Field Experiment on the Effect of Interior Living Walls on Indoor Environmental Quality

Sepideh Daneshpanah

A Thesis in the

Building Science Graduate Program

Presented in Partial Fulfillment of the Requirements for the

Master of Applied Science in Building Engineering / Building Science

School of Construction and Environment

British Columbia Institute of Technology

Burnaby, BC, Canada

April 2019

BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY

Building Science Graduate Program

This is to certify that the thesis prepared

By: Sepideh Daneshpanah

Entitled: Field Experiment on the Effect of Interior Living Walls on Indoor Environmental Quality

And submitted in partial fulfillment of the requirement for the degree of:

Master of Applied Science in Building Engineering/Building Science

Complies with the regulations of the Institute and meets the accepted standards with respect to originality and quality.

Signed by the final Examining Committee:

Chair / Supervisor: Maureen Connelly

Supervisor: Karen Bartlett

Bo Li

Committee member / Examiner: Bo Li

Smalley-Hill

Supervisor Examiner, external to program:
Shauna Mallory - Hill

Approved by:

Graduate Program Director: Fitsum Tariku

Abstract

Indoor environmental quality (IEQ) has multiple aspects such as: indoor air quality (IAQ), acoustics, thermal conditions, lighting, and ventilation. This research focuses on indoor air quality and acoustics and studies the effect of interior living walls on indoor air quality and acoustical characteristics of rooms through field monitoring and experiment. Previous laboratory studies have been carried out at the British Columbia Institute of Technology (BCIT) and the University of British Columbia (UBC) on the effect of living walls on acoustics and indoor air quality. This study, examines the acoustical effect of living walls (background noise level, reverberation time, and speech articulation) as well as the effect of living walls on indoor air quality (Carbon Dioxide, Volatile Organic Compound, and endotoxin) through field measurements in the BC Hydro Theater at the Centre for Interactive Research in Sustainability (CIRS) at UBC. Existing predictive models are verified using field data, and are used to predict the effect of interior living walls on indoor air quality and acoustics in an adjoining lab.

Acknowledgements

I would like to use this opportunity to thank all the individuals who supported me in different ways to complete this study.

Firstly, I would like to express my sincere gratitude to my Supervisor, Dr. Maureen Rose Connelly, and my Co-supervisor, Dr. Karen Bartlett for their support, guidance, enthusiasm, and patience. I was very fortunate to have them both as my mentors.

Besides my supervisors, I would like to thank Tim Herron, the Building Manager at the Centre for Interactive Research (CIRS) at UBC for making things work at CIRS. Rosa Lin, and Omid Tamana at BCIT and Matty Jeronimo at UBC for their help with the equipment, and Ivan Cheung for his help with indoor air quality section of my thesis.

Also, thanks to the Sustainable Building Science Program at UBC for introducing me to different aspects of building science and sustainability, giving me the opportunity to meet great people, and providing the funding for this study with partnership with NSERC CREATE program.

Last but not the least, I would like to express my deepest love and appreciation to my parents for their endless love and support throughout my life. Words cannot express my thankfulness to them. They have been the ones who showed me how to love, and taught me not to give up on myself. Special thanks to my caring sister, Samira, who has been a second mother to me, my inspiring brother and role model, Mehdi, whom I share the most beautiful days of my life, my wonderful husband, Ali, who has been always there for me every step of the way and supported me in many different ways, and finally my smart beautiful daughter, Lillian, who waited so patiently for her mother to finish her studies. I hope I have been able to show her the value of perseverance in life.

This work is dedicated to my beloved parents

Sedigheh and Mohammadhossein

Table of Contents

List of Figures

List of Tables

Glossary and Abbreviations

Absorption coefficient - a measure of how effectively the sound energy is absorbed by a material, a value of 0 indicates no absorption and a value of 1 indicates 100% absorption

Aerosol – solid particle or liquid droplet that can stay suspended in the air for a period of time

Articulation Index (AI) – a measure of intelligibility of speech in terms of the fraction of words understood by the listener, AI of 1 indicates that all the words can be understood, AI of 0 indicates total privacy

Background noise level – noise from all sources unrelated to a particular sound that is the object of interest. Background noise may include airborne, structure borne, and instrument noise

Biophilia – a theory introduced by Edward O. Wilson which states that the human being is biologically and instinctively in need of nature

Biophilic design – a trend in green building design which incorporates nature into the design and reconnects human being with nature

Carbon dioxide (CO_2) – a colorless and odorless gas which is the by-product of human breathing, gas cooking appliances, space heaters, wood burning appliances, and tobacco smoke

Diffuse sound field – sound field in which the incident sound intensity at all frequencies are equally distributed and therefore the sound pressure level is uniform

Diffusion – the scattering of incident sound energy from a surface on reflection quantified as the scattering coefficient

Endotoxins- pro-inflammatory substances found in gram-negative bacteria which are released into the air by destruction of bacteria cell

Hydroponic – the technology of growing plants without soil

Indoor air quality (IAQ) – the quality of air inside buildings that relates to human health and comfort

Indoor environmental quality (IEQ) – the quality of indoor environment that affects health, comfort and well-being of occupants such as: thermal comfort, air quality, lighting, acoustical quality

Insertion Loss – the decrease in sound pressure level, measured at the location of the receiver, when a sound barrier is inserted in the transmission path between the source and the receiver

Living wall (LW) – wall panel(s) which contains substrate and plants that can be attached to the interior or exterior walls – a subset of green walls

Micro-organisms – the life which is too small to be seen by unaided eye

Moisture content (MC) – the ratio of mass of water to the mass of solid in a sample

Off-gassing – release of organic vapor in form of gas from a material

Particulate matter (PM) – small particles or liquid droplets suspended in the air

Relative Humidity (RH) – the ratio of the amount of water vapor in the air to the saturation at the same temperature

Reverberation time (RT) – the time it takes for the sound energy to attenuate by 60 dB

Scattering coefficient – the difference between total reflected sound energy and specular reflected energy

Sound attenuation – decrease in sound level

Sound pressure level (SPL) – logarithmic expression of the measure of the root mean square of the magnitude of sound energy, expressed in (dB), can be also expressed as A-weighted sound pressure level filtered to human perception (dbA)

Speech intelligibility index (SII) – average amount of speech available to or understood by the listener

Total volatile organic compound (TVOC) – a wide range of organic compounds found in indoor air

Ultrafine particulate matter (UFP) – a particulate matter with a diameter less than 0.1μm which can penetrate deep into lungs and enter blood stream

Volatile organic compound (VOC) – compounds that become a gas in room temperature

1 Introduction

Interior living walls have been used in many green building designs as they are aesthetically pleasing and have the capacity to reconnect people to nature. It is also thought that living walls contribute to a better indoor environmental quality, especially indoor air quality and room acoustics. Lab-scale experiments at the British Columbia Institute of Technology (BCIT) and University of British Columbia (UBC) have been completed with living walls to determine if and how they affect the indoor air quality and room acoustics. However, little field experimentation with interior living walls has been done to determine their contribution to improving indoor environmental quality. This research is comprised of field experiments to validate the predictive models from laboratory findings on the effect of interior living walls on acoustics and indoor air quality. Also, as part of this research, predictive modeling is conducted for a similar room.

Interior and exterior green walls, which are relatively new architectural trends, can bring some nature into our cities and spaces. Some sustainable building designs incorporate these technologies into their design. According to the Living Architecture magazine (2013), the green roof and wall industry is growing rapidly. As the research on living walls is limited, it is critical to investigate the effects of incorporating these systems into our biophilic and sustainable buildings.

The Biophilia hypothesis which was initially introduced by Harvard University biologist Edward O. Wilson, declares that the human being is biologically and instinctively in need of nature. However, we have designed our cities and buildings in a way that not only have we separated people from nature, but also degraded nature. Biophilic design is a concept in architecture and design in which nature is incorporated into the design, and the human being is reconnected to the nature (Kellert & Wilson, 1993).

The Green Building Context

Green building design has helped to improve indoor environmental quality. For example, the use of low-emission building materials to improve indoor air quality has helped achieve a better indoor air quality. However, not all green building designs improve indoor environmental quality. Abbaszadeh et al. analyzed the post-occupancy evaluation (POE) of 18 buildings. They found that the occupants of both green and non-green buildings are dissatisfied with the acoustical quality of their indoor environment. They also found that the majority of acoustic complaints in green buildings are related to speech and telephone intrusion between occupants. Moreover, complaints from outdoor and equipment noise was found to be higher in green buildings (Abbaszadeh et al., 2006). Excessive noise occurs when the background noise level is too high and is mainly due to poor sound isolation. Research shows that excessive noise reduces occupant performance (Ryherd & Wang, 2008).

The acoustical environment in green buildings is not acceptable when the specific design techniques used in green buildings worsen the acoustical problems. For example, the use of excess glazing to increase natural daylighting and interior glass partitions to help natural light transmission can result in decreased sound isolation and increased reverberation. Another potential conflict between green design strategies and acoustical quality is natural ventilation used to reduce energy consumption. Natural ventilation requires large penetrations in the building envelope, use of more open plan areas, and ventilation openings between spaces. These design strategies result in decreased exterior-interior as well as interior sound isolation.

Additionally, decreased mechanical ventilation due to presence of natural ventilation results in decreased background noise level and consequently lack of speech privacy. Speech privacy is achieved when the unintended listener does not understand the speech (unintelligible speech). Speech privacy is related to signal to noise ratio and is the difference between speech level and the background noise level at a given location. In open plan offices where the background noise level is low, and the speech level is high, speech privacy is a major issue. To solve the speech privacy problem, the speech energy needs to be reduced and/or the background noise level increased. Additionally, another green building design strategy contributing to acoustical dissatisfaction is the decreased use of sound absorbing materials. For example, use of exposed concrete to have a bigger thermal mass and/or radiant cooling/heating, or lesser use of acoustic tiles or carpets for indoor air quality purposes lead to increased reverberation and noise build-up. Lack of speech clarity occurs when there is excessive background noise and/or reverberation (Muehleisen, 2011). Most of the dissatisfaction from indoor acoustical environment arises from excessive noise, lack of speech clarity, and privacy.

Discomfort in indoor spaces can also be due to poor indoor air quality. Studies show that North American people spend about 90% of their time in indoor spaces. Some Canadians spend more time indoors in winter, and less time indoor in summer than Americans (Leech et al, 2002). People are exposed to higher VOCs level indoors compared with outdoors (Bruno et al., 2008). Indoor air pollution varies in different locations and at different times. The indoor pollution level depends on contaminants emission rates, ventilation, occupant behavior and microclimates (Amodio et al., 2014). People who are exposed to indoor environments constructed from synthetic materials are exposed to more than 300 contaminants daily (EPA 2009), unlike buildings built according to green building rating systems such as LEED or Living Building Challenge, which have limited the use of synthetic materials and associated emissions. Exposure to a single contaminant might not be a health hazard, but the toxicity of chemicals may add up to create major health issues. The energy crisis in 1970 lead to tightly constructed building envelopes and reduced ventilation rates; furthermore, use of synthetic building materials caused a poor indoor air quality and sick building syndrome (Wolverton, 1988). In order to solve this problem, buildings were required to be ventilated by a mechanical system (HVAC) with minimum ventilation rates according to code standards. The amount of fresh air supplied to the system was limited to reduce both the cost of conditioning and adverse environmental effects (Darlington et al., 2000).

As one of the tools to help improve the quality of indoor air, many have investigated the effect of plants on indoor air quality. However, the majority of these studies have investigated the effect of plants on indoor air quality in experimental chambers, and not in the field. NASA in 1980s attempted to reduce the concentration of air contaminants building up in enclosed spaceships using plants. In 1984, NASA researchers were able to remove formaldehyde from an enclosed laboratory chamber by using plants. A more recent study conducted in the field in this area was completed by Darlington and his colleagues who developed a bio-wall. Air is circulated through the bio-wall which is effectively a biological filter consisting of bio-scrubber, aquarium, and planting. The bio-wall effectively cleans the air using this bio-filter; however, this is very different from panelized living wall system to be examined as part of this thesis in the sense that in a panelized living wall the air is not forcibly circulated through the panels (Darlington et al., 2000).

A field study by Wood et al. verified that potted plants can be a supplement to mechanical ventilation system and help reduce indoor air pollution (Wood et al., 2006).

The majority of studies on the capacity of plants to remove VOCs have been done in the laboratory. There is the need for the field studies to verify the lab results as the dynamic of the real-life setting is different than in the laboratory. In real-life the emission of VOCs is constant and the capacity of plants in the removal of contaminants might be affected by exposure time. On the other hand, the CO_2 in real-life is higher than ambient whereas in completed laboratory testing, the CO_2 level is equal to ambient level. The increased relative humidity in the chambers due to the presence of plants is a compound variable that might also affect the results. Therefore, it is critical to validate the lab results in the field (Dela Cruz et al., 2014).

Living Wall Technology

There are three types of green walls: green facades, living walls, and retaining living walls. The living walls are either soil-based or hydroponic, and have three major components: The carrier panel, substrate, and plants. The living walls can be designed for interior or exterior installations. In a living wall, the plants roots are in a structural support (i.e. carrier panel) fastened to the wall, and not the ground. The substrate held in the carrier panel is responsible for providing nutrient and water to the plants. The carrier panel can be made from plastic, stainless steel, polypropylene fabric, or many other materials. The substrate can vary in terms of the percentage of organic matter, aggregate, and moisture content. The substrate can also be manufactured from mineral or natural fibers. The plants can differ physiologically and this determines the amount of light and water they require. Irrigation is usually by an automatic closed-circuit irrigation system (alternatively hand-watered). Some systems have water reservoir, and may have an in-line fertilizer. Standard room size windows can provide enough natural light for the plants (about 5 to 10 μmole/m^2/s). Wherever there is not enough natural light, the plants can grow under artificial lighting (Weinmaster, n.d.) (greeroofs.org).

Figure 1 - Interior living wall installation at the Centre for Architectural Ecology, Burnaby, BCIT.

Indoor Environmental Quality and its Impacts

Indoor environmental quality has multiple aspects which each have to be evaluated for a comprehensive indoor environmental quality assessment of a building. These aspects include: indoor air quality, acoustics, thermal conditions, lighting, and ventilation. All of these aspects directly affect occupant’s health, well-being, comfort, productivity, and satisfaction. In this research, the focus is on indoor air quality and acoustics of the room, and the effect of interior living walls on these two aspects of indoor environmental quality.

Green building design is a movement with a goal of creating a healthy environment and has been advanced in part to combat sick building syndrome. Sick building syndrome is a medical condition where people suffer from symptoms of illness or feel unwell for no apparent reason in a building, and the unwell feeling increases the more time people spend in that building. These environments should promote health and well-being as well as productivity. A study of indoor environmental quality satisfaction of green versus non-green buildings shows that the occupants of green buildings are generally more satisfied with indoor air quality and thermal comfort of their workplace, however, they are less satisfied with acoustical environment and lighting (Abbaszadeh et al., 2006). The primary reason for acoustical dissatisfaction is the lack of acoustic criteria, adopted by the owners, in the design program. For example, the only time that LEED has considered acoustical criteria is for secondary schools (and not universities) (Muehleisen, 2011). The net result is poor acoustical design, and subsequently, occupant dissatisfaction.

Noise in office spaces can be from HVAC systems, occupants (speech), and equipment. Acoustical quality of office spaces is associated with sick building syndrome and can affect annoyance, performance, and speech intelligibility (Keighley 1970).

A-weighting (dBA) acoustical measurements filter out the lower and higher frequencies in a similar manner as the human ear, and is often used as a single number performance matrix in acoustical criteria and evaluations of background noise. However, HVAC system may produce low or unbalanced frequency sound which is not captured in the single number A-weighted sound level reading, therefore, more rigorous criteria and evaluation are required. The majority of acoustic guidelines are applicable to industrial noise exposure with a high noise level can exclude frequency-based noise spectrum. However, in an office space with a moderate noise level of 50-

80 dBA, annoyance, speech, and reduced work performance are issues that require frequency spectrum evaluation (Keighley 1970) (Kjellberg 1994). Study by Waye et al. found that the level of annoyance and disturbed concentration due to noise is dependent on the sound pressure levels of dominant low frequency noise and the total dBA of the noise (Waye et al. 1997). A limited amount of research suggests that low-frequency noise is more disturbing compared with high-frequency noise (Bengtsson et al., 2004) although it depends on the type of sound and context. Annoyance due to noise might interfere with one's activities, or cause stress leading to headache, tiredness, and irritability. Speech may be less articulated and work performance might reduce due to noise (Spengler et al., 2001). In green building design, reduced amounts of sound absorbing materials, natural ventilation, and the excessive use of glass has led to a low-quality acoustical environment. Natural ventilation requires open plan areas with partial or low partitions. Where air flows, sound wave flows. In naturally ventilated buildings, the background noise level from HVAC is very low, and the increased use of low absorbing materials such as concrete and glass, reduces the amount of noise absorption. Additionally, use of glass in the building envelope for providing natural lighting, reduces sound isolation. All of these design strategies result in lack of speech privacy, excessive noise and reverberation, as well as lack of speech clarity (Mueheleisen, 2011).

Hodgson evaluated six green office buildings to determine how their design affects the acoustical environment. He measured noise levels, reverberation time, speech intelligibility index, and noise isolation. A survey was also completed with a small sample of occupants. He concluded that reverberation time at frequencies between 100Hz and 2500Hz is very high in open plan offices, and the use of more sound absorbent material can reduce the reverberation time.

Noise levels were also found to be high close to the exterior walls especially those with open windows. (Hodgson, 2008).

The indoor environmental quality of green and non-green buildings on the UBC Point Grey campus was studied by Khaleghi et al. The indoor air quality (VOCs and ultrafine particulate concentration), acoustical condition (noise level and reverberation time), and ventilation rates were monitored. They concluded that naturally ventilate green buildings have lower ventilation rates, and unacceptable ultrafine particle concentration as there is no air filtration system (the air is exchanged directly between indoor and outdoor). Also, the indoor air quality is greatly affected by opening the windows. In general, mechanical ventilation of the non-green buildings provides a better indoor air quality, but higher HVAC noise which can be controlled by carefully selected components and may even benefit acoustical privacy. The TVOCs level was found to be higher in furnished rooms with carpet and ceiling tiles; therefore, the materials need to be carefully selected to minimize TVOCs emissions. In general, there is a strong relationship between building features and indoor environmental quality (Khaleghi et al., 2011).

The Center for Interactive Research on Sustainability (CIRS)

The Centre for Interactive Research on Sustainability (CIRS) was used in this research to conduct field measurements. CIRS is a LEED (Leadership in Energy and Environmental Design) Platinum building on UBC Point Grey Campus. This 4-storey building was completed in 2011 and includes offices, labs, meeting rooms, an auditorium, and a café in the atrium. The CIRS building was the first building for "the campus as a living laboratory initiative" project at UBC. This building is equipped with a network of sensors and controls that collect data for research projects as well as ensuring that all the systems are operating as planned. This building uses passive design strategies and advanced sustainable technologies. Interior living walls are one of the technologies that is planned to be incorporated into CIRS building.

In CIRS, limited acoustic features have been utilized to provide a comfortable and healthy acoustical environment. For example, 6' x 6' flat acoustic tile panels (reflective cloud) are suspended from the wooden ceilings in the private offices. However, in the meeting rooms, a whitewashed concrete has been used instead of wooden ceiling and acoustic panel. In open plan offices, 1.5 m high fabric partitions have been used to help absorb sound. In this building, the majority of flooring finish is carpet which absorbs high-frequency sound. There is very little background noise level from HVAC system, as heating is through radiant floor heating. The low background noise level leads to lack of speech privacy. There is lack of speech privacy in the meeting rooms and private offices due to internal openings designed to allow natural ventilation (CIRS Manual).

CIRS utilizes a mixed mode ventilation system consisting of both passive and mechanical ventilation. Operable windows give the occupants the ability to have some level of control over the air flow and temperature. Cross ventilation moves the air from smaller perimeter spaces to the central atrium by stack effect, the air is exhausted through the rooftop vents. The mechanical ventilation is provided by two air handling units (AHU) which supply fresh air into the building. One of the AHUs is dedicated to supplying fresh air to the auditorium on the first floor, and the second one serves various parts of the building. The AHU provides filtered cooled or warmed air to the auditorium through diffusers located underneath the seats (displacement ventilation). The second AHU which serves the other parts of the building is heat only and is intended to supplement natural ventilation. Fresh heated air is supplied through the floor plenum and the swirl diffusers can be adjusted manually by the occupants to control local air flows. Figure 2 and Figure 3 illustrate cross and displacement ventilation; this design affects the acoustics of the room as it allows sound to propagate from an office through the hallway and into another office. The service floor plenum can also potentially act as low-frequency sound absorbers in each room.

In CIRS there are heat exchangers with hot water as the heating source. This system is connected to a network of sensors which control the radiation valves (CIRS manual).

Figure 2: General cross ventilation diagram (section/perspective) in open-plan office areas in CIRS (CIRS Manual).

Figure 3: Section/perspective of the diffusers in the raised floor (CIRS Manual).

Research Statement and Objectives

This research project investigates, through field-scale monitoring and experiments, the effect of interior living walls on room acoustics (noise level, reverberation time, and speech articulation) as well as indoor air quality (CO_2, TVOCs, ultrafine particulate concentration, relative humidity, and endotoxin). The goal is to develop an indoor environmental quality field-scale model as a verification of a previously developed lab-scale models. This model will account for the dynamic nature of real spaces by incorporating the spatial and temporal variations of the field site. The predictive model will then be used to predict the effect of living walls on the indoor environmental quality elsewhere in the building.

Monitoring and base measurements were completed in a number of spaces in CIRS: office spaces, meeting rooms, auditorium, and the atrium. The field monitoring and measurements of the living wall installations were conducted in the BC Hydro Theater. Refer to Appendix B for architectural floor plans of CIRS.

Collaborative Research Framework

Lab experiments at UBC and BCIT have been completed as part of two previous Master level research thesis projects. These lab experiments utilized three different living wall systems to investigate the living walls acoustical and environmental characteristics and determine if and how the living walls affect indoor air quality and room acoustics. This research uses the applicable lab data and findings from both of the previous thesis projects and contributes to further understanding of the impact of living walls on indoor environmental quality by validating the lab-scale models in a dynamic and realistic field setting.

2 Literature Review

Poor indoor environmental quality is associated with sick building syndrome, and has costs associated with illness (respiratory diseases, allergy, and asthma symptoms), poor performance, and increased absenteeism from work. Both for the design and retrofit, it should be considered that improving the indoor environmental quality is cost effective considering increased health and productivity (Seppanen & Fisk, 2006). It is important to understand the costs associated with poor indoor environmental quality, so that building professionals consider improvement of indoor environmental quality. Seppanen et al. developed a model to estimate the costs associated with improved indoor environmental quality, and showed that there is a relationship between indoor environmental quality improvement and financial savings. The financial savings included: reduced medical cost, reduced absenteeism due to sickness, higher workers performance, and lower building maintenance costs due to decreased indoor environmental quality complaints. He estimated the cost associated with poor indoor environmental quality to be higher than heating energy costs (Seppanen et al., 1999).

Further studies indicated that by providing better indoor environmental quality, billions of dollars can be saved with productivity gain (Spengler et al., 2001). Another study showed that poor indoor environmental quality adversely affects students' health and performance in schools mainly due to health effects associated with indoor pollutants (Mendell & Heath, 2005).

Considering the effect of indoor environmental quality on health and well-being of the occupant, it is essential to make an effort to design spaces that provide comfortable and healthy environment. This research thesis focuses on two aspects of indoor environmental quality:

acoustics and indoor air quality. The following section is a review of fundamentals, impact of living walls on acoustics and indoor air quality, and modeling of indoor environmental quality.

2.1 Acoustics

The acoustical environment is an important aspect of indoor environmental quality. Occupants are usually dissatisfied with the environment as a result of a lack of adopted acoustical criteria in the design program. According to General Services Administration (GSA), the acoustical environment is one of the most difficult aspects of interior spaces to design and control, and has a great effect on occupants' health and well-being. Also, acoustical conditions affect comfort, productivity, and ability to communicate. Acoustical quality is achieved when a space provides a context for easy interactions, and private conversations (GSA, 2011). The acoustical quality of interior spaces can be defined by various factors such as background noise level, reverberation time, and speech articulation. These factors are described in the following section.

2.1.1 Acoustic Measures

2.1.1.1 Background Noise Level

Background noise is defined as "noise from all sources unrelated to a particular sound that is the object of interest", including airborne, structure borne, and equipment and instrument noise (ASTM C634-13), and is the continuous sound pressure level at a given location. Interior background noise level depends on ambient noise level from the outside such as traffic, construction, people, building systems, HVAC, building envelope (open/close windows), and furnishing characteristics. Background noise level is measured in an unoccupied furnished room when the building services and utilities are operating at maximum level.

Guidelines recommend acceptable background noise level of acoustical environments suitable for the occupants to perform various activities, such as communicating, sleeping, and working (e.g. maximum of 45 dBA for a classroom according to LEED-2007 criteria for schools). Additionally, various methods have been developed to evaluate background noise levels. One method is the Noise Criterion (NC) method in which, after measuring the background noise level at each octave band centre frequency, the background noise level is plotted against noise criterion curves per standard to determine the NC rating (ASHRAE, 2009). The acceptable NC level is based on the use of the space. NC curves are illustrated in Figure 4, and are primarily designed to specify the maximum background noise level over the frequency spectrum for HVAC designers. These curves were developed by Beranek in 1957 to assist with designing satisfactory environments for speech intelligibility and living. Table 1 outlines recommended NC range by ASHRAE for different types of spaces.

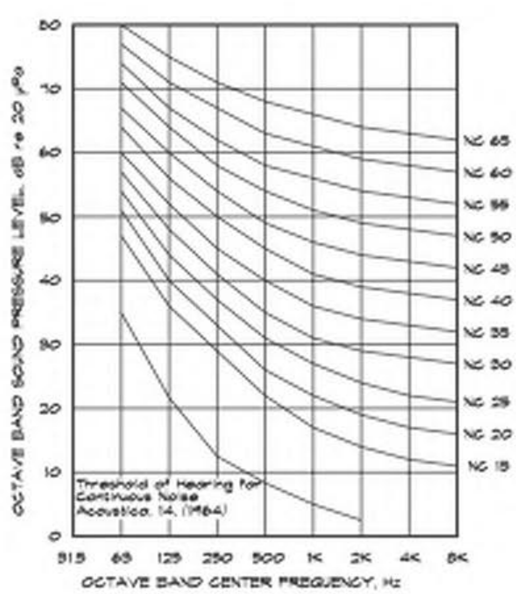


Figure 4: Noise criterion curves (Beranek, 1957).

Table 1: Interior design goal for office spaces (ASHRAE, 2009).

Type of Space	Recommended NC Range
Executive offices	**25 to 30**
Conference rooms	**25 to 30**
Private offices	**30 to 35**
Open plan areas	**35 to 40**
Computer equipment rooms	**40 to 45**
Public circulation areas	**40 to 45**

Another method of evaluating background noise level is to determine the Balanced Noise Curve in a space. The Balanced Noise Criterion curves are illustrated in Figure 5. These Balanced Noise Criterion curves are an extension to NC curves and account for occupant noise and very low frequencies, and have lower permissibility for high frequency noise.

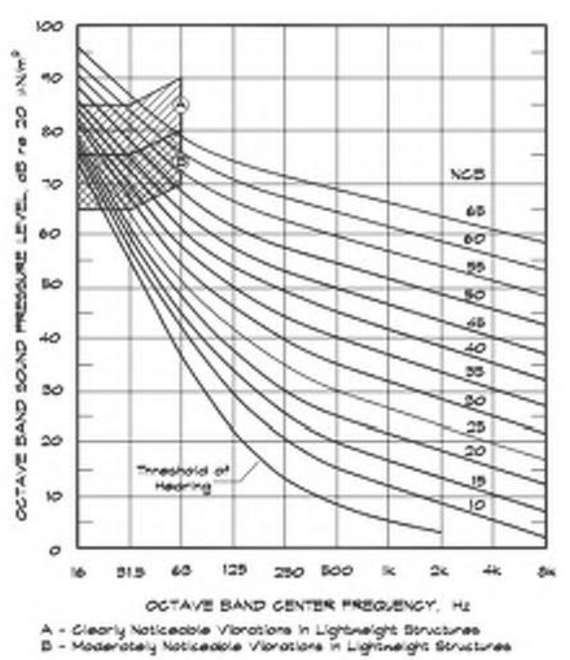


Figure 5: Balanced noise criterion curves (Beranek, 1989).

2.1.1.2 Reverberation Time

Reverberation time (RT) is an important measure of the quality of architectural room acoustics, and is defined as the time it takes for the sound to decrease by 60 dB (Eq. 1 – Wallace Sabine). When a sound is produced, its energy is absorbed by the air and surfaces in the room. The reverberation time in a space depends on the volume of that space, the acoustic absorption of the surfaces, and the surface areas. Sabine's equation relates reverberation time with the volume of the space and acoustic absorption of the surfaces. Optimum reverberation time for different spaces has been proposed by various standards.

The absorption coefficient of the surface materials is known to be the most important influencing factor on the reverberation time (Huber & Bednar, 2008).

$$T_{60} = 0.161 \, {}^{V}\!/_{A}$$

Eq. 1: Reverberation time (Wallace Sabine).

Where,

T_{60}= Reverberation time or the time it takes for the sound to decrease by 60dB (s)
V= Volume of the room (m^3)
A=Total surface absorption of the room= $S_1\alpha_1 + S_2\alpha_{2+}\, S_3\alpha_{3+\ldots+}\, S_n\alpha_n$ (Sabine)

Sabine's equation can return a non-zero result for a perfectly absorptive room, yet remains one of the most reliable prediction models. Other formulas have been developed to calculate reverberation time. These formulas are developed by Norris- Eyring, Millington- Sette, Fitzroy, and Kuttruff. It should be noted that the Sabine and Norris- Eyring reverberation formulas that are commonly used to predict reverberation time, assume a diffuse sound field in a quasi-cubic room. However, in reality, most sound fields are not perfectly diffuse, especially in rooms with non-uniform surface absorption. Sabine's equation generates a longer reverberation time than Eyring because it does not account for air absorption, and this difference becomes smaller as the total amount of sound absorption decreases (Bistafa & Bradley, 2000).

2.1.1.2.1 Sound Absorption Coefficient

When sound waves interact with materials, the energy of the incident sound is reflected (specularly or scattered), transmitted, and absorbed as illustrated in Figure 6. The sound absorption coefficient is the fraction of sound energy absorbed by the material over the total incident sound. Absorption coefficient is a value between zero and one. If the entire incident sound is absorbed, the absorption coefficient is 1.0. Absorption coefficient depends on frequency and the angle of incidence (Long, 2014).

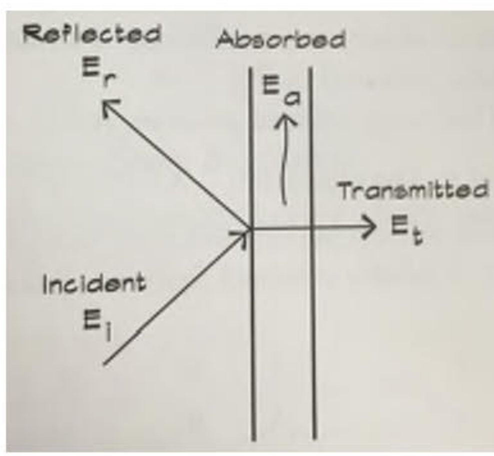


Figure 6: Interaction of sound with a surface (Long, 2014).

In architectural acoustics, material absorbers are divided into porous, panel, and resonant absorbers. Porous absorbers are the most common types. In porous materials, the sound energy is absorbed and degraded slowly into heat by viscous losses (mostly degrades high frequencies) and heat conduction losses (degrades low frequencies). In general, porous materials absorb mid and high frequency sound. If the material thickness is sufficient, these materials can absorb low frequency sound as well (Long, 2014).

The noise reduction (NR) is based on calculated total room absorption using reverberation time data. Eq. 2 and Eq. 3 below calculate the total absorption (Sabine) and noise reduction (dB) respectively. Using Eq. 3, the decrease in ambient noise level due to presence of the living walls is calculated by a logarithmic function of the difference between the amount of absorption in the room with and without the living walls.

$$\mathbf{A = 0.161\,\frac{V}{RT}}$$ Eq. 2: Total Sabine (Wallace Sabine).

Where,

V = Volume of the room (m3)
RT = Room reverberation time (s)

$$\mathbf{NR = 10\log\left(\frac{A2}{A1}\right),\ where\ A = \alpha_1 S_1 + \alpha_2 S_2 + \alpha_3 S_3 + \ldots}$$ Eq. 3: Noise reduction.

Where,

A1= Room's total Sabine at baseline
A2 = Room's total Sabine with living walls
NR = Noise reduction in the room (dB)
α = Noise absorption coefficient of each material
S = Total area of that material

2.1.1.3 Speech Articulation

Speech articulation is a measure of the fraction of words that is understood by the listener. The degree to which noise inhibits intelligibility depends on signal to noise ratio. Signal to noise ratio is speech or signal level minus the background noise level (dB). The background noise level may be significantly affected by reverberation time. Signal to noise ratio is calculated as:

Signal to noise ratio= Sound signal level - Sound signal attenuation at receiver position - background noise level at receiver position (Long, 2014).

The articulation index (AI) method is one of the methods of measuring speech intelligibility in a space. Articulation index calculations can account for the speech masked by low-frequency background noise level. Articulation Index is a number between 0 to 1. AI value of 1 translates into 100% of words are understood by the listener. For AI values above 0.7 intelligibility is excellent, between 0.5 to 0.7 intelligibility is good, and below 0.3 is poor. Table 2 from ANSI S3.5 (1997) summarizes the relationship between articulation index and other measures.

Table 2: Relationship between intelligibility and privacy (ANSI S3.5).

Articulation Index	Signal to Noise Ratio	% of Sentences Understood	Intelligibility	Privacy
>0.4	**>0 dB**	**>90**	**Very Good**	**None**
0.3	**-3 dB**	**80**	**Good**	**Poor**
0.2	**-6 dB**	**50**	**Fair**	**Transitional**
0.1	**-9 dB**	**20**	**Poor**	**Normal**
<0.05	**-12 dB**	**0**	**Very Poor**	**Confidential**

2.1.2 Impact of Interior Living Walls on Acoustical Quality

Acoustical quality in an office space is achieved when the space provides appropriate acoustical environment for interaction, confidentiality, and concentrative work. The sound and acoustic environment is often neglected as sound is invisible and criteria may not have been adopted into the design program. Typically, with an open plan office concept, poor acoustical quality is a major cause of employee dissatisfaction (GSA, 2011).

One of the first studies on the acoustical characteristics of plant species was completed in 1971 by Aylor. He studied the propagation and transmission of random noise over cultivated soil, corn, hemlock plantation, open pine stand, and dense hardwood brush. He concluded that greenery reduces sound transmission especially at higher frequencies, as scattering is enhanced. The sound transmission is decreased with increasing leaf density, width, and thickness. In the case of no leaves, the stems reduce the sound. The ground was found to attenuate lower frequency sound where scattering is not effective (Aylor, 1971).

Martens also investigated the impact of foliage on sound transmission through areas of vegetation. He modeled forests in an anechoic chamber and found that the foliage amplifies noise in mid-frequency range, and filters noise in high frequencies. The amount of filtration is governed by species, size, and biomass of plants (Martens, 1980).

Aylor et al. in another study examined the effect of an Ivy-covered façade on street reverberation time. They found that the effect is negligible except around 4000Hz. They also suggested that the reduction of reverberation time at 4000Hz is due to scattering (Aylor et al., 1973).

Martens and Michelsen studied the absorption of acoustic energy by four different plant species in the lab environment. They used a laser vibrometry method by which the vibration velocity of small areas on plants over a wide range of frequency is measured. They found that the plant leaves absorb acoustic energy and convert it to heat. The amount of acoustic absorption depends on the orientation of the leaf. The absorbed energy was found to be very small; however, it will be considerable with increasing number of plants (Martens & Michelsen, 1981).

One of the field experiments on the acoustical characteristics of living walls was completed by Wong et al. in 2010. They experimented using eight different vertical greenery systems installed in a park. The effect of these systems on the insertion loss of building walls was evaluated. They set up nine concrete walls in the park, and covered each with a different greenery system. A bare concrete wall was used as a “control wall”. To measure the insertion loss, they measured the sound pressure level at a distance from the walls while a sound source was put behind it. The sound pressure level difference, in dB, was interpreted as the insertion loss of different vertical greenery system. The sound pressure level in front of the “control” wall was used as the baseline. This team also explored the absorption coefficient of these greenery systems in a reverberation chamber. Their experimental setup is illustrated in Figure 7 and Figure 8.

