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Occupant Satisfaction with Underfloor Air Distribution Systems in a Cold Climate: A Field Study

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Occupant Satisfaction with Underfloor Air Distribution Systems in a Cold Climate
A Field Study

by

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ABSTRACT

The demand to reduce GHG emissions and corporate rethinking of interior environments has encouraged the use of underfloor air distribution systems (UFAD). This relatively new space conditioning system is believed to provide benefits of better energy performance, improved indoor air quality, workplace flexibility, higher levels of occupant comfort and personal control. However most of the research on this technology and its relation to occupant comfort has been limited to laboratory settings and use of Fanger's heat balance model to determine whether the system provides acceptable thermal comfort. The later fails to confirm that the conditions provided by UFAD are satisfactory to occupants in-situ.

This field study of the City of Calgary's Water Center examined UFAD in terms of occupant comfort in a cold climate. Both physical measurements and occupant response was collected. Overall the findings were very positive. Occupant responses indicated participants were generally satisfied with their comfort level and indoor air temperature. The median PMV value also indicated that the thermal conditions were within the acceptable range.

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1. INTRODUCTION

1.1 BACKGROUND INFORMATION

1.1.1 Energy Efficiency and Occupant Comfort Connections

The rising concern about global warming has researchers and scientists developing new technologies and methods to reduce energy use and greenhouse gas (GHG) emissions. Buildings are one of the leading energy consumers and contributors of GHG emissions compared to all other sectors; consuming approximately 40% of the world's energy and emitting 30% of the world's GHGs (Perez-Lombard et al., 2008: 395). These shocking statistics have pushed the building industry to develop new technologies in an effort to reduce its energy use and GHG emissions (Bauman 2003).

Buildings are large consumers of energy because we mechanically condition interiors to provide constant, uniform and comfortable environments. These conditions provide healthy, satisfactory and productive environments for building occupants (deDear et al., 1997:1). Conditioning interior environments in cold climates, like that of Canada, relies heavily on mechanical and electrical systems; lighting, heating, ventilation and air conditioning (HVAC), plumbing, safety and security and more recently information technology. These systems use much of a building's energy and play a significant role in environmental impact. HVAC systems in particular are receiving a considerable amount of attention, as these systems consume more than 50% of building's energy (Alajmi and El-Amer 2010).

There have been many efforts to optimize HVAC configurations, operations, and controls, all in an attempt to balance energy and resource efficiency while providing comfortable interiors within economic means (Alajmi and El-Amer 2010). Factors such as comfort and behaviour can play a large role on building performance and yet very little is known how these patterns are shaped, especially in commercial buildings (Leaman and Bordass, 2007; Brown, 2009). Feedback from green buildings or the use of energy efficient technology is important. As there exists a fine balance between optimizing energy performance while providing comfortable interiors. Feedback on occupant comfort levels is especially important since people in developed countries spend upward of 90% of their time in indoor environments (Leech, 2002).

1.1.2 Changing Nature of Work

Global warming is not the only factor pushing the development of energy efficient technologies; the rapidly changing nature of work is another contributing factor. Corporations are rethinking the work environment and becoming more aware of the impacts indoor environmental quality (IEQ) has on the health and productivity of occupants (Fisk, 2000; Bauman, 2003). Recently there has been an increase in the amount of information/research available on the impacts IEQ and personal control of ambient conditions can have on the health, well-being, stress level, distractions, and discomfort of occupants (Fisk 2000; Leaman 1995). Indoor environmental quality along with improved occupant satisfaction, workplace flexibility, productivity, and reduced operating cost are now among the leading drivers in recent workplace design (Heerwagen, 1998; Bauman, 2003). Not only is IEQ important to corporations, thermal comfort and indoor air quality (IAQ) are ranks within the top three most important interior environmental conditions amongst office workers and these two conditions least satisfy occupants in terms of their ability to control the ambient environment (CBE, 2000b; Friedman, 2004; Leaman and Bordass: 1995, 2005).

The most common work environment in developed countries is commercial open plan office, where over 60% of office workers work (IFMA 2006:29). Optimal conditions can be hard to manage in open plan offices, as they need to meet the comfort requirements of a larger group of people with varying expectations and preferences. This has been a particular challenge for HVAC designers. One way HVAC designers and engineers have approached this challenge has been to give occupants control of their immediate environment, as with underfloor air distribution (UFAD).

1.1.3 UFAD Systems

The corporate world's rethinking of interior environments and the ways ambient conditions affect employee productivity and health, coupled with the demand for energy efficient technologies, has allowed for the development of underfloor air distribution, one of the many new technologies appearing in building design (Pike Research, 2011:1). Conventional and UFAD systems use the same basic air handling units and process of conditioning the supply air. The difference between these two systems is the location where air is delivered to the room. Conventional systems supply and return air at the ceiling level promoting complete mixing of supply air with room air. The UFAD system however supplies air at floor level within localized zones and returns air at ceiling level. UFAD systems supply air at a slightly higher temperature than conventional systems since it is supplied directly into the occupied zone as seen in Figure 1.1.

UFAD has reported benefits of better energy performance, improved indoor air quality, higher levels of occupant comfort, personal control, and workplace flexibility (Bauman 2003). This new system is increasingly being installed as an alternative to overhead systems and some industry watchers predict that as many as 35% of tomorrow's office buildings will include UFAD (Krepchin, 2001; Fisk, Faulkner et al., 2006) Market research indicates that investment in UFAD will total $1.2 billion in North America during the period from 2010 to 2015 (Pike Research, 2011).

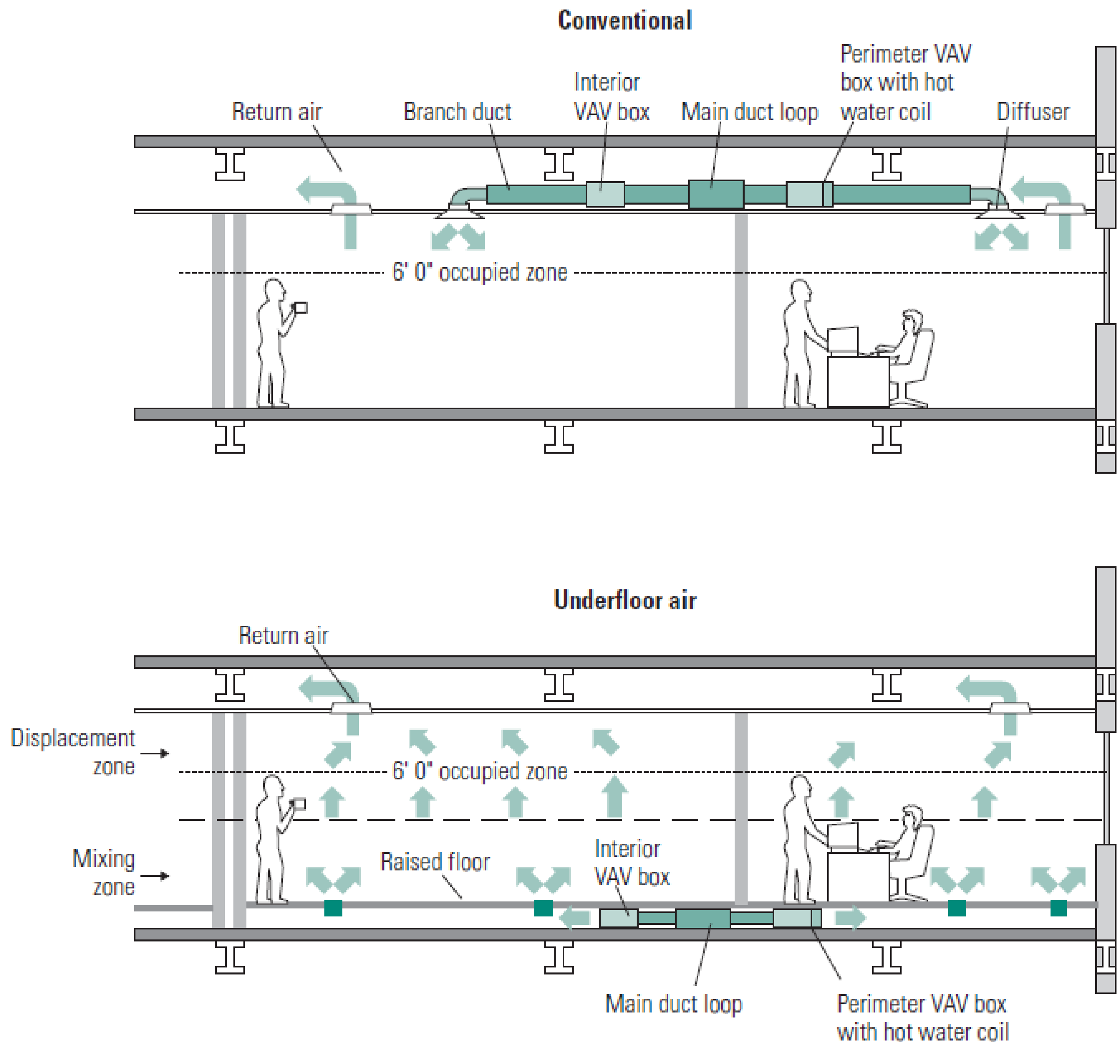

Figure 1.1UFAD system compared to Conventional Overhead System

(Pike research 2001)

1.2 RATIONAL FOR THIS PROJECT

UFAD has reported benefits of better energy performance, improved indoor air quality, higher levels of occupant comfort, personal control, and workplace flexibility (Bauman 2003 Bauman and Webster 2001; Lehrer and Bauman, 2003). However, there are few published reports of rigorous field studies of occupant reactions regarding comfort, satisfaction and control (Fisk et al. 2006; Melikov et al. 2005; Charles 2003). Much of the literature on UFAD systems equates comfort and occupant satisfaction with the level of occupant control over local air flow (Tsuzuki et al. 1999; CBE 2000; Daly 2002;

Bauman 1998, 2003; Wyon 1996). Many laboratory studies of thermal comfort with UFAD have simply used Fanger's heat balance model to determine whether the system was providing acceptable thermal comfort (Charles 2003; Im et al 2005). The latter fail to confirm that the conditions provided by UFAD are satisfactory to occupants. Post occupancy evaluations are needed to more comprehensively assess the performance of UFAD in terms of thermal comfort and control. In terms of many new energy efficient technologies, feedback is needed at all stages of a buildings life cycle: the design, construction, and operations. This feedback can help recognize if the building or technology has been successful at achieving the functions of its intended use (Preiser and Vischer, 2005; Brown, 2009:6). In the case of UFAD that is improved energy performance, comfort and occupant control.

1.3 OBJECTIVES

The objective was to better understand occupant assessment of thermal comfort and control with UFAD systems in cold climates. The approach to evaluating this relationship was to conduct a field survey of physical conditions and occupant perception in the City of Calgary's Water Centre Building located in Calgary Alberta Canada.

The findings of this research could contribute to or confirm the generally accepted notion that UFAD provides increased occupant satisfaction. Conclusions of the research should provide general information regarding the interaction and impact the system and occupant have on one another and how this affects the operation of the system. The possible application of the research findings will be to provide a basis of knowledge needed to design and maintain UFAD so that the system enhances the comfort of building occupants while working at optimal energy efficiency. The conclusions and recommendations made should help engineers, researchers, designers, owners, and buildings managers of UFAD understand the impacts this type of air distribution system has on building occupants.

1.4 OUTLINE

Chapter 2 reviews knowledge around UFAD systems, occupant comfort including indoor environmental quality, control, and comfort standards. This chapter also reviews the findings from previous field studies which investigated the relationship between UFAD systems and occupant comfort. Chapter 3 outlines the methods that were used during the field study to collect both physical and participant responses. The results of the field study are included in Chapter 4. Finally, Chapter 5 includes the discussion of the results and the conclusions of the study.

2. LITERATURE REVIEW

This review of literature on UFAD in relation to occupant comfort will provide a brief overview of UFAD systems as well as their benefits and shortcomings, a review of research regarding IEQ within buildings and how current research approaches relate to this matter, and finally a review of research that has looked specifically at occupant comfort with UFAD system.

2.1 UFAD SYSTEMS

UFAD systems are an alternative method for delivering space conditioning in offices and other commercial buildings. The development of this technology was largely driven by the changing work environment. Organizations sought simpler and less expensive reconfiguration to allow them to adapt to new technologies and business strategies. The advent of computer, communication and internet based technologies along with advances in flexible interior furnishings, which can be easily adjusted and moved to support a variety of work patterns, drove organizations to adapt to these new technologies and business strategies. These advances have benefits including worker productivity, employee retention, reduced operating cost, and increased market value of the facility (Bauman, 2003).

2.1.1 History

The work environment has evolved extensively over the last 30 years, however the HVAC technology used to service these interior environments have not. The changing nature of work, and occupants' concern for the quality of indoor environment, specifically thermal comfort, indoor quality and personal control, allowed for the progression of task ambient conditioning (TAC). TAC uses individually controlled diffusers that are placed in locations near the occupant to provide localized comfort as opposed to conditioning large zones of the building controlled by one or a few thermostats. The idea was to provide small control zones and deliver fresh air near the vicinity of the occupant. TAC was developed to address many of the problems associated with indoor environmental quality and allows for a more adaptive approach to environmental control. UFAD systems originally were used in conditioning spaces with high heat loads such as server rooms. On the other hand, raised flooring systems were being installed to manage the increased amount of cables serving personal computers. With the proliferation of personal electronic equipment in the 1970's, issues of cooling this equipment became a concern. This is when UFAD was first used within the office setting. This move allowed both cable management and UFAD to be combined which proved to be an economical and efficient means of supporting two demands. Since the combination of raised floor and floor level conditioning, Africa, Europe and Japan have accepted UFAD systems while North America has lagged behind in its use until 1990's (CBE, 2000a; Webster and Bauman, 2007:1463). Currently these systems are being considered and installed at an increasingly rapid pace (Bauman and Webster, 2001:1; Fisk et al., 2006:1).

2.1.2 How UFAD Works

UFAD systems, unlike conventional overhead air supply systems, deliver conditioned air at the floor level. The system uses a floor plenum between the structural slab and the raised floor to deliver air through supply diffusers that are within the occupied zones (floor level to head height of a standing person). Once the air is discharged from the in-floor diffuser, the air rises to the return air grills. Since the air is supplied close to the occupants, the supply air temperature must be approximately 3º to 4º C higher than with conventional overhead systems. UFAD systems also supply air at a higher velocity compared to similar systems such as displacement ventilation systems to promote mixing in the occupied zone. Compared to conventional overhead systems UFAD systems supply air at much lower velocities, allowing for the stratification of warmer air and pollutants into the upper zone (Sekher and Ching, 2002; Lin and Linden, 2005:400). There are three basic approaches to designing and installing a UFAD system. These include

1. Supplying air passively to the conditioned space through floor registers supplied by a pressurized under floor plenum with a central air handler delivering air.
2. Supply air actively through locally controlled, fan powered registers which are supplied by a low pressure floor plenum with a central air handler delivering air

3. Supply air actively through underfloor ducts connected to terminal devices or supply outlets with air being supplied by a central air handler. (Bauman, 2003; Bauman and Webster, 2001)

2.1.3 UFAD Benefits

As more and more UFAD systems are being installed there has been a considerable amount of research available asserting its benefits. Relative to traditional overhead air distribution systems:

- Improved ventilation efficiency and indoor air quality since fresh air is supplied at the floor level with some momentum. This can also improve productivity and health. When the air is supplied with some momentum this provides greater mixing of fresh air within the breathing zone which is the space from the floor to 1.22 to 1.83 metres above the floor. The mixing of this air does not occur above the breathing zone and as air moves into the upper zone it does not re mix with the air in the breathing zone. Heat from people and equipment conveys buoyant contaminants and other pollutants from the breathing zone to the upper zone so occupants have a constant supply of relatively fresh air. In addition, in some climates the use of extended economizer cycles allows for higher percentage of outside air in the supply air (Lehrer and Bauman, 2003).
- Reduced energy use is associated to a number of factors
    - Less fan power is required to deliver and mix the supply air because there is less total air volume and static pressure required since the air stratifies upward due to its buoyancy.
    - Energy can be reduced through use of an economizer and chiller COP during cooling season. However these savings are dependent on climate.
    - Structural slab acting as a thermal mass can help save energy. Since the supply air comes in direct contact with the slab, which if precooled from night time cooling, will act as a heat sink during the day, and the temperature from the slab will transfer to the supply air therefore reducing the amount of conditioning required. Although the success of this method is dependent on climate.(Lehrer and Bauman, 2003)

- Reduced Life Cycle and Initial Cost is associated with a number factors during construction and while the building is in operation
    - There is less cost associated with churn rates when tenants reconfigure, relocate or change the interior of the building. The reduced cost associate with this is due to the ease of being able to access the extensive cable system for quick moves and relocations as well as being able to relocate diffusers with ease therefore requiring less specialized technical work by contractors (Addison and Nall, 2001).
    - Reduced floor to floor height in new construction can reduces the overall height of the building which can result in cost savings in structural and facade systems. This reduction is achieved by reducing the overall service plenum heights. Large overhead ceiling plenums for large supply air ducts are not needed and can be reduced to smaller plenum for air return and lighting fixtures and acoustical ceilings. Also underfloor plenums can be lowered for un-ducted plenums. Reductions in floor to floor heights are best achieved when the UFAD system is carefully integrated with the structure particularly flat slab concrete structures (CBE, 2000a).
    - Elimination of overhead duct systems and downsizing of HVAC equipment reduces the amount of material and therefore cost of the initial system and the operating cost of the equipment. (Lehrer and Bauman, 2003)
- Improved thermal comfort by allowing individuals control over their local thermal environment since diffusers are placed in the direct vicinity of the occupant. (Bauman, 2003)

2.1.4 UFAD Barriers

Along with the benefits of UFAD there has been some concern and barriers to using the UFAD expressed; these include:

- UFAD systems being a new and unfamiliar technology and lack of familiarity can create problems during the design, construction and operation of the system.

- There is a lack of whole building performance and simulation tools available to accurately model UFAD systems at the design stage. Whole building performance data is needed from buildings with UFAD systems. The data needed to accurately quantify the benefits in energy use, indoor environmental quality, occupant satisfaction, comfort, health, and life cycle (operating) cost to quantify the benefits.
- Higher initial cost has been one of the main reasons UFAD systems are not used as much as conventional overhead systems in North America. Although these higher first costs can be offset with cost savings provided during the systems lifecycles along with cost savings from the reduction of ductwork and floor to floor height required.
- UFAD systems are perceived by some to produce cold floors, resulting in cold feet and draft discomfort. Because occupants are closer to supply outlets there is an increased possibility of excessive draft. Although these conditions are typically exposed in poorly designed UFAD systems.
- Problems with spillage and dirt entering into the UFAD supply airstream where it can be widely distributed throughout the occupied space, although most UFAD diffusers have been designed with a catch basin to collect liquids and dirt if there was an accident and something was to spill. Tests have also shown that UFAD diffusers do not blow more dirt into the space than other air distribution systems (CBE, 2000a).
- Condensation can occur on the surface of the structural slab. In humid climates; outdoor air must be dehumidified before it is supplied to the underfloor plenum.
- Problems with applicable standards and codes since UFAD are a relatively new technology in the building industry. The system may come in conflict with existing local building codes and standards. (Bauman, 2003)

2.1.5 Summary

With the changing nature of work and the need for more energy efficient building technologies, UFAD systems are becoming an alternative to conventional HVAC systems. As UFAD systems gain market presence, it is crucial that rigorous research be conducted to validate the claims manufacturers have been making about this new technology. The review of the literature indicated that there has been extensive research on the performance aspects of UFAD systems such as stratification and pollutant removal in both laboratory and field studies, however, very few studies report the performance of UFAD systems in relation to occupant expectations, and those that do exist have substantial methodological limitations. Therefore it is critical to review and understand UFAD systems in use, especially in relation to occupant thermal comfort, IAQ, and control.

2.2 IEQ, CONTROL, AND COMFORT STANDARDS

2.2.1 IEQ and IAQ

It is estimated that people in developed countries spend approximately 90% of their lives indoors (Leech, 2002). This shows that the quality of the interior environment can have a significant impact on comfort, health, and overall sense of wellbeing (de Dear et al., 1997). One of the commonly expressed benefits of UFAD system is the improved comfort and indoor environmental quality. Like all HVAC systems UFAD air distribution affects airflow patterns, in turn affecting the air mixing and therefore impacting the physical IAQ and thermal conditions of a space. These physical conditions affect occupant responses to the environment (Charles, 2003). Extraneous factors can affect the performance of air distribution system and affect the IAQ and thermal comfort. Extraneous factors include room geometry, pollutant sources, heat load, and return air location.

2.2.2 Control

The degree of personal control over environmental conditions can also affect occupant perception of their physical environment, regardless of whether the control is used or not. In this sense environmental control is closely related to comfort. A number of research studies have demonstrated that, when occupants have control over their immediate environment, there are a number of benefits including occupants being more tolerant of variations in indoor conditions and environment, fewer health symptoms, higher comfort satisfaction, increases robustness, reduces stress and improves performance and productivity by 2 to 3% according to Clements-Croome (2000;(Boerstra, 2010; Clements-Croome, 2000; Heerwagen, 2000; Kroner and Stark-Martin, 1992; Leaman, 2005; Leaman and Bordass, 1995; Lomonaco and Miller, 1996; Wyon, 2006). Charles (2003) has been concerned that studies that have looked at UFAD systems and occupant comfort in field settings have not fully separated the effects of personal control and physical environment. One study showed that occupants were more satisfied with their environment because they were able to adjust the environment to suit their preferences (Bauman et al., 1998). However the nature of these relationships remains unclear (Charles, 2003).

2.2.3 Comfort Standards

Comfort traditionally was applied to architecture and interior design, more recently it has been applied to defining the norms and standards of acceptable interior environmental conditions and thermal comfort within buildings (Heerwagen 1998; Vischer, 2003). Throughout history the definition of comfort has dramatically changed over the last century, especially in relation to indoor environmental conditions and management. The conditions people have come to expect indoors rely heavily on heating, cooling and lighting technologies (Chappells and Shoves, 2004). Since the 1920's the standards, technologies, and expectations of comfort has changed both qualitatively just as well as quantitatively. Technological development has played a significant role in shaping the physical reality of comfort, helping to turn comfort into a mass commodity. American air-conditioning manufacturers were specifically interested in selling comfort as a commodity; they defined a set of environmental conditions that that could be marketed, desired and therefore delivered and sold (Cooper 1998; Chappells and Shoves, 2004). Not only were HVAC manufacturing companies interested in the development of comfort expectations, building science and engineering researchers worked on defining the physiological parameters of comfort in order to set guidelines and standards for those involved in specifying technologies and buildings (Chappells and Shoves, 2004). In 1923 the comfort zone was defined by Houghton and Yaglou, who specified the "ideal" climate (Chappells and Shoves, 2004). Following the definition of the comfort zone, the landmark definition of thermal comfort was developed by Fanger (1970); this work being the heat-balance model of the human body. This model provided the basis for physiological experiments that helped dictate the ideal climate. Earlier notions of health and safety helped push this model into being the foundation of the technological standards that define comfort zones today (Fanger, 1970; Nevins and Gagge, 1972; Vischer, 2003).

From the heat-balance model, Fanger (1970) developed the comfort equation, which was derived from extensive experiments in climate chambers using university students in a mid latitude climate. This equation defined the conditions of air temperature, mean radiant temperature, relative humidity, and air velocity that ensured 80% of occupants of a controlled environment would feel comfortable for any specified activity and clothing level (Fanger, 1970; Vischer, 2003).

Fanger's thermal comfort standard has been developed and adopted by a number of professional guidelines and national standard, the main thermal comfort standards being ISO 7730: Ergonomics of the Thermal Environment and ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy and ASHRAE Standard 62.1 Ventilation of Acceptable Indoor Air Quality. These standards are based upon the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) thermal comfort indices. PMV predicts the mean value of thermal sensation for a large group of people on a seven point thermal sensation scale determined by Fanger that being +3 = hot; +2 = warm +1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold. The PPD predicts the percentage of people in a large group who are likely to feel uncomfortably "too warm" or "too cool". This standard also provides methods to assess local discomfort caused by drafts, temperature gradients, and asymmetric radiation. For review of the equations used to calculate the ISO 7730 PMV and PPD refer to Appendix G. Along with this particular 7730 standard, ISO 7726 (measuring instruments), ISO 8996 (estimate of metabolic rate production), ISO 9920 (estimation of clothing properties) and ISO 10551 (subjective assessment methods) are all used to complete the ISO 7730 analysis to assess whether environmental conditions are within international regulations (Chappells and Shoves, 2004; ISO, 2005; Oleson and Parsons, 2002).

Recently this model has been challenged by adaptive comfort researchers and advocates. The model has gone through extensive laboratory experiments which produce consistent, reproducible results within climate chambers. However field studies fail to support the the heat balance model (Oleson and Parsons, 2002). Researchers are starting to question if this research approach can be applied to describe real-world thermal perception since it reveals little about how occupants define and experience comfort. This model also neglects the interaction of occupant perception and expectations (Chappells and Shoves, 2004). Some believe that the wide discrepancies found between observed and predicted mean thermal sensation within real buildings can be categorized into the following methodological limitations (Brager and Dear, 1998; Oleson and Parsons, 2002).

