AN INVESTIGATION OF THE INDOOR ENVIRONMENTAL QUALITY OF A SUSTAINABLE BUILDING AT UBC

by

Yizhong Lei

B.Eng., Tsinghua University, 2011

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

The Faculty of Graduate and Postdoctoral Studies

(Mechanical Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2014

© Yizhong Lei, 2014
Abstract

Aspects of the indoor environment that directly influence the occupants are ventilation, indoor-air quality (IAQ), acoustic and thermal conditions, as well as lighting. All five aspects were studied to investigate the indoor environmental quality (IEQ) in a sustainable building (CIRS) at the University of British Columbia, Vancouver campus.

Physical measurements were made in several selected spaces (mainly offices and meeting rooms) to monitor indoor parameters such as background noise level, reverberation time, VOC and CO₂ concentrations, ambient temperature, relative humidity, indoor illuminance level, etc. Building performance was analyzed by comparing the measurement results to standard criteria, and to the design goals of CIRS. Several selected spaces in CIRS were found unsatisfactory in some aspects of IEQ – e.g. the mechanical ventilation system was unable to remove 80% of outdoor ultrafine particles; more than 20% of the measured spaces exceeded the maximum recommended background noise level; 100% of the noise isolations between offices and their surroundings were inadequate; speech privacy between adjacent private offices was poor; rooms in the South wing suffered from very high illuminance levels, etc.

Building features and management details that influenced IEQ were discussed to analyze the relationships between building design/operation and performance. Several room features were discussed, such as air change rate, furnishing material, ventilation types, acoustical characteristics, etc. Several conclusions were drawn – e.g. ventilation conditions of rooms were highly affected by the door/windows statuses; rooms with the lowest air change rates had the highest UFP concentrations; crowd noises in the atrium caused high background noise levels; inadequate noise isolations were caused by indoor light-weight partitions, etc.
Preface

This thesis is an original intellectual product of the author, Y. Lei, done under the supervision of Professor Murray Hodgson and Professor Karen Bartlett.

In Chapter 3: Figures 4, 5 and 8 are used with permission from applicable sources. Portions of the CIRS building description text are modified from the CIRS Technical Manual (2012).
# Table of Contents

Abstract.................................................................................................................................................. ii  
Preface....................................................................................................................................................... iii  
Table of Contents ..................................................................................................................................... iv  
List of Tables ............................................................................................................................................... vii  
List of Figures ............................................................................................................................................ viii  
Acknowledgements .................................................................................................................................... x  

Chapter 1. Introduction ......................................................................................................................... 1  
1.1. Ventilation ........................................................................................................................................ 2  
1.2. Indoor Air Quality .............................................................................................................................. 2  
1.3. Acoustic Conditions ........................................................................................................................... 2  
1.4. Thermal Conditions ........................................................................................................................... 3  
1.5. Lighting ............................................................................................................................................ 3  
1.6. The Centre for Interactive Research on Sustainability ................................................................. 3  
1.7. Research Objective ........................................................................................................................... 4  

Chapter 2. Literature Review ................................................................................................................. 6  
2.1. Background ....................................................................................................................................... 6  
2.2. Theory and Relevant Criteria ........................................................................................................... 7  
2.2.1. Ventilation .................................................................................................................................... 8  
2.2.2. IAQ ............................................................................................................................................... 8  
2.2.3. Indoor acoustics ............................................................................................................................ 10  
2.2.4. Thermal balance and occupancy comfort ................................................................................... 12  
2.2.5. Lighting ....................................................................................................................................... 13  

Chapter 3. CIRS Building Description .................................................................................................. 14  
3.1. HVAC Systems ............................................................................................................................... 14  
3.2. Lighting System ............................................................................................................................... 16  
3.3. Acoustic Features ............................................................................................................................ 17  

Chapter 4. Measurement Methodology ................................................................................................. 19  
4.1. Areas of Study ................................................................................................................................. 20  
4.1.1. Cellular offices ............................................................................................................................ 20  
4.1.2. Open-plan areas ........................................................................................................................... 21  
4.1.3. Meeting rooms ............................................................................................................................ 22
Appendix D: Building Floor Plans ................................................................. 68
Appendix E: CO₂ Monitoring Results ...................................................... 70
Appendix F: Ventilation Results ............................................................... 74
Appendix G: Ultrafine Particles Measurement Summary ......................... 76
Appendix H: VOC Measurement Results ................................................ 79
Appendix I: Noise Isolation Calculation Results ..................................... 82
Appendix J: Speech Intelligibility Index Calculation Results ................. 83
List of Tables

Table 1 Possible sources and health issues related to IAQ contaminants ...............2
Table 2 The A-weighted BNL criteria and the acceptable NC levels for measured spaces [20].................................................................9
Table 3 Diffuser amount of each selected section .............................................15
Table 4 Measurement equipment or methods information ..................................19
Table 5 Specific furniture details of spaces .......................................................35
Table 6 BNL measurement results of private offices in octave-bands...............37
Table 7 BNL measurement results of open-plan areas in octave-bands .............38
Table 8 BNL measurement results of meeting rooms in octave-bands ...............40
Table 9 BNL measurement results of public circulation areas in octave-bands ......41
Table 10 Reverberation time summary ...............................................................42
Table 11 Verbal-communication quality associated with an SII value ..............46
Table 12 Air change rates for the selected offices during monitoring period .......74
Table 13 Air change rates for the selected meeting rooms during monitoring period75
Table 14 Speech Intelligibility Index results and detailed descriptions ..............83
List of Figures

Figure 1 The Centre for Interactive Research on Sustainability .............................................. 4
Figure 2 Thermal comfort zone on Psychrometric chart [5] ................................................ 12
Figure 3 An operable window in CIRS ............................................................................ 14
Figure 4 Operable windows and openings for natural ventilation [28] .............................. 15
Figure 5 Displacement system for mechanical ventilation [28] ........................................ 15
Figure 6 Swirl diffuser installed on the floor ....................................................................... 15
Figure 7 Artificial lighting in office areas (left); meeting rooms (right) .............................. 17
Figure 8 Lighting diagram for the office blocks [28] ........................................................ 17
Figure 9 Private office (left); meeting room (top right); open-plan area (bottom right). .......................................................................................................................... 20
Figure 10 Cellular office ..................................................................................................... 21
Figure 11 Meeting rooms layout and the lighting measurement points ............................. 24
Figure 12 Office layout and lighting measurement points .................................................. 25
Figure 13 Estimated air change rates of measured spaces (the shaded area shows the recommended rate [16]) ................................ ............................................................... 29
Figure 14 Indoor-minus-20%-of-outdoor UFPs amount related to air change rates .31
Figure 15 Indoor to outdoor ratio of UFPs concentration related to air change rates32
Figure 16 BNL measurement positions on 2nd Floor South wing marked with round points 36
Figure 17 BNL measurement positions on 3rd Floor South wing marked with round points .............................................................................................................................. 37
Figure 18 A-weighted BNL measurement results of private offices in octave-bands 38
Figure 19 A-weighted BNL measurement results of open-plan areas in octave-bands ................................ ................................................................. 39
Figure 20 A-weighted BNL measurement results of meeting rooms in octave-bands ................................ ................................................................. 40
Figure 21 A-weighted BNL measurement results of public circulations in octave-bands .............................................................................................................................. 41
Figure 22 Reverberation time summary ........................................................................... 42
Figure 23 Fabric partition (top); whitewashed wall (below) .................................................. 43
Figure 24 Noise isolation class between meeting rooms and their surroundings (case A-#: meeting room 2336; case B-#: meeting room 3336; case C-#: meeting room 3357) ................................................................................................................................. 44
Figure 25 Noise isolation class between private offices and their surroundings (case O-#: office 2352 and its surroundings; case D-#: office 3342, 3343, 3344 and the adjacent open-plan area 3352) ................................................................................................................................. 44
Figure 26 A leak below the meeting room’s door ................................................................. 45
Figure 27 Return airflow inlets inside and outside of the meeting room are connected
Figure 28 Thermal conditions of monitored spaces on psychrometric chart............50
Figure 29 Illuminances measured in offices: the yellow band shows the recommended range..........................................................53
Figure 30 Illuminances measured in meeting rooms: the yellow band shows the recommended range..........................................................53
Figure 31 Details of the air handling unit for office wings in CIRS .....................64
Figure 32 Heating exchanger sensors and indoor thermal condition monitors display of the 2\textsuperscript{nd} floor in the south wing..........................................................65
Figure 33 Heating exchanger sensors and indoor thermal condition monitors display of the 3\textsuperscript{rd} floor in the south wing ..........................................................66
Figure 34 Omni-directional loudspeaker (left); Human-simulated loudspeaker SSARAH (middle); Rion NA-28 sound level meter (right)..................................................67
Figure 35 TSI Q-Trak (left); TSI P-Trak 8525 (middle); ppbRAE VOC model PGM-7240 (right) ............................................................................................................67
Figure 36 UEi DLM2 Digital Light Meter .................................................................67
Figure 37 Floor plan of the 2\textsuperscript{nd} floor of CIRS ..............................................68
Figure 38 Floor plan of 3\textsuperscript{rd} floor of CIRS.....................................................69
Acknowledgements

I would like to express my deep gratitude to Professor Murray Hodgson and Professor Karen Bartlett, my research supervisors, for their patient guidance, enthusiastic encouragement and useful critiques of this research work. I would also like to thank Mr. Scott Yonkman and Mr. Roland Schigas, for their help in collecting the monitoring data of CIRS building and of the UBC Earth, Ocean and Atmospheric Science ESB Rooftop Weather Station. I would also like to extend my thanks to Mr. Alberto Cayuela, and other staff of CIRS building for their help in offering me the resources in running this program. This work has been funded by Modern Green and NSERC CREATE Sustainable Building Science Program, of which I was a trainee.

Finally, I wish to thank my parents for their support and encouragement throughout my study.
Chapter 1. Introduction

In the building industry, sustainable buildings are becoming the mainstream, more and more appearing in people’s lives, and are attracting more and more attention.

There is a sustainable building science course offered at the University of British Columbia which is taught by several sustainable building sciences related professors and professionals. Basic knowledge, up-to-date techniques, and experiences were summarized in this course, which is about sustainable building concepts, life-cycle assessment, evaluation codes, building materials, IEQ, etc. Through this course, I realized that for one particular building to reach the standard of sustainable, it must achieve a very high sustainability in three main aspects throughout its lifecycle, which are: improving the local and global environment, improving indoor comfort, and achieving cost-effectiveness and adaptability. Among these, improving indoor comfort especially gained my attention, since it matches my educational background and interests.

According to the ASHRAE standard 189.1-2001 [1], high-performance green buildings (HPGBs) are “designed, constructed, and operated in a manner that increases environmental performance and economic value over time, while establishing an indoor environment that supports the health, comfort, and productivity of occupants”.

To evaluate the indoor environment of a building, the main aspects of IEQ must be monitored. Aspects of IEQ that directly influence the comfort of occupants of a building are ventilation, indoor-air quality (IAQ), acoustic and thermal conditions, and lighting. Each of the above environmental qualities is a pre-requisite for occupant comfort, health, productivity and satisfaction, which must be considered carefully in the lifecycle of a building. Related building staff like building designers or managers could easily ignore one or two of these aspects, which results in the indoor environment being unable to meet guidance standards. For example, indoor acoustics is a crucial and often neglected aspect of the Indoor Environmental Quality. In the case of academic buildings on campus, proper indoor acoustical conditions can’t be ignored, and are also hard to achieve. Whether the indoor environment is too noisy or too quiet, it brings disturbances and distractions to students, academic staff, and researchers, and has a noticeable effect on teaching and lab activities.

Moreover, according to a study by Khaleghi et al. [2], which studied ventilation, IAQ and acoustics, there exist close relationships between building features and IEQ. This study also took thermal and lighting comfort into consideration. IEQ was analyzed with consideration of building design and operation.


### Table 1 Possible sources and health issues related to IAQ contaminants

<table>
<thead>
<tr>
<th>IAQ parameters</th>
<th>Possible indoor sources</th>
<th>Possible health issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPC</td>
<td>Printers, fax machines, photocopiers, fruits, cooking, smoke, outdoor air, etc.</td>
<td>Exacerbate heart and respiratory diseases, change lung function and immune structure, etc [3].</td>
</tr>
<tr>
<td>VOCs</td>
<td>Perfumes, foam, chipboard, fibreboard, plywood, carpets, furnishings, etc.</td>
<td>Eye and respiratory tract irritation, headaches, skin rashes, lethargy, dizziness, visual disorders, etc [4].</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>Occupants’ breath</td>
<td>Dizziness, etc.</td>
</tr>
</tbody>
</table>

#### 1.1. Ventilation

The role of an air-conditioning system is to control the following factors in an environment: ambient temperature, air velocity, mean radiant temperature, and relative humidity. All-air systems, such as constant-volume (CV), variable-air-volume (VAV) and displacement ventilation system, have to provide supply air to dilute and exhaust contaminants and stale air from the environment.

#### 1.2. Indoor Air Quality

IAQ problems arise in non-industrial buildings when there is an inadequate amount of ventilation air being provided, given the amount of air contaminants present in a space. Insufficient ventilation can possibly cause Sick Building Syndrome (see Table 1). The three factors related to the evaluation of air quality in the spaces that are of concern in this research are: ultrafine particulate matter (UPC), volatile-organic-compound (VOC) concentration, and carbon-dioxide (CO₂) concentration.

#### 1.3. Acoustic Conditions

Indoor acoustic conditions are one of the most difficult aspects to design, control and optimize. The characteristics of the physical sound field result in an acoustic environment which directly influences the integrity of structures as well as the health, safety, comfort, ability to communicate, the productivity, the efficiency and the enjoyment which people experience. Physical characteristics that determine the acoustical conditions are background-noise level, reverberation time, noise isolation,
and speech intelligibility and privacy.

1.4. Thermal Conditions

The main factors that influence the thermal comfort in a building are indoor air temperature, relative humidity, air flow rate and radiant heat transfer between the human body and the surroundings.

These factors are not only connected to air-conditioning system performance, but also the building concept, because the building envelope and materials can keep the wanted heat inside or obstruct the unwanted heat from outside. When temperature and humidity exceed accepted comfort parameters, they can, by themselves, negatively impact air quality, and can be detrimental to health. We now know that the comfort factors of temperature and humidity can also interact, and influence contaminants that may affect health, affirming the multi-dimensional nature of the indoor environment [5]. Maintaining the standard of thermal comfort for occupants of buildings or other enclosures is one of the important goals of HVAC (heating, ventilation, and air conditioning systems).

1.5. Lighting

Good-quality lighting can support visual performance and interpersonal communication, and improve our feelings of well-being. Poor-quality lighting can be uncomfortable and confusing, and can inhibit visual performance [6].

Visual quality consists of visual efficiency combined with visual comfort. Visual efficiency is a measure of a person’s ability to perform tasks involving vision. The most important factors in visual quality are the intensity of illumination on the area of interest, glare from light sources, and the uniformity of illumination. There are other factors, such as glare from light sources, and the uniformity of illumination, etc. [6], but they won’t be considered in this research.

1.6. The Centre for Interactive Research on Sustainability

The Centre for Interactive Research on Sustainability (CIRS) (Figure 1) has been awarded LEED Platinum certification, the highest designation in green building performance from the Leadership in Energy and Environmental Design rating system and the first for the University of British Columbia. In November 2011, CIRS opened as North America’s greenest building. This is one of the most important reasons why CIRS was chosen to be the target building for this study.
CIRS is located at 2260 West Mall, near the Earth Sciences Building, next to two roads on the west and south sides. CIRS is an 4-storey, U-shape, integrated educational office building, with many laboratories, cellular offices, open-plan offices, conference rooms with various sizes, and an auditorium, which is mainly used for educational or laboratory objectives. The main sections of CIRS include two 4-storey office wings on the South and North sides, connected by an auditorium on the first floor and a 4-storey atrium.