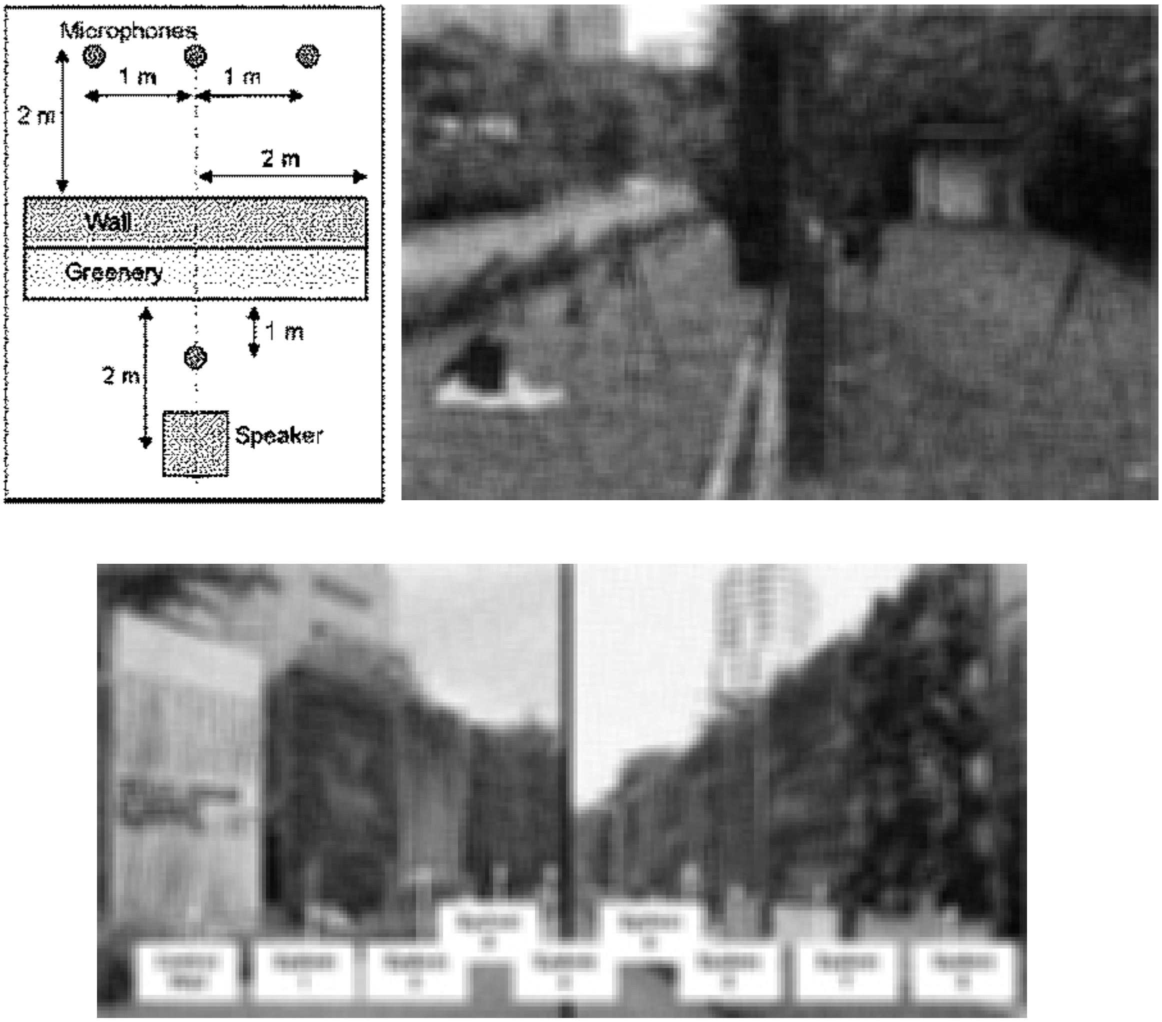


Figure 7: Vertical greenery system experimental setup in the park (Wong et al., 2010).

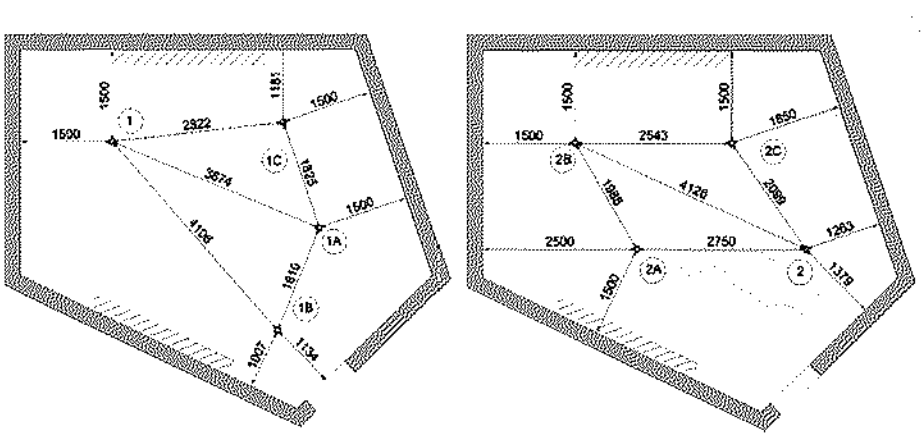


Figure 8: Testing sound absorption coefficient of vertical greenery systems in reverberation chamber (Wong et al., 2010).

They concluded that the substrate of vertical greenery systems contributes to a large sound attenuation at low to medium frequencies, while at high frequencies, the sound is scattered by the greenery and less insertion loss was observed. Reverberation time was reduced by the vertical greenery systems especially at 200-1000Hz. The absorption was found to be lower at 1000-5000Hz (Wong et al., 2010).

Another study on acoustical characteristics of plants was done by Horoshenkov et al. They studied the acoustic absorption of five different plants typically used in living walls. They also studied two types of soil: a light density soil and a heavy density clay base soil. An impedance tube was used to measure the sound absorption. The amount of absorbed acoustic energy was found to be mainly dependant on leaf area density and angle of leaf orientation. They also found that light density soil absorbs more acoustic energy (Horoshenkov et al., 2013).

Vegetated roofs are found to have highly absorptive characteristics. Research has shown that 20 to 60% of sound energy is absorbed by green roofs (Connelly, 2011). According to studies, these roofs can have a noise reduction coefficient ranging from 0.2 to 0.63. It was also found that the substrate provides an important role in absorbing sound. Increased percentage of organic matter leads to increased absorption, and increased moisture content and compaction lowers the absorption of the vegetated roof. In general, the sound absorption capacity of vegetated roofs depends on substrate depth, plant community establishment, and moisture content of the plants and substrate (Connelly & Hodgson, 2015).

Smyrnova et al. studied the diffusion coefficient of plants. Diffusion coefficient indicates the uniformity of the reflected sound. In other words, diffusion coefficient shows how uniformly the scattered energy is distributed from the plants. They found that plants diffusely reflect sound energy at middle and high frequencies, and reconfirmed that leaf size and stems play an important role in diffusivity of plants. They also found that scattering from the plants depends on the angle of incidence of sound (Smyrnova et al., 2012).

A recent study by Akbarnejad at the Centre for Architectural Ecology at British Columbia Institute of Technology (BCIT) examined the acoustical characteristics (absorption and scattering coefficients) of interior living walls and their effect on room acoustics. The experiments were done in a reverberation chamber and the effect of substrate, carrier panel, and plants were studied separately as well as the whole living wall system (Akbarnejd, 2017). Akbarnejad and Connelly, 2017 suggested a predicative model for absorption (Sabine) of living wall panels per below:

Table 3: Akbarnejad Connelly 2017 predictive model (Akbarnejad, 2017).

Frequency Band (Hz)	Predictive model (Sabine)
125	**S125= 0.1054N + 0.1435**
250	**S250= 0.6485N + 0.7537**
500	**S500= 0.4346N + 0.7440**
1000	**S1000= 0.2665N + 0.7906**
2000	**S2000= 0.4358N + 0.8144**
4000	**S4000= 0.6896N + 0.8515**

Where,

N = Number of living wall panels
S = Sound absorption (Sabine) at each frequency band

2.1.3 Acoustics Modeling

Numerical modeling along with computer modeling have been used to predict the acoustical characteristic of.

In addition to Sabine and Eyring formulas previously discussed, many different formulas have been used to predict reverberation time in rooms with non-uniform surface absorption (Bistafa and Bradley, 2000).

On the other hand, there are generally two main types of computer programs used to predict acoustical environment: wave-based and ray-based, the latter being the most common type. ODEON is one of the popular software programs used for predicting acoustic properties of interior spaces that uses image-source method and ray tracing. The software requires the geometry, and the surface properties of absorption and scattering coefficients to predict room acoustics.

Bistafa and Bradley examined the computer models along with some of the numerical models, and compared them with experiments to determine their accuracy. They simulated a classroom with varying sound absorptions. Their conclusions and the percentage error of each of the formulas and computer models are shown in Table 4 and Table 5. They assumed that a 10% error is satisfactory for practical applications. As it is shown in this table, none of the models for predicting reverberation time has less than 10% error. Since the models all have high percentage error, they need to be calibrated to predict reverberation time, more precisely, for non-uniform surface absorptions. Calibration procedures consist of measuring the reverberation time in a room with similar characteristics and model the room in the computer program, and finally adjust the computer model based on the measured reverberation time. This can be a reliable way to study the acoustical properties of a room (Bistafa & Bradley, 2000).

Table 4: Average relative error of numerical models in predicting RT (Bistafa & Bradley, 2000)

Absorption Exponent	Overall Average Relative Error (%) Frequency Bands Included in the Averages		
	1 kHz	500 Hz – 2 kHz	125 Hz – 4 kHz
Sabine	**38.8**	**31.6**	**21.5**
Eyring	**42.6**	**35.7**	**24.7**
Millington	**36.1**	**30.4**	**21.1**
Cremer	**26.7**	**23.9**	**17.4**
Kuttruff	**68.0**	**63.5**	**49.3**
Fitzroy	**92.0**	**95.8**	**65.7**
Arau-Puchades	**22.9**	**22.7**	**16.7**

Table 5: Average relative error of computer models in predicting RT (Bistafa & Bradley, 2000)

Computer Program	Overall Average Relative Error (%) Frequency Bands Included in the Averages		
	1 kHz	500 Hz – 2 kHz	125 Hz – 4 kHz
Raynoise 3.0	**40.1**	**37.8**	**32.8**
	44.7	**42.7**	**31.6**
Odeon 2.6	**136.7**	**135.5**	**110.2**
	29.5	**30.8**	**23.0**

2.2 Indoor Air Quality

2.2.1 Indoor Air Quality Measures

One of the aspects of indoor environmental quality is indoor air quality that affects the health, well-being, and performance of occupants. The quality of indoor air reduces when there is not sufficient ventilation. The ventilation system is responsible for diluting the contaminated indoor air with clean, fresh, and conditioned outdoor air, and finally deliver it to the interior spaces in a balanced way. Insufficient ventilation can lead to discomfort, health problems, and reduced productivity. As plants may contribute to providing a better indoor air quality, multiple criteria have been selected in this research to assess the effect of interior living walls on indoor air quality.

2.2.1.1 Carbon Dioxide

Carbon dioxide (CO_2) is a colorless and odorless gas. CO_2 in inside air is the by-product of human breathing, gas cooking appliances, space heaters, wood burning appliances, and tobacco smoke. The ambient CO_2 level varies according to seasons, weather, and industrial exhaust. (Hess-Kosa, 2002). However, the major source of CO_2 in indoor air is generated by the occupants' respiration. Seppanen et al. measured the CO_2 in office buildings to be between 350 to 2500ppm (Seppanen et al, 1999).

ASHRAE 62.1 2013 recommends the CO_2 concentration in indoor air not to exceed about 700ppm above ambient level which is 300 to 400ppm. This applies to fully occupied spaces and equals a level of about 1000ppm. It should be noted that high concentration of indoor CO_2 may be associated with insufficient ventilation, lack of air movement, or unusually high occupancy level.

Carbon dioxide rarely exceeds the point that causes significant health impact. However, it can be used as an indicator of ventilation efficiency (Hess-Kosa 2002). In many studies, carbon dioxide has been used as an indicator of ventilation efficiency as well as a surrogate for concentration of other contaminants generated by the occupants or off-gassing pollutants from building materials. However, CO_2 concentration is not necessarily an indication of all other contaminants. CO_2 uptake by plants does not necessarily indicate plants contaminant uptake capacity. Apte et al. in an analysis of CO_2 concentration in office buildings concluded that there is a strong relationship between CO_2 concentration and sick building syndromes such as: sore throat, irritated nose and sinus, and tight chest. This study suggests that reducing the indoor CO_2 concentration to outdoor level (about 350ppm) will reduce the adverse health effects by 70 to

85 percent. It should be noted that there is no correlation between CO_2 concentration and sick building syndrome; however, CO_2 concentration is an indicator of other pollutants' concentration in indoor air that might be related to sick building syndrome (Apte et al., 2000).

As plants take up CO_2 and many other contaminants through photosynthesis, they may be able to help ventilating indoor spaces.

2.2.1.2 Volatile Organic Compound

Volatile organic compounds (VOCs) are organic chemicals with very low boiling point that result in molecules evaporating at room temperature from the liquid or solid form and entering the surrounding air as gas. The source of VOCs indoors is often chemicals used in manufactured product. There are several sources of indoor VOCs such as: common building materials, furnishings, cleaning products, paints, caulking, glues, cosmetic sprays, varnishes, interior furnishings such as furniture, tiles, rugs, carpets, and draperies (Samfield, 1992). Human activities such as cooking, cleaning, and smoking also produce VOCs (Kostiainen, 1995).

The VOC concentration is often higher in indoor air due to the off-gassing of materials at room temperature. As people spend most of their time indoors, it is critical to pay close attention to indoor air pollutants such as VOCs. Kostiainen measured VOCs in normal houses versus houses with residents complaining from symptoms of sick building syndrome. He found that the majority of sick buildings have higher VOCs concentration; however, there were some sick houses that had similar VOCs concentrations as a normal house. Therefore, he suggests that other indoor air criteria need to be investigated for a full understanding of indoor air quality (Kostiainen, 1995).

The adverse health effects caused by VOCs involve one or the combination of: eye, nose, and throat irritation, headache, lightheadedness, and nausea (Hess-Kosa, 2002). According to

World Health Organization (2009), benzene in indoor air can cause blood dyscrasias (disorder of the blood due to presence of abnormal material in blood) and formaldehyde can cause sensory irritation and nasopharyngeal cancer (upper part of throat behind the nose) (WHO, 2009).

Although industrial exposure to VOCs is higher than office and residential spaces, the mix of chemicals results in occupant dissatisfaction in office and residential spaces, as up to 300 chemicals or more can be found in these spaces. In offices, VOCs originate from outside air, furniture off-gassing, office equipment, cleaning products, construction and renovation activities, environmental pollution, and industrial exhausts (Hess- Kosa, 2002). Even if the concentrations are low for each type, they can add up and cause illness or sick building syndrome. Sick building syndrome is known by United States Environmental Protection Agency (EPA) as the reason for one-third of absenteeism, and therefore, lost money. On the other hand, short term exposure to VOCs can cause eye and respiratory irritation, visual disorders, dizziness, headache, and memory impairment. Long term exposure can damage liver, kidneys, and nervous system, and may even cause cancer (Amodio, 2014). As major sources of VOCs in indoor air are found within the building, monitoring the changes in VOCs with and without living walls gives information on the effect of living walls on VOCs level.

2.2.1.3 Particulate Matter

Particulate matter as an air pollutant is made of very small particles, and also liquid droplets that contain acid, metals, organic chemicals, and dust. Particulate matter is divided into different categories based on their aerodynamic diameter. PM_{10} measurements contain ultrafine ($PM_{0.1-2.5}$) and coarse ($PM_{2.5-10}$) particles. The number of these particles increases as the particle diameter decreases. On the other hand, the mass decreases with decreasing particle diameter.

In a PM_{10} sample, the majority of particles are ultrafine, but this makes up a small portion of sample's mass (Anderson et al., 2012). Figure 9 illustrates a hypothetical particle distribution.

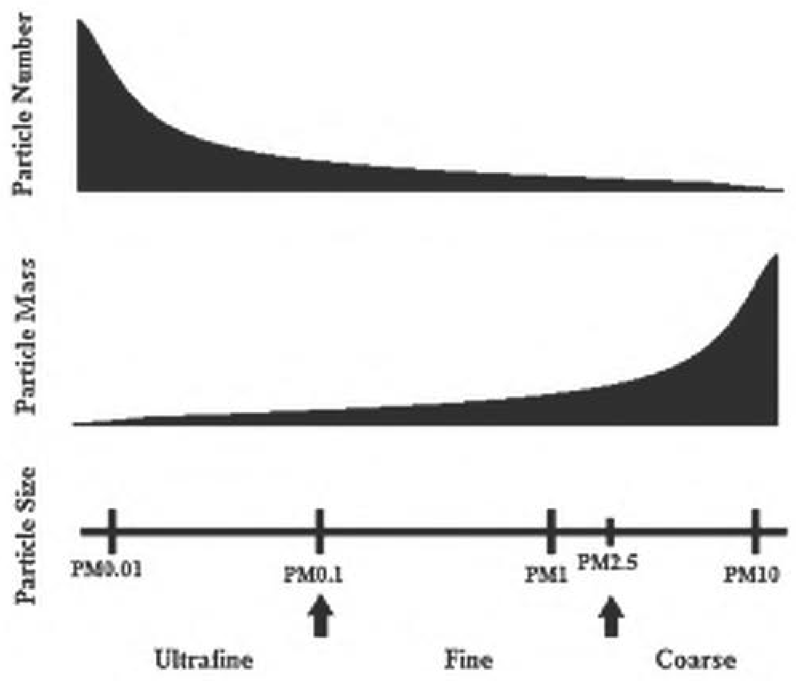


Figure 9: A particle distribution based on size, mass, and number (Anderson et al., 2012).

The sources of particulate pollution can be natural sources such as volcanoes and dust storms, or anthropogenic sources such as construction dust, combustion products, and industrial processes. The health hazards are mostly associated with ultrafine particles as they penetrate deeper into lungs. There is a significant correlation between ultrafine particulate concentration and sick building syndrome complaints (Spengler et al., 2001).

Research has verified an association between fine particulate matter and minor restrictions in activity and respiratory diseases that might lead to work loss and significant disability in adults (Ostro & Rothschild, 1989). A Canadian study found correlation between long-term exposure to ambient $PM_{2.5}$ and lung cancer (Hystad et al., 2013). According to the World Health Organization (WHO), particulate matter in the air is the 13th cause of mortality. It is estimated that particulate matter in the air leads to 800,000 premature deaths every year. Particulate matter, through systemic inflammation, contributes to cardiovascular and cerebrovascular diseases. Research has shown that long-term exposure to particulate matter leads to a higher rate of cardiovascular incidents and death (Anderson et al., 2012). Exposure to particulate matter also leads to premature mortality (Chow et al., 2006). A national study of non-immigrant Canadians found that long-term exposure to $PM_{2.5}$ is associated with death. It was also found that even exposure to very low concentrations, a few micrograms per cubic meter, can be fatal (Crouse et al., 2012). Long-term exposure to ultra-fine particulate matter is found to be a risk factor for cardiopulmonary diseases and lung cancer (Pope et al., 2002).

Another study recorded emergency room visits in eight Seattle hospitals, and found that even short-term exposure to low concentration of particulate matter (PM_{10}) is associated with increased respiratory irritation symptoms, use of asthma medications, hospitalization due to asthma, and mortality due to chronic respiratory diseases (Schwartz et al., 1993).

Currently, there are no guidelines or regulations for the ultrafine particulate matter; however, it is recommended that the ultrafine particulate matter (smaller than 0.1 µm) be less than 20% of the outdoor level. This rule is used in the performance evaluation of filters in mechanical systems (Bearge, 1993). In fact, an efficient building envelope filters 80% of ultrafine particulate concentration. Khaleghi et al. in their study of indoor environmental quality of green and non-green buildings in 2011, used *indoor-20% of outdoor* as an indicator for ultrafine particulate concentration.

2.2.1.4 Endotoxins

Endotoxins are pro-inflammatory substances in gram-negative bacteria (GNB) found in organic material. The lipopolysaccharide (LPS) is a biologic associated with the cell membrane of gram-negative bacteria. The lipopolysaccharide molecule has two components: lipid and polysaccharide. The lipid component (Lipid "A") makes lipopolysaccharide toxic. When the bacteria die, the cell membrane breaks apart and lipopolysaccharide is released into the air along with the cell membrane (Health Council of Netherlands, 2010).

Endotoxin levels are associated with the level of gram-negative bacteria that is itself affected by environmental conditions (substrate availability, humidity, and temperature). Endotoxin can be mostly found in outdoors as the environmental conditions are favorable (Spengler et al., 2001). Endotoxins are mostly found in agricultural and related industries as they mainly originate from faecal material and contaminated plant material (Health Council of Netherlands, 2010).

Elevated endotoxin level (>50 EU/m^3) is associated with decreased pulmonary function (Spengler et al., 2001). Exposure to high levels of endotoxin can induce organic dust toxic syndrome causing fever, coughs, headache, and tiredness (Rylander, 2002).

As soil is a common habitat for bacteria, it is very probable that endotoxins are found in the living walls. On the other hand, the building occupants are exposed to this environment for a long time which worsens the health effects (Spengler et al., 2001). The possibility of dispersing airborne endotoxins by the living walls needs to be investigated in the field environment.

2.2.1.5 Relative Humidity

Relative humidity (RH) is the concentration of water vapour in air compared to the maximum water vapour that air can hold at a specific temperature (saturation vapour pressure point) expressed as a percentage. A person's sensation of heat depends not only on temperature, but is also influenced by relative humidity. High relative humidity can help the microbial growth, and very low relative humidity can cause skin dryness; therefore, it is important to keep the indoor relative humidity in an acceptable range (i.e. 40-60% recommended by ASHRAE 55-2013).

The building materials in occupied spaces adsorb or desorb water vapor in order to reach equilibrium with the air around them. Plants contribute to increase of relative humidity of indoor air. As a result, all the materials in contact with the air will adsorb water vapor to reach equilibrium with indoor air. The absorbed water can trigger the growth of microorganisms such as bacteria and fungi (WHO 2009). The bacteria and fungi can then easily disperse into the air and increase the concentration of airborne microbes. Therefore, it is critical to identify and study the effect of living walls on indoor relative humidity.

2.2.2 Impact of Living Walls on Indoor Air Quality

NASA in 1980s explored the possibility of using plants as in enclosed spaces to produce fresh air, and proved that plant leaves uptake CO_2 and other gaseous chemicals through small openings (stomata) and produce oxygen. Wolverton studied a system of filtering indoor air through plant roots surrounded by activated carbon. This study found that plant leaves can remove CO and formaldehyde, but the carbon/plant filter resulted in further reduction of chemical concentrations (Wolverton, 1988).

Research has shown that plants are capable of removing pollutants from the air through different paths. Pollutants enter the plant through contaminated soil or deposits on the waxy cuticle of leaves or through the stomata. Xylem that transports water from the roots to the leaves, or the phloem that transports photosynthatates to the roots, relocates the organic pollutants. Figure 10 illustrates the contaminant uptake mechanism by plants. Pollutant uptake by vegetation is influenced by temperature, exposure duration, plant species and its lipid content, pollutant concentration, type, and state. This study suggests that the mechanism of organic pollutant uptake by each plant species be validated under field conditions (Stacil et al., 1995).

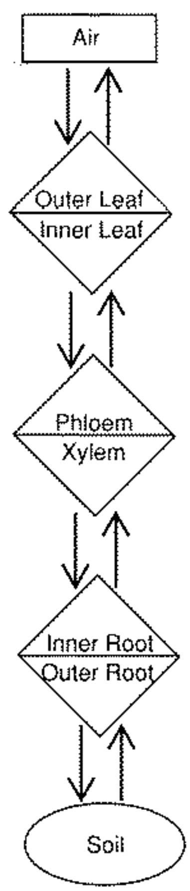


Figure 10: Uptake mechanism of biological pollutants by plants (Stacil et al., 1995).

Another study examined the VOC uptake capacity of different plant species. They studied benzene, trichloroethylene (TCE) and toluene. The removal capability was found to be dependent on plant species and the type of chemical. They studied the morphology of leaves and their stomata in addition to stomata abundance. All their tests were done in chambers and under controlled light and relative humidity and not in the field condition (Cornejo et al., 1999).

In evaluating the effect of interior living walls on indoor air quality, not only contaminant uptake capacity of plants needs to be investigated, but also the contaminant emissions of plants should be investigated. It is known that plants emit VOCs, such as isoprene and monoterpenes. These VOCs contribute to the formation of tropospheric ozone and consequently global warming. However, this is mostly a concern for outdoor plants. Research has shown that the VOC emission of vegetation is a light dependent process (Owen et al., 2002).

Song et al. conducted a field study using a full-scale mock-up model in Korea to examine the uptake of contaminants by plants. The variables in this study were different seasons, plant coverage, and different species. They did the field measurements in two identical rooms. One room was used for base measurements and the other room was covered with 5% and 10% plants located near the windows. The room was vented for 30 minutes and then kept closed for five hours before measuring VOC level. Measurements were done at 24h, 48h, and 72h. It was found that the reduction of VOCs was greatest in summer, and *Ficus benjamina* was most effective in reducing formaldehyde. The VOC reduction was increased with increasing plant area (Song et al., 2007).

A field study was conducted by Darlington et al. They attempted to use a biological complex containing a bio-scrubber, an aquarium and planting to reduce air contaminants and clean the air. This field study was done in a section of an office building. The air was recirculated through a relatively air tight “environmental room” with a considerably lower supply of fresh air compared to other rooms in the office building. This study found that the TVOCs and formaldehyde levels were less than or equal to other spaces in the mechanically-ventilated office building. The airborne microbial spore counts were slightly higher, but comparable to other buildings (Darlington et al., 2000).

Another study used an innovative way to compare test results conducted in the lab and field simulating setup. He tested the ability of plants in the uptake of CO_2 and VOCs. He examined variables such as: relative humidity, ventilation rate, light, temperature, pollutant concentration, and composition. In the lab, the contaminant was injected and decay was assessed, whereas in the field simulating setup, the contaminant emission was continuous. He found that the removal rate increases with increased exposure time (Dela Cruz et al., 2014). This demonstrates the importance of field testing to confirm the effect of plants on indoor air quality.

A one-week VOC monitoring of a shopping mall was done both spatially and temporally. The spatial monitoring (sampling at 48h periods) identified the problematic areas which were the storehouses in the mall, and the temporal monitoring (continuous analyzer) helped identify the dynamics of the emission sources. This field study demonstrated that temporal and spatial variations of VOCs give information on high VOC areas as well as the nature of the source and that it is important to measure VOCs at different locations and times (Amodio et al, 2014).

As part of the collaborative research framework on the effect of interior living walls on indoor air quality and acoustics, experiment was done in a controlled environmental chamber at BCIT to study the effect of plants on indoor air quality criteria such as: CO_2, TVOCs, endotoxin, and bio-aerosols. This study indicated that interior living walls reduce CO_2, generate some VOCs, reduce other VOCs, increase relative humidity, and increase some microbial populations (Cheung, 2017).

2.2.3 Indoor Air Quality Modeling

In general, the prediction of CO_2 level as a surrogate for other air contaminants is based on the CO_2 generation rate per person (dependent on the activity level - illustrated in Figure 11), outdoor air flow per person, and the ambient CO_2 concentration per the equation below:

$$V_o = N / (C_s - C_o) \qquad \text{Eq. 4: CO2 mass balance (ASHRAE 62.1-2013)}$$

Where,

V_o= outdoor air flow rate per person
N= CO_2 generation rate per person (depends on physical activity level)
C_s= CO_2 concentration in the space
C_o= CO_2 concentration in outdoor air

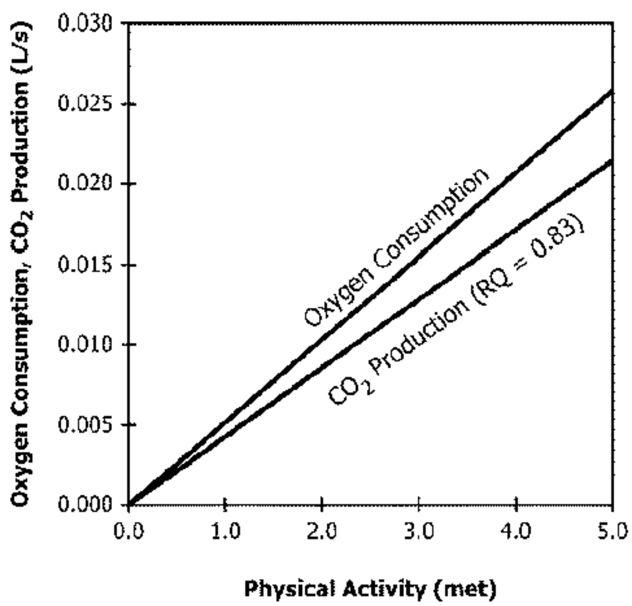


Figure 11: CO_2 production based on activity level (ASTM D6245-12)

In the present study, CO_2 is used as a surrogate for other air contaminants and a measure of room ventilation for modelling the indoor air quality. Due to the complex nature of this field study, and by using the CO_2 decay rates from data collected in the BC Hydro Theatre, the CO_2 level with living walls in the room is predicted in a similar space (i.e. Policy Lab) at CIRS. The Policy Lab was selected for prediction modeling as it has a very similar use, physical characteristic, and ventilation system as BC Hydro Theatre. Therefore, the findings in the BC Hydro Theatre was assumed to be applicable to the Policy Lab. It should be noted such modeling/prediction is based on some assumptions which will be discussed further in Chapter 4.

3 Research Methodology

3.1 Acoustics

The sound absorption and scattering of interior living walls and their effect on acoustical characteristics of the room has been previously studied in the reverberation chamber by Akbarnejad in 2017. The objective of this research is to validate the findings and predictive model proposed by Akbarnejad and Connelly in 2017. This study examines the effect of interior living walls on acoustical quality of the space through field measurement experiments. The acoustic field monitoring and measurements were conducted in the BC Hydro Theater at the Center for Interactive Research (CIRS) at the University of British Columbia Point Grey Campus. Also, preliminary data was collected at four other spaces at CIRS, and it was decided that the Policy Lab can be used for modeling and prediction purposes.

3.1.1 Field Monitoring and Experiment

Preliminary data was collected at five spaces in CIRS (BC Hydro Theatre, auditorium, atrium, and the Policy Lab on level one and an open plan office on the North wing of the second level). The BC Hydro Theatre was selected for living wall experimental setup, and the Policy Lab was decided to be used for modeling, as the physical shape of the room and ventilation were very similar to the BC Hydro Theatre.

The acoustical parameters (background noise level, reverberation time, and speech articulation) were measured in the BC Hydro Theatre and in the Policy Lab. The rooms were unoccupied during measurements. The purpose of such measurement and monitoring was to provide a baseline and a pre-living wall indoor environmental quality condition. **Error! Reference source not found.** illustrates the plan and section drawings of the BC Hydro Theatre in CIRS, UBC, and **Error! Reference source not found.** illustrates the BC Hydro Theatre and the typical acoustic measurement setup.

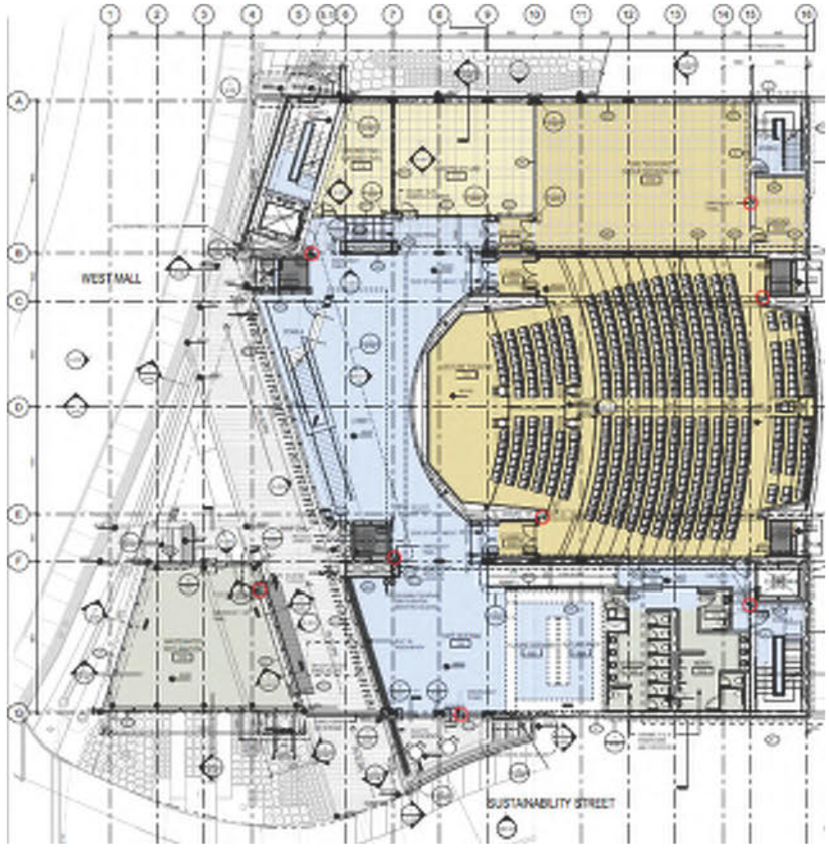


Figure 12a - Partial Ground Floor Plan, CIRS, UBC (Perkins+Will, 2009).


Figure 12b – Section, CIRS, UBC (Perkins+Will, 2009).

Figure 13a - BC Hydro Theatre used for Experimental Setup (Daneshpanah, 2019).

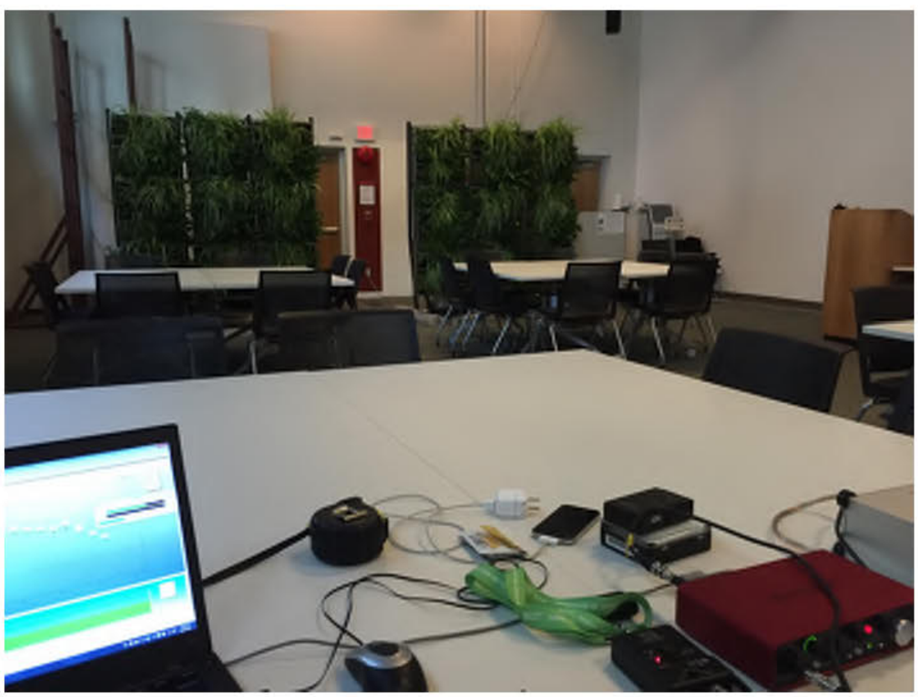


Figure 13b – Typical acoustic measurement setup at BC Hydro Theatre, CIRS, UBC (Daneshpanah, 2019).

To evaluate the effect of living walls on the indoor environmental quality, three different permutations, each consisting of 18 living wall panels, were tested at the BC Hydro Theater for evaluating the living wall's effect on indoor environmental quality of the space.

As the experimental setup was in an occupied building, several meetings were held with Tim Herron, CIRS Building Manager, to coordinate the delivery of the living walls and to determine the living wall configurations to accommodate room use, timing of data collection with respect to room occupancy, and limits of the amount of living walls.

Modular soil-based living walls manufactured by Plant Connection (G-O_2 living wall system) were used for the experimental setup. This living wall system has a low water consumption of 220 L/year.m^2, and can be used for interior and exterior installations. The plants are planted vertically inside a 600 mm X 600 mm X 156 mm (HXWXD) carrier, and the soil is exposed. The carrier is made of stainless steel, and the plants are normally irrigated by a self-regulating low-output soak hose (myplantconnection.com). In this study, the plants were hand-watered at consistent intervals. All the acoustic testing was done at least 48 hours after irrigation to maintain a consistent soil moisture content as much as possible. The soil mix was made of approximately 70% potting soil and 30% clay in order to allow for sufficient water retention as well as drainage. The living walls can have a diverse pallet of plant species. In this experimental setup, the living wall panles were planted the same with a mix of six different plant species: English Ivy (*Hedera helix*), Fern (*Filicophyta*), Golden pothos (*Epipremnum aureum*), Pilea (*Pilea microphylla*), Spider plant (*Chlorophytum comosum*), and Creeping fig (*Ficus pumila*). Full plant coverage was maintained throughout the testing period. The living walls in this study were supported on purpose-built structural racks, and not on room walls, resulting in a distance between panels and room walls. This installation is not considered standard, as the sound energy can go behind the panels.

Figure 14: The soil was being mixed, and the plants are being planted in the living wall panels in the lab (Daneshpanah, 2019).

Figure 15: Living walls were first planted and placed on a horizontal surface (Daneshpanah, 2019).

Figure 16: Living wall panels were planted the same with a mix of six different plant species (Daneshpanah, 2019).

Three permutations of living wall panels (LW-A, LW-B, and LW-C) were tested at the BC Hydro Theater. Each permutation represents a different setup. In LW-A configuration, the panels act as a partition. In LW-B configuration, the panels are concentrated in one corner of the room, containing a smaller space. Lastly, in LW-C configuration, the panels are located vertically. The three tested configurations are illustrated in Figure 17 to Figure 22 and Appendix C.

Figure 17: LW-A permutation at BC Hydro Theatre (18 living wall panels mounted on 2-3X3 steel frames) (Drawing retrieved from Busby Perkins + Will Architectural drawings, 2009).

