the night flush are captured in the figure. This is most pronounced in moderate and cold climates, where a low night flush air change rate adequately cools the exposed mass, and then leads to less recirculation of air for cooling the next day. In almost all cases, the optimizer chose air change rates at less than 2 ACH, and commonly chose rates close to 1 ACH or lower. The optimizer varied pressure drop as a function of air change rate for the mechanical night flush, and due to the cubic relationship in the fan power laws, a 4-fold reduction in air flow results in a 64-fold reduction in fan energy.

$$kW_2 = kW_1 * \left(\frac{ACH_2}{ACH_1}\right)^3 \quad (5.1)$$

As a result, another unexpected finding was that in San Francisco, CA, where very low air change rates were needed to accomplish the night flush, the energy savings of the mechanical case was nearly indistinguishable compared to the passive night flush case. The max night flush air change rate chosen by the optimizer was 1.3 ACH in the summer, and one shoulder season month selected 0.34 ACH. In all other climates, the passive night flush case produced distinguishably more energy savings than the mechanical night flush case, although the difference was not as high as expected. For Boulder, CO, the passive night flush saved 23% more energy than the mechanical night flush.

Energy savings are additionally expressed as a percentage of energy use in Appendix F. Building total energy, fan energy, cooling energy and heating energy are displayed for all passive and mechanical night flush cases. Reporting the savings in kWh captures the gross energy savings potential and gives insight that fan energy savings exceeds cooling energy savings in some cases. Percent savings provides perspective on the impacts of passive cooling on building energy performance, at different mass depths. Building energy saving are maximized in Boulder, CO at

7% of the total energy use. Cooling energy savings are above 20% in the four cooler and mixed climates, whereas they are below 10% in the two hottest climates because passive cooling is not adequate during much of the cooling period. Heating savings are mixed, being below 10% in the colder climates and above 40% in Phoenix, AZ where heating requirements are low to begin with, and heat gains absorbed by the mass can offset subsequent heating loads.

## **5.2 Parametric Analysis on Building Sensible Load Reduction**

Building sensible load reduction was not optimized directly but is the opportunistic load reduction based on optimizing for energy savings. The reported load reduction is not the steady state calculation based on DDY files, but the peak rates observed in the annual simulation, which more directly accounts for the dynamic behavior of mass.

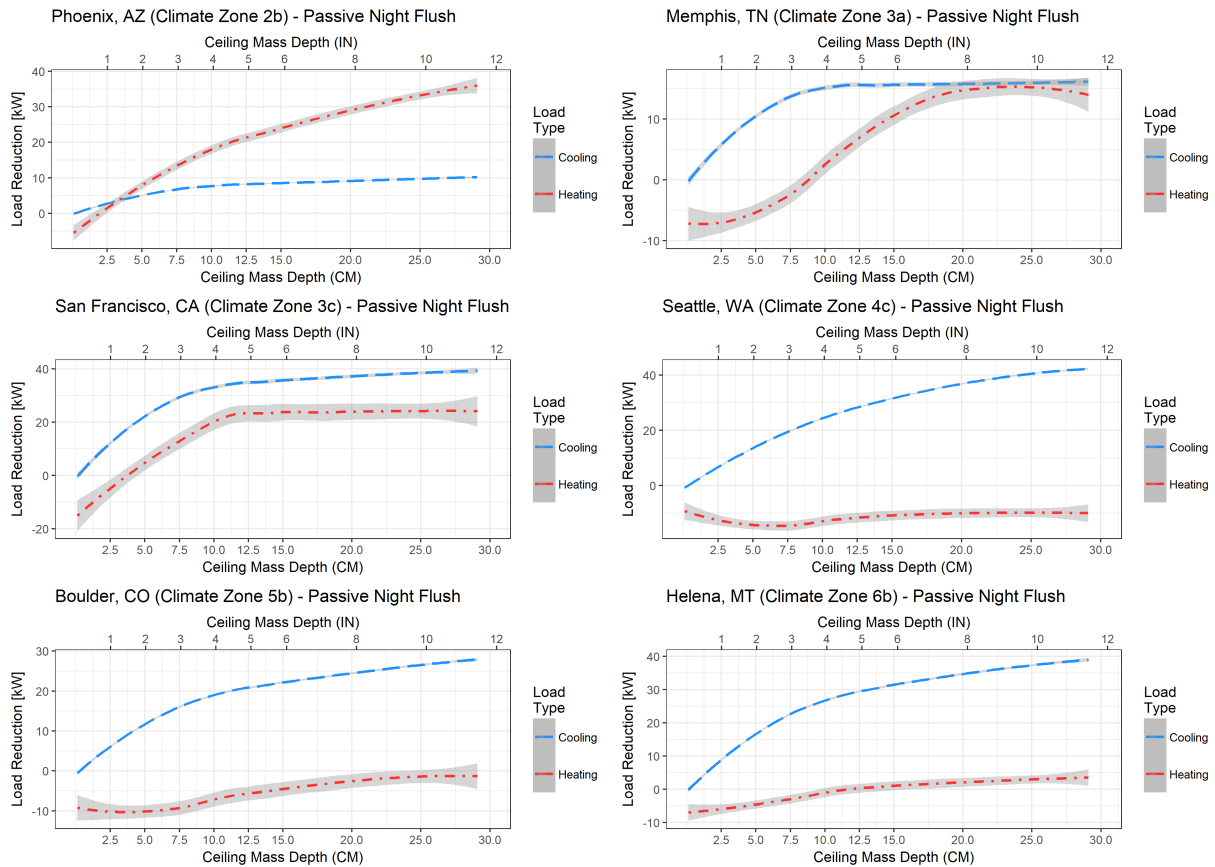


Figure 5.3: Parametric Study on Mass Depth and Building Sensible Load Reduction, Passive Night Flush

Figure 5.3 illustrates the building sensible load reduction for the 4 ACH passive night flush cases. The mechanical night flush cases were very similar, and therefore not shown here. The shoulder which was so prevalent for energy savings and mass depth is no longer present, and the results at first appear more scattered. Plateaus exist but differ between heating and cooling and across different climates. One clear pattern however is that for mixed and cool climates, additional mass continues to reduce the peak cooling load, although with some diminishing returns. Meanwhile, in the hot climates, additional mass does not lead to additional reduction in the peak cooling load. While this seems counter intuitive, it is simply because a night flush is not adequate at the peak times for the hot climates. In Phoenix especially, a night flush was not attempted in the summer, as a review of the weather data indicated that night time outdoor temperatures were

still warmer than indoor temperatures. For Memphis, TN, there was beneficial passive cooling in all summer months, but it did not completely cool the thermal mass, and the ability to reduce cooling loads is not increased beyond 10 cm of mass.

With respect to peak heating loads, the presence of mass is not always a benefit. Relative to 0.1 cm of mass as a starting point, adding mass in the colder climates creates an immediate increase in peak heating load. As pointed out by Braun, a theoretically massless building would have zero preheat time [9]. If the peak heating occurs coincident with morning warmup, it would be logical that more mass would lead to a higher peak load. Never the less in the coldest two climates, these results indicate that as more mass is added, the peak heating loads are reduced again, as more constant temperatures are being provided. It is noteworthy that in Climate Zone 6b, 10 cm of mass has roughly the same peak heating as 0.1 cm, where as in Climate Zone 5b 10 cm of mass is a heating load penalty. This may be attributable to a better envelope being required in Climate Zone 6b than in 5b. This comparison also extends between Climate Zones 5b and 4c, but is not repeated in warmer climates which show heating load benefit from typical mass levels. As indicated by the BRE, mild conditions can experience a heating benefit from thermal mass “during autumn and spring, lightweight buildings may require both heating and cooling over the diurnal cycle, whereas the thermally heavy buildings can maintain comfortable internal conditions without either supplementary heating or cooling” [7].

Building sensible cooling and heating loads are additionally expressed as a percentage of the total loads in Appendix F. Building sensible cooling load reduction is up to 38% in San Francisco, and is insignificant in Phoenix, AZ for reasons discussed above. Heating load reduction ranges from a load penalty in colder climates to 52% load reduction in Phoenix, AZ.

### **5.3 Excitability of Mass**

A review of the thermal mass surface temperatures at 10, 20 and 30 cm thicknesses indicates that the 10 cm mass thickness is more excitable than the 20 cm or 30 cm cases. Figure 5.4 shows a three-day period where cool night temperatures are available for the night flush. At these periods,

the 10 cm case can be cooled more thoroughly at night, and still has the capacitance to maintain lower temperatures through the majority of the next afternoon.

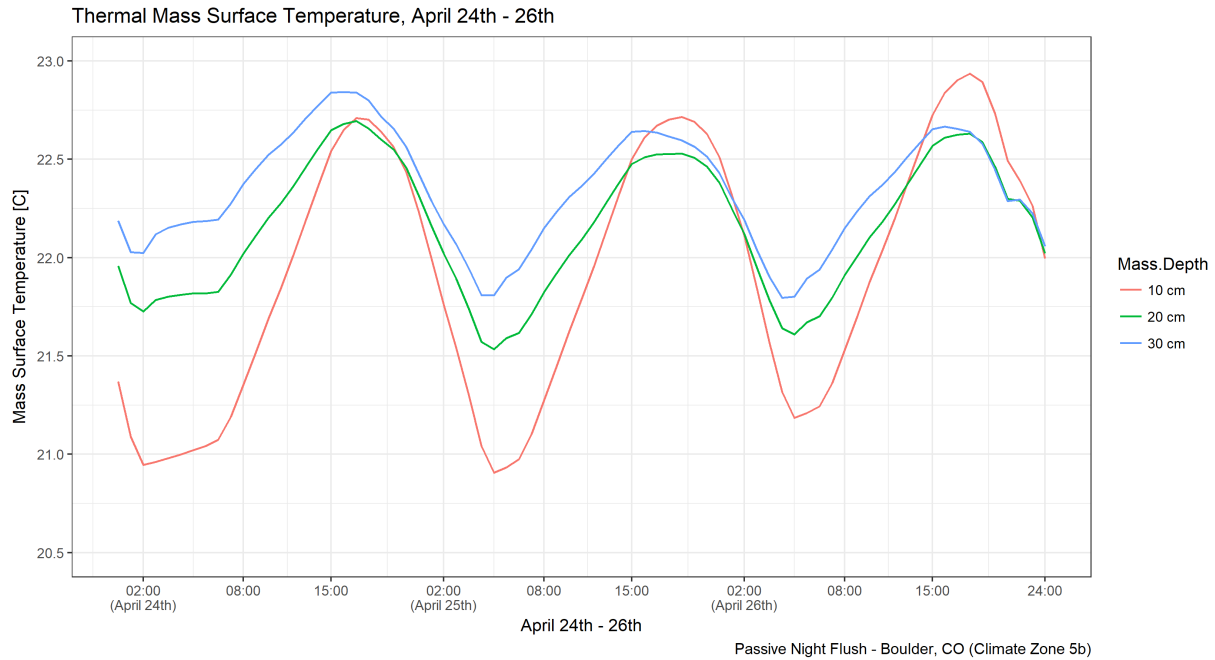


Figure 5.4: Thermal Mass Surface Temperature, April 24th thru 26th

While Figure 5.4 suggests better performance from lower mass levels in a particular situation, it is not a complete picture of the behavior of mass. Figure 5.5 shows another situation where the night temperatures are not adequately low to cool the mass as much as desired. In this case, the deeper mass levels are able to maintain lower temperatures over consecutive warming days. This reflects how deeper mass can be important for maintaining thermal comfort in a fully passive case and is also supported by the Building Sensible Load Reduction results, which indicate deeper mass continues to reduce loads at the peak cooling period. It is notable that the 20 and 30 cm behave similarly, suggesting that if more passive autonomy is targeted, there still may be a diminishing return with thicker mass to consider.