- Estimating insulation of clothing garments or ensembles: Brager et al. has demonstrated that the clo value can vary as much as 20% depending on the table used. Clothing measured under laboratory settings may differ from in-situ clothing. Recent thermal comfort study completed in a field setting by Garcia (2011) found that PMV was relatively insensitive to small variations in clo estimates. Also the insulation of the chair is commonly not accounted for in the clo calculation (Brager and de Dear, 1998). McCullough et al. (1994) have shown that upholstered chairs add approximately 0.15 clo to the calculated value. Although in ASHRAE Standard 55 a typical office chair adds 0.1 clo to the calculated value (ASHRAE 2010:12).
- Estimating activity patterns and associated met level: the estimation and translation of people activity patterns is one of the least developed methods of thermal comfort research (Brager and de Dear, 1998). Becker and Paciuk (2009) found from a field study in residential buildings that PMV is not so sensitive to met variations.
- Non-uniformities of physical measurements: spot-measurements of ambient thermal parameters may not be representative of the indoor microclimate that is actually being experienced by the occupant if measurements are not taken in the immediate location of the occupant and taken from a representative location. This

is important especially in buildings with passive ventilation or where occupants have a higher degree of control (Brager and deDear, 1998).

- Model assumptions – steady state vs. transient: static heat balance models were developed in laboratory setting which are static while conditions in buildings are much more dynamic in terms of thermal and activity level (Brager and deDear, 1998).
- Non thermal Factors- the response to conditions in real buildings can be influenced by many complex factors which are not accounted for in the heat balance models. These include demographics, context, other environmental interactions and cognition, although these factors have been demonstrated to be irrelevant in climate chambers. Researchers feel these factors cannot be dismissed so easily, particularly the perception of control since it has been demonstrated by psychologist that adverse or noxious stimuli can be less irritating when subjects perceive to have more control over them. (Brager and Dear, 1998)

Field studies of thermal performance in buildings and comfort perceptions of occupants offer insight into the physiological and psychological variables that influence the interpretation of comfort in the real world (Chappells and Shoves, 2004). One of the first studies of people in their 'natural habitat' was done by Bedford's 1930's investigation factory worker comfort and its relation to productivity. Since this initial study, field studies have been used in qualifying, refining and refuting physiologically-based models for thermal preference (Chappells and Shoves, 2004). Field studies provided an abundance of evidence that helped Humphreys and Nicol (1998) develop the adaptive approach to thermal comfort. In this adaptive approach comfort is defined as a dynamic achievement rather than the static definable condition or attribute which is defined in heat balance model (Humphreys and Nicol, 1998). Researchers have evaluated the variation of defined comfort zones relative to occupant perception. They found substantial differences between perception of comfort in buildings and the comfort values based on Fanger's PMV PPD approach (Humphreys, 1994). Researchers have also found differences in thermal sensations of the same group of people in comfort chambers, homes and offices. The correlation with predicted values was poor and suggests that comfort is influenced by a number of factors including the type of environment people inhabit (Chappells and Shoves, 2004; Shove, 2003).

The adaptive model takes a more holistic approach to analyzing the interior environment and its effect on occupant comfort. The adaptive model acknowledges that perception of thermal comfort in the real world goes beyond simple physics of the body's heat balance and is influenced by a number of factors including past thermal history, social conditioning, economic considerations, cultural and technical practice, and other contextual factors (Brager and Dear, 1998).The key difference between the adaptive model and the heat balance model is that the adaptive model views the occupant as an active agent interacting with and adjusting the person-environment system via multiple feedback loops where the heat balance model views the occupant as a passive recipient of thermal environments where thermal stimuli are mediated by the physics of heat and mass exchange between environment and body (Brager and Dear, 1998). The adaptive model indicated that there are three distinguished modes of adaptation: behavioural (personal, environmental, technological or cultural), physiological (genetic adaptation or acclimatization) and psychological (habitation or expectations).

2.2.4 Summary

The literature reviewed regarding IEQ, environmental control and comfort models, shows that thermal comfort is a contested field. There are a number of disciplines that are investigating relationship between indoor environment, technology and human comfort/body. The understanding of how comfort, control and IEQ affects occupants of buildings has been questioned by a number of researchers who have been able to define and quantify comfort by testing human responses in laboratories. Recently there has been rigorous research being undertaken in field surveys of occupant perceptions. These enquires have refined and expanded the heat balance equation and in some cases this model has been coupled with models of comfort that better represent the dynamics and the diversity of the thermal experience. These two approaches to comfort have sparked debate around the relevance of the scientific models, design standards and the assumptions on which they are based (Chappells and Shoves, 2004). As new technology continues to proliferate buildings it is essential that proper investigations are conducted to ensure these technologies are not merely meeting the static heat balance standards but are considerate of both the physiological and psychological factors that affect occupant satisfaction with their environment and these specific technologies.

2.3 UFAD AND COMFORT FIELD STUDIES

2.3.1 Relevant UFAD and Comfort Field Studies

The publications considered in this literature review included only reports of occupant satisfaction with field or laboratory (office mockup) UFAD installations. There was four studies that looked at the above mentioned criteria. The purpose of this review was to understand the existing research on UFAD and occupant satisfaction that has been conducted in occupied buildings and mockup workstations. The review was also used to understand the methodological rigor along with limitations of existing research so as to ensure future research design and methods are refined to make certain they are of rigorous quality and reduce methodological limitations.

Charles, K. E. (2003). *A Review of Occupant Responses to Localized Air Distribution Systems*. (NRCC-46271). Retrieved September 30, 2011, from The National Research Council of Canada, Institute in Construction: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc46271/nrcc46271.pdf.

Charles (2003) conducted a literature review of existing research that has been conducted specifically related to occupants’ response to localized floor and desk mounted air distribution systems. The studies included in her review where from a wide source of electronic databases spanning from psychology to ergonomic to building science journals. Studies were included in the review if they examined UFAD or task ambient conditioning systems and if occupant responses were measured in an office setting or field /laboratory setting with office mock ups. Charles concluded that between the period of 1990 and 2003 there were only 11 relevant studies with 7 of those addressing UFAD performance.

One study Charles noted to be relevant and of higher research quality was a post occupancy evaluation conducted by Hedge et al. (1993). Hedge conducted a survey of 151 office occupants and six facilities managers and exampled their response to a UFAD system that had been in place for 6 months. Hedge concluded that the occupants were satisfied with the heating, ventilation and IAQ and expressed that it positively impacted their health and productivity. Although Hedge et al. 1993 did conduct a pre-post installation comparison of occupant responses to the system the study excluded systematic comparison of the physical conditions with the occupant's responses.
Charles also considered two more related articles. Specifically a study conducted by Fukao et al in 1996, which compared occupants working in areas with UFAD with those working in areas with conventional ceiling-mounted conditioning systems. Fukao found occupants' perception of air pollution and comfort in area with UFAD was slightly better than area with ceiling mounted conditioning systems. However Fukao did not find any conclusive evidence that one system was better than the other in relation to thermal sensation, comfort and acceptability because occupant responses were favorable under both conditions. Another study conducted by O'Neill 1992 concluded that occupant perception of air freshness and temperature did not vary between those exposed to UFAD conditions and those exposed to conventional ceiling-mounted conditioning systems. O'Neill did find that occupants with the UFAD system perceived the seasonal variation in temperature to be better than those who used traditional over head systems.
The studies reviewed by Charles that dealt specifically with UFAD systems provides some evidence that occupant satisfaction is improved with the use of UFAD systems.

Although Charles review of the literature concluded that there were major methodological limitations that reduced the strength of most research. Charles first concern with the research was that most of it was conducted in the laboratory setting and focused solely on the physical characteristics of the systems. Secondly, there was limited information provided in relation to research design and sample population, which could have resulted in extraneous variables affecting the results. Thirdly, there were no studies that consistently correlated the physical environmental measurements with occupant's responses. Charles also expressed concern with studies that compared UFAD systems with conventional systems. This concern being the inadequate control for differences in building, indoor environment or occupants which may have confounded the results (Charles, 2003). Charles suggested that future studies should systematically compare physical conditions and occupant responses to help clarify the mechanism causing the relationship between UFAD systems and occupant satisfaction. (Charles, 2003)

Fisk, W. J. et al. (2006). Performance of Underfloor Air Distribution in a Field Setting. *International Journal of Ventilation* 5(3): 291-300.

Fisk et al. (2006) conducted a field study of the performance of underfloor air distribution. The objective of the study was to determine whether UFAD systems in the practice provide ventilation efficiency above unity. Ventilation efficiency above unity means the air change effectiveness (ACE) calculated by taking the "effective ventilation rate at the breathing zone divided by the ventilation rate that would occur throughout the indoor space with the same amount of outdoor air supply and perfect mixing of the indoor air. If the ACE is greater than unity, the minimum required rate of outdoor air supply can be reduced." The secondary objective of this study was to add to existing information on thermal stratification, occupant satisfaction with thermal conditions and air quality using UFAD systems. The study involved 47 occupants of a two story 3100 m^2 office building in Pennsylvania with high performance insulation, windows, window configuration, and UFAD supply plenum and swirl diffusers. Survey results were compared with the results of a database collected from 63 buildings using conventional overhead systems and 4 buildings that used UFAD systems from all over the US. The survey collected background information on respondents and their workspace and asked the occupants to rate their level of satisfaction with office layout, furnishings, thermal comfort, air quality, lighting, acoustic quality and cleanliness using a seven point scale (+3= very satisfied to -3 very dissatisfied). Findings from the occupant satisfaction survey was that thermal comfort ratings were substantially above average, at the 85th percentile and air quality ratings were slightly below average, at the 40th percentile. Fifty-seven % of respondents indicated that they preferred the UFAD system to conventional overhead air distribution systems. However the percentile ranks of thermal comfort ratings from the four UFAD buildings that the base building was compared to varied considerably (95%, 36%, 85%, and 48%) with a mean percentile rank of 66% (p.10). Therefore in this very small sample, the level of thermal comfort in UFAD buildings was only moderately superior to the average level of thermal comfort in conventional buildings.

The major limitation of the study was that it examined the performance of a single building where UFAD and HVAC operating conditions could not be modified. Also the method of study was solely by survey. The qualitative data was not correlated with the quantitative environmental condition data measured during the field study (Fisk et al., 2006).

Sekher, S. C., and Ching, C. S. (2002). Indoor Air Quality and Thermal Comfort Studies of an Underfloor Air-Conditioning Systems in the Tropics. *Energy and Building, 34*(5): 431-444.

Sekhar and Ching 2002 conducted a study on UFAD to determine the effects on thermal comfort and IAQ for office environments in a hot humid climate. The experiment was conducted in an office setting where empirical measurements of temperature, relative humidity, air velocity, carbon dioxide, and particulates, where measured at selected grid points along imaginary horizontal and vertical planes between the supply diffuser at floor level and a return grill at floor level between 2.5 m and 4.5 m away from supply grill. The empirical measurements were used to calculate the PMV and PPD. Statistical tools including correlation analysis and simple linear regression were used to derive relationships between air velocity and the other variables. The study found that there was a strong inverse relationship between air velocity and other variables such as temperature, relative humidity, PMV and PPD. It was also found that relative humidity and temperature had a strong inverse relationship. There was a moderate correlation between dust concentration and air velocity when measurements were taken higher in the room at locations prone to traffic such as halls. There was where opposite effects in unoccupied zones with little traffic. In terms of thermal comfort the study showed that thermal gradients were small except at points close to the diffuser. The PMV and PPD at each point along the imaginary grid confirmed that cold discomfort would occur at points close to the diffuser, confirming the cold feet phenomenon. The conclusion of the study was that IAQ associated with UFAD system was within reasonable limits set out by local guideline and international standards.

This study was comprehensive and rigorous in its scope. However the study did not include actual occupant response in relation to thermal comfort and solely used the Fanger thermal comfort equations. By using this method a number of assumptions were made with regard to the clo and metabolic rate values. These assumptions could have confounded the analysis made between the correlations of the various variables.

2.3.2 Relevant Comfort Field Studies Involving Displacement Ventilation

Melikov, A., Pitchurov, G., Naydenov, K., and Langkilde, G. (2005). *Field Study on Occupant Comfort and the Office Thermal Environment in Rooms with Displacement Ventilation*. Indoor Air 15: 205-214

Melikov, et al. (2008) conducted a field study to identify occupants response to IEQ in rooms with displacement ventilation in actual buildings. It should be noted this study looked at displacement ventilation rather than UFAD systems specifically. Although these two forms of ventilation are different the approach Melikov et al. used to undertake this study on displacement ventilation can provide assistance when developing the methods for the field study of UFAD systems in cold climates.

The surveys that they used focused on investigating local discomforts due to draft and vertical temperature differences. Melikov conducted this study in 10 office buildings, investigating 119 open plan and landscaped office spaces with 227 occupants. The study was conducted through the summer season from July to October. The clo value was calculated based on occupant attire and a value of 0.15 clo was added to represent the insulation value of the chair. Participants were expected to have spent 30 minutes in the office prior to the study to ensure a steady state metabolic rate of 1.2 met. Environmental conditions such as mean velocity, turbulence intensity and air temperature were measured at 0.05, 0.1, 0.3, 0.6, 1.1 and 1.7 m above the floor using a multi channel low velocity thermal anemometer with unidirectional velocity transducers. Radiant temperature, relative humidity, and operative temperature were measured using an indoor climate analyzer. The instruments complied with the requirements of ISO 7726 (1998) and ASHRAE Standard 55 (2004). Measurements were performed as close as possible to the exact positions of the participant desk chair with participants absent during the measurements. The questionnaires used were based on those used by Cena and de Dear (1998); de Dear and Fountain (1994); Donnini et al (1997); Fanger et al (1988); Schiller (1990). The survey was divided into two parts: background and thermal comfort/preference. The thermal preference questions included thermal sensation based on the ASHRAE 7 point scale, thermal preference; thermal acceptance of current conditions, and whether the participant was subject to draft or vertical temperature differences by indicating on a diagram of the body where they felt warm or cool, where they felt air movement, and where they felt discomfort. The background survey covered a number of factors including workplace design, job satisfaction, and health, and garment checklist, human sensitivity to environmental parameters such as light, noise, air quality, ergonomics, social relations, and privacy. To analyze the data collected from both environmental measurements and survey results the team used the SAS statistical package. Logistic and probit regression analyses, ANOVA test, Chi-square test, multiple regression analysis, etc were applied.

The findings showed that 1/3 of the occupants felt thermally neutral and 1/3 assessed themselves as slightly warm. The remaining 1/3 felt slightly hot, warm, cool or cold. The study also found that 24% of the participants complained that they where bothered daily by draft at the leg level, 49% complained that they were bothered daily by uncomfortable room temperature with an average air temperature of 23.4 ºC and 48% where not satisfied with air quality.

This study conducted by Melikov was extremely rigorous in its method and analysis and could be used as a precedent in developing methods for future research in relation to UFAD systems and occupant response in a field setting. The only limitation to this study is that it was conducted in the summer months and did not address occupant responses for the winter conditioning period for cold climates.

2.3.3 Summary of Findings from Field Studies

Through the review of existing research, it was evident that few field studies of UFAD systems have been conducted and the research that is available has some limitations. The most noticeable limitation was that the studies focused on physical measurements and characteristics of the system that were not correlated with occupant responses. Another limitation was that the research methods were not rigourous enough. It can also be noted that the results related to occupant satisfaction varied, precluding definitive conclusions regarding the capacity of UFAD with respect to occupant satisfaction. There seems to be conflicting evidence that UFAD systems provide environments that are comfortable and satisfactory to occupants. Studies limited to Fanger's comfort equations all demonstrated acceptable thermal comfort conditions, while results varied for studies that consulted occupants in situ. Most studies found clear evidence that occupants were satisfied with thermal comfort; however the one study that was most rigorous in method found that a larger group of occupants were dissatisfied with the thermal comfort. On the other hand, IAQ results varied. Some studies confirmed satisfactory IAQ levels while others showed a large number of occupants being dissatisfied with the IAQ levels. In relation to draft and vertical temperature differences a couple of studies found issues with draft at leg level which confirmed the cold feet phenomenon.

The review of the literature showed that further research is required to flesh out occupant perception of UFAD systems. Use of Fanger's approach alone excludes a number of factors also a number of assumptions are often made when calculating clo and met values. A common limitation expressed throughout a number of the studies, was the lack of correlation between the physical environment measurements and occupant responses. Evaluating this correlation would provide a better understanding of the relationship between UFAD systems and occupant satisfaction.

2.4 CONCLUSION

Better energy performance proven through energy simulation and flexibility are two main benefits of UFAD. However, the small number of rigorous field studies involving building occupants has yet to confirm the benefits in terms of occupant comfort, satisfaction and control within the occupant work space (Bauman and Webster 2001; Im, Cho et al. 2005; Fisk, Faulkner et al. 2006; Huizenga, Abbaszadeh et al. 2006; Alajmi and El-Amer 2010). Much of the literature on UFAD systems equates comfort and occupant satisfaction with the level of control the occupant has over the system (Tsuzuki, Arens et al. 1999; CBE 2000b; Addison and Nall 2001; Daly 2002; Bauman 2003; Wyon 2006). Most research on occupant comfort was in lab settings or merely used the thermal comfort equation developed by Fanger to confirm conditions were within the acceptable thermal range. This research did not support that the UFAD systems provided comfortable temperatures or IAQ levels that are satisfactory to actual occupants. UFAD system will continue to prove their benefits, although there has been expressed concern around the lack of data available from occupied buildings with UFAD to accurately quantify the benefits of energy use, indoor environmental quality, occupant satisfaction, comfort, health and life cycle cost. A number of researchers in this field have expressed that field data correlated with occupants' response to their interior environment is essential to understand the relationship between UFAD systems and occupant comfort and control.

3. METHODS

3.1 OBJECTIVE, BUILDING DESCRIPTION AND OVERALL STRATEGY

The objective was to better understand occupant assessment of thermal comfort and control with UFAD systems in cold climates. The approach was to undertake a field survey of physical conditions and occupant perception in a selected building.

3.1.1 Description of the Case Study Building

The building used to conduct this case study was the City of Calgary Water Centre. This building is located on 25th Avenue S.E. and Spiller Road, Calgary, Alberta, Canada. The Water Center in Figure 3.1 is a 16,800 m^2 four storey building housing approximately 400 office employees and 400 field employees from the City of Calgary Water Resources and Water Services business unit. The building includes a number of water efficient, energy efficient, lighting and ventilation innovations which have helped the building achieve a LEED Gold designation from the Canadian Green Building Council for its energy efficient and environmentally sensitive design. Underfloor air distribution is one of these innovations. This type of ventilation is located throughout all of the office space and meeting rooms. Air speed and amount of ventilation is controllable by occupants by adjusting floor diffusers. Exterior windows are quadruple-glazed, providing an unusually high level of indoor-outdoor thermal separation. Other details of the buildings innovation and design considerations can be found in Appendix E.

Figure 3.1 City of Calgary Water Centre

The narrow building footprint is oriented along the east west axis (Figure 3.2). A typical floor includes a large atrium rising the height of the building on the south side of the building. A main corridor and meeting rooms are located along the south side overlooking the atrium, while cubicles are located on the north side, providing diffuse daylight. The ground floor includes main reception, meeting and training rooms along with a cafeteria. The second, third and fourth floors are all narrow open plan office space with meeting rooms scattered throughout. There is also underground parking below grade. Mechanical and electrical rooms are located in the penthouse.

At the request of the facility manager, the field study included only participants who worked on the third floor in order to limit disruption to that area.

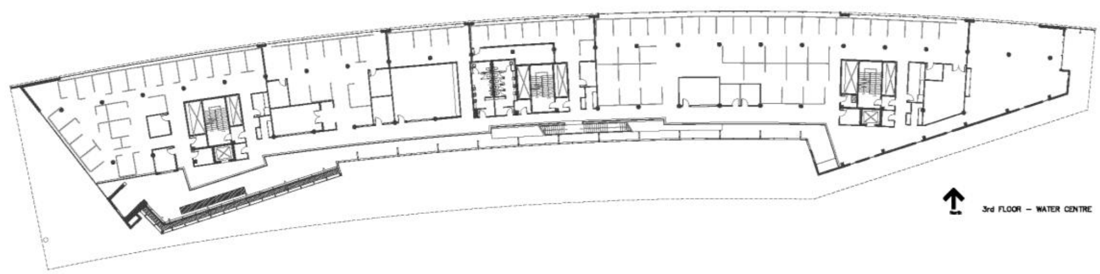

Figure 3.2 Water Centre Third Floor

3.1.2 Overall Strategy

The survey was conducted April 24th through 27th and May 3rd. The field study included both physical measurements and occupant questionnaires. The field measurements and occupant thermal comfort questionnaires followed the research methods used in ASHRAE RP-921 (Cena and deDear, 1998, 11-23) ASHRAE RP- 702 (de Dear et al 1993), ASHRAE PR-462 (Schiller et al 1988), ASHRAE RP-821 (Donnini et al 1998; Garcia 2011; Tian and Love (2008)

Figure 3.3 provides a research methods flow chart that was developed based on previous thermal comfort studies. The flow chart shows the data collected and the procedures for collecting and analyzing this data. (Cena and de Dear , 1998; Tian and Love, 2008; Garcia, 2011)

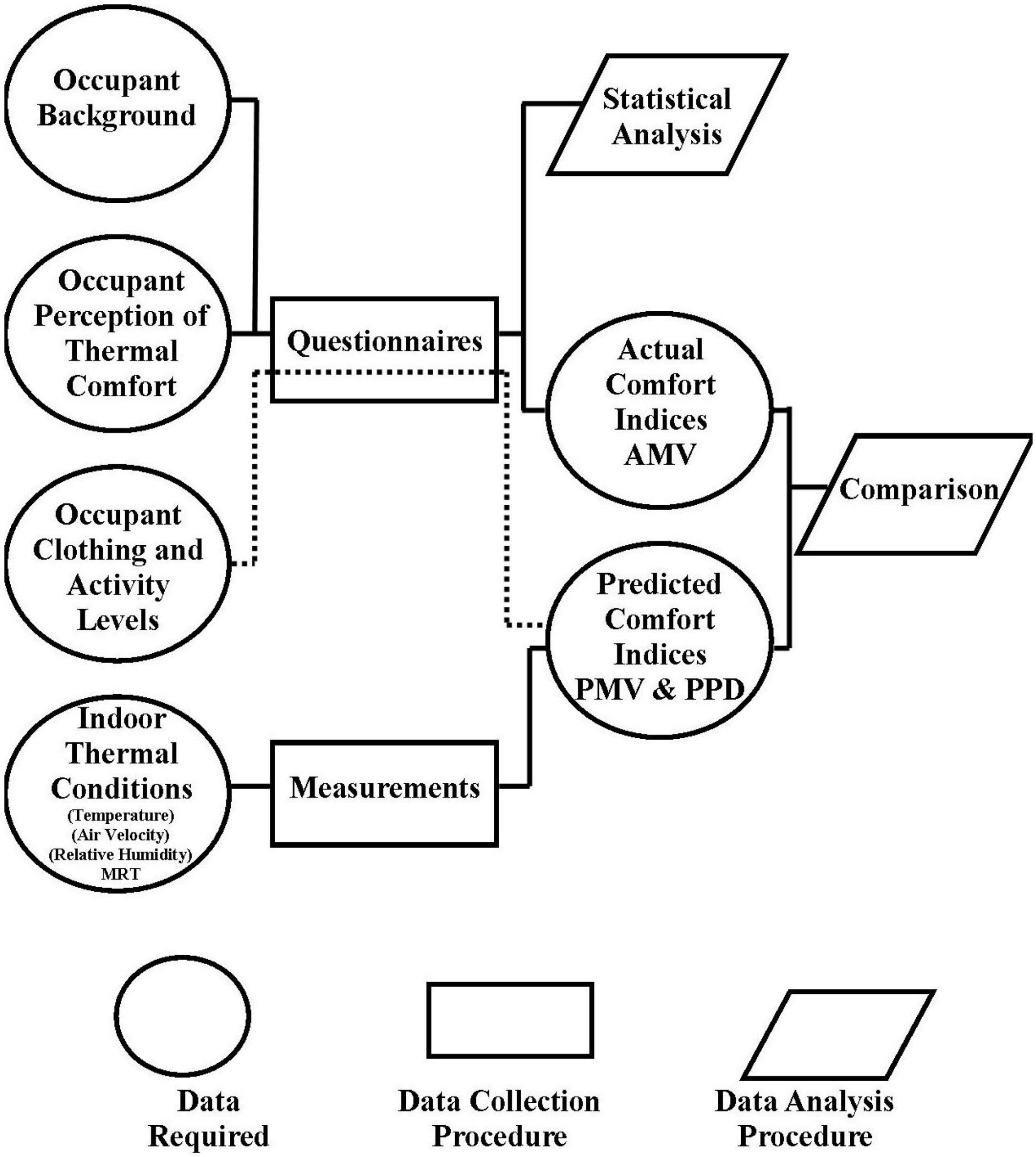

Figure 3.3 Research methods flow chart for thermal comfort assessment. (Garcia, 2011)

The data were analyzed in two ways to evaluate the thermal environment the UFAD system provides. First, indoor thermal comfort conditions were determined from measurements. These values were then used to calculate the predicted comfort indices including predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). Second, the actual mean vote (AMV) and actual percent dissatisfied (APD) were determined from the thermal comfort questionnaire responses. Both the actual and predicted comfort indices were compared against each other and with ASHRAE Standard 55 (2010:5). A number of statistical tests were used to generate data to determine if there were any significant differences between the thermal comfort indices derived from measurements and the results from the participant questionnaire responses.