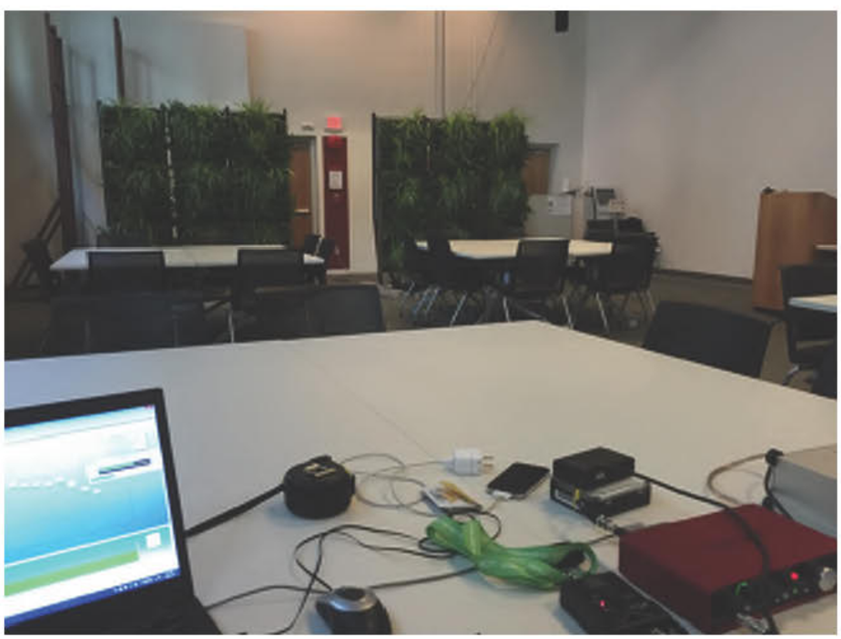


Figure 18: LW-A located approximately 5' away from the east wall of the BC Hydro Theatre (Daneshpanah, 2019).

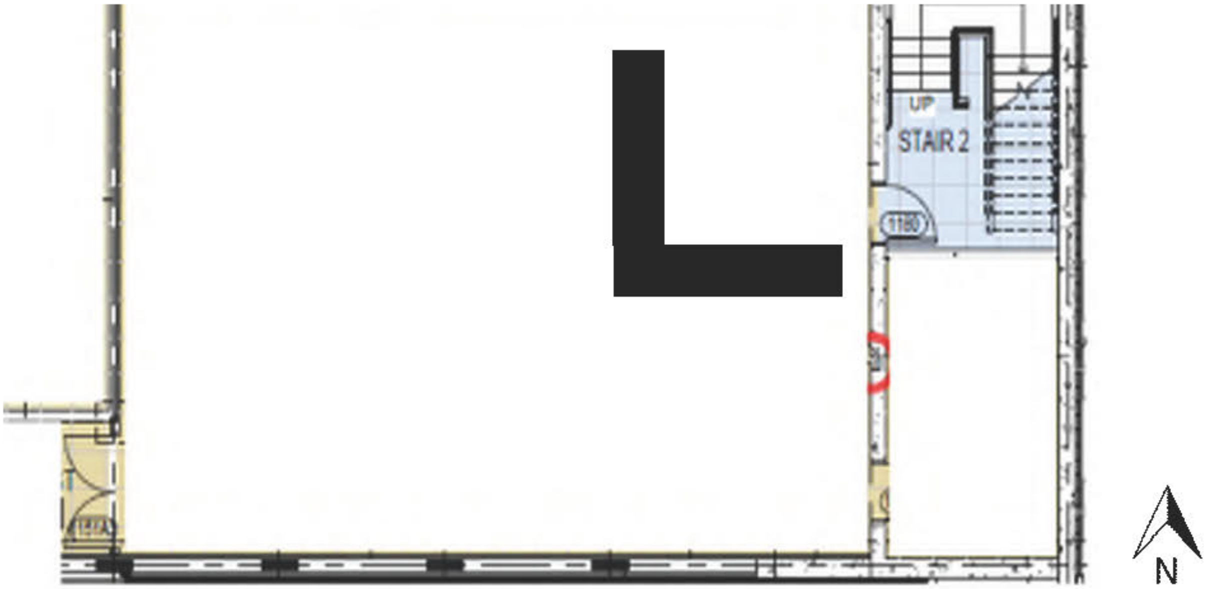


Figure 19: LW-B permutation at BC Hydro Theatre (18 living wall panels mounted on 2-3X3 steel frames) (Drawing retrieved from Busby Perkins + Will Architectural drawings, 2009).

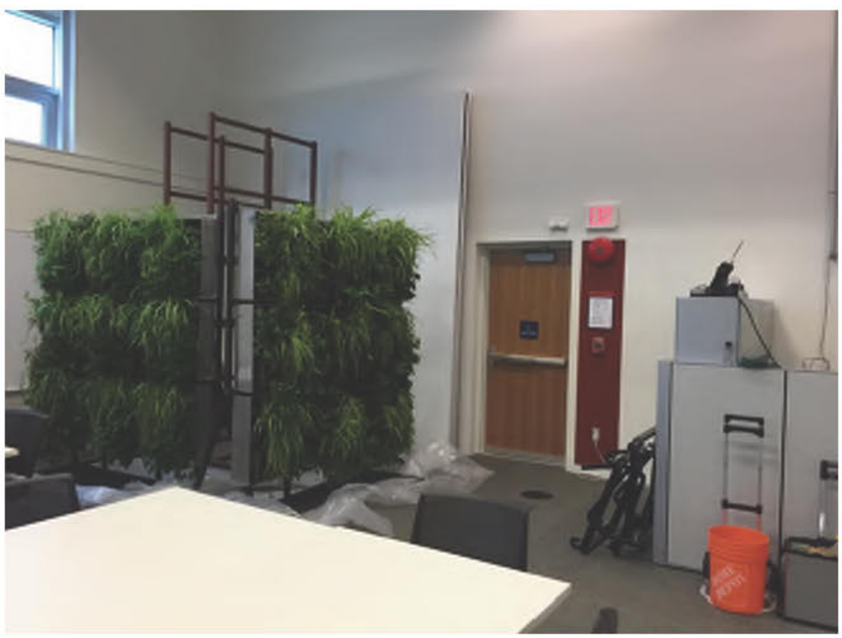


Figure 20: LW-B located at northeast corner of the BC Hydro Theatre (Daneshpanah, 2019).

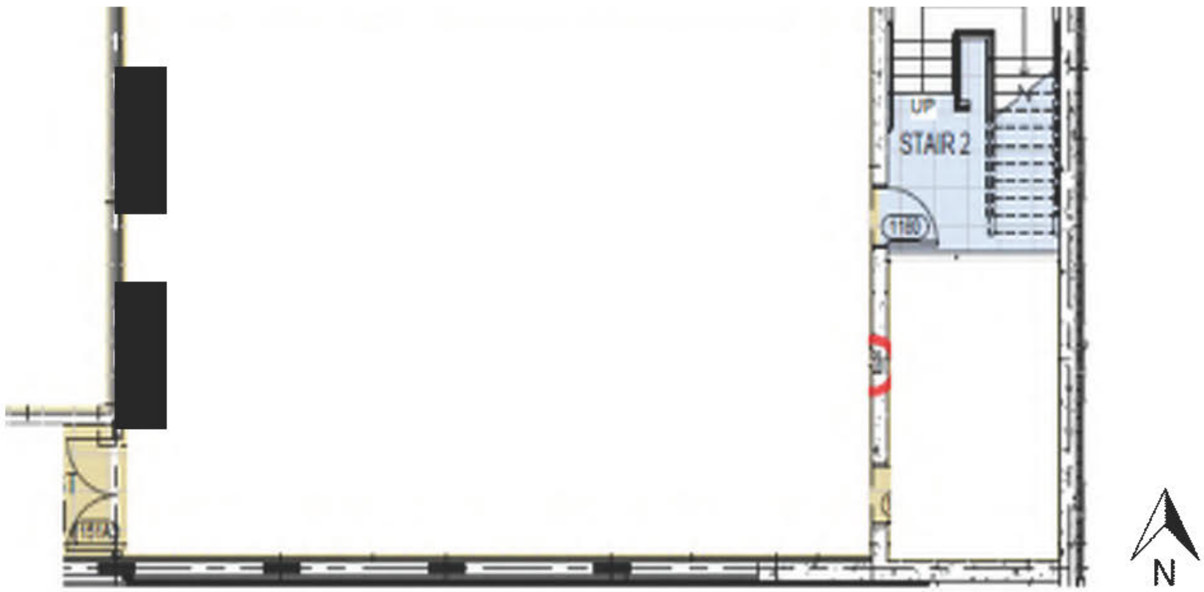


Figure 21: LW-C permutation at BC Hydro Theatre (18 living wall panels mounted on 2-2X5 steel frames) (Drawing retrieved from Busby Perkins + Will Architectural drawings, 2009).

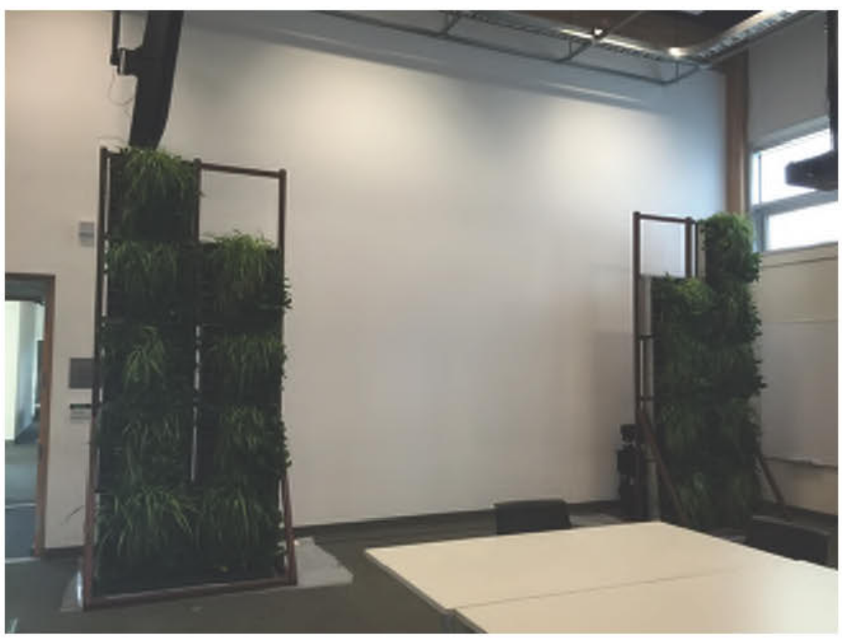


Figure 22: LW-C located approximately 2’ away from the west wall of the BC Hydro Theatre (Daneshpanah, 2019).

The instrumentation used for acoustic measurements for this study was provided by the Centre for Architectural Ecology at BCIT, and included the following:

- Sound Level Meter: Larson Davis Type 831 (S/N: 0003129)
- Microphone: Larson Davis Type 3777B20 (S/N: LW131539)
- Calibrator: Larson Davis Type 200 (S/N: 11875) calibrate January 26, 2015
- Speaker:
    - Omni directional, InfraQsources
    - Directional, JBL EON-10G2 (S/N: 10G2-20576)
- Amplifier: Norsonic Nor 280 Power Amplifier
- Sound Card: Scarlet 2i2
- Software: WinMLS 2004 (a sound-card based software used for acoustic measurements and analysis).

All the instrumentation was calibrated prior to taking to the field for use.

For background noise level measurements, 40 location points were identified and measured in the room as illustrated in Figure 23 below.

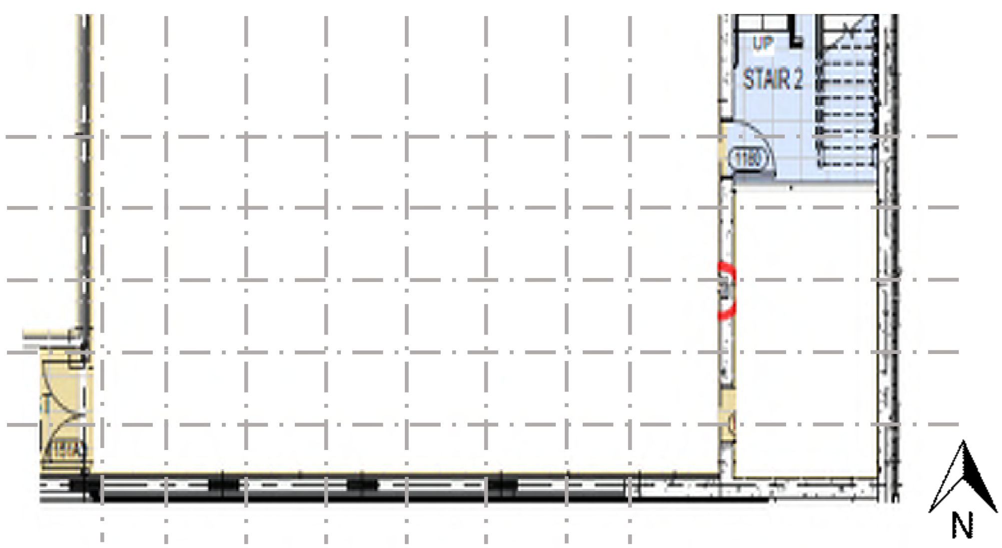


Figure 23: The measurement grid of 40 measurement location points at BC Hydro Theatre (Drawing retrieved from Busby Perkins + Will architectural drawings, 2009).

One of the methods to evaluate the background noise level in the BC Hydro Theatre, was to determine the noise criterion (NC). This method developed by Beranek in 1957, is commonly used to evaluate the room loudness. ASHRAE developed recommended NC range as an interior noise design goal. For school lecture and classrooms, the recommended NC range is 25 to 30 (ASHRAE, 2009). The assumption in this study was that the BC Hydro Theatre is designed to have a NC range of 25 to 30 similar to a lecture/classroom.

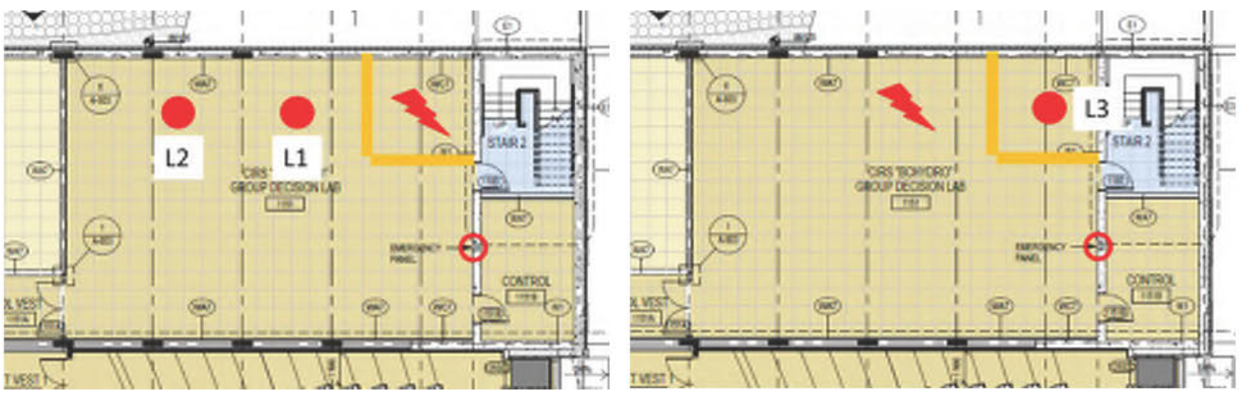
The second criteria evaluated, reverberation time, was measured at baseline and each living wall configuration at 5 random points for each test with 2 speaker positions based on ASTM C423-07a, Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method. The room and its furniture layout were kept consistent for all tests in order to keep the room's baseline sound absorption consistent as much as possible.

To evaluate the speech articulation (articulation index), the speaker and listener positions as illustrated in Figure 24 to Figure 26 were tested at baseline and each living wall configuration based on ASTM E1130 – 02, Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index. The background noise level and noise level with speaker was measured at each point to determine the noise attenuation. The frequency weighted signal to noise ratio based on ASTM E1110-06 (Standard Classification for Determination of Articulation Class) was used to calculate the articulation index at each point.

Speaker position

Listener position

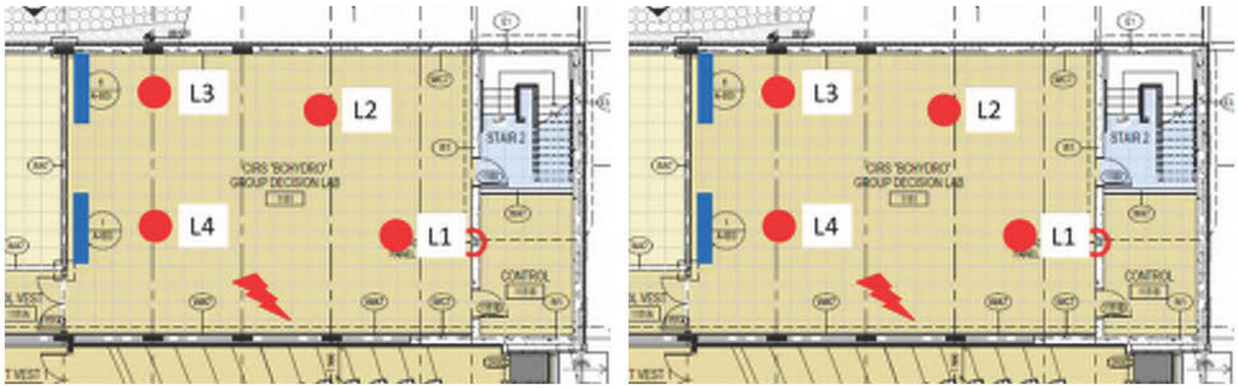
Figure 24: Speaker and listener positions at LW-A configuration (Drawing retrieved from Busby Perkins + Will architectural drawings, 2009).



Speaker position

Listener position

Figure 25: Speaker and listener positions at LW-B configuration (Drawing retrieved from Busby Perkins + Will architectural drawings, 2009).



Speaker position

Listener position

Figure 26: Speaker and listener positions at LW-C configuration and baseline (Drawing retrieved from Busby Perkins + Will architectural drawings, 2009).

3.1.2 Integration of Lab and Field Data

The reverberation time data measured with and without living walls at BC Hydro Theatre along with the reverberation time data previously measured in other field studies at a small room by Koh (2018) and medium room by Connelly (2017), was analyzed to validate the predictive model by Akbarnejad and Connelly (2017).

3.1.3 Predictive Modeling

The Policy Lab at CIRS was selected for acoustic modeling as part of this research project. This space is a smaller room of approximately half the size of the BC Hydro Theatre with very similar use and physical characteristics. The unoccupied Policy Lab was modeled with interior living walls with a goal of reducing the reverberation time in this room with living walls to an acceptable range recommended by standards.

The Policy Lab was selected for acoustics and indoor air quality modeling among other spaces in CIRS where the preliminary data were collected, as the findings of the BC Hydro Theatre experimental setup were more reliably applicable to quasi-cubic rooms of similar size and ventilation system.

3.2 Indoor Air Quality

The effect of living walls on indoor air quality of interior living walls has been previously studied in the lab environment by Cheung (2017). The objective of this research was to verify and validate the results from this field/lab study through field measurement experiments. The results from the field study was then used to predict the effect of interior living walls on indoor air quality.

The indoor air quality field monitoring and measurements were conducted in the BC Hydro Theater at the Center for Interactive Research (CIRS) at the University of British Columbia Point Grey Campus. As previously mentioned, preliminary data was collected at four other spaces at CIRS (refer to Appendix G), and it was decided that the Policy Lab can be used for modeling and prediction purposes.

3.2.1 Field Monitoring and Experiment

The indoor air quality parameters (CO_2, TVOCs, UFP, endotoxin, temperature and relative humidity) were monitored for a week in the BC Hydro Theatre and a week in the Policy Lab to establish the baseline condition. The rooms were occupied during measurements. The CO_2 samples were taken at 5-minute intervals for the entire duration of field monitoring and experiment. Where possible, the samples were taken in close proximity of the room exhaust to reflect, as much as possible, a well-mixed air sample. CO_2 samples were not collected in the breathing zone. The TVOCs samples were also taken at 5-minute intervals, and the temperature and relative humidity was recorded every 30 minutes. The ultrafine particulate matter concentration was discretely measured based on the room access and equipment limitations. The endotoxin samples were collected both at baseline condition, close to the living walls (2' away), and away from living walls (20' away) at all three permutations. The air samples to measure endotoxin were each collected over a period of 5 hours with a rate of about 2000cc/min (i.e. 600 liters per sample). The building's HVAC system shut down during off hours. Floor protection (i.e. 6min poly sheet) was placed under living wall panels, and covered two diffusers; the impact on air flow in the room was assumed to be negligible. The exterior relative humidity, temperature, UFP, and CO_2 were discretely measured to verify external conditions.

The instrumentation used for indoor air quality measurements for this study was provided by the School of Population and Public Health at UBC, and included the following:

- Ultrafine Particulate Matter: P-Trak 8525 (TSI - Shoreview, MN)
- CO2: Q-Trak 7575 (TSI - Shoreview, MN)
- TVOCs: ppbRAE 3000 (RAE Systems by Honeywell - Sunnyvale, CA)
- Temperature/Relative Humidity: QuesTemp 36 (3M - Oconomowoc, WI)
- Endotoxin:
    - Air sampling pump: GilAir Plus (Sensidyne, St. Petersburg, FL)
    - Samplng heads: 7-hole sampling head (SKC Inc., Eighty Four, PA)
    - Filters: Glass fibre filters (Type A/E 37 mm, Pall Corporation). The filters were depyrogenated by baking at 180 °C for 2 hours before use. The filters were stored at 4 °C until conducting the analytical test.

Endotoxin analysis (Limulus Amebocyte Lysate (LAL)) was conducted by Ivan Cheung. For detailed information on the analysis, refer to Appendix E.

The instrumentation was calibrated prior to taking to the field for use.

Figure 27 illustrates a typical indoor air quality test setup at CIRS, UBC.

Figure 27 - Typical indoor air quality test setup.

3.2.2 Integration of Lab and Field Data

The findings from living wall experiment at BC Hydro Theatre were compared with the results by previous lab studies at UBC by Cheung in 2017. This study evaluated the same living wall system in a smaller field/lab room at BCIT Burnaby campus.

3.2.3 Predictive Modeling

Among the monitored spaces at CIRS, the Policy Lab was selected for modeling the indoor air quality. This space is a smaller room (half the size) compared with the BC Hydro Theatre with a very similar use, physical characteristic, and ventilation system. Based on the CO_2 decay rates measured at the BC Hydro Theatre with living wall installations, the CO_2 decay was predicted for the Policy Lab.

4 Results

4.1 Acoustics

4.1.1 Background Noise Level

The effect of living walls on background noise level was evaluated using noise criterion (NC) curve analysis, total background noise level (dBA) within the room, and noise reduction due to absorption. The background noise level in the room was analyzed for possible subsets of acoustical environments.

A general approach to quantify the background noise level in the BC Hydro Theatre, is to plot the measured background noise level data on ASHRAE noise criterion (NC) curves (Figure 28). The BC Hydro Theatre at baseline condition was found to have a NC-55 and NC-50 at all living wall installations. The results indicate that living walls lowered the background noise level and therefore NC curve.

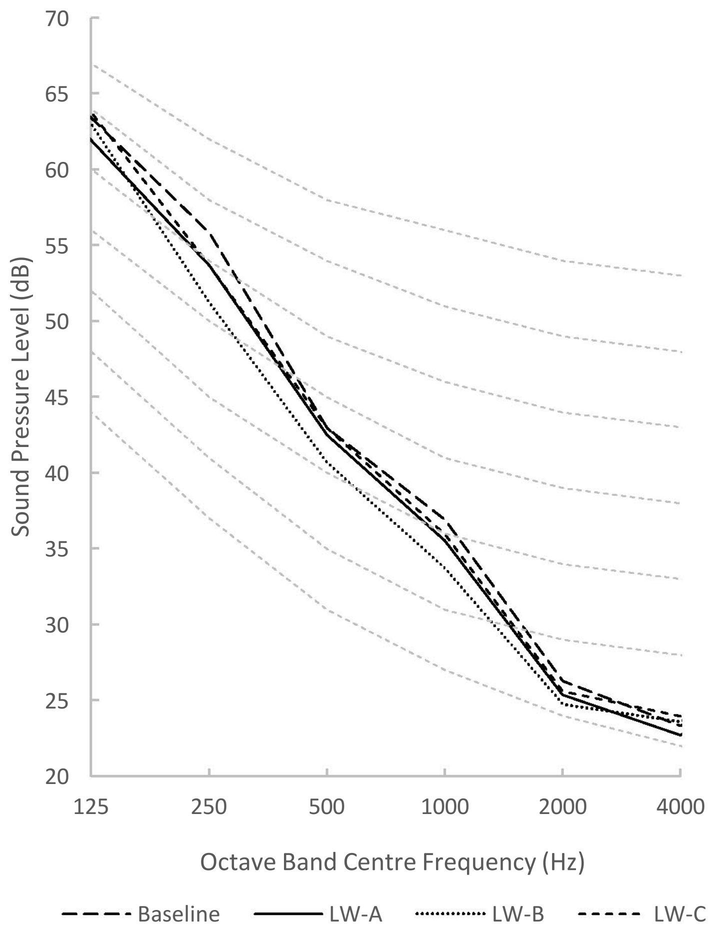


Figure 28: BC Hydro Theatre's background noise level with and without living walls plotted on noise criterion curves.

The other method used to evaluate the background noise level is the maximum background noise level criteria. As illustrated in Figure 29, the BC Hydro Theatre at baseline condition was found to have a total background noise level of 39.3 dBA. The living wall installations A, B, and C had a total background noise level of 37.3 dBA, 36.9 dBA, and 38.4 dBA respectively. Therefore, the living walls reduced the total background noise level by 1.7 dBA, 2.1 dBA, and 0.6 dBA at living wall configurations A, B, and C respectively.

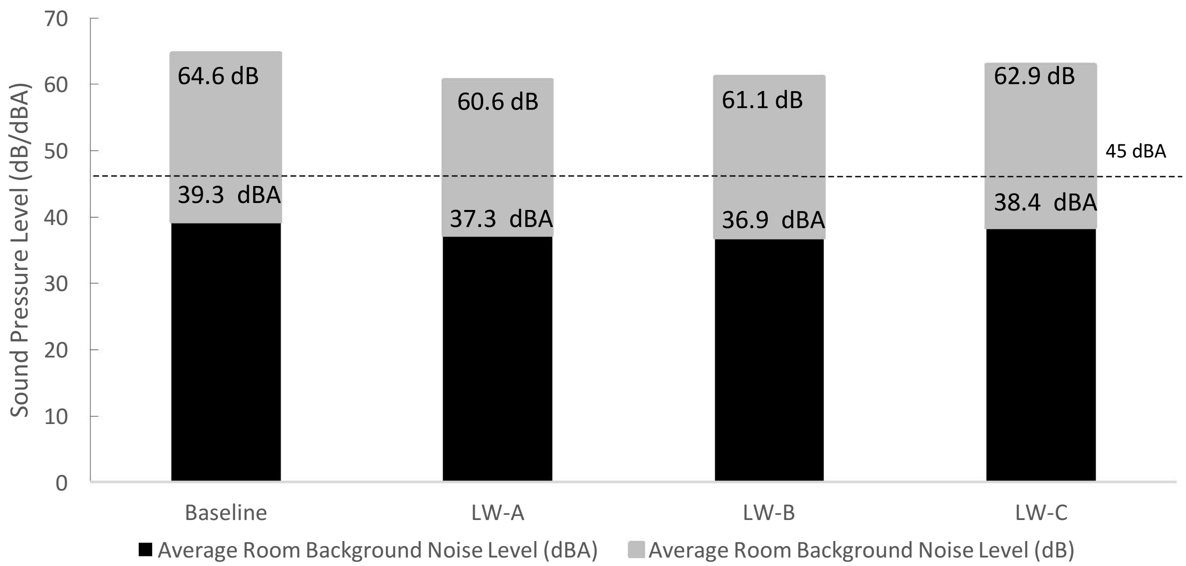


Figure 29: Total background noise level in the BC Hydro Theater with and without living walls averaged over 40 location points.

The dashed line in Figure 29 marks 45 dBA for evaluation of background noise level. 45 dBA is the maximum background noise level recommended by LEED criteria for schools. The background noise level at BC Hydro Theater is below the maximum recommended background noise level at baseline and all living wall configurations.

The average background noise level at each octave band centre frequency at the BC Hydro Theatre was also evaluated. Figure 30 and Figure 31 illustrate the background noise level averaged over 40 location points at one-third octave frequency bands at each configuration. As illustrated, the BC Hydro Theatre has a slightly lower background noise level with living wall installations in the room. The LW-C configuration has the highest background noise level among living wall configurations followed by LW-A and LW-B configurations.

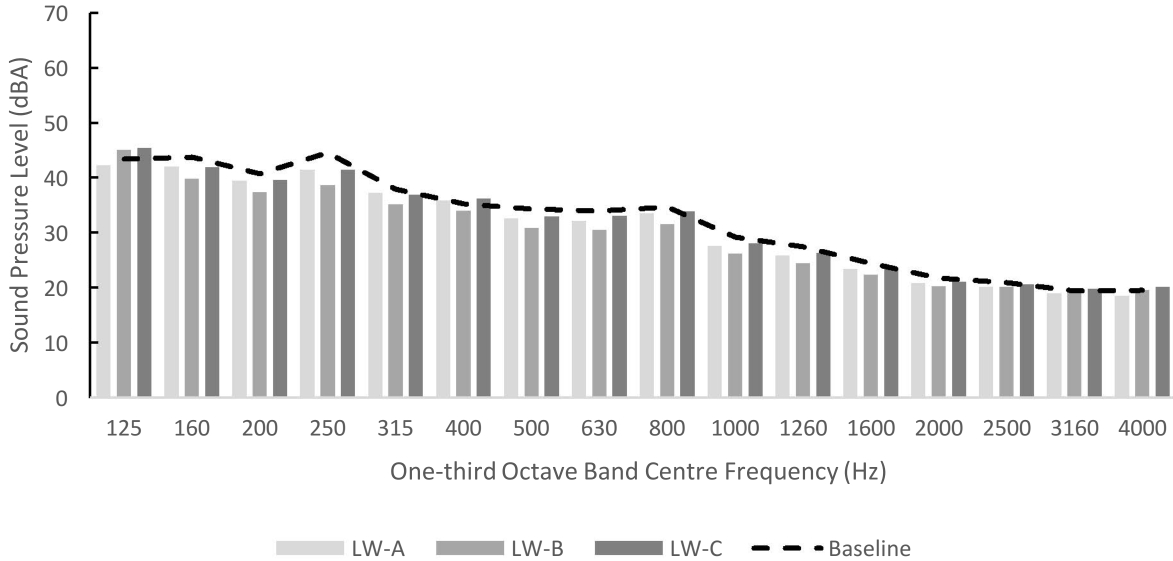


Figure 30: Average background noise level (dBA) at BC Hydro Theatre with and without living walls.

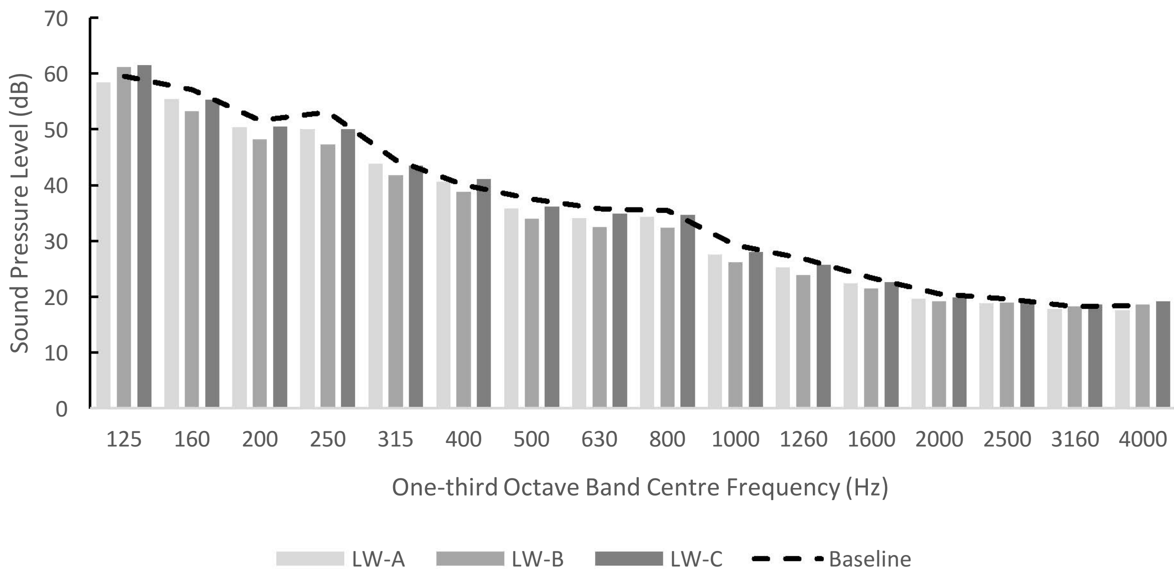


Figure 31: Average background noise level (dB) at BC Hydro Theatre with and without living walls.

The background noise level in the room was also analyzed for possible subsets of acoustical environments. On the preliminary review of background noise levels, the BC Hydro Theatre was considered to have two acoustic zones (east and west as illustrated in Figure 32), and the effect of interior living walls was evaluated relative to the room as a whole and their baseline zone.

Figure 32: BC Hydro Theatre considered to have two acoustic zones for analysis purposes (Drawing retrieved from Busby Perkins + Will architectural drawings, 2009).

The background noise level at east and west half of the room is plotted in Figure 33. This figure illustrates that the east half of the room has slightly higher (an average of 1.8 dBA) background noise level especially at frequencies between 400 to 4000Hz.

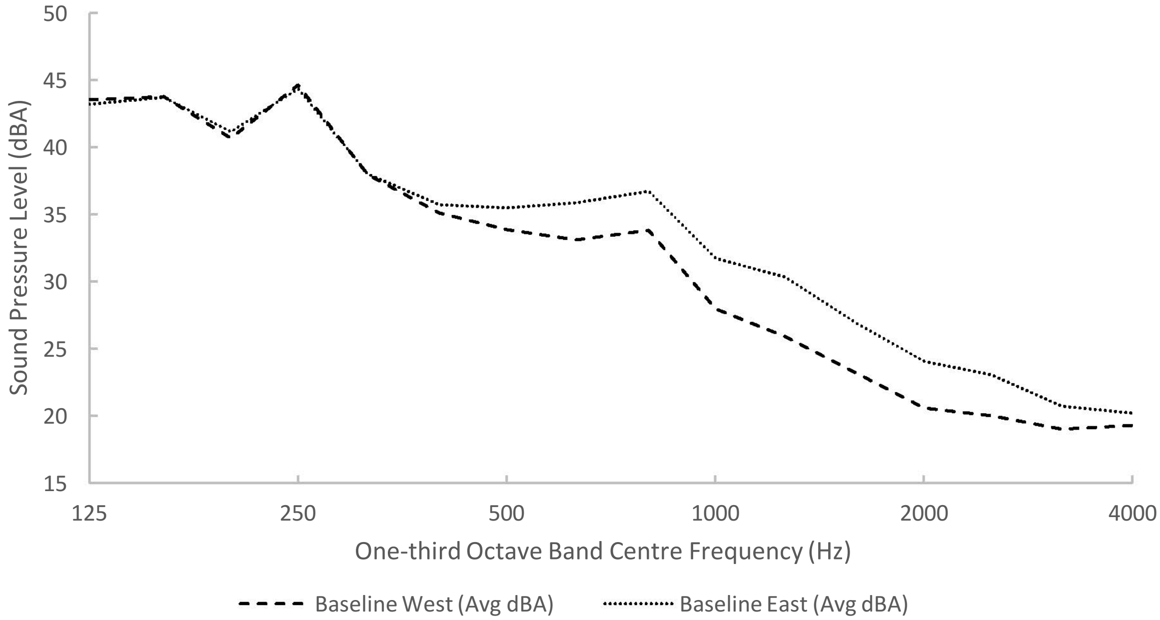


Figure 33: Background noise level at west and east half of BC Hydro Theatre.

Figure 34 to Figure 36 illustrate the background noise level measured over 40 location points at the BC Hydro Theatre at each living wall configuration. At each configuration, the room noise was analyzed based on two acoustical environment subsets (east and west), and the relevant zone (i.e. zone with living wall installation) was considered, as appropriate, to determine the deviation from baseline condition.

In LW-A configuration, the background noise level decreased in both sides of the room compared to baseline at east side (where living walls were located). The west side of the room, where there were no living walls, was found to have slightly (about 1 dBA) lower background noise level.

In LW-B configuration, the background noise level decreased in both sides of the room compared to baseline at east side (where living walls were located). The west and east side of the room were found to have very similar background noise levels (only about an average of 0.2 dBA difference). This configuration appears to have the highest effect on the background noise level compared to other configurations.

In LW-C configuration, the background noise level decreased in the west side of the room (where the living walls were located) compared to baseline at west side. The east side of the room was found to have slightly higher (about 1.8 dBA) background noise level compared with the west side.

