THERMAL AND HYGROTHERMAL ANALYSIS IN BUILDING ENVELOPE COMMISSIONING

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ABSTRACT

As the focus of new building construction shifts towards sustainability with emphasis on energy efficient design, more importance is placed on performance of the building envelope. Ensuring the envelope performs up to specifications is, at least in part, the purview of whole building commissioning. Government developments in Canada and the United States have been commissioning the building envelope for many years. Commissioning is becoming more common in the commercial sector, as developers require more specific project targets, either to meet enhanced building code requirements or earn LEED certification.

However, no amount of physical testing or field observation can compensate for an envelope who's design was flawed from the outset. It is therefore important for building scientists to support a project's design with quantitative data, prior to construction commencing. Computer simulation programs aid in this respect, giving building scientists the ability to model simulations that would be difficult to calculate otherwise. Simulations provide the ability to quickly verify a design's expected performance, highlight problem areas for revision by the principal designers, or predict potential long term problems in novel, un-tried assemblies.

This paper focuses on several case studies where thermal analysis and hygrothermal simulation software aided in the evaluation and adjustment of several building envelope designs. The software aided the commissioning process in several ways:

- 1. They helped determine whether or not an assembly would function as required by project targets.
- 2. They pin-pointed potential or unforeseen problems of new design concepts.
- 3. They provided clear graphical outputs that could be easily related to the client.
- 4. They quickly assessed the effect of a minor change to an assembly.

The push towards green building design marks an important step in the building science industry. Being able to verify the quality of the building envelope design is equally important. Many programs exist that can model a building assembly's performance. The software can be used to verify a traditional method or test a new design concept. The results offer an effective way to certify a building envelope's performance and help clients reach their project targets.

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1.0 INTRODUCTION

As our societies become increasingly aware of the impact of buildings on energy use and resource consumption, more and more focus will be placed on sustainability in the built environment. The emergence of building assessment and rating systems such as LEED, BREEAM, Green Globes, and others reflects our increasing awareness of sustainability issues within the construction sector. All of these assessment and rating systems reflect the key role Whole Building Commissioning plays in achieving sustainable buildings. It is not only industry that has taken up the call of sustainable development, but governments as well. European and North American jurisdictions have implemented voluntary, and in some cases mandatory resource conservation enactments. Many Canadian and US government agencies require buildings built directly for them, funded by them, or leased on their behalf have some form of environmental or sustainable rating.

The importance of Commissioning in sustainable development practices cannot be understated - for both LEED and BREEAM, building commissioning is a pre-requisite. Under the traditional understanding of commissioning the process is one where mechanical and electrical systems were tested, balance and adjusted to conform to a required project specification or performance standard prior to acceptance of the building by the owner. It was understood by many as simply a third party inspecting the operation of the HVAC system.

This understanding is being redefined to what is being referred to as Total or Whole Building Commissioning. Current commissioning practices have evolved to acknowledge the integrated nature of all building systems which impact workplace productivity, occupant safety and security as well as sustainability. In North America Total Building Commissioning is being redefined to incorporate all building systems from the traditional mechanical and electrical systems to now include HVAC & R systems, structural systems, exterior enclosure (i.e. all systems separating the interior environment from the exterior, including exterior walls, fenestration, and roofing and roof openings, below grade perimeter walls and the slab-on-grade or crawlspace 10), interior systems, plumbing systems, lighting systems, fire protection systems, and elevators.

The evolution of commissioning has been reflected in the development of guidelines over the last 30 years as building systems became more complex and integrated and the desire for energy conservation becomes more intense. In the UK commissioning of the building envelope with regards to air leakage has been mandatory since 2003 for all commercial buildings with a gross floor area of over 1,000 m². Those regulations were revised in 2006 and essentially required mechanically ventilated or air-conditioned buildings to use 28% less energy than compliant buildings in 2002 (Potter 2007). The regulations present Commissioning as being performed on the HVAC systems and although building enclosure testing (air barrier) is included, it is presented as a separate function.

A key component of Whole Building Commissioning is commissioning of the building enclosure or building envelope. The importance of the building envelope to the Whole Building Commissioning process is reflected in the production of NIBS Guideline 3 – 2006 *Exterior Enclosure Technical Requirements for the Commissioning Process* as the first Supplemental

Guideline to ASHRAE Guideline O – 2005. NIBS Guideline 3 covers performance objectives including control of heat flow, air flow, noise, fire, light, infrared, ultraviolet, rain penetration, moisture, structural performance, durability, security, reliability, aesthetics, value, constructability, maintainability, and sustainability.