1.7. Research Objective

To guarantee indoor comfort in a building, professional and experienced guidance not only is required in its design and construction, but also in its building management and maintenance stages after it has been constructed. Building managers need to keep their buildings functioning well, and meet the standards of IEQ, while considering building features, and combining relevant professional knowledge. However, the maintenance of IEQ in sustainable buildings is normally more difficult, since environmentally-friendly techniques used in these buildings, such as natural ventilation and natural lighting, are more challenging to regulate than mechanical ventilation and artificial light sources. Thus, it is necessary to monitor whether sustainable buildings are functioning properly.

To determine whether the indoor comfort of a building reaches applicable standards, objective site measurement methods were used. Compared to subjective survey methods, the measurement methods, based on objective measurement data, are no doubt more efficient, more straightforward, and more reliable.

Figure 1 The Centre for Interactive Research on Sustainability
Selected IEQ parameters were measured in the CIRS building, in order to judge if it reaches its design objectives and the standards of IEQ; the engineering design of building elements and furnishings were examined for their contribution to the measured data. It is the first time that similar investigations have been done in the Centre for Interactive Research on Sustainability (CIRS).

The objectives of this research were:

- Measurement of selected IEQ parameters in CIRS
- Analysis and explanation of IEQ measurement data in relation to design engineering parameters of the building features and functions.

The overall objective of this research was to investigate and explain a sustainable building’s Indoor Environmental Quality parameters through a series of thorough measurements, monitoring of the building’s management, and comparison to design criteria and function.
Chapter 2. Literature Review

2.1. Background

Sustainable buildings are characterized by integrated building practices that are environmentally responsible and resource-efficient throughout a building’s life-cycle in comparison to conventional buildings, according to U.S. Environmental Protection Agency [7]. Sustainable development is the most vibrant and powerful force to impact the building design and construction field in more than a decade [8]. Since the concept of ‘green building’ has been put into practice during the energy crisis of the 1970s, sustainable building is increasing and expanding very fast worldwide. Descriptions of sustainable buildings generally focus on a number of common elements, especially siting, energy, water, materials, waste, and occupant health [9]. According to the White Paper on Sustainability, which was conducted on the behalf of Building Design & Construction, the common benefits, such as energy and water savings, waste reduction, and environmental improvement, are becoming well proven, and widely accepted by people. However, the human benefits of sustainable building, which always refer to human health, comfort and productivity, may be more challenging to achieve [8].

In 2002, Fisk stated that estimated potential health and productivity gains from improved IEQ are large [10]. In 2005, Mendell summarized a similar literature, and indicated that indoor air quality and thermal aspects of IEQ may directly or indirectly link to children’s performance, attendance and health [11]. Since sustainable building hasn’t been developing for a very long time, compared to conventional building, there is a limited amount of research on sustainable building indoor environmental quality done in the last few decades.

Abbaszadeh et al. [12] of University of California conducted a study of occupant satisfaction with IEQ in sustainable buildings in 2006. They used Post Occupancy Evaluation (POE), and mainly focused on subjective survey methods, to evaluate the buildings’ indoor environmental quality by measuring occupant satisfaction and self-reported productivity. According to the study, occupants in green buildings are on average more satisfied with their air quality and thermal comfort, but lighting and acoustic quality in sustainable buildings are comparable to conventional buildings.

To determine whether the indoor environmental quality of a building reaches applicable standards, many methods have been developed in related fields. The most common methods include subjective survey methods, and objective site measurement methods. There has been more and more similar research, using
similar subjective survey methods to evaluate the degree to which newly-built buildings fulfill their intended goals. However, the research based on subjective methods is highly determined by occupants, and usually occupants are not professionals, and the feedback they provide can’t be as accurate as that obtained using technical equipment. Though equipment can’t measure what people think or feel, the measurement methods, which are based on objective measurement data, are no doubt more efficient, and more reliable for testing the IEQ, compared to subjective survey methods.

In 2012, Wiegand et al. [13] evaluated the indoor lighting conditions and ventilation of a building by objective measurement. According to Federspiel et al. [14], they found that workers performed talking tasks fastest when the ventilation rate was highest, also by measurement. However, the amount of research based on objective measurement methods is limited, and this kind of research normally only focused on indoor air quality or thermal comfort. There are other similar studies, which are only about one or two aspects of IEQ, most of which did not focus on sustainable buildings.

In 2011, the National Research Council conducted a study, which used POE to evaluate the indoor environmental quality and building performance on energy of six buildings [15]. The study is comprehensive, and the methodology it used is also appropriate for my study. However, there are a few disadvantages of the NRC’s study. Since the research was focusing on six buildings, the depth of every one of them is not enough. Moreover, only one of their buildings was LEED certified, and its ranking is Gold. In this research, the targeted building CIRS is LEED certified “platinum”.

In summary, the amount of research based on objective measurement methods is limited, and there has never been similar research about buildings as sustainable as the CIRS building at UBC.

2.2. Theory and Relevant Criteria

In order to evaluate to what extent the building performance has fulfilled its designed targets after it has been constructed, the measured IEQ results need to be compared to relevant criteria. While the criteria are being introduced, the theories used in this study need to be discussed.

Indoor environmental quality assessment is one of the most efficient methods to evaluate the performance of a building. To analyze IEQ of a building as comprehensively as possible, the following elements of IEQ must be analyzed: ventilation, indoor air quality, acoustic and thermal conditions, and lighting. Each element has its unique widely-used evaluation theories. These theories include
measurement protocols and analysis methods. The theories and related criteria will be discussed in this section.

2.2.1. Ventilation

Maintenance of indoor ventilation is crucial, because ventilation not only can offset the thermal load, but also can provide fresh air for occupants. Ventilation should be carefully designed, so that it reaches related standards, and improves indoor environment. Air change rate has to be estimated to investigate indoor ventilation. The acceptable outdoor air rate for the spaces in office buildings is considered to be 0.3 (L/s \cdot m^2) or 2.5 (L/s \cdot person) [16]. By multiplying with the room areas or the numbers of occupants, the minimum air change rate could be estimated for selected spaces.

According to the study by Roulet et al. [17], air change rate can be calculated by using CO\(_2\) concentration decays, since CO\(_2\) generated by occupants can be used as a tracer gas. When a period of CO\(_2\) concentration decay is monitored, air change rate can be calculated using the following equation:

\[
\text{AirChangeRate} = \ln(C_N) = \ln\left(\frac{C(t) - C_O}{C(0) - C_O}\right)
\]

- \(C(0)\) is the initial concentration at the beginning of the decay period
- \(C(t)\) is the final concentration at the end of the decay period
- \(C_O\) is the outdoor concentration.

The indoor air distribution is also important to indoor air quality. This parameter was not considered in this study.

2.2.2. IAQ

IAQ problems arise in non-industrial buildings when there is an inadequate amount of ventilation air being provided, given the amount of air contaminants present in a space. The three factors related to the evaluation of air quality in the spaces that will be investigated are: ultrafine particle, volatile-organic-compound (VOC), and carbon-dioxide (CO\(_2\)) concentrations.

2.2.2.1. Ultrafine particles (UFPs)

Ultrafine particles (UFPs) are particulate matter of nanoscale size (less than 100 nanometres in diameter). UFPs are a very important type of contaminant that IAQ standards require be controled. UFPs are both manufactured and naturally occurring.
Smoke, emission from printers, fax machine, photocopies, etc., are major sources of indoor UFPs. Excessive UFPs indoors can exacerbate heart and respiratory diseases, change lung function and immune structure, etc. [3].

Regulations do not exist for this size class of ambient air pollution particles. For satisfactory indoor-air quality, the concentration of ultrafine particles should be less than 20% of that of the outdoor air. The selected criterion is applied, as a basic rule, in the evaluation of the performance of filters in mechanical ventilation systems with respect to absorbing particles [18].

2.2.2.2. **Volatile organic compounds (VOCs)**

Volatile organic compounds (VOCs) are organic chemicals that have a high vapor pressure at ordinary room temperature. VOCs are emitted as gases from certain solids or liquids. Concentrations of many VOCs are consistently higher (up to ten times higher) indoors than outdoors. According to U.S. Environmental Protection Agency [4], VOC sources vary from paints, building materials and furnishings, to office equipment such as copiers and printers. For acceptable indoor air quality, VOC concentrations in spaces should be less than 300 ppb [19].

2.2.2.3. **Carbon dioxide (CO₂)**

According to the study mentioned before [17], there are two concepts that can help understand the usefulness of carbon dioxide in evaluating IAQ. The first one is that the carbon dioxide amount emitted by occupants depends on their body size and activity level. The second is that, since the indoor carbon dioxide concentration is higher than outdoors, it can be used as a tracer gas.

Through the observation and analysis of occupant-generated or indoor carbon-dioxide (CO₂) concentrations, we can directly determine if the indoor fresh air exchange is adequate. The ASHRAE standard [16] outlines that, based on the occupancy and use of the space, the mass balance of occupant generated CO₂, and the supply of dilution fresh air, will result in a steady state of approximately 1000 ppm.

**Table 2 The A-weighted BNL criteria and the acceptable NC levels for measured spaces [20]**

<table>
<thead>
<tr>
<th>Spaces</th>
<th>A-weighted BNL criteria</th>
<th>NC levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices - small, private</td>
<td>44-48</td>
<td>35-40</td>
</tr>
<tr>
<td>Open-plan areas</td>
<td>44-48</td>
<td>35-40</td>
</tr>
<tr>
<td>Conference rooms - small</td>
<td>39-44</td>
<td>30-35</td>
</tr>
<tr>
<td>Public circulation</td>
<td>48-57</td>
<td>40-50</td>
</tr>
</tbody>
</table>
2.2.3. Indoor acoustics

Control and optimization of indoor acoustics need an understanding of the major factors that must be monitored, and the methods to measure them. The main factors that will be considered are as follows:

- Background-noise level (BNL—un-weighted and A-weighted octave-band and total; equivalent noise criterion (NC));
- Reverberation time in spaces (RT);
- Noise isolation between rooms (in octave-band, noise isolation (NI));
- Speech intelligibility index (SII) from talkers to listeners.

2.2.3.1. Background noise level (BNL)

BNL is the continuous background sound pressure level at a given location. BNLs will vary greatly from location to location. In urban locations such as in Vancouver, the main contributors to noise are: traffic, building plants, general construction, people and music. Beside the outdoor ambient noise, BNL inside buildings is also related to building envelope, noise-generating devices or systems, window status, furnishing details, etc.

BNL must be within an acceptable range, especially at mid and higher frequencies close to critical human-conversation frequencies, to provide suitable conditions for the different activities of the occupants. The measured level is compared with the A-weighted criteria developed for specific spaces on the basis of space use. After measuring the octave-band and total BNL in dB and dBA, the corresponding NC rating (NC curves presented in Appendix A) can be determined, and the results compared to values recommended in standards [20] to evaluate the acceptability of the noise in the environments. Table 2 shows the A-weighted criteria and the acceptable NC levels for selected spaces [20].

2.2.3.2. Reverberation Time (RT)

Reverberation time (RT) measures the persistence of sound in a particular space after the original sound is produced. The sound energy is attenuated with distance travelled and is absorbed by multiple interactions with the surfaces, and by the air. Its value is related to the acoustic absorption of the room surfaces, surface areas, room volumes, and the number of occupants in the room. Sabine’s reverberation equation below established a relationship between RT of a room, its volume, and its total absorption [21]. For example, in a more reflective room with hard furnishings, or a larger room, it will take longer for sound to die away:
\[
RT = \frac{4 \ln 10^6 V}{c S a} \approx 0.1611m^{-1} \frac{V}{S a}
\]  

- \(c\) is the speed of sound in the room (m/s);
- \(V\) is the room volume (m\(^3\));
- \(S\) is total surface area of the room (m\(^2\));
- \(a\) is the average absorption coefficient of room surfaces.

Normally, acoustic conditions are better in conventional buildings, because sound-absorptive materials such as acoustical ceilings, partitions and carpet are more widely used in conventional buildings than in sustainable buildings, since they are not considered ‘environmentally-friendly’. Optimum RTs for various types of indoor space have been proposed by many authors (e.g. Long [22]; Egan [23]). The ideal RT for offices hasn’t been determined. It is proposed to use 0.6 s as the maximum RT for cellular offices, as this has general agreement by acoustical engineers [24]. For open-plan offices and meeting rooms, the ideal RT is also 0.6 s [22] [23].

2.2.3.3. Noise Isolation (NI)

The quality of construction and the ventilation system designed for a room may impose constraints on the structure of the partitions and the doors separating the space from a corridor, for example. These constraints may exist in both conventional buildings (such as ventilation grilles in doors) and modern buildings (ventilators such as Z-ducts between a naturally-ventilated space and a controlled-pressure environment). Poor sound isolation occurs due to light-weight partitions, such as thin glass, which is widely used in many sustainable buildings. Thus, the ventilation system and the materials chosen can affect the noise-isolation performance of the assemblies (walls and doors) between rooms and corridors. For office buildings, the Noise Isolation Class (NIC) between an office/ a meeting room and its surrounding area should be no less than 35, in order to provide adequate sound isolation [25].

2.2.3.4. Speech Intelligibility Index (SII)

Speech intelligibility is a direct measure of the fraction of words or sentences understood by a listener. The degree to which noise inhibits intelligibility is dependent on the signal-to-noise ratio, which is simply the speech signal level minus the background noise level in dB, and on the reverberation time. When the noise is higher than the speech level, the signal-to-noise ratio is negative. When good speech intelligibility is desired, such as in conference rooms, values of Speech Intelligibility
Index (SII – a speech intelligibility measure between 0 and 1) above 0.75 are recommended. An SII value between 0.45 and 0.75 indicates acceptable speech intelligibility, and below 0.45 is considered to be poor [26]. There have been other recommendations indicating that SII=0.20 is the maximum value for achieving ‘acceptable’ speech privacy [27].

2.2.4. Thermal balance and occupancy comfort

The following thermal comfort parameters were monitored: indoor ambient temperature and relative humidity. ASHRAE Standard-55 defines a comfort ‘zone’ based on these variables, where the majority of occupants are likely to feel comfortable [5]. When the indoor ambient temperature and relative humidity are measured, the thermal condition of the spaces can be presented on the Psychrometric chart (see Appendix A), and it can be determined whether it is in the comfort ‘zone’. If it is not in the comfort ‘zone’, then the thermal condition can be regarded as unsatisfactory, and needs to be improved. There are two comfort zones: winter and summer comfort zones. The outdoor temperature of a measurement day can be used to determine which zone to use.

![Psychrometric chart](image)

**Figure 2** Thermal comfort zone on Psychrometric chart [5]
2.2.5. Lighting

According to the US Department of Energy, 51% of the energy used in commercial buildings is consumed by lighting systems. Illumination intensity, measured in lux or footcandles (1 FC = 10.76 lux), has a major effect on both visual efficiency and comfort. Uniformity of task illumination is considered important to visual comfort, although the effect cannot be measured accurately. For visual comfort evaluation, the recommended illumination level in the unit of FC by NRCC-45620, Advanced Energy Design Guide (AEDG) and Illuminating Engineering Society of North America (IESNA) was used. These standards recommend that, for desk activities, the minimum and average maintained illumination should be 30 FC and 50 FC, respectively, by a combination of natural and supplemental lighting; however, there should not be any desk that is illuminated at more than 70 FC, to avoid over-exposure and glare [6].
Chapter 3. CIRS Building Description

3.1. HVAC Systems

The performance of comfort air conditioning is mainly determined by the human comfort, indoor temperature and humidity design standards.