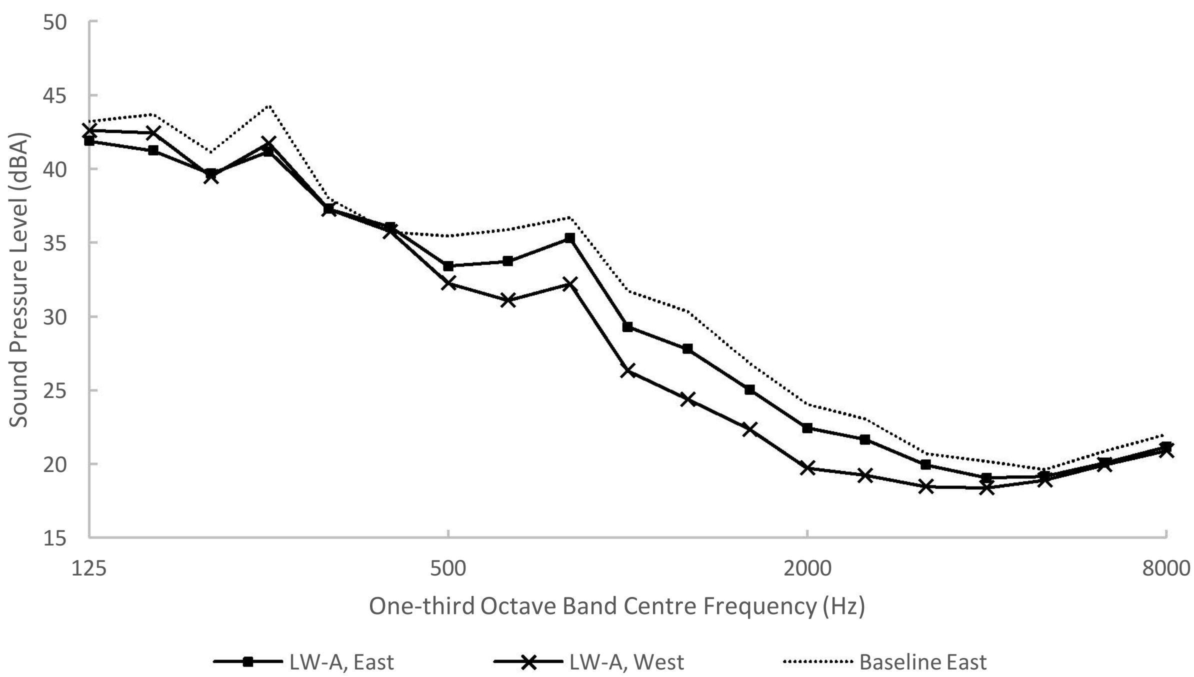


Figure 34: LW-A, Background noise level over 40 location points.

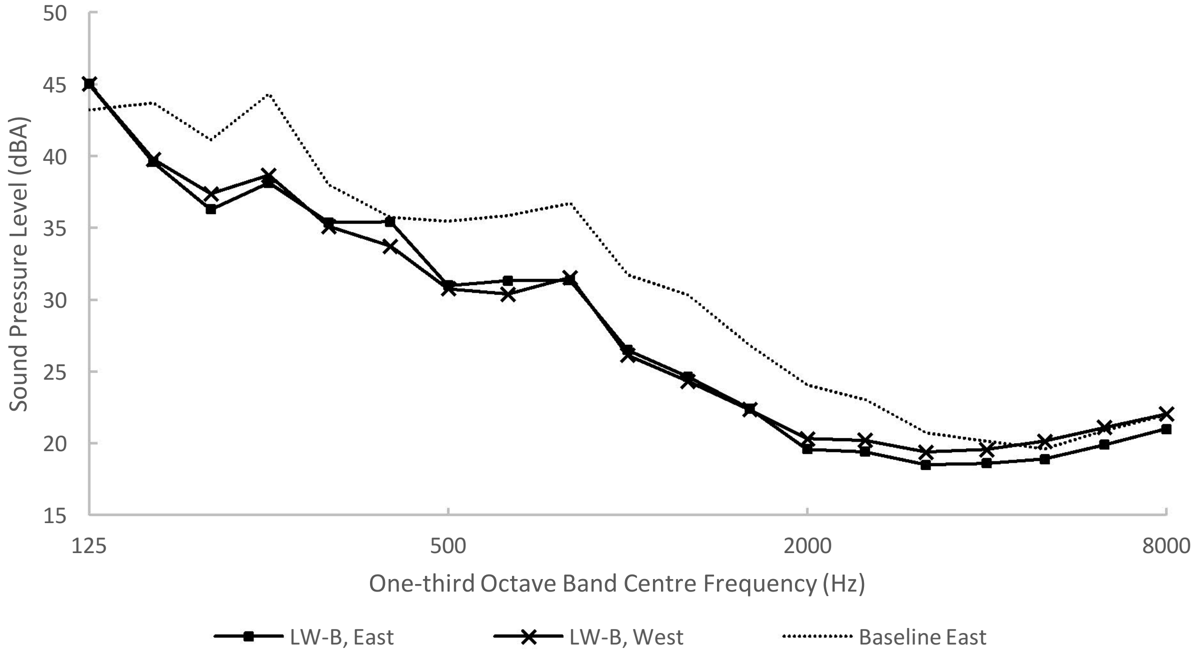


Figure 35: LW-B, Background noise level over 40 location points.

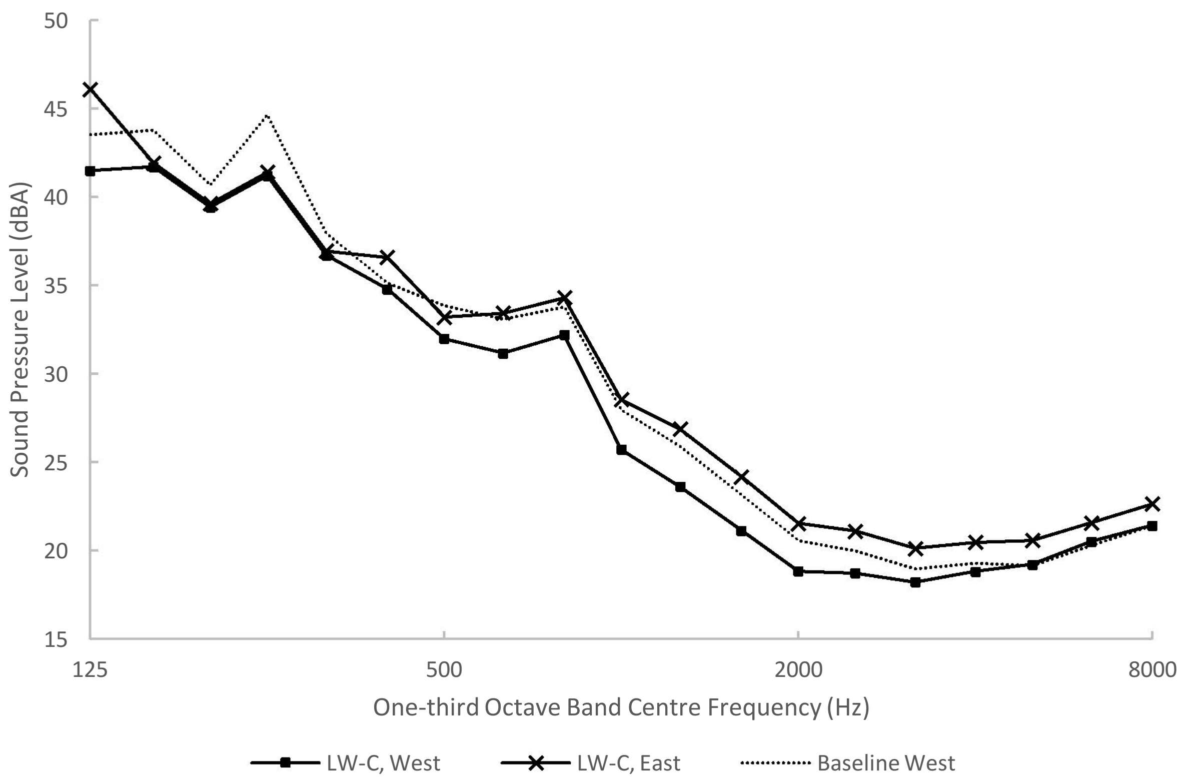


Figure 36: LW-C, Background noise level over 40 location points.

4.1.2 Reverberation Time

The average reverberation time in the BC Hydro Theatre was found to be about 1.09 seconds. at baseline condition. Standards suggest 0.4 - 0.6 second as the acceptable reverberation time range for a classroom with a similar use as the BC Hydro Theatre. Considering the acceptable range, the BC Hydro Theatre has a high reverberation time. Figure 37 illustrates that the BC Hydro Theatre's reverberation time with different living wall configurations is quite similar, and that living walls reduced reverberation time both at low and high frequencies (by an average of about 0.13 seconds).

This graph also illustrates that reverberation time in the room slightly increases with frequency up to about 2000Hz.

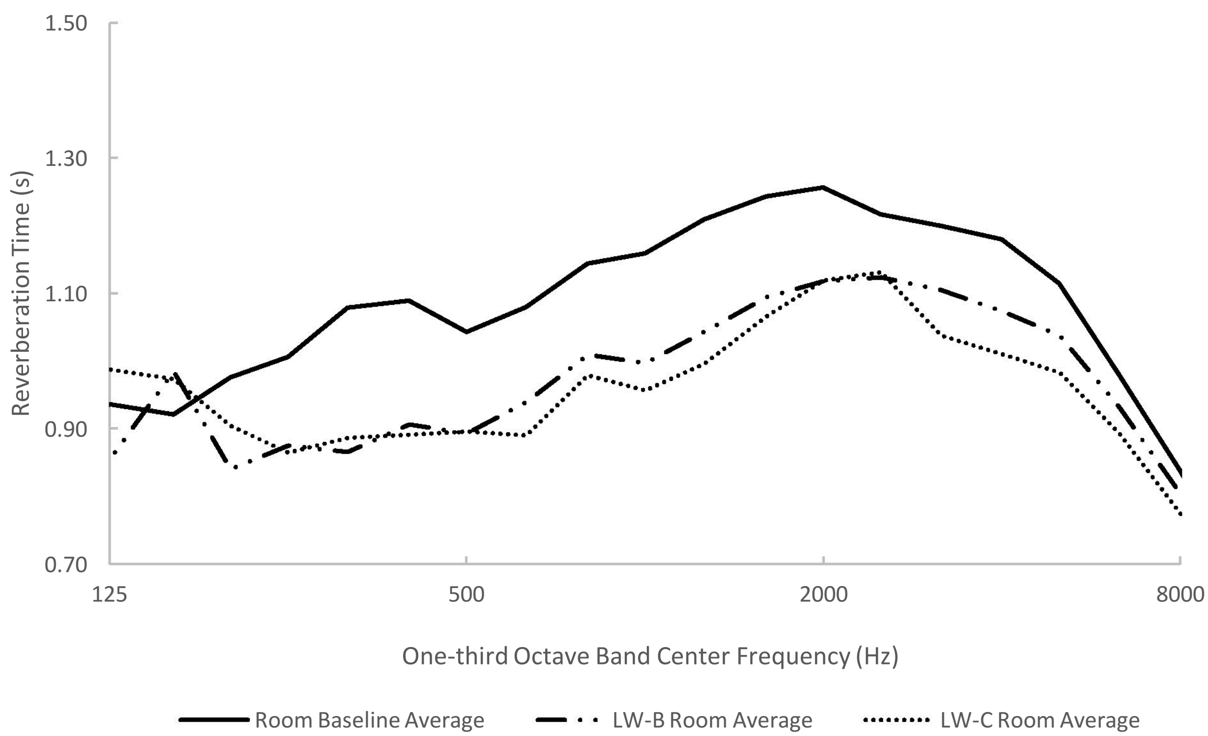


Figure 37: BC Hydro Theatre's average reverberation time with and without living walls.

Figure 38 and Figure 39 illustrate the reverberation time at east and west sides of the BC Hydro Theatre at each living wall configuration. At each configuration, the reverberation time is analyzed based on two subsets of acoustical environment (i.e. east and west). The relevant zone (i.e. zone with living wall installation) was considered, as appropriate, to determine the deviation from baseline condition. LW-A configuration is not included in the analysis as the collected reverberation time data was found to be unreliable.

The following two figures illustrate that at both LW-B and LW-C configurations, the living walls reduced reverberation time especially at lower frequencies. Also, it can be observed that the reverberation time is reduced at both sides of the room in a similar way at both configurations.

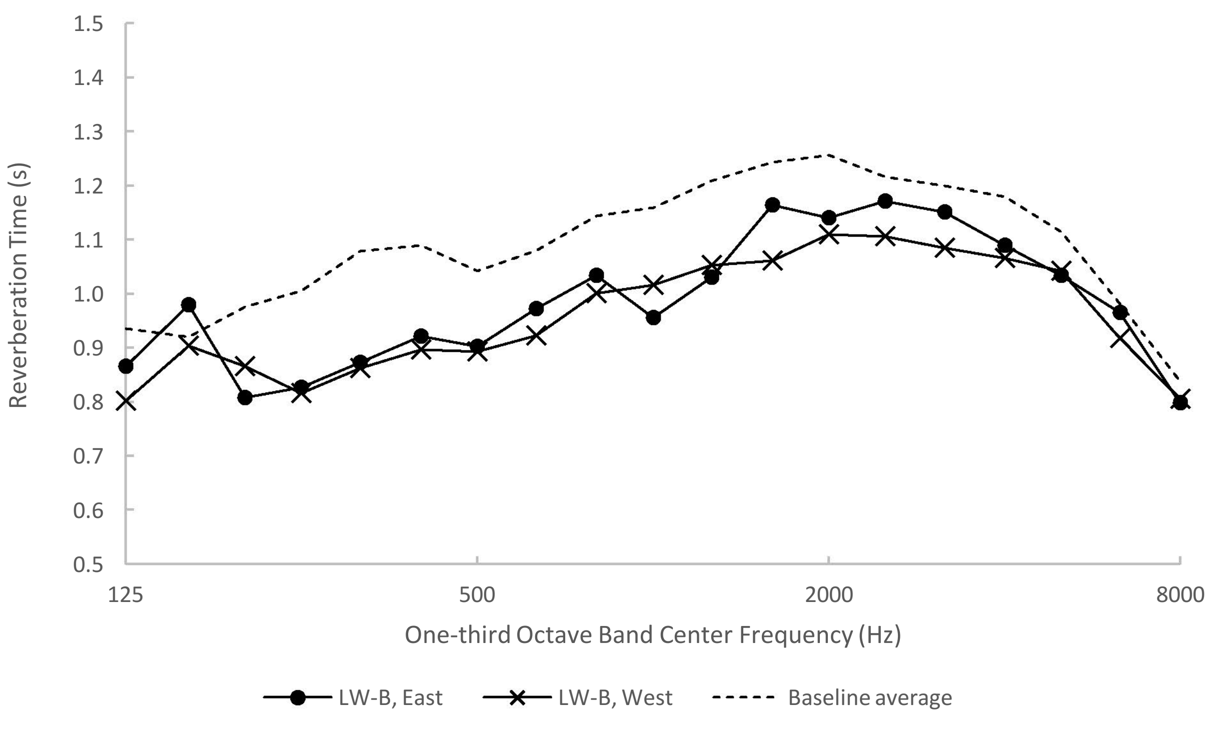


Figure 38: LW-B, Reverberation Time.

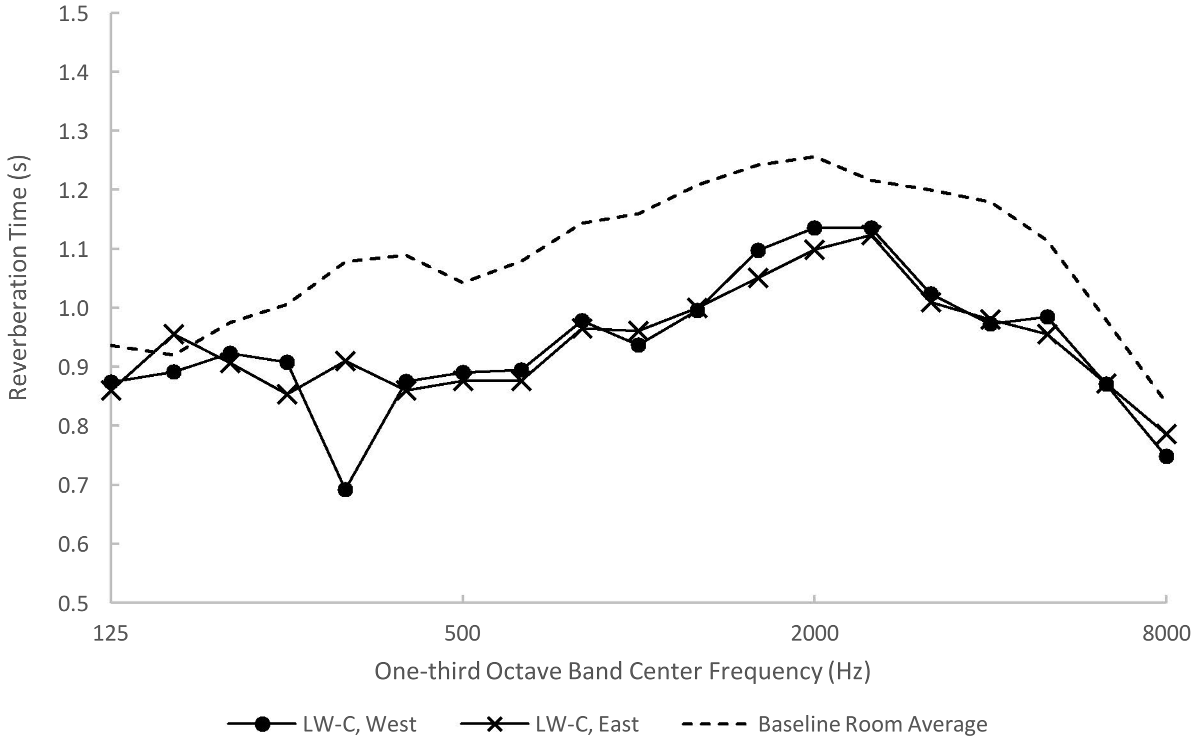


Figure 39: LW-C, Reverberation Time.

To determine if the living walls affected the reverberation time adjacent to living walls any differently than away from them, the average reverberation time deviations from baseline of the area away from the living walls was compared with average reverberation time deviations from baseline of area close to the living wall boundary. The results indicate that the living walls in LW-B configuration affected the area away from it slightly more compared to the area close to the living wall boundary (0.15s vs. 0.04s). For LW-C configuration, the average reverberation time deviations from baseline of area away from the living wall was found to be the same as average reverberation time deviations from baseline of area close to the living wall boundary (0.08s). This indicates that LW-C similarly affected the reverberation time in areas close to and away from it.

4.1.3 Speech Articulation

The articulation index at the majority of listener positions was calculated to be above 0.4 both at baseline condition and with the living wall installations.

Based on the summary of calculations in Table 6 and standard criteria defined by ANSI S3.5 (1997), the BC Hydro Theatre with and without living walls has a *very good speech intelligibility* and *no privacy*. The average articulation index has been slightly reduced with living walls compared to baseline condition, however, the difference does not affect the speech privacy or intelligibility level.

Based on the results, only listener positions 3 and 4 at LW-A configuration were found to have a *good intelligibility* and *poor privacy*.

Table 6: Articulation index at baseline condition and living wall configurations.

	Listener 1	Listener 2	Listener 3	Listener 4	Listener 5	Listener 6	Average
Baseline	**0.66**	**0.68**	**0.69**	**0.76**	**-**	**-**	**0.70**
LW-A	**0.75**	**0.41**	**0.29**	**0.26**	**0.42**	**0.37**	**0.42**
LW-B	**0.66**	**0.54**	**0.67**	**-**	**-**	**-**	**0.62**
LW-C	**0.58**	**0.61**	**0.65**	**0.69**	**-**	**-**	**0.63**

4.2 Indoor Air Quality

To determine if and how the interior living walls affect the indoor air quality of the space, only the data collected when there was one event in the room, and no windows / doors were opened (i.e. no further ventilation) was considered. This set of data was used in the analysis, as it could be the closest to a true indication of possible effect of living walls due to elimination of other sources of ventilation as much as possible.

4.2.1 Carbon Dioxide

The average CO_2 level at nighttime (12am – 7am) was considered for a measure of ambient CO_2 level. Table 7 summarizes the ambient CO_2 level with and without living walls. Based on the data, the living walls reduced the ambient CO_2 level from about 530ppm to 480ppm (about 50ppm reduction). The placement/configuration of living walls does not appear to affect the reduction of ambient CO_2 level.

Table 7: Ambient CO_2 level with and without living walls.

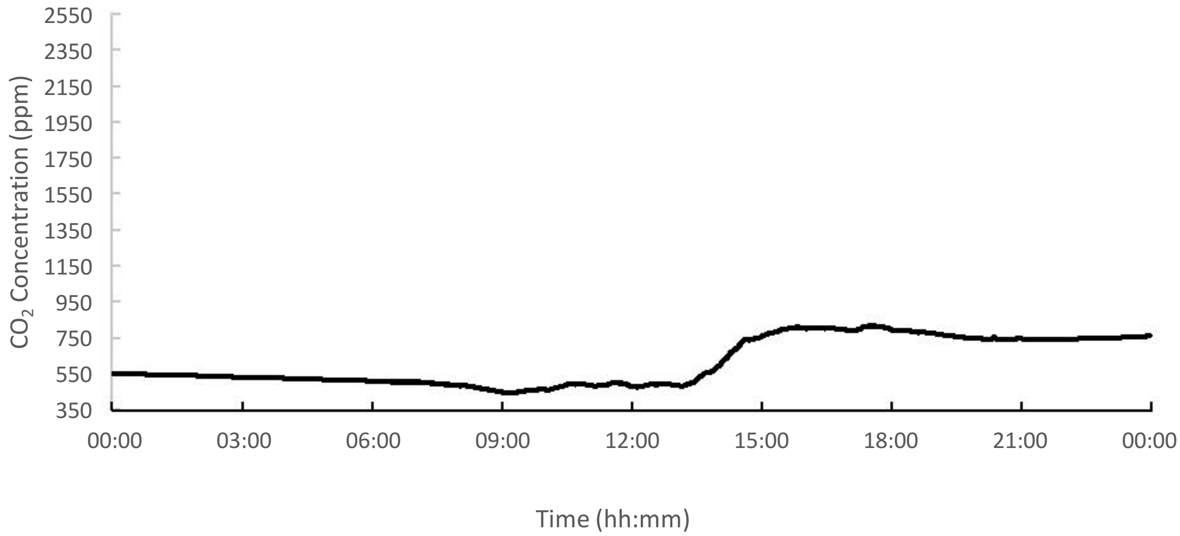
Configuration	Ambient CO_2 Level (nighttime) - ppm
Baseline	529
LW-A and LW-B (east side)	478
LW-C (west side)	484
Average ambient CO_2 level with living wall	481

In order to examine the possible effect of interior living walls on ventilation, CO_2 was considered as a surrogate for other contaminants and its decay was evaluated. The slope of CO_2 decay after people left the room was compared between baseline condition and living wall configurations. Table 8 summarizes the CO_2 decay of scenarios with living walls and a baseline scenario. The results in this table indicate that there is a possible increase in CO_2 decay rate with living walls after people leave the room (i.e. CO_2 generation is stopped).

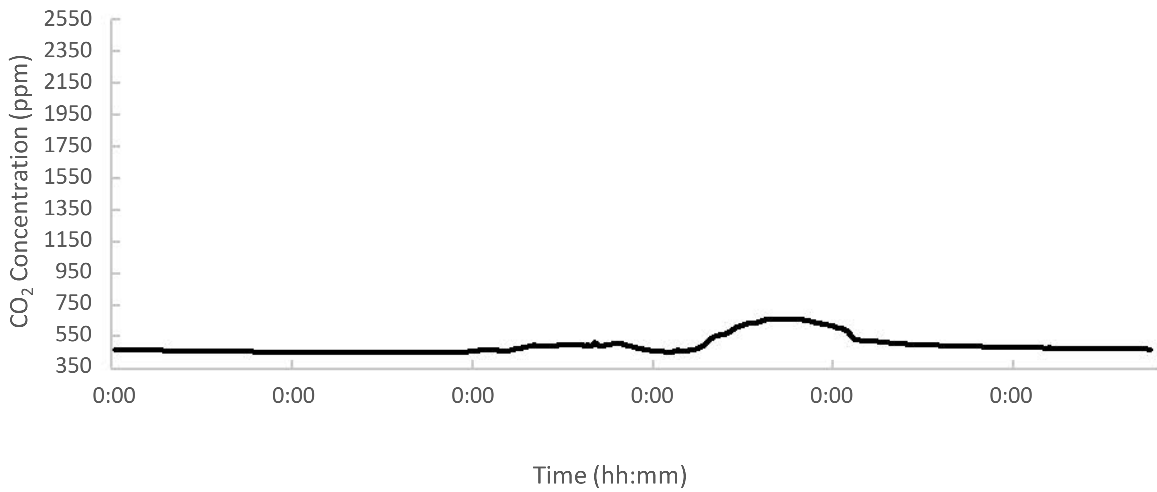
Table 8: Comparison of CO_2 decay with and without living walls.

	BC Hydro Theatre at Baseline	BC Hydro Theatre with Living Wall
Slope of CO_2 Decay	**2**	**35, 22, 26, 20, 22, 24, 12, 38, 13 (average of 23.5)**

Figure 40 illustrates an example of CO_2 decay comparison between baseline and living wall configuration, where the CO_2 decay slope without living walls is about 2.4, and is approximately 22 with living walls.



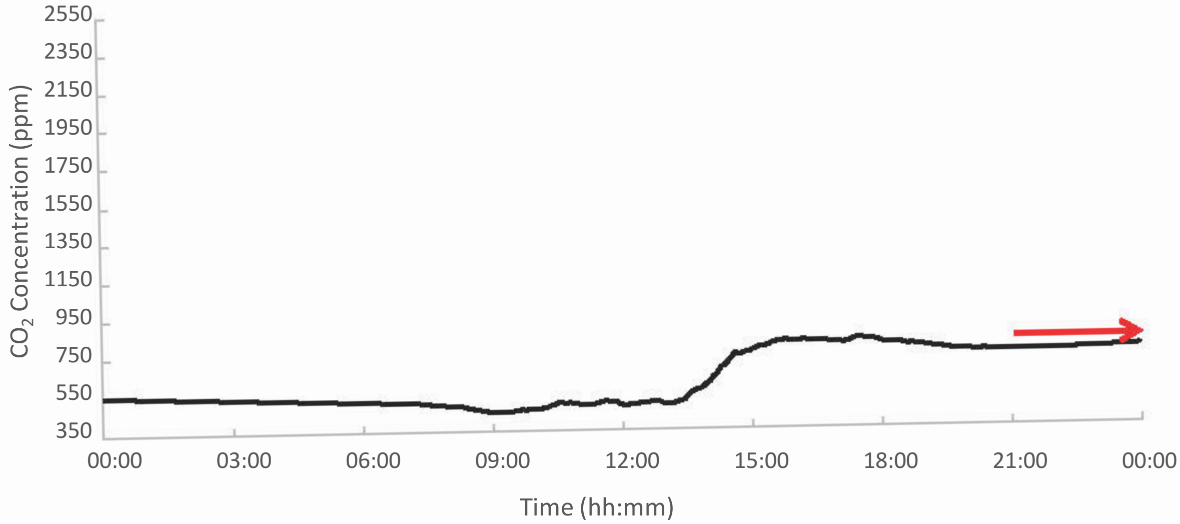
Day 1



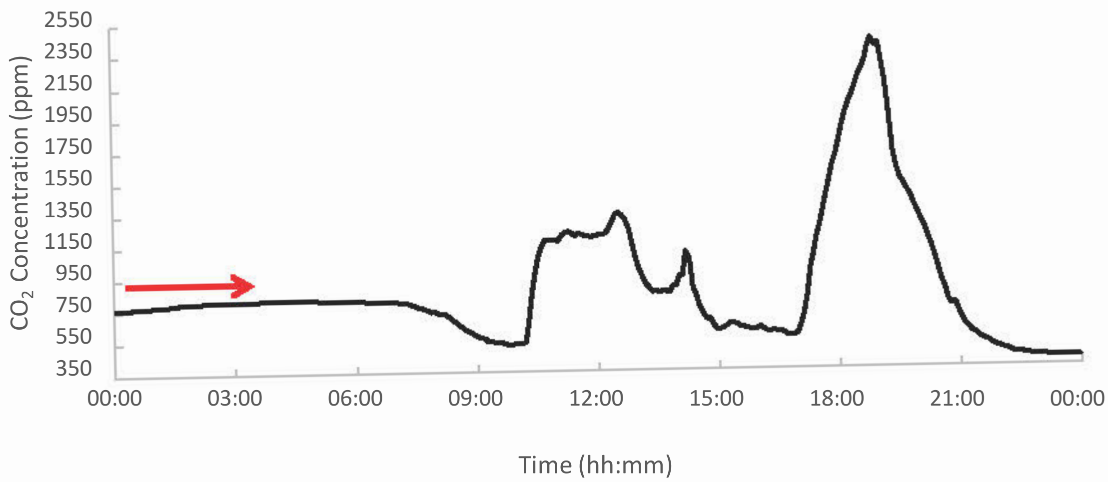
Day 2

Figure 40: The CO_2 decay slope without living walls (top) is about 2.4, and with living walls (bottom) is about 22.

The CO_2 level the morning after the days with events happening later in the day was also evaluated to determine if the living walls contributed to any further reduction of CO_2 in the room overnight. Figure 41 and Figure 42 illustrate two consecutive days without (Figure 41) and with living walls (Figure 42). In these graphs, the baseline data indicates no decay of CO_2 overnight until 8am (likely when the mechanical ventilation started running and/or doors/windows were opened). Whereas, with living walls, the CO_2 level decreased from 590ppm to 450ppm overnight. This suggests that living walls slightly contributed to decay of CO_2 overnight. The maximum recorded CO_2 level at baseline was approximately 2400ppm, and 1700ppm with the living wall installation.

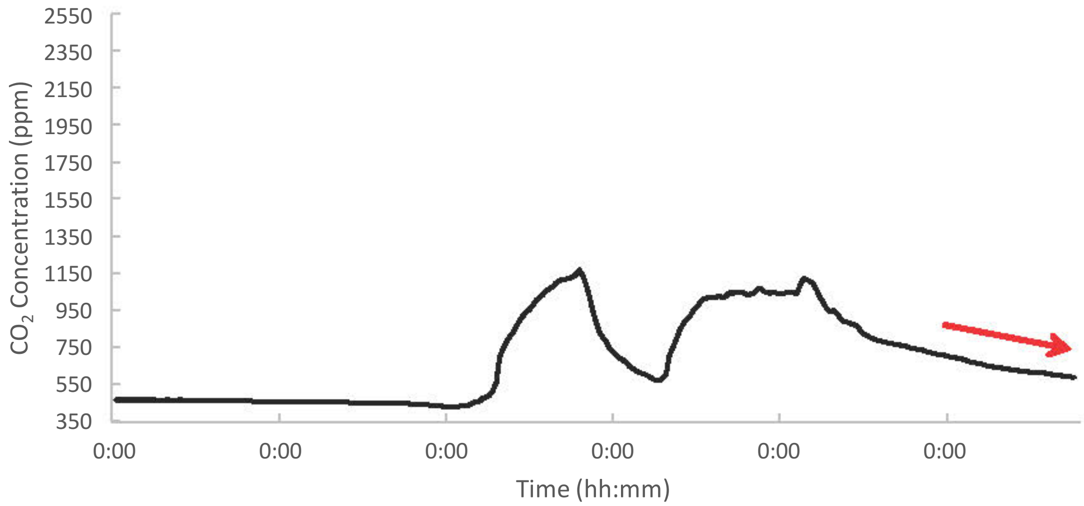


Day 1

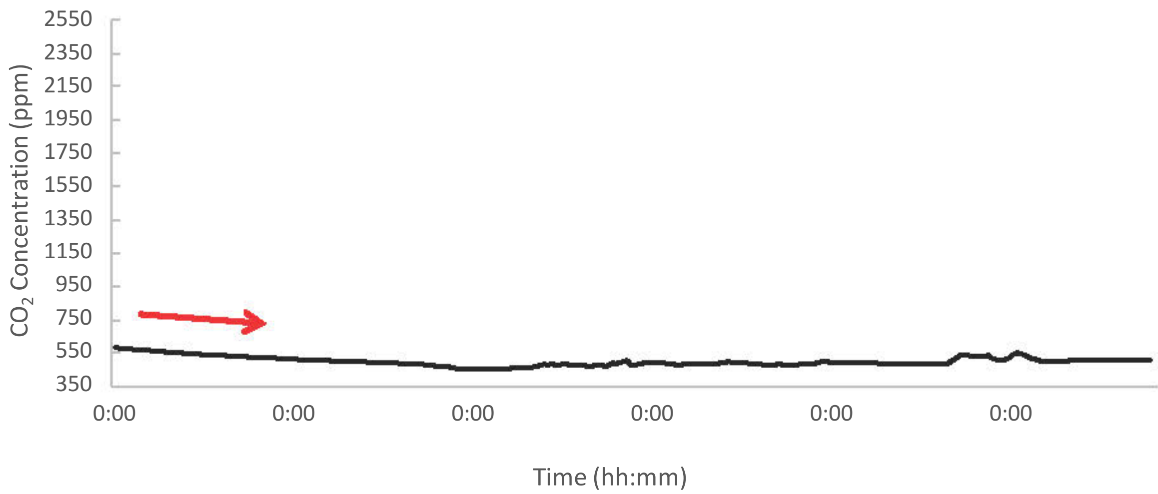


Day 2

Figure 41: No decay of CO_2 overnight at baseline condition between two consecutive days (Day 1 and Day 2).



Day 1



Day 2

Figure 42: CO_2 decays overnight with living walls between two consecutive days (Day 1 and Day 2).

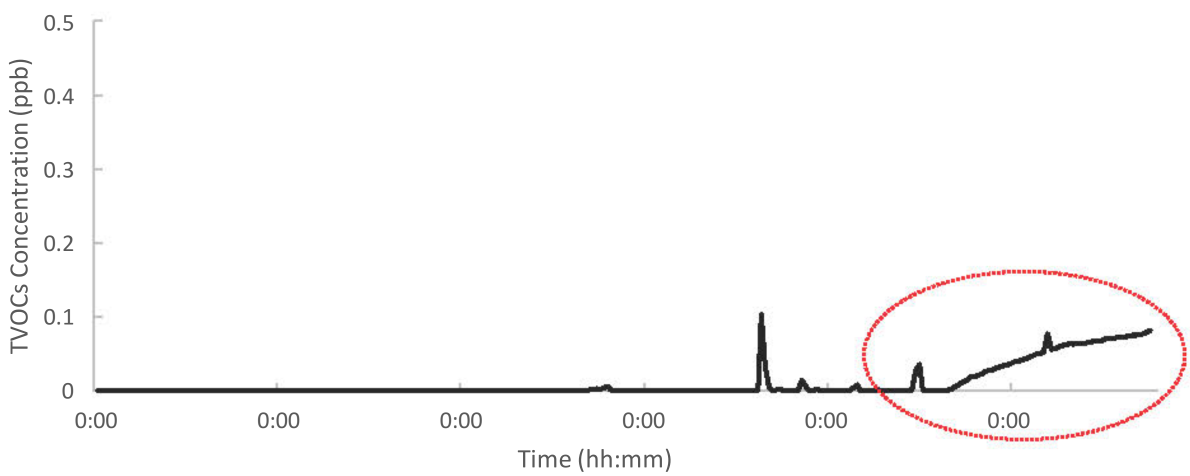
4.2.2 Volatile Organic Compound

In general, the BC Hydro Theatre was found to have a very low level of TVOCs with an ambient average of 0.3 ppb. Considering 300 ppb target value for maximum TVOCs level for green buildings, this room has a very low concentration of TVOCs at baseline condition. In general, TVOCs concentration appears to be associated with presence of people in the room. The average ambient TVOCs concentration in the BC Hydro Theatre was compared with and without living walls and summarized in Table 9. The BC Hydro Theatre at baseline condition was found to have an ambient TVOCs level of 0.3ppb and 0.89ppb with living walls.

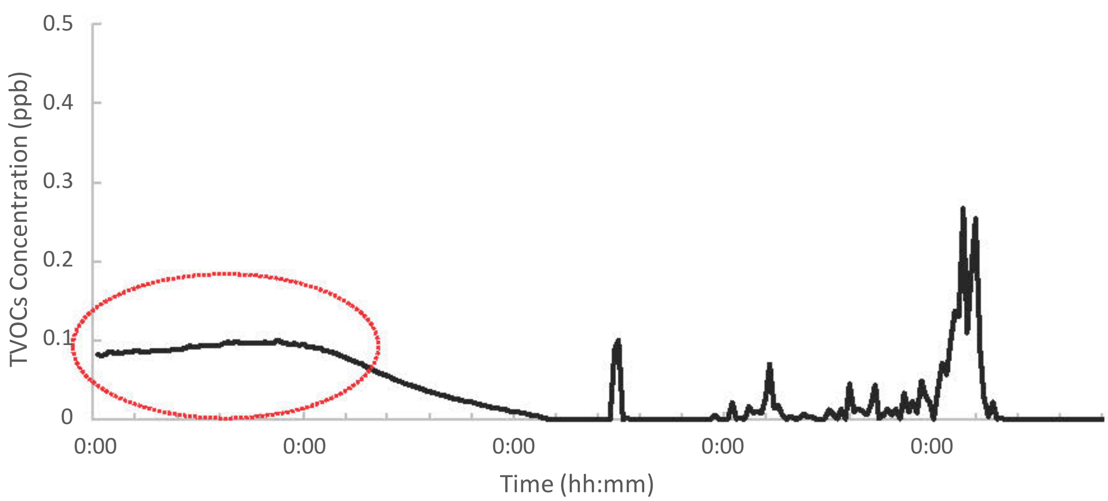
Table 9: Comparison of TVOCs concertation with and without living walls.

Configuration	Ambient TVOCs (nighttime) - ppb
Baseline	**0.30**
LW-A and LW-B (east side)	**0.12**
LW-C (west side)	**1.66**
LW average	**0.89**

Data suggest that interior living walls were found to possibly contribute to slight increase of TVOCs between evening and early morning. Figure 43 illustrates an example of elevated TVOCs levels overnight where the TVOCs concentration slightly increases with living walls from 7:30pm to 4am by about 0.1 ppb.