3.2 PARTICIPANT THERMAL COMFORT ASSESSMENT

Participant satisfaction with the thermal environments was addressed through two surveys – a thermal comfort survey and a background survey. All occupants on the third floor of the Water Centre were potential participants with a target minimum sample size of 30 in order to account for inter- and intra-individual differences and ensure unbiased results (Kenkel, 1989:322). The thermal comfort questionnaire (Appendix B) included questions regarding thermal sensation, acceptability of thermal environment, thermal preference, satisfaction with air movement, general comfort, activities of previous hour, clothing values, and thermal comfort/discomfort of local body areas. The thermal comfort survey was administered while the participants were seated at their workstations. The background survey covered several general areas of inquiry ranging from demographic data to contextual and psychological factors identified based on the literature review. This survey was administered to participants at a location away from the workstation after they completed the thermal comfort survey.

3.2.1 Questionnaire Content

ASHRAE RP-921(Cena and De Dear 1998), ASHRAE RP- 702 (de Dear et al 1993), ASHRAE PR-462 (Schiller et al 1988), and ASHRAE RP-821 (Donnini et al 1998), which followed ASHRAE Standard 55- 1992 guidelines, were used to develop the research method and surveys. Some improvements were incorporated in the questionnaires to respond to recommendations from more recent thermal comfort studies (Tian and Love, 2008;1668, Garcia, 2011;38) Questions regarding ethnic background, English as primary language, education level and job satisfaction were eliminated as they add time to the questionnaire and past participants often found these questions too personal and failed to see the relevance of these types of questions to the objective of the research (Cena and De Dear 1998: 81; de Dear et al 1993: 89; Tian and Love, 2008: 1667). Refer to Appendix A for a detailed explanation of questionnaire modifications.

3.2.1.1 Thermal Comfort Questionnaire

The thermal comfort questionnaire used the ASHRAE 7-point continuous scale for thermal sensation and preference (cold = -3, cool= -2, slightly cool= -1, neutral = 0, slightly warm = +1, warm= +2, hot=+3). The key data to be collect from the questionnaire include participant responses regarding

- thermal sensation
- acceptability of thermal environment
- thermal preferences
- air movement preferences
- general comfort
- metabolic rate: determined based on the activities of the previous hour that is divided up into 4 time intervals (met rate to be determined using ASHRAE 55-2010 – Appendix A)
- clothing values (clo value to be determined using ASHRAE Standard 55- 2010 – Appendix B).
- thermal comfort/discomfort of local body areas

A copy of this questionnaire is included in Appendix B

Previous research (Garcia 2011; Tian and Love 2008) indicated that participants frequently make errors when recording their clothing levels. Therefore the clothing checklist was reviewed by the researcher to determine the magnitude and effect of these reporting errors. Two clothing checklists were included in this study: the participant's original checklist and the researcher's corrected checklist.

Thermal preference will be a key factor when analyzing data for participant thermal comfort, as previous research has indicated that thermal preference rather than thermal sensation is more relevant to defining comfort zones. Thermal sensation tends to be dependent on climatic context and clothing levels (Cena and de Dear 1998:70; Garcia 2011; 39).

As indicted in the literature, cold feet and draft discomfort has been a concern with UFAD systems. Therefore local discomfort and draft were another key factor when analyzing the data and determining UFADs performance in relation to occupant comfort.

3.2.1.2 Background Questionnaire

The information to collected through the background questionnaire included: demographic background, work area satisfaction, personal comfort, personal control of environment, environmental sensitivity and health. A copy of this questionnaire is included in Appendix C.

The literature indicated that personal control is a contributing factor in the perception of comfort and a number of other productivity and health benefits. Therefore personal control was a factor to be considered, along with participant adaptive behavior such as personal adjustment actions, use of environmental controls and thermoregulation. Past studies have indicated that adaptive behavior is important when one interprets questionnaire results.

3.2.2 Recruitment of Participants and Survey Procedure

The recruitment method was approved by the University of Calgary ethics committee.

1) Participants were contacted by an appointed City of Calgary representative who gave a brief overview of the research study and demands on the participants. Prospective participants were then asked if they would be involved in the study. Those participants who accepted scheduled a time that was most convenient for them to have the study conducted at their workstation. The location and preferred time for each workstation was given to the researchers.

2) The researcher approached the prospective participant, asked if the time was still convenient, and presented an ethics consent form (Appendix I). The researcher briefly described the nature of the study and what was required of the participant. The researcher then asked the participant to read over the consent form, and sign and date it if they consented. The researcher then signed and dated the consent form (two copies were made, one for the participant and one for the researcher)

3) The thermal comfort survey was then given to the participant to complete while seated at their workstation.

4) Once the thermal comfort questionnaire was completed, the participant was asked to complete the background survey at a location away from their workstation.

5) The measurement system was then placed at the position of the participant's office chair. The measurement system thermal sensors were allowed to stabilize for ten minutes. Then the workstation environmental conditions were measured for a minimum of three minutes.

6) During the survey and measurement period the researcher measured and recorded the surface temperature of six surfaces including floor, ceiling, and walls, using a handheld infrared thermometer.

7) While measurements were being made, the researcher also recorded observations (e.g. type of chair, location of diffusers, workstation layout and measurements, window location, shading devices, heat loads, occupant clothing)

8) While the background questionnaire was being completed, the thermal comfort questionnaire responses were reviewed by the researcher for completeness and for the accuracy of the clothing checklist with observed attire.

9) Once the background questionnaire was complete, the participant was asked to look over questions in the comfort questionnaire and comment on any discrepancies between observed and noted clothing.

10) The researcher thanked the participant for their time and involvement and offered a University of Calgary branded item as a token of appreciation.

11) The researcher collected the two questionnaires, removed the measuring system and proceeded to the next scheduled workstation (Cena and De Dear 1998; de Dear et al 1993; Schiller et al 1988; Donnini et al 1998; and Melikov et al 2005; Garcia 2011).

3.3 COMFORT PARAMETER ASSESSMENT

3.3.1 Indoor Environmental Measurements

The interior environmental conditions affecting thermal comfort sensation were measured (Fig. 4.1) to assess whether the conditions complied with ASHRAE Standard 55-2010. Air temperature, mean radiant temperature, relative humidity, and relative air velocity were measured using a protocol and instrumentation that were compliant with the requirements of ISO 7726:1998 and ASHRAE Standard 55-2010. The specifications of this instrumentation can be found in Appendix D

Measurements were made at individual workstations. Air temperature, air speed, and relative humidity measurements were measured at 0.1, 0.6 and 1.1 metres from the floor for workstations where occupants are sedentary. These heights simulate the relative location of the occupant foot, back and head levels and are compliant with ASHRAE Standard 55-2010 (p. 14).

Measurements were taken at the participant chair location after they had temporarily moved to another location to avoid affecting readings. Measurements were taken using a stand with sensors attached at the heights indicated above and black globe sensor located at 0.6 m. To simulate a chair while measurements were being taken, a foam piece attached to the stand was used to simulate the back of the chair and a stool was placed below the black globe and desk surface to simulate the seat of the chair.

3.3.2 Secondary Parameters and Calculation of Comfort Indices

Local discomfort can be caused by unwanted cooling or heating of a particular part of the body and can happen due to number of causes. Secondary parameters that affect localized discomfort including operative temperature, vertical air temperature difference, radiant temperature asymmetry, draught, and cold or warm floors were calculated from primary data.

Operative temperature (t_o) is the average between air temperature (t_a) and mean radiant temperature (t_r) as indicated in equation 3.1. only under four certain conditions outlined in ASHRAE 55 Appendix C. These temperatures were taken at 0.6m for seated occupants.

$$t_o = (t_a + t_r)/2 \qquad \textit{equation 3.1}$$

Vertical air temperature difference ($\Delta\ t_{a,v)}$ was calculated by determining the temperature difference between feet and head heights, 0.1 and 1.1m respectively. Once $\Delta\ t_{a,v}$ was calculated, the percentage of people dissatisfied with vertical air temperature difference was determined using Fig 2 (Local discomfort caused by vertical air temperature difference when $\Delta\ t_{a,v}$ is less than 8 ºC) ISO 7730-2005.

Radiant temperature asymmetry was determined by measuring the surface temperature of six surfaces including floor, walls, and ceiling in the participant's workstation at a height of 0.6 m for seated occupants and 1.1 for those who usually stand (ASHRAE, 2010:13). The metabolic rate was calculated using the responses from participants regarding the activities they had been engaged during the four intervals in the hour preceding completion of the thermal comfort questionnaire. The activities were then translated into metabolic rates based on ASHRAE standard 55 – 2010 Appendix A. and the median met rate for all four time intervals was calculated.

Comfort indices including predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) were calculated by using the computer code provided in ASHRAE Standard 55- 2010- Appendix D (the code was corrected based on errata published by ASHRAE).

The calculated thermal environment conditions measured during the field study were compared to the comfort zones defined in the ASHRAE 55- 2010 standard.

3.4 SUMMARY

This section provided the methods used during the field study of the City of Calgary Water Centre UFAD system performance in terms of occupant comfort and control.

4. RESULTS

4.1 GENERAL DISCRIPTION OF SURVEY

The thermal comfort field study involved both the administration of a thermal comfort questionnaire to 33 participants and the measurement of indoor environmental conditions at each participant's workstation. The study required five days of field measurements (April 24th through 27th, and May 3rd). The outdoor temperatures are shown for each study day in
Table *4.1*.

Table 4.1 Outdoor Temperature on Study Day (Environment Canada, 2012)

Field Study Date	Temperature (°C)											
	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	AVG
April 24	6.6	7.5	8.7	10.6	12.1	13.3	14.9	16.0	15.4	14.5	11.3	11.9
April 25	5.1	5.3	5.5	6.1	7.6	9.8	12.5	14.4	17.6	17.8	18.1	10.9
April 26	3.6	3.4	3.4	3.5	4.0	5.0	5.5	5.5	5.9	6.2	5.9	4.7
April 27	4.3	5.3	5.9	6.7	6.6	7.2	7.3	7.3	7.4	7.0	7.2	6.5
May 3	2.9	2.5	2.5	4.3	7.9	9.2	10.4	10.4	9.9	8.9	8.8	7.0

4.2 DESCRIPTION OF EQUIPMENT BUILDING SETUP AND BUILDING CONDITIONS

Appendix F provides the location and layout of each surveyed workstation. Most participants (20) were located at the north perimeter of the building. Five participants were located at the west perimeter. The remaining 8 participant workstations were located in the core of the open plan office. In the case of the west perimeter workstations, four were surveyed in the morning, so were free of any incident solar radiation; the survey of workstation 3 began at 1417 – this is daylight saving time and Calgary near the west end of the mountain time zone, so solar noon was around 1330 during the time of the survey. At this time the solar altitude is about 50^{o}. Given that the building has a large overhang (Figure 3.1) and workstation near the north side of the 3rd floor, the window would have been shaded. Figure 4.1 shows the thermal comfort station and its typical measurement location at each workstation.

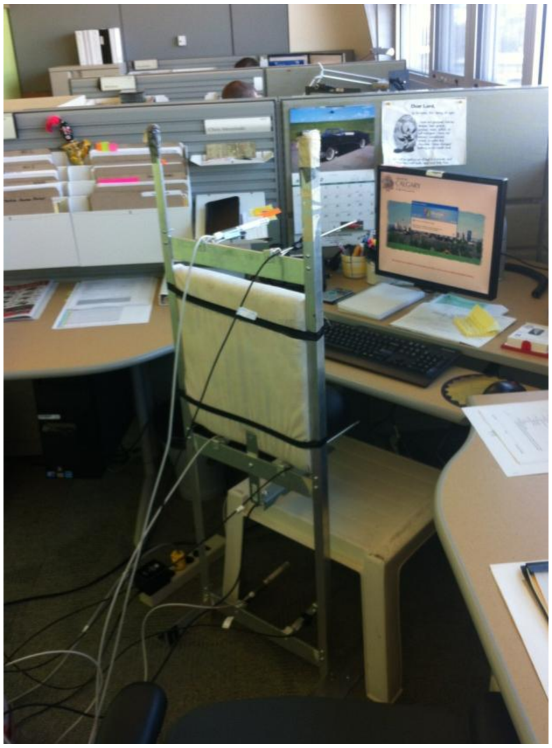

Figure 4.1 Thermal comfort station used for study

4.3 INDOOR ENVIRONMENTAL CONDITIONS

4.3.1 Indoor Air Temperature and MRT

Temperatures at all levels of the evaluated workstations were very similar during the measurements. The median indoor air temperature was 23.1 ± 0.5 ^{o}C for all tests and heights measured. The minimum indoor air temperature measured was 21.7 ^{o}C (0.1m) while the maximum air temperature measured was 24.8 ^{o}C (0.1 m). The median outdoor temperature was 7.3 ± 3 ^{o}C and ranged from 3.4 ^{o}C to 17.6 ^{o}C. The conditions outlined in ASHRAE 55 Appendix C were all met; it can be assumed that the operative temperature is equal to the air temperature. These air temperatures are within range of ASHRAE 55 for acceptable operative temperatures. The median difference between temperature and MRT for each workstation was 0.1 ^{o}C, which is within the instrument error. The median operative temperature was 23.1 ± 0.5 ^{o}C with the maximum value calculated from measured air temperature and mean radiant temperature being 24.2 ^{o}C and a minimum of 22.2 ^{o}C.

Figure 4.2 shows the temperatures at the three measurement heights and along with the MRT at each workstation.

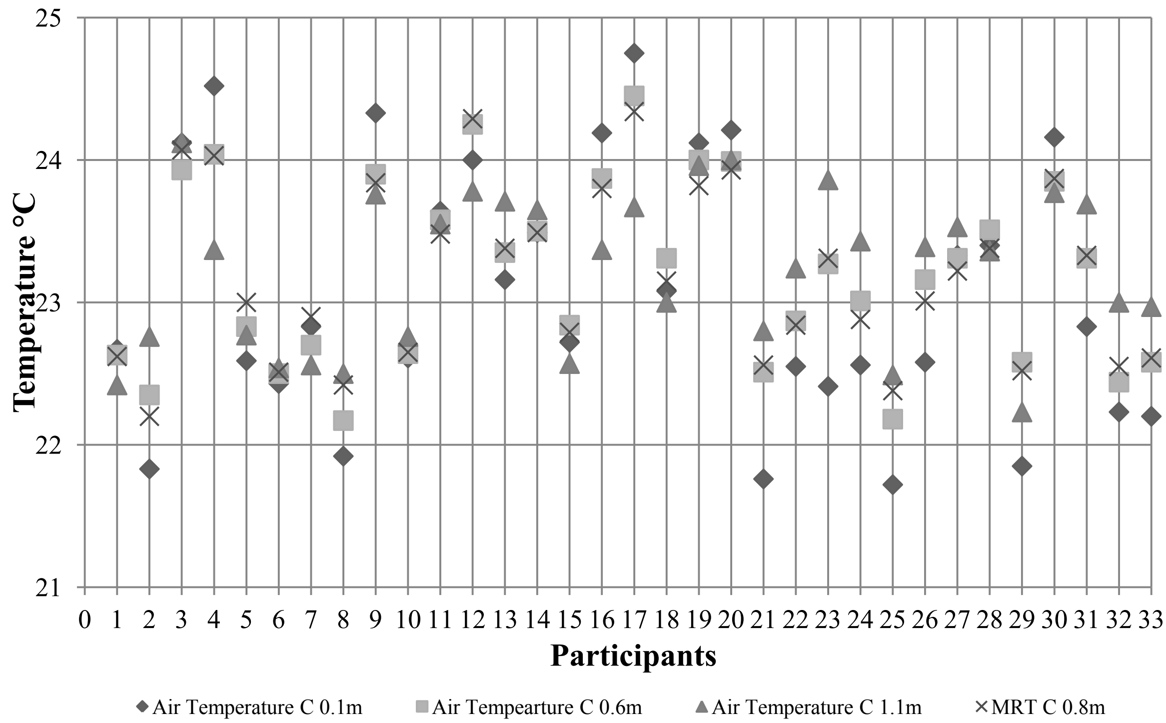

Figure 4.2 Air temperature at three sensor heights and mean radiant temperature for 33 participants.

The median vertical head-foot air temperature difference of 0.1 ± 0.3 ^{o}C was uniformly mixed and well below ASHRAE 55 limit of 3 ^{o}C. The temperature difference between head and foot level ranged from a maximum of 1.5 ^{o}C to a minimum of 0.0 ^{o}C.

4.3.1.1 Temperature by Participant Location

The temperature at workstations which are adjacent to each other are compared in Figure 4.3

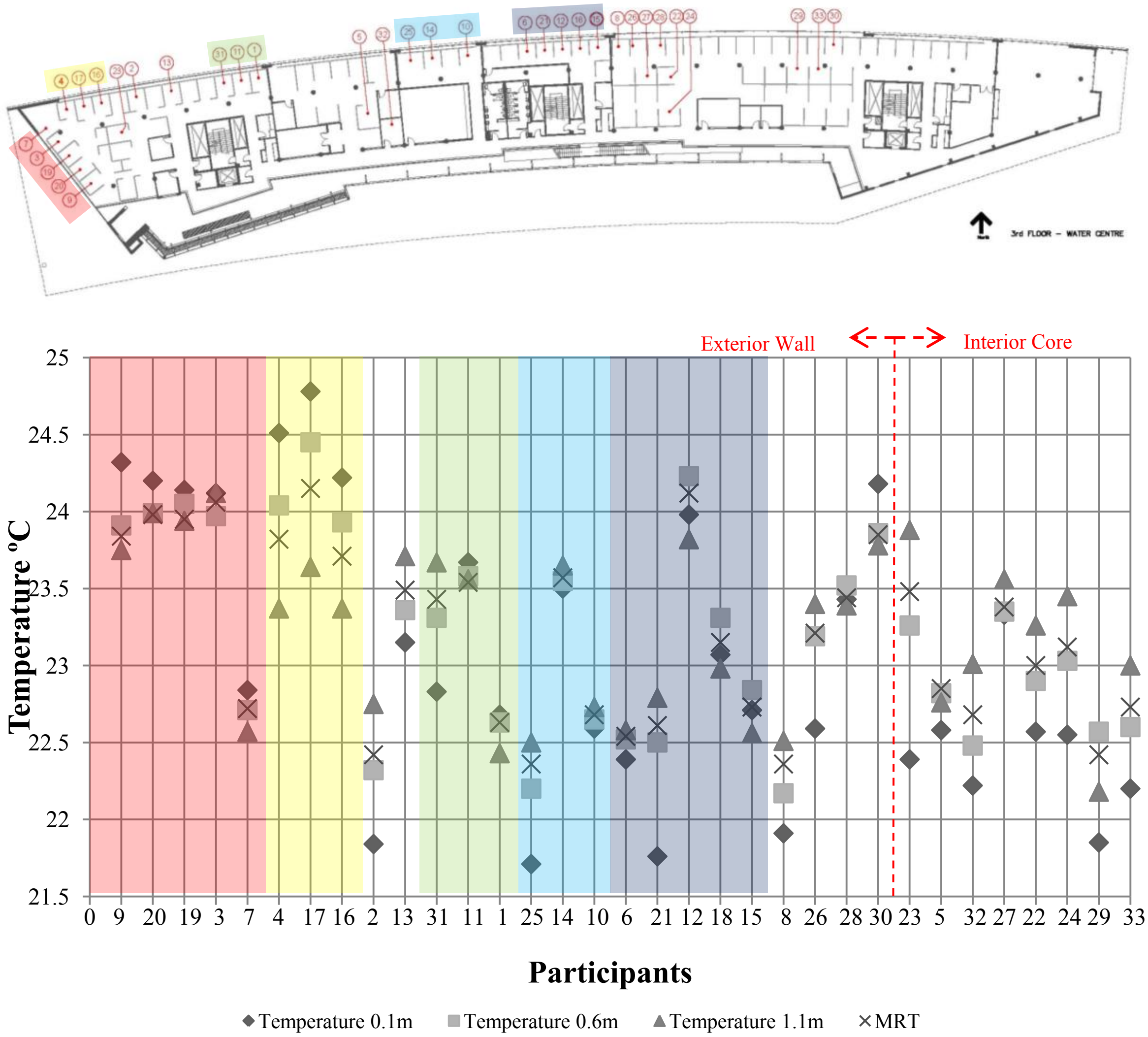

Figure 4.3 Temperature at Three heights and MRT arranged by adjacent workstations

4.3.2 Air Velocity

The median air velocity for all measured points was 0.05 ± 0.02 m/s. The maximum air velocity measured was 0.13 m/s while the minimum was 0.00 m/s. Figure 4.4 shows that most participants experienced higher air velocity at head than foot level. There were only 4 workstations with higher air velocity at foot level. The median air velocities at foot (0.1 m) and head (1.1 m) height were 0.03 m/s and 0.06 m/s respectively. The maximum air velocity difference between foot and head height was 0.08 m/s. The median air velocity difference was 0.04 m/s between these heights.

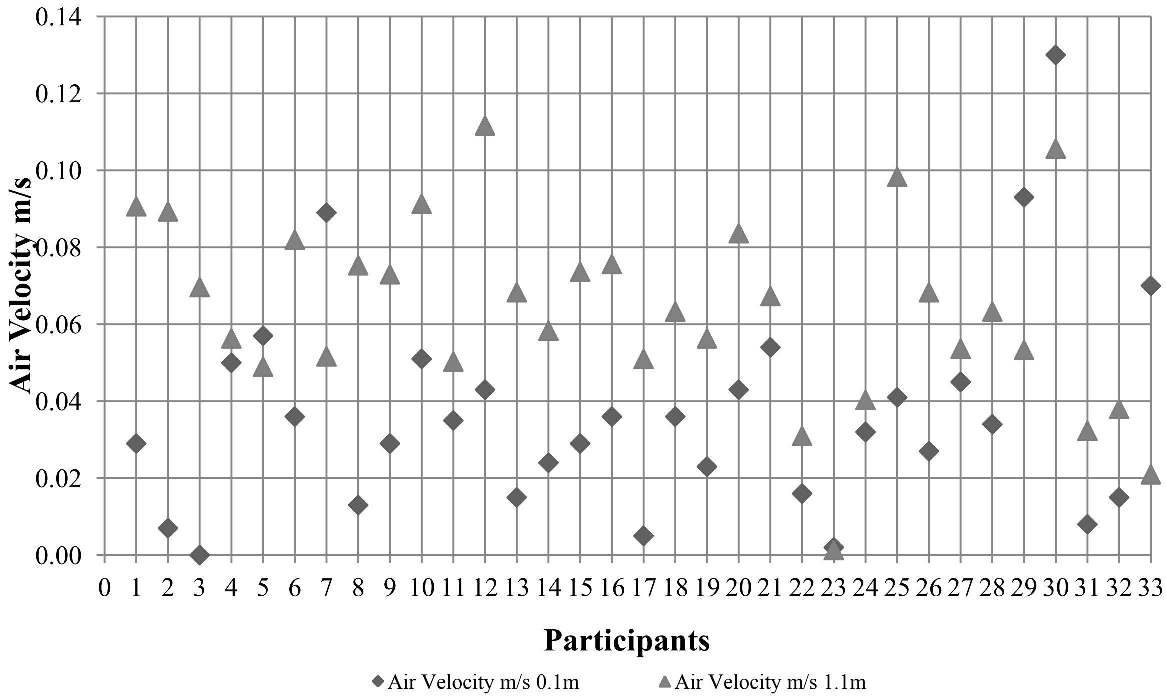

Figure 4.4 Air Velocity at foot (0.1m) and head (1.1m) heights

4.3.3 Relative Humidity

Relative humidity ranged from 25.3% to 35.1% with a median of 31 ± 1.6 % overall. Figure 4.5 shows that the variation in relative humidity with height was small for a given workstation.