Aldous *et al* (2008) summed it up best when they proposed the question "Why Commission a Building Enclosure?" In answering their own question, they cite a paper by Bomberg and Brown (1993) reporting 80% of construction claims in the United States related to rainwater or other moisture ingress. In addition to mitigating moisture ingress, building enclosure commission should also seek answers to the following questions: Will the envelope assemblies, components and materials be durable over their expected service life?

Will the envelope assemblies deliver the anticipated thermal performance?

Given the complexity of modern construction and the introduction of novel and innovative assemblies, these questions may not be straightforward to answer. Emerging technologies and new building materials on the market today, finding wider application in sustainable developments, do not have substantial in-service histories upon which the designers nor the Commissioning Authority can base judgment.

1.1 Design Review in the Commissioning Process

Whole Building Commissioning includes a series of exercises throughout the life cycle of a building or facility including several during the design stage. These exercises are intended to "verify that each exterior enclosure system documented in the Basis of Design fulfills the requirements within the Owner's Project Requirements (OPR) document and that the various enclosure systems are coordinated with each other and with other related systems" (NIBS 2006).

The focus of this paper is on those commissioning activities performed during the design stages including design development. There are a host of other equally important commissioning activities that take place during other phases of project development and into the building's service life. Commissioning activities subsequent to design phase are beyond the scope of this paper.

It is intuitively obvious that no amount of testing or inspection can compensate for an envelope whose design was flawed from the outset. Given the multiple systems, components and trade contractors involved in envelope construction combined with expected service life of several decades it is critical that the design is inherently sound from the outset. To ensure the design is sound and will achieve the OPR, design reviews are routinely performed at various stages of design development

Traditionally, the design review was performed by an experienced practitioner manually reviewing a selection of assemblies and details from various design development phases. This traditional approach relies heavily on the experience of the Commissioning Authority and is necessarily subjective. The deliverable from this process was a design review report which contained comments reflecting the opinions, and preferences of the commissioning authority but lacking quantitative data.

Because the traditional or Conceptual Design Evaluation process is based on the experience of the Commissioning Authority it is limited in its ability to develop a solid objective assessment of the merits of innovative designs. The absence of quantitative data, can lead to differences of opinion between the principal designers and the Commissioning Authority and provides little or no objective basis for evaluating design alternatives. It becomes clear that an objective analysis tool to support the Conceptual Design Evaluation process is required.

These tools exist and their use is supported by various standards including ASTM E-241 (2000) and ASHRAE/ANSI 160 (2007). Despite the existence of such tools, their use in building envelope design and more critically, Whole Building Commissioning is sporadic. These tools generally take the form of computer based analysis and simulation software. Ideally there would be one single integrated tool to support all aspects of building envelope design (Sathyanarayanan et al, 2003) but this is likely not reasonable given the complexity of the analysis required. Instead, there are a number of analysis programs, each with its own merits and each with its own specific application. For the purposes of building envelope design and design review there are three broad classification of simulation and analysis programs that have direct applicability: Thermal analysis, HAM or Hygrothermal simulation and Whole Building Energy Simulation.

2.0 SIMULATION PROGRAMS AND MODELS

The advent of analysis software for building envelopes has greatly streamlined the commissioning design review process. These programs allow for more efficient and well-informed design review with quantitative output. The use of simulation programs eliminates the need to depend on conventional methods or practices that are regional-specific and have 'limited performance assessment results' (Mukhopadhyaya et al 2003). There are a number of programs available today for both commercial and research purposes. The variety of scope and outputs from these programs means that the possibilities and applications are wide-ranging. For those interested, there are many in-depth comparisons and summaries of thermal, hygrothermal and whole building programs available today. For the purposes of this paper, the focus will remain on programs with support in North America.

As noted above, computer simulation software is available from numerous sources, most built originally for research purposes. Some programs have been adapted for commercial purposes and find application in the commissioning process. Most of the simulation software presented here is of the commercial variety with increasingly complex simulation software not explored. 2-D hygrothermal and 3-D thermal analysis programs are available but require considerably more detailed input and as a result their commercial applications are limited.

Within the context of commissioning activities for typical structures, commercial simulation programs are adequate to fulfill the mandate "The intent of this review is to determine if there are systematic errors for exterior enclosure materials and interface coordination, not to fully check the drawings. The responsibility for fully checking the drawings ... remains with the Design Team" (NIBS Guideline-3). Within the context of commissioning design review, it would be appropriate practice to use commercial simulation software to identify aspects of the project that may not achieve the OPR. Resolution of these issues or selection of the most ideal

option for resolution should be undertaken by the Design Team and may, in some circumstances, be aided by further modeling. In the case of highly complex building enclosures or special occupancies (i.e. research facilities, museums, adapted heritage structures, etc.) such resolution of commissioning design review concerns may be aided by the more complex software. Such necessity to employ complex modeling software would likely have been identified at the Predesign or Schematic Design stage and agreed to by the Commissioning Team.