Day 1



Day 2

Figure 43: TVOCs concentration slightly increase with living walls starting from 7:30pm to 4am by about 0.1 ppb between two consecutive days.

4.2.3 Ultrafine Particulate Matter

Due to limitations of measuring device and room access only, discrete measurement of Ultrafine Particulate Matter (UFP) was done in the room with and without living walls. Due to complexity of source(s) and field condition, it was unclear whether living walls contributed to any change in concentration of UFP. Also, no clear conclusion could be made on whether the building is capable of reducing outdoor UFP for the same reasons. Therefore, this study does not comment on the effect of interior living walls on UFP level.

4.2.4 Endotoxins

In general, the endotoxin level in the BC Hydro Theatre was found to be very low with a baseline average of 2.12 EU/m^3 considering elevated level of 50 EU/m^3 as a health concern. The t-Test for the collected samples indicated no significant difference in endotoxin level at baseline condition and with living walls. Also, there was no indication of significant difference between samples collected close to the living wall compared to samples collected away from the living wall. Table 10 summarizes the average endotoxin concentration with and without living walls in the BC Hydro Theatre. Data suggest that the endotoxin concentration is generally very low and has slightly increased to an average of 3.83 EU/m^3 with living walls from the baseline of 2.12 EU/m^3. Also, the endotoxin concentration does not appear to be dependent on sample location.

Table 10: Comparison of Endotoxin level with and without living walls.

Configuration	Average Endotoxin Level (EU/m^3)
Baseline	**2.12**
Living walls at east side of room – Sample taken 2’ away from the living wall	**4.13**
Living walls at east side of room – Sample taken 19’ away from the living wall	**5.80**
Living walls at west side of room – Sample taken 2’ away from the living wall	**3.30**
Living walls at west side of room – Sample taken 19’ away from the living wall	**2.08**
LW average	**3.83**

4.2.5 Relative Humidity

Figure 44 illustrates relative humidity over a typical week with and without living walls. As illustrated in these graphs, the living walls appear to increase the relative humidity in the BC Hydro Theatre from an average of 34% to approximately 50% under conditions measured. Also, both graphs illustrate that the relative humidity is slightly less during daytime. This may be a result of a more active mechanical ventilation or introducing further ventilation by opened doors and windows. The following graphs also illustrate that people (in large events) contribute to increase of relative humidity.

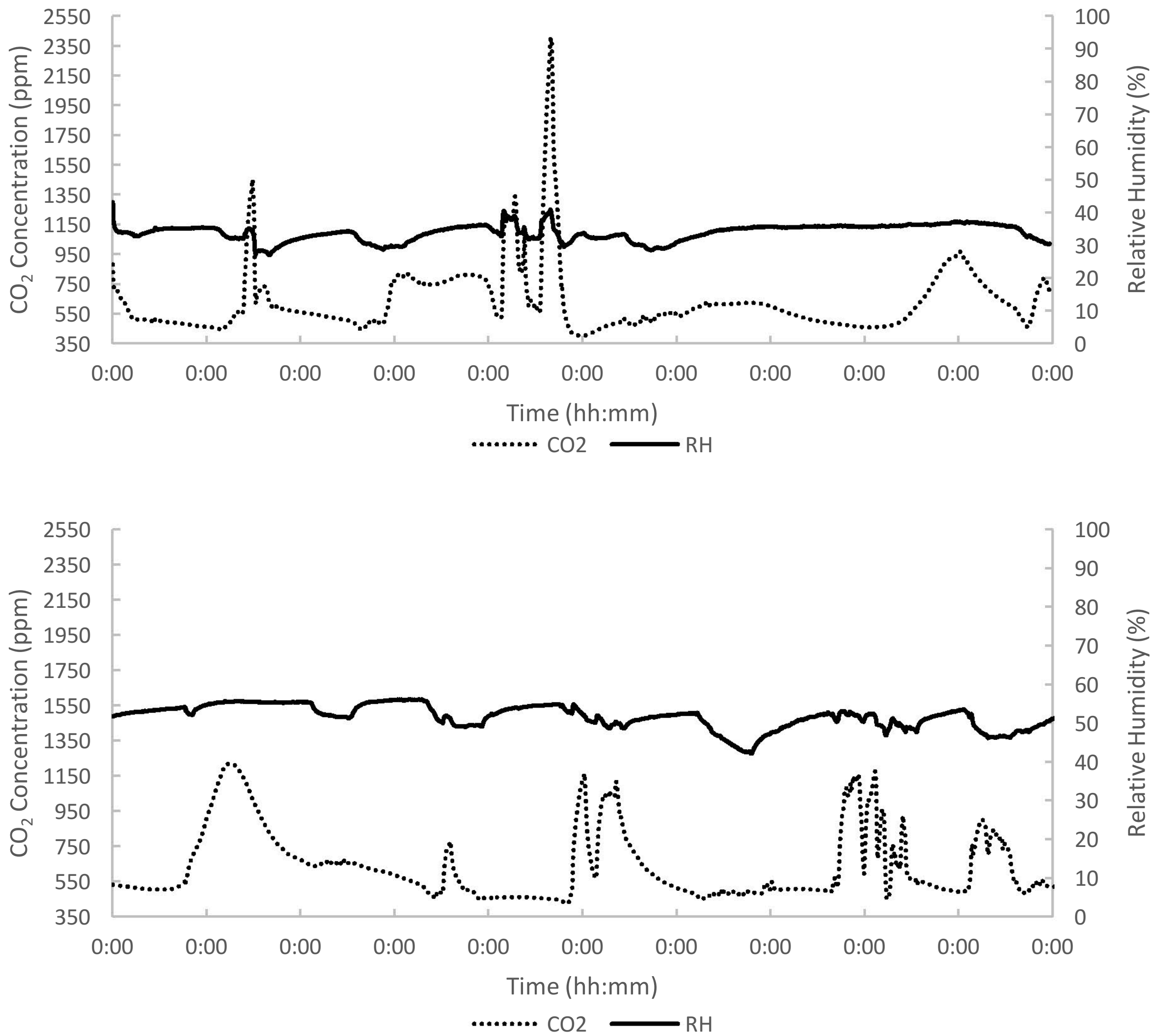


Figure 44: Relative humidity over a typical week without (top) and with (bottom) living walls.

4.3 Predictive Modeling

The Policy Lab at CIRS (Figure 45) shares a common wall with the BC Hydro Theatre, and has a similar shape, use, and ventilation system. The Policy Lab was selected for prediction of indoor environmental quality. The Policy Lab is about 400 m^3 and is approximately half the volume of the BC Hydro Theatre. For acoustic modeling purposes, it was assumed that the Policy Lab is diffuse and the living wall panels are distributed equally in the room.

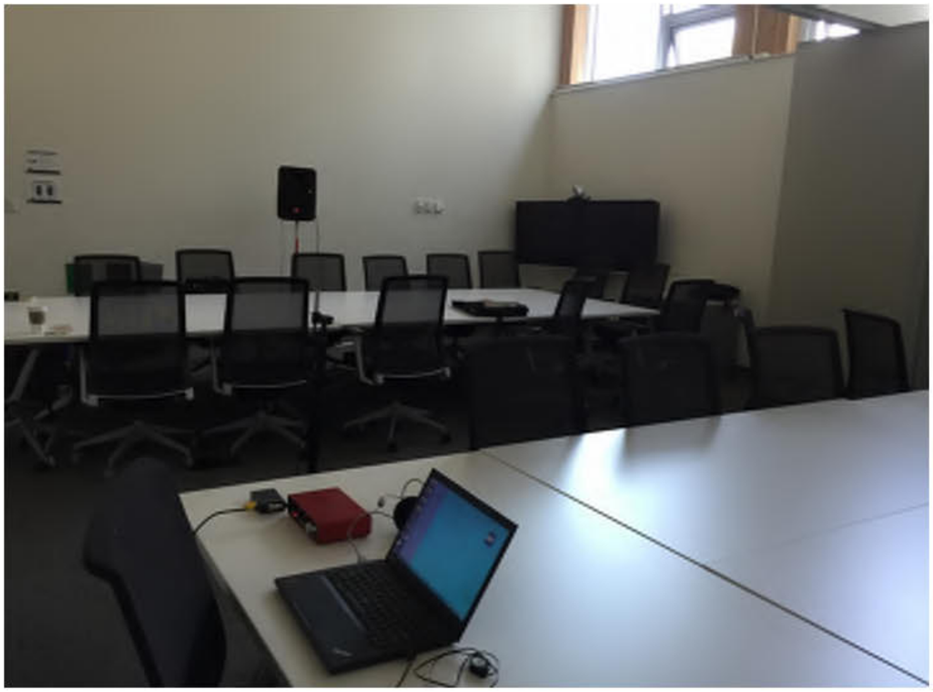


Figure 45 - The Policy Lab at CIRS, UBC.

4.3.1 Acoustics

The average measured baseline reverberation time in the Policy Lab is quite high (1.05 seconds). The acceptable reverberation time for a classroom / lecture room is 0.4 to 0.6 seconds. Akbarnejad and Connelly 2017 model, predicts that the room reverberation time cannot be reduced to this acceptable range with the use of the 18 living wall panels, as used in the experimental setup. However, based on Akbarnejad and Connelly 2017 model, 124 living walls panels with a surface area of 44.64 m^2 is predicted to reduce the average reverberation time in this room to about 0.6 seconds as illustrated in Figure 46. With the extensive use of living walls (i.e. 124 panels) in an attempt to reduce the reverberation time in the room, the effect on indoor air quality criteria should be considered. Criteria to consider are increased room relative humidity and TVOCs and their effect on human health and comfort.

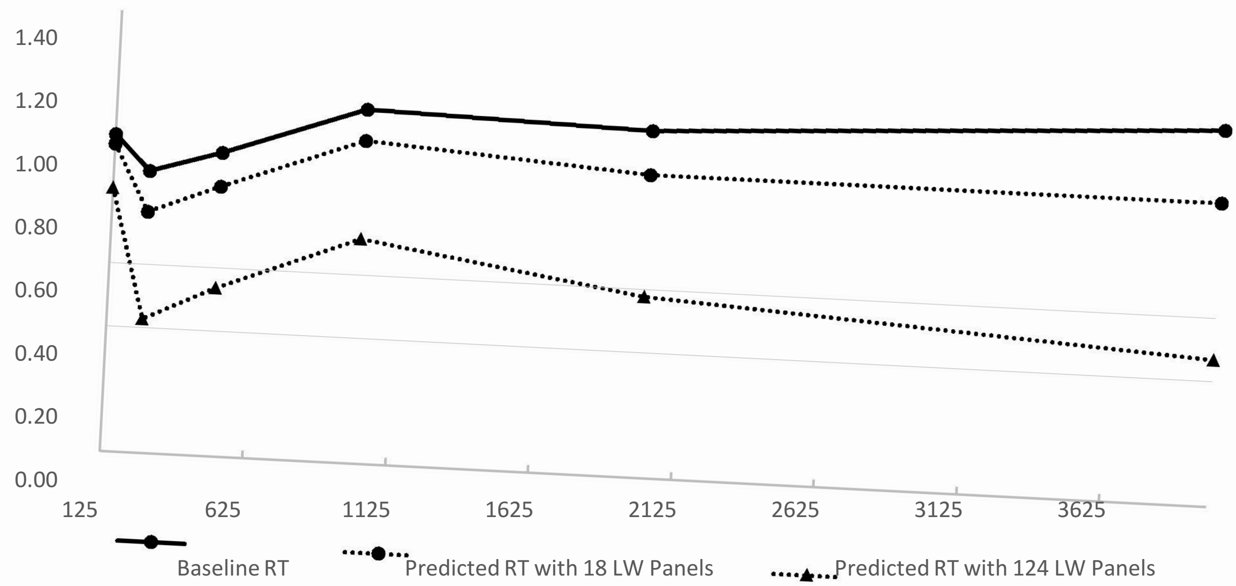


Figure 46: Predicted (Akbarnejad, Connelly, 2017) reverberation time at Policy Lab – CIRS.

The effect of 18 and 124 living wall panels on speech intelligibility was predicted. Noise reduction was predicted and was found to be nominal with 18 living wall panels, and up to 4 dB with 124 living wall panels. The living walls would not affect the intelligibility level in the Policy Lab.

4.3.2 Indoor Air Quality

For the purpose of modeling the indoor air quality of the Policy Lab in CIRS based on field experiment in the BC Hydro Theatre, CO_2 concentration was modeled as a surrogate for all other air contaminants.

Baseline data collected without living walls over a day at the Policy Lab was selected for modeling indoor air quality. Since the windows / doors were opened after this event, the data had to be interpolated to determine baseline condition in case no further ventilation (i.e. opening of windows and doors) was introduced into the room. In Figure 47, the interpolated baseline CO_2, actual measured CO_2, and predicted CO_2 is shown. Interpolation and prediction was done based on CO_2 decay slope measured with and without living walls at the BC Hydro Theatre based on the values from Table 8.

It should also be noted that several assumptions were made for the purpose of this modeling:

- The Policy Lab with a volume of approximately 400 m^3, is about half the size of BC Hydro Theatre with a volume of about 803 m^3. Therefore, the effect of 18 living wall panels was assumed to be twice in the Policy Lab.
- It was also assumed that the boundary conditions of the Policy Lab are similar to the BC Hydro Theatre. This means that fresh air is supplied through the floor plenum and taken away through the exhaust at the top of the room.
- Based on observations in the BC Hydro Theatre, it was assumed that the positioning/configuration of living walls does not affect the CO2 concentration or decay.
- The room has reached equilibrium.

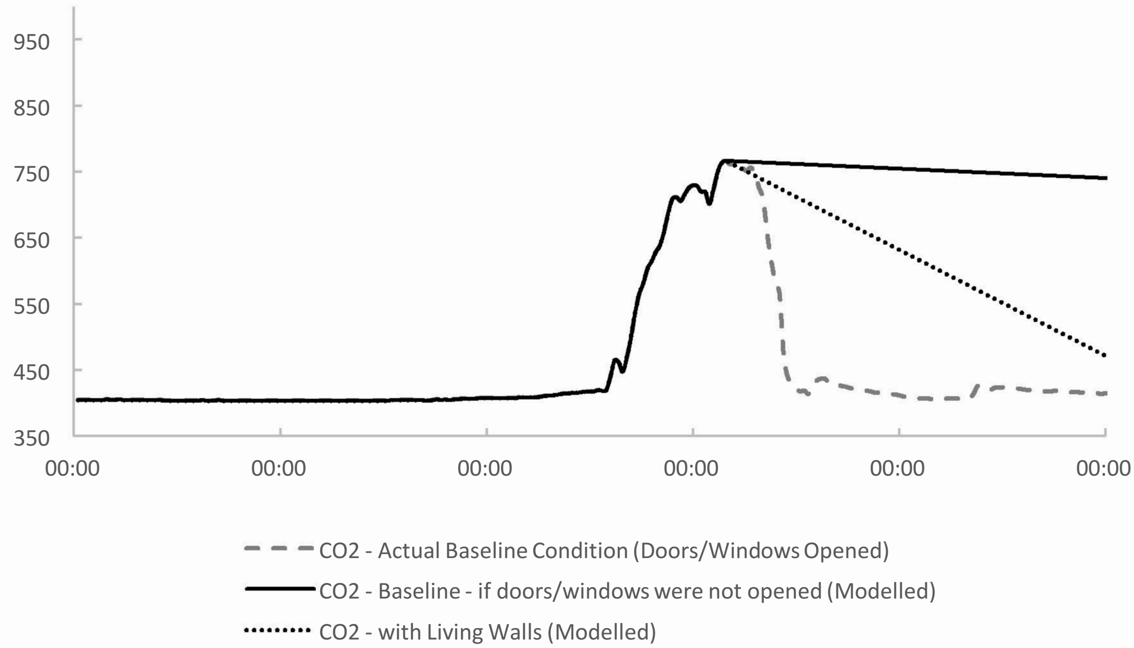


Figure 47: Predicted CO_2 decay at the Policy Lab, CIRS.

5 Discussion

5.1.1 Acoustics

The BC Hydro Theatre was found to have high NC levels: NC-55 and NC-50, without and with living wall installations respectively. The living walls slightly reduced the NC level, however, the NC levels both at baseline condition and with living walls are above the ASHRAE recommendation of NC-25 for this use.

It should be considered that NC curves are based on dB values and not dBA, therefore, do not filter the low-frequency noise. Based on ASHRAE (2009), Sound and Vibration Control, if the difference between dBA and dBC is greater than 25, the low frequency noise in the room is excessively high. Based on the background noise level data measured in the BC Hydro Theatre, and as summarized in Table 11, the difference between dBA and dBC is 25 for baseline condition and LW-C configuration. This shows that the BC Hydro Theatre has a high level of low-frequency noise at baseline and LW-C configurations. The LW-A and LW-B configurations also have high (close to 25) difference between dBA and dBC. In general, the BC Hydro Theatre has a high level of low-frequency noise with and without living walls. The high level of low-frequency noise in BC Hydro Theatre results in high NC levels in this room.

Table 11: Difference between dBA and dBC of the background noise level at BC Hydro Theater with and without living walls.

	Baseline	LW-A	LW-B	LW-C
dBC	64.6	60.6	61.1	62.9
dBA	39.3	37.3	36.9	38.4
dBC-dBA	**25**	**23**	**24**	**25**

The noise level in the BC Hydro Theatre was also compared with other criteria, such as maximum acceptable total background noise level criteria. As illustrated in Figure 29, the total background noise level in the BC Hydro Theatre is below the 45 dBA (maximum background noise level specified by LEED criteria for schools).

Given the possible inconsistent testing environment during background noise level measurements, noise reduction (NR) was calculated based on Eq. 3 to validate the effect of living walls on background noise level.

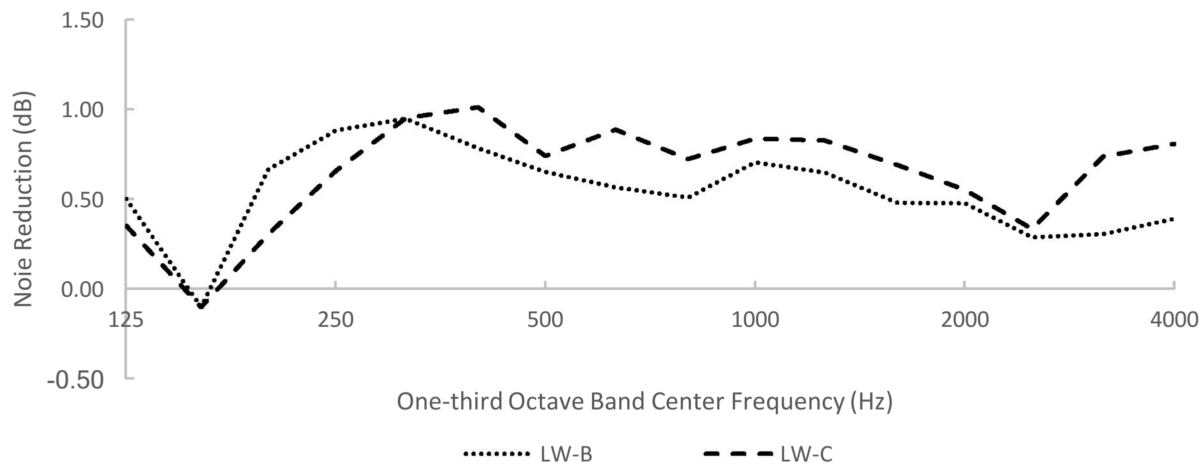


Figure 48: Noise reduction in BC Hydro Theatre with living walls.

Figure 48 illustrates that generally the noise reduction with living walls in the BC Hydro Theatre is very minimal with a maximum of about 1 dB. This indicates that the added sound absorption by the living walls is very minimal. It should be considered that the amount of living walls in this experimental setup was nominal compared to the size of the room (i.e. only 1% of room's surface area). Hence, the total added absorption and noise reduction is minimal. Figure 48 also illustrates that living wall configurations reduced the noise in the room similarly. Regardless, it is evident that living walls reduced the noise level in the room by increasing absorption. This finding is in line with previous research such as studies conducted by Martens and Michelsen (1981), Wong et al. (2010), Connelly (2011), and Akbarnejad (2017) that showed plants and substrates absorb acoustic energy.

As illustrated in Figure 48, the living walls do not absorb significant amount of low-frequency noise, however, they appear to be capable of absorbing mid to high frequency noise. Consequently, the human perception of low frequency noise may increase.

The BC Hydro Theatre was found to have a higher noise level at the east side of the room. It is possible that the equipment located at the east side of the room contributes to higher background noise level at low frequencies between 400 and 4000 Hz at this side of the room. The equipment may generate low-frequency noise that is not as diffuse, due to long wavelengths and room size, resulting in increased noise level in this side of the room. The presence of such subsets of acoustical environment in the room explains why the side of the room with living wall installation at LW-A and LW-B (i.e. where living walls located at east side of the room) has higher background noise level compared to room baseline.

As illustrated in Figure 37, the reverberation time has reduced with living wall installation in the room. Also, all three installations appear to have reduced the reverberation time similarly. However, the amount of reduction is not significant nor sufficient to reduce the room's reverberation time to the acceptable range of 0.4 - 0.6 second. Also, it should be considered that this amount of reduction in reverberation time would not be identified by general population (i.e. non-trained ears). Also, comparing Figure 38 and Figure 39, it can be concluded that LW-C configuration has a slightly greater effect on the room's reverberation time. This is in agreement with calculated noise reduction illustrated in Figure 48 that shows LW-C has generally a higher noise reduction compared to LW-B.

The speech articulation results indicated that only listener positions 3 and 4 at LW-A installation demonstrated a better speech intelligibility compared to other tested listener positions (see Figure 24, Figure 25, and Figure 26). Such positions of better speech intelligibility were the only scenarios where the listener and speaker were separated by the living wall installation. The nature of the test setup may be the reason for slightly better speech intelligibility at these listener positions. It is important to note that the living wall system used in this experimental setup has approximately 2-3 cm gaps around each of the panels and the bottom panels were 15 cm above the floor. These gaps significantly decrease insertion loss of the living wall installation, and consequently affect measured speech intelligibility.

In order to validate Akbarnejad and Connelly 2017 predictive model, field reverberation time data with and without living walls previously measured in two additional spaces was analyzed:

- Small non-quasi-cubic room of 40 m^3: Data collected by Koh (2018) in Room 105 at Building NE 03 at BCIT Burnaby Campus,
- Medium room of 159 m^3: Data collected by Connelly (2017) in Room 317 at Building NE 01 at BCIT Burnaby Campus,

Figure 49 to Figure 51 illustrate the reverberation time measured by others and predicted by Akbarnejad and Connelly 2017 model in each of the above spaces:

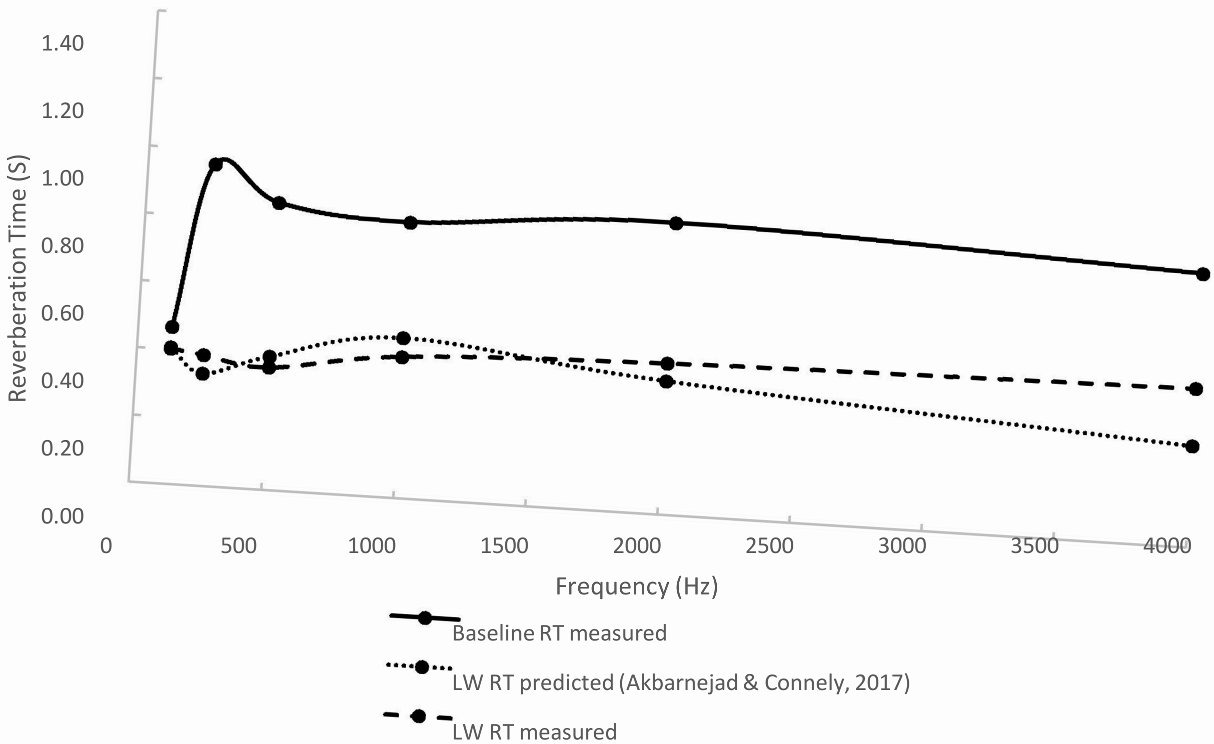


Figure 49: Predicted and measured reverberation time with and without living walls in a small room.

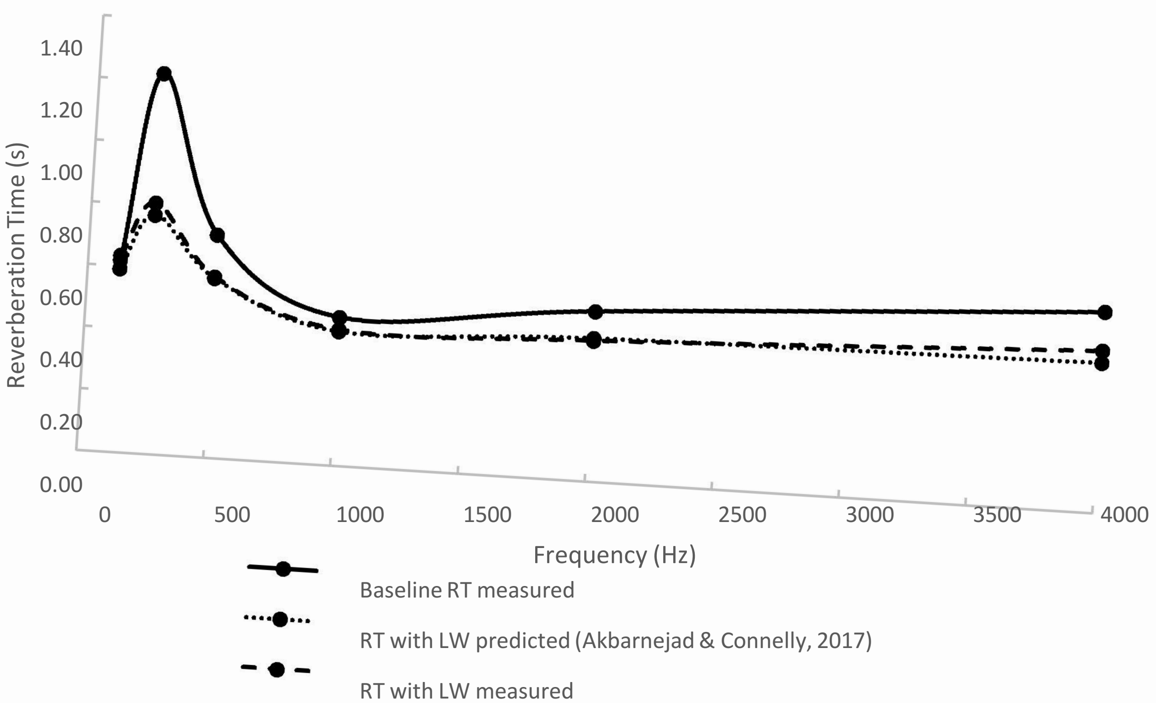


Figure 50: Predicted and measured reverberation time with and without living walls in a medium room.

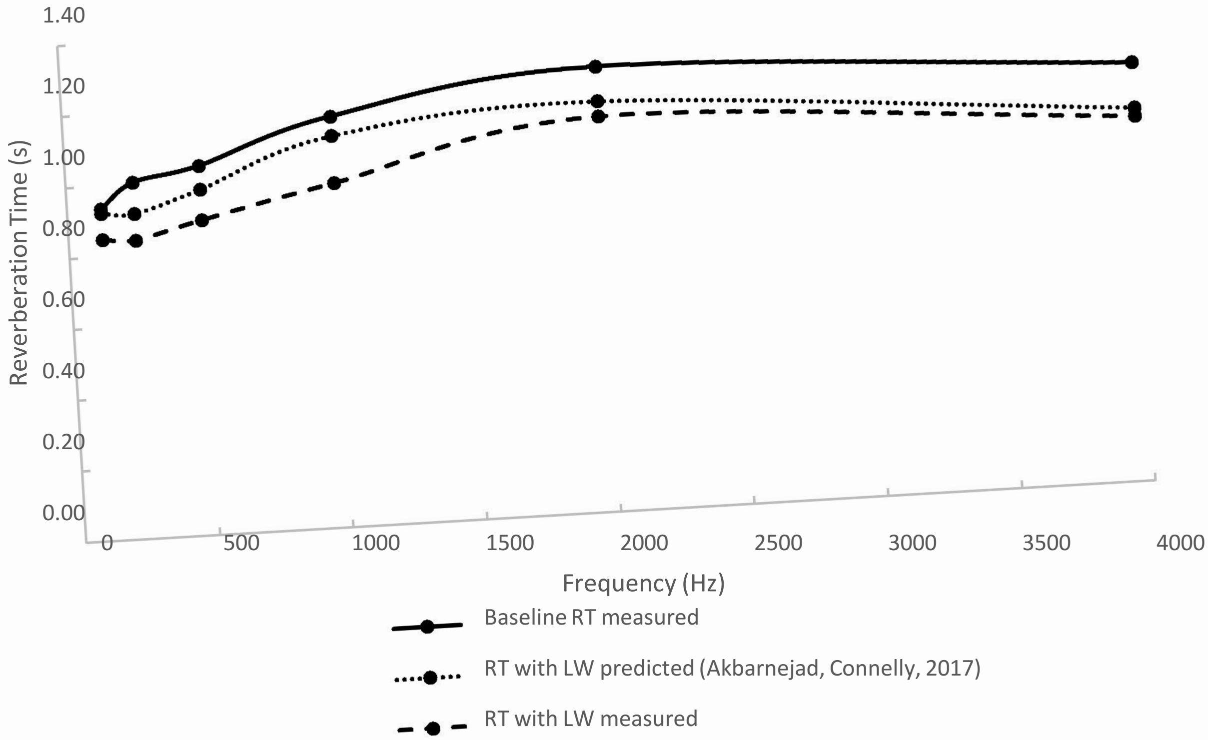


Figure 51: Predicted and measured reverberation time with and without living walls in a large room.

Based on the comparison of predicted and measured reverberation time with and without living walls in small, medium, and large room (Figure 49 to Figure 51), it can be concluded that Akbarnejad Connelly 2017 predictive model, developed by lab data, has generally a good prediction trend, and only very small deviations can be found between predicted and measured reverberation time.

Based on the summary of percentage of error of this predictive model illustrated in Table 12, the prediction at small room has a high percentage of error (36%). This is possibly due to the low reverberant nature of this room as well as the shape of the room. The small room has high vaulted ceiling, and the living walls were only place at a height of 1m. The noise may have trapped high in the room and may never have any incidence with the living wall panels to be absorbed by them. However, the predictive model by Akbarnejad and Connelly 2017 has a very low percentage error of 2% for medium room, and 10% for large room that were both quasi-cubic. Previous research by Bistafa and Bradley (2000), assumed 10% to be acceptable level of error for predictive models.

Table 12: Percentage of error of the predictive model by Akbarnejad & Connelly (2017), and percentage of living wall area to room surface area.

	Small Room	Medium Room	Large Room
Percentage of error of the prediction by Akbarnejad & Connelly 2017	**36%**	**2%**	**10%**
Percentage of living wall area to room surface area	**14%**	**4%**	**1%**

The deviation between measured and predicted reverberation time in the BC Hydro theatre is mainly at lower frequencies below 2000 Hz as illustrated in Figure 51. This deviation is not significant considering the minimal surface area of living walls compared to the room surface area (1%), and high level of low-frequency noise in the room. It should also be noted that the geometry of the stands supporting this particular living wall installation, located the living wall panels 60 cm away from the room wall. Akbarnejad and Connelly 2017 model assumes the living wall panels are mounted directly on the room wall surfaces. In general, the Akbarnejad and Connelly 2017 predictive model is reliable and can be used to predict the reverberation time in rooms with living wall panels.

5.1.2 Indoor Air Quality

In this field experiment, interior living walls were found to be able to reduce CO_2 generated in the space. This is in line with previous research such as studies conducted by NASA (1980s) and Dela Cruz et al. (2014) that showed that plants are capable of reducing CO_2. However, the idea of using plants to reduce air contaminants in lieu of mechanical ventilation requires further research and consideration, as plants do not appear to have a great impact when mechanical or natural ventilation is present. On the other hand, it is unclear how much plants are required to reduce the CO2, ideally to the ambient level, without compromising other indoor air quality criteria such as TVOCs and relative humidity.

The interior living walls in this study were found to slightly increase the TVOCs in the room. The previous studies in this area show mixed results. For example, Cornejo et al. who studied the VOC uptake capacity of plants, indicated that the removal capacity depends on plant species and type of chemical (Cornejo et al., 1999). On the other hand, Cheung (2017) confirmed production of pinene, reduction of butanone and no change in concentration of Toluene by the plants. It is important to examine the VOC emission of plants as well as their VOC uptake capacity (Owen et al. 2002). In the present study, considering the very small amount of TVOCs produced by the plants and the type of VOC (pinene, which has a pleasant smell), the increased level of TVOCs by plants is not considered a negative effect on indoor air quality.

In this study, the plants were found to humidify the space to about 50% from an average of approximately 34%. In this scenario, the increase in relative humidity is considered a positive effect, as it resulted in increased comfort level considering recommended relative humidity of 40-60% by ASHRAE 55 (2013) for comfort. However, it should be considered that in this research, the amount of living walls was minimal compared to the size of the room. The increased relative humidity could have been a negative outcome if larger area of living walls was tested. In dry climates, the increased relative humidity may be considered a positive effect of interior living walls.

Both graphs in Figure 44 illustrate that the relative humidity is slightly less during daytime. This may be a result of a more active mechanical ventilation or opened doors and windows introducing natural ventilation during the day. It also illustrates that people (in large events) contribute to slight increase of relative humidity.

The previous lab study by Cheung (2017) suggested that there is a correlation between amount of irrigation and increase in relative humidity. However, this field study did not find any obvious correlation between irrigation and relative humidity. This outcome may be a result of minimal irrigation due to limited drainage of living wall system used in this study.

5.1.3 Indoor Environmental Quality

The model predicts that 18 living wall panels can potentially help with reduction of CO_2 in the Policy Lab, however, it would take 124 living wall panels to reduce the reverberation time and improve the acoustical quality of the Policy Lab. The effect of 124 living wall panels on room indoor air quality criteria such as relative humidity and TVOCs may be negative. On the other hand, the human experience needs to be investigated and addressed in the design.

At the onset of this project, CIRS management was considering installation of a living wall in the atrium of CIRS. The findings from this research suggests that a living wall, if installed at the two ends of the atrium as planned, may not affect the overall indoor environmental quality.

However, it may affect the individual's perception and biophilic response to the space that is suggestive of future research.

Recommendation for Further Research

To further research the effect of interior living walls, it would be valuable to investigate the effect of interior plants such as effect on human well-being, psychological response, and work performance.

Specific acoustical investigation could include the inclusion of scattering coefficient in computer-based predictive software for comparison against field data.

Specific indoor air quality investigation could include: testing whether the effect of living walls in reduction of CO_2 is linear; impact of flowering plants producing pollens that may affect indoor air quality and human health and comfort.

It is recommended to conduct field studies in a less ideal indoor environment than the LEED certified CIRS building to fully capture the effect of interior living walls on indoor environmental quality.

Limitations and Strengths

Monitoring the indoor environmental quality criteria in the field environment was the biggest challenge of this research project. Limited data collection windows due to availability of the BC Hydro Theatre for testing, as well as complex dynamic nature of the space were challenges both at time of data collection and data analysis. It was also challenging to find patterns in the data and draw general conclusions due to various factors affecting the results and dynamic nature of field environment. Additionally, the amount of living walls installed for the experimental setup was minimal (about 1% of room surface area) which made the effect on indoor environmental quality smaller and harder to capture. Given that the CIRS building was designed and built to LEED Platinum standard, the indoor environmental quality is at a high level. It is expected that a greater impact of the living wall would have been measured in a less ideal environment.

Despite the complexity of the field environment, minimal surface area of living walls, and high level of indoor environmental quality in CIRS this study was able to capture the effect of interior living walls on indoor air quality and acoustics of the room under conditions measured.

Conclusion

Interior living walls are used in various interior spaces as architectural features, as they are aesthetically pleasing and have a biophilic nature; the green building design movement emphasizes health and well-being of the occupants. This research thesis monitored and experimented with living walls in the field environment to determine the effect of living walls on indoor air quality and acoustics of the room and validate the results of previous studies conducted in lab environment. As the initial and maintenance cost of living walls is high, it is important to incorporate the living wall into design where they can positively affect the indoor environmental quality as well as providing an aesthetically pleasing environment.