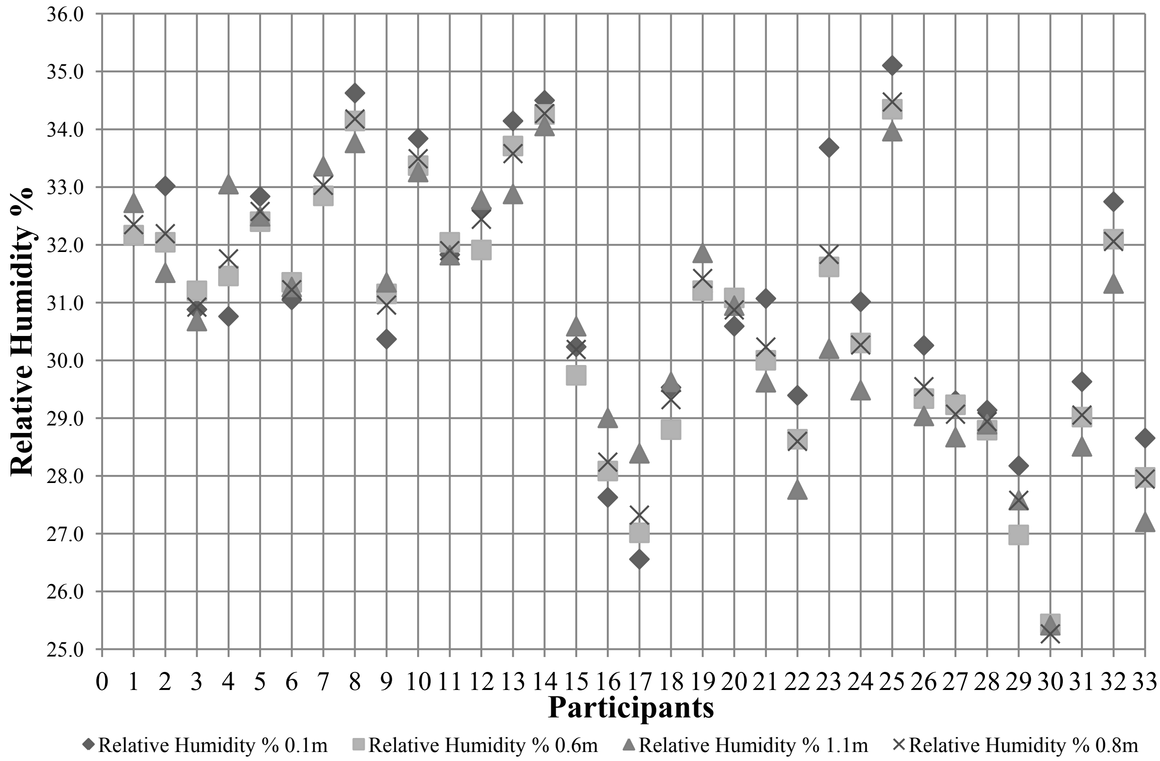

Figure 4.5 Relative Humidity at 3 sensor heights.

4.3.4 Operative Temperature

Operative temperature was calculated for each workstation by taking the mean of the median air temperature from all three measurement heights and the MRT. The operative temperature ranged from 22.2 ^{o}C to 24.2 ^{o}C with a median of 23.1 ± 0.5 ^{o}C. Figure 4.6 shows the very small variation between indoor air temperature, MRT and operative temperature.

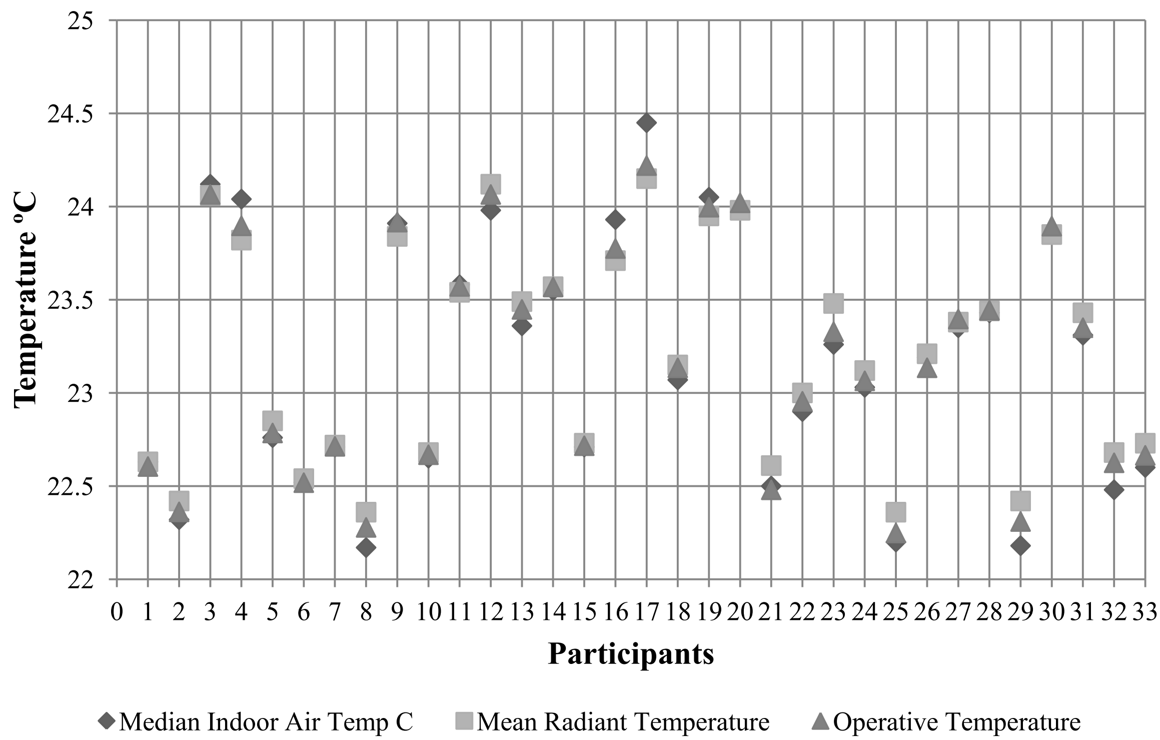

Figure 4.6 Median Temperature, MRT, and Operative Temperature

4.3.5 Summary of Indoor Environmental Conditions

Table 4.2 Summary of descriptive statistics for the measured indoor environmental conditions.

		0.10m	0.60m	1.10m
Air Temperature °C	Median	22.8	23.3	23.4
	Median Abs Dev	0.8	0.6	0.5
	Max	24.8	24.5	24.1
	Min	21.7	22.2	22.2

MRT °C	Median	23.2
	Median Abs Dev	0.5
	Max	24.2
	Min	22.4

Operative Temperature °C	Median	23.1
	Median Abs Dev	0.5
	Max	24.2
	Min	22.2

Relative Humidity %	Median	31.0
	Median Abs Dev	1.6
	Max	35.1
	Min	24.9

		0.10m	0.60m	1.10m
Air Velocity m/s	Median	0.03	-	0.06
	Median Abs Dev	0.02	-	0.02
	Max	0.13	-	0.11
	Min	0.00	-	0.00

4.4 SUBJECTIVE ASSESSMENT OF INDOOR ENVIRONMENT

4.4.1 Description of Respondents

The thermal comfort survey was completed by 33 participants. The median age was 47 ± 6 years, with a range of 25 to 55 years. The majority of participants had lived in a cold climate for longer than one year, with many of them living in Calgary for a large portion of their lives. There were only three participants who have lived in Calgary for less than 1 year they were participant 17, 18, and 25 and have lived in Calgary for 8 months, 5 months, and 6 months respectively. Of the 33 participants 36% of them were male and the remaining 64% were female (Table 4.3 and Figure 4.7).

Table 4.3 Summary of descriptive statistics for demographic data

Gender	Male	Female
	12 (36%)	21 (64%)

Age yrs	Median	47
	Median Abs Dev	6
	Max	55
	Min	25

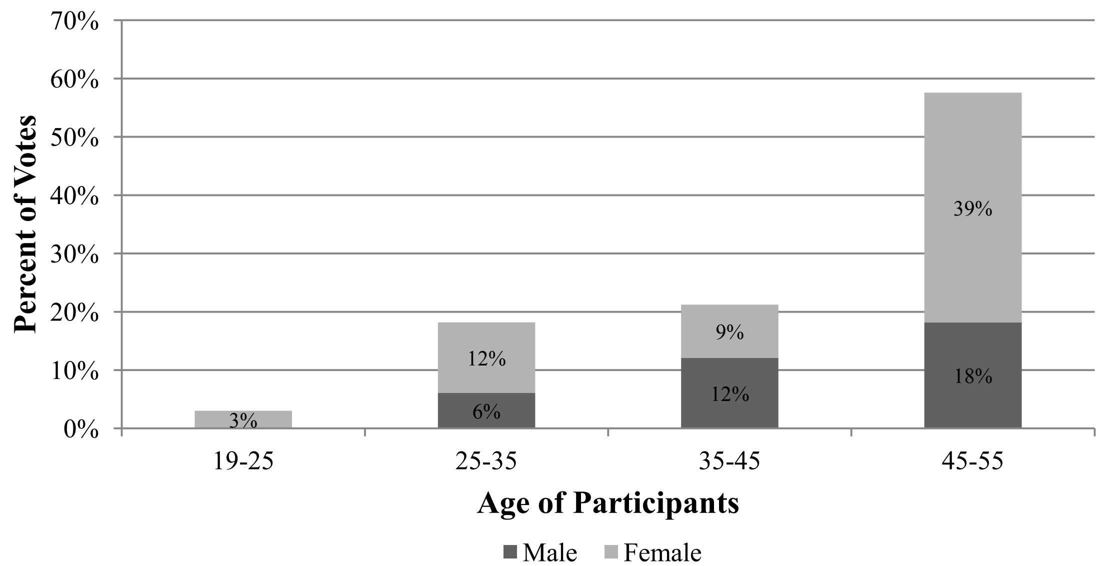

Figure 4.7 Distribution of Age by Gender

4.4.2 Thermal Sensation, Air Movement, General Comfort and Local Discomfort.

The median actual mean vote was -0.5 ± 0.5. The range of votes was -2.0 to 2.0. The AMV was slightly lower than the calculated PMV (the three participants who had been in Calgary voted 0.5, 0 and 0 with corresponding PMV of 0, -.5 and -.4).

Figure 4.8 shows the distribution of thermal sensation votes for question # 6 on the thermal comfort questionnaire. The response to the 7-point scale thermal sensation question showed that 39% of occupants felt slightly cool. However 91% of the participants had voted within the three central categories of sensations (slightly cool, neutral, slightly warm). Considering all participants 54% voted cooler than neutral sensation, 27 % voted warmer than neutral and 18% voted neutral (Figure 4.9).

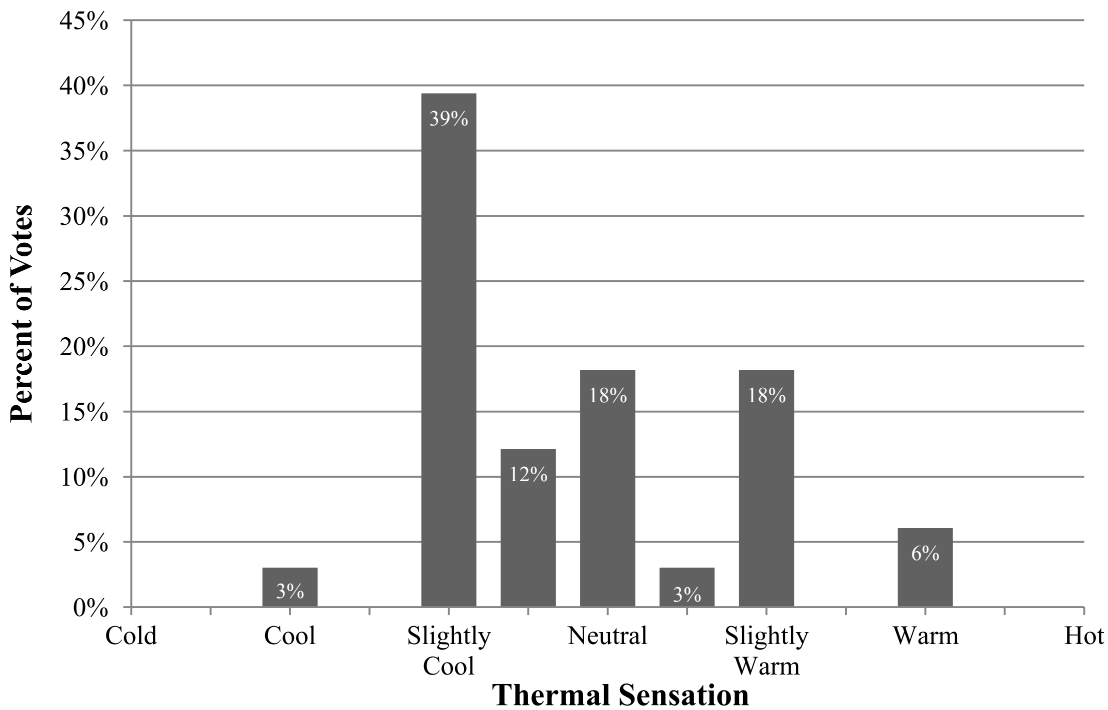

Figure 4.8 Thermal Sensation Response

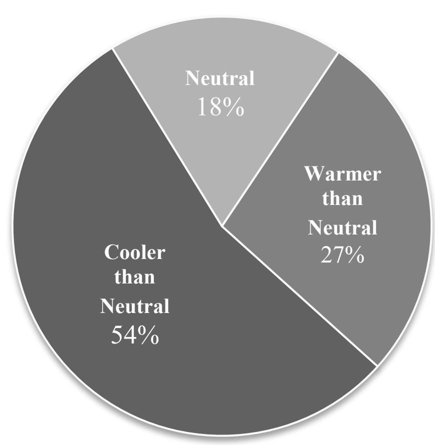

Figure 4.9 Distribution of Thermal Sensation

4.4.3 Air Movement

The air movement within the office was voted within the comfortable range by 75% of the participants while only 25% of participants indicated the air movement to be uncomfortable. Figure 4.10 shows the results of participant satisfaction with air movement. 38% participants stated that they were moderately comfortable and 28% considered the air movement to be very comfortable. When participants were asked what they would prefer in terms of air movement. 31% of the participants would prefer more air movement, 58% no change and 10% less air movement (Figure 4.11)

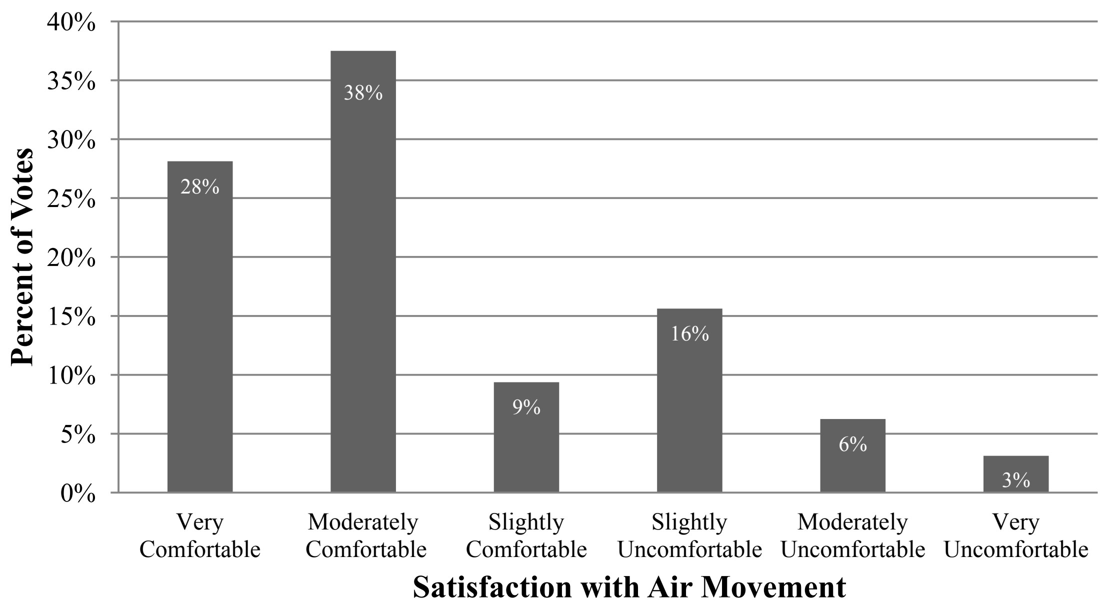

Figure 4.10 Satisfaction with Air Movement

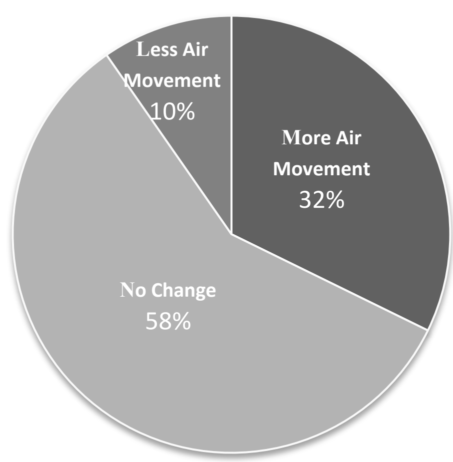

Figure 4.11 Air Movement Preference

4.4.4 General Comfort

In terms of general comfort 94% of participants agreed that the thermal environment was acceptable while only 6% stated that the thermal environment was unacceptable. Only 11% of participants felt uncomfortable; none stated they were very uncomfortable. Of the remaining 89% of participants who felt comfortable, 52% were moderately comfortable, 9% were slightly comfortable and 27% felt very comfortable (Figure 4.12).

Although 94% of participants stated that the thermal environment was acceptable when asked if they would like to be warmer, cooler or prefer no change, only 55% responded that they would prefer no change in the thermal environment; 30% stated they would like to be warmer and 15% stated that they would like to be cooler. Of the 30% of participants who wished to be warmer, 80% of them were women; the other votes are closer to evenly divided between women and men (Figure 4.13).

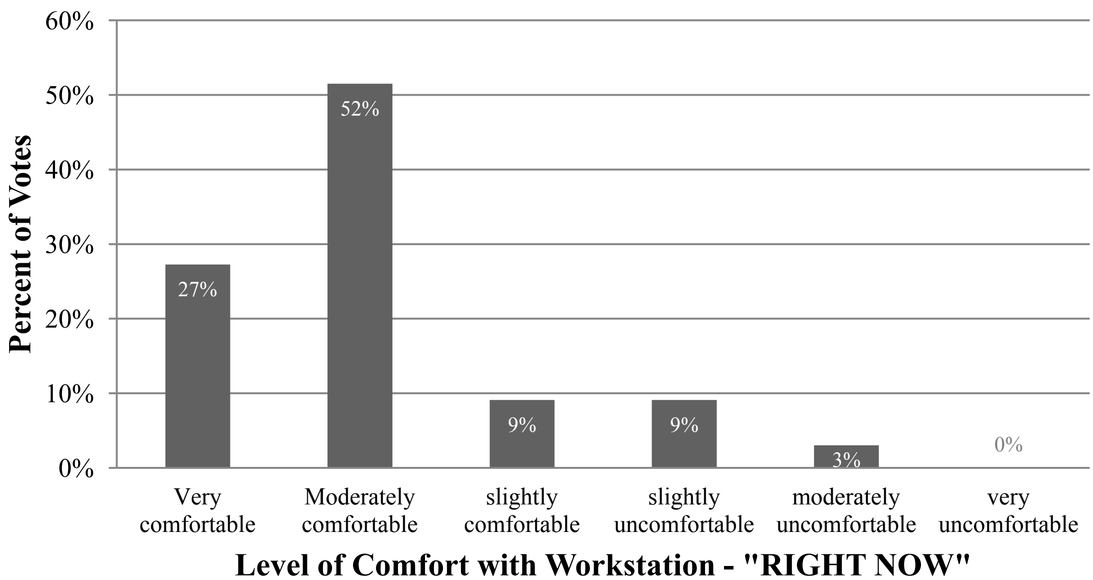

Figure 4.12 General Comfort

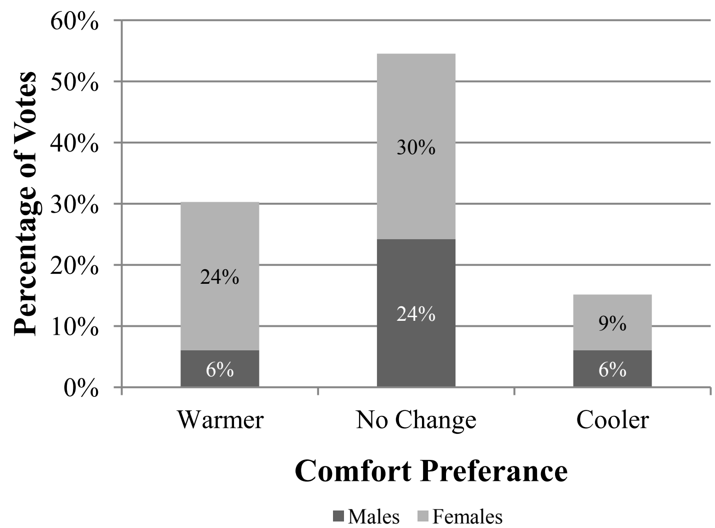

Figure 4.13 Thermal Comfort Preference

Table 4.4 Summary of descriptive statistics for actual responses

		Sample size 33
AMV (ASHRAE 7-point scale)	Median	-0.5
	Median Abs Dev	0.50
	Max	2.0
	Min	-2.0
Air Movement Acceptability (1= very uncomfortable 6= very comfortable)	Median	2.0
	Median Abs Dev	1
	Max	6.0
	Min	1.0
General Comfort (1= very uncomfortable 6= very comfortable)	Median	2.0
	Median Abs Dev	0
	Max	5.0
	Min	1.0

When participant temperature estimates were compared to actual average temperatures measured at participant work stations, on average, participants underestimated their workstation temperature by 2.6 ^{o}C

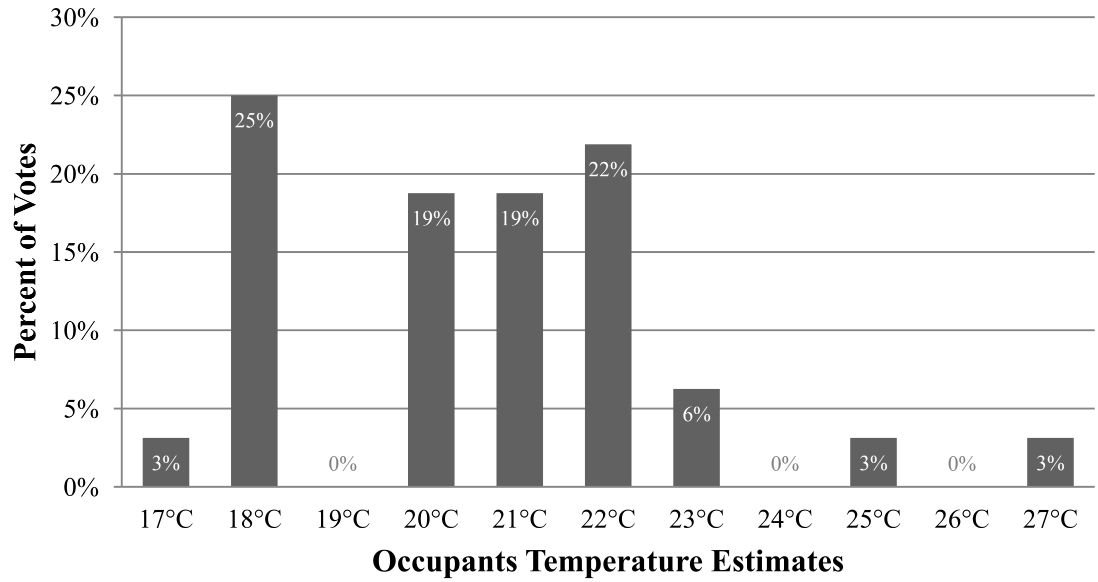

Figure 4.14 Participant Estimated Temperature

Table 4.5 Summary of estimated versus actual temperature

Estimated Temperature	**Percentage of Votes**	**Average Approx difference between estimated temperature and actual temperature**
17°C to 19°C	28%	5.0 °C underestimated
20°C to 22°C	60%	2.0 °C underestimated
23°C +	12%	-0.9 °C over estimated
All participants		2.6 °C underestimated

Table 4.6 shows the perceived temperature and the actual temperature, MRT, and OT measured for each participant who stated that their workstation was acceptable and there was no change needed (n=18).

Table 4.6 Thermal Sensation Versus Sensible Temperature, MRT, and OT

Participants wanting no change and felt environment was acceptable	Gender	Thermal Sensation	Temperature (°C)	MRT (°C)	OT (°C)
4	Female	Neutral	24.0	23.8	23.9
5	Female	Neutral	22.7	22.9	22.8
7	Male	Neutral	22.7	22.7	22.7
8	Female	Warm	22.2	22.4	22.3
10	Male	Slightly cool	22.7	22.7	22.7
12	Male	Neutral/slightly warm	24.0	24.1	24.1
13	Female	Slightly warm	23.4	23.5	23.4
15	Male	Neutral	22.7	22.7	22.7
17	Female	Slightly cool	24.3	24.2	24.2
18	Male	Neutral/slightly cool	23.1	23.2	23.1
22	Female	Neutral	22.9	23.0	23.0
24	Female	Neutral/slightly cool	23.0	23.1	23.1
25	Male	Neutral/slightly cool	22.1	22.4	22.2
26	Female	Slightly warm	23.1	23.2	23.1
27	Female	Neutral	23.4	23.4	23.4
28	Male	Slightly warm	23.4	23.4	23.4
30	Female	Slightly warm	23.9	23.9	23.9
31	Male	Slightly cool	23.3	23.4	23.4

Based on the above results, thermal acceptability was in the range of 22.1 °C to 24.3 °C for temperature, 22.4 °C and 24.2 °C for MRT and 22.2 °C and 24.2 °C for OT. The median Temperature, MRT, and OT for participants satisfied with their thermal environment were 23.1 °C, 23.2 °C and 23.1°C respectively.