2.1 Thermal Programs: THERM/Window

Perhaps the most prevalent and well-known thermal simulator in the industry today is the THERM software. Developed by the Lawrence Berkeley National Laboratory, THERM is a finite element analysis software that models two-dimensional steady-state heat flow.

2.1.1 Capabilities and Outputs.

THERM is a drawing-based program that allows users to calculate the thermal performance of a specific assembly, based on composition and orientation. It is primarily used in conjunction with WINDOW, another LBNL software development, to calculate the U-values of glazing systems. It can also be used to determine various thermal properties, such as R-values and solar heat gain coefficients, of wall or roof assemblies.

In addition to the numerical computations performed by THERM, the results can be displayed in a variety of visual forms. THERM 5.2 allows the user to choose from the following displays: finite mesh elements, flux vectors, constant flux lines, colour flux magnitude, isotherms and colour infrared. While some of these formats require a certain amount of background knowledge on the concepts of thermal movement and are not conducive to client understanding, some of the more graphical outputs, such as the colour infrared setting, are useful in conveying thermal principles to clients in an easy-to-understand format that does not alienate. Figure A below shows a simple wall cross-section and the various outputs that can be generated for use.



Figure A: Typical Wood-Frame Wall Assembly with Fibre-Cement Cladding. (a) Original Model, (b) Isotherms and (c) Colour Infrared

2.1.2 Limitations. While THERM is fairly easy to learn and to use, there are some drawbacks to the software. The software is only capable of simulating two-dimensional steady state conditions; this inability to account for variations in thermal and moisture conditions limits the applicability and accuracy of the results. Another shortcoming of THERM is the user interface. The interface is based on a drawing system that is somewhat cumbersome – it can take up to an hour to develop a model, depending on the complexity of the system. Also, the finite-element analysis system cannot calculate results for overly complex assemblies, thus limiting what can and cannot be modeled.

2.1.3 Professional Applications. The THERM/WINDOW suite can be used in a number of applications during the Conceptual Design Evaluation process. THERM is mainly helpful in comparing effective versus nominal thermal performance of assemblies. As Peer (ASHRAE 2007) explores, the presence of support systems for cladding greatly reduce the overall effectiveness of insulation and should not be neglected during the design process. The effects of other building envelope details, such as windowsills or jambs and floor slabs, greatly reduce the effects of insulation within an assembly. As will be discussed later in the paper, this information was critical when trying to achieve LEED certification and ensure building code compliance with a new social housing development.

In addition to its use in Conceptual Design Evaluation, THERM and WINDOW are also the programs of choice for the National Fenestration Rating Council (NFRC) for determining U-values and solar heat gain coefficients of various glazing products. This provides a common reference point when assessing the suitability of a given glazing system for a particula application.

2.2 Hygrothermal Programs: WUFI

One of the shortcomings of thermal analysis software is its inability to account for moisture within the building envelope, or fluctuating exterior/interior conditions. This problem is largely addressed by WUFI, a program created at the Fraunhoffer Institute for Building Physics in Germany. Though its roots are in Europe, a partnership with the Oakridge National Laboratory (ORNL) resulted in the development of a North American version. Currently, WUFI is in use in both Canada and the United States.

2.2.1 Capabilities and Outputs. WUFI is a one-dimensional simulation program that can model hygrothermal performance of porous materials. The program uses archived weather data to simulate in-situ conditions. A new feature of WUFI is the ability to account for imperfections within the building materials by introducing moisture sources into specific components and adding ventilated areas. WUFI includes an extensive library of materials and weather data from around the world.

Results from simulations include graphs showing the moisture content of the entire assembly as well as each layer within the system. Graphs are also available showing the temperature and relative humidity data for the simulations. There is also the option of graphing isopleths, an alternative metric generated by the simulation. Each point in this graph represents the hygrothermal conditions at the surface of a component at a certain time. The graph also shows the limiting isopleths for building materials, LIM B I and LIM B II, below which no deterioration is usually to be expected. If the conditions lie above the limiting isopleths for a longer period of time, deterioration may be possible, but additional criteria are needed for a firm assessment. This graph therefore allows a quick assessment whether deterioration is unlikely (conditions always below the corresponding LIM), or whether more detailed investigations are needed for a definitive evaluation (conditions above the corresponding LIM for longer periods of time). A typical isopleth output for a well behaving wall assembly can be seen in Figure B below.



Figure B: Isopleth outputs from a WUFI simulation for: (a) interior gypsum wall board and (b) exterior wood plank sheathing.