The living walls were found to increase sound absorption in the room. Using data collected as part of this research and collected in other field scales, it was concluded that Akbarnejad and Connelly 2017 predictive model for sound absorption (Sabine) of interior living walls is valid. Therefore, calculated predications should be made to determine the surface area of living walls required along with other room materials to meet the criteria. It was also concluded that living walls can affect the indoor air quality with reducing CO_2 concentration. Also, living walls were found to possibly humidify the space, introduce very small amount of TVOCs, and have no significant effect on endotoxin level under conditions measured. With that said, the idea of using interior living walls to ventilate a space requires further consideration, as the effect of living walls on ventilating a space cannot replace the mechanical or natural ventilation. Also, the combined effect of interior living walls on indoor air quality and acoustics should be considered at the design stage to achieve a balanced indoor environment.

References

Abbaszadeh, S.; Zagreus, Leah; Lehrer, D.; & Huizenga, C. (2006). Occupant satisfaction with indoor environmental quality in green buildings. *Center for the Built Environment*. UC Berkeley: Center for the Built Environment.

Akbarnejad, M. (2017). The absorption and scattering characteristics of interior living walls. British Columbia Institute of Technology, Burnaby, British Columbia.

Amodio, M., Dambruoso, P. R., de Gennaro, G., de Gennaro, L., Loiotile, A. D., Marzocca, A. Tutino, M. (2014). Indoor air quality (IAQ) assessment in a multistorey shopping mall by high-spatial-resolution monitoring of volatile organic compounds (VOC). Environmental Science and Pollution Research, 21(23), 13186-13195.

Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the air: A review of the effects of particulate matter air pollution on human health. Journal of Medical Toxicology, 8(2), 166-175.

ANSI S3.5 (1997). Methods for calculation of the Speech Intelligibility Index. Acoustical Society of America.

Apte M.G., Fisk W.J., Daisy J.M. (2000). Associations between Indoor CO_2 Concentrations and Sick Building Syndrome Symptoms in U.S. Office Buildings: An Analysis of the 1994-1996 BASE Study Data. Indoor Air, 10, 246-257.

ASHRAE (2009). Handbook of Fundamentals, Chapter 8, Sound and Vibration.

ASHRAE (2009). Sound and Vibration Control, Chapter 47.

ASHRAE (2013). ASHRAE Standard 62.1- 2013. Ventilation for Acceptable Indoor Air Quality.

ASHRAE (2013). ASHRAE Standard 55- 2013. Thermal Environmental Conditions for Human Occupancy.

ASTM C423-07a, Standard Test Method for Sound Absorption and Sound Absorption Coefficient by the Room Reverberation Method.

ASTM C634-13, Standard Terminology Relating to Building and Environmental Acoustics.

ASTM D6245-12 Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation.

ASTM E110-06, Standard Classification for Determination of Articulation Class.

ASTM E1130 - 02, Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index.

Aylor, D. (1971). Noise reduction by vegetation and ground. The Journal of the Acoustical Society of America, 51(1B), 197.

Aylor, D., Parlange, J., & Chapman, C. (1973). Reverberation in a city street. The Journal of the Acoustical Society of America, 54(6), 1754.

Bearge D.W. (1993). *Indoor Air Quality and HVAC Systems*. Lewis Publisher.

Bengtsson, J., Persson Waye, K., Kjellberg, A., Ämnesavdelningen för inomhusmiljö, Högskolan i Gävle, & Institutionen för teknik och byggd miljö. (2004). Evaluations of effects due to low-frequency noise in a low demanding work situation. Journal of Sound and Vibration,278(1), 83-99.

Beranek (1989). Leo L. Beranek, "Balanced noise-criterion (NCB) curves." Reprinted with permission from J. Acoust. Soc. Am. vol. 86, No. 2, © 1986, Acoustical Society of America: Melville, NY, Aug. 1989.

Beranek (1957). Leo L. Beranek, "Revised criteria for noise in buildings." Noise Control, Jan. 1957.

Bistafa, S. R., & Bradley, J. S. (2000). Predicting reverberation times in a simulated classroom. Journal of the Acoustical Society of America, 108(4), 1721-1731.

Bruno, P., Caselli, M., De Gennaro, G., Iacobellis, S., & Tutino, M. (2008). Monitoring of volatile organic compounds in non-residential indoor environments. Indoor Air, 18(3), 250-256.

Cheung, I. (2017). Impact of interior living walls on indoor air quality: Study in a dynamic environment. Master of Science, University of British Columbia, Vancouver, BC.

Chow, J.C., Watson, J.G., Maudely, J. L., Costa D. L., Wyzga R. E., Vedal, S., Hidy, G. M., Altshuler, S. L., Marrack, D., Heuss, J. M., Wolff, G. T., Pope C. A., Dockery, D. W. (2006). Health Effects of Fine Particulate Air Pollution: Lines that Connect. Journal of Air and Waste Management Association, Vol. 56.

CIRS Building Manual: http://cirs.ubc.ca/building/building-manual.

Connelly, M. R. (2011). Acoustical characteristics of vegetated roofs - contributions to the ecological performance of buildings and the urban soundscape. University of British Columbia, Vancouver, British Columbia.

Connelly, M., & Hodgson, M. (2015). Experimental investigation of the sound absorption characteristics of vegetated roofs. Building and Environment, 92, 335-346.

Connelly, M. (2017). Reverberating time measurements, experiments with living walls in room 317 at NE1 building at BCIT Burnaby campus.

Cornejo, J. J., Muñoz, F. G., Ma, C. Y., & Stewart, A. J. (1999). Studies on the decontamination of air by plants. Ecotoxicology, 8(4), 311-320.

Crouse, D. L., Peters, P. A., van Donkelaar, A., Goldberg, M. S., Villeneuve, P. J., Brion, O., Burnett, R. T. (2012). Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: A Canadian national-level cohort study.

Darlington, A., Chan, M., Malloch, D., Pilger, C., & Dixon, M. A. (2000). The biofiltration of indoor air: Implications for air quality. Indoor Air, 10(1), 39-46.

Dela Cruz, M., Müller, R., Svensmark, B., Pedersen, J. S., & Christensen, J. H. (2014). Assessment of volatile organic compound removal by indoor plants—a novel experimental setup. Environmental Science and Pollution Research, 21(13), 7838-7846.

EPA. An Introduction to Indoor Air Quality (IAQ). Washington: US Environmental Protection Agency, 2009.

Green Roofs for Healthy Cities: www.greeroofs.org.

GSA. (2011). Sound Matters: How to Achieve Acoustic Comfort in the Contemporary Office.

Health Council of Netherlands (2010). Endotoxins: Health- based recommended occupational exposure limit.

Hess-Kosa, K. (2002). Indoor air quality: Sampling methodologies. Boca Raton, Fla: Lewis.

Hodgson, M. (2008). acoustical evaluation of six 'green' office buildings. Journal of Green Building, 3(4), 108-118.

Horoshenkov, K., Khan, A., & Benkreira, H. (2013). Acoustic properties of low growing plants. Journal of the Acoustical Society of America, 133(5), 2554-2565.

Huber, F., & Bednar, T. (2008). The influence of the scattering coefficient on the reverberation time. The Journal of the Acoustical Society of America, 123(5), 3355.

Hystad, P., Demers, P. A., Johnson, K. C., Carpiano, R. M., & Brauer, M. (2013). Long-term residential exposure to air pollution and lung cancer risk. Epidemiology, 24(5), 762-772.

Keighley, E. C. (1970). Acceptability criteria for noise in large offices. Journal of Sound and Vibration, 11(1), 83-93.

Kellert, S. R., & Wilson, E. O. (1993). The Biophilia Hypothesis. Covelo: Island Press.

Khaleghi, A., Bartlett, K., & Hodgson, M. (2011). factors affecting ventilation, indoor-air quality and acoustical quality in 'green' and non-'green' buildings: A pilot study. Journal of Green Building, 6(3), 168-180.

Kjellberg, A., & Landström, U. (1994). Noise in the office: Part II — the scientific basis (knowledge base) for the guide.International Journal of Industrial Ergonomics, 14(1), 93-118.

Koh, H. (2018). Reverberation time measurements with living walls in room 105 at NE3 at BCIT Burnaby campus.

Kostiainen, R. (1995). Volatile organic compounds in the indoor air of normal and sick houses. Atmospheric Environment, 29(6), 693-702.

Leech, J. A., Nelson, W. C., Burnett, R. T., Aaron, S., & Raizenne, M. E. (2002). It's about time: A comparison of canadian and american time-activity patterns. Journal of Exposure Analysis and Environmental Epidemiology, 12(6), 427-432.

LEED for Schools, for New Construction and Major Renovations, U.S. Green Building Council (2007).

Living Architecture Magazine. (2013). Green Roofs for Healthy Cities.

Long, M. (2014). Architectural acoustics. Burlington, MA: Elsevier Academic Press.

Martens, M. J. M. (1980). Foliage as a low-pass filter: Experiments with model forests in an anechoic chamber. The Journal of the Acoustical Society of America, 67(1), 66.

Martens, M., & Michelsen, A. (1981). Absorption of acoustic energy by plant leaves. Journal of the Acoustical Society of America, 69(1), 303-306.

Mendell, M., & Heath, G. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. Indoor Air, 15(1), 27-52.

Muehleisen, R. T. (2011). Acoustics of green buildings. The Journal of the Acoustical Society of America, 130(4), 2350. doi:10.1121/1.3654413

Ostro, B. D., & Rothschild, S. (1989). Air pollution and acute respiratory morbidity: An observational study of multiple pollutants. Environmental Research, 50(2), 238-247.

Owen, S. M., Harley, P., Guenther, A., & Hewitt, C. N. (2002). Light dependency of VOC emissions from selected mediterranean plant species. Atmospheric Environment, 36(19), 3147-3159.

Plant Connection G-O2. Green walls. Retrieved from http://www.myplantconnection.com on January 9, 2016.

Pope, A. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., Thurston, G. D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. Journal of American Medical Association. Vol 287, No.9.

Ryherd, E. E., & Wang, L. M. (2008). Implications of human performance and perception under tonal noise conditions on indoor noise criteria. The Journal of the Acoustical Society of America, 124(1), 218-226.

Rylander, R. (2002). Review: Endotoxin in the environment - exposure and effects. Journal of the International Endotoxin Innate Immunity, 8(4), 241-252.

Sabine, W. (1900). “Reverberation”. The American Architect and The Engineering Record, from the Collected Papers on Acoustics, Wallace Clement Sabine. 1964, New York, NY.

Samfield, M.M. (1992). Indoor Air Quality Data Base for Organic Compounds. United States Environmental Protection Agency. Air and Energy Engineering Research Laboratory.

Schwartz, J., Slater, D., Larson, T., Pierson, W., & Koenig, J. (1993). particulate air-pollution and hospital emergency room visits for asthma in seattle. American Review of Respiratory Disease, 147(4), 826-831.

Seppänen, O. A., & Fisk, W. (2006). Some quantitative relations between indoor environmental quality and work performance or health. HVAC&R Research, 12(4), 957-973.

Seppänen, O. A., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and CO_2 concentrations with health andOther responses in commercial and institutional buildings. Indoor Air, 9(4), 226-252.

Smyrnova Y., Kang J., Blackford C., Cheal C. (2012). Diffusion Coefficient of Vegetation: Measurement and Simulation. Societe Francaise d'Acoustique. Acoustics 2012.

Song, J., Kim, Y., & Sohn, J. (2007). The impact of plants on the reduction of volatile organic compounds in a small space. Journal of PHYSIOLOGICAL ANTHROPOLOGY, 26(6), 599-603.

Spengler, J. D., Samet, J. M., & McCarthy, J. F. (2001). Indoor air quality handbook. New York: McGraw-Hill.

Stacil, S., Hites, R. (1995). Organic Pollutant Accumulation in Vegetation. The Journal of environmental Science & Technology, 29(12).

Waye K.P., & Rylander, R., Benton, S., and Leventhall, H.G. (1997). Effects on Performance and Work Quality due to Low-Frequency Ventilation Noise. Journal of Sound and Vibration, 205(4), 467-474.

Weinmaster, M. (n.d.). Are Green Walls as “Green” as They Look? An Introduction to the Various Technologies and Ecological Benefits of Green Walls. Journal of Green Building 4(4).

WHO (2009). WHO Guideline for Indoor Air Quality: dampness and mould.

Wolverton, B. C. (1988). Foliage plants for improving indoor air quality.

Wong, N. H., Wong, N. C., Kwang Tan, A. Y., Tan, P. Y., & Chiang, K. (2010). Acoustics evaluation of vertical greenery systems for building walls. Building and Environment, 45(2), 411-420.

Wood, R. A., Burchett, M. D., Alquezar, R., Orwell, R. L., Tarran, J., & Torpy, F. (2006). The potted-plant microcosm substantially reduces indoor air VOC pollution: I. office field-study. Water, Air, and Soil Pollution, 175(1), 163-180.

Appendices

A. CIRS Manual

B. CIRS Architectural and Mechanical Drawings

C. Living Wall Configurations at BC Hydro Theatre

D. List of Standards

E. List of Equipment

F. Collected Data at CIRS

G. Preliminary Data Collection at Five Spaces at CIRS

Appendix A

The Centre for Interactive Research on Sustainability (CIRS) at UBC

Building Manual

CIRS

Building Overview

"It's a wonderful idea: that nature and building are working together."

- Peter Busby, Managing Director, Perkins + Will Architects

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

CIRS
CENTRE FOR INTERACTIVE RESEARCH ON SUSTAINABILITY

BUILDING BACKGROUND

The CIRS building is the flagship project of UBC's Campus as a Living Laboratory initiative, which combines building and operational infrastructure, construction and retrofits with research and teaching opportunities to advance sustainability on and off campus. It is used as a test-bed to study sustainable technologies, systems, processes, practices and behaviours.

The building was designed to push the envelope of sustainable performance in both environmental and human terms by providing net positive benefits to both its surroundings and its inhabitants. The design approach included the integration of building systems and passive strategies to achieve high standards of performance while remaining adaptive to changing needs and uses over time.

FACILITIES

Lobby/Atrium As the core of CIRS, it welcomes visitors and visually connects them to key sustainability features. Electronic signage displays information on building performance, research projects, and campus-wide activities.

Modern Green Auditorium This 423 seat lecture hall, one of the largest on campus, draws many students to CIRS. It is day-lit and ventilated through an underfloor air system.

The Loop Cafe This popular lunch spot serves fresh and organic choices sourced locally whenever possible. Products use minimal packaging that is mostly recyclable or compostable.

Offices and Labs As a space for multidisciplinary education and research, CIRS provides dedicated lab and office space for UBC researchers and partners.

BC Hydro Theatre A flexible and adaptive facility for high-quality, data-intensive visualizations, modeling and scenario generation. This space allows a variety of configurations to maximize user experience and facilitate unanticipated uses.

CIRS
CENTRE FOR INTERACTIVE RESEARCH ON SUSTAINABILITY

FEATURES

Wood Structure demonstrates the use of both pine beetle-damaged and certified wood products as viable materials for institutional applications that store carbon and reduce the building's greenhouse gas emissions from construction.

Living Roof recreates a meadow environment for birds, insects and native or adaptive plants, and contributes to reducing heat island effects by providing evapotranspiration cooling.

Living Façade provides shading during the summer and allows warmth from the sun to be absorbed by the building in winter. The vegetated wall of vines uses reclaimed water for irrigation.

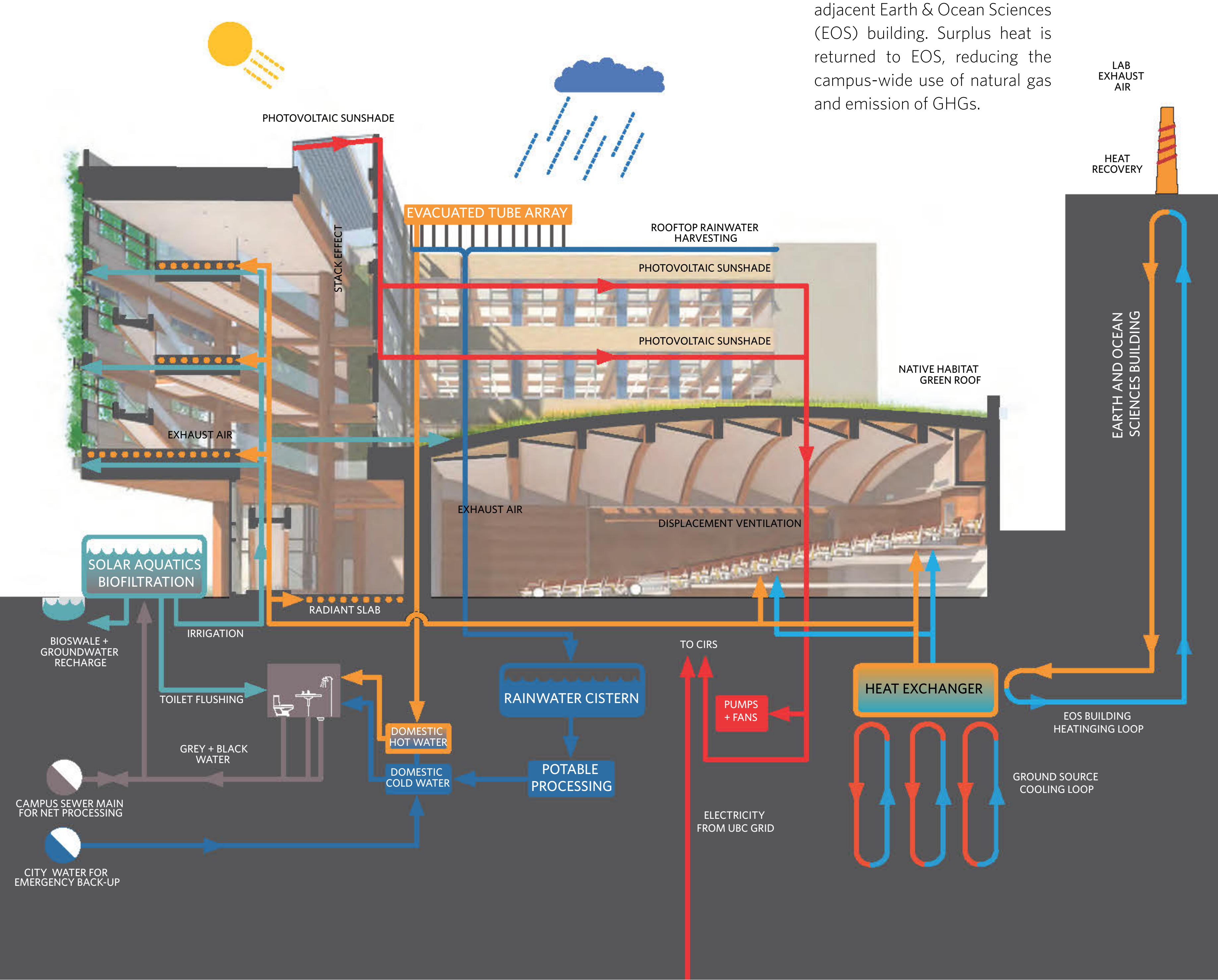
Reclaimed Water System treats campus waste water using solar aquatics and constructed wetland technologies. The reclaimed water is used to flush toilets and for irrigation.

Solar Energy is harvested through collectors that provide hot water for the building and through photovoltaic panels that convert it to electricity used to power the building systems.

Rainwater System harvests rain water from the roof, purifies it using filtration and disinfection and stores it for use in the building. Stormwater runoff is redirected through bioswales to the local aquifer.

Geoexchange System transfers thermal energy between the building and the ground, providing heating in the winter and cooling in the summer.

Heat Exchange System collects waste heat from within CIRS building systems and from the adjacent Earth & Ocean Sciences (EOS) building. Surplus heat is returned to EOS, reducing the campus-wide use of natural gas and emission of GHGs.



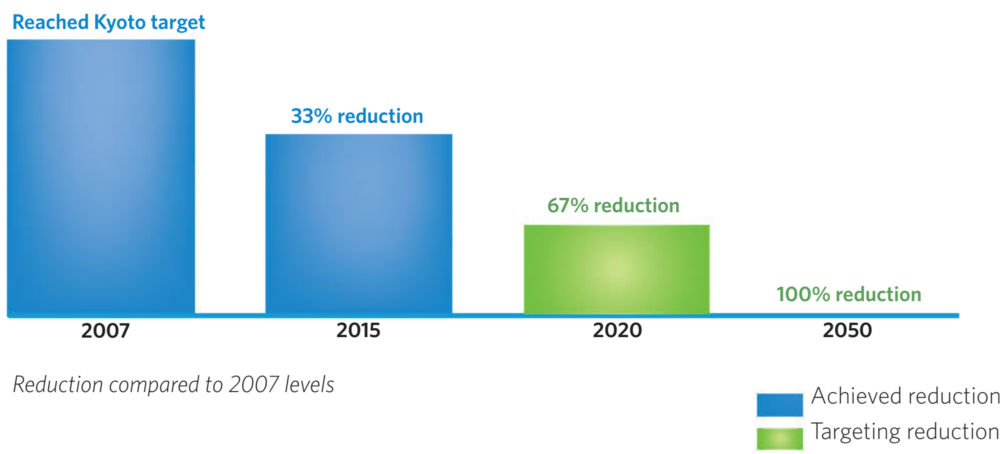
CIRS CONTEXT

INTRODUCTION

The global challenges associated with climate change, rapid urbanization, and degradation of the biosphere and natural systems that sustain life, as well as the mammoth task of providing food and drinking water for a rapidly expanding population, require that society accelerate dramatically the adoption of more sustainable practices. The Centre for Interactive Research on Sustainability at the University of British Columbia campus in Vancouver, Canada was created in response to these challenges.

The University of British Columbia is Canada's second largest university and a research leader in science, engineering, social sciences and humanities. It is a global leader among post-secondary institutions that are using their campuses as living laboratories: test-beds and demonstration sites for sustainability in education, research, infrastructure and operations, individual behavior and community building. UBC actively engages with non-academic partners — industry, government, NGOs and community groups — to develop policies, set ambitious performance targets, patent new technologies, create commercially successful spin-off companies, and, of course, educate and train the next generation in sustainability related knowledge and skills. Through these highly qualified graduates and collaborative partnerships, the lessons learned at UBC influence sustainability practices around the world.

UBC's commitment to reduce its GHG emissions:



Vancouver campus at a glance:

- academic centre, mixed-use residential neighbourhoods and agricultural land
- 400+ hectares (988 acres) of land
- over 1.4 million square meters (15 million square feet) of institutional floor space divided into nearly 400 buildings
- 40,000+ registered students
- 13,000+ staff and faculty employees
- 10,000+ students living on campus
- 10,000+ non-student residents
- 39 active campus as a living lab projects

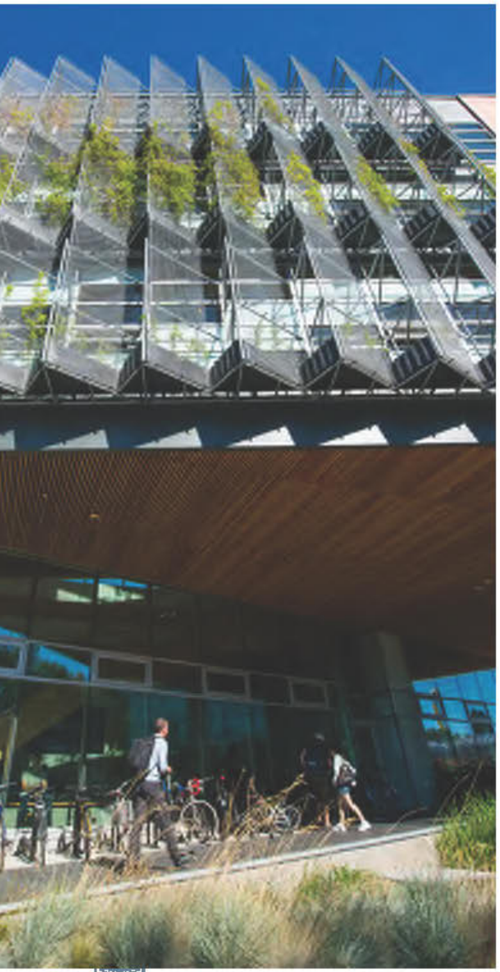
- Data from 2013/2014 Annual Sustainability Report

Photo credit: Don Erhardt

"Our vision for UBC is to create campus environments that nurture the wellbeing of UBC's community, visitors and ecology."

- Gerry McGeough, Director of Campus Planning and Design

The Centre for Interactive Research on Sustainability (CIRS) was one of the first demonstration projects of UBC's campus as a living lab initiative. The CIRS building was designed using regenerative sustainability principles, targeting net-positive performance in terms of both environment and human wellbeing. As the home of an interdisciplinary research centre, the building functions as a real-world research and education project, as well as a means of engaging its inhabitants and community. The ultimate goal is the introduction of innovative solutions for urban areas that begin to address the global challenges facing humanity.



WHAT'S NEXT?

Buildings like CIRS — that adhere to and operationalize the principles of regenerative sustainability, seek to improve their communities and provide opportunities for learning — are deeply transformative and have a catalytic effect toward the establishment of higher sustainability targets in their constituent organizations.

UBC is beginning to apply the principles and lessons learned from CIRS to projects at both the building and neighbourhood scale, as well as longer term planning initiatives.

REGENERATIVE SUSTAINABILITY

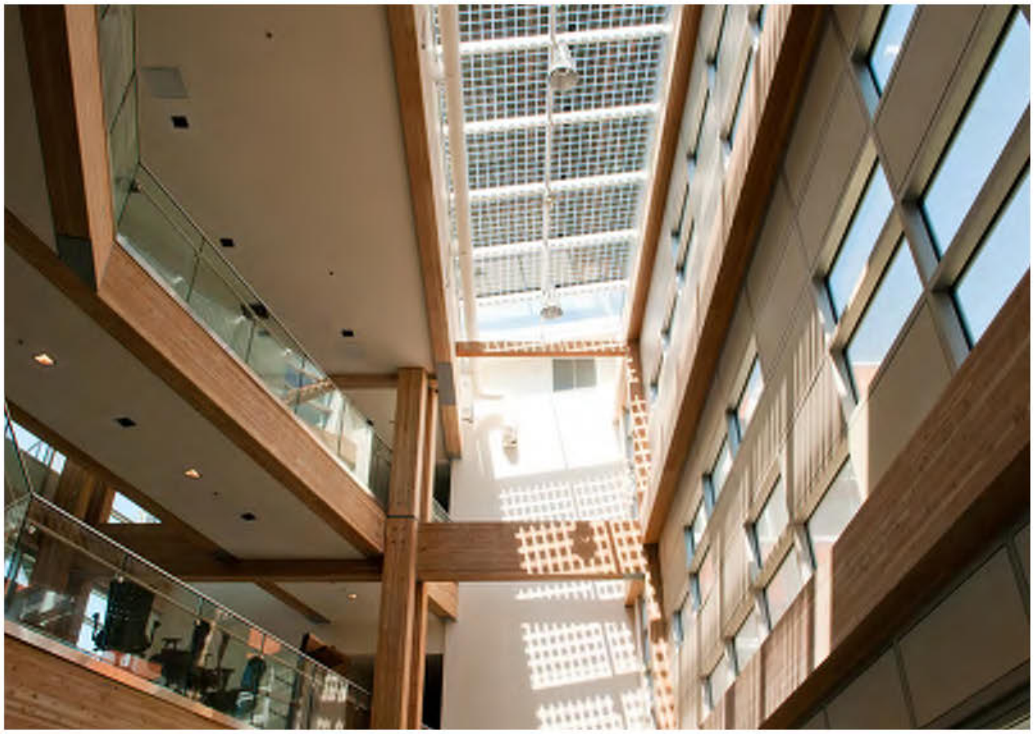
"At UBC's Vancouver campus, sustainability means simultaneous improvements in human and environmental wellbeing, not just reductions in damage or harm. By 2035, such regenerative sustainability is embedded across the University throughout teaching, learning, research, partnerships, operations and infrastructure, and the UBC community."

- 20 year Sustainability Strategy for UBC

NET POSITIVE IMPACTS

Contemporary environmentalism has shown itself to be ill-equipped to address the immense global sustainability challenges facing humanity. We can no longer afford the current practice of pursuing goals that simply reduce our environmental impacts — it's simply insufficient as a driving force for the magnitude of required changes.

To address this crisis we need to think of every aspect of modern life, including constructing buildings and developing land, as acts of restoration and regeneration. We need to inspire people to repair and restore the biosphere, sequester carbon dioxide and seek out significantly more effective use of resources, especially non-renewables. This shift in perspective has the potential to motivate us to move beyond a practice of trying to create buildings and developments that are simply "less bad" into a new paradigm that strives to achieve the creation of "good" development. It helps us shift our mindset from measuring impacts into providing benefits, from sacrifice to contribution and finally, from net zero to net positive. This is the foundation of regenerative sustainability.



REGENERATIVE SUSTAINABILITY IN PRACTICE

How do we apply, in a practical sense, these regenerative sustainability principles to the urban context (buildings, communities, cities, etc.)?

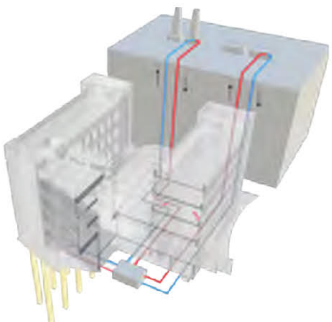
UBC built CIRS to try to better understand this challenge.

The CIRS building was the first project at the University to adhere to and operationalize the two dimensions of regenerative sustainability as outlined by Dr. John Robinson: the active restoration and regeneration of the environment; and the active pursuit of improvement in the wellbeing of the human community. The design, construction and operation of the CIRS building at UBC provides insights and practical experience on what is technically, economically and institutionally feasible and what barriers and challenges must be overcome in order to realize regenerative sustainability principles at the building and neighbourhood scales. The opportunity for learning is huge.

The CIRS experience indicates that is possible for buildings and neighbourhoods to:

- capture and exchange more energy than is obtained from current utility networks;
- become self-sufficient in water use by harvesting rainwater, treating and recycling wastewater, and recharging groundwater reservoirs with storm-water runoff;
- capture and store more carbon dioxide in building materials and structural components than the amount emitted during construction activities;
- and improve the conditions that impact the health, happiness and productivity of building inhabitants. This can be achieved through a high quality indoor environment with natural light and natural ventilation, and through the active participation of the inhabitants in operational decisions that impact both their comfort and wellbeing, in effect, creating a mutually beneficial symbiotic relationship between people and buildings.

ENABLERS



Energy Exchange

Heat exchangers capture waste heat from the Earth and Ocean Sciences (EOS) building. Excess heat is returned to EOS which results in natural gas savings and fewer GHG emissions.

Wooden Structure

Using wood as the main structural material, CIRS sequesters more carbon than was produced during its construction, making it a net carbon negative project.

CIRS REGENERATIVE SUSTAINABILITY ENABLERS

The regenerative sustainability principles embodied by CIRS — the net-positive improvement of environmental and human well-being through the act of building — are enabled by a set of interconnected design and operational strategies.

- **Systems thinking and integration**

  Optimizing at the whole system level, rather than sub-optimizing at the component level, changes the scope and outlook of the design effort. It leads the planning and design team to look for opportunities for systems to interact with the building surroundings and for potential contributions of net benefits into the encompassing community.

- **Application of industrial ecology principles**

  The basic notion that the by-products of some processes can become inputs for others can be successfully adapted from product manufacturing to the planning and design of sustainable buildings. This approach reconsiders "wastes" as useful resources and, through connection with other buildings and infrastructure, can create larger networks of resource exchange with community scale benefits.

- **Building engines of carbon sequestration**

  The exploitation of wood structures and building materials to sequester the carbon that was absorb by the trees while they were alive. This goes beyond simply limiting the CO_2 generated during building construction — through the extraction, manufacturing, transportation and installation of materials and components — to begin to offset those emissions.

› **Rational use of natural resources**

Not all equipment and systems require the highest quality of resources for operation. Within buildings, specific applications can be strategically matched with the appropriate grade and quality of resources, eg. using grey water rather than potable water to flush toilets. This application limits waste and emissions, and optimizes the use of secondary resources, equipment and infrastructure required to limit overall waste and emissions, and clean, heat or otherwise upgrade primary resources.

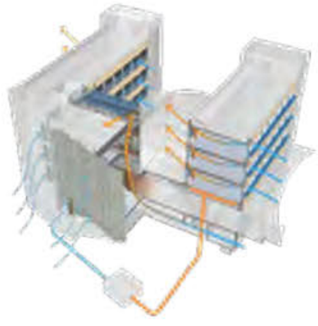
› **Empower occupants to become inhabitants**

Building *occupants* are generally passive recipients of building systems and infrastructure, are not normally in control of their indoor environment and do not usually get involved in the operation and optimization of their buildings. In contrast, building *inhabitants* are considered part of the building ecosystem. They have control over the conditions that impact their comfort, are encouraged to get involved in the operations of the building and are motivated to contribute to the long-term sustainability of the building. Without active inhabitant engagement and participation sustainable buildings cannot meet their performance targets.

Reclaimed Water

Black water (from toilets and urinals) and grey water (from showers and sinks) is collected from fixtures in the building.

The Solar Aquatics bio-filtration system treats the waste water which is pumped back into CIRS and used to flush toilets and for landscape irrigation.



Ventilation

CIRS takes advantage of natural ventilation. Manually operable windows allow for inhabitant control over airflow and temperature.

CIRS CONSTRUCTION

CONSTRUCTION AND RESEARCH INFRASTRUCTURE

CIRS was first conceived in 1999 by UBC professor Dr. John Robinson as an opportunity to create a sustainability showcase in the province of British Columbia: a building in which to push the envelope of sustainable design by integrating passive design strategies with the most advanced sustainable technologies of the time to achieve an off-the-chart level of performance. Completed in 2011, the CIRS building has become UBC's sustainability flagship and is the home of dozens of UBC sustainability researchers, planners, operators and partners.

The building's systems and infrastructure, as well as the processes of planning, designing, building and operating the facility are part of the research agenda of CIRS. It is equipped with a robust network of sensors and controls that are part of a sophisticated building automation and monitoring system with more than 3,000 points. This capability facilitates performance tracking and reporting, and enables the collection of real-time data for research projects. Every system and component in the building will be studied over the course of its useful life, and improved through the application of design innovations, new operational practices and advancements in technology.

Principles of flexibility, modularity and adaptability were emphasized in the design of the CIRS building to ensure that it can easily and cost-effectively respond to future requirements. This resiliency allows spaces to change to fit inhabitant needs and support research projects, and ultimately enables the complete disassembly of the building and the repurpose of its constituent components at the end of its useful life.

Project Goals

- Design CIRS to be as passive and as simple as possible.
- Produce a building that exemplifies replicable, economical solutions.
- Neutralize ecological impacts on site.
- Regenerate ecosystems to attract local fauna.
- Conduct a life cycle assessment of all building components for environmental impact.
- Provide inhabitants control over their environment and comfort conditions.
- Ensure that water leaving the site is as good or better quality than when it arrived.
- Collect and treat all wastewater on-site or within the precinct.
- Control, dispose of, reuse and discharge 100% of stormwater on-site.
- Become a living lab for researchers and companies to test innovative products and technology.
- Advance knowledge of sustainable design strategies.

DEVELOPMENT OF THE CIRS BUILDING started in 1999. In the following years, the project went through three different iterations, at different sites and with different proposed inhabitants. During that time, there have been significant advancements in public awareness, policy and market developments, and technological capabilities related to sustainable buildings. The dedicated leadership team maintained a strong project vision through all of these changes and ensured that the ambitious project goals would be achieved.

- Idea is born
- Design iteration
- People join the team
- Partnership forged
- Feasibility study
- $$$ Funding
- Construction

University of British Columbia, 2009
Busby, Perkins + Will

1999

Dr. Martha Piper, president of UBC at the time, asks all the research units on campus to develop a strategic plan for future development.

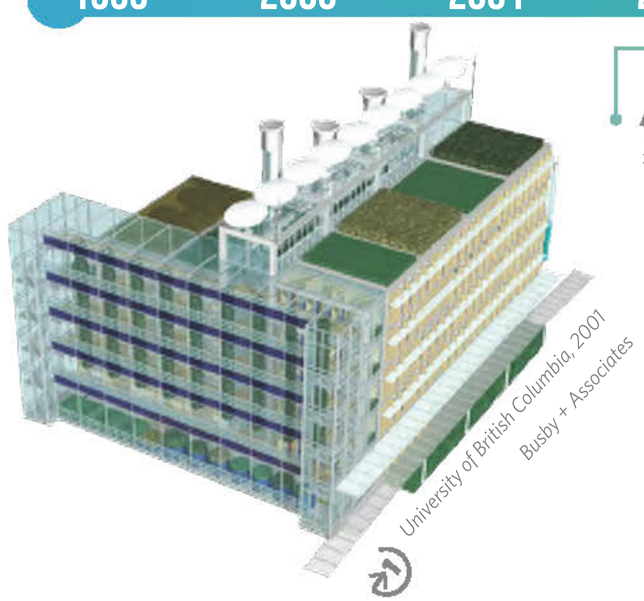
Dr. John Robinson, then at the Sustainable Development Research Initiative, proposes an idea to create a "BC Showcase", a building that would demonstrate sustainable principles and practices holistically.

2000

2001

Dr. John Robinson meets with Peter Busby, the architect, to discuss the creation of the "greenest building in North America". Multiple key concepts including the "living laboratory" and "accelerating sustainability" are developed during this meeting.

Busby & Associates Architects (now Perkins+Will Architects Canada) prepares a feasibility study for the first iteration of the CIRS building, located on UBC's Vancouver Campus.



University of British Columbia, 2001
Busby + Associates

2002

BC Hydro becomes a strategic partner.

2003

A decision is made to move the CIRS building to a site on the Great Northern Way Campus.