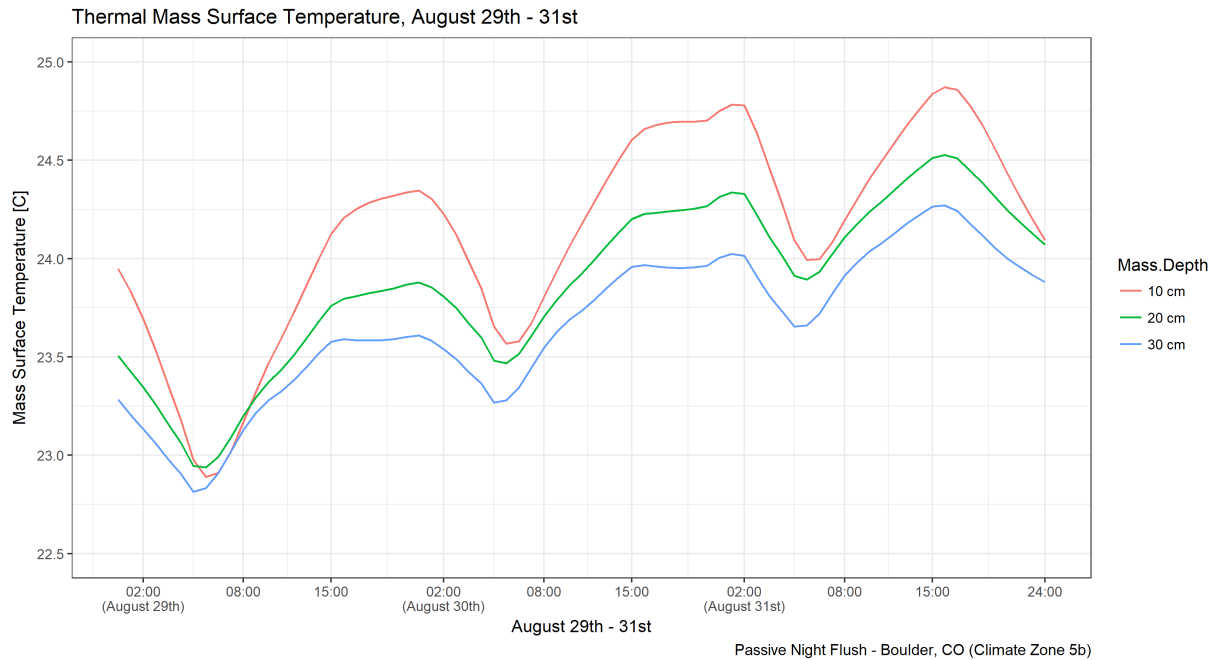


Figure 5.5: Thermal Mass Surface Temperature, August 29th thru 31st

With thinner mass sometimes being an asset and sometimes not, the annual simulations reconcile which factor is more important and more prevalent. These results indicate that there is no local maxima for thinner mass due to the excitability of the concrete, but also that the deeper mass which can maintain lower temperatures over consecutive warm days does not offer significant energy savings over the lower mass in a mixed-mode case for any of the six climates studied.

#### 5.4 Air Change Rate Sensitivity Analysis

Figure 5.6 shows the results of air change rates at 2, 4, 6, 8, 10 and 20 ACH for the passive night flush case in Boulder, CO. The optimization was not repeated for each air change case, but the results for the 4 ACH case were applied. Results are shown for June to August only, so as not to not include any reheat which was otherwise present in shoulder months with higher air changes.

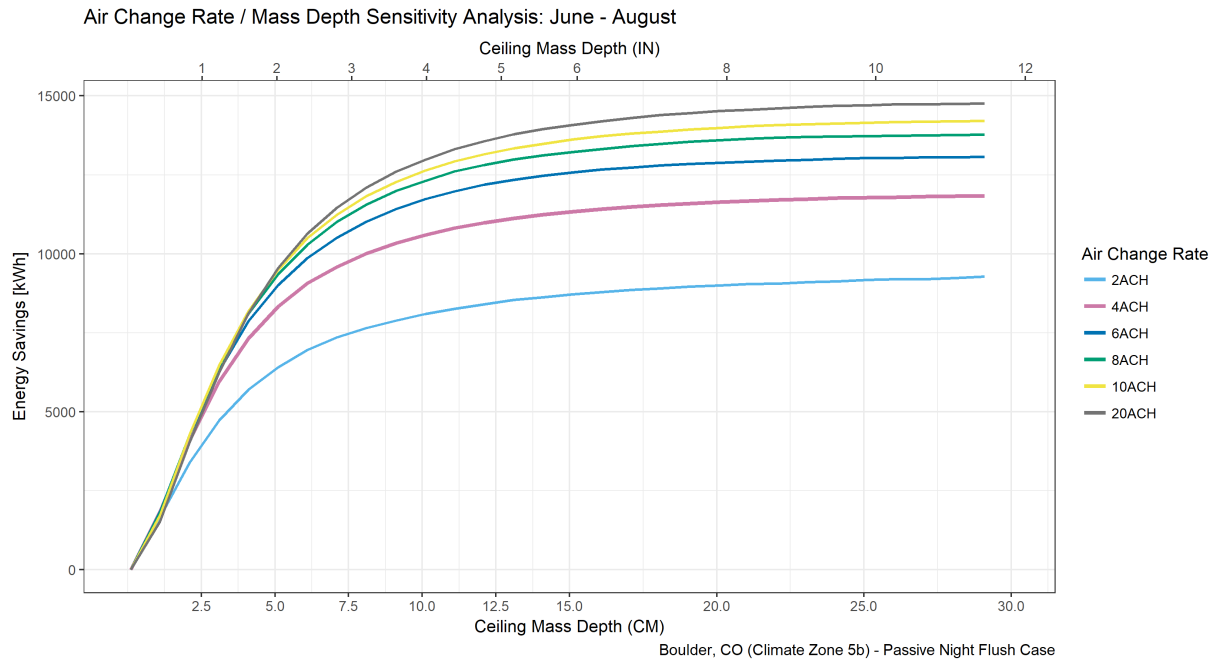


Figure 5.6: Night Flush Air Change Rate Sensitivity

It was expected that higher air changes would more heavily favor deeper mass levels, and while that can be seen on a small level, the same basic behavior exists of a prevalent shoulder beyond which are only diminishing returns. 2 ACH captures 55% of the savings that is available in the 20 ACH case, 4 ACH captures 83%, and 6 ACH captures 93% of the available savings. Beyond these air change rates, there is little benefit indicated for additional air flow within the current convection correlations. 10 and 20 ACH are nearly indistinguishable. This is in line with other research, which indicates that because natural convection is driven by temperature difference, additional air changes beyond a point of achieving the temperature difference offers little benefit [4, 43].

## 5.5 Convection Sensitivity

### 5.5.1 Hard-set convection coefficients

To investigate the relationship between convection, mass depth, and energy savings, Figure 5.7 shows hard-set convection coefficients for the ceilings at 2, 4, 6, 8, 10, 20 and 50  $W/m^2 K$ . This

graph shows June through August and reheat energy was removed in post processing because at low mass levels and high convective heat transfer, the thermal mass was cooled to the point of the outdoor air, which lead to reheat.

At  $20 \text{ W/m}^2 \text{ K}$ , the shoulder is still present, but it is significantly flattened, and it is difficult to ascertain where the shoulder ends. This is in contrast to the sensitivity tests of air change rates, in that increasing the convection coefficient actually does significantly favor more mass. Results at  $10$  and  $20 \text{ W/m}^2 \text{ K}$  are almost theoretical, although this maybe relevant for situations which force air through floor voids, increasing the convective heat transfer [4].  $50 \text{ W/m}^2 \text{ K}$  was added upon seeing this relationship, along with increased airflow at  $20 \text{ ACH}$ . This is intended as a purely theoretical investigation. The relationship is much more linear at  $50 \text{ W/m}^2 \text{ K}$ , although still not completely.

Meanwhile, for real situations with typical convective heat transfer coefficients found in buildings, the shoulder is very much prevalent and is located around  $10 \text{ cm}$  of mass. This demonstrates how surface heat transfer is a limiting factor in the use of thermal mass.

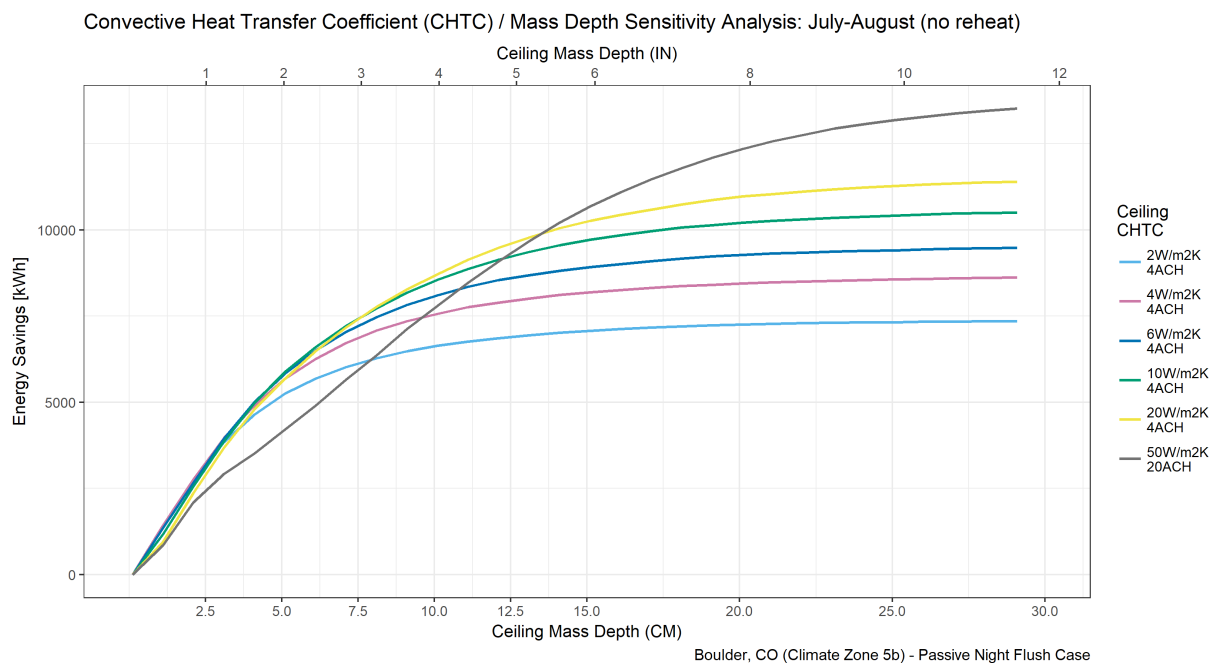


Figure 5.7: Convection / Mass Depth Relationship

### 5.5.2 Parametric Results of Convection Correlations

To complete the investigations on convective heat transfer and relate it back to the research question regarding the depth of thermal mass, parametric analyses were repeated with different convection correlations assigned to stable and unstable ceiling conditions through the Adaptive Convection Algorithm.