The isopleths are mainly helpful in determining the probability of mould propagation within an assembly. WUFI also includes a 'quick report' option, which compiles all relevant information on the assembly, and subsequent results, into a standard report format. The graphs supplied by WUFI are not as straightforward as those produced by THERM, however the graphical outputs do provide a good platform for communicating design principles and rationale to clients.

2.2.2 Limitations. Though WUFI does address some of the problems and limitations of THERM, it also has a few key limitations of its own. WUFI is only able to model onedimensional systems. The interactions between bridged materials, such as insulation and framing, cannot be accounted for. A two-dimensional version of WUFI has been released in recent years, however it is still in development and is missing several critical features from the traditional WUFI in use today. Also, WUFI is, in essence, designed to model only porous materials. Metals, glass and other effectively impermeable materials are cumbersome to model and require a certain manipulation of program settings. These manipulations, if not done properly, have the potential to produce erroneous results, thus the modeling of non-porous materials should be kept to a minimum.

Another major limitation with WUFI is its German foundation. There have been amendments made to its database of weather data and building materials as the program becomes more popular in North America, however the lack of weather data for many major Canadian and American cities makes the use of WUFI difficult in certain areas. Also, the materials database is filled mainly with European materials that are generally not prevalent in North America. Much of the material data within the database comes from multiple sources and the reported values are based on a variety of test methods. As a result the material database has to be employed with caution. The addition of more typical North American materials is difficult as a lot of the properties required to create a new material in the database are not readily available. ORNL is currently in the process of developing a comprehensive North American materials database and when that becomes available, this deficiency will be largely rectified.

2.2.3 Professional Applications. The authors of this paper have used WUFI in two primary applications: during preliminary design development of new structures and during analysis of rehabilitation projects. During the preliminary design process, WUFI was used as a "check", verifying and quantifying inferences made in the Conceptual Design Review process. Once the thermal capabilities of the assembly were confirmed, WUFI was used to verify if the designed system could actually withstand real-life hygrothermal conditions. With rehabilitation projects, WUFI was used as an aid to find the weak point, or flaw, within the existing wall structure and to test various solutions.

Because of the limitations noted above, unless one is an expert in verification of input data, the model is limited to the value of "warning – change your design to one that is more safe". This is sufficient and appropriate for commissioning activities and consistent with the role of the Commissioning Agent.

2.3 Hygrothermal Programs: HygIRC

HygIRC is a Canadian program developed for research purposes by the Institute for Research in Construction (IRC) of the National Research Council (NRC) of Canada. The program was part of MEWS (Moisture Management for Exterior Wall Systems) Research Program as a way to analyze the building physics in low-rise, wood-frame construction. Though it was initially designed for research purposes, HygIRC is slowly being introduced into the commercial sector.

2.3.1 Capabilities and Outputs. HygIRC is a parametric program that computes onedimensional hygrothermal performance of building assemblies. The main parameters required to run a simulation include: wall construction details, material properties, boundary conditions, exposure duration, initial moisture content and temperature and accidental moisture entry (similar to the sources option in WUFI). Some of the properties needed for the simulations are derived from laboratory results. Boundary conditions have been developed to be in conformance with ASHRAE recommendations for relative humidity and temperature. A major benefit of programs such as HygIRC is their ability to not only identify the area of greatest moisture buildup, but also the duration of the wetting period (Mukhopadhyaya et al 2003). HygIRC not only pinpoints a potential problem, it also aids in determining the magnitude and severity of that problem.

The main outputs supplied by HygIRC are the relative humidity and temperature contour plots. These are taken across the section of the assembly, similar to WUFI and THERM outputs. HygIRC also uses the RHT index, which is derived from laboratory experiments and assigns a linear weight for the relative humidity and temperature within a system. The RHT index is calculated for a specific area of interest within the wall assembly – usually the area where moisture accumulation is considered the greatest concern.

2.3.2 Limitations. HygIRC is a relatively new program and has only in use in the commercial sector for approximately ten years. The newness of this software means that its accuracy and reliability are still uncertain and can only be confirmed by long-term, controlled experiments. As such, the program is constantly undergoing adjustments to its algorithm and set-up. Another drawback is the RHT scale that is unique to this program. As previously mentioned, the RHT scale applies a linear weight to relative humidity and temperature; this assumption may not always be the case. Only through long-term, controlled experiments will the validity of the RHT assumptions be confirmed. Also, the RHT scale is not immediately intuitive. Unlike HygIRC's contemporaries, which can give numbers and results that can be easily interpreted, the RHT scale requires a certain amount of background knowledge and understanding of how that scale was derived.

2.3.3 Professional Applications. HygIRC was developed primarily as a research tool to help better understand the building physics behind the 'leaky condo crisis' of the 1990's; however, HygIRC is becoming more prevalent within professional settings as well. The capabilities and outputs are similar to WUFI. One major advantage that HygIRC has is its Canadian platform. The Canadian platform allows for greater utility, particularly with regards to materials selection.