The CIRS Steering Committee is created to provide expert advice and guidance on the project. It included representatives from local academic institutions, government agencies, academic researchers and industry.

Alberto Cayuela, a consultant at Stantec at the time, joins the team as program manager.

The other academic institutions of the Great Northern Way campus (GNWC) become partners in the project: Emily Carr University of Art and Design, British Columbia Institute of Technology, Simon Fraser University.

A feasibility study is undertaken for the Great Northern Way campus context with a new program accommodating all four academic institutions.

$$$ The team applies for a Canada Foundation for Innovation (CFI) grant.

The team applies for a British Columbia Knowledge Development Fund (BCKDF) grant.

2004

The feasibility study is completed.

$$$ The CFI and BCKDF grants are approved.

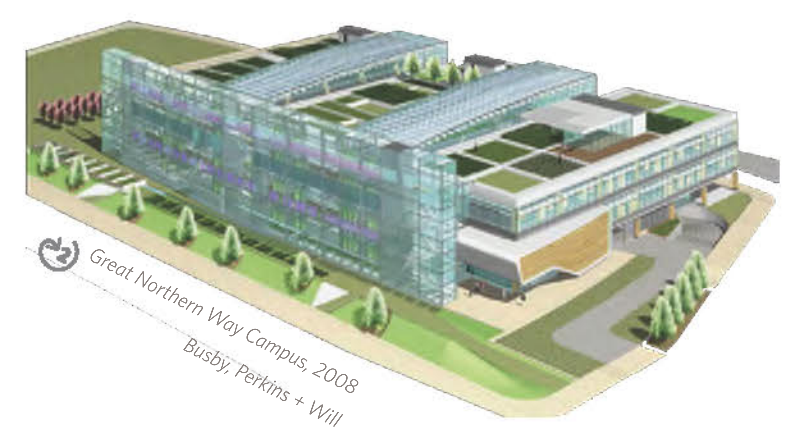
2005

$$$ A Sustainable Development Technology Canada grant is secured for Innovative building envelope and renewable energy components.

2006

2007

Honeywell and Haworth become strategic partners.



Great Northern Way Campus, 2008
Busby, Perkins + Will

2008

The CIRS building project returns to the UBC Campus, with UBC as the sole owner and under the management of UBC Properties Trust.

A site is selected on West Mall adjacent to Sustainability Street, a public commons area and the first planned green corridor on campus.

Over the winter, the design teams respond to new requests for proposals (RFPs) for the new project program and context.

Four interdisciplinary design charettes are held between March and July.

Schematic design begins in May and transitions to design development in September.

$$$ A Western Economic Diversification Canada grant is secured.

2009

Construction documents for the tender set are completed in September.

Site service work, utility relocation and demolition of the previous building occurs over the summer.

Construction begins in October.

2010

Modern Green Development becomes a strategic partner.

2011

Construction is completed and building occupancy is granted in August.

Building inhabitation begins in September.

"Celebrating CIRS" conference and official opening of the CIRS building happen in November.

2012

Building performance and occupancy starts to be monitored and analyzed by operators and researches.

A series of optimization projects starts to be implemented towards addressing building system performance shortcomings, increasing energy and water efficiency, and creating a better place for CIRS inhabitants to work.

2013

Dr. Ray Cole is appointed as academic director of CIRS in July.

The CIRS building becomes UBC's first LEED Platinum certified project.

2014

CIRS is officially established as a UBC research centre.

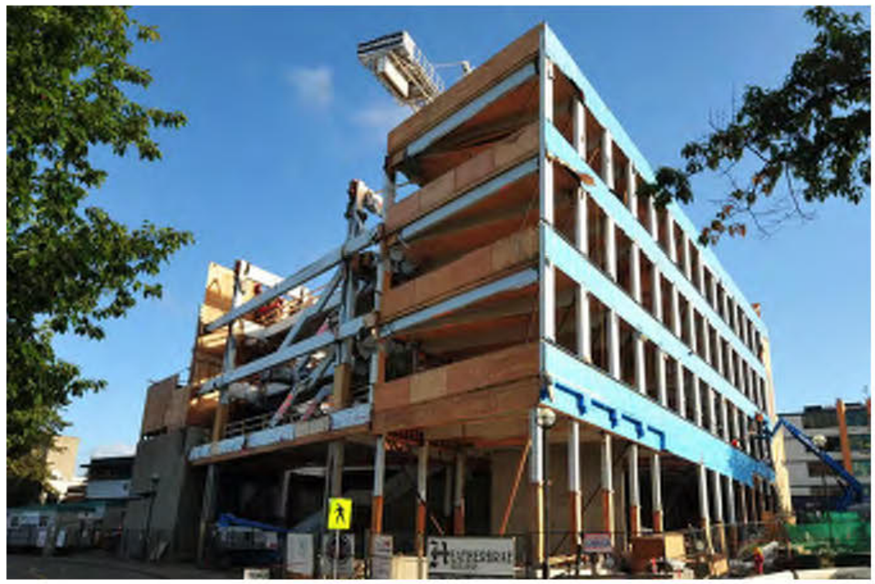
CIRS begins to recognize designated faculty researchers from multiple disciplines.

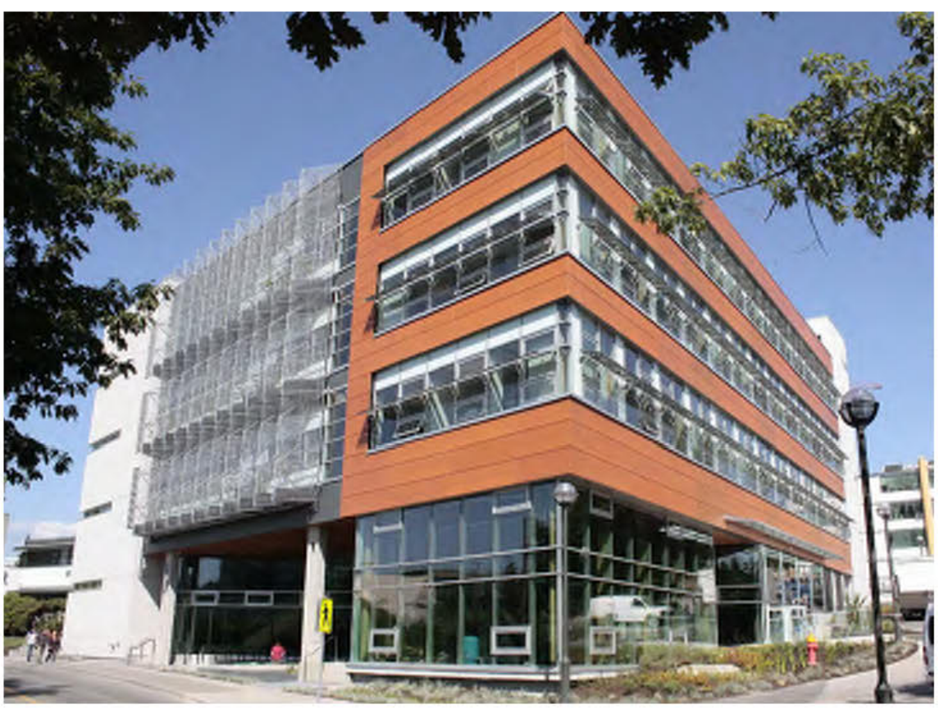
An Advisory Board is created with representatives from academic institutions, NGOs and industry partners.

CIRS
CENTRE FOR INTERACTIVE RESEARCH ON SUSTAINABILITY

"It's crucial not to be guided too much by what it is possible. If it is possible it's boring, and we don't want to be boring. Let's figure out what is impossible and get as close as we can to that."

Dr. John Robinson, CIRS Project Sponsor and Founder





A PLACE FOR BIG IDEAS THAT MAKE BIG IMPACTS

AWARDS + CERTIFICATIONS

INTERNATIONAL SUSTAINABLE CAMPUS NETWORK EXCELLENCE AWARD
International Sustainable Campus Network | *2015*

2015 ROYAL ARCHITECTURAL INSTITUTE OF CANADA GREEN BUILDING AWARD
Royal Architectural Institute of Canada | *2015*

CANADIAN GREEN BUILDING AWARD
SAB Magazine | *2014*

SUSTAINABLE BUILDING OF THE YEAR
World Architecture News | *2013*

LEED PLATINUM CERTIFICATION
Canada Green Building Council | *2013*

SUSTAINABLE DEVELOPMENT AWARD
Golder Associates | 2013

BC GREEN BUILDING AWARD
WoodWorks! | 2013

ARCHITECTURAL INNOVATION AWARD
Architectural Institute of British Columbia | *2012*

AWARD FOR ENGINEERING EXCELLENCE
Association of Consulting Engineering Companies-BC | *2012*

EXCELLENCE IN STRUCTURAL ENGINEERING AWARD
National Council of Structural Engineers Associations | *2012*

WOOD DESIGN AWARD
Wood Design & Building | 2012

BEST OFFICE OR COMMERCIAL DESIGN & READER'S CHOICE WINNER
Treehugger Best of Green | *2011 & 2012*

PROJECT TEAM:

Architect	**Perkins + Will Architects**
Structural Engineers	**Fast+Epp**
M/E/P	**Stantec Consulting**
Landscape Architect	**PWL Partnership**
Solar Aquatic Biofilter	**Eco-Tek Ecological Technologies**
Environmental consultant	**Nova Tec Consultants**
Construction Manager	**Heatherbrae Builders**

CENTRE FOR INTERACTIVE RESEARCH ON SUSTAINABILITY

GENERAL INQUIRIES:

phone: **604-822-9376**

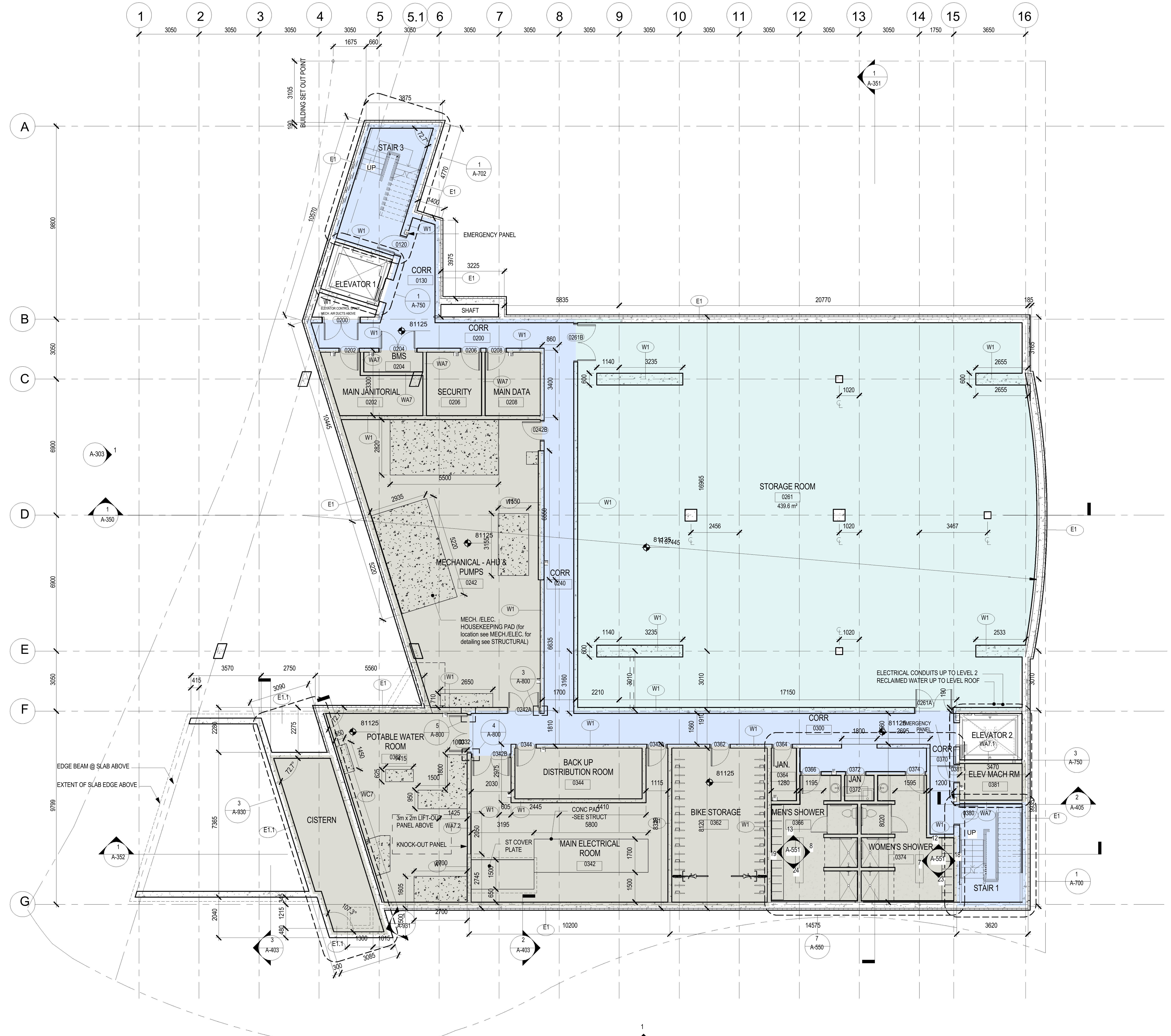
e-mail: **cirs.admin@ubc.ca**

2260 West Mall,
Vancouver, BC, V6T 1Z4
CANADA
cirs.ubc.ca

Appendix B

The Centre for Interactive Research on Sustainability (CIRS) at UBC

Architectural and Mechanical Drawings



1 BASEMENT FLOOR PLAN
1 : 100

GENERAL NOTES:

1. LOCATION AND DIMENSIONES OF HOUSEKEEPING PADS ARE TO BE COORDINATED W/ MECHANICAL + ELECTRICAL EQUIPMENT REQUIREMENTS.

BUSBY PERKINS + WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET

Oct 16, 2009

Drawing Issue	Date
Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

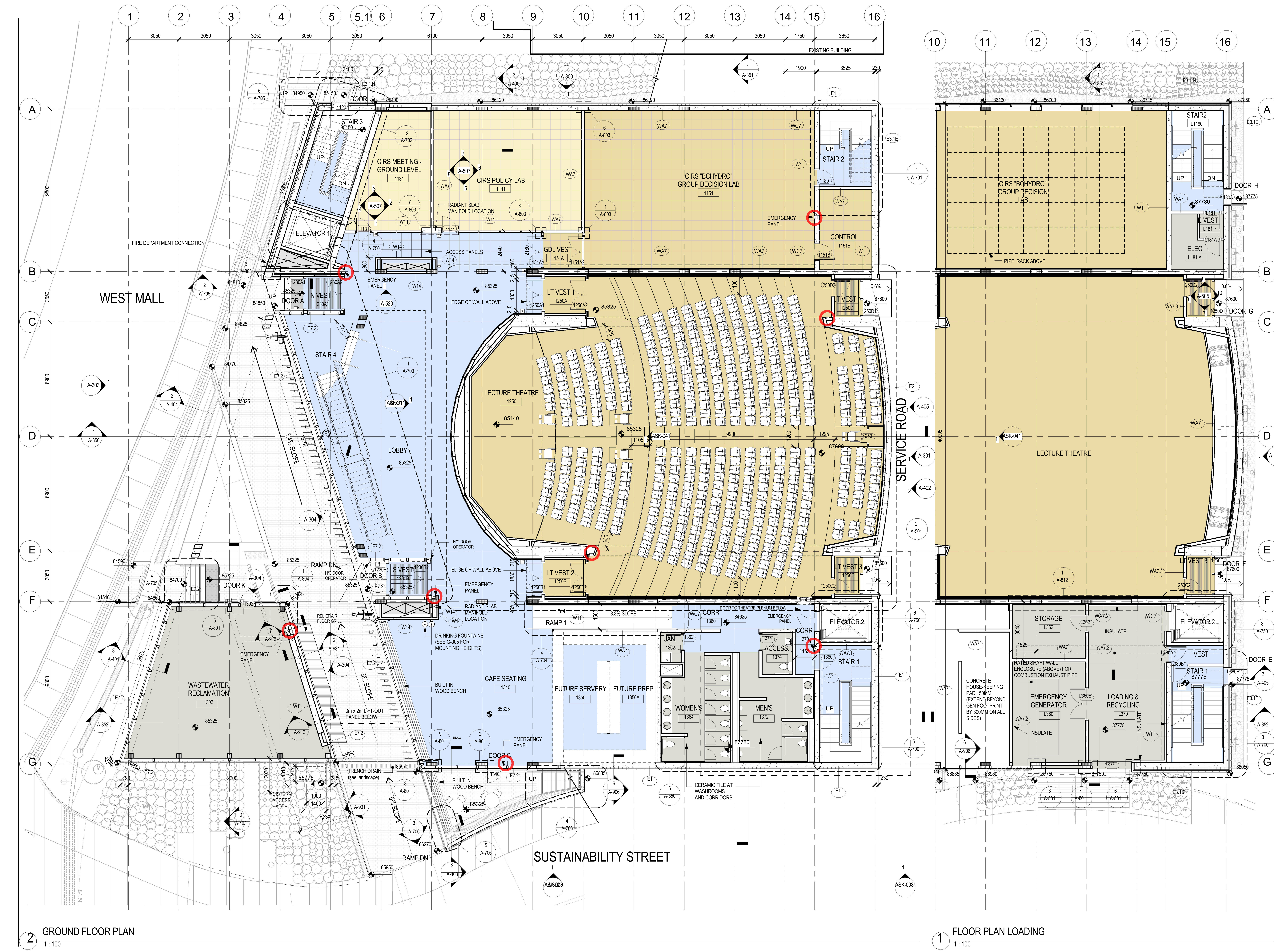
Title

Floor Plan Level B1

Sheet

A-100

10/15/2009 7:08:35 PM
C:\Documents and Settings\gasmena\Desktop\UBC-CIRS IFC(gasmena) 2009-05-10).rvt



BUSBY PERKINS + WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET

Oct 16, 2009

Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008
Drawing Issue	Date

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

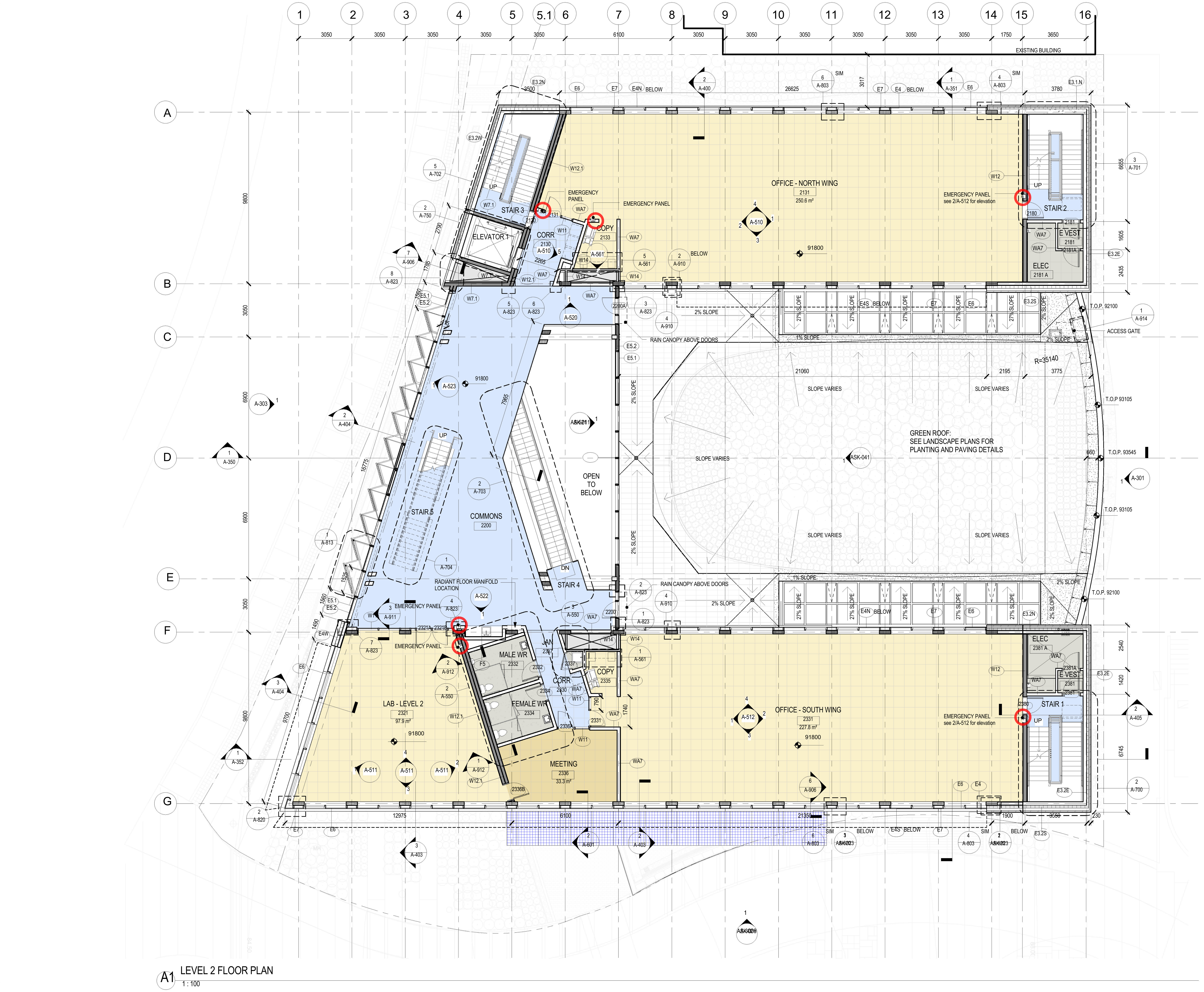
Title

Floor Plan Level Ground

NORTH TRUE NORTH

Sheet

A-101



BUSBY PERKINS + WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET

Oct 16, 2009

Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008
Drawing Issue	Date

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

Title

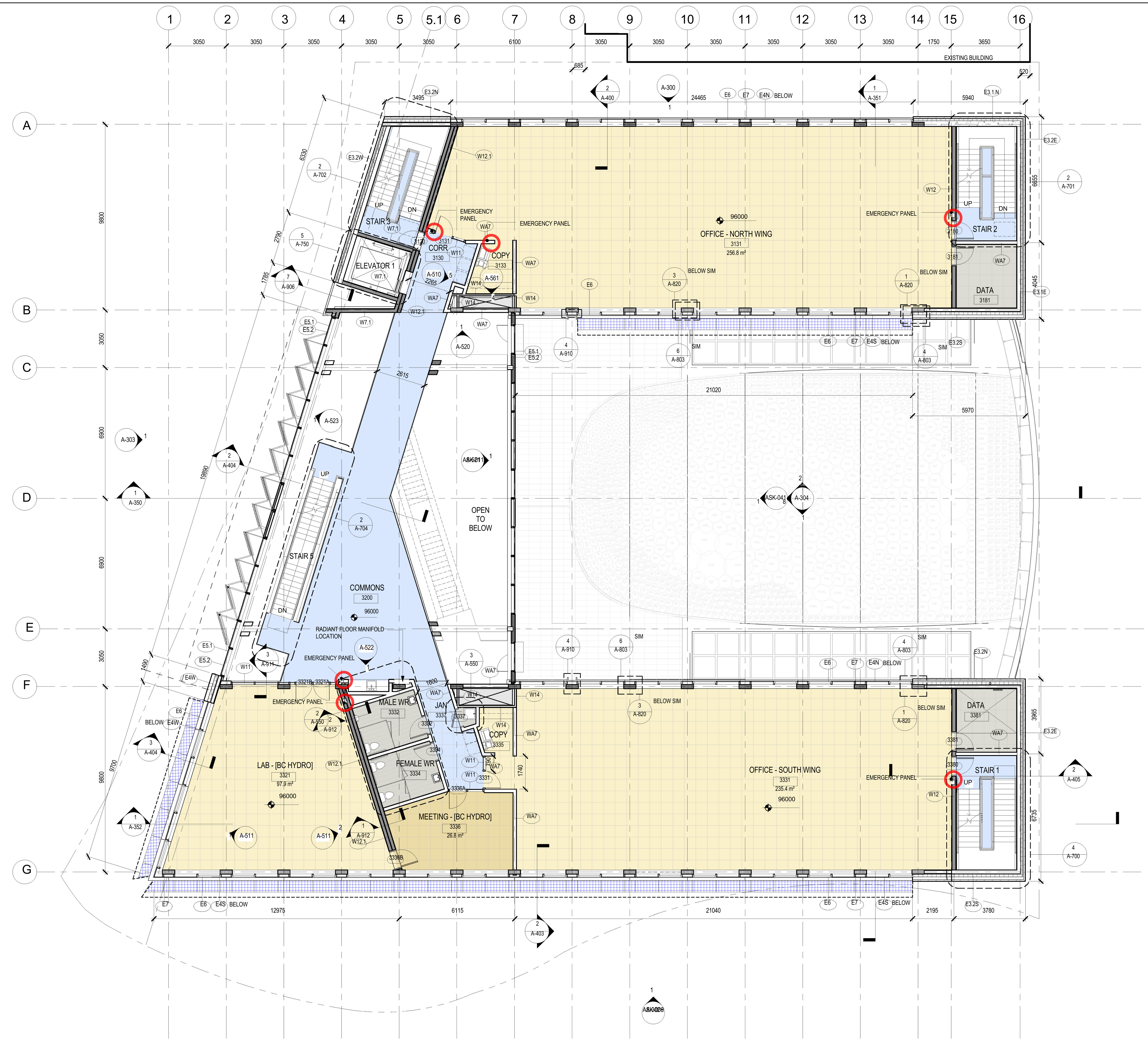
Floor Plan Level 02

NORTH TRUE NORTH

Sheet

A-102

10/15/2009 7:09:35 PM
C:\Documents and Settings\gasmenab\Desktop\UBC-CIRS IFC(gasmenab 2009-05-10).rvt



1 LEVEL 3 FLOOR PLAN
1 : 100

BUSBY
PERKINS
+ WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET

Oct 16, 2009

Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008
Drawing Issue	Date

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

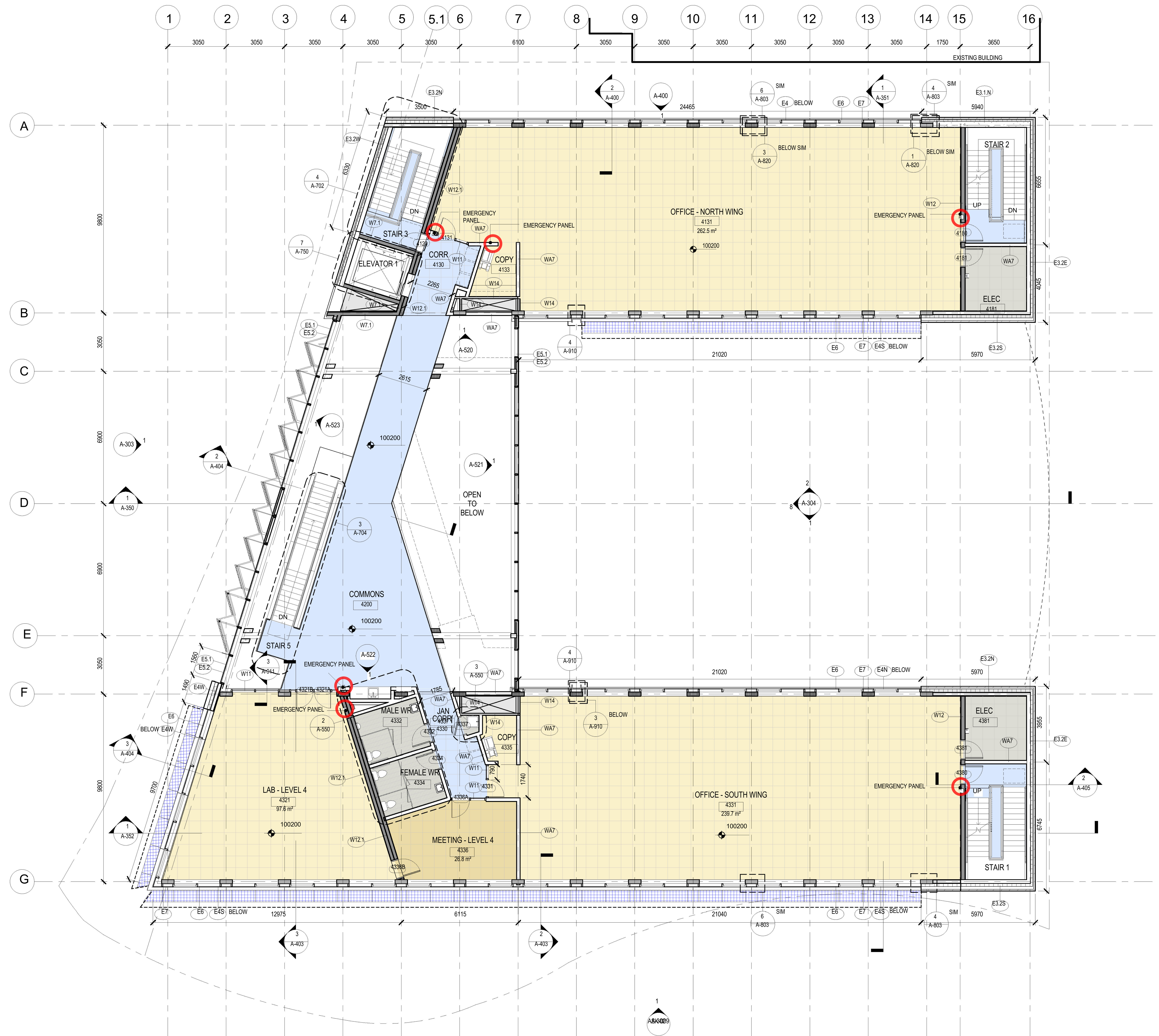
Title

Floor Plan Level 03

Sheet

A-103

10/15/2009 7:09:55 PM
C:\Documents and Settings\gasmenab\Desktop\UBC-CIRS IFC(gasmenab 2009-05-10).rvt



1 LEVEL 4 FLOOR PLAN
1 : 100

BUSBY
PERKINS
+ WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET
Oct 16, 2009

Drawing Issue	Date
Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

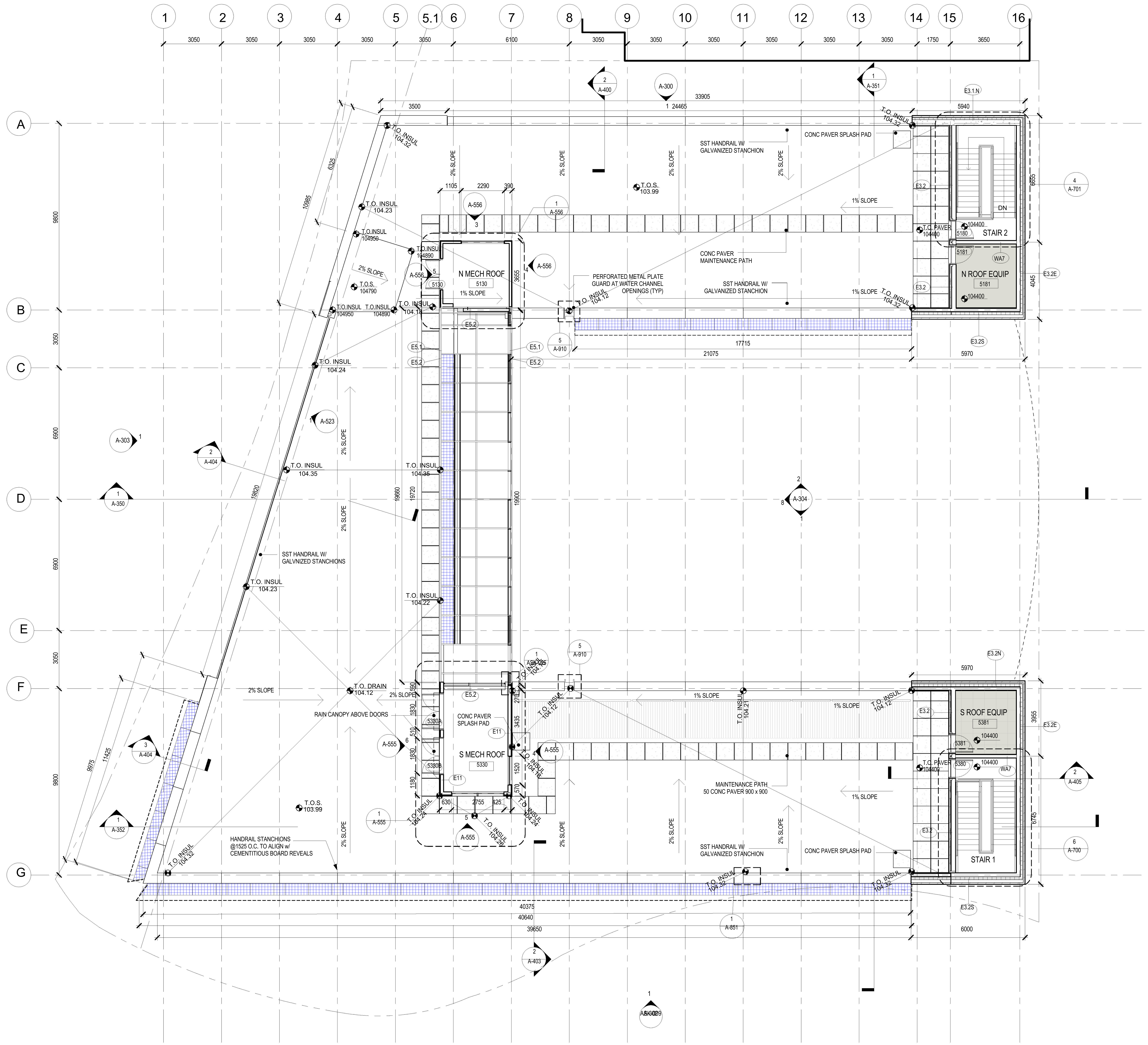
Title

Floor Plan Level 04

Sheet

A-104

10/15/2009 7:10:04 PM
C:\Documents and Settings\gasmenab\Desktop\UBC-CIRS IFC(gasmenab 2009-05-10).rvt



1 PENTHOUSE PLAN
1 : 100

BUSBY
PERKINS
+WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET

Oct 16, 2009

Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008
Drawing Issue	Date

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

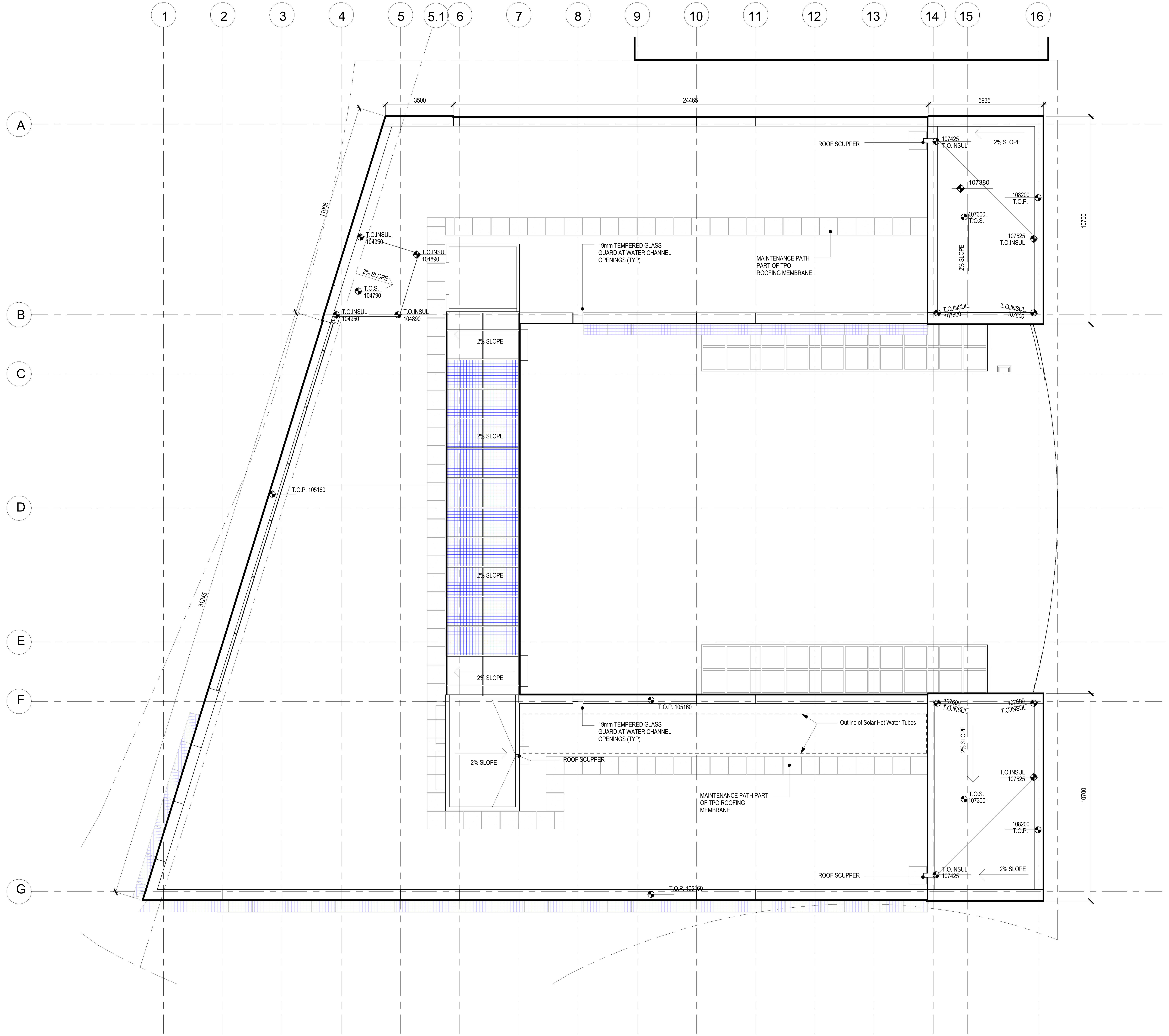
Title

Floor Plan Level Penthouse

Sheet

A-105

10/15/2009 7:10:12 PM
C:\Documents and Settings\gasmenab\Desktop\UBC-CIRS IFC(gasmenab 2009-05-10).rvt