4.4.5 Local Discomfort

When participants were asked about local thermal discomfort, regions of the body that experienced the most discomfort were the head, arms and hands, and feet and legs. 36% of participants reported their head to be warmer than the rest of their body of these participants four of them (12, 13, 19, and 28) indicated that their feet and legs and arms and hands were also warmer than the rest of the body. 42% of participants reported that their arms and hands were cooler than the rest of their body with only one participant experiencing all part of the body being cool. Thirty-nine percent of participants reported their feet and legs to be cooler than the rest of their body, of these 39%, seven participants (6, 11, 18, 20, 21, 23, and 33) experienced their hands and arms being cooler than the rest of their body as well. The participants who expressed one part of their body to be either cooler or warmer than the rest, there were a total of six participants (11, 15, 21, 23, 29 and 33) who reported that their feet and legs to be cold and their head to be warm.

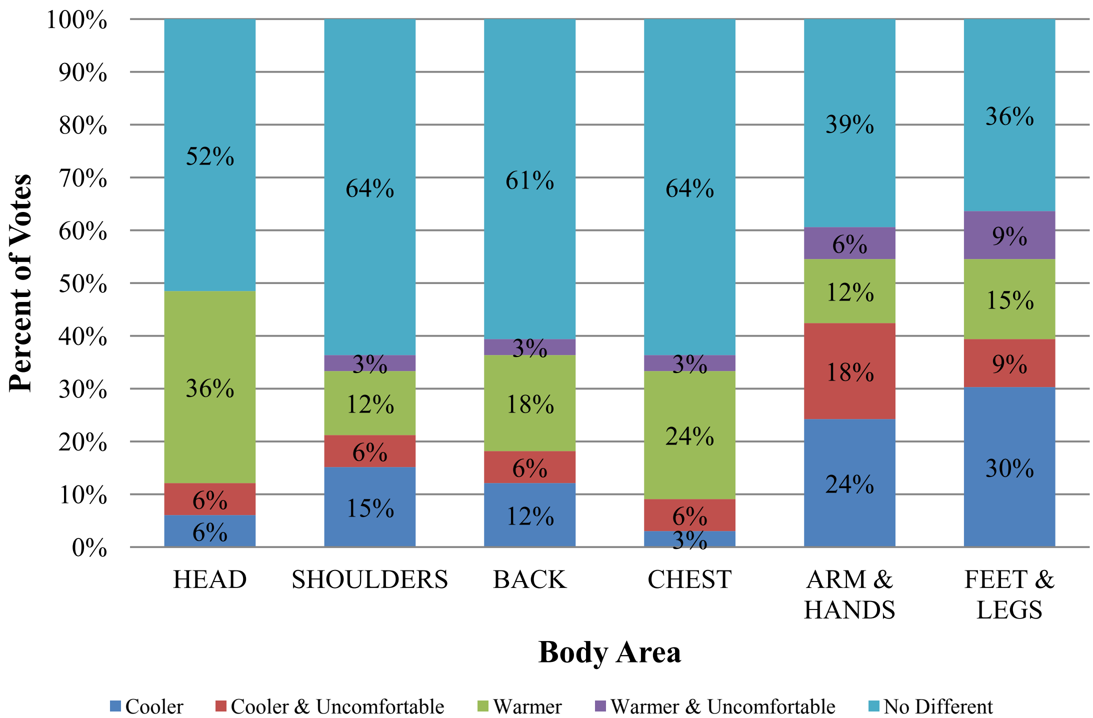

Figure 4.15 Local Discomfort

Figure 4.16shows the temperatures at the workstations of the five participants who voted certain body parts to be either cooler or warmer. The temperatures were measured at three standard heights representing conditions for different areas of the body while seating. The main concern investigated was the difference between the feet being cold and the head being warm. Only at workstations 21 and 23 was the measurements significantly different between the temperature at the feet (0.1 m) being ±1 °C cooler than the head (1.1 m). However these temperature differences were within the 3 ^{o}C limit stated in ASHRAE Standard 55.

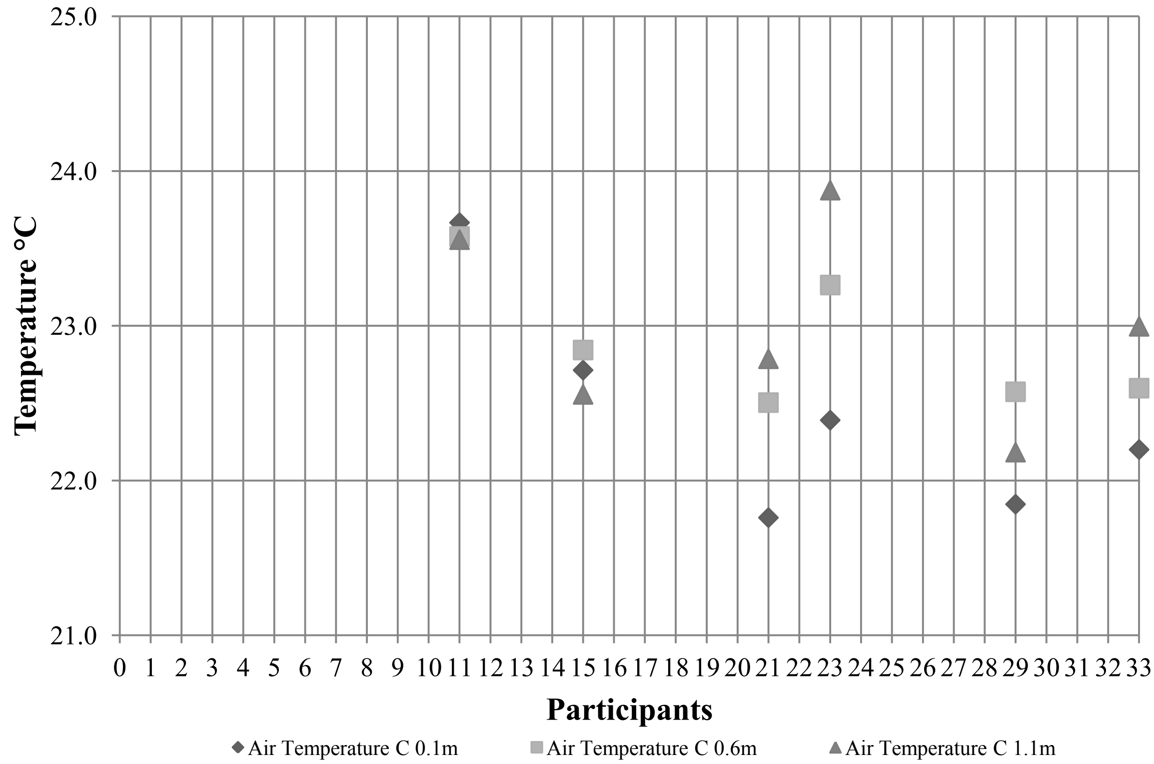

Figure 4.16 Air Temperature for participants who voted certain body parts cooler and warmer.

13 participants voted that their feet were cooler than the rest of their body. However, the temperatures measured at feet level (0.1m) were within the acceptable range (Figure 4.17).

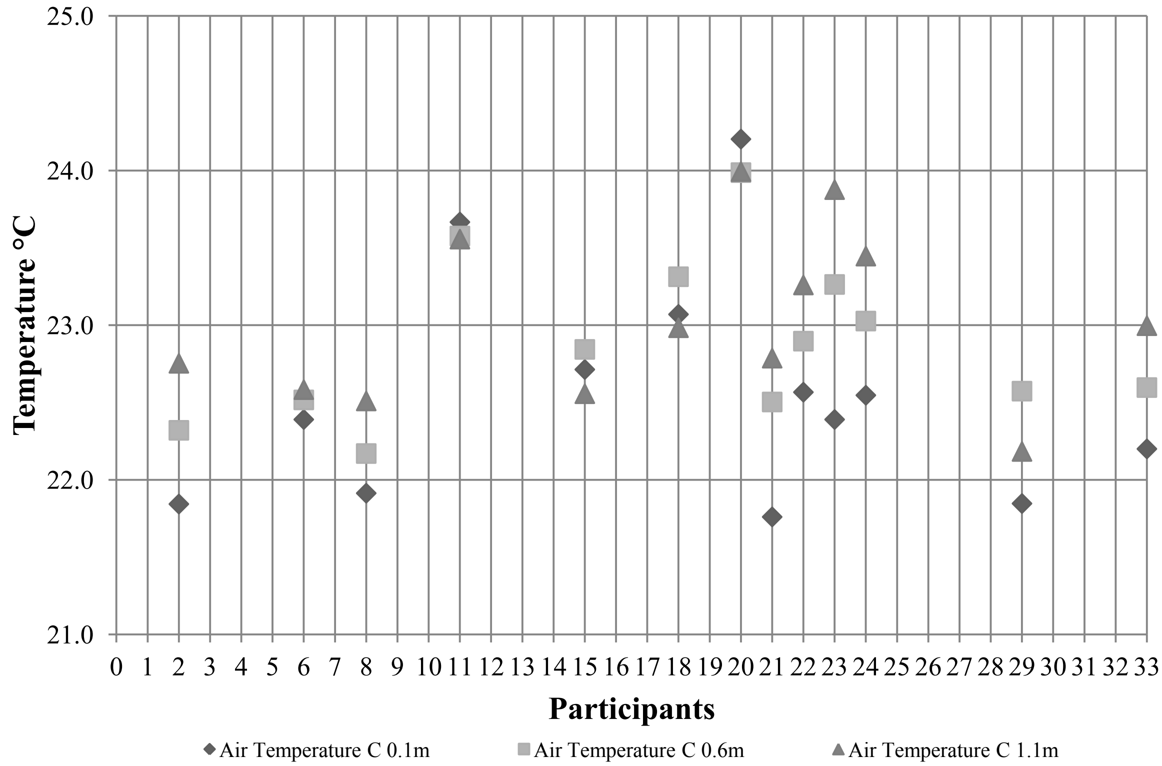

Figure 4.17 Participants who voted their feet cooler than the rest of their body

Twelve participants reported their heads to be warmer. The temperatures around these participants head height (1.1m) were all above 22 ^{o}C. Nine participants head height temperatures were above 23^{o}C. (Figure 18)

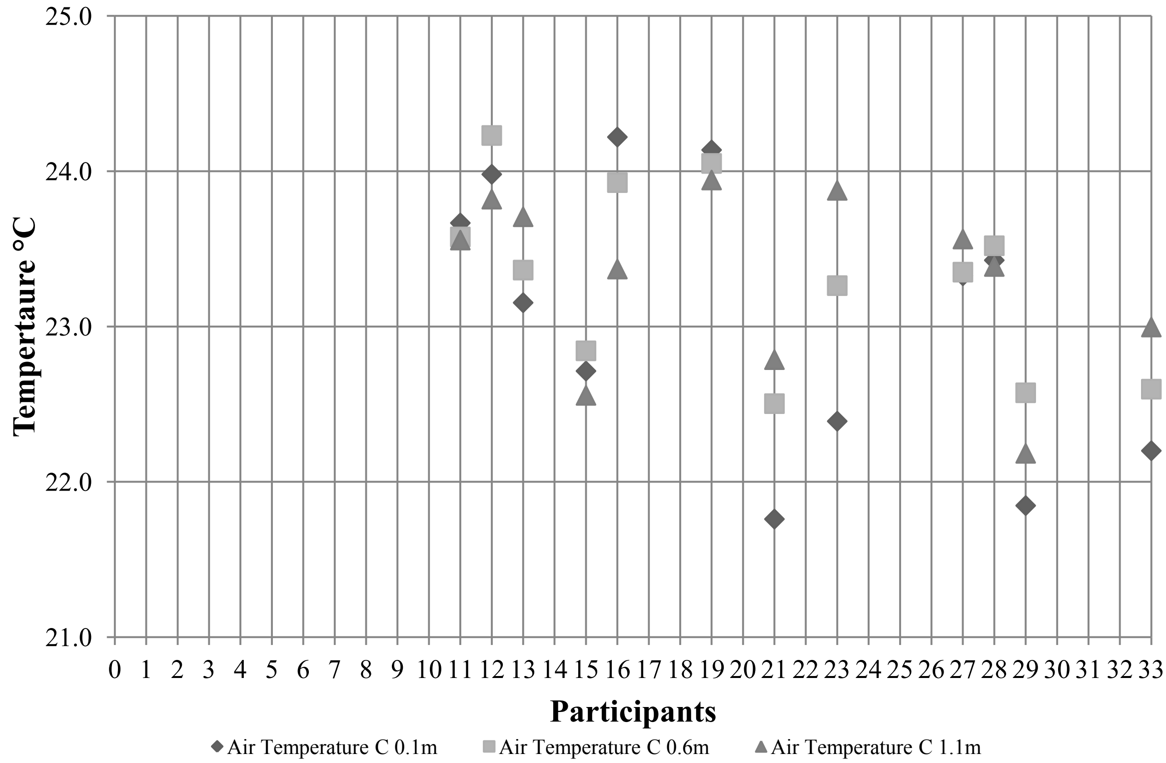

Figure 4.18 Temperature at workstations of participants who had warm heads

The cool feet phenomenon will require more investigation from researchers as the temperatures measured are within acceptable range.

4.5 CLOTHING INSULATION AND METABOLIC RATES

All participants indicated that they were satisfied with the amount of clothing they were wearing. Clothing insulation levels were taken from ASHRAE 55 Appendix B . One difficulty in calculating clo values was that the survey used different wording than the ASHRAE standard to describe the thickness of clothing. To overcome these issues appropriate clo values were assigned to each clothing category presented to participants. These values were arrived at by interpolating values defined in ASHRAE Standard 55 so there were set values for all three categories defined in the survey: light/medium/heavy. These values can be found in Appendix G**.** To account for the clothing insulation factor of the standard office chair, 0.1 was added to the reported participant clothing value, this is in accordance with Standard 55 Table B3 (ASHRAE 2010:12).

The minimum and maximum calculated clothing values were 0.49 clo and 1.1 clo. The median clothing value was 0.69 ± 0.11 clo. Since the field study was conducted in April in Calgary, a transitional season between cold and warmer seasons, the median clo value makes sense for this period. The median clo value was 0.7 ± 0.1 clo for women and 0.67 ±0.1 clo for men.

Table 4.7 Clo Values

Corrected clothing Insulation (clo)	Male (sample 12)	Female (sample 21)	Sample size 33
Median	0.67	0.76	0.69
Median Abs Dev	0.1	0.1	0.11
Max	1.1	0.99	1.1
Min	0.49	0.5	0.49

Metabolic rate was calculated based on the activities participants reported for the 60 minutes before completing the thermal comfort questionnaire. Four intervals were addressed in the questionnaire: 10 minutes prior to survey, 10 prior to that, 10 minutes prior to the last 10 minutes, and 30 minutes prior to starting the survey. The metabolic rate used for each specific task can be found in Appendix G.

The median metabolic rate for the surveyed participants was 1.15 ± 0.05. The median metabolic rate for male and female participants was 1.14 and 1.17 respectively.

4.6 CALCULATED COMFORT INDICES (PMV-PPD)

Predicted mean vote (PMV) was used to calculate the thermal sensation for the group of participants involved in the field study. The PMV was compared with the actual mean vote (AMV) to evaluate PMV prediction of thermal sensation. The percent of people dissatisfied (PPD) was calculated and compared to the actual percent of people dissatisfied (APD), which was calculated from the survey results.

A program was used to calculate PMV and PPD. This program was developed based on standards ISO 7730 (1994) and ASHRAE 55 (ASHRAE 2012:23). The six input values that affect comfort sensation were the independent variables: temperature, relative humidity, air velocity, mean radiant temperature, clo values and metabolic rate. The values used for air velocity and air temperature were the medians for the three heights (1.1 m, 0.6 m, 0.1 m) where these values were measured.

Table 4.8 shows the statistical summary of PMV and PPD results. The median value for PMV was 0.06 ± 0.38. This shows a thermal sensation which is relatively neutral for most of the occupants and within an acceptable comfort range of -0.5>PMV>0.5.

Table 4.8 Summary of descriptive statistics for PMV and PPD

		Sample size 33
PMV	Median	0.06
	Median Abs Dev	0.38
	Max	0.46
	Min	0.86
PPD	Median	7.64
	Median Abs Dev	2.04
	Max	20.20
	Min	2.04

4.7 SECONDARY COMFORT INDICES

4.7.1 Draft

The PPD due to draft was calculated with the ASHRAE Comfort Standard 55 formula using air temperature (t_a in ^oC), air speed (v in m/a) and turbulence intensity (T_u %). Since turbulence intensity was unknown 40% was used as directed in ISO 7730.

$$DR = ([34 - t_a] * [v - 0.05]^{0.62}) * (0.37 * v * T_u + 3.14)$$

At foot level the median DR was 0.0 ± 0.0%, with a maximum DR was 6.5%, which was found for participant 30. This cubicle had an air temperature of 24.18^oC and an air velocity of 0.13m/s. The maximum DR at 1.1 head level was 1.9 ± 1.94%, with a maximum of 5.8%. At both levels foot and head the DR was within the acceptable range of <20% set by ASHRAE 55.

Table 4.9 Summary of descriptive statistics for draft

		Sample size 33
Draft Foot Level 0.1m	Median	0.0
	Median Abs Dev	0.0
	Max	6.5
	Min	0.0
Draft Head Level 1.1m	Median	1.9
	Median Abs Dev	1.9
	Max	5.8
	Min	0.0

4.7.2 Vertical Air Temperature Difference

The median vertical air temperature difference between head and foot levels was 0.4 ± 0.3 ^{o}C. The maximum temperature difference was 1.5 ^{o}C. No participants reported uncomfortable temperature differences. Therefore the PPD for vertical temperature difference was below the 2% limit in ASHRAE 55.

Table 4.10 Summary of descriptive statistics for vertical air temperature difference

		Sample size 33
Vertical Air Temp Difference 0.1-1.1m	Median	0.4
	Median Abs Dev	0.3
	Max	1.5
	Min	0.0

4.7.3 Floor Surface Temperature

An infrared handheld thermometer was used to measure the surface temperature randomly selected spots of each workstations floor. The maximum temperature measured was 26.7^{o}*C* and the minimum 21.2^{o}C. The median floor temperature for all 33 participants was 23.3 ± 1.2 ^{o}C. This range of temperatures was within the allowable range set by ASHRAE 55 (19-29^{o}C).

Table 4.11 Summary of descriptive statistics for floor surface temperature

		Sample size 33
Floor Temperature ^{o}C	Median	23.3
	Median Abs Dev	1.2
	Max	26.7
	Min	21.2

4.7.4 Radiant Temperature Asymmetry

Radiant temperature asymmetry was measured by measuring the temperature of the cubicle walls, and exterior walls where applicable. In some cubicles, there were only three partitions/walls due to adjacent corridors. The median temperature difference between the measured walls was 1.4 ± 0.7 ^{o}C and 0.8 ± 0.7^{o}C between walls and floors. The maximum difference between walls was 3.2^{o}C and 4.0^{o}C between walls and floors. These values are within the allowable radiant asymmetry differences of 10 ^{o}C for cool walls and 23 ^{o}C for warm walls set by ASHRAE 55 to keep fewer than 5% of the participants dissatisfied.

Table 4.12 Summary of descriptive statistics for radiant asymmetry

		Sample size 33
Max Temperature Difference Between Walls	Median	1.4
	Median Abs Dev	0.7
	Max	3.2
	Min	0.1
Maximum Temperature Difference Between Walls and Floor	Median	0.8
	Median Abs Dev	0.7
	Max	4.0
	Min	0.0

4.8 OVERALL SATISFACTION WITH INDOOR ENVIRONMENT

4.8.1 Environmental Conditions

Participants were asked to rate their satisfaction with other indoor environmental conditions (Figure 1.19 to 1.23).