2.4 Whole Building Programs: Design-Builder

DesignBuilder is a graphical, menu-driven interface for the energy simulators BLAST and DOE-2. Both of these simulation algorithms have been designed by the United States Department of Energy. DesignBuilder is a three-dimensional energy modeler that takes into

account a building's geographical location, intended use, construction assemblies and HVAC system specifications to run a full energy analysis on the building.

2.4.1 Capabilities and Outputs. For those who have experience with BLAST and DOE-2, it is known that their interfaces are not very intuitive or user-friendly. The menu-driven interface of DesignBuilder is easy to use and to navigate. Also, the ability to take multiple building parameters and properties into consideration allows for a well-rounded, fairly accurate depiction of energy use within the structure. And, unlike other programs available today, developing construction assemblies and adding new materials into the database is simple.

Outputs produced by the simulations include graphs detailing energy usage, operation temperatures, heat gains and losses, ventilation, occupant comfort and HVAC loads. A digital rendering of the final model can also be developed and imported into Google's popular drawing program *SketchUp*® (see below in Figure C). A 'quick report' format is also available that compiles all of the graphs and applicable information into a standard report.





2.4.2 Limitations. The major limitation with DesignBuilder, and all whole-building simulators, is its accuracy. With so much information required from many different perspectives, a lot of assumptions and estimates have to be made. As with all simulation programs available for commercial use today, it is important to keep the results in perspective and understand that the results presented within the model are approximate. Another weakness of DesignBuilder is the

lengthiness of the modeling process. The drawing interface, though fairly straightforward, is tedious; to model a large-scale building would be a lengthy process.

2.4.3 Professional Applications. Whole building energy models are already used extensively by mechanical engineers to determine a building's energy load, both for new construction and rehabilitation, but building scientists can also apply them to their work as well. The programs may be used as a means of determining the expected overall benefits of a specific retrofit or improvement. As with other simulation programs, multiple simulations can be performed to see the difference between various improvement options.

2.5 Whole Building Programs: EE4

EE4 is a whole-building simulation platform that is currently used to compute energy performance of buildings to ensure it is in compliance with current standards and codes. The program uses the Canadian Model National Energy Code for Buildings (MNECB) as its standard when determining a building's compliance. According to National Resources Canada, "the MNECB is a model upon which energy-conscious building designers, developers and contractors across Canada can base cost-effective, energy-efficient building designs." (2005).

2.5.1 Capabilities and Outputs. Like DesignBuilder and other whole building simulators, EE4 can account for detailed transmission, solar, internal and ventilation load calculations; a broad range of primary and secondary systems and components; as well as scheduling of occupancy, lighting and equipment loads (Natural Resources Canada 2009).

EE4 can produce graphs and compliance reports. These outputs provide a detailed explanation of a building's efficiency and overall compliance with the MNECB.

2.5.2 Limitations. The Canadian platform of EE4 is both an advantage and a limitation of the program. The built-in relation to MNECB makes it exclusive to Canada and cannot be readily applied in other jurisdictions. Also, EE4 is not the most sophisticated program on the market today; air leakage rates, which can greatly affect a building's energy efficiency, are not elegantly managed within the EE4 algorithm, relying on pre-determined settings with little opportunity to adjustment by the modeler. As a result, the benefits of constructing a considerably more air tight structure than the baseline are not reflected in the model.

2.5.3 Professional Applications. Despite the shortcomings of EE4, it is used by many firms to confirm a building's energy conformance with current codes. Both the Canadian Green Building Council (CGBC) and the Canadian Mortgage and Housing Council (CMHC) recognize EE4 as a certified confirmation of energy performance.

3.0 CASE STUDIES

3.1 Woodward Hill Elementary School

3.1.1 Project Overview. Woodward Hill Elementary School is a new elementary institution located in Surrey, British Columbia constructed in 2009. The authors were part of a Commissioning

Authority team led by CES Engineering and provided support in the area of envelope engineering and commissioning. As part of those services the authors undertook design reviews to confirm the validity of the design and to ensure that it met the project OPR. These included:

- Achieve LEED Gold certification including 6 Points from Credit EAc1.
- Conform to CSA Standard S478 (2007) Minimum Design Service Life 50 years. (LEED Credit MRc8 – Canada only)

3.1.2 Models Used. Both THERM and WUFI were used during the commissioning process to model the three principal wall assemblies and two roof assemblies. These assemblies were taken from architectural plans and utilized standard Canadian building materials.