During winter, CIRS is heated by two mechanical methods – a heating coil in the supply air duct in the AHU and water heat exchangers under the window sills. Furthermore, occupants can adjust the air ventilation and indoor temperature for themselves by controlling operable windows (see Figure 3). Normally, it is not recommended for staff to open windows to control the indoor environment in winter, since the outdoor ambient temperature in Vancouver is normally around 0-7 °C during the monitoring period, and a direct outdoor airflow could create a great thermal load, and a waste of heating energy. According to the AHU operation history, during the monitoring period the supply air was heated to around 26°C, which equaled the supply air set point. In CIRS, the heat exchangers use hot water as the heating source, and run 24/7. Radiation valves are controlled by percentage, according to temperature sensors, but because the system uses a high gain system, the valves are mostly used at 0% or 100% (like an ON/OFF control).

CIRS has a mixed mode ventilation system. The building is designed to utilize natural ventilation strategies in most of the space. However, since it has been introduced that natural ventilation by controlling operable windows is not common in winter, the ventilation for CIRS could be inadequate. The ventilation systems are described here to help understand the CIRS mechanical features.

There are two mechanical ventilation air handling units (AHU1 and AHU2) in CIRS. AHU2 is used to serve the auditorium between the office wings, and AHU1 (for air handling unit details, see Appendix B) serves the rest of the building, which can be identified as the office wings, the investigated areas.

Figure 3 An operable window in CIRS
Figure 4 Operable windows and openings for natural ventilation [28]

Figure 5 Displacement system for mechanical ventilation [28]

Figure 6 Swirl diffuser installed on the floor

Table 3 Diffuser amount of each selected section

<table>
<thead>
<tr>
<th>Section</th>
<th>Offices</th>
<th>Meeting rooms</th>
<th>Ventilation rates per diffuser in office areas</th>
<th>Ventilation rates per diffuser in meeting rooms</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd F North</td>
<td>23</td>
<td>--</td>
<td>25.2L/s</td>
<td>--</td>
</tr>
<tr>
<td>2nd F South</td>
<td>18</td>
<td>2</td>
<td>29.7L/s</td>
<td>33.5L/s</td>
</tr>
<tr>
<td>3rd F South</td>
<td>18</td>
<td>2</td>
<td>29.7L/s</td>
<td>33.5L/s</td>
</tr>
</tbody>
</table>
Cross-ventilation is designed to move air through the office wings (see Figure 4). Although, the figure shows the cross-ventilation created by top operable windows, this is not normally the case in CIRS. In the office wings, occupants control bottom windows much more frequently than top windows. However, bottom windows might not provide ventilation as sufficiently as top windows, which could result in inadequate air ventilation in CIRS.

Mechanical ventilation supplements natural ventilation in CIRS. Mechanical ventilation is heated only. The mechanical ventilation air is supplied through displacement ventilation mode from the floating floor (see Figure 5). Swirl diffusers (see Figure 6) are installed, and are operable manually. Each private office has one swirl diffuser on the floor to provide mechanical ventilation.

According to data presented in the CIRS design/construction Schematic – Ventilation Systems drawing, the mechanical ventilation supplies air at a rate of 4*145 L/s for the 2nd floor, north wing, 2*267 L/s each for the 2nd, and 3rd floors, south wing offices, and 67 L/s for the meeting room on each floor. According to the actual construction of CIRS, the number of diffusers and their ventilation rates on each floor are presented in Table 3. Besides the natural ventilation by operable windows and the mechanical ventilation by AHU, there is also air infiltration.

The AHU has a frequency control system, which only reacts to the feedback of pressure. Dampers on each floor are controlled automatically, and can adjust the mechanical ventilation to each floor.

3.2. Lighting System

In CIRS, the office wings use both natural lighting and artificial lighting strategies (see Figure 7). Artificial lights have both dimming sensors and motion sensors, limiting unnecessary use. Some spaces also have lighting controls, allowing occupants to adjust the level of illumination, minimizing the use of artificial lighting.

The office spaces are divided in two blocks. The design criteria for illumination levels in the original open plan office space was 300 lux (30 foot-candles). A series of reflective surfaces - 6x6 foot flat panels of acoustic tiles, called reflective clouds - are installed to the underside of the ceiling (see Figures 7 and 8). The reflective clouds reflect and disperse the light throughout the space. Two T5 fluorescent lighting fixtures projecting upwards are mounted below each surface according to the CIRS building manual [28].
The installation of interior partitioning to create private offices, though glazed, has reduced the amount of daylight available to the space, and changed the artificial lighting strategy. According to the CIRS building manual [28], the overall illumination level is 205 lux (19 foot-candles) and task lighting will likely be required. Meeting rooms 2336 and 3336 use both natural and artificial illuminations. The task surfaces are directly lighted and there are no reflective clouds.

These design features will be compared to measured results, and will be used to analyze the indoor lighting conditions.

### 3.3. Acoustic Features

There are some indoor acoustic features designed for CIRS. First are the 1830 x 1830 mm (6x6 foot) flat panels of acoustic tiles, called reflective clouds, which were briefly introduced in the last section (see Figure 7). There is one suspended in every private office under a wooden ceiling. In meeting rooms, instead of acoustic tiles and wooden ceiling, there is only a whitewashed ceiling.
Second is the 1.5 m high fabric partitions between workstations, and the fabric walls between spaces in the office areas. These partitions could absorb a little low-frequency sound, and provide sound attenuation. The floor material used in CIRS is carpet, which can absorb some high-frequency noise.
Chapter 4. Measurement Methodology

To investigate ventilation, indoor-air quality (IAQ), acoustic and thermal conditions, and lighting, the following environmental factors were measured in the building rooms: background-noise level (BNL), reverberation time (RT), speech intelligibility index (SII) and noise isolation (NI); ultrafine particles amount (UFPs), volatile-organic compounds (VOCs) concentration, and carbon dioxide (CO₂) concentration; indoor ambient temperature and relative humidity; and indoor illuminance level. The measurement instruments are displayed in Appendix C. The information of measurement equipment and some methods were presented in Table 4.

Table 4 Measurement equipment or methods information

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Equipment or methods</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAQ UFPs concentration</td>
<td>TSI P-Trak 8525 Ultra-fine Particle Counter</td>
<td>particles per cc (pt/cc)</td>
</tr>
<tr>
<td>IAQ VOCs concentration</td>
<td>ppbRAE PGM-7240</td>
<td>parts per million (ppm)</td>
</tr>
<tr>
<td>IAQ CO₂ concentration</td>
<td>TSI Q-Trak model 8550/8551</td>
<td>parts per million (ppm)</td>
</tr>
<tr>
<td>Thermal Ambient temperature</td>
<td>CIRS sensors</td>
<td>degree (°C)</td>
</tr>
<tr>
<td>Thermal Relative humidity</td>
<td>CIRS sensors</td>
<td>percentage (%)</td>
</tr>
<tr>
<td>Acoustics Reverberation time</td>
<td>winMLS on Acer laptop, amplifier, Rion NA28 (or NA-29E), omni-directional loudspeaker</td>
<td>second (s)</td>
</tr>
<tr>
<td>Acoustics Background noise level</td>
<td>Rion NA28 (or NA-29E)</td>
<td>decibel (dB)</td>
</tr>
<tr>
<td>Acoustics Noise isolation</td>
<td>Rion NA28 (or NA-29E), winMLS on Acer laptop, amplifier, omni-directional loudspeaker, NIC spreadsheet</td>
<td></td>
</tr>
<tr>
<td>Acoustics Speech intelligibility</td>
<td>Rion NA28 (or NA-29E), winMLS on Acer laptop, amplifier, SSARAH (Speech Source for Acoustical Research in Architecture and Hearing), SII spreadsheet</td>
<td></td>
</tr>
<tr>
<td>Lighting Illumination</td>
<td>DLM2</td>
<td>illuminance (FC)</td>
</tr>
</tbody>
</table>
4.1. Areas of Study

Figure 9 Private office (left); meeting room (top right); open-plan area (bottom right).

This study investigated environmental quality in a number of spaces in CIRS, including cellular offices, open-plan offices, and conference rooms of various sizes, which are all in the office wings. The auditorium was not studied, since it is ventilated by a different air handling unit from the rest of the building, and it is not directly comparable to the other spaces. Moreover, the regular occupants of CIRS – the staff – spend much more time in offices and meeting rooms than in the rest of the building. Therefore, the areas chosen for this study are the private offices, open-plan office areas, and meeting rooms (Figure 9).

Floor plans of selected 2nd and 3rd floors and their room layouts are presented in Appendix D. Efforts were made to select a collection of spaces with a range of indoor occupancy conditions, furniture densities, door/windows and ventilation statuses, resulting in a range of acoustical, air-quality, lighting, and thermal-comfort conditions.

4.1.1. Cellular offices

Measurements were done in 13 cellular offices, to evaluate their indoor
environmental quality. In CIRS, offices are located in both wings. Offices with both window orientations (south and north) were measured. Cellular offices (see Figure 10) are separated from adjacent spaces by a movable fabric-surface barrier, glazed barrier and a door. An air gap is designed over the glazed barrier, for natural ventilation.

Normally, there is one L-shaped table and a bookshelf installed by the wall. It is designed for 1 or 2 occupants to do regular office work. During monitoring period, CIRS staff worked in a quiet sitting condition. The dimension of a cellular office is:

- Area (m$^2$): 12.350
- Length (m): 3.050
- Width (m): 4.050
- Room height (m): 3.720
- Room volume (m$^3$) $\approx$ 46
- Indoor ambient temperature set-point: 22°C (varies in some circumstances).

4.1.2. Open-plan areas

In CIRS, open-plan office areas are common spaces for occupants to study, to work, and to communicate. Normally, each staff has a workstation. The partitions used to separate workstations are only 1.5 m high. The open concept brings advantages to interaction and communication in CIRS, yet its effect on indoor environmental quality is necessary to be determined.

Figure 10 Cellular office
4.1.3. Meeting rooms

The indoor environmental quality of rooms 2336, 3336, 3357 were investigated. The meeting room 3357 has the same furnishing materials as the offices. The meeting rooms 2336 and 3336 are directly facing the atrium, and have whitewashed ceilings and walls instead of fabric walls and wood ceilings. There are no acoustic tiles in these meeting rooms.

4.2. Acoustical Measurement

Four major acoustic parameters, reverberation time (RT), background noise level (BNL), speech intelligibility index (SII) and noise isolation class (NIC), were measured and estimated. The results were compared with design/acceptability criteria.

4.2.1. Reverberation time

Impulse-response (IR) measurements were made using the WinMLS2000 program on an Acer laptop. An omnidirectional loudspeaker was connected through a power amplifier to the output. From the filtered IR, the 125 to 8000 Hz octave-band sound-decay curves and the reverberation time were calculated.

4.2.2. Background noise level

Background-noise measurements were performed in octave bands from 125 to 8000 Hz, using a Rion NA-28 (or a Rion NA-29E) sound-level meter, averaging over 10 seconds, when the office wings of the building was unoccupied.

4.2.3. Noise isolation

The noise isolation (NI) of test partitions was determined by comparing the noise levels sampled inside the source and receiving rooms separated by the partition. An omni-directional loudspeaker array radiated white noise. In each room the averaged sound-pressure level was measured in third-octave bands from 125 Hz to 4000 Hz. The microphone positions were located 1 m away from the test partition.

4.2.4. Speech intelligibility index (SII)

To estimate the SII, a human-head-simulator directional speaker model called SSARAH was used to simulate a human speaking as a source. Then the sound levels of selected receiver positions were measured with a Rion NA-28 (or a Rion NA-29E) sound-level meter. The SII was estimated using the SII spreadsheet developed by the Acoustics and Noise Research Group in UBC.
4.3. Indoor Air Quality Measurement

The following IAQ parameters were monitored: ultrafine particles concentration; Volatile Organic Compounds (VOC concentration); CO₂ measurement, when the buildings were occupied (Occupancy variables change).

4.3.1. Ultrafine particles

A TSI P-trak 8525 Ultra-fine Particle Counter was used to measure particle concentrations in indoor spaces (in particles per cc). Measurements were taken over the entire space, with data logging intervals of 10 s. Particles are drawn through the P-Trak Ultra-fine Particle Counter using a built-in pump. Upon entering the instrument, particles pass through a saturator tube where they mix with an alcohol vapour. The particle/alcohol mixture is next drawn into a condenser tube where alcohol condenses on the particles, causing them to grow into droplets that can be counted more easily. The droplets then pass through a focused laser beam, producing flashes of light. The light flashes are sensed by a photo-detector and counted to determine particle concentration.

4.3.2. Volatile organic compounds

A ppbRAE VOC model PGM-7240 manufactured by RAE systems was utilized to measure VOC concentrations in spaces. VOC was measured over the entire room, at a height at least 1.2 m above the floor. In survey mode, data was logged every second. The monitor uses a dual channel photo-ionization detector (PID) and an electrodeless discharge UV lamp as a high energy photon source. As organic vapours pass by the lamp, they are photo-ionized and the ejected electrons are detected as current.

4.3.3. Carbon dioxide

A TSI Q-Trak was used to monitor the CO₂ concentration throughout a whole working day from 10AM to 4PM, to evaluate the indoor air quality, and the ventilation conditions.

4.4. Thermal Comfort

The following thermal parameters were monitored by the CIRS sensors throughout the period of measurements: indoor temperature and indoor relative humidity. These were recorded and downloaded for selected spaces.
4.5. Lighting Comfort

The most important factor in visual quality is the intensity of illumination on the area of interest. Additionally, outdoor sunlight intensity, which was documented by UBC Earth, Ocean and Atmospheric Science Rooftop Weather Station, is discussed to show the quality of outdoor solar radiation, and to compare with indoor illuminance levels. This outdoor sunlight intensity was also used to verify the time when the strongest illuminance outdoors appears, so the time of measurement for the strongest indoor illuminance could be determined (normally at 2:00 PM afternoon). In order to determine the relationship between the curtain status and the illuminance, the illuminance of various curtain statuses have been measured when the rooms were unoccupied.

4.5.1. Intensity of illumination on the area of interest

To measure the intensity of illumination, the areas of interest were firstly defined for the target rooms/spaces. For most of meeting rooms and offices, the common working areas for occupants are the table surfaces, black/white board surfaces, and computer surfaces. Among these areas, illumination is mostly needed on the table surfaces.

In meeting rooms 2336, 3336 and 3357 of CIRS, tables are shaped like long ellipses, located in the centre of the spaces (see Figure 11). In meeting rooms, the tables are normally shared by several occupants at the same time. In order to measure the intensity of illumination, several points were chosen for measurement. They were east-end point, middle point and west-end point. DLM2 was placed at each of the chosen points to measure the intensity of illumination. Due to the sunlight coming from south windows, through the glass, the illuminance varied from point to point.

Figure 11 Meeting rooms layout and the lighting measurement points
Figure 12 Office layout and lighting measurement points

In offices of CIRS, there is one L-shaped table for one occupant per room, located along the wall (see Figure 12). The desktops are normally placed at the corner of the L-shaped tables, but vary from office to office. There is a bookshelf right above the table in every office. For some of the offices, there is a bookshelf or cabinet, or both, in the locations shown in Figure 12. In order to measure the intensity of illumination, two points were chosen for measurement. They are table surface areas. One of them is near the window side, and the other near the centre of the office, right below the artificial lighting. DLM2 was placed at each of the chosen points to measure the intensity of illumination.
Chapter 5. Results and Discussion

This chapter presents the measurement results and data analysis for each aspect of IEQ for CIRS.