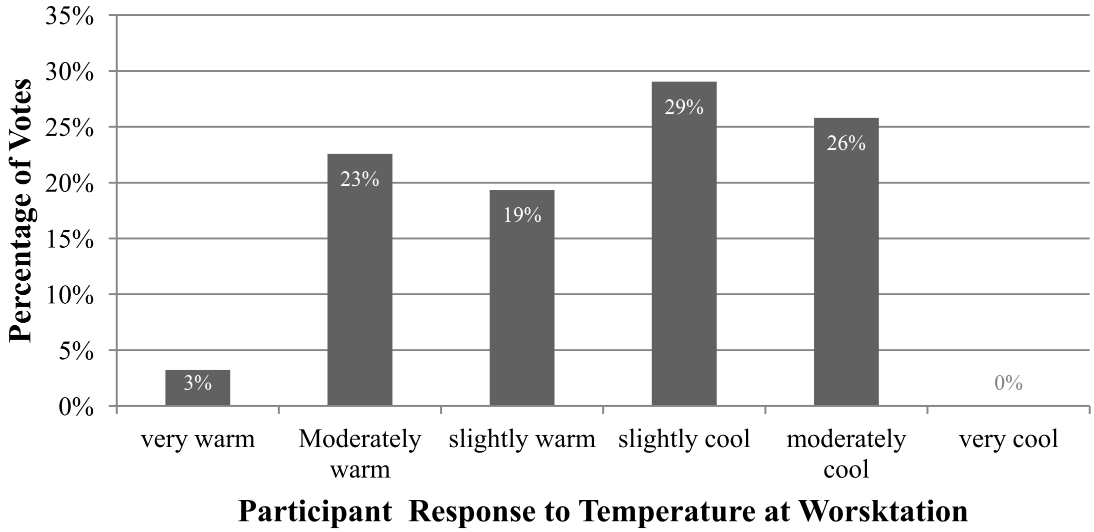

Figure 4.19 Satisfaction with Temperature

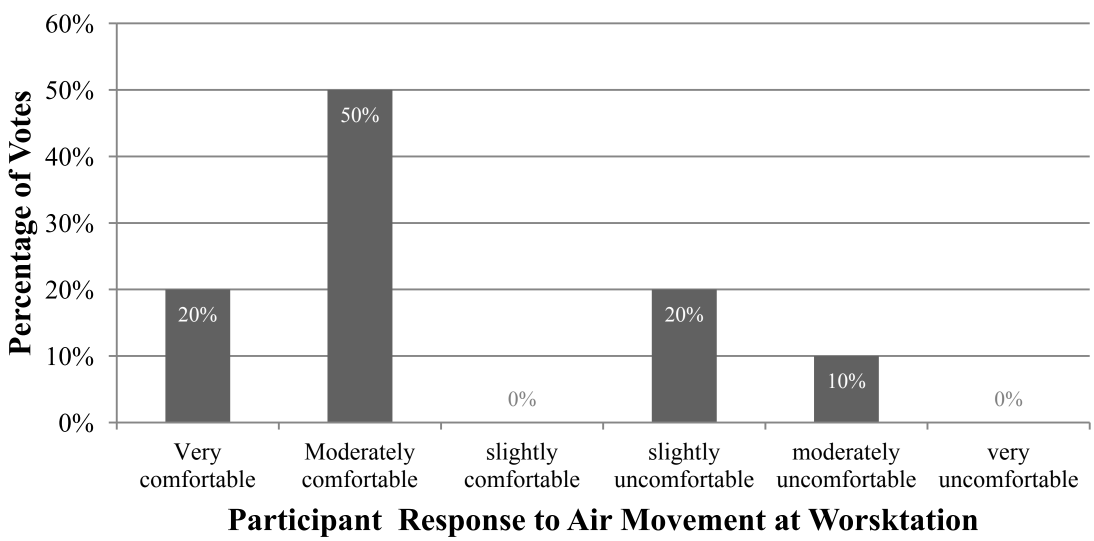

Figure 4.20 Satisfaction with Air Movement

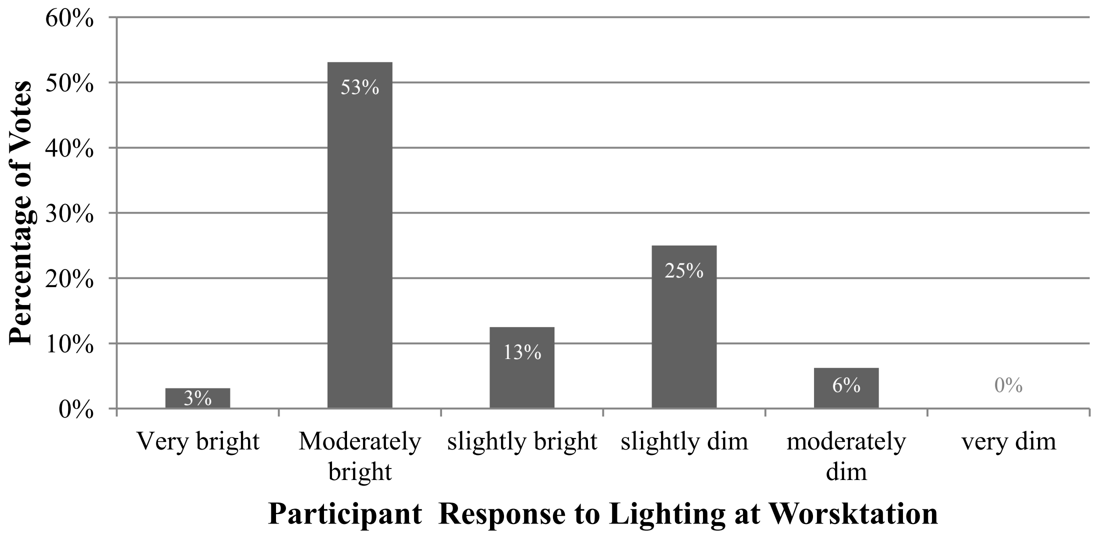

Figure 4.21 Satisfaction with Lighting

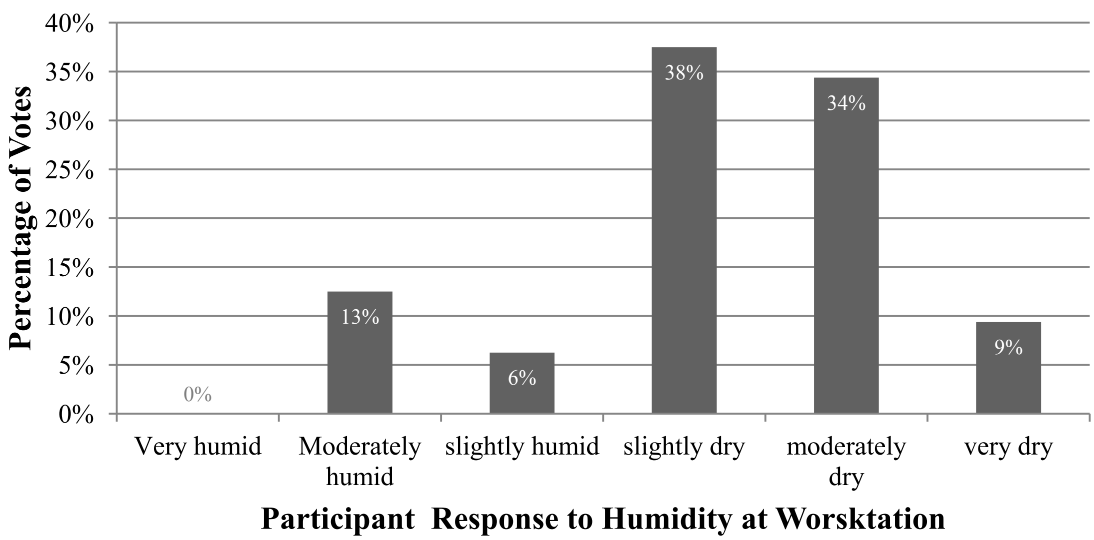

Figure 4.22 Satisfaction with Humidity

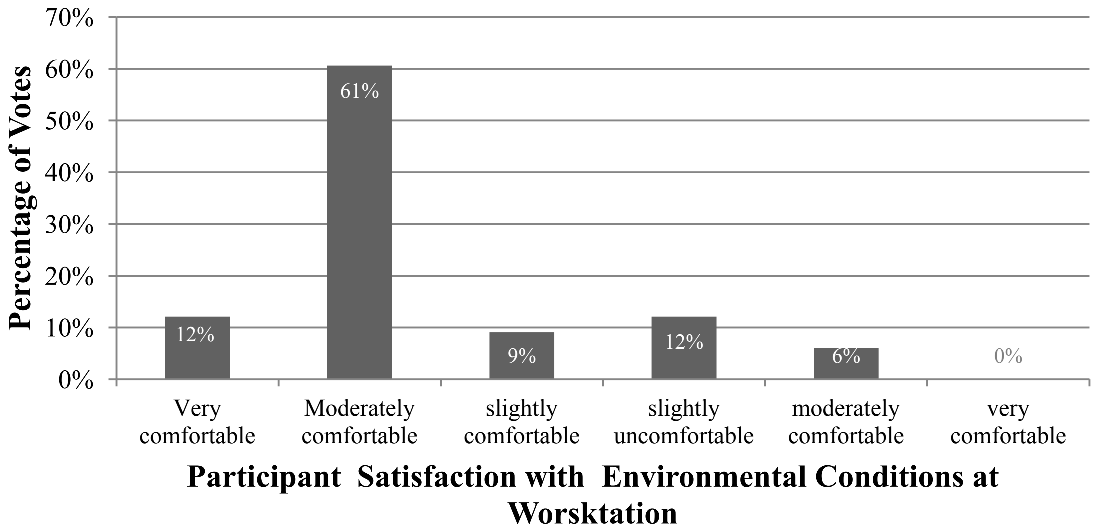

Figure 4.23 Satisfaction with Overall Environmental Conditions

The above charts indicate that 82% of participants found their work area to be in the comfortable range. Temperature was relatively uniform in terms of participant assessments. Eighty-one percent of participants found their environment to be dry, and 70% were comfortable with the amount of air movement. Sixty-nine percent found their environment to be brighter rather than dim.

4.8.2 Environmental Control

In terms of environmental control 80% of participants felt they had slight to no control of their environmental conditions (Figure 4.24), although, when asked if they were satisfied with the amount of control, 60% stated that they were satisfied with the amount of control they had (Figure 4.25).

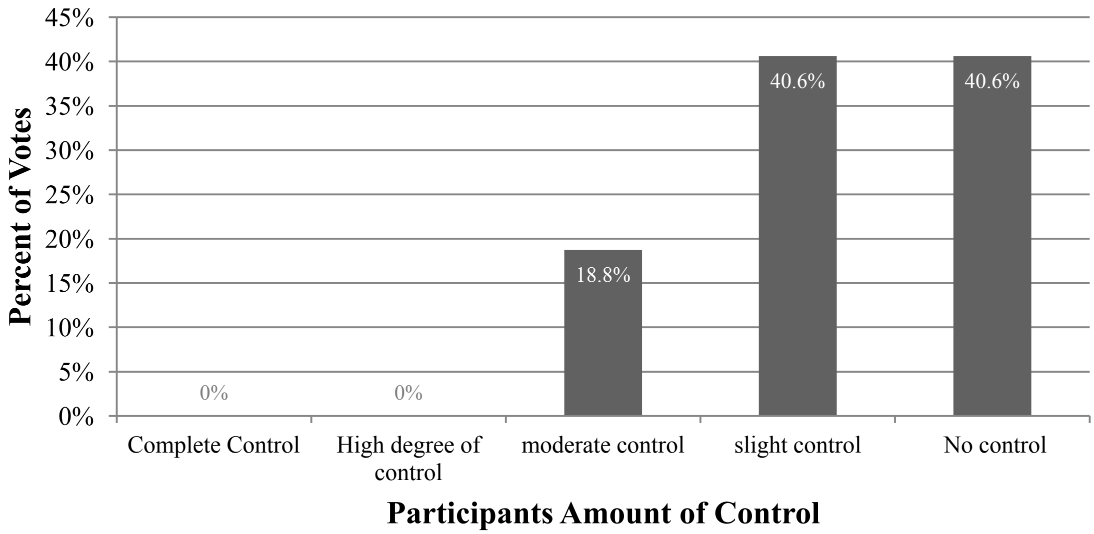

Figure 4.24 Participant Perception of Amount of Control

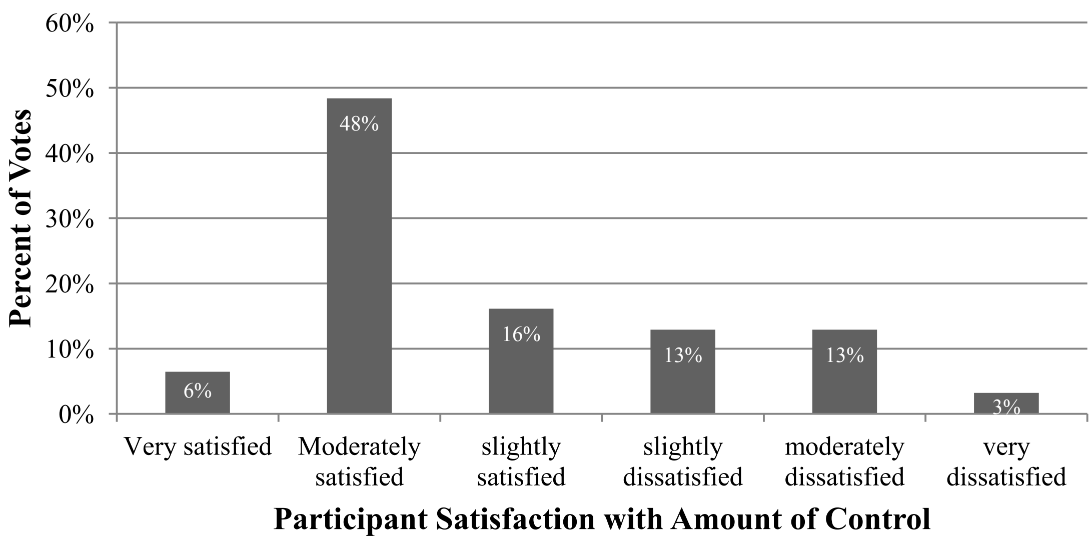

Figure 4.25 Participant Satisfaction with Amount of Control

When participants were asked about the adaptive methods they used to adjust their thermal environment over 50% indicated that they could adjust blinds and open and close windows (Figure 4.26). Participants reported they had very little control over or access to other means of adjusting workstation environmental conditions.

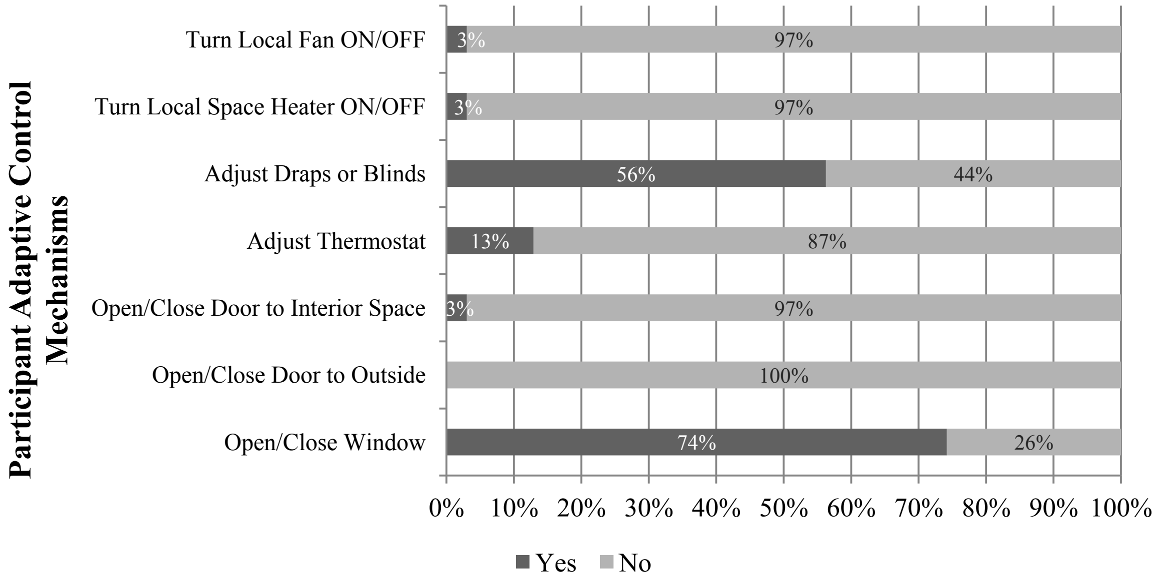

Figure 4.26 Participants Access to Adaptive Control Mechanisms

When asked how often participants actually adjusted the adaptive comfort mechanisms, over 50% said they opened or closed their window either always/often/sometimes. Only 33% of participants indicated they adjusted their blinds and floor diffuser either always/often/sometimes (Figure 4.27).

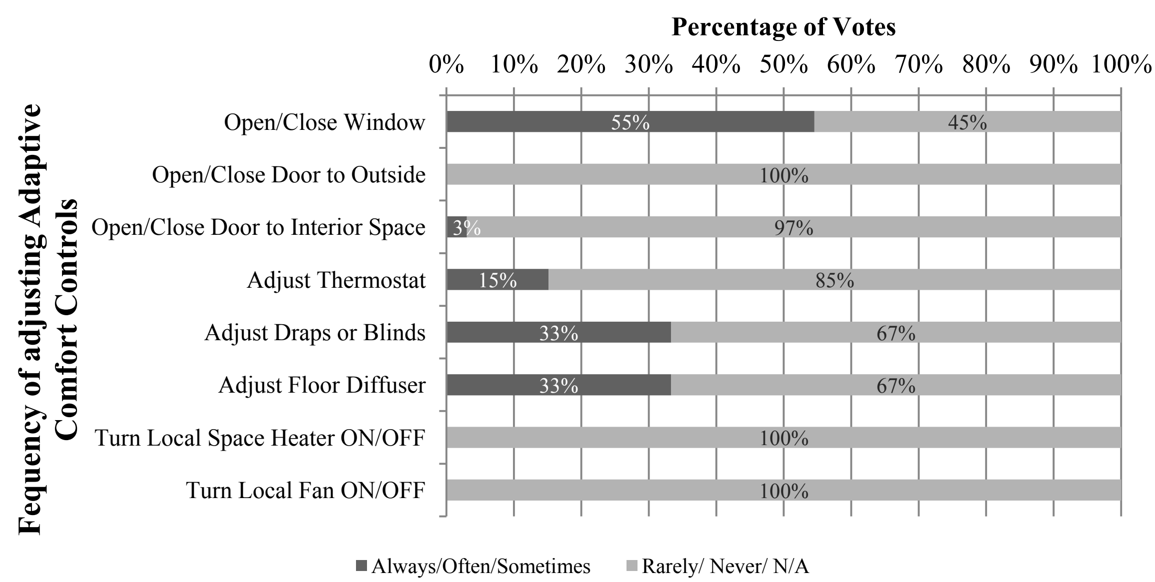

Figure 4.27 Frequency of adjusting Adaptive Controls

Participants were asked how often they made specified personal adjustments to reduce thermal discomfort. The most commonly used were 1) putting on or removing a sweater and 2) drinking a hot/cold beverage. Compared with actions taken to adjust environmental control, personal adjustments were more commonly reported.

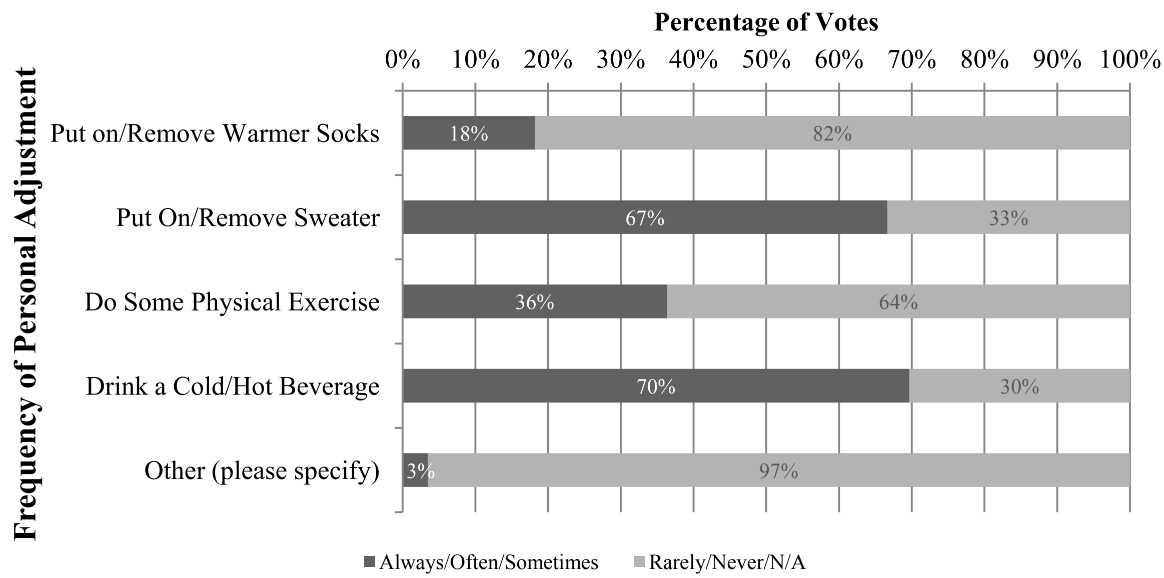

Figure 4.28 Frequency of Personal Adjustments

In terms of health symptoms reported by participants, sleepiness, fatigue, and skin irritation and dryness were the most common (Figure 4.29).

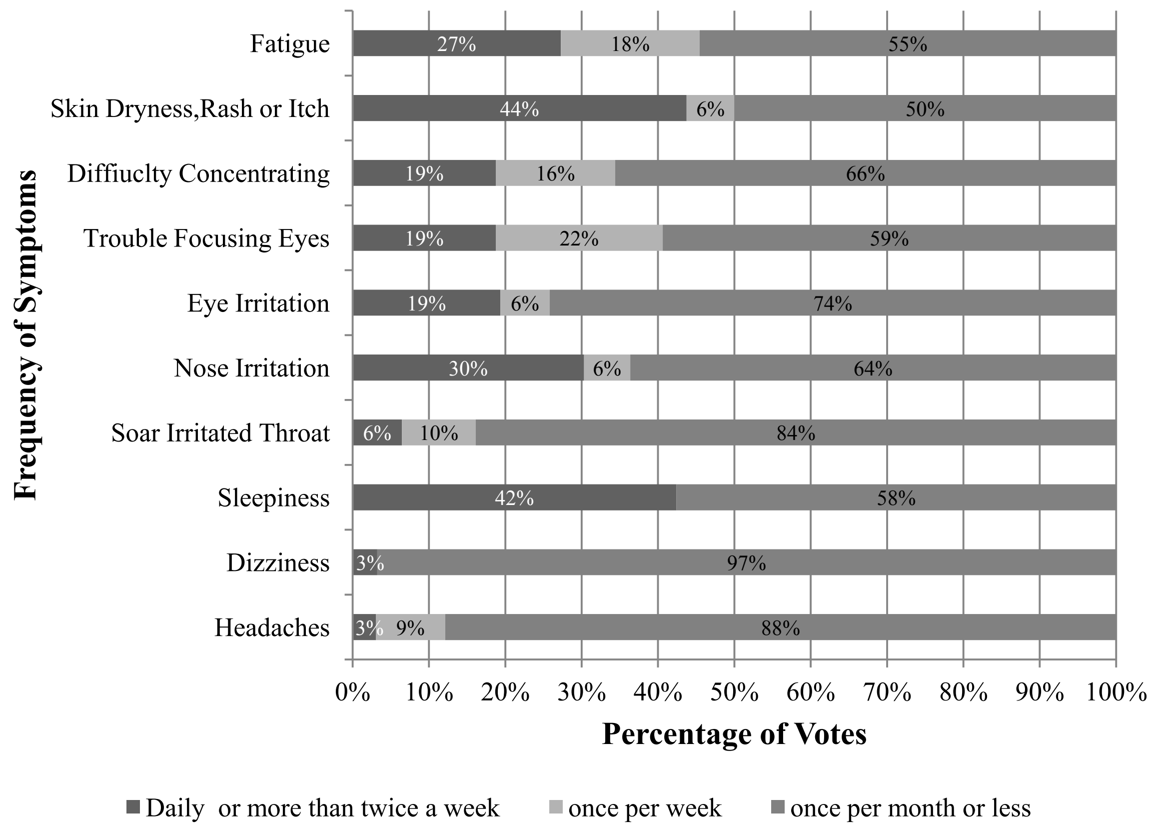

Figure 4.29 Participant Reported Health Symptoms

4.9 SUMMARY

Overall the results of the field study at the water center indicate that the building is working at providing occupants a comfortable environment. All measured environmental conditions were within the guidelines set by ASHRAE 55. The calculated PMV and PPD also indicated the thermal environment conditions were comfortable. The median PMV values was very close to neutral at 0.06 and the median PPD values were also relatively low at 7.65%. The subjective responses from the questionnaires also indicated that the majority of participants were comfortable with the environmental conditions.

5. DISCUSSION

5.1 COMPARISON OF INDOOR THERMAL CONDITIONS TO COMFORT ZONE

The following figure shows that when the indoor conditions were plotted on the ASHRAE 55 comfort zone chart, all workstations were within the 1.0 clo comfort range. Even the workstations of two participants who voted the thermal environment to be unacceptable had conditions within the comfort range. This indicates the Water Center indoor conditions were similar throughout and that the indoor conditions were comfortable according to the Fanger thermal comfort model.

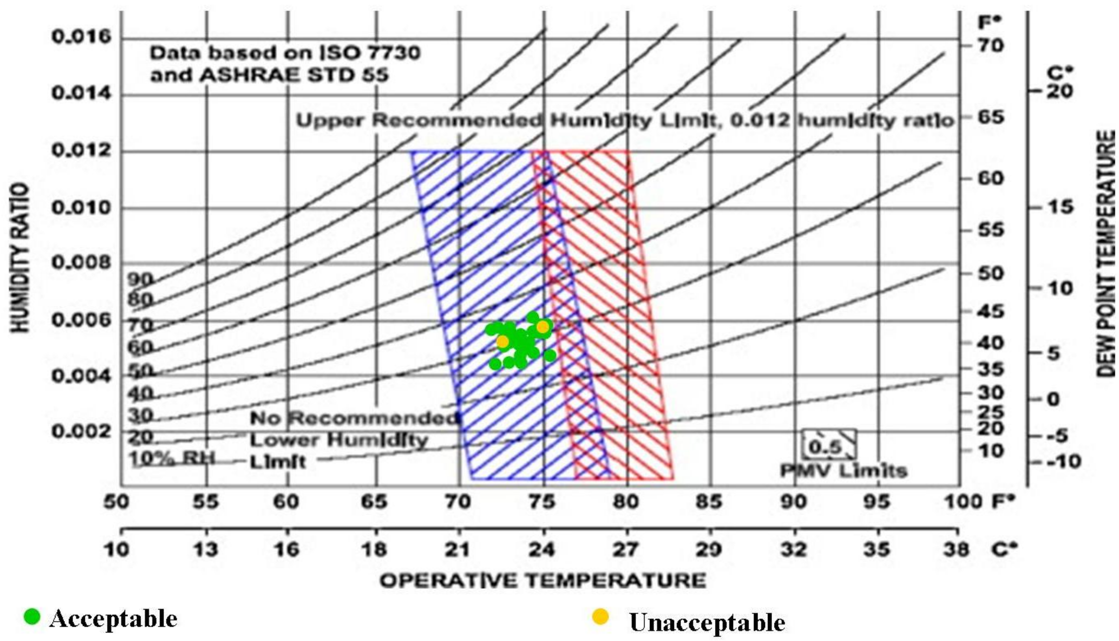

Figure 5.1 Validation of Comfort Zone Compared to Participant Response

5.2 COMPARISON OF PMV TO AMV AND PPD TO APD

The median AMV was -0.5 ± 0.5 within a range of -2.0 to 2.0. 51% of participants voted that they were slightly cool. Most participants (91%) voted within the three central categories. The median PMV was 0.06 ± 0.38 and the median of the paired workstation differences between AMV and PMV was 0.56. This shows thermal sensation should be relatively neutral for most of the occupants based on the environmental conditions measured and within an acceptable comfort range of -0.5>PMV>0.5.

The AMV was slightly cooler than the calculated PMV but by only 0.56. Given this the findings for the Water Center confirmed the relevance of PMV to predict thermal comfort.

The following must also be considered when PMV is calculated with no account for error Humphreys and Nicol (2002:669) suggest that the median PMV-AMV discrepancy distribution should equal approx zero with a standard deviation of ± 0.25. In the case of the Water Center the PMV-AMV discrepancy distribution was 0.68 ± 0.50. In this case the actual calculated median is closer to 1 than 0 and the standards deviation is above 0.25 suggest. Therefore according to Humphreys and Nicol the PMV failed to predict thermal comfort in the Water Center

Table 5.1 PMV-AMV discrepancy

		Sample size 33
PMV – AMV discrepancy	Median	0.68
	Median Abs Dev	0.50
	Max	2.85
	Min	0.00

In terms of PPD and APD, there was some variation. The median PPD was 7.64 ± 2.04%. The APD was higher with a median of 26.12 ± 0.0%. This indicates that the thermal environment exceeded the ASHRAE 55 standard of 20% dissatisfied. Although PMV and AMV were relatively close, the difference between the calculated PPD from indoor conditions and the calculated APD from survey results showed a large discrepancy. The following *Table 5.2* chart shows the statistical summary for this discrepancy.

Table 5.2 PPD- APD discrepancy

		Sample size 33
PPD – APD discrepancy	Median	16.60
	Median Abs Dev	4.45
	Max	70.66
	Min	0.00

It is also interesting to note that participants were generally comfortable with all conditions as indicated through the survey responses. Therefore the reason(s) participants voted to they were comfortable when a there was high percent dissatisfied based on their thermal sensation response should be investigated further.

When looking at the PMV and AMV discrepancies further in there were three participants with discrepancy of PMV and AMV in order of magnitude of discrepancy Table 5.3 it can be seen that three participants had discrepancy's exceeding 2. From the table the model seems to be poorer for people over 45 and mainly women.