WUFI simulations were run for all five assemblies using archived weather data from Vancouver, British Columbia over a three-year period. In addition, THERM models were produced in section and plan views for the three wall assemblies and in section view for the roof assemblies. The section and plan views were to investigate the bridging effects of the vertical steel studs within the wall as well as the horizontal steel furring and z-girts used as cladding support. The models were run using both thermally-broken and non thermally-broken z-girts as well as two different types of insulation. A summary of the calculated R-values is detailed in Table A below.

| Component | Assembly | | U-Value (W/m ² K) | R-Value (hrft ² F/Bt u) | % Exceeds ASHRAE 90.1 |
|--------------------------------|---|---------|---------------------------------|--|---|
| STANDARD WALL ASSEMBLIES | CASE 1: Exterior 160 mm Concrete tilt-up panel 127 mm Cavity with: 100 mm SPF insulation 27 mm Air space 64 mm Steel studs at 400 mm o/c 16mm Gypsum wall board Interior | Section | 0.2413 | 24 | 215 |
| | CASE 2: | Section | 0.2010 | 28 | |
| | Exterior Prefinished metal cladding 22 mm Horizontal steel furring at 400 mm o/c Building paper (1 ply) 190 mm Cast concrete 100 mm SPF 27 mm Air space 16 mm Gypsum wall board Interior | Plan | 0.2296 | 25 | 242 (Based on a net value of R-26) |

Table A: Woodward Hill Elementary THERM Summary

| | CASE 3: Exterior Prefinished metal cladding Building paper (1 ply) 102 mm Polyisocyanurate insulation with 16-gauge, continuous z-girts at 400 mm o/c Peel and stick air/vapour retarder 13 mm Exterior gypsum wall board 152 mm Air space with 152 mm steel studs at 400 mm o/c 16 mm Gypsum wall board Interior | Section | 0.4944 | 11 | |
|------------------|---|---------|---------|----|--|
| | | Plan | 0.2019 | 28 | 176 (Based on an effective value of R- 21) |
| STANDARD ROOF | CASE 1: Exterior Pre-finished metal roofing 16-gauge clip and z-girt system at 900 mm o/c 100 mm Polyisocyanurate insulation Bituminous air/vapour retarder 6 mm Gypsum sheathing Corrugated steel deck Interior *Set on 20° slope | Section | 0.5582 | 10 | - Below ASHRAE minimum of R-15 |
| ASSEMBLIES | CASE 2: Exterior 2-ply Modified bitumen roofing system 11 mm Low-density fibreboard 150 mm Polyisocyanurate insulation Roof vapour retarder 6 mm Gypsum sheathing Corrugated steel deck Interior | Section | 0.01485 | 38 | 153 |

3.1.3 Conclusions. The calculated effective R-values, especially for the roof assemblies, were lower than those supplied by the architect. This was due to the fact that the designer did not account for the bridging effects introduced into the system by the steel studs and furring. The THERM outputs also determined that Roof Assembly 1 did not meet the minimum thermal performance requirement of R-15 as stipulated by ASHRAE 90.1 (2004 Standard). This non-conformance was due to the spacing and design of the z-girt and clip system of the roof assembly.

The hygrothermal analysis performed on the assemblies indicated a potential for mould propagation within Wall Assembly 2. The assembly, which performed the best thermally, had moisture content, on average, nine times that of Wall Assembly 1 or 3.

The results obtained through the models showed weak points within Wall Assembly 3 and Roof Assembly 1. More thorough investigation and design was recommended, as the assemblies did not meet the minimum requirements of ASHRAE 90.1 or LEED, nor did they conform to the Owners Project Requirements. The quantitative analysis and easily interpreted graphical outputs facilitated rapid re-design and an objective assessment of design alternatives. The problematic assemblies were altered to improve performance and the resulting revised assemblies were rapidly modeled to confirm acceptable performance.

3.2 BC Housing Four Sites: Low-Income Housing Initiative

3.2.1 Project Overview. The Four Sites project, part of a larger social housing strategy, includes the development of four low-income housing solutions around the Vancouver area. BC Housing, a provincial body that oversees the development of subsidized housing, is managing the project. In line with Provincial government policy, rigorous sustainability standards have been put in place for all new developments managed by BC Housing (LEED Gold certification among others). The four developments are currently in various stages of development with one building under construction.

The authors were retained to conduct building envelope commissioning and provide building science consulting to DYS Architecture of Vancouver, BC. Three of the buildings will be mid-rise non-combustible structures with metal and masonry claddings. The fourth building, currently in construction, is a wood frame structure with similar cladding assemblies. All the buildings are mixed-use with commercial and community amenity spaces on the lower floor and below grade parking structures.