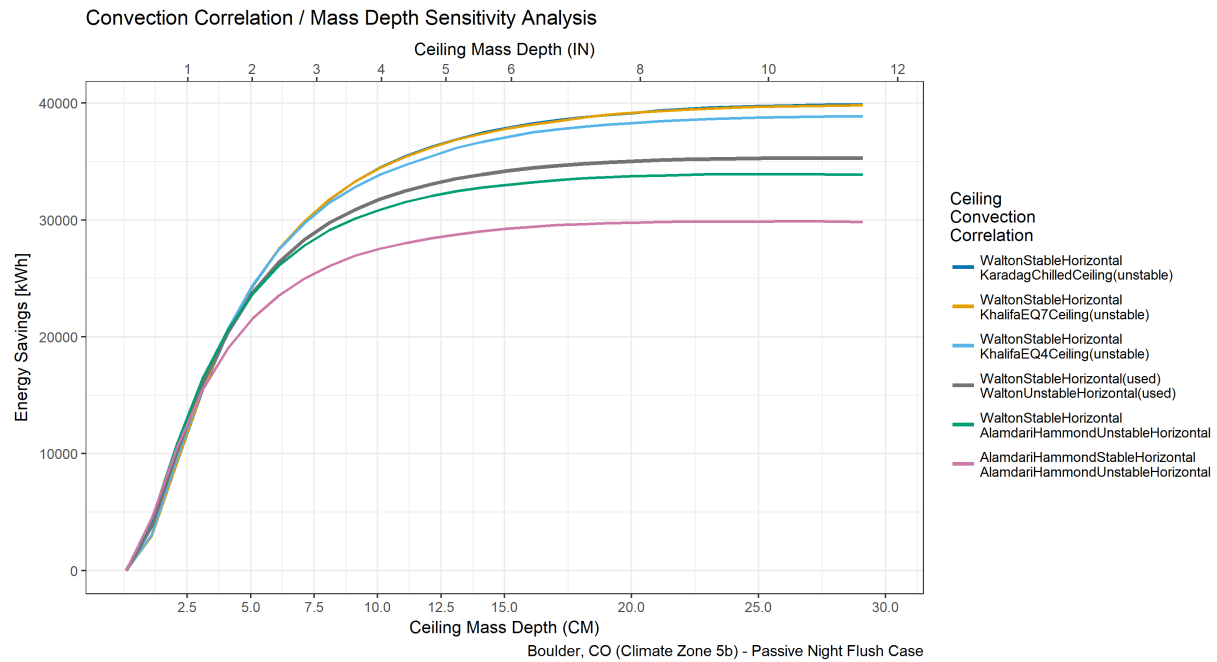


Figure 5.8: Convection Correlation Sensitivity

Figure 5.8 shows a variation of up to 25% energy savings, indicating that the choice of convection correlation remains important regardless of radiant heat transfer offsetting some of the differences in convection. Yet still, the results clearly indicate that for all convection correlations studied, there is a presence of a shoulder beyond which additional mass provides only marginal returns. In even the case which most heavily favors deeper mass, a typical floor slab of 10 cm still captures 86% of the available savings.

## 5.6 Interior Load / Mass Depth Sensitivity

Figure 5.9 shows a sensitivity test to the relationship between interior loads, mass depth and energy savings. The default loads in the DOE Reference building were stepped to  $\pm 30\%$  on 10% increments, which could have relevance for other commercial building types, or densely or sparsely occupied office buildings. The results indicate that the shoulder is still very prevalent, and the shape has only minor changes. As expected, there are more savings available with more internal loads, as the mass is being further exercised. However, this does not lead to deeper mass being significantly more favorable.

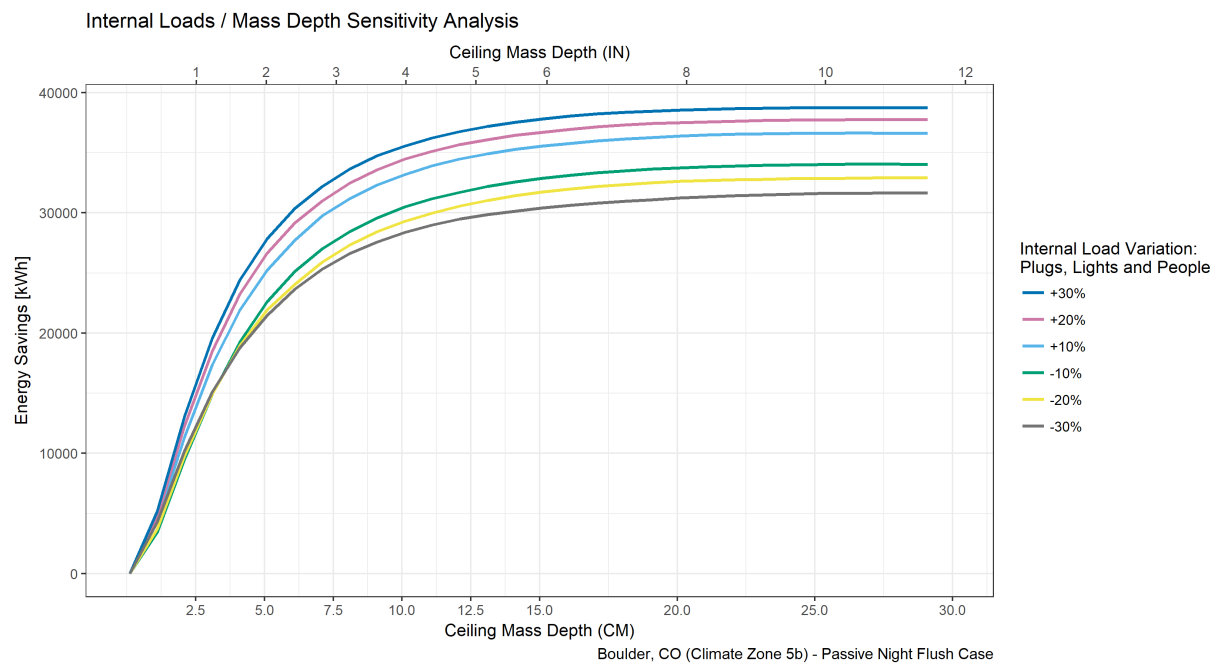


Figure 5.9: Interior Loads Sensitivity

## 5.7 Comfort

Comfort is the limiting factor with respect to how deep of a night flush should be performed, when the night air is cool enough to do so [31]. The optimized models for all climate zones targeted a PMV of  $\pm 0.5$  for the occupied hours of 08:00 to 18:00, which corresponds with a PPD of 10%.

Comfort charts for each model were reviewed to ensure this. In isolated cases, PPD exceeded 10% in the morning following a night flush, but never did so for over 20 hours in a year, and never exceed 12% PDD, except during unoccupied periods. This was considered acceptable.

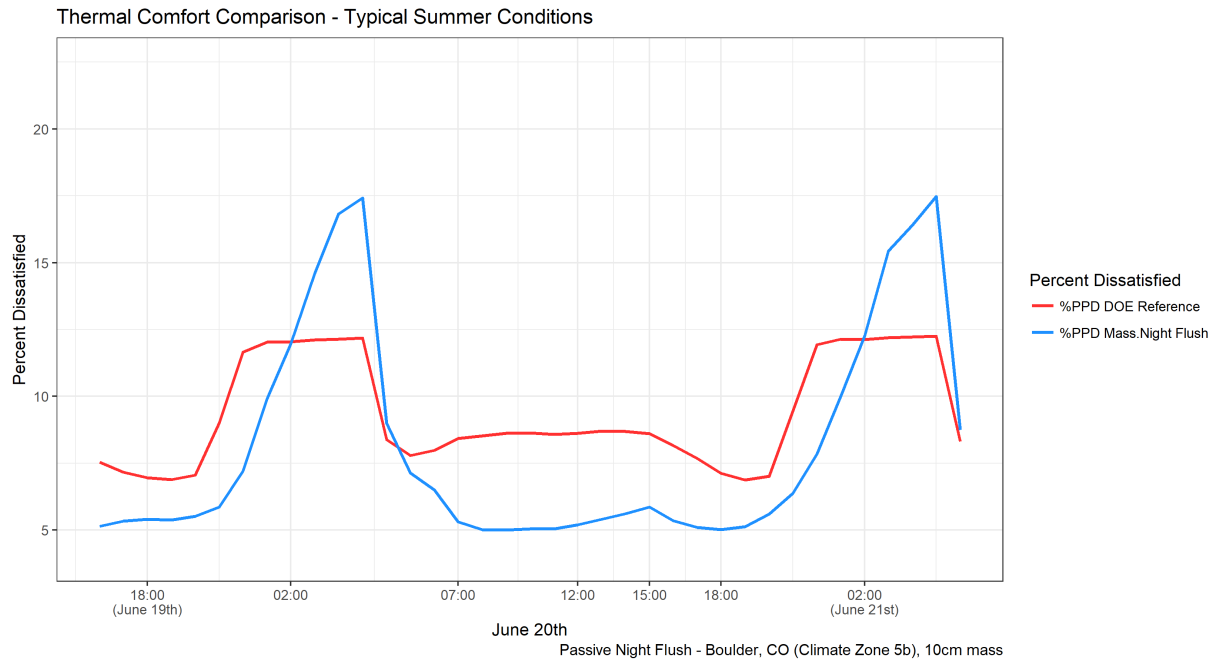


Figure 5.10: Comfort Comparison: Typical Summer Conditions

Figure 5.10 shows a typical summer comfort scenario, displayed for June 20th. Discomfort would be high during the night flush, but the building is unoccupied. At 04:00, the night flush stops and temperatures quickly rise in the building, which is the final heat exchange between mass and air (not reheat). By 07:00, PPD is approximately 5%, which is the lowest possible value and indicates excellent comfort. By contrast, the DOE Reference Building is consistently around 8% PPD.