Table 5.3 Comparison of PMV-AMV discrepancy with clo, age, and gender

PMV-AMV Discrepancy (Highest to Lowest)		**Participant**	**Clo Level**	**Gender**	**Age**
Above 2	2.9	8	0.57	F	54
	2.3	6	0.7	F	55
	2.2	19	0.63	F	53
Between 1 - 2	1.7	30	0.54	F	50
	1.5	26	0.67	F	48
	1.5	31	0.69	M	35
	1.4	23	0.86	F	33
	1.3	16	0.67	M	41
	1.2	20	0.5	F	52
	1.2	32	0.7	F	49
	1.1	12	0.49	M	54
	1.1	17	0.8	F	29
	1.1	28	0.57	M	34
	1.0	9	0.76	F	54
	1.0	14	0.67	M	53

PMV-AMV Discrepancy (Highest to Lowest)		Participant	Clo Level	Gender	Age
Below 1	0.8	11	0.69	F	33
	0.7	3	0.84	F	25
	0.6	1	0.9	F	53
	0.6	13	0.85	F	30
	0.6	21	0.78	F	51
	0.6	33	0.78	M	43
	0.5	2	0.64	F	47
	0.4	10	0.57	M	53
	0.3	7	0.93	M	47
	0.3	27	0.99	F	46
	0.2	24	0.57	F	54
	0.2	46	0.66	F	46
	0.1	4	0.84	F	52
	0.1	15	1.1	M	41
	0.1	25	0.54	M	47
	0.0	18	0.66	M	48
	0.0	22	0.79	F	45
	0.0	5	0.88	F	42

5.3 ANALYSIS OF RELATIONSHIP BETWEEN COMFORT PARAMETERS

5.3.1 Local Discomfort

The literature has indicated that UFAD systems cause the cold feet phenomenon and draft discomfort. In the case of this field study there was some participants who experienced this discomfort. In general local thermal discomfort was experienced mainly at the head (warm), arms and hands (cool) and feet and legs (cool). However there seemed to be a discrepancy between the perceived temperature difference between legs and head and the measured temperatures. Participants reported their legs to be cooler than their heads, however the measured temperatures indicated that the foot level was warmer than the head level for most participants. The reason as to why this is the case, people feel cold however the temperature is within acceptable range, requires further investigation. The possible explanations could be that the sample size is too small or clothing distribution was not considered.

5.3.2 Environmental Control

Control is one of UFAD systems many benefits. Actual adjustment of floor diffusers was practiced by 33% of participants on a always/often/sometimes basis while 51% rarely/never adjusted their diffusers. 15% of participants indicated that adjusting floor diffusers was not applicable.

The literature review pointed out that the degree of personal control over environmental conditions can effect occupants perception of their physical environment, regardless of whether the control is used of not. I the case of the Water Centre many participants indicated they had little control over environmental conditions. 40% indicated they had slight control and 40% no control. Although they had limited personal control of environmental conditions, 94% of participants thought the thermal environment was acceptable, and 60% of participants were satisfied with the amount of control they had. This may be due to the fact that over 50% of participants stated they had control over adaptive features such as operable windows and blinds. In floor diffusers were adjusted by 33% of participants often

5.4 FIELD STUDY LIMITATIONS

Limitations associated with this field study included:

The field study being conducted during a transitional season between heating and cooling seasons. The data can not represent occupant responses or physical conditions for either heating season or cooling season experienced in Canada's cold climate.

Access to the whole building was another limitation. To reduce disruption to the staff at the water centre researchers were only granted access to participants on the third floor of the water centre. By only having access to the third floor this data can not represent the results that may have been found on various floors of the building.

Due to the participants having access to operable windows the results regarding control require further investigation as access to adaptive mechanisms may have confounded the results specifically related to control and UFAD systems

Due to the variability of weather and the office environment inconsistencies such as physical conditions, sunlight and various other psycho-social factors. These factors could not be controlled during the field study.

5.5 SUMMARY OF FINDINGS

- Indoor temperature ranged from 21.7 °C to 24.8 °C. with a median of 23.1 ± 0.5 °C. There was very small variation of 0.1 °C between indoor air temperature, MRT and operative temperature. The mean operative temperature was 23.1 ± 0.5 °C and ranged from 22.2 °C to 24.2 °C. while the median MRT was 23.2 ± 0.5 °C with a range from 22.4 °C to 24.2 °C.
- Air stratification measured through vertical air temperature difference was relatively low. The maximum temperature difference experienced was 1.5 °C and a minimum of 0.0 °C with a median of 0.4 ± 0.3 °C.. However 8 participants experienced temperatures at head level to be cooler than foot level which is opposite of the designed intent of UFAD systems.
- Relative humidity ranged from 25.3% to 35.1% with a median of 31 ± 1.62%.
- clo values ranged between 0.49 and 1.1 with a median of 0.69 ± 0.11 clo . The median clo value for both men and women varied vary little with a difference of 0.03 clo.
- The median metabolic rate for the surveyed participants was 1.15 ± 0.05. The median metabolic rate for both male and female participants was 1.14 and 1.17 respectively.
- In terms of general comfort 94%of participants agreed that the thermal environment was acceptable while only 6% stating that the thermal environment was unacceptable. Of all the participants 30% expressed they would like to be warmer with 80% of these responses came from women.
- 82% of participants found their work area to be in the comfortable range. Temperature was relatively uniform in terms of people assessments. 81% of

participants found their environment to be dry, and 70% were comfortable with the amount of Air Movement. 69 % found their environment to be brighter rather than dim.

5.6 CONCLUSIONS

The finding from the field study identified that occupants were generally satisfied with the indoor environment of the Water center and the UFAD system. Participants general comfort with their environment were generally acceptable and most indicated that there be no changes. There were no striking results that indicated any thermal comfort parameter was an issue and caused severe discomfort. The physical conditions measured were relatively stable with very little variation throughout all workstations studied. The PMV indicated that the median result were very close to neutral. The calculated PMV-AMV were low. This indicates that Fanger's PMV model is suitable in predicting thermal comfort within the Water Centre. The discrepancy between the PPD and APD was much higher than that of the PMV-AMV discrepancy. The reasons as to why this is the case need more investigation. When variables such as age gender, clo values, PMV-AMV discrepancy were considered the model is less reliable in predicting comfort for people over 45 and particularly women. Overall the field study concluded that in the case of the Water Centre people were very comfortable with their environment and Fanger's heat balance model was successful in determining thermal comfort.

5.7 SUGGESTIONS FOR FUTURE WORK

5.7.1 Survey protocol

While conducting the field study the type of clothing indicated on the survey caused some confusion with a number of participants. Most participants did not realize that the under layer clothing was referring to items such as undershirts, long johns, etc. But thought they were general shirts and pants so therefore checked these boxes. It is suggested for future research surveys to clearly indicate the type of clothing the participant has to choose from or provide more detail description of what constitutes a certain piece of clothing. Using the referenced clothing in ASHRAE 55 Appendix B - Table B2 as the survey options may help clarify options participants have to choose from.

This may also help the researcher when they are tasked with interpreting the participants selected clothing and allocating an appropriate clo value. This should result in more accurate calculations of clo values therefore allowing the calculation of PMV to be more accurate.

5.7.2 Future research

More field studies in buildings with UFAD systems would be helpful in concluding the benefits of UFAD systems. These field studies should aim to provide information on the relationship between the physical conditions and occupant responses. Research particularly on the behavioural, physiological and psychological adaptation process of occupants in buildings in terms of environmental control patterns, habits and preferences would help understand how these types of behaviours impact the indoor environment, thermal comfort perceptions and energy use. Field studies should also be conducted in other climates to verify UFAD systems actually provide indoor occupant comfort and reduced energy use in these varied climates. Finally further field study research is required to determine the actual energy use of UFAD systems in context, as most UFAD energy use information is developed from energy simulation models. Once these relationships are better understood, this information can be translated into better designs of UFAD systems and other energy efficient building systems that achieve appropriate indoor environments for occupants and improve energy efficiency.

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GLOSSARY OF TERMS

Acceptable thermal environment: an environment that a substantial majority of the occupants would find thermally acceptable.

Actual mean vote (AMV): in a field survey, the mean value of the actual votes of a large group of people on the seven-point thermal scale.

Air speed: the rate of air movement at a point, without regards to directions.

Air temperature (ta): the temperature of the air surrounding the occupant.

Clo: a unit to express the thermal insulation provided by garments and clothing ensembles, where 1 clo = 0.155 $m^2 \cdot {}^{\circ}C/W$ (0.88 $ft^2 \cdot h \cdot {}^{\circ}F/Btu$)

Coefficient of Performance (COP): is a measure of the amount of power input to a system compared to the amount of power output by that system

Draft: the unwanted local cooling of the body caused by air movement

Draft rate (DR): percentage of people predicted to be dissatisfied due to draft

HVAC: heating, ventilating and air conditioning

Indoor Air Quality (IAQ): Indoor air quality (IAQ) is a term referring to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.

Indoor Environmental Quality (IEQ): refers to the overall comfort of a building's interior and the comfort and health of its occupants. Many factors may contribute to indoor environmental quality, including: lighting, thermal conditions, sound, indoor air quality, and psycho-social factors.

Mean radiant temperature (MRT): the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non uniform space.

Met: a unit to describe the energy generated inside the body due to metabolic activity, defined as 58.2 W/ m^2 (18.4 Btu/h$\cdot$ ft^2), which is equal to the energy produced per unit surface area of an average person seated at rest. The surface area of an average person is 1.8 m^2 (19 ft^2)

Metabolic rate (M): the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. In this standard, metabolic rate is expressed in met units.

Occupied zone: the region normally occupied by peopled within a space, generally considered to be between the floor and 1.8 m (6 ft) above the floor and more than 1.0 m (3.3 ft) from outside walls/windows or fixed heating, ventilating, or air conditioning equipment and 0.3 me (1ft) from internal walls.

Operative temperature (OT): the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment

Plenum: a compartment or chamber to which one or more ducts are connected, that forms a part of the air distribution system, and that is not used for occupancy or storage. A plenum often is formed in part or in total by portions of the building.

Percent dissatisfied (PD): percentage of people to be dissatisfied due to thermal discomfort

Predicted percent of dissatisfied (PPD): an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.

Predicted mean vote (PMV): an index that predicts the mean value of the votes of a larger group of persons on the seven-point thermal sensation scale.

Radiant temperature asymmetry: the difference between the plane radiant temperature of the two opposite sides of a small plane element.

Relative humidity (RH): the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure.

SHGC (Solar heat gain coefficient): the fraction of incident solar radiation admitted through a window, expressed as a number between 0 and 1

Thermal comfort: the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

Thermal neutrality: the indoor temperature index value corresponding with a mean vote of neutral on the thermal sensation scale

Thermal sensation: a conscious feeling commonly graded using the categories cold, cool, slightly cool, neutral, slightly warm, warm, and hot; it requires subjective evaluation.

Ventilation Effectiveness: description of an air distribution system's ability to remove internally generated pollutants from a building, zone or space.

APPENDIX A
QUESTIONNAIRE MODIFICATIONS

The questionnaires were based on previous thermal comfort research including ASHRAE RP-921(Cena and De Dear 1998), ASHRAE RP- 702 (de Dear et al 1993), ASHRAE PR-462 (Schiller et al 1988), and ASHRAR RP-821 (Donnini et al 1998), as well as more resent academic research including Tian and Love (2008) and Garcia (2011).

Background Questionnaire Modifications

There were some questions that were deleted as these questions added time to the questionnaire and participants often express they are too personal and fail to see the relevance of these types of questions to the objective of the research. Also in past thermal comfort research these factors did not correlate to with specific comfort responses. Questions they were removed included

- Ethnic background
- English as primary language
- Education level
- Job satisfaction

The question "In general, how often DO YOU TAKE THE FOLLOWING ACTIONS to improve your comfort at your workstation?" was added to the personal control section (Section 4 Question #26). This question was added to the questionnaire to gage thermoregulation actions. Also the action "adjust floor diffuser" was added to the question regarding adjustments of thermal environment (section 4 Question #15). This will gage the amount of control that is exercised specifically relating to UFAD system.

The original 5 point scale (very often, often, sometimes, rarely, never) used when asking the frequency of symptoms affecting health (Section 5 Question #27) was changed to a scale with more specific choices (daily, more than twice per week, once per week, once per month, less than once per month). This will help avoid vague responses.

Similarly, to avoid vague responses in regards to participants sensitivity the original 6 point scale (very sensitive, moderately sensitive, slightly sensitive, slightly insensitive, moderately insensitive, very insensitive) was replaced with a 5 point scale that is more specific (much more sensitive than other people I know, more sensitive than other people I know, about the same as other people I know, less sensitive than other people I know, much less sensitive than other people I know).

Thermal Comfort Questionnaire Modifications

A question about the adequacy of participant's thermal clothing level was added to evaluate the satisfaction with the thermal environment (Question 16)

APPENDIX B
THERMAL COMFORT QUESTIONNAIRE

Thermal Comfort Questionnaire

Please note: All survey responses will remain confidential. Participants will remain anonymous and will only be identified as and assigned ID code

This is an adaption of a standard questionnaire developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

[1] Participant ID Code:____________ **[2]** Date: _____________ **[3]** Time: _______AM / PM

[4] Building: ____ **[5]** Floor: ___________

In this part of the survey we would like to know how you feel <u>RIGHT NOW</u>, at this moment.

[6] Please tick the scale below at the space that best represents how you feel at this moment. You may tick in an appropriate place between two categories, if you wish.

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

[7] Is the thermal environment at your workstation at the moment acceptable to you?

☐ Unacceptable ☐ Acceptable

[8] Please select the box below that best represents how you feel at this moment.
I would like to be:

☐ Warmer ☐ No change ☐ Cooler

[9] Please identify in the list below whether any part of your body is warmer or cooler than the rest of your body. Mark all of the parts that feel different at the moment. If no parts feels different, please go to the next question

Indicate which part of your body feels different:	**Circle one for each item** Cooler	Cooler and Uncomfortable	Warmer	Warmer and Uncomfortable
1. Head...	☐	☐	☐	☐
2. Shoulder.......................................	☐	☐	☐	☐
3. Back	☐	☐	☐	☐
4. Chest..	☐	☐	☐	☐
5. Arms and hands............................	☐	☐	☐	☐
6. Feet and legs	☐	☐	☐	☐

[10] Please select the boxes that best represent how you feel at the moment about the AIR MOVEMENT in your workspace

☐ Very comfortable ☐ Moderately comfortable ☐ Slightly comfortable
☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable

I would like:

☐ More air movement ☐ No change ☐ Less air movement

[11] How comfortable is your desk area right now?

☐ Very comfortable ☐ Moderately comfortable ☐ Slightly comfortable
☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable

[12] What would you estimate the temperature at your desk area to be RIGHT NOW? __________ºC or ____________ºF

[13] What activities have you been engaged in during the preceding hour?

What activities have you been doing in the:	Sitting Quietly	Sitting Typing	Standing Still	On your feet working	Walking Around	Exercising
1. Last 10 minutes?..........................	☐	☐	☐	☐	☐	☐
2. The 10 minutes preceding?..............	☐	☐	☐	☐	☐	☐
3. The 10 minutes before that?............	☐	☐	☐	☐	☐	☐
4. The half hour before that?................	☐	☐	☐	☐	☐	☐

Circle one for each item

[14] Please indicate whether you are wearing any of the items listed below

Circle one for each item

	Not wearing item	Light weight item	Medium weight item	heavy weight item
A. wearing any of the following UNDERLAYER clothing:				
1. Top - short sleeve..........................	☐	☐	☐	☐
2. Top - long Sleeve..............................	☐	☐	☐	☐
3. Bottom - short................................	☐	☐	☐	☐
4. Bottom - long................................	☐	☐	☐	☐
3. Slip (women)................................	☐	☐	☐	☐
B. wearing any of the following MIDLAYER clothing:				
1. Short sleeved shirt.........................	☐	☐	☐	☐
2. Long sleeved shirt..........................	☐	☐	☐	☐
3. Pants	☐	☐	☐	☐
4. Shorts..	☐	☐	☐	☐
5. Dress (women).............................	☐	☐	☐	☐
6. Skirt (women)................................	☐	☐	☐	☐
C. wearing any of the following OUTERLAYER clothing:				
1. Sweater.......................................	☐	☐	☐	☐
2. Vest...	☐	☐	☐	☐
3. Jacket..	☐	☐	☐	☐
D. wearing any of the following FOOTWEAR:				
1. Socks...	☐	☐	☐	☐
2. Pantyhose (women)........................	☐	☐	☐	☐
3. Shoes...	☐	☐	☐	☐
4. Boots..	☐	☐	☐	☐

[15] At this moment are you wearing more/less clothing at your desk than you prefer/expect?

☐ More clothes than preferred ☐ OK ☐ Less clothes than preferred

[16] Please indicate whether you have consumed any of the following items within the last 15 minutes.

☐ Hot drink ☐ Caffeinated drink ☐ Cold drink
☐ Snack or Meal ☐ Cigarette

APPENDIX C
BACKGROUND QUESTIONNAIRE

Background Questionnaire

Please note: all survey Responses will remain confidential. Participants will remain anonymous and will only be identified by the assigned ID Code

This is an adaption of a standard questionnaire developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

[1] Participant ID Code:______________**[2]** Date: ______________**[3]** Time: _______AM / PM

[4] Building: ____**[5]** Floor: __________

1 - BACKGROUND CHARACTERISTICS

[6] Occupation: ____

[7] How long have you lived in Calgary? __________________ Years ________Months

[8] What is your age? _______________ yrs **[9]** What it your gender? ☐Male☐Female

[10] What is your Height? _______ft-in or ______**[11]** What is your weight? ______lbs _____ k

[12] On average, how many hours per week do you work at this job? _________________ Hrs

[13] On average, how many hours per day do you sit at your work area? _____________ Hrs

2 - PERSONAL COMFORT

Please complete the following statements by checking the box that best expresses your personal feelings or preferences.

[14] On average, during the last 5 to 10 work days, I found the TEMPERTURE of my work area to be: (Disregarding the effects of air movement, lighting and humidity)

☐ Very warm ☐ Moderately warm ☐ Slightly warm
☐ Slightly cool ☐ Moderately cool ☐ Very cool

[15] On average, during the last 5 to 10 work days, I found the AIR MOVEMENT of my work area to be: (Disregarding the effects of temperature, lighting and humidity)

☐ Too much ☐ Just right ☐ Slightly little

☐ Very comfortable ☐ Moderately comfortable ☐ Slightly comfortable
☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable

[16] On average, during the last 5 to 10 work days, I found the LIGHTING of my work area to be: (Disregarding the effects of temperature, air movement and humidity)

☐ Very bright ☐ Moderately bright ☐ Slightly bright
☐ Slightly dim ☐ Moderately dim ☐ Very dim

[17] On average, during the last 5 to 10 work days, I perceive the HUMIDITY of my work area to be: (Disregarding the effects of temperature, air movement and lighting)

☐ Very humid ☐ Moderately humid ☐ Slightly humid
☐ Slightly dry ☐ Moderately dry ☐ Very dry

[18] On average, during the last 5 to 10 work days, I found my work area to be:

☐ Very comfortable ☐ Moderately comfortable ☐ Slightly comfortable
☐ Slightly uncomfortable ☐ Moderately uncomfortable ☐ Very uncomfortable

3 - PERSONAL CONTROL

To what extent are you able to control the environment of the office space where you usually work?
For each question below make a check mark next to the statement that best expresses your personal feelings or behavior patterns

[19] HOW MUCH CONTROL do you feel you have over the thermal conditions of your workspace? (check one)

- ☐ Complete control
- ☐ High degree of control
- ☐ moderate control
- ☐ Slight control
- ☐ No control

[20] HOW SATISFIED ARE YOU with the level of control? (check one)

- ☐ Very satisfied
- ☐ Moderately satisfied
- ☐ Slightly satisfied
- ☐ Slightly dissatisfied
- ☐ Moderately dissatisfied
- ☐ Very dissatisfied

[21] CAN YOU EXERCISE ANY OF THE FOLLOWING OPTIONS to adjust the thermal environment at your workspace? (check one for each item)

Can You:	Yes	No
1. Open or Close a window……………………………………	☐	☐
2. Open or close a door to the outside………………………	☐	☐
3. Open or close a door to an interior space…………	☐	☐
4. Adjust a thermostat……………………………………………	☐	☐
5. Adjust the drapes or blinds………………………………	☐	☐
6. Turn a local space heater on or off………………………	☐	☐
7. Turn a local fan on or off…………………………………	☐	☐

[22] In general, how often DO YOU EXERCISE ANY OF THE FOLLOWING OPTIONS to adjust the thermal environment at your workspace?

Circle one for each item

How often do you:	Always	Often	Sometimes	Rarely	Never	N/A
1. Open or close a window………………	☐	☐	☐	☐	☐	☐
2. Open of close a door to the outside..	☐	☐	☐	☐	☐	☐
3. Open or close a door to an interior space	☐	☐	☐	☐	☐	☐
4. Adjust a thermostat……………………	☐	☐	☐	☐	☐	☐
5. Adjust the drapes or blinds…………	☐	☐	☐	☐	☐	☐
6. Adjust the floor diffuser………………	☐	☐	☐	☐	☐	☐
7. Turn a local space heater on or off…	☐	☐	☐	☐	☐	☐
8. Turn a local fan on or off……………	☐	☐	☐	☐	☐	☐

[23] In general, how often DO YOU TAKE THE FOLLOWING ACTIONS to improve your comfort at your workstation?

How often do you:	Always	Often	Sometimes	Rarely	Never	N/A
	Circle one for each item					
1. Put on/remove warmer socks..........	☐	☐	☐	☐	☐	☐
2. Put on/remove sweater....................	☐	☐	☐	☐	☐	☐
3. Do some physical exercise................	☐	☐	☐	☐	☐	☐
4. Drink a cold/hot beverage.............	☐	☐	☐	☐	☐	☐
5. Other (please specify)...................	☐	☐	☐	☐	☐	☐

[24] Over a year, how often do you adjust your personal air flow (infloor diffuser)?

☐ Multiple times per day (if more frequent than daily) ☐ Daily ☐ Weekly ☐ Monthly

☐ yearly (if less frequent than monthly)

4 - HEALTH CHARACTERISTICS

[25] Below are some symptoms that people experience at different times. Please indicate how often YOU HAVE EXPERIENCED EACH SYMPTOM IN THE PAST MONTH

How often do you experience these symptoms:	Daily	More than twice a week	Once per week	Once per month	less than once per month
	Circle one for each item				
1. Headaches..................................	☐	☐	☐	☐	☐
2. Dizziness.....................................	☐	☐	☐	☐	☐
3. Sleepiness	☐	☐	☐	☐	☐
4. Sore or irritated throat..................	☐	☐	☐	☐	☐
5. Nose irritation (itch of running)	☐	☐	☐	☐	☐
6. Eye irritation................................	☐	☐	☐	☐	☐
7. Trouble focusing eyes...................	☐	☐	☐	☐	☐
8. Difficulty concentrating..................	☐	☐	☐	☐	☐
9. Skin dryness, rash or itch...............	☐	☐	☐	☐	☐
10. Fatigue	☐	☐	☐	☐	☐

[26] Do you take over-the-counter or prescription medication that might influence your comfort while at work?

☐ Yes ☐ No

[27] How many cigarettes do your smoke per day? ______________________cigarettes

[28] How many cups of caffeinated beverages do you drink per day?___________cups

[29] How many hours do you exercise per week? __________________________ hours

6 - ENVIRONMENTAL SENSITIVITY

[30] A number of questions related to YOUR TYPICAL RESPONSE TO ENVIRONMENTAL CONDITIONS are given below. To indicate your answer to a question circle the number from the following scale which best expresses how you TYPICALLY feel

Circle one for each item

Do you tend to be SENSITIVE to environments which:	Much more sensitive than other people I know	More Sensitive than other people I know	About the same as other people I know	Less sensitive than other people I know	Much less sensitive than other people I know
1. Are TOO NOISY?...........................	☐	☐	☐	☐	☐
2. Are TOO HOT?..............................	☐	☐	☐	☐	☐
3. Are TOO COLD?......................................	☐	☐	☐	☐	☐
4. Have TOO LITTLE AIR MOVEMENT?..	☐	☐	☐	☐	☐
5. Have TOO MUCH AIR MOVEMENT?...	☐	☐	☐	☐	☐
6. Are TOO DIMLY LIT?.......................	☐	☐	☐	☐	☐
7. Are TOO BRIGHT?.........................	☐	☐	☐	☐	☐
8. Have POOR AIR QUALITY?.............	☐	☐	☐	☐	☐

[31] Do you have any other comment about sensitivity to environmental conditions?