3.2.2 Models Used. The primary simulation programs used for the building envelope analysis were THERM and WUFI with DesignBuilder used for focused occupant comfort analysis. Various wall assemblies and details were modeled including numerous novel assemblies that were discarded at the conceptual design stage. Details modeled included: windowsills, window jambs, window heads, floor slabs and wall assemblies. These details were modeled using steel, concrete and wood frame construction, different insulation materials as well as metal versus masonry cladding options. Cladding support structures were also modeled and eventually optimized. From these details, their zone of influence was determined and an effective R-value was calculated using proportions of the building's surface area. Table B below

presents a list of the details modeled, their zone of influence as well as their effective R-value. The details were modeled using THERM 5.2 using average Vancouver winter temperatures.

| Compone | nt | Area (m ²) | U-Value (W/m ² K) | R-Value (hrft ² F/Btu) |
|----------|--------------------------|---------------------------|---------------------------------|--------------------------------------|
| | Steel Stud Wall Assembly | 247.32 | 0.2745 | 20.7 |
| Masonry | Floor Slab | 74.06 | 0.7126 | 8.0 |
| Cladding | Window Jambs | 8.38 | 1.975 | 2.9 |
| | Window Sills/Head | 7.68 | 1.683 | 3.4 |
| | Steel Stud Wall Assembly | 311.44 | 0.2845 | 20.0 |
| Metal | Floor Slab | 48.31 | 0.6226 | 9.1 |
| Cladding | Window Jambs | 7.43 | 2.0915 | 2.7 |
| | Window Sills/Heads | 29.01 | 1.7656 | 3.2 |
| TOTAL: | | 733.63 | 0.4574 | 17.1 |

Table B: Four Sites Building Envelope Details

As the numbers suggest, the effects of such details greatly affects the thermal performance of the wall system. By identifying the most significant thermal bridges, design effort could be focused on these locations such that, remedial options could be rapidly assessed. The figure provided in Appendix A shows the range of influence of the different components for a typical elevation.

The elevation was designed with both concrete and steel frame substrates with metal cladding. An average of 100 mm (4") of insulation was used within the wall assemblies with a nominal R-value of 22.7 hr·ft²·F/Btu. The windows were modeled as thermally broken aluminum frames supporting double-glazed, low-emissivity coated insulating glass units (IGU) with 90% Argon fill. After taking into account the various details as illustrated above, the effective R-value of the elevation was approximately 17.1 hr·ft²·F/Btu – approximately 75% that of the nominal value.

One example is the thermal bridging caused by the concrete floor slabs. Despite the use of continuous insulation exterior to the air barrier, concrete floor slabs still had a negative effect on assembly thermal resistivity yielding an R-value of 8 hr·ft²·F/Btu. By recessing the floor slabs 25 mm (1") beyond the face of the steel stud infill walls and placing additional insulation in front of the slab edge, the effect was reduced and a net R-value of 12 hr·ft²·F/Btu (50% improvement) was realized. Figure D shows the THERM output for the revised detail.



Figure D: THERM output for revised floor slab detail Wall Assembly Description: Recessed floor slab detail with thermally broken z-girt, 4" of Roxul and metal cladding. 1" of additional insulation at slab edge U-Value (W/m²K): 0.51 R-Value (hr ft² F/Btu): 12

Given the small size of the social housing units being constructed and the desire to avoid air conditioning due to its energy demand, concerns were raised during design development over potential for occupant discomfort. The proposed response to this perceived concern was to add solar shading devices above windows. In light of budgetary constraints, the proposed method of providing solar shading was to extend the reinforced concrete floor slabs to form 'eyebrows' above the windows. THERM modeling quickly identified not only reduced thermal performance associated with such a scheme but also potential for moisture accumulation and biological growth. The results of this modeling are shown in Figure E.



Figure E: Wall Assembly Description: Cantilevered floor slab extension with metal cladding. U-Value (W/m^2K) : 1.5064 R-Value (hr ft² F/Btu): 3.8

DesignBuilder was used to assess the potential for occupant discomfort and the efficacy of the proposed slab extensions. A typical suite with a South-West exposure was modeled with the model set to run over a typical summer and the occupant comfort levels assessed as per ASHRAE Standard 55 (2004) - Thermal Environmental Conditions for Human Occupancy. This standard specifies the combination of indoor thermal environmental factors which will produce conditions which are acceptable to the majority of occupants within the space. Figure F shows the 3-D rendering of the model with and without the slab extension.





Results of the modeling indicated that there were few if any "uncomfortable" hours where the conditions within the suite exceeded the conditions recommended in ASHRAE 55 and that the addition of solar shading had negligible effect. These results are shown graphically in Figures G (a) and G (b) as well as summarized in Table C.