5.1. Ventilation

5.1.1. Ventilation rate calculation based on CO₂ monitoring

In Section 3.1, it was mentioned that, in office wings in CIRS, there are two sets of operable windows – top and bottom windows. Natural ventilation by controlling operable windows of CIRS was designed under consideration of controlling top windows. However, in fact this is normally not the case in CIRS. Occupants use bottom windows much more frequently than top windows, which could have less effect on cross-ventilation in office wings, and result in inadequate ventilation. The mechanical ventilation provided by each swirl diffuser of CIRS was obtained through related Mechanical Drawings, and is shown in Table 3. However, the air change rate including natural ventilation and air infiltration in CIRS is unknown.

According to the CO₂ monitoring results for several spaces presented in Appendix E, by using the CO₂ concentration decays, air change rates of ventilation of selected spaces in CIRS were estimated. The theory has been discussed in Section 2.2. The acceptable area outdoor air rate for the spaces in office buildings is considered to be 0.3 (L/s · m²) or 2.5 (L/s · person) [16]. By multiplying with the room areas or the numbers of occupants, the minimum air change rate could be estimated for selected spaces. The higher minimum air change rate were chosen for selected spaces – e.g. a private office is normally occupied with three occupants when a regular meeting is held, then the minimum air change rate determined by three people was 0.60 ACH, while by area was 0.29 ACH. Then 0.60 ACH was chosen. The estimated air change rates for offices and meeting rooms are shown in Tables 12 and 13 in Appendix F.

North wing, 2nd floor, private office

Room 2156 is the only private office in this section. During the monitoring period, the room was occupied in two conditions. At first, two occupants were talking casually. Then, the room was mainly occupied by one occupant, working in a quiet sitting situation. When the room was occupied by two people, a steady CO₂ concentration averaging 950 ppm was observed. The equivalent outdoor airflow rate calculated for this situation is 33.9 m³/(hr · person), higher than the required 30 m³/(hr · person). When the room was occupied by one person, a steady state of 875 ppm was
observed for CO$_2$, and the equivalent outdoor airflow rate changes to 38.8 m$^3/$(hr $\cdot$ person), also higher than the required 30 m$^3/$(hr $\cdot$ person). The outdoor airflow rate calculated from various decays in this room is 4.09 ACH, on average, which is above the minimum acceptability criteria of 0.60 ACH.

**South wing, 2$^{nd}$ floor, private offices (windows facing North)**

Room 2344 – during the monitoring period, this room was occupied with one CIRS staff, working in a quiet sitting situation, with windows closed, while the mechanical ventilation was ON. Through various CO$_2$ concentration decays, the ventilation rate was estimated as 5.83 ACH, on average.

Room 2345 – this room was unoccupied for a large portion of the monitoring day. There were four occupants in the room at a time, and a CO$_2$ decay was observed when they left. The corresponding ventilation rate was 2.28 ACH.

From these two similar cases, the ventilation caused by the office door being open in these rooms is estimated at 3.55 ACH, approximately. Due to the limitation that the measurements were performed on different monitoring days, and in different rooms, and the fact that ventilation could vary significantly and unpredictably due to weather issues, this conclusion needs more work to verify.

**South wing, 2$^{nd}$ floor, private offices (windows facing South)**

Room 2352 – the bottom window of this room was slightly open (approximately 20%) for the whole monitoring day; the mechanical ventilation was operating. There were two door statuses during the measurements (open/closed). When the door was open, the estimated ventilation was 5.35 ACH. When the door was closed, the estimated ventilation was 3.14 ACH.

Room 2354 – the windows of the room were closed in this case; mechanical ventilation was operating. There were two statuses for the door – open/closed. The estimated ventilation was 7.71 ACH when the door was open, and 5.24 ACH when it was closed.

From these four cases in these two similar rooms, the ventilation caused by the office doors in these rooms being open can be estimated as 2.21 ACH for room 2352, and 2.47 ACH for room 2354. Again, due to the limits of ventilation estimation, these results need more verification.

**South wing, 3$^{rd}$ floor, private offices (windows facing North)**

Room 3342 - during the monitoring period, the window of this room was closed; the
door was open. The mechanical ventilation for this room was turned off during the monitoring period. The ventilation for this room was only air infiltration and potential air exchange with other indoor adjacent spaces at that time. The air change rate calculated for this room was only 1.06 ACH.

Room 3344 – both the bottom window and the door of this room were open throughout the whole monitoring period. The mechanical ventilation was turned on for around one hour that day. The estimated ventilation rate was 4.88 ACH when the mechanical ventilation was ON, and 3.98 ACH when it was OFF.

Comparing cases 3342 and 3344, the results indicate that, when both the mechanical ventilation system and windows were closed, the ventilation rate can be quite low. Comparing cases 3342 and 3344, it can be estimated that the natural-to-mechanical ventilation ratio was approximately 3.24:1 for this case. This could be used as a reference data for the following sections, yet it lacks statistical significance due to the limited number of measurement cases.

Meeting rooms

A meeting room is normally occupied with less than 10 occupants when a regular meeting is being held, then minimum air change rate is 1.38 ACH.

Room 2336 and 3336 – during the monitoring period for meeting room 2336 the window/door were closed, and the mechanical ventilation was operating. According to various CO2 concentration decays, the estimated air change rate is 7.30 ACH. During the monitoring time for room 3336, every time the door was open, a sudden CO2 concentration drop was observed. The estimated air change rate is 6.14 ACH when the door was closed, and 17.90 ACH when it was open. Clearly, since its door is facing the atrium, and cross-ventilation exists, the ventilation through the open door could be significant.

Room 3357 – this is a meeting room in the office section: during most of the monitoring period, the windows were closed. The total ventilation rate estimated by CO2 decays is 4.48 ACH. In this case, there was a period of time when the window was open, which caused a direct drop of CO2 concentration in this space. The estimated air change rate during that period of time is 10.12 ACH. The natural ventilation rate due to the open window in this case should be approximately 5.64 ACH.
Figure 13 Estimated air change rates of measured spaces (the shaded area shows the recommended rate [16])

Summary of ventilation results

During most of the monitoring, the dampers which control mechanical ventilation were open fully. From Figure 13, it can be observed that 100% of the spaces in CIRS achieved the recommended air change rate.

The following conclusions can be drawn from the ventilation results:

- opening the door can increase ventilation in all conditions;
- offices can’t achieve an acceptable air change rate when the mechanical ventilation system is OFF;
- natural ventilation in CIRS is stronger than mechanical ventilation according to some results;
- ventilation rate in the meeting rooms with the door facing the atrium can extremely exceed the maximum acceptable air change rate when the door or their exterior window is open.
5.2. Indoor Air Quality (IAQ)

The indoor air quality has a significant effect on the satisfaction and productivity of occupants in indoor environments. In the Introduction chapter, it was mentioned that this project evaluated the air quality of the selected spaces from the following three perspectives:

- Ultrafine particles (UFPs) concentration;
- Volatile organic compounds (VOCs) concentration;
- Carbon dioxide (CO₂) concentration.

In Chapter 2 – Theory and Related Criteria, the importance of these contaminants, and the standards that require the measurement of them, have been briefly discussed. In this section, the measurement results and analysis will be presented.

5.2.1. Ultrafine particles (UFPs) concentration

Ultrafine particles can be generated by several sources in a sustainable educational building like CIRS - e.g. printers, ventilation air intake, both mechanically and naturally (vehicle exhaust). Ventilation systems also have a main role in controlling ultrafine particles. The performance of ventilation systems in CIRS in achieving a satisfactory air quality for occupants is evaluated here by analyzing the UFP measurement results, which are presented in Appendix G. The particle amounts in the rooms are highly dependent on the amount of outdoor particles that day. To investigate the air quality performance by evaluating the UFP concentration results, the following parameters were analyzed:

- Indoor particle concentration minus 20% of the outdoor concentration;
- Ratio of inside-to-outside particle concentrations.

To achieve good indoor air quality, it is recommended that the value of indoor-minus-20%-of-outdoor UFP concentration should be zero or negative. According to the measurement results, it can be clearly observed that the amounts of ultrafine particles concentration in the rooms were higher than 20% of outdoor value.

The highest indoor UFP concentration was 5300 pt/cc, and the highest average UFP concentration was 3954 pt/cc, both measured in room 2156. The highest indoor UFP concentration that day in office 2156 was measured at 10:00AM, which indicates that this high concentration of UFPs could result from the remaining particles from the night before. In this case, the average UFP concentration indoors was 4953 pt/cc, when there were two occupants in this room in the morning, and was 3205 pt/cc when there was one occupant. This could be due to the particles caused by occupancy
activities, such as movement. The UFP concentration decrease in this case was a result of filters in the mechanical ventilation system with respect to absorbing particles.

Figure 14 shows the relation between air change rate and the UFP concentration. The highest indoor-minus-20%-of-outdoor UFP concentration was found in office 3342, which had the lowest air change rate. In room 2352, the UFP concentration didn’t decrease until the door was open in the afternoon, when the ventilation rate increased. In room 3344, at first there was only air infiltration and indoor air exchange for ventilation in the morning, and the UFP concentration was 4255 pt/cc, on average; after the dampers controlling mechanical ventilation for that section were opened and the window was opened, the UFP concentration decreased to 2176 pt/cc. It can be concluded that the operation of CIRS’s hybrid ventilation systems efficiently reduced the indoor UFP concentration.

Figure 15 also illustrates this conclusion. When the air change rate increased, the indoor-outdoor ratio of UFP concentration decreased significantly, and approached an approximate value of 0.3. Since the ventilation rate of CIRS was not at its full capacity, according to the driving frequency record of its AHU, there is a lot of potential for controlling UFP concentrations.

Figure 14 Indoor-minus-20%-of-outdoor UFPs amount related to air change rates
5.2.2. Volatile organic compounds (VOCs)

The VOC monitoring was performed under mechanical ventilation conditions, which indicates that operable windows were shut during the monitoring period. Therefore, mainly indoor sources of VOCs were involved – building furniture/furnishing materials and occupancy activities. There are some common sources of VOCs that could exist in a sustainable building like CIRS – e.g. perfumes, wood products, floor/wall coverings such as carpets, structural materials such as plywood, suspended acoustic tiles on flat panels, etc. In the analysis section of VOCs, these building features, as well as operation history of CIRS, such as the HVAC history and window/door status monitoring records, are considered. In VOC monitoring cases, since private offices 2156, 2344 and 2345 shared a common outdoor environment, which was the green roof of CIRS, and meeting rooms 2336 and 3336 shared a common outdoor environment too, it is reasonable to assume that the outdoor VOC concentration for all the comparable cases was the same.

In this part of the indoor air quality assessment, the concentration of VOCs was investigated. Measurement results were presented in Appendix G. For acceptable indoor air quality, VOC concentrations in spaces should be less than 300 ppb (0.300 ppm) [19].

In all of the private offices, carpets, wood ceilings and acoustical panels are installed. In the meeting rooms 2336 and 3336, whitewashed ceilings are installed, different from the offices, and there are no acoustical panels. Due to the displacement mechanical ventilation supplied from the floating floor, the VOCs generated by
carpets could easily be brought into working areas.

From the VOC concentration monitoring, it could easily be observed that these selected spaces have very different forms of VOC concentration curves (). According to the measurement results, private office 2156 (0.819-5.235 ppm; max VOC) exceeded the recommended VOC value the most, and remained a very high concentration of VOCs of more than 0.300 ppm. It was highest in the morning, when the ventilation system had been turned on for a relatively short time. During the monitoring period of this case, the windows were closed, and air infiltration was the only ventilation, besides the mechanical ventilation. The relatively high VOCs compared to other spaces were due to the high density of furniture and the many paintings/photographs on the walls. Also, room 2156 was in IEQ lab 2160, and connected with the rest of the space of this lab by the large opening above the interior door, which mainly served the Acoustics and Noise Research Group; many sound absorptive porous materials were in this space, potentially generating VOCs.

The results for office 2344 varied. Every hour a sudden rise and then a drop occurred in the VOC concentration. This was due to the window opening by the occupant every hour for natural ventilation purposes, and the source of outdoor VOCs increased the indoor concentration. However, as soon as the window closed, mechanical ventilation was able to reduce the indoor VOC concentration efficiently within a few minutes. Office 2344 had the highest air change rate in all of the offices measured for VOCs. Except for the common acoustical panel on the ceiling, office 2344 had lower furniture density, and decorations that could potentially generate VOCs, than office 2156 (no painting/photographs or other sound absorptive porous materials). These could be the reasons why the indoor concentration of VOCs in office 2344 was much lower than that of office 2156. Similar conclusions can also be drawn by comparing office 2344 and office 2345. There was only one workstation in office 2345, and two in office 2344. A fabric partition between two tables was installed in 2344, which could possibly generate VOCs. In office 2345, the windows/door were mostly closed, due to the low occupancy that day, and the VOC concentration remained in the very low range of 0-30 ppb.

The measured VOC levels of meeting rooms 2336 and 3336 were much lower than 0.300 ppm. For meeting rooms, there were whitewashed ceilings, comparing to the wood ceiling of the offices, and there weren't any acoustical panels. The wall coverings in meeting rooms were also whitewashed, instead of the offices' fabric walls. According to room occupancy records, the VOC levels remained very low, even when there were meetings in these spaces.

In summary, according to the VOC monitoring results, the following conclusions can be drawn:
- mechanical ventilation in CIRS can control indoor VOCs concentration efficiently;
- natural ventilation provided by operable windows in CIRS can cause an unwanted increase of indoor VOC concentrations;
- VOC concentrations in spaces are highly dependent on its occupants’ activities; e.g. a lab intended for acoustic purposes, which has many sound absorptive materials, can have an exceedingly high indoor VOC concentration.

5.2.3. Carbon dioxide (CO₂) concentration

Here, the concentration of carbon dioxide is analyzed. Measurement results are presented in Appendix H. The ASHRAE standard [16] outlines that, based on the occupancy and use of the space, the mass balance of occupant-generated CO₂, and the supply of dilution fresh air, result in a steady state of approximately 1000 ppm (taking into consideration the metabolism, oxygen demand and diets of the occupants).

To control the indoor CO₂ concentration, the numbers of occupants in rooms need to be determined. Every occupant who is working in a quiet sitting situation normally generates 20 L/(hr • person) of CO₂. Since CIRS was not running in a full occupancy condition, the ventilation rates for the monitored spaces were mostly insufficient, which caused some IAQ problems with respect to UFP and VOC concentrations. However, only one office (2156) exceeded the level of 1000 ppm of CO₂ due to the relatively high occupancy level. Though there are hardly any CO₂ issues in CIRS so far, it is still of concern that the indoor CO₂ concentration could be much higher when CIRS is fully occupied at a future date, and there are no CO₂ control strategies in the mechanical ventilation systems in CIRS, since CO₂ sensors in the building only serve for monitoring purposes.

5.3. Acoustics

In this section, the acoustical measurement results in the spaces are presented. Noise levels and reverberation times are compared to the related acceptability criteria. The noise isolation (NI), the corresponding noise-isolation classes (NIC) of partitions in the spaces, and the speech intelligibility index (SII) results are estimated and discussed.