Without any doubt the original DOE Reference Building indicates more summer discomfort with PMV and PPD as metrics. During July and August in the DOE Reference Building, PPD exceeds 10% during some occupied periods, and on some occasions for nearly the entire day. This is with air conditioning present and is likely attributable to warm mean radiant temperatures in the

thermally lightweight building. In addition to these outlier scenarios, it is also clear that summer comfort conditions are consistently approaching the 10% PPD threshold in the DOE Reference Building, with mechanical cooling keeping comfort just under the threshold. By contrast, when the 10 cm of mass is exposed and cooled through an optimized night flush, comfort is consistently closer to the minimum of 5% PPD, and only reaches 8% on specific instances. There is active cooling in both cases to be clear, but the presence of cooled mass improves comfort in the summer while reducing mechanical dependence.

## 5.8 Embodied Energy of Concrete

The above parametric analysis and sensitivity tests clearly indicate that the majority of energy savings are achieved at moderate mass levels, but the results also indicate that deeper mass levels do perform the best when only considering operational energy costs. Concrete contains a high amount of embodied energy however, and so a more complete energy evaluation includes embodied energy costs.

Hammond et al. indicates that the embodied energy of concrete can vary from 0.81 MJ/kg to 2 MJ/kg, depending primarily on the amount of cement needed for the concrete specifications, and that floor slabs are typically 1.1 MJ/kg [17]. Lenszen et al. indicates a similar value, at 1.0 MJ/kg [24]. This analysis was conducted with the embodied energy of concrete at 1.1MJ/kg. When considering the density of concrete in this research at 2,322 kg/m<sup>3</sup> (normal weight concrete) and the facility at 4,982 square meters, each centimeter of concrete thickness added to the floor slab costs 35,350 kWh of embodied energy. In consideration of this, Figure 5.11 shows the previously analyzed parametric curves relating mass depth and annual energy savings, but with embodied energy included. The embodied energy has been annualized over 10, 25, 50 and 100-year payback periods (e.g., 10-year payback line is total embodied energy divided by 10). This is useful for showing the payback period relative to various mass depths, which are still continuous on the x-axis.

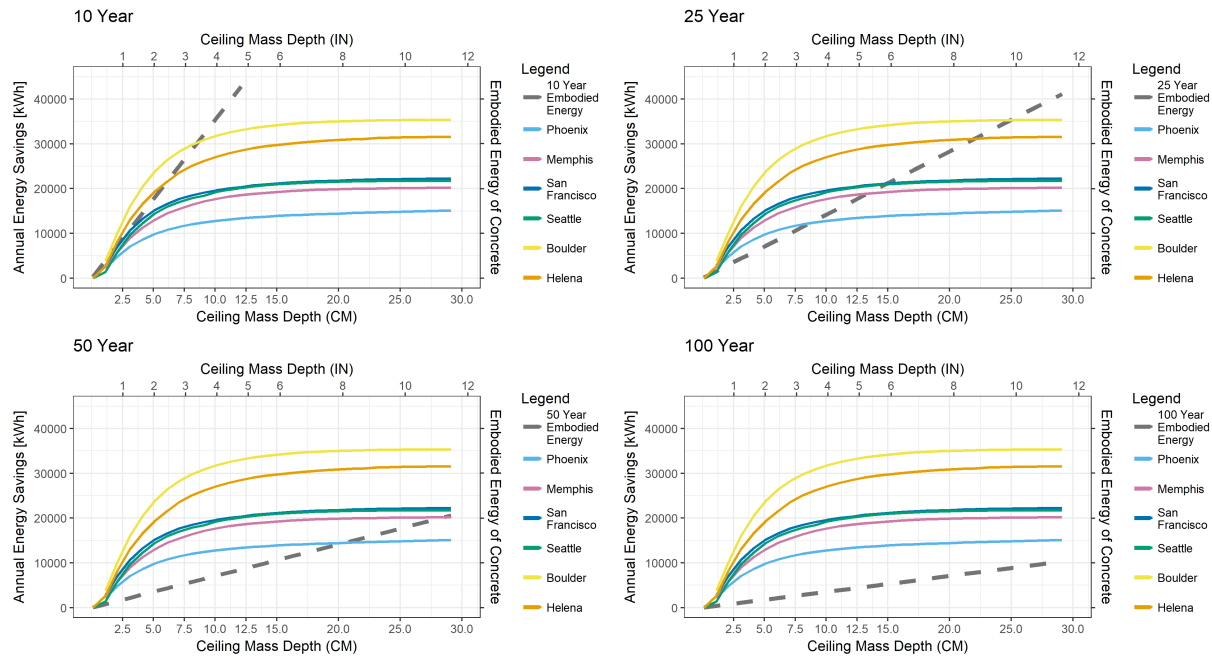


Figure 5.11: Payback Period for Embodied Energy of Concrete

Figure 5.11 illustrates that even 10 cm of concrete, which is on the shoulder of the energy savings curves, does not payback its embodied energy within a 10-year period relative to a theoretically near massless floor slab (0.1 cm). In considering a much longer payback period of a 100-year life span, 30 cm of mass pays back its embodied energy for every location analyzed, and in some cases three times over. This poses a question to the reader, how long of an energy payback is appropriate? On one hand, building life spans are long enough to seemingly justify the added mass. On the other hand, carbon reductions for controlling climate change are typically expressed over shorter periods, where the embodied energy of concrete would still be causing a cumulative energy deficit. The Intergovernmental Panel on Climate Change recently indicated that to keep warming to  $1.5^{\circ}\text{C}$ , carbon emissions must be reduced to 45% of 2010 levels by 2030, and no net carbon emissions can be added beyond 2050 [32]. These are stark reductions over the next 32-years, and the deeper mass levels do not appear to be in sync with near term goals despite having good long-term performance.

Figure 5.11 is not a complete story for most commercial buildings however, because most

commercial buildings contain 10 cm of mass as a topping slab. A more complete view for most commercial buildings is to look at the incremental benefit of deeper mass beyond 10 cm, and the incremental embodied energy cost, as displayed in Figure 5.12.

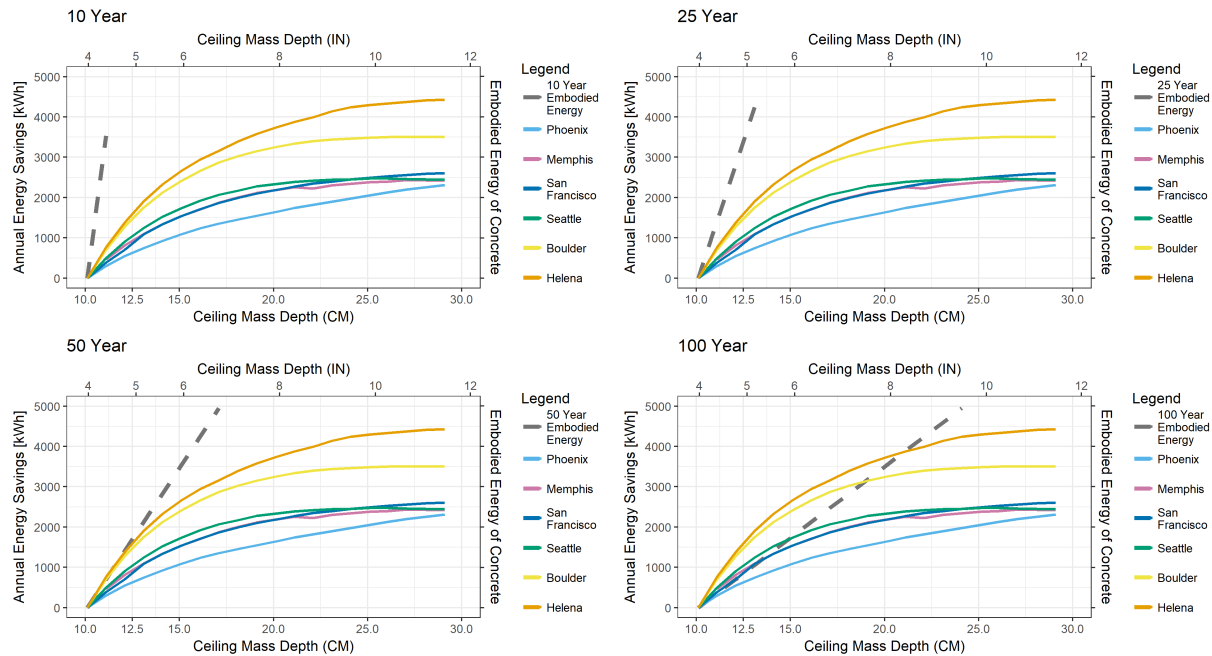


Figure 5.12: Incremental Benefits and Costs of Concrete Beyond 10 cm

The results of this figure indicate that if a 10 or 25-year payback of embodied energy is the target, any added mass beyond the inherent 10 cm does not come close to achieving the goal in any of the six locations analyzed. If a 50-year payback is the goal, the two best performing locations can increase an extra 2.5 cm of mass before the incremental benefit is outweighed by the incremental costs. 20 cm of mass (10 cm extra) only pays back its added embodied energy over a 100-year period in the best climate analyzed for passive cooling, Boulder, CO.

These results are also displayed as a ratio of incremental benefit over incremental cost in Appendix C. The ratio is never above 1 in the 10 or 25-year period. For the 50 year period the ratio is only above 1 for the Boulder, CO case and only up to 12.5 cm of mass. In a 100-year period, most cases are above 1, but never for mass depths beyond 22.5 cm.

To conclude this embodied energy assessment, Figure 5.13 shows total cumulative energy costs and savings for increasing time periods. Years was moved to the x-axis and the four graphs now show results for different mass depths: 10 cm (no added mass), 15 cm (5 cm added mass), 20 cm (10 cm added mass) and 30 cm (20 cm added mass).