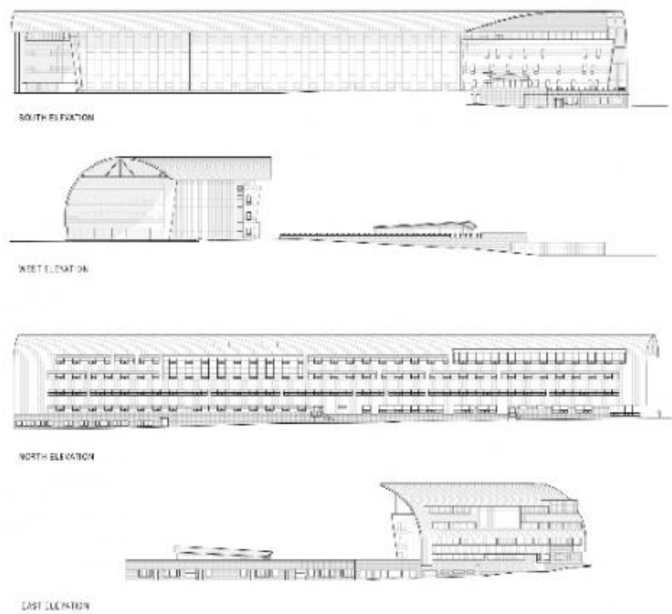
APPENDIX D

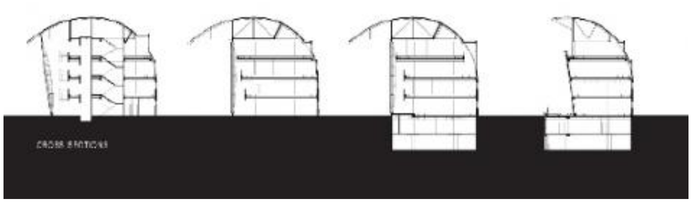
INSTRUMENTATION SPECS AND CALIBRATION

Equipment	Manufacturer – Model	Accuracy	Calibration	Comment
Air velocity transducer	Campbell Scientific (Canada) Corp. Model 8475	±3.0% of reading ± 1.0 % of full scale of selected range	by manufacturer	Readings for standard conditions (21.1 ºC air temperature, 101.4 kPa)
Temperature probe	Campbell Scientific (Canada) Corp. Model 107	± 0.2 ºC over the range of 0 ºC to 50 ºC	by manufacturer	
Temperature and relative humidity probe	Campbell Scientific (Canada) Corp. Model HC-S3	± 0.35 ºC over the range of -50 ºC to 50 ºC	by manufacturer	
Black globe	Campbell Scientific (Canada) Corp.	± 3.0 % over the range of -3 ºC to 90 ºC	by manufacturer	
Handheld infrared thermometer	Omega 0S951	2 ºC or ±1 % over the range of -45 ºC to 287 ºC	by manufacturer	

APPENDIX E
WATER CENTER BUILDING/GREEN BUILDING DESIGN COMPONENTS

Picture Source: http://www.archinnovations.com/featured-projects/civic/the-water-centre-sturgess-architecture/





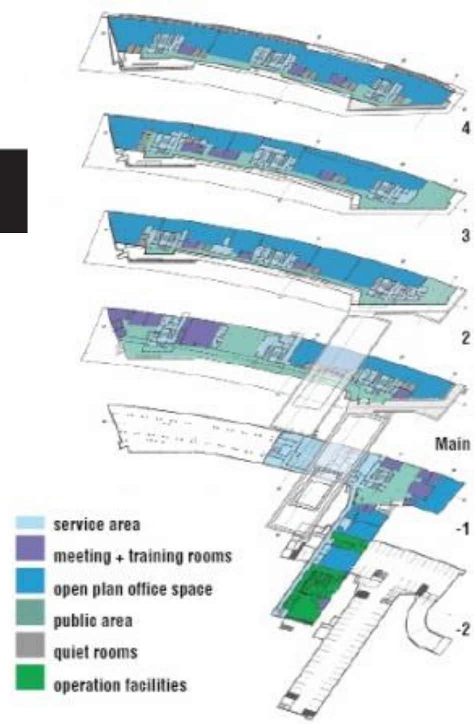


Diagram Source: http://www.canadian-architects.com/en/projects/35440_the_water_centre/47/indexAll

BUILDING ENERGY USE

The Water Centre has unique features that eliminate the need to use drinking water for irrigation, eliminate and significantly reduce the use of energy to light work spaces, creative heating and cooling systems that minimize energy use and loss, as well as a stunning building envelope that prevents heat-loss in the winter and shields the interior from thermal gain in the summer.

The Water Centre was designed to use 58 per cent energy, or 99 kWh/m2/yr compared to the Model Natural Energy Code for Buildings (MNECB) benchmark for this building type of 235 kWh/m2/yr. This compares favourably to the US EPA Energy-Finder 50 per cent energy target figure of about 150 kWh/m2/yr.

Capital cost savings of over $130,000 were realized from the installed cooling system, which included a smaller chiller, pumps, piping and electrical equipment serving the cooling system. The cooling system provides 165 tons of cooling. A comparable building would require approximately 400 tons of cooling. The energy saved on the reduced cooling system results in a savings of approximately 71 metric tonnes of CO_2 emissions per year. Additional savings not included in this value are reduced manufacturing and transportation requirements for smaller equipment. The cooling system is installed in the underside of the concrete slab.

Comparing the Water Centre to a structure built to the conventional Model Natural Energy Code for Buildings (MNECB) standards results in several benefits including:

- 58 per cent reduction in energy use.
- 59 per cent reduction in water usage.
- 72 per cent reduction in production of wastewater.

The actual construction of the Water Centre resulted in some significant environmental achievements including:

- Recycling 91 per cent of the building's construction waste.
- Using 100 per cent recycled steel frame material (700,000 kg).
- Preventing 800 metric tonnes of CO_2, equivalent to roughly 430 fully inflated hot air balloons, from entering the atmosphere.

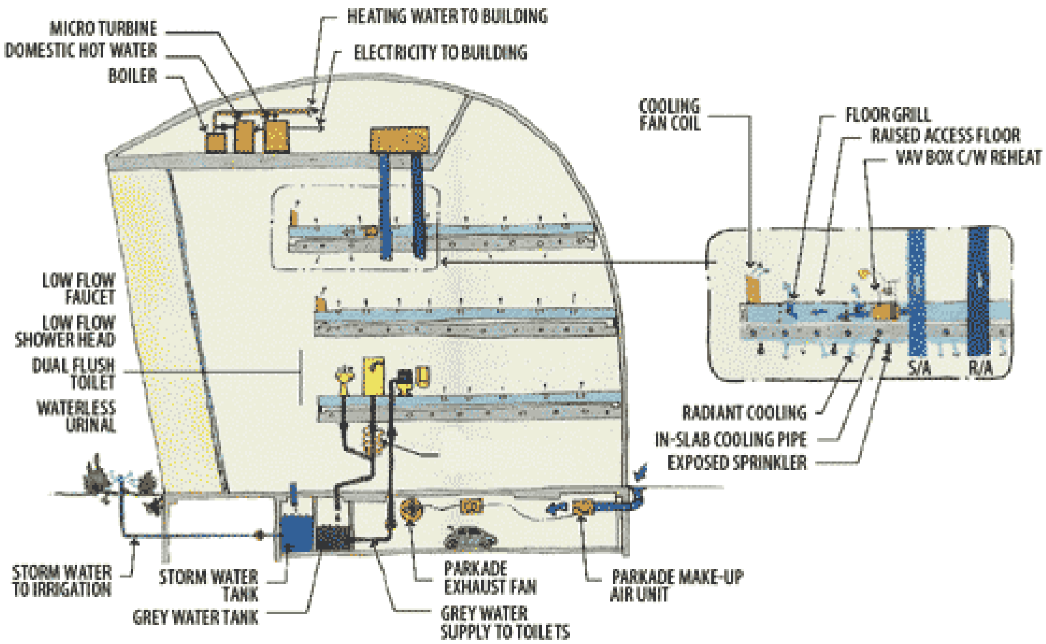
The building components and design considerations that lead to these energy and capital cost savings include the following:

MATERIALS

- Only Forest Stewardship Council approved wood was used.
- All workstations and chairs were made of recycled material.
- Wheatboard panelling replaced wood on interior railings.
- Fly-ash concrete replaced cement.
- Over 700,000 kilograms of reinforcing steel used was recycled product.
- Environmentally preferable carpet tile is laid over the access floor, eliminating volatile organic compounds (VOC) from the workspace.
- Paint, adhesives and sealants are free of VOCs; no off-gassing.
- Minimal amounts of drywall were incorporated into the interior, both for economic and technical reasons.
- Wherever possible, strawboard was used as a finish or for millwork, because of its rapidly renewable nature and lack of formaldehyde in its binders.
- Ninety-one per cent of construction waste was recycled.
- Built on reclaimed brown-field site
- Virtually every piece of the building can, itself, be recycled

WATER

- Rainwater channels into retention ponds and then into underground cisterns for irrigation, nullifying need to use potable water.
- Drought-resistant native prairie grass makes the land more absorptive.
- Dual- and low-flow toilets, low-flow faucets and showerheads, and waterless urinals help the facility reduce water use by 59 per cent over a conventional building.
- Meter-testing (grey) water is recycled through low-flow toilets to help reduce waste water by 72 per cent over a conventional building.
- The Soprema green roof over the administration wing insulates the building, reduces stormwater runoff.



http://209.205.95.211/joomla/index.php/planning/35-feature/44-energy savers?tmpl=component&print=1&page=

HEATING COOLING AND VENTILATION

- The innovative mechanical design includes radiant ceiling slab cooling in combination with under floor ventilation. Displacement ventilation uses natural convection: warm indoor air rises through the under-floor air system, and radiant cooling slabs in the ceiling push cool air down, meaning only having to heat the space to the height of a person standing. This cuts energy use by 20 per cent
- Workers can adjust the local heat source or open nearby windows to achieve optimum temperature in their own workspace.
- The raised access-floor systems in all office areas allow for the ready integration of cabling, power and air distribution, and provide flexibility for future change and configuration of workstations and offices.
- Evaporative cooling is used in the air-handling units, minimizing the need for mechanical cooling.
- Heat recovery is provided in all air-handling units.
- Siemens Apogee Building Management System monitors and controls indoor building performance right down to the zone level.
- The size of the cooling system was greatly reduced through the integrated design process. Four main factors contribute to the reduced cooling load on the building.
    - Glazing selection:
    - Orientation of the glazing and overhangs:
    - Reduced lighting load:
    - Evaporative cooling:

LIGHTING:

- 100-per cent daylit building, vast amounts of natural lighting for employees reduce both glare and energy costs (1,250,000kWh per year saved on lighting costs)
- Installed lighting is designed to be direct/indirect, high performance, low-energy lighting, to complement daylight in all workplaces.
- A low-voltage lighting control system, including motion sensors, photo electric cell, daylight sensors and override switches provide for zone switching of lighting during normal hours, after hours and daylight sensing in the atrium and perimeter offices areas.
- Area lamps allow workers to customize the light they need to work effectively.
- The building's long, narrow footprint (average 18 m) allows this light to penetrate deep into the workable space. Also the majority of the office areas are located on the north side of the building to take advantage of the diffuse northern light.
- Window sizes and glazing types were specifically designed to allow maximum daylight deep into the building. Interior glazing provides daylight even to the quiet rooms and meeting rooms.
- White ceilings and light-coloured work surfaces enhance overall light levels.
- The lighting system was designed with a target lighting power density throughout the occupied areas of the building not to exceed 0.5W/sq. ft.

ENVELOPE

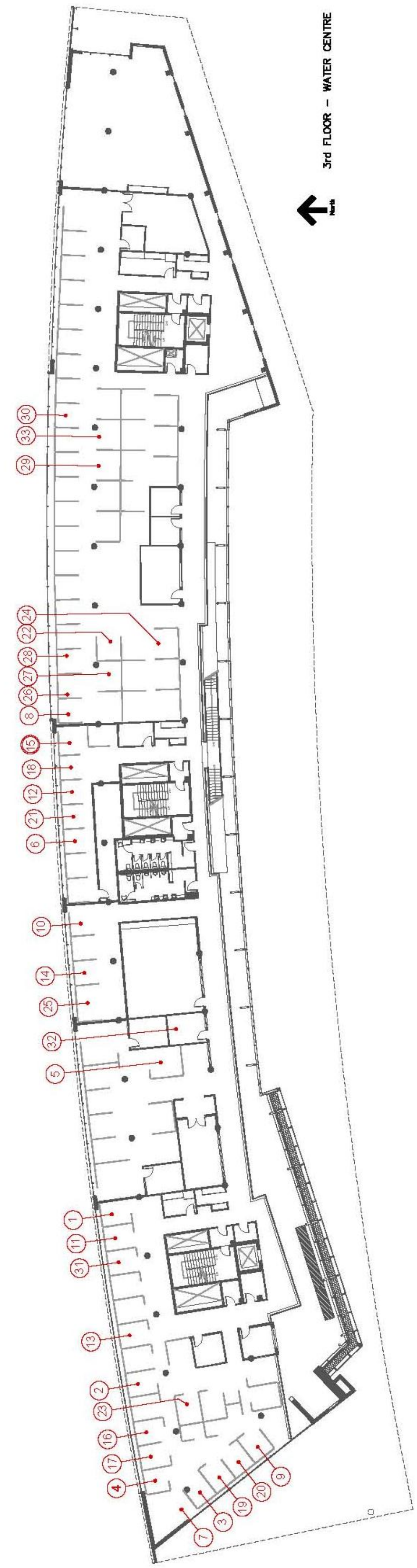
- A three-colour glass curtain wall on the south face minimizes solar gain and maximizes visible light, reducing overall operating costs.
- The highly-insulating glass curtain wall, located along the south facing side, is especially significant to the building's energy performance. Sixty per cent of the curtain is resolved as four colours of glass made from a variety of transmittances and colours. The balance of the area (40 per cent) is made up of solid spandrel panels. Selected to minimize air infiltration, the wall reduces the heating or cooling loads
- The glass area has an imperial R-value of approximately 7 (sq.ft.hr.F/BTU), which corresponds to a U-value of about 0.14 $W/m^2\ ^oC$. The opaque wall areas have an imperial R-value of approximately 15, which corresponds to a U-value of approximately 0.067.
- The solar heat gain coefficient for the glass ranges from 0.30 (in areas with little or no direct sunlight), to a pattern of tinted glass ranging from 0.13 to 0.24 (on the south and exposed east elevations of the building, for an average of about 0.20 in these areas).

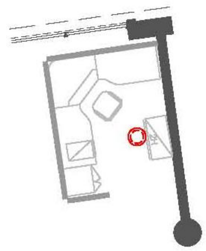
- The Water Centre’s thin shape and southern exposure lets the sun help warm the building during winter, while the roof overhang keeps out the heat of summer.
- The typical wall/roof system consists of a continuous membrane air/vapour barrier on rigid sheathing, which is insulated using mineral wool insulation. A formed-metal pressure-equalized rain screen cladding is then applied to the wall. The cladding is waterproof, but allows incident moisture penetration (at joints or windows and doors) to drain to the exterior within the exterior wall such that it does not enter the building or accumulate in the wall assembly.
- Fenestration to wall ratio for the building is 55 per cent.

Information Source: City of Calgary, 2007

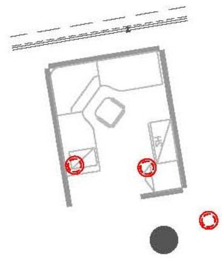
APPENDIX F

WATER CENTER STUDY LOCATION AND WORKSTATION PLANS

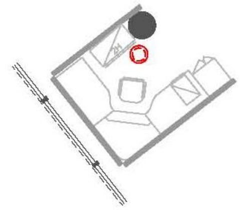




Participant 1 Workstation

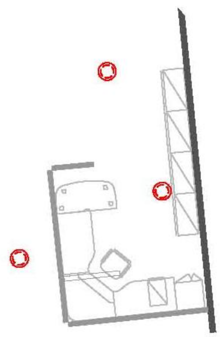


Participant 2 Workstation

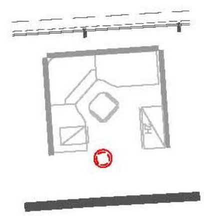


Participant 3 Workstation

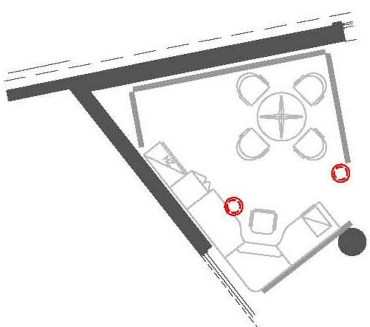
Participant 4 Workstation



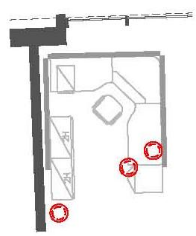
Participant 5 Workstation



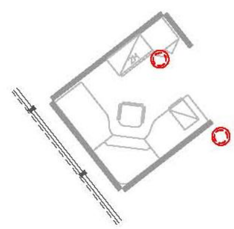
Participant 6 Workstation



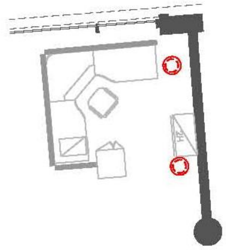
Participant 7 Workstation



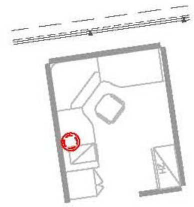
Participant 8 Workstation



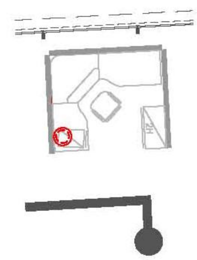
Participant 9 Workstation



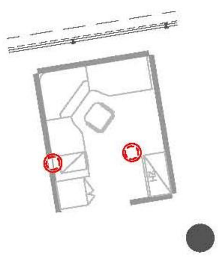
Participant 10 Workstation



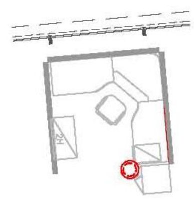
Participant 11 Workstation



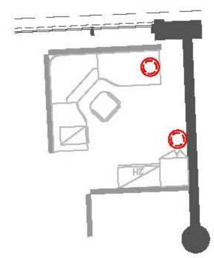
Participant 12 Workstation



Participant 13 Workstation

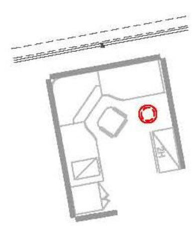


Participant 14 Workstation

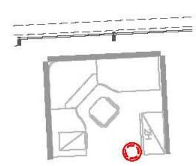


Participant 15 Workstation

Participant 16 Workstation



Participant 17 Workstation



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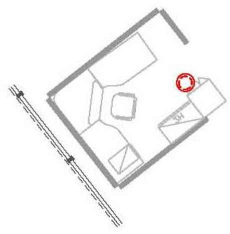

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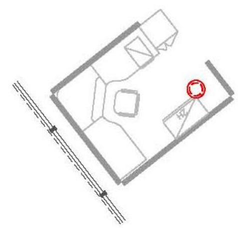

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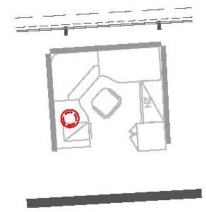

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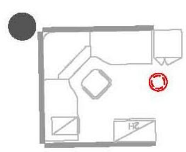
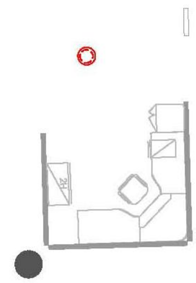


Participant 22 Workstation

Participant 23 Workstation



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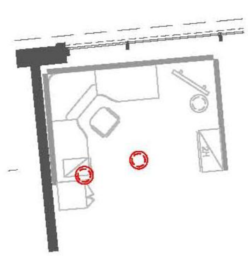

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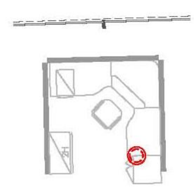
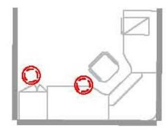


Participant 26 Workstation

Participant 27 Workstation

Participant 28 Workstation



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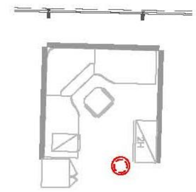
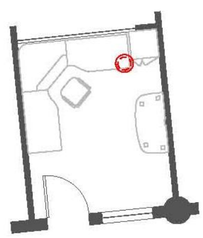
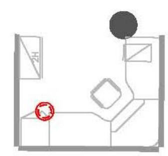


Participant 30 Workstation

Participant 31 Workstation



Participant 32 Workstation



Participant 33 Workstation

APPENDIX G
CLO VALUES AND MET RATE USED IN CALCUALTION

CLO VALUES FOR ASSEMBALAGE

	thin	medium	thick
Top - Short Sleeve	0.08	-	-
Top - Long Sleeve	0.2	-	-
Bottom - Short	0.03	0.04	0.06
Bottom - Long	0.15	-	-
Slip (women)	0.14	0.15	0.16
Short Sleeved Shirt	0.17	0.18	0.19
Long Sleeved Shirt	0.25	0.3	0.34
Pants	0.15	0.19	0.24
Shorts	0.06	0.07	0.08
Dress (women)	0.23	0.35	0.47
Skirt (women)	0.14	0.18	0.23
Sweater	0.25	0.3	0.36
Vest	0.1	0.13	0.17
Jacket	0.36	0.42	0.48
Socks	0.02	0.03	0.06
Pantyhose (women)	0.02	-	-
Sandals/Shoes/Boots	0.02	0.05	0.1

MET VALUES	survey response	MET VALUE
sitting quietly	1	1
sitting typing	2	1.1
standing still	3	1.2
on your feet working	4	1.4
walking around	5	1.7
excercising	6	3

APPENDIX H
PMV AND PPD EQUATIONS

Taken from ISO 7730:2005 Standard

Calculate **PMV** using equation (1) to (4)

$$PMV = \left[0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028\right] \cdot \left\{ \begin{aligned} &(M - W) - 3{,}05 \cdot 10^{-3} \cdot \left[5\,733 - 6{,}99 \cdot (M - W) - p_a\right] - 0{,}42 \cdot \left[(M - W) - 58{,}15\right] \\ &-1{,}7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0{,}0014 \cdot M \cdot (34 - t_a) \\ &-3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{aligned} \right\} \quad (1)$$

$$t_{cl} = 35{,}7 - 0{,}028 \cdot (M - W) - I_{cl} \cdot \left\{3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\right\} \quad (2)$$

$$h_c = \begin{cases} 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} > 12{,}1 \cdot \sqrt{v_{ar}} \\ 12{,}1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2{,}38 \cdot |t_{cl} - t_a|^{0{,}25} < 12{,}1 \cdot \sqrt{v_{ar}} \end{cases} \quad (3)$$

$$f_{cl} = \begin{cases} 1{,}00 + 1{,}290\, l_{cl} & \text{for } l_{cl} \leqslant 0{,}078 \text{ m}^2 \cdot \text{K/W} \\ 1{,}05 + 0{,}645\, l_{cl} & \text{for } l_{cl} > 0{,}078 \text{ m}^2 \cdot \text{K/W} \end{cases} \quad (4)$$

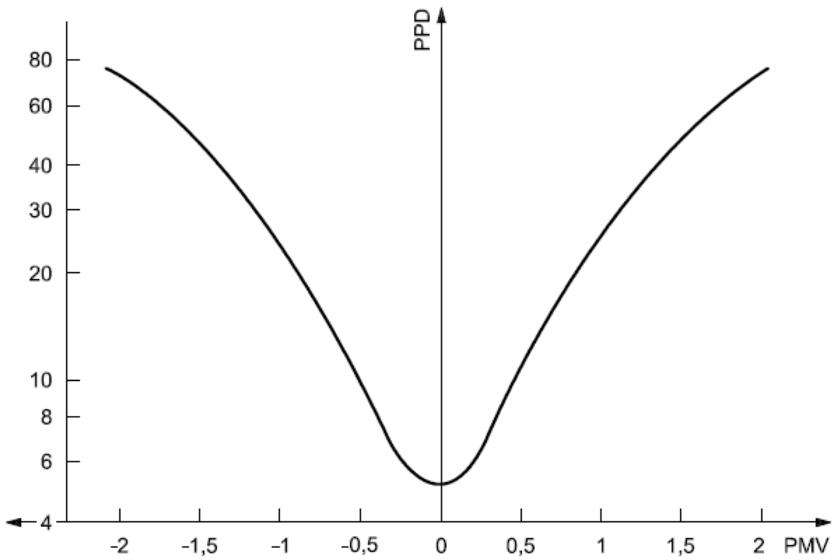
where

- M is the metabolic rate, in watts per square metre (W/m^2);
- W is the effective mechanical power, in watts per square metre (W/m^2);
- I_{cl} is the clothing insulation, in square metres kelvin per watt ($m^2 \cdot K/W$);
- f_{cl} is the clothing surface area factor;
- t_a is the air temperature, in degrees Celsius (°C);
- $\bar{t}_r$ is the mean radiant temperature, in degrees Celsius (°C);
- v_{ar} is the relative air velocity, in metres per second (m/s);
- p_a is the water vapour partial pressure, in pascals (Pa);
- h_c is the convective heat transfer coefficient, in watts per square metre kelvin [$W/(m^2 \cdot K)$];
- t_{cl} is the clothing surface temperature, in degrees Celsius (°C).

NOTE 1 metabolic unit = 1 met = 58,2 W/m^2; 1 clothing unit = 1 clo = 0,155 $m^2 \cdot °C/W$.

With the PMV value determined , Calculate **PPD** using Equation (5), See Figure 1:

$$PPD = 100 - 95 \cdot \exp(-0{,}033\,53 \cdot PMV^4 - 0{,}217\,9 \cdot PMV^2) \quad (5)$$



Key

PMV predicted mean vote

PPD predicted percentage dissatisfied, %

Figure 1 — PPD as function of PMV

The PPD predicts the number of thermally dissatisfied persons among a large group of people. The rest of the group will feel thermally neutral, slightly warm or slightly cool. The predicted distribution of votes is given in Table 2.

Table 2 — Distribution of individual thermal sensation votes for different values of mean vote

PMV	PPD	Persons predicted to vote [a] %		
		0	–1, 0 or +1	–2, –1, 0, +1 or +2
+2	75	5	25	70
+1	25	30	75	95
+0,5	10	55	90	98
0	5	60	95	100
–0,5	10	55	90	98
–1	25	30	75	95
–2	75	5	25	70

[a] Based on experiments involving 1 300 subjects.