According to the ANSI S12.2-2008 [20], the background-noise level (BNL) of the private offices should not exceed 44 dBA and NC 35; BNL of the open-plan areas
should not exceed 44 dBA and NC 35; BNL of meeting rooms should not exceed 39 dBA, and NC 30; and BNL of public circulation area should not exceed 48 dBA, and NC 40. The reverberation time (RT) of these spaces should be less than 0.6 s.

5.3.1. Furniture details

Specific furniture details of selected spaces are displayed in Table 5. Besides the specific furniture details of each space, there is also standard furniture in these spaces. For instance, for each occupant, there is one workstation.

Table 5 Specific furniture details of spaces

<table>
<thead>
<tr>
<th>Spaces</th>
<th>Acoustical tiles</th>
<th>Diffusers</th>
<th>Occupants</th>
<th>Specific details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Private offices</td>
<td></td>
<td></td>
<td></td>
<td>two 1*2 bookshelf, 3 plants, a few photographs and paintings.</td>
</tr>
<tr>
<td>2156</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>two 1*2 bookshelf, 3 plants, a few photographs and paintings.</td>
</tr>
<tr>
<td>2342</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2 chairs; 1 partition between workstations</td>
</tr>
<tr>
<td>2344</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2 chairs; 1 partition between workstations</td>
</tr>
<tr>
<td>2345</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3 plants; 1 cabinet</td>
</tr>
<tr>
<td>2351</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3 chairs; one 2<em>2m bookshelf; two 1</em>0.5 cabinets</td>
</tr>
<tr>
<td>2352</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>almost the same as 2351, except one 1*2 bookshelf</td>
</tr>
<tr>
<td>2353</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1 poster</td>
</tr>
<tr>
<td>2354</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2 cabinets</td>
</tr>
<tr>
<td>3342</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3 chairs; 1 plant</td>
</tr>
<tr>
<td>3344</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3 chairs</td>
</tr>
<tr>
<td>3351</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3 chairs; one 2<em>2m bookshelf; two 1</em>0.5 cabinets</td>
</tr>
<tr>
<td>Open-plan areas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2331</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2 chairs; 1 partition aside table; 1 printer; two 1<em>0.5 cabinets; one 2</em>1 sofa</td>
</tr>
<tr>
<td>2160</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3347</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3352</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>open-plan area, with 7 plants</td>
</tr>
<tr>
<td>Meeting rooms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2336</td>
<td>0</td>
<td>2</td>
<td></td>
<td>4 windows; 2 luminances (photoed); 11 chairs; 1 return inlet above door; one 4<em>1m long table; one 2</em>0.5 cabinet</td>
</tr>
<tr>
<td>3336</td>
<td>0</td>
<td>2</td>
<td></td>
<td>same as 2336</td>
</tr>
<tr>
<td>3357</td>
<td>1</td>
<td>4</td>
<td></td>
<td>7 chairs, 1 plant, one 1*2 bookshelf, 1 poster</td>
</tr>
</tbody>
</table>
5.3.2. Comparison of background-noise levels in different spaces

The background-noise level measurements were made when the office wings were unoccupied, following the instructions of the related standard [20]. This study aimed to investigate the acoustic conditions on a regular weekday in CIRS, when the auditorium is normally occupied for lecture purposes; under this circumstance, the auditorium is a source of noise in the atrium. Moreover, one of the background noise sources – the mechanical ventilation system – is only operating during weekdays or when the building is scheduled to be occupied. The BNL measurement date was chosen on a weekend, while the auditorium was being fully occupied. There were distinguishable noises transmitted from the crowd in the atrium and noises from the mechanical ventilation below the floating floors. While measuring the BNL, all windows were closed. The spaces that BNL were tested in are displayed in Figure 16 and 17. Besides these points, room 2156, and the open-plan area 2130 of north wing the 2nd floor, were also measured, but on a different date, when CIRS was unoccupied.

Figure 16  BNL measurement positions on 2nd Floor South wing marked with round points
Figure 17 BNL measurement positions on 3rd Floor South wing marked with round points

Private offices

According to the criteria, the background-noise level of the private offices should not exceed 44 dBA, and NC 35. According to the measurement results shown in Table 6 and Figure 18, no BNL exceeded 44 dBA. However, rooms 2351 (NC 38), 3342 (NC 36), and 3344 (NC 38) exceeded NC 35. Rooms 2352 and 3351 were close to NC 35. From the location of these offices, it can be easily observed that they are closer to the atrium and the return air duct inlets, which are located at the reception area 2331, and normally generate a constant noise when HVAC systems are operating.

Table 6 BNL measurement results of private offices in octave-bands

<table>
<thead>
<tr>
<th>Spaces</th>
<th>31.5</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>NC level</th>
<th>A-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>2156</td>
<td>54.6</td>
<td>44.5</td>
<td>38.6</td>
<td>33.7</td>
<td>25.8</td>
<td>21.3</td>
<td>18.2</td>
<td>14.3</td>
<td>12.6</td>
<td>21</td>
<td>30.2</td>
</tr>
<tr>
<td>2342</td>
<td>46.2</td>
<td>44.8</td>
<td>42.4</td>
<td>38.4</td>
<td>34.7</td>
<td>32.2</td>
<td>31.6</td>
<td>29.1</td>
<td>26</td>
<td>33</td>
<td>38.9</td>
</tr>
<tr>
<td>2344</td>
<td>53.8</td>
<td>49.7</td>
<td>46.3</td>
<td>40.2</td>
<td>33.7</td>
<td>31</td>
<td>28.4</td>
<td>24.2</td>
<td>17.9</td>
<td>30</td>
<td>38.1</td>
</tr>
<tr>
<td>2345</td>
<td>53</td>
<td>50.4</td>
<td>45.8</td>
<td>41</td>
<td>39.4</td>
<td>32.8</td>
<td>30.4</td>
<td>26.1</td>
<td>21.6</td>
<td>34</td>
<td>40.5</td>
</tr>
<tr>
<td>2351</td>
<td>53</td>
<td>50.3</td>
<td>46.1</td>
<td>45.5</td>
<td>42.9</td>
<td>36.7</td>
<td>32.6</td>
<td>26.6</td>
<td>20.5</td>
<td>38</td>
<td>43.7</td>
</tr>
<tr>
<td>2352</td>
<td>55.2</td>
<td>46.3</td>
<td>46.2</td>
<td>42.9</td>
<td>40</td>
<td>32.5</td>
<td>30.2</td>
<td>28</td>
<td>22.8</td>
<td>35</td>
<td>41.1</td>
</tr>
<tr>
<td>2353</td>
<td>47.9</td>
<td>48.7</td>
<td>43.7</td>
<td>36</td>
<td>31.1</td>
<td>27.8</td>
<td>26.5</td>
<td>23.7</td>
<td>19.7</td>
<td>28</td>
<td>35.4</td>
</tr>
<tr>
<td>2354</td>
<td>54.9</td>
<td>49.5</td>
<td>44.8</td>
<td>41.5</td>
<td>36.1</td>
<td>30</td>
<td>30.9</td>
<td>25.9</td>
<td>19.8</td>
<td>32</td>
<td>39.1</td>
</tr>
<tr>
<td>3351</td>
<td>53.3</td>
<td>48.3</td>
<td>42.1</td>
<td>43.4</td>
<td>37.1</td>
<td>31.7</td>
<td>33.3</td>
<td>26.3</td>
<td>17.1</td>
<td>35</td>
<td>40.4</td>
</tr>
<tr>
<td>3344</td>
<td>45.4</td>
<td>42.3</td>
<td>38.7</td>
<td>40.3</td>
<td>36.5</td>
<td>35.7</td>
<td>37.3</td>
<td>30.5</td>
<td>24.1</td>
<td>38</td>
<td>42.1</td>
</tr>
<tr>
<td>3342</td>
<td>45.8</td>
<td>41.5</td>
<td>38.9</td>
<td>37.2</td>
<td>34.2</td>
<td>31.6</td>
<td>35.1</td>
<td>29.2</td>
<td>19.9</td>
<td>36</td>
<td>39.6</td>
</tr>
</tbody>
</table>
Room 2156 (NC 21), which is located in the North wing of CIRS, has a far lower BNL than the offices at South wing (NC 28 – 38). It can be clearly seen that the major difference between BNL of 2156 and the South wing offices are mid and high frequency noises. Because noises created by mechanical ventilation systems are normally low frequency noises, this difference should be mainly due to the crowd in the atrium and the auditorium.

This could be also due to the fact that Stores road is on the South side of the building, and the difference is due to the traffic noise. However, during the BNL measurements, there was hardly any traffic, and all exterior windows were shut.

**Open-plan areas**

According to the criteria, the background-noise level in open-plan areas should not exceed 44 dBA and NC 35. According to the measurement results shown in Table 7 and Figure 19, no BNL exceeded 44 dBA. Only space 2331 (NC 36) exceeded the recommended maximum NC 35.

**Table 7 BNL measurement results of open-plan areas in octave-bands**

<table>
<thead>
<tr>
<th>Spaces</th>
<th>31.5</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>NC level</th>
<th>A-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>2130 (BSS lab)</td>
<td>49.4</td>
<td>43.6</td>
<td>38.6</td>
<td>34.5</td>
<td>25</td>
<td>21.6</td>
<td>17.7</td>
<td>14.3</td>
<td>13</td>
<td>22</td>
<td>30.2</td>
</tr>
<tr>
<td>2331</td>
<td>55.3</td>
<td>45.3</td>
<td>44.3</td>
<td>42.7</td>
<td>41.8</td>
<td>35.3</td>
<td>31</td>
<td>26.1</td>
<td>19.9</td>
<td>36</td>
<td>42.1</td>
</tr>
<tr>
<td>3347</td>
<td>45.8</td>
<td>41.4</td>
<td>41.4</td>
<td>40.7</td>
<td>35.8</td>
<td>32.5</td>
<td>29.2</td>
<td>24.7</td>
<td>19.9</td>
<td>31</td>
<td>38.5</td>
</tr>
<tr>
<td>3352</td>
<td>41.4</td>
<td>40.2</td>
<td>37.2</td>
<td>35.5</td>
<td>27.3</td>
<td>24.4</td>
<td>22.3</td>
<td>18.5</td>
<td>15.6</td>
<td>23</td>
<td>31.8</td>
</tr>
</tbody>
</table>
Figure 19 A-weighted BNL measurement results of open-plan areas in octave-bands

Space 2331 is the reception area on the 2nd floor of the South wing, which is located near the front door of this office wing and near the atrium, and a return air inlet is installed right above this area. When the HVAC system is operating, a clear noise can be distinguished in this area. According to the BNL of space 2331 and office 3352 in octave bands, the difference was in all frequencies. For mid and high frequency BNL, since 2331 is on the 2nd floor, closer to the atrium than 3352, this difference should be mainly due to the crowd in the atrium and the auditorium. The low frequency noises of 2331 should be due to the mechanical ventilation noise from the return air inlet right above the space.

Open-plan area 2130 (NC 22) has the lowest BNL compared to other open-plan areas, which are located in the South wing. Similarly, during the measurement of room 2130 in the North wing, the atrium and the auditorium weren’t as fully occupied as during the measurement in the South wing.

Meeting rooms

According to the criteria, the background-noise level of open-plan areas should not exceed 39 dBA and NC 30. According to the measurement results shown in Table 8 and Figure 20, rooms 3336 (with door open: 43.3 dBA, NC 40) and 3357 (39.1 dBA, NC 33) exceeded the recommended NC 30, and the A-weighted criteria of 39 dBA.
Table 8 BNL measurement results of meeting rooms in octave-bands

<table>
<thead>
<tr>
<th>Spaces</th>
<th>31.5</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>NC level</th>
<th>A-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>2336 (door closed)</td>
<td>45.3</td>
<td>42.1</td>
<td>39.8</td>
<td>39.8</td>
<td>32.4</td>
<td>28.1</td>
<td>27.2</td>
<td>19.3</td>
<td>13.2</td>
<td>29</td>
<td>35.9</td>
</tr>
<tr>
<td>3336 (door closed)</td>
<td>43.6</td>
<td>39.3</td>
<td>40.8</td>
<td>37.5</td>
<td>31.2</td>
<td>29.8</td>
<td>24.8</td>
<td>18.2</td>
<td>13.6</td>
<td>29</td>
<td>35.0</td>
</tr>
<tr>
<td>3336 (door open)</td>
<td>46.1</td>
<td>43.2</td>
<td>42.1</td>
<td>39.4</td>
<td>41.2</td>
<td>40.5</td>
<td>31.7</td>
<td>23.4</td>
<td>15.9</td>
<td>40</td>
<td>43.3</td>
</tr>
<tr>
<td>3357 (door closed)</td>
<td>46.8</td>
<td>41.9</td>
<td>41.4</td>
<td>38.6</td>
<td>38.3</td>
<td>33</td>
<td>29.3</td>
<td>23.4</td>
<td>19.9</td>
<td>33</td>
<td>39.1</td>
</tr>
</tbody>
</table>

Figure 20 A-weighted BNL measurement results of meeting rooms in octave-bands

When the door is open, room 3336 is directly influenced by the noise transmitted from the atrium and toilets, and this noise increases the BNL from 35 dBA to 43.3 dBA, NC 29 to NC 40. This could be due to the crowd in the atrium, or the exhaust air ducts in toilets. According to Figure 20, the difference was mainly at mid and high frequencies, and mechanical ventilation systems normally produce low frequency noises. Therefore, it can be concluded that the noise increase by opening the door was mainly because of the people in the atrium.

Public circulation areas

According to the criteria, the background-noise level of public circulation areas should not exceed 48 dBA and NC 40. According to the measurement results in Table 9 and Figure 21, spaces 2330 (52.6 dBA; NC 50) and 3330 (49.6 dBA; NC 45) exceeded the 48 dBA and NC 40 criteria. Both spaces are the front entrance areas on that floor which connect the office wing and the atrium. The following factors could be the reasons behind this result – there are noises transmitting from the atrium, such as traffic noise from west of CIRS; three sources of ventilation noise, one from the return
air inlet of office reception area, and another from the return air inlet right above the meeting room door, and the third one from the toilets’ exhaust air ducts; the crowd in the atrium and the auditorium.

From Figure 21, it can be clearly observed that the gap between mid-frequency noises of 2330, 3330 and the rest of spaces were the main difference, which leads to the conclusion that the crowd in the atrium and the auditorium is the main problem of the high BNL in these two spaces. Because during the measurement period, there were no vehicles on the roads, and mechanical ventilation noises are normally low-frequency.