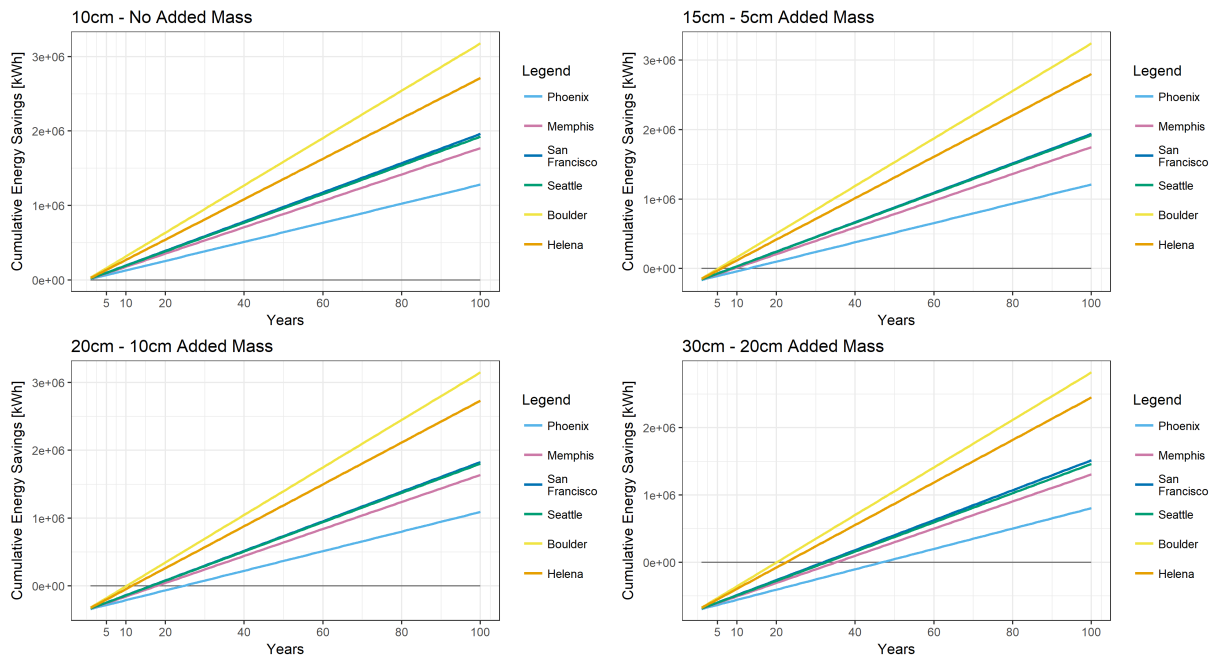
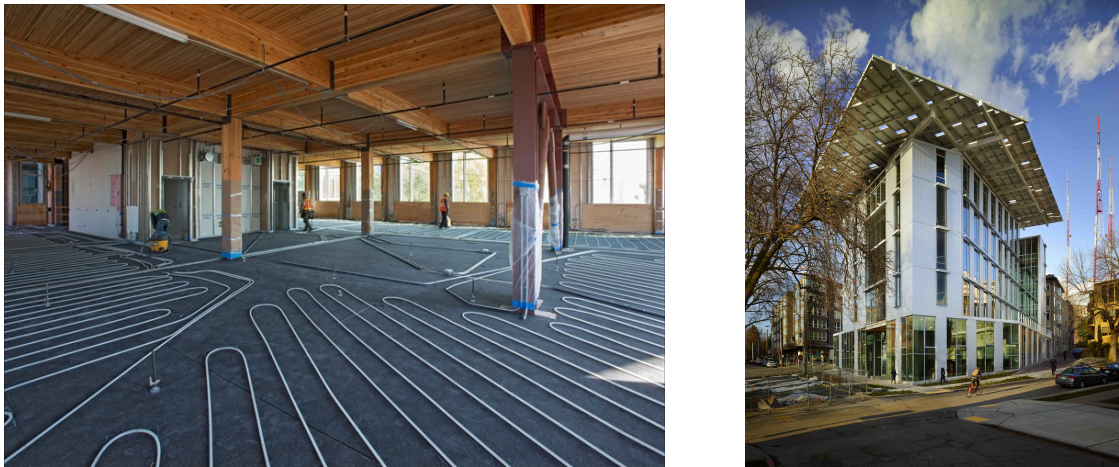


Figure 5.13: Cumulative Energy Benefits and Costs for Different Mass Depths

Figure 5.13 indicates that cumulative energy savings over a 100-year period is highest for the 10 cm and 15 cm cases, both of which outperform the 20 cm and 30 cm cases over a 100-year life span. This is an unexpected finding, given the long-life span considered. The 15 cm case has a slightly steeper energy savings slope than the 10 cm case, but starts at an energy deficit, and is therefore catching up to the 10 cm case over its entire 100-year life span for the best performing climates. In the worse performing case of Phoenix, AZ, the 15 cm case never reaches the same cumulative savings as the 10 cm case. While the 20 cm case pays for its embodied energy many times over the course of the building's life, it never catches the same cumulative energy savings as the 10 cm case, even over 100-year period in the best performing climate analyzed.

While these results strongly discourage added normal weight concrete beyond the typical 10 cm for the cases analyzed, three clear exceptions to this analysis exist. The first is showcased by the Bullitt Center in Seattle, WA. This six-story building uses timber construction, even for the floor's structure, and a thin topping slab for passive cooling and in-slab radiant heating. This challenges the assumption that 10cm of mass is necessary, and 5 cm to 7.5 cm of mass would be the most appropriate depth depending on the payback period desired, not 10 cm.

Figure 5.14: Timber construction with thin topping slab at the Bullitt Center. Images courtesy of [bullittcenter.org](http://bullittcenter.org)



The second exception rests on the notion that actual design conditions need to be considered. Passive cooling is not the only form of passive strategies utilizing thermal mass, and if solar energy is being harnessed or if mass is being used to temper ventilation air, the appropriate mass depth can vary. Air being passed through hollow core slabs substantially increases convection, which can lead to greater mass depths being favorable. There is also the question of thicker mass adding benefit at the peak cooling periods to improve both comfort and passive autonomy, which can lead to reduced embodied energy costs in systems, especially for a fully passive case. Added mass in surface area, such as the interior side of exterior walls, can also be useful.

The third exception is that fly ash can greatly reduce the embodied energy of concrete because it offsets a portion of the most energy intensive component, the cement. Fly ash has a similar heat

capacity to the cement it replaces, but with less density, leading to less total storage capacity and less conductivity [6]. It would therefore behave similar to lightweight concrete, which the BRE indicates would have a 10% storage performance variation for the normal weight concrete case [4]. This can be another area of further study.

## Chapter 6

### Conclusions

This research investigated how well how suited typical commercial construction topping slabs are for use as thermal mass, relative to other mass depths. In all climates analyzed, it was found that there was a pronounced shoulder where energy savings from passive cooling of increasing mass depths was steep until roughly 7.5 cm to 10 cm, and thereafter the energy savings diminished rapidly.

Sensitivity tests were conducted on internal loads, convective heat transfer, air change rates and thermal properties of concrete. It was found that increased convection would reduce or even eliminate this shoulder and favor greater mass levels, however this doesn't happen in a significant way for any reasonable convection levels found in buildings. The sensitivity tests for other variables also showed that for values typically seen in buildings, the trend remained clear that 10 cm of mass captured the majority of savings that were available to thicker mass levels. At a minimum 10 cm of mass captured 83%, and at a maximum, it captured 91% of the available energy savings at 30 cm.

An unexpected finding was that radiant heat transfer was as dominate as convective heat transfer at the exposed mass ceiling during the night flush. At night when warm air rises, natural buoyancy forces slow the convection at the ceiling (stable convection scheme). Meanwhile, the buoyancy forces enhance convective heat transfer at the floor, which is also thermally light and cools on the surface quicker. In turn, this relationship leads to the floor and walls providing radiant cooling of the exposed mass ceiling. An interesting side note is that the convection correlations

which lead to the lowest convective heat transfer also lead to the highest radiant heat transfer. While the choice of a convection correlation remains important, the actual surface heat transfer of thermal mass is more consistent than would be intuitively concluded by looking at the difference in convection coefficients alone.

Another unexpected finding was that with night flush settings optimized on a seasonal (monthly) basis, the mechanical night flush cases saved total fan energy, and in some cases fan energy savings even exceeded cooling energy savings. Due to the cubic relationship between airflow and fan energy in the fan power laws, the low air change rate at night was not a large fan energy penalty, but offsetting recirculation air when airflow was at its highest was significant for fan energy savings. In the San Francisco, CA case, where very low flow rates were required to accomplish the night flush, and the mechanical night flush savings were nearly indistinguishable from the passive night flush savings. In all other climates, the passive night flush saved considerably more energy which was expected.

When considering the embodied energy of concrete, the incremental benefits from additional mass over 10 cm did not justify the incremental costs from an energy standpoint alone. While all cases with even the thickest mass analyzed showed that the cumulative energy savings from passive cooling paid back the initial embodied energy, the incremental benefit did not payback back the incremental cost relative to the 10cm starting point, except for the 15cm case when considering a 100-year life span. While this should encourage more judicious use of mass which is inherent in commercial buildings before adding mass, it is also important add context that additional mass can still be useful, and consideration should be given to actual design conditions. For instance, if deeper mass and greater passive autonomy leads to less mechanical dependence, then embodied energy savings may exist in the systems. None the less, the findings in the research show that 10 cm of concrete found in typical commercial construction topping slabs is well suited for passive cooling, and are even preferable from an energy standpoint when considering the embodied energy of concrete.