1 ROOF PLAN
1 : 100

BUSBY PERKINS + WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET
Oct 16, 2009

Drawing Issue	Date
Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

Title

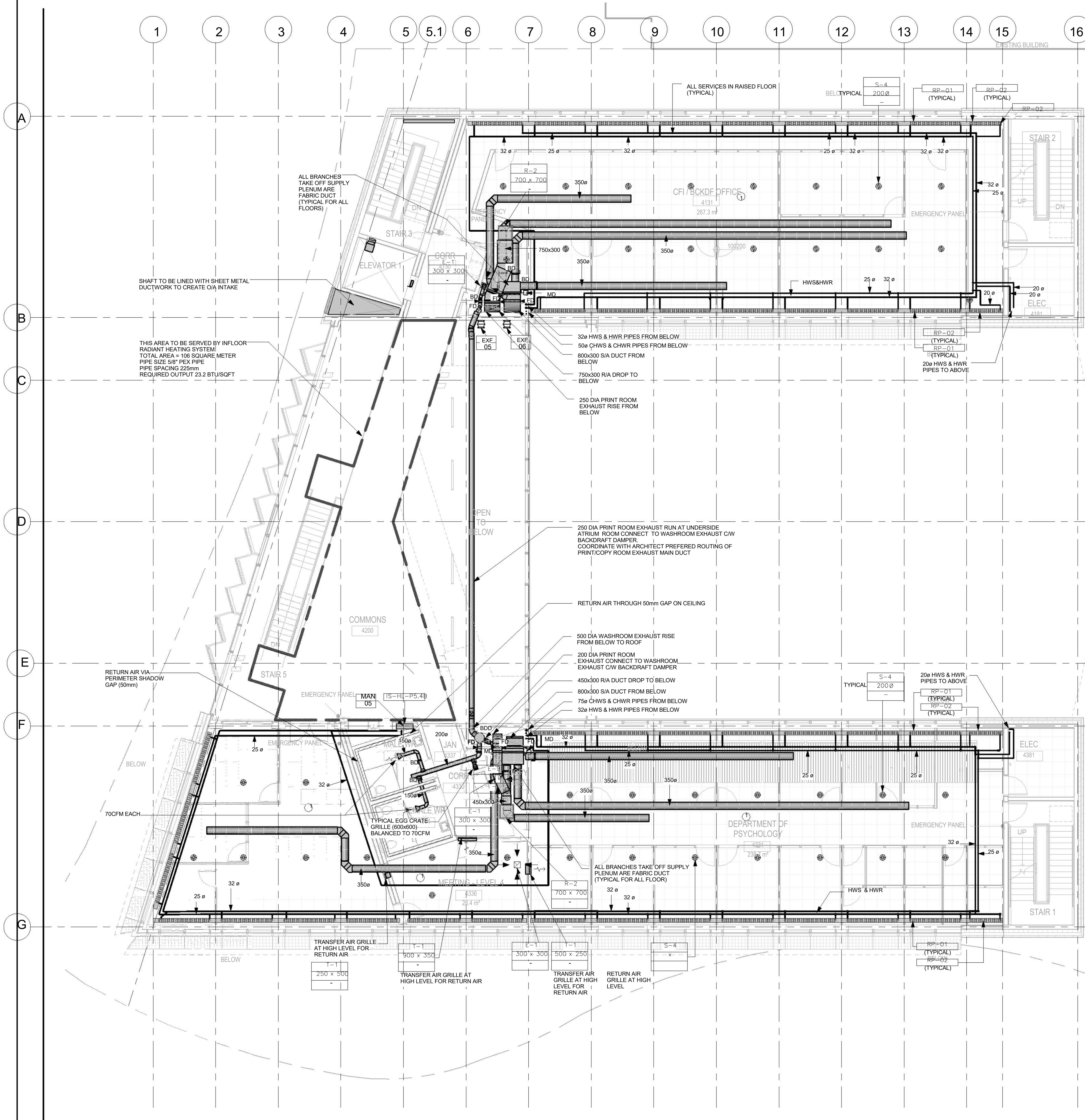
Floor Plan Level Roof

NORTH TRUE NORTH

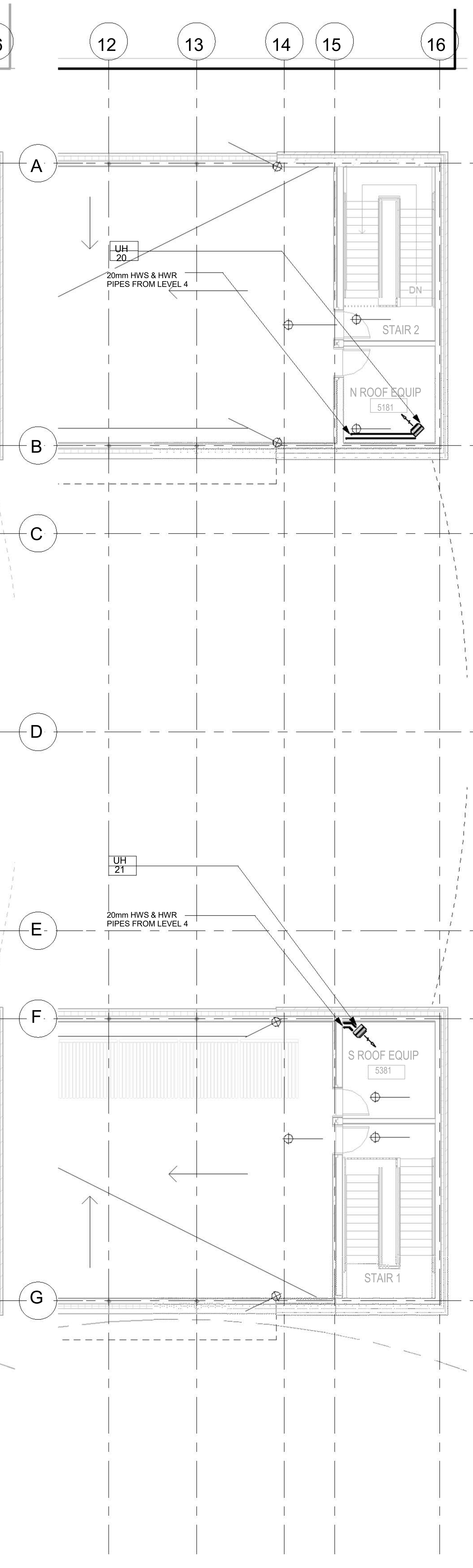
Sheet

A-106

10/15/2009 7:10:21 PM
C:\Documents and Settings\gasmenab\Desktop\UBC-CIRS IFC(gasmenab 2009-05-10).rvt



Level 4
1 : 100



Level Penthouse
1 : 100

NOTES:
1. CONTRACTOR TO CO-ORDINATE WITH CONTRACTOR TO PROVIDE A SEALED AIRTIGHT FLOOR PLENUM.

GENERAL NOTES

1. FOR LOCATION OF ALL MOTORIZED DAMPERS INSTALLED ON VARIOUS SUPPLY, RETURN OR EXHAUST BRANCHES, REFER TO AIR FLOW SCHEMATIC DRAWING M-102.

2. ALL ROOM SENSORS ARE NOT SHOWN ON DRAWINGS (LISTED IN DDC POINT LIST COORDINATE LOCATION OF SENSORS WITH ARCHITECT & OWNER PRIOR TO INSTALLATION.

3. ALL CONVECTOR LENGTH SHOWN IN APPROX. DIMENSION. CONTRACTORS IS TO MEASURE ON ARCH. DRAWINGS EACH CONVECTOR PRIOR TO SHOP DRAWINGS SUBMISSION. COORDINATE WITH ARCH FOR FUTURE WALL INSTALLATIONS BETWEEN OFFICES FOR CONVECTORS REQUIRED LENGTH.

4. COORDINATE WITH ALL OTHER TRADES FOR INSTALLATION OF SERVICES IN RAISED FLOOR.

5. REFER TO AIR SCHEMATIC DRAWING M-102 FOR ALL AIR TERMINALS FLOW RATES (TYPICAL FOR ALL FLOORS).

6. ALLOW FOR APPROX. 10 LOOPS PER MANIFOLD FOR THE INFLOOR RADIANT HEAT SYSTEM. IF MORE LOOPS ARE REQUIRED COORDINATE WITH ENGINEER AND ARCH. (FINAL CABINET MANIFOLD SIZE TO BE DETERMINED PRIOR TO SHOP DRAWING SUBMISSION).

Stantec Consulting
1100 - 111 Dunsmir Street
Vancouver, BC Canada
V6B 6A3
Tel. 604-696-8000
Fax. 604-696-8100
www.stantec.com

CIRS - Centre for Interactive Research on Sustainability

UBC
2300 West Mall
Vancouver BC V6T1Z4

Record Drawing

These drawings have been prepared based on information provided by others. Stantec has not verified the accuracy and/or completeness of this information and shall not be responsible for any errors or omissions which may be incorporated herein as a result.

Drawing Issue	Date
AS - RECORDED DRAWINGS	NOV. 29, 2011
ISSUED FOR CONSTRUCTION	OCT.16,2009
STAGE 2 - BUILDING PERMIT	JULY 21,2009
TENDER SET	JUNE 15,2009
TENDER REVIEW SET	MAY 29, 2009
BUILDING PERMIT	APRIL 20, 2009

Revisions

NO	ISSUE	DATE

Sheet Information

Date	NOV. 29, 2011
Job Number	115661077
Drawn	DP
Checked	RO
Approved	BMc

Title

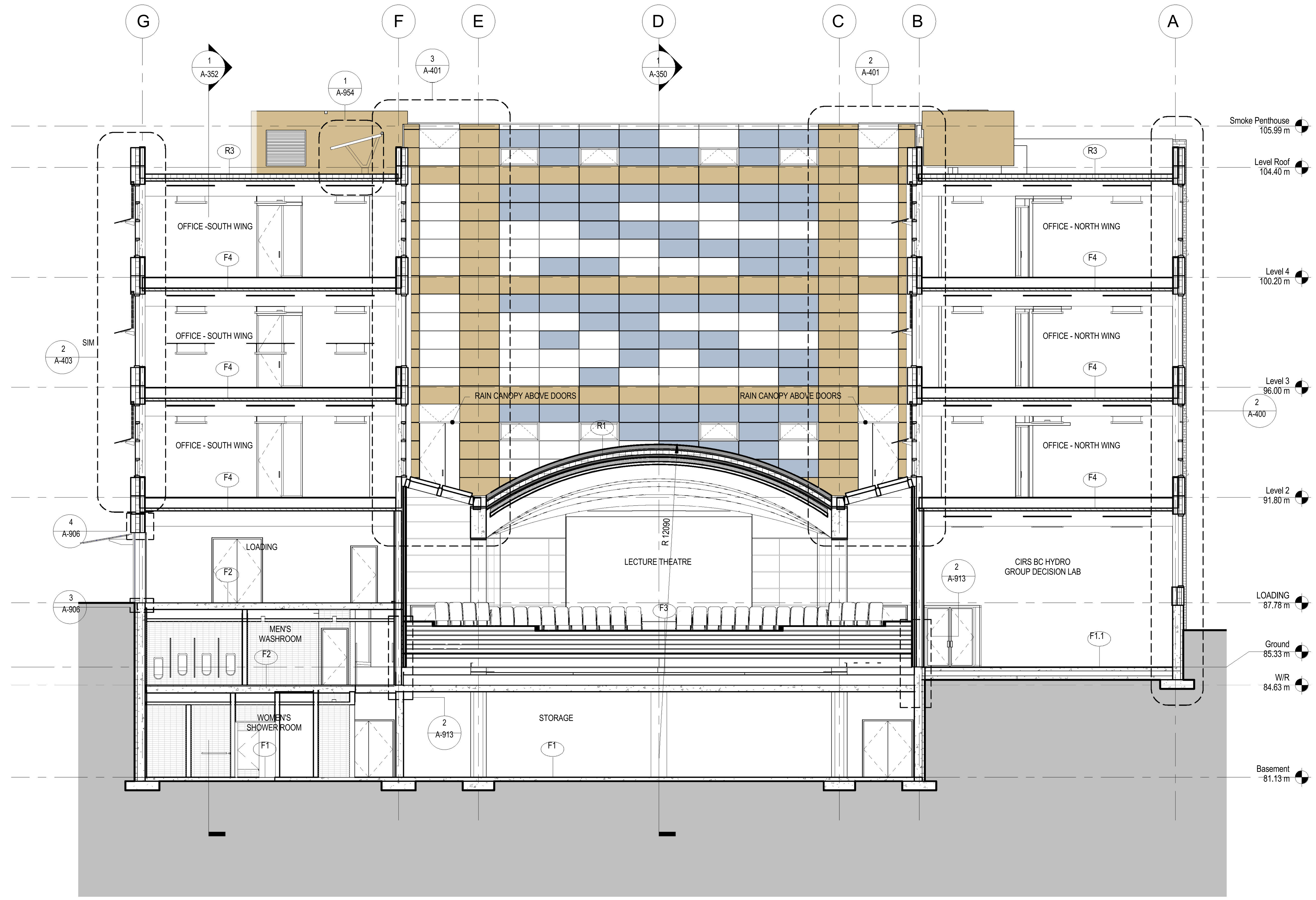
HVAC - LEVEL 04 / PENTHOUSE PLAN

NORTH TRUE NORTH

Sheet
M.204

11/28/2011 12:52:45 PM
V:\1156\active\115661077\mechanical\drawing\archive\AS_RECORDED_NOV_21_2011\Revit\CIRS_MAIN_as_built.rvt

633-08-013



1 N-S SECTION
1 : 100

BUSBY
PERKINS
+WILL

1220 Homer St.
Vancouver, British Columbia
Canada V6B 2Y5
t 604.684.5446
f 604.684.5447
www.busbyperkinswill.ca

CIRS - Centre for Interactive Research on Sustainability

UBC
2260 West Mall
Vancouver BC V6T 1Z4

IFC SET

Oct 16, 2009

Issue for Construction	Oct 16, 2009
BP-Set Issue #12	July 21, 2009
Tender Set Addendum I Issue #10	July 3, 2009
Tender Set Issue #9	June 15, 2009
Tender Review Set Issue #8	May 29, 2009
DD-Set Issue #2	Dec 03, 2008
DP-Set Issue #1	Aug 15, 2008
Drawing Issue	Date

Revisions

Sheet Information

Date	OCT 16, 2009
Job Number	410826
Drawn	Author
Checked	Checker
Approved	Approver

Title

Building Section N-S

Sheet

A-351

10/15/2009 7:14:11 PM
C:\Documents and Settings\gasmenab\Desktop\UBC-CIRS IFC(gasmenab 2009-05-10).rvt

Appendix C

BC Hydro Theatre at
CIRS - UBC

Living Wall Configurations

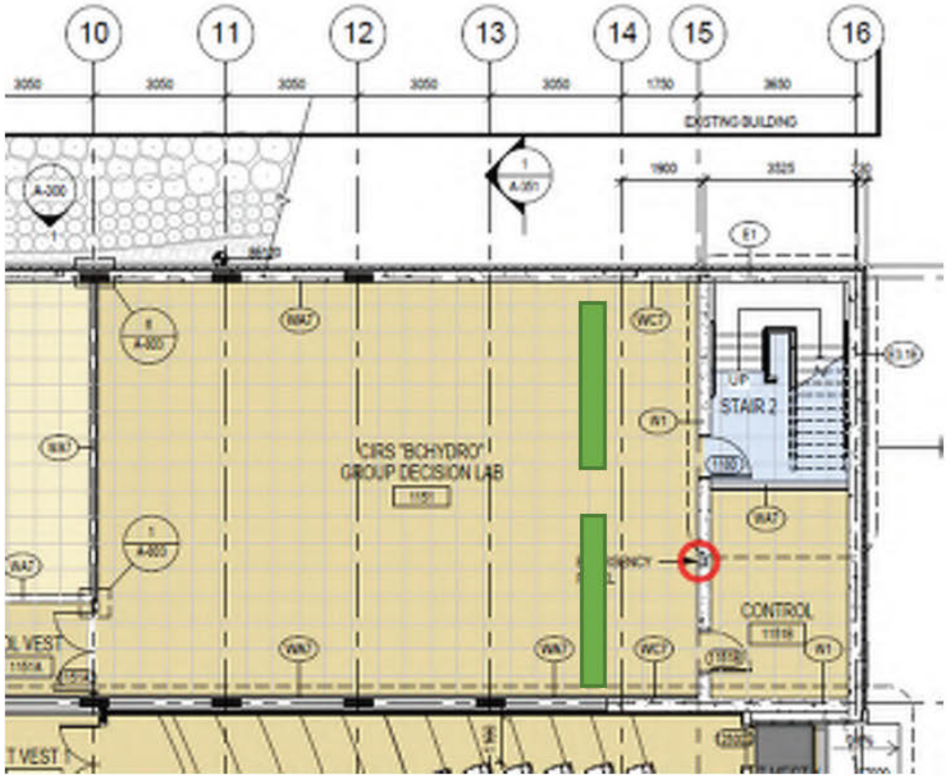


Figure 1-C: Plan drawing of BC Hydro Theatre at CIRS, UBC showing LW-A installation (Perkins+Will, 2009)

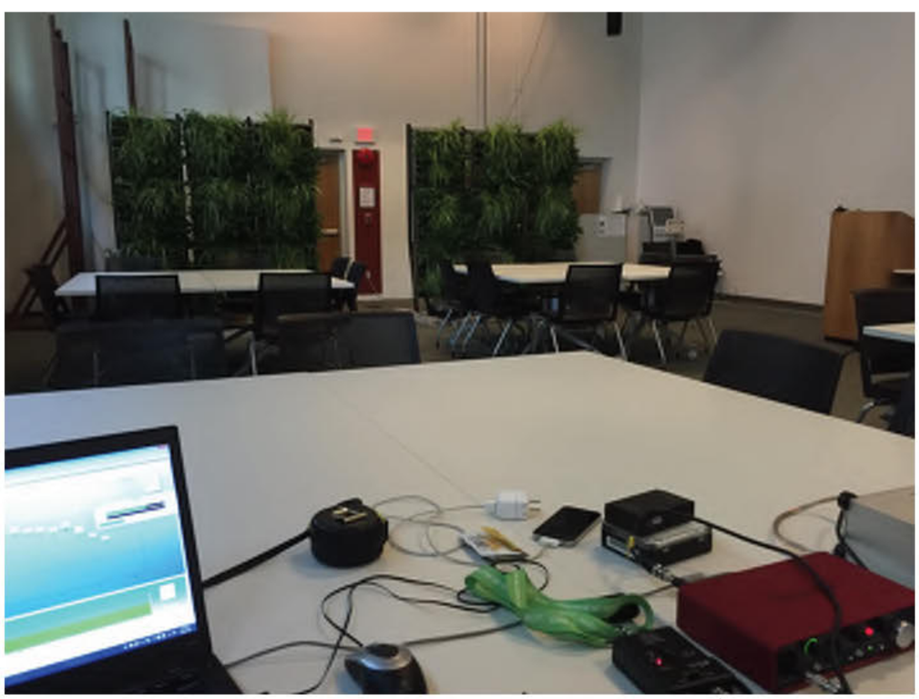


Figure 2-C: LW-A Installation at BC Hydro Theatre, CIRS, UBC (Daneshpanah, 2019).

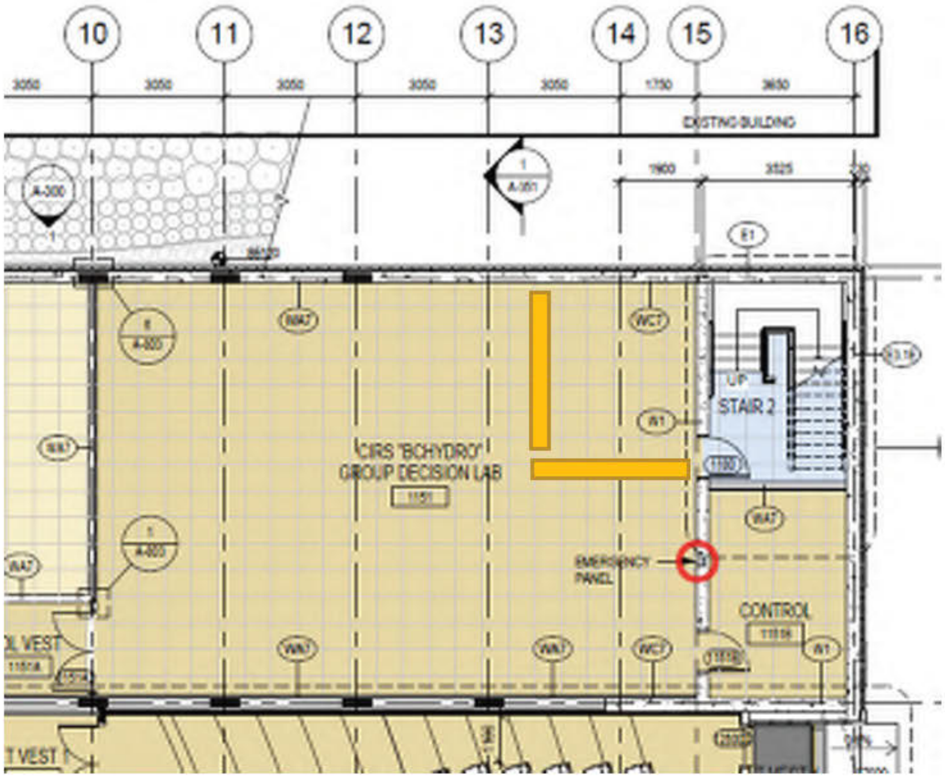


Figure 3-C: Plan drawing of BC Hydro Theatre at CIRS, UBC showing LW-B installation (Perkins+Will, 2009)


Figure 4-C: LW-B Installation at BC Hydro Theatre, CIRS, UBC (Daneshpanah, 2019).

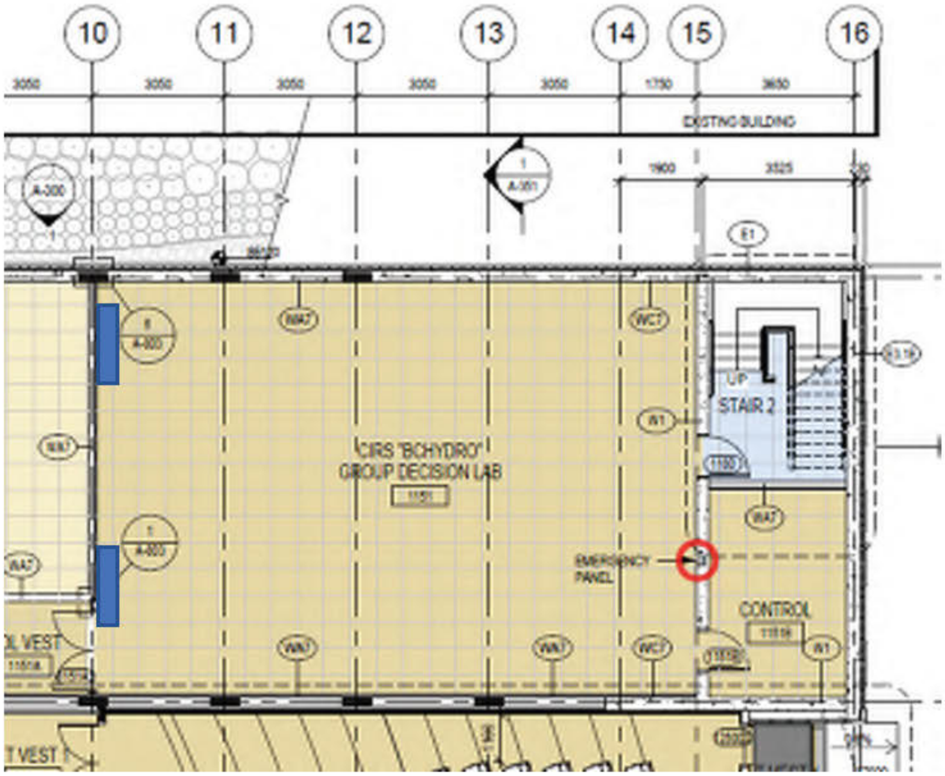


Figure 5-C: Plan drawing of BC Hydro Theatre at CIRS, UBC showing LW-C installation (Perkins+Will, 2009)

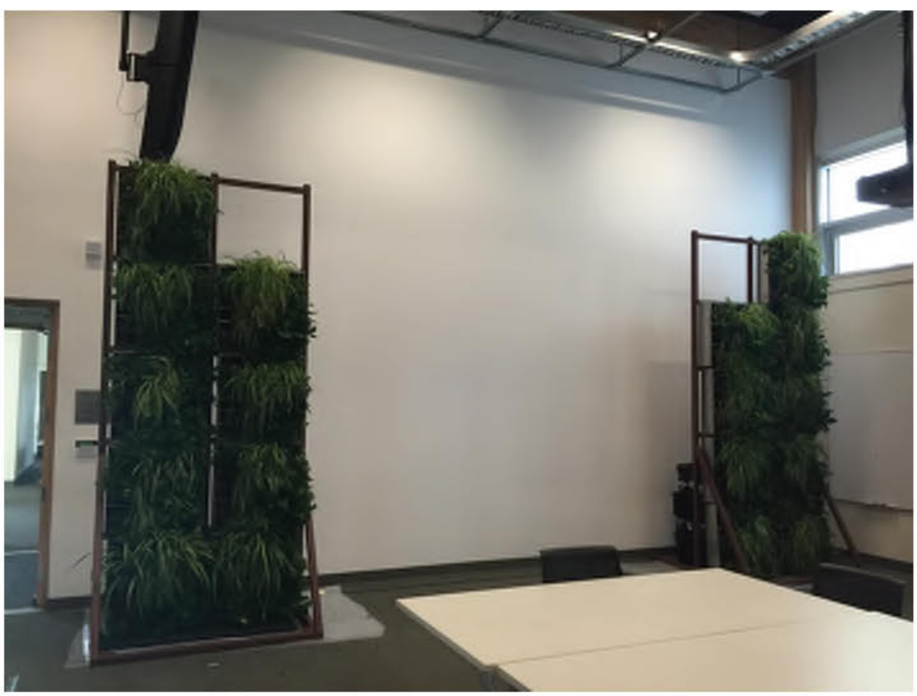


Figure 6-C: LW-C Installation at BC Hydro Theatre, CIRS, UBC (Daneshpanah, 2019).

Appendix D

List of Standards

The standards used for acoustic measurements and analysis in this study included:

- ASTM C423-07a Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method.
- ASTM C634-13 Standard Terminology Relating to Building and Environmental Acoustics
- ASTM E 1130-02 Standard Test Method for Objective Measurement of Speech Privacy in Open Offices Using Articulation Index.
- ASTM E1110 Standard Classification for Determination of Articulation Class.
- ANSI/ASA S12.2-2008 Criteria for Evaluating Room Noise.

The standards used for indoor air quality measurements and analysis in this study included:

- ASHRAE 55-2013 Thermal Environmental Conditions for Human Occupancy
- ASHRAE 62.1-2013 Ventilation for Acceptable Indoor Air Quality
- ASTM D6245-12 Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation

Appendix E

List of Equipment

The instrumentation (all calibrated prior to testing) used for acoustic measurements for this study was provided by the Centre for Architectural Ecology at BCIT, and included the following:

- Sound Level Meter: Larson Davis Type 831 (S/N: 0003129)
- Microphone: Larson Davis Type 3777B20 (S/N: LW131539)
- Calibrator: Larson Davis Type 200 (S/N: 11875) calibrate January 26, 2015
- Speaker:
  - Omni directional, InfraQsources
  - Directional, JBL EON-10G2 (S/N: 10G2-20576)
- Amplifier: Norsonic Nor 280 Power Amplifier
- Sound Card: Scarlet 2i2
- Software: WinMLS 2004 (a sound-card based software used for acoustic measurements and analysis).

The instrumentation (all calibrated prior to testing) used for indoor air quality measurements for this study was provided by the School of Population and Public Health at UBC, and included the following:

- Ultrafine Particulate Matter: P-Trak 8525 (TSI - Shoreview, MN)
- CO2: Q-Trak 7575 (TSI - Shoreview, MN)
- TVOCs: ppbRAE 3000 (RAE Systems by Honeywell - Sunnyvale, CA)
- Temperature/Relative Humidity: QuesTemp 36 (3M - Oconomowoc, WI)
- Endotoxins:
  - Air sampling pump: GilAir Plus (Sensidyne, St. Petersburg, FL)
  - Samplng heads: 7-hole sampling head (SKC Inc., Eighty Four, PA)
  - Filters: Glass fibre filters (Type A/E 37 mm, Pall Corporation). The filters were depyrogenated by baking at 180 °C for 2 hours before use. The filters were stored at 4 °C until conducting the analytical test.
  - Analysis: Limulus Amebocyte Lysate (LAL) analysis. The endotoxin analysis was conducted by Ivan Cheung per below:

The filters were extracted with 0.05% v/v of Tween-20 (Fisher Chemical cat. BP33, Fisher Scientific, Hampton, NH) in depyrogenated water (LAL Reagent Water, Lonza, Walkersville, MD). Afterwards, the filters were vortexed to keep the whole filter in water and were placed on a shaker for 60 minutes. The filters then were laced in a sonicator bath for 60 minutes, and then in a centrifuge at 1000 g for 15 minutes at room temperature to complete the extraction.

To determine the concentration of endotoxin a kinetic Limulus amebocyte lysate assay, Kinetic-QCL (Lonza Group Ltd., Walkersville, MD) was used. A standard 4-parameter fit curve was generated using E. coli O55:B5 endotoxin (Lonza, Walkersville, MD) over the range of 50 EU/mL to 0.049 EU/mL based on the following:

$$V_{max} = \frac{A - D}{1 + \left(\frac{X}{C}\right)^{B}} + D$$

Vmax is maximal velocity of the reaction involving endotoxin, x is the concentration of endotoxin in EU/mL extracted, and A, B, C, D are the constants of the 4-parameter fit curve.

Samples and standards and their duplicates were dispensed in 96 well microtitre plates, and incubated at 37 °C for 75 minutes. Using a spectrophotometer, the absorbance of light at a wavelength of 405 nm was read at 30 second intervals, Molecular Devices SpectraMAX 190 microplate reader (Thermo-Fisher Scientific, Waltham MA). If the standard curve generated had a coefficient of determination (r2) greater than 0.98, the samples of a kinetic assay were accepted for further analysis. However, the samples were rejected if the coefficient of variation was greater than 25% between the sample and its duplicate.

Appendix F

Collected Data at CIRS

Stored at:

https://drive.google.com/drive/folders/1sESy80DBIQafiSbyKg_F3T_jL84Mv-wQ?usp=sharing

Appendix G

Preliminary Data Collection at Five Spaces at CIRS

Figure 1-G: BC Hydro Theatre, CIRS, UBC (Daneshpanah, 2019).

Figure 2-G: Auditorium, CIRS, UBC (Daneshpanah, 2019).

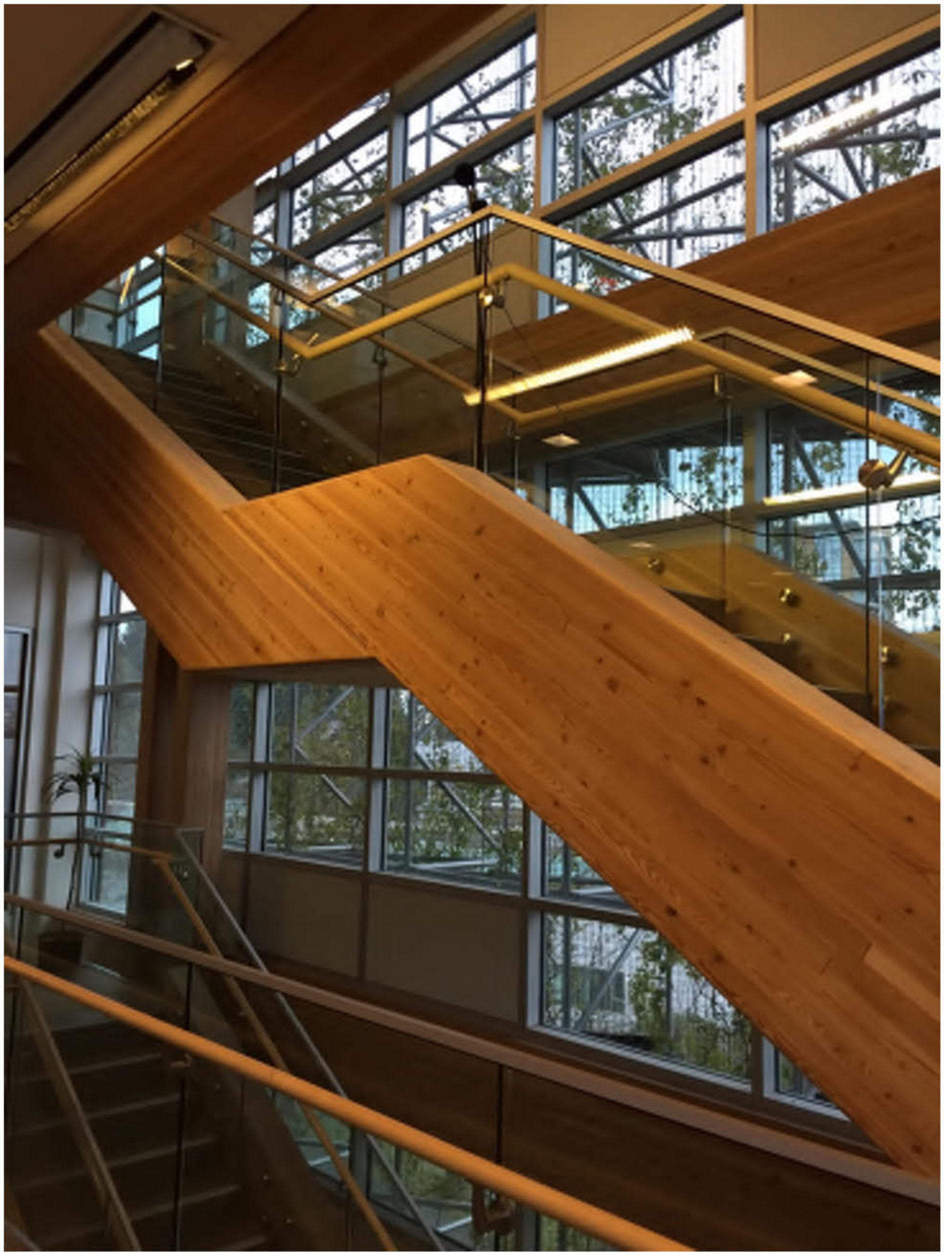


Figure 3-G: Atrium, CIRS, UBC (Daneshpanah, 2019).

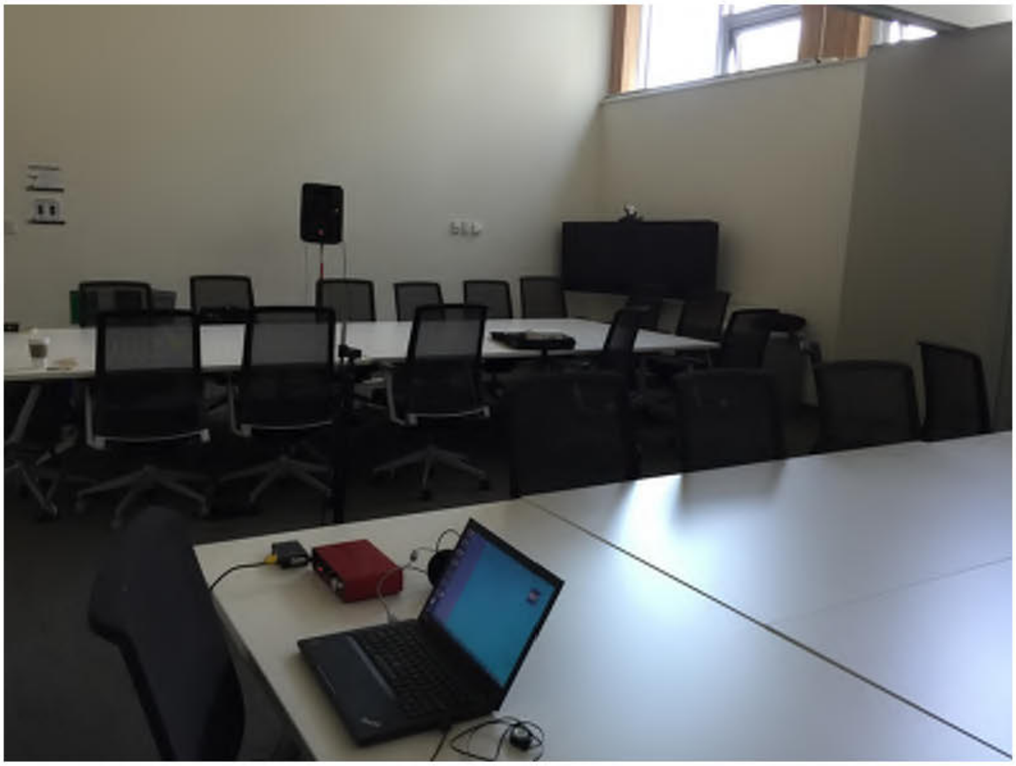


Figure 4-G: Policy Lab, CIRS, UBC (Daneshpanah, 2019).

Figure 5-G: Open-plan office, CIRS, UBC (Daneshpanah, 2019).