Table 9 BNL measurement results of public circulation areas in octave-bands

<table>
<thead>
<tr>
<th>Spaces</th>
<th>31.5</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>NC level</th>
<th>A-weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atrium 1F</td>
<td>58.2</td>
<td>52.4</td>
<td>49.5</td>
<td>39.8</td>
<td>37.8</td>
<td>32.7</td>
<td>29.3</td>
<td>25.2</td>
<td>22.9</td>
<td>33</td>
<td>40.2</td>
</tr>
<tr>
<td>Atrium 2F</td>
<td>49.5</td>
<td>49.4</td>
<td>45.4</td>
<td>39</td>
<td>34.7</td>
<td>29</td>
<td>23.6</td>
<td>18.8</td>
<td>17.2</td>
<td>30</td>
<td>36.8</td>
</tr>
<tr>
<td>Atrium 3F</td>
<td>42.9</td>
<td>40.2</td>
<td>38.5</td>
<td>35</td>
<td>28.5</td>
<td>26.1</td>
<td>22.3</td>
<td>17.9</td>
<td>14.1</td>
<td>24</td>
<td>32.3</td>
</tr>
<tr>
<td>2330 (front door)</td>
<td>65</td>
<td>51.5</td>
<td>45.6</td>
<td>50.9</td>
<td>53.4</td>
<td>46.2</td>
<td>40.4</td>
<td>32.9</td>
<td>27.3</td>
<td>50</td>
<td>52.6</td>
</tr>
<tr>
<td>2nd F Corridor 1</td>
<td>50.5</td>
<td>47.5</td>
<td>43.5</td>
<td>39.5</td>
<td>37.5</td>
<td>33.1</td>
<td>31.8</td>
<td>28.2</td>
<td>21.4</td>
<td>33</td>
<td>39.8</td>
</tr>
<tr>
<td>2nd F Corridor 2</td>
<td>56.1</td>
<td>48.5</td>
<td>45</td>
<td>39.9</td>
<td>38.1</td>
<td>35.4</td>
<td>33.1</td>
<td>31.4</td>
<td>24.7</td>
<td>30</td>
<td>41.3</td>
</tr>
<tr>
<td>2nd F Corridor 3</td>
<td>55</td>
<td>45.7</td>
<td>42.6</td>
<td>38.5</td>
<td>37.7</td>
<td>33.5</td>
<td>30.4</td>
<td>27.2</td>
<td>20.8</td>
<td>33</td>
<td>39.4</td>
</tr>
<tr>
<td>3330 (front door)</td>
<td>60.5</td>
<td>48.3</td>
<td>45.3</td>
<td>49</td>
<td>48.4</td>
<td>45.4</td>
<td>38.5</td>
<td>31.2</td>
<td>26.2</td>
<td>45</td>
<td>49.6</td>
</tr>
<tr>
<td>3rd F Corridor</td>
<td>48.6</td>
<td>44.4</td>
<td>43.2</td>
<td>41.3</td>
<td>38</td>
<td>33.8</td>
<td>31.9</td>
<td>28.2</td>
<td>22.1</td>
<td>33</td>
<td>40.4</td>
</tr>
</tbody>
</table>

Figure 21 A-weighted BNL measurement results of public circulations in octave-bands
5.3.3. Reverberation time

When the rooms are unoccupied, the reverberation time (RT) of these spaces should be less than 0.6 s. The following rooms have RT measured – 2156, 2160, 2336, 3336 and 3357. Reverberation time was measured at several different points in each room and the average RT was calculated. The values are presented in Table 10. The RT of room 2156 was also analyzed independently. Since the private offices are very similar in size, surface finishes and density of furniture, RT was measured only in 2156 as a representative private office.

According to the measured RT results shown in Table 10 and Figure 22, room 2336 and 3336 are not within the acceptable maximum RT value (0.6 s) for meeting rooms. In these two meeting rooms, the major sound-absorptive material used is carpet, which has low absorption coefficients in the low-frequency bands. Room 3357 is another meeting room, and the 500 Hz RT is also slightly higher than 0.6 s. Since these spaces are used as meeting rooms, the RT can slightly exceed 0.6 s.

Table 10 Reverberation time summary

<table>
<thead>
<tr>
<th>octave band Hz</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2336</td>
<td>0.48</td>
<td>0.64</td>
<td>0.83</td>
<td>0.69</td>
<td>0.52</td>
<td>0.41</td>
<td>0.31</td>
</tr>
<tr>
<td>3336</td>
<td>0.87</td>
<td>0.73</td>
<td>0.77</td>
<td>0.63</td>
<td>0.51</td>
<td>0.48</td>
<td>0.36</td>
</tr>
<tr>
<td>3357</td>
<td>0.51</td>
<td>0.53</td>
<td>0.63</td>
<td>0.56</td>
<td>0.56</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>2130</td>
<td>0.50</td>
<td>0.44</td>
<td>0.47</td>
<td>0.60</td>
<td>0.58</td>
<td>0.55</td>
<td>0.42</td>
</tr>
<tr>
<td>2156</td>
<td>0.31</td>
<td>0.42</td>
<td>0.37</td>
<td>0.36</td>
<td>0.30</td>
<td>0.33</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 22 Reverberation time summary
The reason that the RT of room 3357 is lower than the other two meeting rooms could be the partition panels installed as the west side wall, separating 3357 from the adjacent office. The partition panels has low absorption coefficients in the low-frequency bands, which are different from the usually installed whitewashed walls in CIRS (for details, see Figure 23).

**5.3.4. Noise isolation between spaces**

In this section, the performance of the partitions of the selected rooms in attenuating airborne noise is discussed. For office buildings, the NIC between an office/ a meeting room and its surrounding area should be no less than 35, in order to provide adequate sound isolation [25].

The NIC results were calculated from octave-band Noise Reduction (NR) data. The calculated NIC results are displayed in Appendix I. NIC results separated by groups are shown in Figure 24 (meeting rooms) and Figure 25 (private offices).
Figure 24 Noise isolation class between meeting rooms and their surroundings (case A-#: meeting room 2336; case B-#: meeting room 3336; case C-#: meeting room 3357)

Figure 25 Noise isolation class between private offices and their surroundings (case O-#: office 2352 and its surroundings; case D-#: office 3342, 3343, 3344 and the adjacent open-plan area 3352)

### Meeting rooms

NICs between meeting rooms and their surroundings were measured. During measurement, meeting room doors were locked. Except in cases A-2, A-3 and B-2, the NICs were lower than 35.

Cases A-1 and B-1: NIC 26 and 27 were measured between meeting rooms 2336/3336 and the public circulation area in front of the meeting room doors when the doors were closed. The doors were made of hardwood, installed within glazed
partition areas. Leaks existed around the door (see Figure 26). Moreover, the two return airflow inlets inside and outside of the meeting rooms are connected, providing a transmission path for noises (see Figure 27). In addition, the thin glazed partition could be one of the factors explaining the poor NIC, but additional efforts need to be made to prove this.

Cases A-2, A-3 and B-2: NICs of more than 35 were measured between meeting rooms 2336/ 3336 and the office areas (A-2: reception area 2331; A-3: office 2351; B-2: open-plan area 3352). Adequate NICs were provided between these spaces by multiple partitions.

Case C: Inadequate NICs were measured between meeting room 3357 and its surrounding areas. Case C-1 was between meeting room 3357 and its adjacent open-plan area 3347. Cases C-2, C-3 and C-4 were between meeting room 3357 and the further open-plan areas 3354, 3353 and 3352, where multiple partitions were installed between them. These inadequate NICs were caused by the sound propagation through the air gap over the glazed partition. The air gap in the heating exchanger area under the window sill can be one of the factors that caused the inadequate NIC between 3357 and the further open-plan areas 3354, 3353 and 3352, but its cross-sectional area is much less than the air gap over the glazed partition, so it is negligible.

Figure 26 A leak below the meeting room’s door
Figure 27 Return airflow inlets inside and outside of the meeting room are connected

Table 11 Verbal-communication quality associated with an SII value

<table>
<thead>
<tr>
<th>SII range</th>
<th>0.45&lt;SII&lt;0.75</th>
<th>SII&gt;0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI quality</td>
<td>‘acceptable’</td>
<td>‘good’</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SII range</th>
<th>SII&lt;0.1</th>
<th>0.1&lt;SII&lt;0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP quality</td>
<td>‘good’</td>
<td>‘acceptable’</td>
</tr>
</tbody>
</table>

Private offices

Cases O and D: Inadequate NICs were measured between private offices and their surroundings. This indicates that the noise isolation provided by the light-weight fabric walls and glazed partitions in CIRS were totally unsatisfactory. The air gap over glazed partition is one of the main reason behind the inadequate NIC.

5.3.5. Speech intelligibility

In meeting rooms, values of SII above 0.75 are recommended. An SII value between 0.45 and 0.75 indicates acceptable speech intelligibility, and below 0.45 is considered to be poor [26].

For open-plan offices, another recommendation indicates that values of AI=0.15 (equivalent to SII=0.20) have been suggested as a maximum value for achieving ‘acceptable’ or ‘normal’ speech privacy in open-plan offices [27].

The SII results were calculated by using a SII calculation spreadsheet developed by
Acoustics and Noise Research Group in UBC. The spreadsheet calculates a value for SII for a verbal-communication configuration involving a talker and a listener in a room with background noise and reverberation. The talker is assumed to be an average male/female adult, talking in a 'normal' voice, and facing the listener. The calculated SII results are displayed in Appendix J.

The verbal-communication quality associated with an SII value is given in Table 11 (SI = speech intelligibility [26]; SP = speech privacy [27]).

**Case 1**

In this case, the source (speaker/talker) is in meeting room 2336, while most of the receivers are located on the 2nd floor, and one receiver in 3336.

Case 1-1: The receiver is also in the meeting room. This case represents a regular meeting in 2336. ‘Good’ speech intelligibility is desired and was almost achieved in this case (SII=0.71). The main acoustic issue in this meeting room was its relatively high RT value due to the lack of sound absorptive materials.

Case 1-2 to 1-13: The receiver positions were distributed in spaces adjacent to meeting room 2336. In these cases, listeners were outside of meeting room 2336, so ‘acceptable’ or better speech privacy (SII<0.2) is required. However, case 1-2 (SII=0.43), 1-4 (SII=0.46) and 1-8 (SII=0.27) didn't achieve this goal. Case 1-2, represents possible overhearing outside the meeting room, or a potential distraction at the door to the occupants in the meeting room, when the meeting room’s door is open. Case 1-4 mainly represents potential distractions from the atrium. This could be due to the fact that there are few sound attenuating partitions between the atrium and meeting room 2336. Case 1-8 represents the poor attenuation between reception area 2331 and the meeting room. In these cases, closing the door is a very effective way to improve speech privacy. However, if the door is open, the distraction from the public circulation areas could be significant.

**Case 2**

In this case, the source is in a private office (2352), while the most of receiver positions are on the 2nd floor, and one receiver in 3352.

Case 2-1: In this case, the receiver is in the same office. This case represents a normal meeting in a private office, where ‘acceptable’ or better speech intelligibility is desired and well achieved (SII=0.80; ‘good’ SI).

Case 2-2 to 2-7: These cases can represent both communication between spaces, and desired SP within them. For example, in cases 2-2 and 2-3, on one hand,
‘acceptable’ SI could be required, due to the wish for communications between the corridor and a private office. On the other hand, ‘acceptable’ or better SP is also a common desire for a private office. In all these cases, SP couldn’t be guaranteed. This could be due to the sound transmission through natural ventilation openings above each door, and the heat exchanger gaps at the ends of private offices (there is a gap below the exterior window areas, with the heat exchanger installed inside, connecting private offices). Therefore, when the talker and the listener are located with only one partition or one corridor, the speech privacy is poor. When doors are open, ‘acceptable’ or ‘good’ SI can be easily achieved, so potential communication needs between adjacent spaces can be fulfilled.

Case 2-8 to 2-17: These cases are similar to cases 2-2 to 2-7, yet with a different desire for the acoustical conditions. In these cases, ‘acceptable’ or better SP is desired, since the talker and the listener are separated by several partitions. However, only cases 2-9 (SII=0.18, ‘acceptable’ SP), 2-11 (SII=0.14, ‘acceptable’ SP) and 2-15 (0.05, ‘good’ SP) met the requirement. In conclusion to these cases, when there are two or more partitions between these spaces, the ‘acceptable’ SP can be achieved. When there is only one partition between the spaces, speech privacy would be poor.

Case 2-18 (SII=0.00): This case indicates that there is negligible sound transmission between two adjacent floors.

Case 3

This case is similar to case 1. The source is in meeting room 3336. Receivers are mainly on the 3rd floor. One receiver is in the atrium on the 1st floor.

Cases 3-1 to 3-3: similar to cases 1-1 to 1-3.

Cases 3-4 & 3-7: These cases indicate that neither noise transmitted from the 1st floor in the atrium nor from the adjacent office wing can affect the speech privacy of meeting room 3336.

Case 4

In this case, the source is in the meeting room at the east end of the south office wing. This case reveals the acoustical conditions in the office area of the south wing of 3rd floor, when there is a meeting going on in meeting room 3357.

Case 4-1: This case is similar to 1-1.

Cases 4-2 to 4-7: In these cases, mainly speech privacy is needed. However, only case 4-7 (SII=0.20) met the higher end of the SII range for ‘acceptable’ SP. This indicates that having only one partition between spaces can’t guarantee speech
privacy.

**Case 5**

The source in case 5 is located at one workstation in the open-plan area 3352. In part, this case could be regarded as the reverse situation of case 4. However, this case is more common, since the open-plan areas 3352, 3353, and 3354 are more frequently used by CIRS staff than the meeting room 3357.

Cases 5-1 to 5-3: In these cases, ‘acceptable’ or ‘good’ SI is desired, and case 5-1 achieved ‘good’ SI, while the rest met ‘acceptable’ SI, which indicates that there is little problem in communication within open-plan areas 3352 to 3354.

Cases 5-4 to 5-11: In these cases, both ‘acceptable’ SI and ‘acceptable’ SP could be needed in some circumstances. For communication, the results showed that only case 5-10 (receiver in room 3344, SII=0.21) and 5-11 (receiver in room 3344, SII=0.18) do not meet the SI requirement. The reasons behind the fact that SII in room 3344 is much lower than in adjacent offices 3342 and 3343 could be the long sound propagation distance, and the fabric partition between talker and listener. On the other hand, for speech privacy, only case 5-11 met the requirement, which indicates that the speech privacy between the open-plan areas and the adjacent private offices, or the reception area, is poor. This could be due to the lack of acoustical treatments, and sound attenuating partitions.

Cases 5-12 to 5-14: These cases suggest that occupant activities within the open-plan areas hardly influence occupants at the east end of this office wing. The reason behind this could be that the sound propagation distance is long enough to attenuate the noise, and there is no direct path for sound transmission.

**Case of BSS lab (open-plan area 2131)**

This case has been discussed in a recent publication [29]; there exists no good speech privacy between workstations in the open-plan area 2131. Low background-noise level and lack of acoustical treatments contribute to the high SII (SII varies from 0.72 at closer distances to 0.58 at longer distances) within this space.

**5.4. Thermal Conditions**

ASHRAE Standard-55 defines a comfort ‘zone’ based on temperature and relative humidity, where the majority of occupants are likely to feel comfortable [5].

The ambient temperature (operative temperature) and relative humidity monitoring
results were organized and drawn on the psychrometric chart (Figure 28). The data was compared to the recommended comfort zone.

Since there was no specific concept of winter or summer in CIRS in controlling the thermal comfort, the HVAC system were controlled according to the outdoor temperature. The cases are discussed according to the outdoor temperature measured on that day. Connections between cases are discussed later. For case 2156, the indoor temperature set-point was 21°C, and the measurement was done when the outdoor temperature was approximately 7°C. It should be discussed as winter conditions. According to the measurement results, the ambient temperature of office 2156 was relatively low in the winter comfort zone, with its relative humidity around 40%. Its thermal conditions achieved the comfort zone for approximately 88% of the monitoring time.

![Psychrometric Chart](image)

**Figure 28 Thermal conditions of monitored spaces on psychrometric chart**
For the rest of the offices, the outdoor temperature was approximately 15°C during the monitoring period. These cases were discussed as summer conditions according to the weather history of Vancouver. For the offices on the 2nd floor, the indoor temperature was relatively low in the summer comfort zone. During the monitoring periods, the approximate percentages of time when the thermal conditions were not in the comfort zone for offices were: 17% for office 2344, 50% for office 2352, and 67% for office 2354. These offices all started at a low ambient temperature in the morning, and the water heat exchangers were all tuned to 100% to increase the indoor temperature throughout the monitoring day. For the offices on the 3rd floor, the temperature was relatively high in the comfort zone. During the monitoring periods, all measurement points were in the comfort zone. The thermal conditions of office 3342 and office 3344 were completely satisfactory.