Figure G (a): Summer Discomfort Hours for Suite without Slab Extension



Figure G (b): Summer Discomfort Hours for Suite with Slab Extension

| Case | Description | % Discomfort Hours |
|------|------------------------------|--------------------|
| 1 | Suite without slab extension | 1.8% |
| 2 | Suite with slab extension | 0.7% |

Table C: Summary of Results – Occupant Comfort Study

The modeling revealed there is little potential for occupant discomfort within the suites as originally designed and that the addition of solar shading provided no statistically significant improvement. Given the reduced overall wall thermal performance, the additional cost, and increased envelope system complexity, the introduction of solar shading was not supportable from a technical perspective. As a result of this modeling, costly and difficult to maintain solar shading was not implemented on this project and the building elevations as currently designed are reflected in the drawing contained in Appendix A.

3.2.3 Conclusions. The main difficulty encountered on this project was the coordination between the different consulting parties, delivering their own "packages" within the overall housing strategy. The presence of multiple design teams led to discrepancies with the calculated R-values; there was no consistency between the different modeling techniques. Certain teams elected to simply take the nominal R-value of the insulation as the thermal performance of the wall. As shown in the previous section, the nominal thermal performance of a wall is severely inflated when compared with the effective thermal performance. A separate design charette was

arranged between the designers, owner, sustainability consultants and Commissioning Authorities to establish a protocol for thermal simulation and energy modeling to ensure a consistent approach across the entire social housing program.

Also, modeling the details with different framing and cladding options eased the design process. More information was available to the designers and a comparison of different building materials or techniques allowed for design decisions to be made more efficiently.

3.3 Cross-Iron Mills Shopping Centre

3.3.1 Project Overview. Cross-Iron Mills Shopping Centre is a new retail development constructed in Balzac Alberta, a suburb of Calgary. The development included a number of large commercial retail spaces as well as semi-detached spaces housing major retailers such as BassPro Shops. The authors were retained after design was complete and as mobilization for construction was underway. The authors acted as an independent Commissioning Authority reporting directly to the developer. The main shopping centre building was being designed by a local architect while the design of the BassPro Shop was being undertaken by an architect engaged directly by the retailer.

The buildings were primarily structural steel frames with infill walls of light gauge steel stud framing. The original design called for the gypsum sheathed steel stud walls to be insulated with 9.5" of fiberglass batt (including sheet polyethylene vapour retarder) and the walls to be finished with an EIFS cladding. The EIFS cladding on the main building has a 2" (50 mm) expanded polystyrene (EPS) substrate while the EIFS cladding designed for the BassPro Shop was to have only a 1" (25 mm) substrate.

3.3.2 Models Used. Concerns over the relative imbalance of insulation within and outboard of the stud cavity as well as the presence of multiple planes of vapour resistive materials suggested that hygrothermal simulation was warranted. WUFI was used to rapidly assess the potential for moisture accumulation within the wall assemblies. Alternative designs were modeled to provide guidance to the designers on possible solutions. Based on the hygrothermal simulations performed a considerable potential for premature deterioration of wall systems employing less than 2" of EPS as an EIFS substrate was noted. In particular, high moisture contents occur in exterior gypsum sheathing leading to loss of strength, facer delamination and possible fastener corrosion. These results are reflected in the isopleths output for the exterior gypsum sheathing shown in Figure H.



Figure H

Figure H above demonstrates that for a considerable period of time the internal relative humidity (and consequently the moisture content) of the exterior gypsum in the Bass ProShops original wall design (Case 1) exceeded recommended maximums and deterioration was likely. Each green 'dot' represents a time step in the simulation and the red curve represents the limiting isopleths for bio-utilizable substrates.

3.3.3 Conclusions. The hygrothermal modeling employed as part of this commissioning exercise allowed the Commissioning Authority to rapidly identify potential problems and to present our concerns to the design teams with quantifiable data. By presenting this data in easy to interpret graphical output, the designers were able to internalize the Commissioning Authority's concerns and the designs were altered.

4.0 CONCLUSION

The Conceptual Design Evaluation exercise is a critical step in Whole Building Commissioning. The push towards more sustainable, energy efficient buildings and the development of new materials makes this process subjective as the Commissioning Authority typically has little prior history with these materials or assemblies to base their assessments on.

Commercial thermal, hygrothermal, and whole building energy simulation software can be used to rapidly assess the efficiency and potential durability of otherwise difficult to assess assemblies. While not a panacea nor a replacement for good judgement, these simulations can assist the Commissioning Authority to identify potential problems long before construction commences. The ability to rapidly modify simulation models allows the Commissioning Authority, and the entire design & construction team for that matter, to assess potential alternatives while still achieving the project OPRs. Graphic output aids in presenting what would otherwise be esoteric concepts and achieving buy-in from multiple stakeholders. Quantifiable data reduces subjectivity of assessments and provides solid targets for further commissioning activities later in the project delivery cycle.

APPENDIX A



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