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# Appendix A

## Full Size Image - Energy Savings / Mass Depth

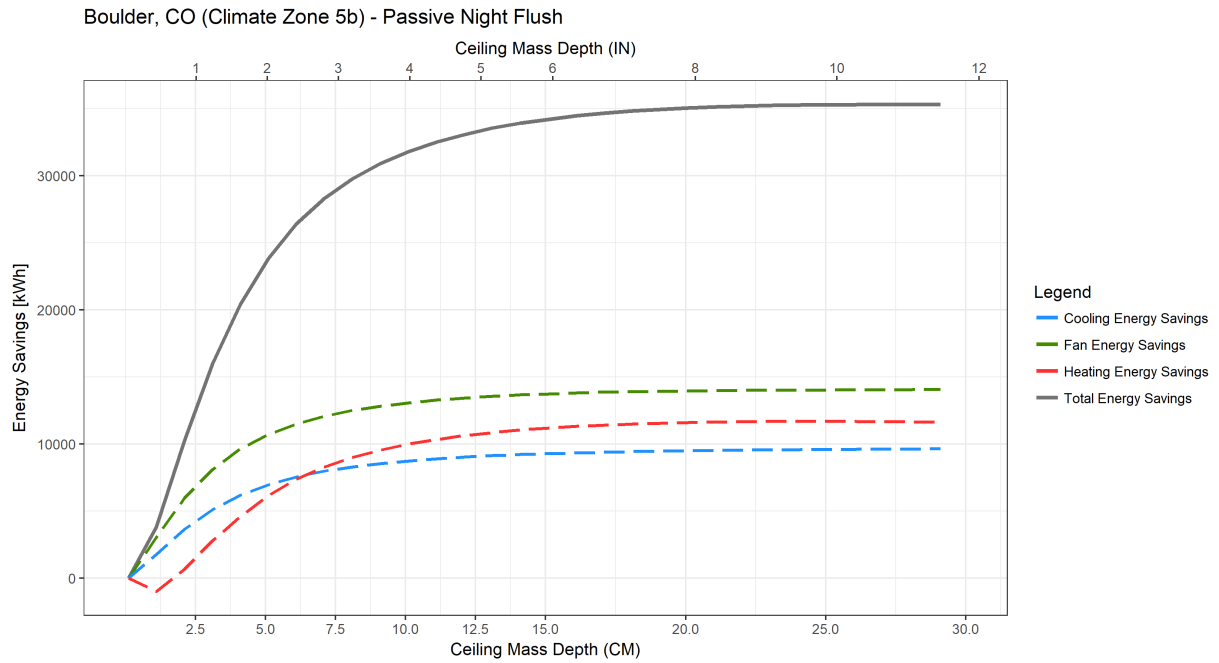


Figure A.1: Passive Night Flush Energy Savings - Boulder, CO, 4ACH

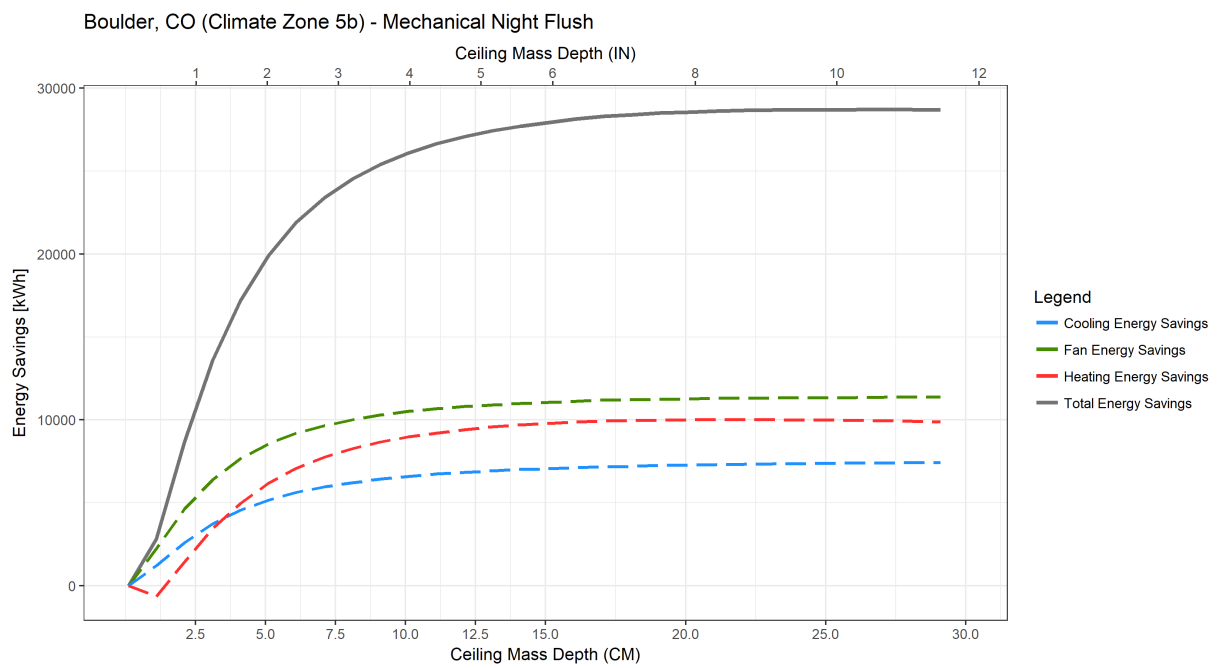


Figure A.2: Mechanical Night Flush Energy Savings - Boulder, CO, 4ACH

## Appendix B

### Additional Sensitivity Tests

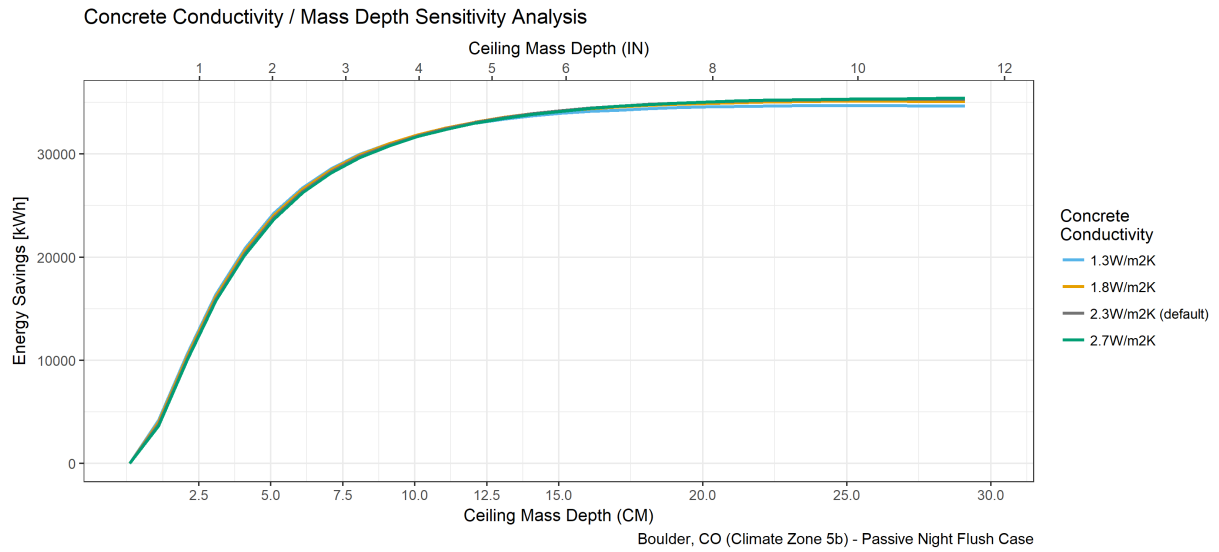


Figure B.1: Conductivity Sensitivity Analysis

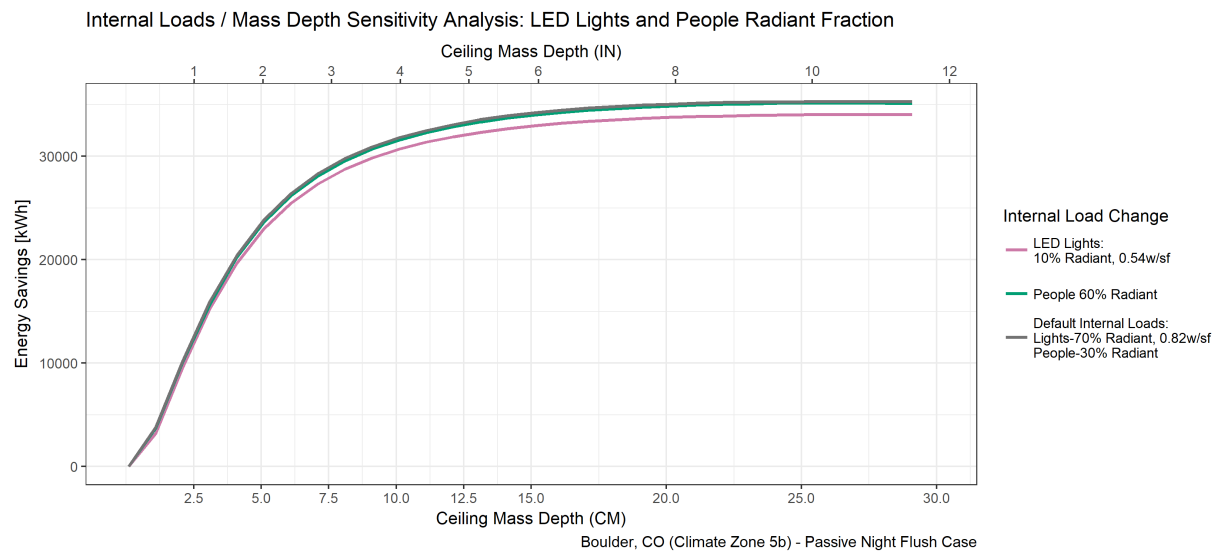


Figure B.2: Internal Loads Sensitivity Analysis - LED Lights and People Radiant Fraction