The last part of investigation of thermal conditions in CIRS was for meeting rooms. The measurement was done when the outdoor temperature was approximately 11°C, which could be regarded as winter or interchange season. Due to the fact that the relative humidity of these meeting rooms were around 23%, which was too low, the thermal conditions of these meeting rooms were in the comfort zone for less than 50% of the time. This was due to fact that, during the monitoring period of the meeting rooms, the occupancy densities were low, and there were no humidification.

5.5. Lighting

Lighting conditions were evaluated by measuring horizontal illumination, which is the density of luminous flux falling onto a horizontal surface, measured in footcandles (FC - lumens per square foot). Measurement locations were visual task planes, such as the surface of tables, which were chosen with consideration of inner design and the furniture layout of the spaces. According to the IESNA Lighting Handbook [6], for an educational office building like CIRS, the recommended illuminances should be more than 30 FC, with an appropriate average being 50 FC; the maximum acceptable illumination is 70 FC.

5.5.1. Offices

The main task surfaces in offices are tables. In each private office, an L-shaped table was installed, with one end placed at the center, right under the mechanical luminance, and with another end near the exterior windows. The end at the center is normally the primary task surface. Each artificial luminance in the offices was controlled by a movement sensor, and was turned on during the measurements. All measurements were made during cloudy days, with a solar radiation level of around 200~300 W/m² in mornings and around 400~600 W/m² in afternoons (obtained from
the UBC weather station). There is a non-lighttight blind in each office, and the status of the blind during measurements was determined by the occupants. In each office, lighting conditions at two positions were investigated – table surface 1 near exterior windows, and table surface 2 in front of computers.

According to Figure 29, it can be observed that the status of the blind can affect the relationship between the illuminances of position 1 and position 2. When the blind covered 100% of the window area, the illuminances of the table surfaces near exterior windows was lower than those of table surfaces at the center, since the major lighting sources in offices in this circumstance were the mechanical luminance at the center. When the blind was not covering all of the window, the illuminances near windows were higher than at the center.

For cases in the north wing office room 2156, its lighting conditions during the measurement day were not very satisfactory. The illuminance levels were a little above the minimum requirement of 30 FC at primary task position 2 in the center, and mostly below 30 FC at task position 1. The lighting conditions in this room were only acceptable when both natural lighting and artificial lighting were used.

For south wing offices, with windows oriented towards the north, the lighting conditions of the primary task surfaces (position 2) were mostly acceptable in mornings, and unacceptable in afternoons. In morning measurements, outdoor solar radiations were lower than those of afternoon measurements; 3 out of 4 measured illuminances were in the range of 30-70 FC, with a combination of natural and artificial lighting. In afternoon measurements, when the solar radiations were high, both measurements were higher than 70 FC. In the case of room 3344-afternoon measurement, the indoor illuminances were much higher than the maximum recommended 70 FC.

For south wing offices with windows facing south (facing Stores Rd.), the indoor measured illumination levels were clearly higher than in the rest of CIRS, and 100% of the measured illuminances exceeded the maximum recommended level of 70 FC. This could be due to the fact that offices on the south sides were affected by both direct and indirect solar radiation, while direct solar radiation was mostly blocked by the building in offices on the north sides (south wing) and offices in the north wing. A recommendation could be made that the blinds in these offices be closed (covering 100% of the window areas) to achieve acceptable indoor lighting condition.

According to the design criteria for office areas of CIRS, which were described in Section 3.2, it was designed for 19 FC for private offices, and all the measured illuminations exceeded this criterion. However, this fairly low level of designed illuminance can explain the relatively poor lighting condition of office 2156.
Figure 29 Illuminances measured in offices: the yellow band shows the recommended range.

The effect of blinds on indoor illumination were not considered in this study, due to its complexity and the limit of efforts. The status of blinds during measurements was set according to occupants’ descriptions of their regular habits.

Figure 30 Illuminances measured in meeting rooms: the yellow band shows the recommended range.
5.5.2. Meeting rooms

The main task surfaces for meeting rooms are in two sections – the mid-table surface, and the cabinet surface. The illuminances of both surfaces were measured in both morning and afternoon for each meeting room. As stated in Chapter 4, the table surface was divided into three sections – the two ends and the middle part.

Before the measurements, it was learned that complaints have been made about the extremely strong illuminance in meeting rooms during sunny days. Therefore this study focused on the lighting comfort of meeting rooms on sunny days. During the measurement day, the weather was sunny, and the solar radiation obtained from the UBC weather station was 736 W/m² in the morning, and 805 W/m² in the afternoon.

For meeting rooms 2336 and 3336, there are two layers of blinds installed, and one of them is light-proof. During the measurement, due to the strong solar radiation outdoors, the light-proof blind was always half way down (covering 50% of the window area), and the non-lighttight blind was covering approximately 75% of the window areas in the morning for all meeting rooms, including 3357, and 100% in the afternoon for rooms 2336 and 3336. There is a non-lighttight blind and no light-proof blind in room 3357. Mechanical luminances in meeting rooms were turned off on sunny days according to the normal occupancy activity record.

According to the measurement results, a clear conclusion can be made that the illuminances were higher in the morning than in the afternoon. This is because windows in the meeting rooms were facing northeast, and the rooms are affected by direct sunlight more strongly in the morning than in the afternoon. From the measurement results, it could be observed that 35.7% of measurements were within the recommended comfort zone of 30-70 FC, and approximately 53.6% of measurements exceeded the maximum recommended illuminance of 70 FC. It was clearly observed that sills, walls and tables were overly exposed to direct sunlight, even when a fairly large percentage (75% or 100%) of the window areas were covered by blinds. This fact not only caused extremely high values of illuminance, but also caused an unevenly distributed indoor illuminance. In room 3357, the illuminance of table position 3 was approximately half those of positions 1 and 2.

The measured indoor illuminations that were visually comfortable were the ones measured in the afternoon in room 3336 with 100% of the window areas covered by the non-lighttight blind, and in late afternoon in room 3357 (case 3357 afternoon-2 in Figure 30).

Since tables are at the centres of the meeting rooms, and cabinets are in the corners farthest from the windows, the illuminances of the tables are higher than those of the cabinets.
Chapter 6. Conclusion

In this study, the indoor environmental quality of the Centre for Interactive Research on Sustainability (CIRS), which has been awarded LEED Platinum certification, was investigated, to see whether it achieves relevant acceptability criteria and its design goals. Ventilation, indoor air quality, acoustic and thermal conditions, and lighting were considered. Furthermore, several CIRS design features and operation details have been identified and discussed as the factors that influenced the IEQ results potentially, when they were found to be unacceptable.

6.1. Study Conclusions and Recommendations

All measurement results and subsequent calculations were organized and analyzed, grouped by related aspects of IEQ. The ventilation conditions in CIRS was estimated by CO$_2$ monitoring data; IAQ conditions were investigated by analyzing three air quality parameters – UPC, VOC and CO$_2$ concentrations; acoustic conditions were characterized by measuring BNLs, RTs, NICs, and SIIs; thermal conditions were determined by comparing indoor ambient temperature and relative humidity with comfort zones developed by ASHRAE; and lighting conditions were analyzed by indoor illuminance measurements. The measurement results were compared to relevant acceptability criteria, and the reasons behind the IEQ performance of CIRS were discussed by considering related building features, such as furnishings and occupancy records.

100% of the selected spaces of CIRS were found to have adequate air change rates, according to the estimated results. For offices, when the mechanical ventilation system was ON, and natural ventilation by exterior windows was OFF, air change rates in private offices varied from 2.28 ACH to 7.71 ACH accordingly, with effects of door status and weather issues. When the mechanical system was ON and exterior windows were open, it varied from 3.14 ACH to 5.35 ACH accordingly, also with effects of door status and weather issues. When mechanical ventilation was OFF and exterior windows were closed, it was 1.06 ACH for a private office. It was concluded, that in the offices, opening the door or the exterior window can improve the air change rate effectively. For meeting rooms, ventilation was also sufficient; when a window or the door was opened to increase natural ventilation, the space can be easily overly-ventilated, due to a potential cross-ventilation, since the doors of meeting rooms are directly facing the atrium.

IAQ was found not to be completely satisfactory in CIRS according to measurements of several air quality parameters. All indoor ultrafine particle concentrations were
higher than 20% of outdoor values due to some of the insufficient ventilation rates, which were unacceptable. However, it was concluded that the operating of CIRS's hybrid ventilation systems can efficiently reduce the indoor UFP concentration, but can't manage to reduce 80% of the ambient UFP concentration.

In some spaces, the VOC levels exceeded the required maximum 300 ppb. Several building features and operation details were possible reasons behind unacceptably high VOC levels, such as a high density of furniture, furnishing materials that generate VOCs, and occupancy activities. The highest VOC levels were found in the IEQ lab on the second floor in the north wing of CIRS, where many sound absorptive porous materials are located for experiment purposes. Furthermore, this space had a relative high furniture density. It was also found that the activity of opening a window could lead to unacceptable high VOC concentrations in spaces, and mechanical ventilation would reduce the VOC concentration efficiently after windows have been closed. In meeting rooms with whitewashed ceilings instead of wood panels and acoustic panels, and with whitewashed walls instead of offices' fabric walls, the VOC levels were very low and acceptable.

The CO₂ concentrations were mostly acceptable, due to the low occupancy density in CIRS. Even with insufficient air change rates, only in one case did measured CO₂ levels exceed the recommended 1000 ppm; the reason behind this high level could be the relatively high occupancy density. Though there are hardly any CO₂ issues in CIRS so far, it is still of concern that the indoor CO₂ concentration could be much higher when CIRS is fully occupied at some time, and there are no CO₂ control strategies in the mechanical ventilation systems in CIRS, since CO₂ sensors in the building only serve for monitoring purposes.

The background noise levels of the acoustic conditions were measured in 11 private offices, 4 open-plan office areas, 3 meeting rooms and 9 public circulation areas, and were compared not only to criteria, but with each other as well. The BNLS of 27.2% of private offices, 25% of open-plan office areas, 50% of meeting room measurements, and 22.2% of public circulation areas exceeded recommended maximum Noise Criterion values. Several issues determined the BNLS of the spaces – potential crowd noises in the atrium or the auditorium, and the locations of spaces in CIRS with respect to the indoor noise sources, such as the mechanical ventilation below floating floors, the return air inlets and the exhaust air ventilation in the washrooms. Because of these sources, the BNLS of spaces near the atrium, such as the entrance area of office wings and the reception areas, were relatively high.

Reverberation times of several selected spaces were slightly over the recommended 0.6 s for offices and meeting rooms in CIRS. In meeting rooms with whitewashed ceiling and walls, instead of acoustic panels under a wooden ceiling and fabric walls,
the only sound absorptive material was carpets, which has low absorption coefficients in the high-frequency bands. The RTs were as high as 0.8 s. However, since these spaces were used as meeting rooms and unoccupied during measurement, these RTs could be acceptable when the spaces are occupied. A private office and an open-plan office area selected as typical spaces had satisfactory RTs.

Noise isolation was found unsatisfactory in CIRS. Calculated NICs between meeting rooms and the front door areas outside were unacceptable, due to the leaks around the doors and the connections between the two return airflow inlets inside and outside the meeting rooms. For private offices, 100% of the calculated NICs were inadequate, because of sound propagation through the air gap over the glazed partition. The low sound attenuation provided by the light-weight fabric barriers and the glazed partitions was also one of the main reasons behind this inadequate NIC.

Speech intelligibility index was estimated and analyzed in spaces. Within meeting rooms 2336, ‘acceptable’ or better speech intelligibility was desired and well met. The reason why SII values within meeting rooms were slightly lower than 0.75, resulting in ‘good’ speech intelligibility (SI) could be the lack of sound absorptive materials and high RT. Between meeting rooms and adjacent spaces, ‘acceptable’ or better speech privacy (SP) was desired. However, when a meeting room’s door was open, distractions or overhearing outside in the public circulation areas could occur and SP would be unacceptable. Even a casual conversation in the reception section of the office area, or a noise on the same floor in the atrium, could cause a distraction to occupants in meeting rooms. These problems could be solved by simply closing the door. For communications within a private office, or between an adjacent corridor area and a private office, ‘acceptable’ or better SI was desired and well met when the door was open. However, closing the door for a private office didn't provide ‘acceptable’ SP from adjacent spaces, including the private office next door. This could be due to the fact that sound could transmit easily through the openings above each door in the office areas. A similar lack of speech privacy also exists in meeting room 3357. SII levels in open-plan office areas indicate that there exist few problems of communication between workstations, but no speech privacy can be guaranteed due to the insufficiency of acoustic materials and partitions.

For thermal conditions, the ambient temperature (operative temperature) and relative humidity monitoring results were organized and drawn on the psychrometric chart. The data was compared to the recommended comfort zone. According to measurement data, there were some thermal issues in CIRS. The temperatures of offices normally started at a fairly low value in the morning. This was due to temperature drops in the night. The relative humidity of meeting rooms was very low, which caused the thermal conditions in the meeting rooms to be within the comfort zone for less than 50% of the time. This could be due to the low occupancy density in
The last part of this study was the investigation of lighting conditions. The lighting conditions were one of the worst IEQ aspects in CIRS. The measured illuminances varied from 17 FC to 214 FC in offices, and from 20 FC to 222 FC in meeting rooms. Illuminances were affected by location of spaces, window orientations, blind status, and outdoor solar radiation levels. Illuminances measured in the office area in the north wing, where direct solar radiation was mainly blocked, were around the lower end of the required 30 FC. Illuminances measured in the offices in the south wing with exterior windows facing south were always much higher than the recommended maximum value of 70 FC, which was highly affected by the direct sunlight. This indicates that the blinds of the north wing offices should always be open; those of south wing offices with windows facing south should always be closed when the outdoor solar radiation is high. For meeting rooms, more than 50% of measured illuminances were above the recommended maximum value of 70 FC. This indicates that meeting rooms were mostly overly exposed to solar radiation, and blinds should cover a larger proportion of the window areas.

6.2. Suggestions for Future Work

In this study, all aspects of IEQ were investigated. However, this study lacks statistical significance due to the limited amount of physical measurements. Only a relatively small set of ventilation conditions in CIRS were investigated. In order to study the ventilation conditions of CIRS more comprehensively, various ranges of factors need to be considered: outdoor wind velocity and direction; cases of both top and bottom windows in office wings being controlled, in cooperation with controlling interior doors, etc. Furthermore, an analysis of the air distribution is also important.

For IAQ aspects, further measurements of UFP concentration are needed to quantify the relationship between indoor air quality and air change rate. Also, measurements should be done when CIRS is fully occupied.

For acoustic conditions, further analysis should be done after the room furniture density and occupancy density have been quantified.

To investigate thermal conditions thoroughly, radiant temperature is also an important factor to measure. Moreover, the thermal conditions should be monitored throughout a whole typical year.

For lighting, obviously the high levels of illuminances caused over-exposure and glare issues in CIRS, and the uniformity of lighting conditions in spaces are also an interesting topic of future work.
Bibliography


Appendices

Appendix A: Reference Tables & Figures

![Graph showing Sound Pressure Level (dB) vs Frequency (Hz) for NC-15 to NC-65]
Appendix B: HVAC Details

Figure 31 Details of the air handling unit for office wings in CIRS
Figure 32 Heating exchanger sensors and indoor thermal condition monitors display of the 2nd floor in the south wing
Figure 33 Heating exchanger sensors and indoor thermal condition monitors display of the 3rd floor in the south wing
Appendix C: Measurement Instruments

Figure 34 Omni-directional loudspeaker (left); Human-simulated loudspeaker SSARAH (middle); Rion NA-28 sound level meter (right)

Figure 35 TSI Q-Trak (left); TSI P-Trak 8525 (middle); ppbRAE VOC model PGM-7240 (right)

Figure 36 UEi DLM2 Digital Light Meter
Appendix D: Building Floor Plans

Figure 37 Floor plan of the 2nd floor of CIRS
Figure 38 Floor plan of 3\textsuperscript{rd} floor of CIRS
Appendix E: CO$_2$ Monitoring Results

CO$_2$ concentration in office 2156

CO$_2$ of office 2344

CO$_2$ of office 2345
CO2 of office 2352

CO2 of office 2354

CO2 of office 3342
CO2 of meeting room 3357

ppm

0 200 400 600 800 1000
10:00 11:00 12:00 13:00 14:00 15:00 16:00
### Appendix F: Ventilation Results

Table 12 Air change rates for the selected offices during monitoring period

<table>
<thead>
<tr>
<th>Room #</th>
<th>Window status</th>
<th>Door status</th>
<th>Mech. Vent.</th>
<th>Diffuser amount</th>
<th>Natural ventilation by window</th>
<th>Natural ventilation by door</th>
<th>Total ventilation rates (ACH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2156</td>
<td>Closed</td>
<td>Open</td>
<td>✓</td>
<td>1</td>
<td>X</td>
<td>✓</td>
<td>4.09</td>
</tr>
<tr>
<td>2344</td>
<td>Closed</td>
<td>Open</td>
<td>✓</td>
<td>1</td>
<td>X</td>
<td>✓</td>
<td>5.83</td>
</tr>
<tr>
<td>2345</td>
<td>Closed</td>
<td>Closed</td>
<td>✓</td>
<td>1</td>
<td>X</td>
<td>X</td>
<td>2.28</td>
</tr>
<tr>
<td>2352</td>
<td>Slightly open</td>
<td>Closed</td>
<td>✓</td>
<td>1</td>
<td>✓</td>
<td>X</td>
<td>3.14</td>
</tr>
<tr>
<td>2352</td>
<td>Slightly open</td>
<td>Open</td>
<td>✓</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>5.35</td>
</tr>
<tr>
<td>2352</td>
<td>Slightly open</td>
<td>Open</td>
<td>X</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>4.45</td>
</tr>
<tr>
<td>2354</td>
<td>Closed</td>
<td>Open</td>
<td>✓</td>
<td>1</td>
<td>X</td>
<td>✓</td>
<td>7.71</td>
</tr>
<tr>
<td>2354</td>
<td>Closed</td>
<td>Closed</td>
<td>✓</td>
<td>1</td>
<td>X</td>
<td>X</td>
<td>5.24</td>
</tr>
<tr>
<td>3342</td>
<td>Closed</td>
<td>Open</td>
<td>X</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>1.06</td>
</tr>
<tr>
<td>3344</td>
<td>Open</td>
<td>Open</td>
<td>✓</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>4.88</td>
</tr>
<tr>
<td>3344</td>
<td>Open</td>
<td>Open</td>
<td>X</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>3.98</td>
</tr>
</tbody>
</table>

Note: ventilation for offices also includes air infiltration and ventilation through the openings above the door frames.
Table 13 Air change rates for the selected meeting rooms during monitoring period

<table>
<thead>
<tr>
<th>Room #</th>
<th>Window status</th>
<th>Door status</th>
<th>Mech. Vent.</th>
<th>diffuser amount</th>
<th>Natural ventilation by window</th>
<th>Natural ventilation by door</th>
<th>By opening above door</th>
<th>Total ventilation rates (ACH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2336</td>
<td>Closed</td>
<td>Closed</td>
<td>✓</td>
<td>2</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>7.30</td>
</tr>
<tr>
<td>3336</td>
<td>Closed</td>
<td>Closed</td>
<td>✓</td>
<td>2</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>6.14</td>
</tr>
<tr>
<td>3336</td>
<td>Closed</td>
<td>Open</td>
<td>✓</td>
<td>2</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>17.90</td>
</tr>
<tr>
<td>3357</td>
<td>Closed</td>
<td>Closed</td>
<td>✓</td>
<td>2</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>4.48</td>
</tr>
<tr>
<td>3357</td>
<td>Open</td>
<td>Closed</td>
<td>✓</td>
<td>2</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
<td>10.12</td>
</tr>
</tbody>
</table>

Note: ventilation for meeting rooms also include air infiltration.
Appendix G: Ultrafine Particles Measurement Summary

Ultra-fine particulate matter (UPC) Rm 2156

- Outdoor
- Indoor
- Average indoor
- 20% outdoor

Ultra-fine particulate matter (UPC) Rm 2344

- Outdoor
- Indoor
- Average indoor
- 20% outdoor
Ultra-fine particulate matter (UPC) Rm 2352

Ultra-fine particulate matter (UPC) Rm 2354

Ultra-fine particulate matter (UPC) Rm 3344
Ultra-fine particulate matter (UPC) Rm 3342

- **Outdoor**
- **Indoor**
- **Average indoor**
- **20% outdoor**

Ultra-fine particulate matter (UPC) Rm 3351

- **Outdoor**
- **Indoor**
- **Average indoor**
- **20% outdoor**
Appendix H: VOC Measurement Results

VOCs in office 2156

VOCs in office 2344
## Appendix I: Noise Isolation Calculation Results

<table>
<thead>
<tr>
<th>Source</th>
<th>Cases #</th>
<th>Noise Reduction in Octave Bands (dB)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>125 Hz</td>
<td>250 Hz</td>
<td>500 Hz</td>
<td>1000 Hz</td>
<td>2000 Hz</td>
<td>4000 Hz</td>
<td>NIC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meeting room 2336</td>
<td>A-1</td>
<td>19.3</td>
<td>20.3</td>
<td>25.9</td>
<td>26</td>
<td>26.9</td>
<td>26.7</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A-2</td>
<td>33.6</td>
<td>32.2</td>
<td>35.6</td>
<td>37.4</td>
<td>40.3</td>
<td>39.6</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A-3</td>
<td>27.9</td>
<td>31.5</td>
<td>38.5</td>
<td>41.7</td>
<td>42</td>
<td>43.7</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A-4</td>
<td>32.4</td>
<td>37.9</td>
<td>46</td>
<td>50</td>
<td>55.6</td>
<td>53</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meeting room 3336</td>
<td>B-1</td>
<td>18.7</td>
<td>22.8</td>
<td>26.3</td>
<td>27.5</td>
<td>28</td>
<td>27.7</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B-2</td>
<td>35.1</td>
<td>45.2</td>
<td>48.8</td>
<td>50.3</td>
<td>49.8</td>
<td>49.7</td>
<td>49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meeting room 3357</td>
<td>C-1</td>
<td>7.9</td>
<td>15</td>
<td>14.9</td>
<td>12.6</td>
<td>14.1</td>
<td>13.1</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C-2</td>
<td>26.5</td>
<td>27.7</td>
<td>29.8</td>
<td>30.7</td>
<td>31.7</td>
<td>32.1</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C-3</td>
<td>25.1</td>
<td>29</td>
<td>31.4</td>
<td>31.3</td>
<td>34.5</td>
<td>35</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C-4</td>
<td>28.6</td>
<td>31.5</td>
<td>30.7</td>
<td>33.8</td>
<td>35.2</td>
<td>35.4</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office 2352</td>
<td>O-1</td>
<td>12.5</td>
<td>14.9</td>
<td>14</td>
<td>10.8</td>
<td>14.6</td>
<td>13</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-2</td>
<td>12.5</td>
<td>15.5</td>
<td>17.8</td>
<td>18</td>
<td>20</td>
<td>21.2</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-3</td>
<td>11.8</td>
<td>17.8</td>
<td>22.6</td>
<td>22.8</td>
<td>25.7</td>
<td>26.1</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-4</td>
<td>19.3</td>
<td>25.5</td>
<td>28.9</td>
<td>25.5</td>
<td>31</td>
<td>32.7</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-5</td>
<td>23.1</td>
<td>30.9</td>
<td>29.5</td>
<td>28.6</td>
<td>34.9</td>
<td>36</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-6</td>
<td>18.5</td>
<td>18.4</td>
<td>22.2</td>
<td>18</td>
<td>22.3</td>
<td>22.5</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-7</td>
<td>26.1</td>
<td>28.9</td>
<td>32.5</td>
<td>31.6</td>
<td>34.8</td>
<td>36.3</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-8</td>
<td>20.9</td>
<td>24.2</td>
<td>25.6</td>
<td>23.8</td>
<td>28.7</td>
<td>29.2</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O-9</td>
<td>36.9</td>
<td>43.7</td>
<td>51.9</td>
<td>52.5</td>
<td>61.1</td>
<td>58.9</td>
<td>53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open-plan area 3352</td>
<td>D-1</td>
<td>6.1</td>
<td>13.4</td>
<td>12.2</td>
<td>11.7</td>
<td>13</td>
<td>9.1</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D-2</td>
<td>7.9</td>
<td>12</td>
<td>14.9</td>
<td>13.3</td>
<td>15.9</td>
<td>14.9</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D-3</td>
<td>15.4</td>
<td>15</td>
<td>19.9</td>
<td>18.1</td>
<td>20.2</td>
<td>19.9</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Appendix J: Speech Intelligibility Index Calculation Results

**Table 14 Speech Intelligibility Index results and detailed descriptions**

<table>
<thead>
<tr>
<th>Source room</th>
<th>Case</th>
<th>Receiver room</th>
<th>Door(s) status</th>
<th>SII</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (2336)</td>
<td>1-1</td>
<td>2336</td>
<td>Door of 2336 closed</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-2</td>
<td>2330</td>
<td>Door of 2336 open</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-3</td>
<td></td>
<td>Door of 2336 closed</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-4</td>
<td>Atrium 2F</td>
<td>Door of 2336 open</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-5</td>
<td></td>
<td>Door of 2336 closed</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-6</td>
<td>Atrium 1F</td>
<td>Door of 2336 open</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-7</td>
<td></td>
<td>Door of 2336 closed</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-8</td>
<td>2331</td>
<td>Door of 2336 open, office wing front door open</td>
<td>0.27</td>
<td>Note: during measurements, the front door of office wing is always open.</td>
</tr>
<tr>
<td></td>
<td>1-9</td>
<td></td>
<td>Door of 2336 closed, office wing front door open</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-10</td>
<td>2351</td>
<td>Door of 2336 open, door of 2351 closed</td>
<td>0.01</td>
<td>Note: private office door (2351) tends to be closed for speech privacy.</td>
</tr>
<tr>
<td></td>
<td>1-11</td>
<td></td>
<td>Door of 2336 closed, door of 2351 closed</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-12</td>
<td>3336</td>
<td>Meeting rooms door open.</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-13</td>
<td></td>
<td>Meeting rooms door closed.</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>2 (2352)</td>
<td>2-1</td>
<td>2352</td>
<td>Door of 2352 closed.</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-2</td>
<td>corridor mid-point between 2343 and 2352</td>
<td>Door of 2352 open.</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td></td>
<td>Door of 2352 closed.</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>Source room</td>
<td>Case</td>
<td>Receiver room</td>
<td>Door(s) status</td>
<td>SII</td>
<td>Notes</td>
</tr>
<tr>
<td>------------</td>
<td>--------</td>
<td>---------------</td>
<td>------------------------------------------</td>
<td>------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2-4</td>
<td>2342</td>
<td>Both doors of 2352 and 2342 open.</td>
<td>0.52</td>
<td></td>
<td>Note: In this case, only doors status of ‘both open’ and ‘both closed’ were calculated, since only the best and worst SP were considered.</td>
</tr>
<tr>
<td>2-5</td>
<td></td>
<td>Both doors of 2352 and 2342 closed.</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-6</td>
<td>2353</td>
<td>Both doors of 2352 and 2353 open.</td>
<td>0.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-7</td>
<td></td>
<td>Both doors of 2352 and 2353 closed.</td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-8</td>
<td>2354</td>
<td>Both doors of 2352 and 2354 open.</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-9</td>
<td></td>
<td>Both doors of 2352 and 2354 closed.</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-10</td>
<td>2344</td>
<td>Both doors of 2352 and 2344 open.</td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-11</td>
<td></td>
<td>Both doors of 2352 and 2344 closed.</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-12</td>
<td>corridor mid-point between 2345 and 2354</td>
<td>Door of 2352 open.</td>
<td>0.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-13</td>
<td></td>
<td>Door of 2352 closed.</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-14</td>
<td>2345</td>
<td>Both doors of 2352 and 2345 open.</td>
<td>0.26</td>
<td></td>
<td>Note: In this case, only doors status of ‘both open’ and ‘both closed’ were calculated, since only the best and worst SP were considered.</td>
</tr>
<tr>
<td>2-15</td>
<td></td>
<td>Both doors of 2352 and 2345 closed.</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-16</td>
<td>corridor mid-point between 2347 and 2356</td>
<td>Door of 2352 open.</td>
<td>0.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-17</td>
<td></td>
<td>Door of 2352 closed.</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-18</td>
<td>3352</td>
<td>All door open</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 (3336)</td>
<td>3-1</td>
<td>Door of 3336 closed.</td>
<td>0.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-2</td>
<td>3330</td>
<td>Door of 3336 open.</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td></td>
<td>Door of 3336 closed.</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>Atrium 1F</td>
<td>Door of 3336 open.</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-5</td>
<td></td>
<td>Door of 3336 closed.</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-6</td>
<td>3352</td>
<td>Door of 3336 open.</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source room</td>
<td>Case</td>
<td>Receiver room</td>
<td>Door(s) status</td>
<td>SII</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------</td>
<td>------</td>
<td>---------------</td>
<td>----------------</td>
<td>-----</td>
<td>-------</td>
</tr>
<tr>
<td>3-7</td>
<td></td>
<td></td>
<td>Door of 3336 closed.</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>4 (3357)</td>
<td>4-1</td>
<td>3357</td>
<td>Door of 3357 closed.</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4-2</td>
<td>3347</td>
<td>Door of 3357 open.</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4-3</td>
<td></td>
<td>Door of 3357 closed.</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4-4</td>
<td>3354</td>
<td>Door of 3357 open.</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4-5</td>
<td></td>
<td>Door of 3357 closed.</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>3352</td>
<td>Door of 3357 open.</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4-7</td>
<td></td>
<td>Door of 3357 closed.</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>5 (open-plan 3F)</td>
<td>5-1</td>
<td>3352</td>
<td></td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-2</td>
<td>3353</td>
<td></td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-3</td>
<td>3354</td>
<td></td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-4</td>
<td>entrance inside 3F office area</td>
<td></td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-5</td>
<td>reception 3F</td>
<td></td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-6</td>
<td>3342</td>
<td>Door of 3342 open.</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-7</td>
<td></td>
<td>Door of 3342 closed.</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-8</td>
<td>3343</td>
<td>Door of 3343 open.</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-9</td>
<td></td>
<td>Door of 3343 closed.</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>3344</td>
<td>Door of 3344 open.</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-11</td>
<td></td>
<td>Door of 3344 closed.</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-12</td>
<td>3357</td>
<td>Door of 3357 open.</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-13</td>
<td></td>
<td>Door of 3357 closed.</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-14</td>
<td>3347</td>
<td></td>
<td>0.17</td>
<td></td>
</tr>
</tbody>
</table>