# Appendix C

## Incremental Benefit/Cost Ratio

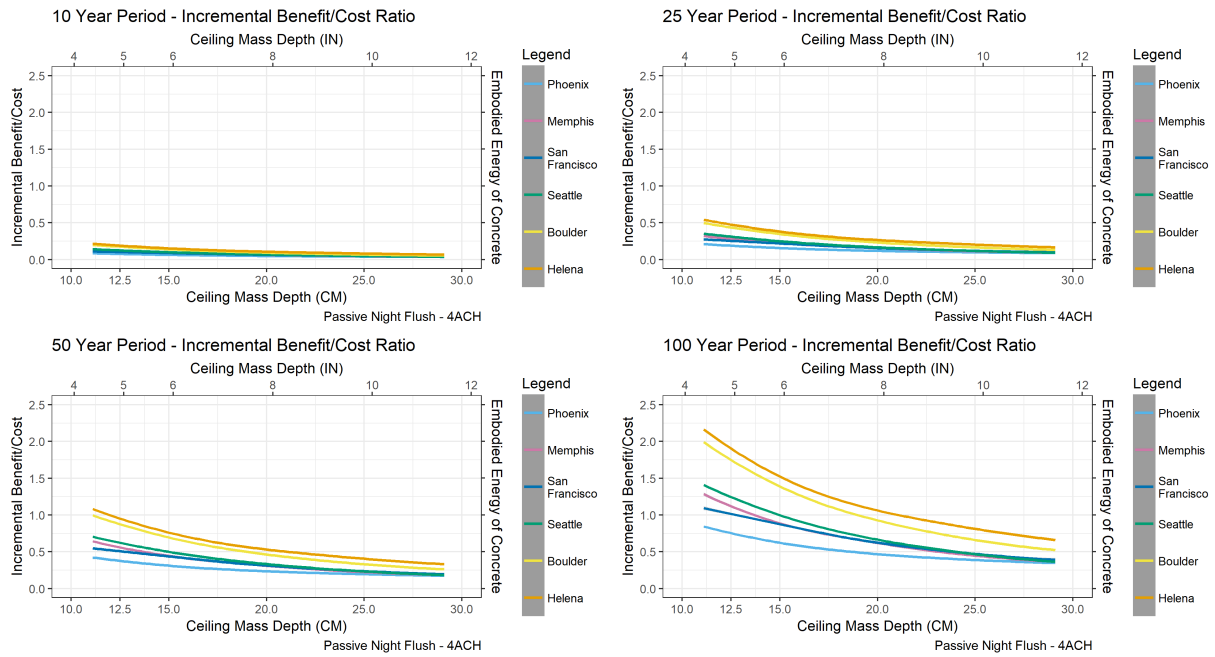


Figure C.1: Incremental Benefit/Cost Ratios

# Appendix D

## Energy Source Breakout

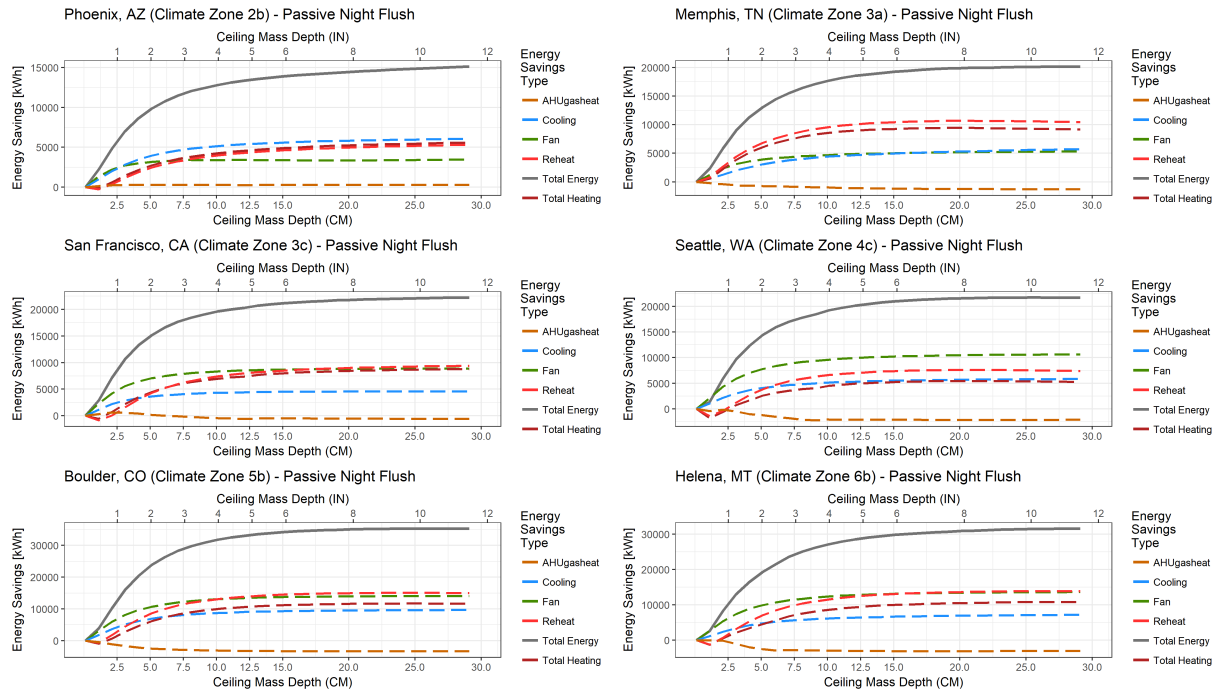


Figure D.1: Energy Source Breakout

## Appendix E

### Optimization Period

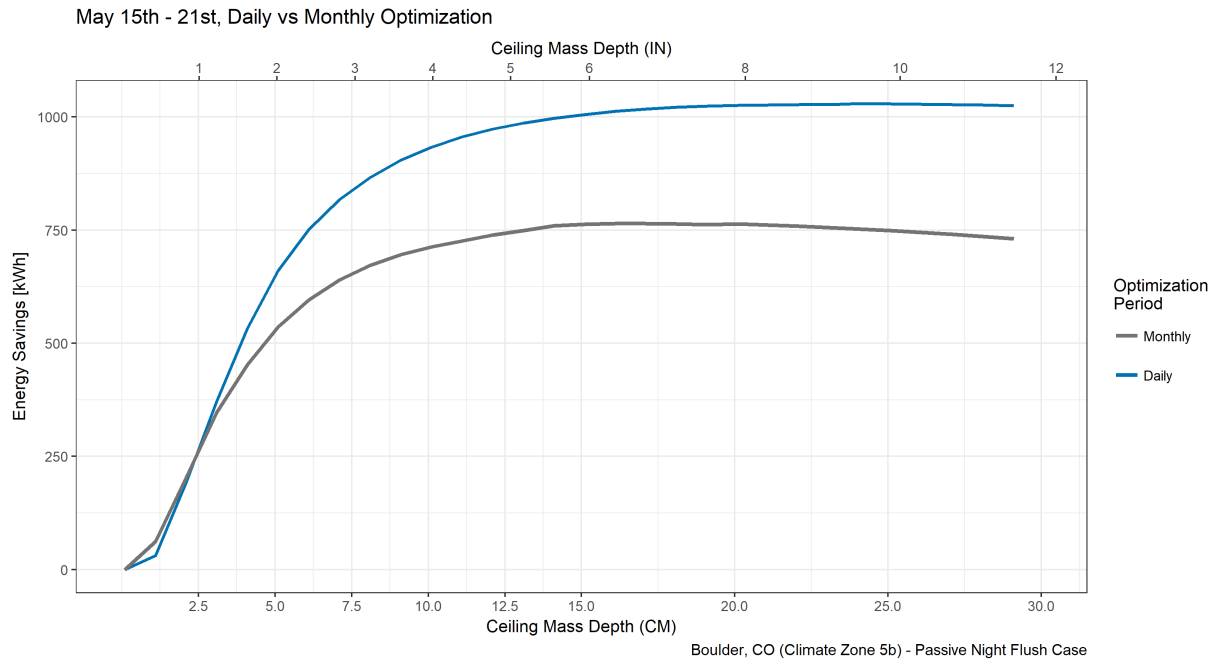


Figure E.1: Daily vs Monthly Optimization - May 15th through 21st

Optimized night flush settings for the entire month of May were reviewed against daily optimized night flush settings for the most dynamic week in the shoulder season of May in Boulder, CO. At 10 cm, there is an additional 23.5% savings available in this dynamic week through daily optimization. Further breakout of end uses indicates that the energy savings was in reduced reheat, not additional passive cooling.

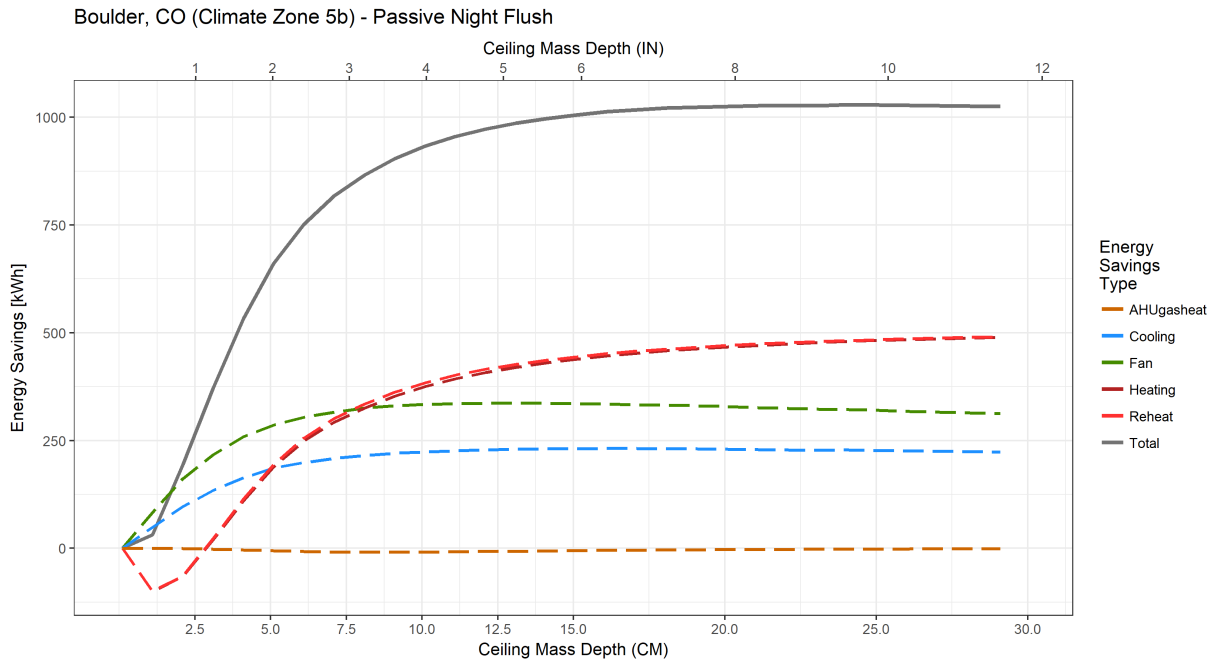


Figure E.2: Daily Optimization End Use Breakout - May 15th through 21st

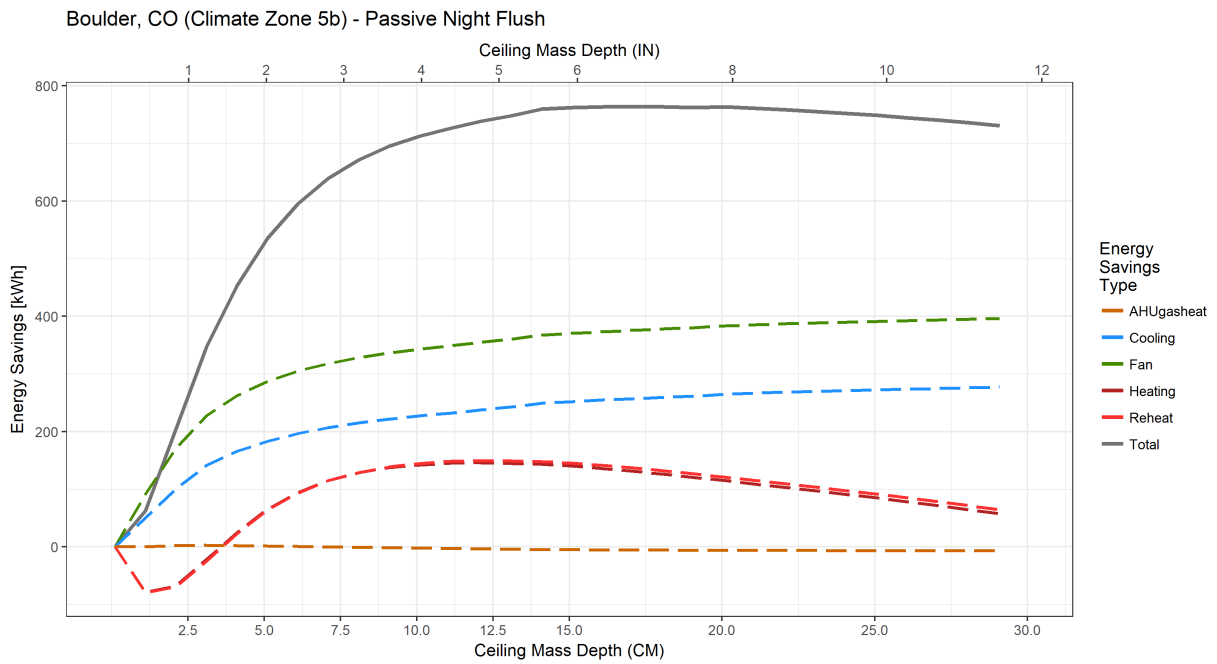


Figure E.3: Monthly Optimization End Use Breakout - May 15th through 21st

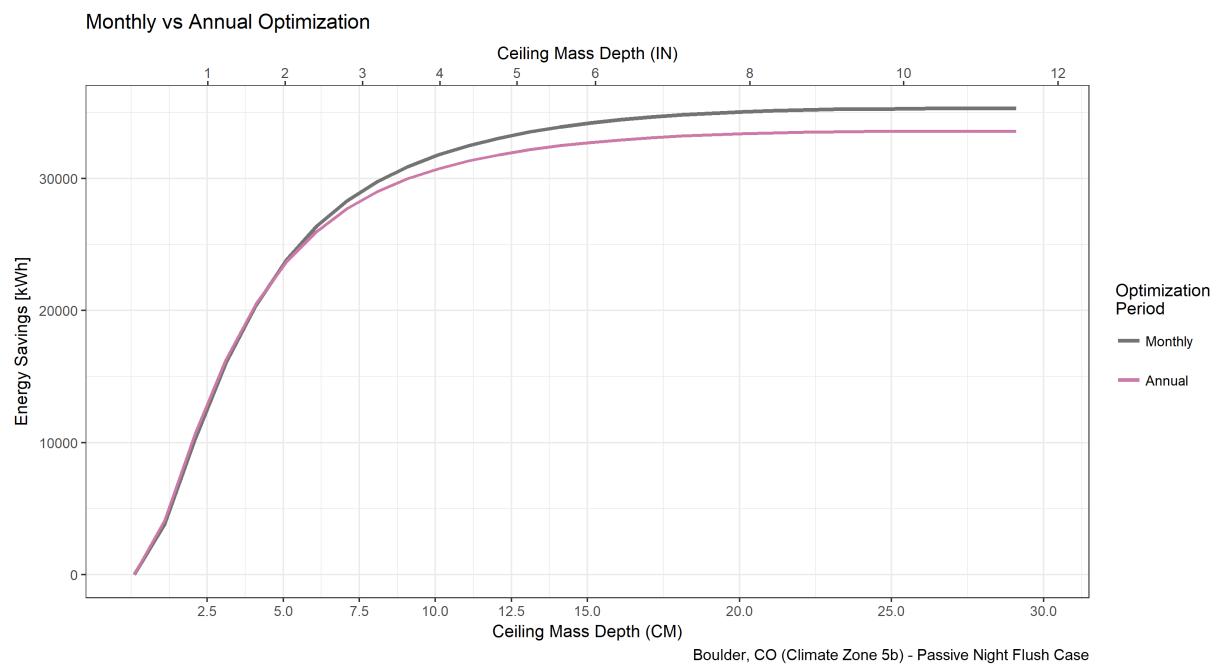


Figure E.4: Monthly vs Annual Optimization

## Appendix F

### Energy Savings and Load Reduction Expressed as a Percentage of Total

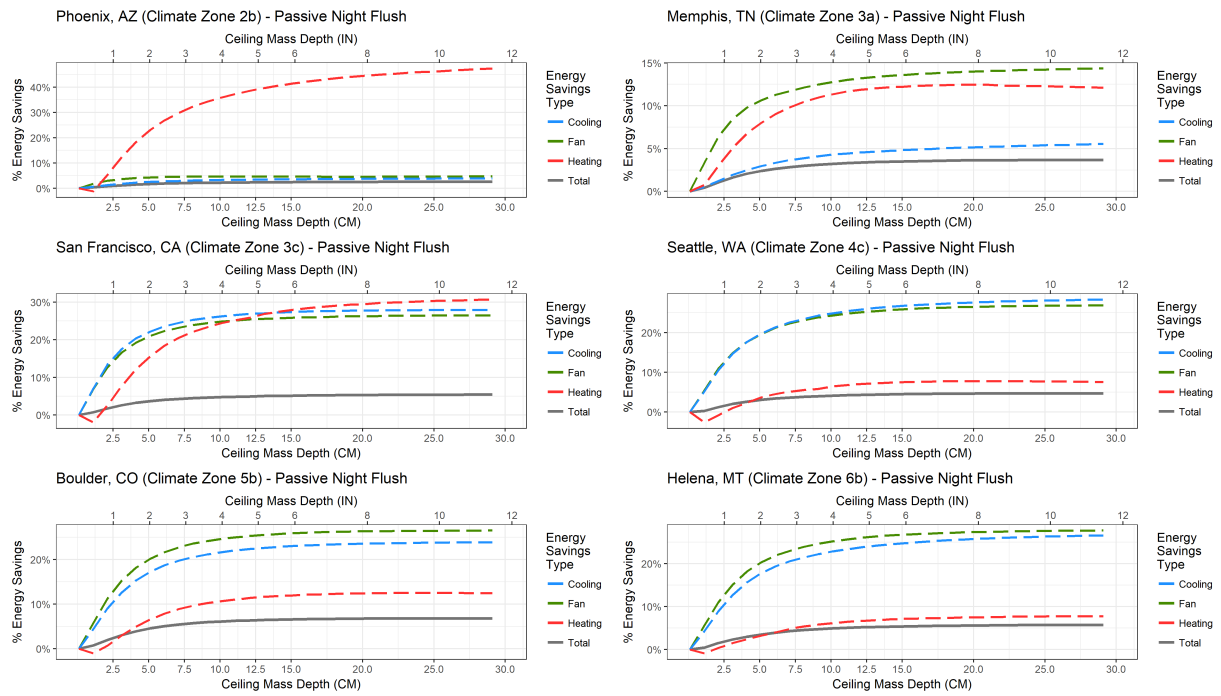


Figure F.1: Energy Savings Expressed as a Percentage of Total - All Passive Night Flush Cases

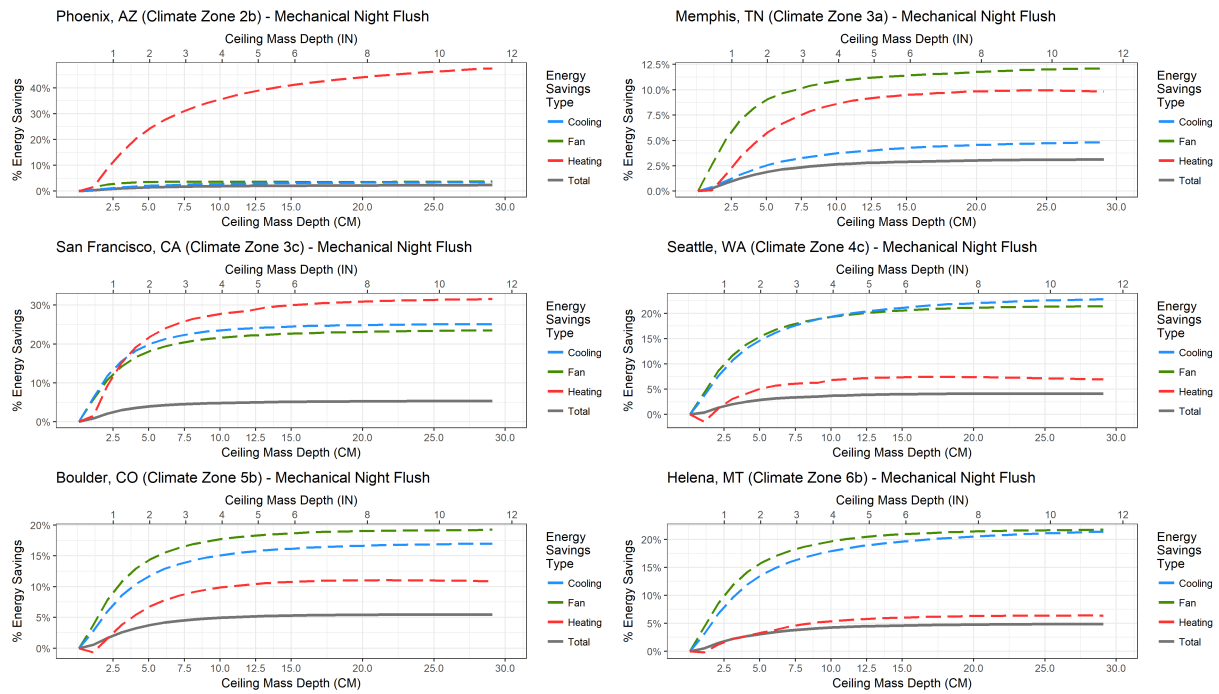


Figure F.2: Energy Savings Expressed as a Percentage of Total - All Mechanical Night Flush Cases

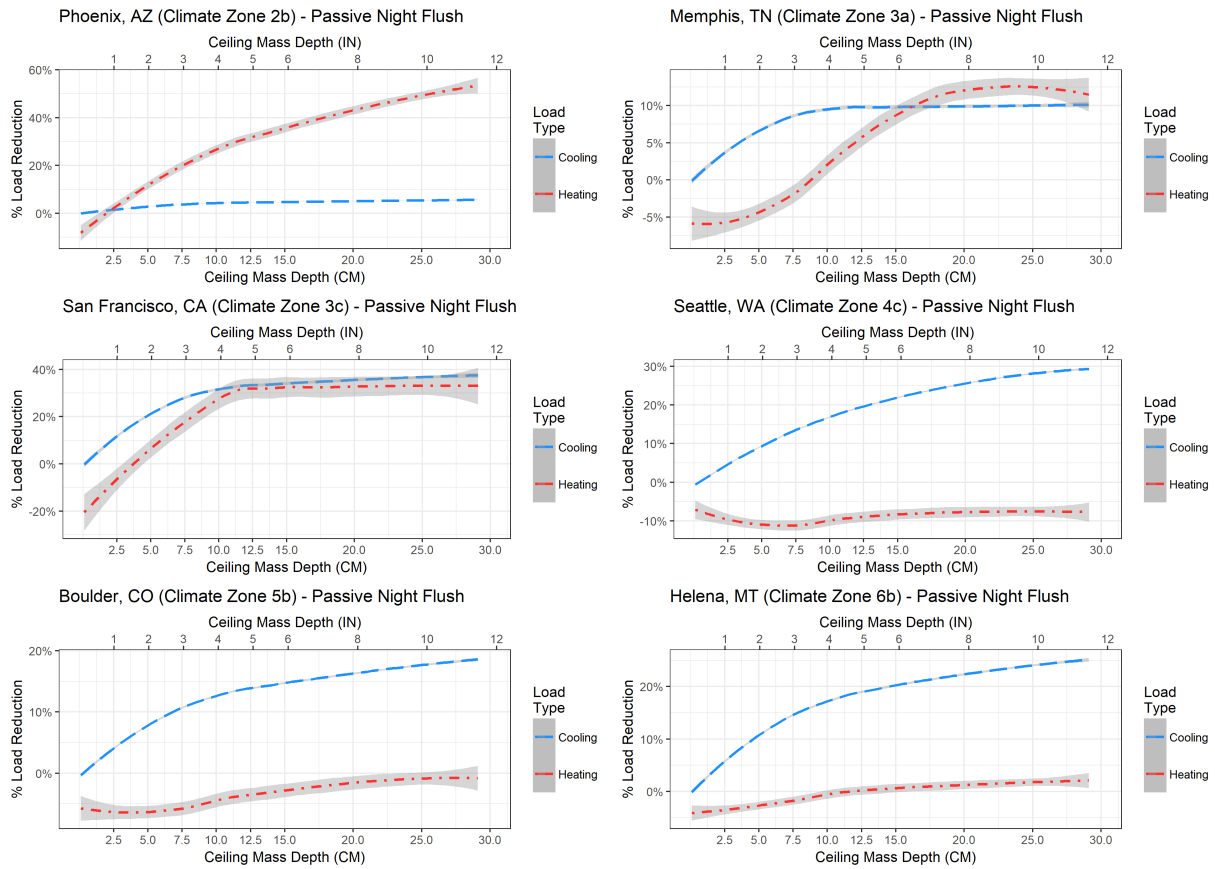


Figure F.3: Building Sensible Load Reduction Expressed as a Percentage of Total - All Passive Night Flush Cases