The BeTOP facility for performance testing of building systems

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Abstract. Proposing new materials and systems to improve buildings' performance and energy efficiency often requires testing their performance in the field. Experimental performance characterization of new and existing building systems is crucial to understanding their behaviour. Full-scale experimental test cell facilities have been at the forefront of experimental performance evaluation in building-related research, as they provide a realistic representation of buildings, including environmental conditions, assembling challenges, and operational characteristics. In this paper, trends in the design and construction of outdoor testing facilities are first discussed. Then, based on the current literature and the knowledge gained through visits to multiple facilities, the new test cell facility “BeTOP”, located in Toronto (Ontario), is described. BeTOP is a full-scale experimental facility with the capacity to perform multiple experimental tests simultaneously. This paper describes its characteristics, including structure details, testing capabilities, system details, current monitoring campaigns, and future testing potential. The paper concludes by showing that the design of a full-scale testing facility is crucial to observe the long-term performance of new systems under variable boundary conditions in a continental climate with cold winters and hot and humid summers.

1 Introduction

Innovations in building materials and systems have significantly increased in the past decade to conform to the new requirements and targets to achieve enhanced energy efficiency and improved sustainability in buildings. Reducing the negative environmental impacts of buildings is one of the crucial strategies in response to climate change-associated challenges. While the range of strategies and technologies used in buildings varies case-by-case basis, several trends can be identified from the industry and research and development studies. Improving the performance of the building enclosure for enhanced indoor environmental quality, durability, and reduced energy consumption is the primary strategy adopted by the building industry. In addition to enhancing the building enclosure, energy-efficient, and high-performance heating, cooling, and ventilation systems have also seen increasing attention.

The critical step in any research and development project is to assess how a prototype performs in relation to the required performance targets and the subjective case it was designed for. Experimental tests are a proven approach to quantifying the behaviour and performance of building systems [1]. Real-scale or field experimental tests have been shown in the literature as reliable testing methods to assess the performance of building components as they closely represent real environmental boundary conditions [2,3].

Experimental performance evaluation of building systems can be categorized based on the testing facility characteristics and research focus [4]. The main type of facilities for field measurement or experimental performance quantification observed in the literature are real-scale facilities (full-sized test cells or full-sized houses), small-scale test cells, and climate chambers.

Another categorization of these testing facilities could be based on the boundary conditions, as some test cells are directly exposed to the outdoor environment, while other test cells are located inside a lab facility with a controlled environment surrounding the outside and inside of the cells. The advantage of real-scale facilities lies in the ability to quantify the performance of building systems on the whole-building scale, close to reality.

Experimental test cell facilities can overcome several limitations attributed to performance modelling and steady-state lab testing of building components due to the dynamic nature of boundary conditions. However, given the subjective nature of building performance, each research facility uses specific construction techniques and equipment with unique capabilities.

Table 1 describes examples of full-scale outdoor test cell facilities with multi-purpose testing capabilities to showcase consistent trends in constructing test cells. The list of facilities is not complete due to the limited space, as some facilities are missing, including the ones operating at the US. Herick Labs or at Oak Ridge National Labs; however, Table 1 is sufficient to show common characteristics. Most test cells are designed to evaluate the performance of building enclosure components or building services integrated into the building enclosure. The key characteristic of experimental test cells is how the environmental boundary conditions are controlled. Several test cells have fully controlled indoor and outdoor conditions as they were constructed fully or partly in a lab environment, although a highly prominent approach is to construct the test cells to be fully exposed to the outdoor environments. Comparative testing is the main trend; in fact, most test cells have multiple rooms allowing comparison against a reference case.
Table 1. Full-scale experimental test cell facilities in the literature.

<table>
<thead>
<tr>
<th>Test cell name</th>
<th>Setup dimensions (W × L × H)</th>
<th>Characteristics</th>
<th>Equipment</th>
<th>Testing focus</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLIET Test Building</td>
<td>Long box with two individual modules exposed to outdoor environment in combination with a semi-hot box with dimensions of 7.2 m × 25.25 m × 2.7 m.</td>
<td>- Indoor environment in each module can be controlled. - Provides 20 wall panels for testing (2.7 m high). - Automatic and continuous data logging.</td>
<td>- Local weather station. - Double air conditioning system. - Local humidifiers. - Thermocouple, Relative humidity and air pressure sensor in the envelope.</td>
<td>- Hydrothermal behaviour of building components. - Passive solar energy control.</td>
<td>[5]</td>
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<tr>
<td>Leuven, Belgium (50.8 °N)</td>
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<tr>
<td>Testing Window Innovative Systems (TWINS)</td>
<td>The test cell consists of two rooms. Each room has dimensions of 1.6 m × 3.6 m × 2.5 m</td>
<td>- One cell used as a reference with no changes to the façade. - The other cell is capable of testing multiple systems. - The test cells are located on the roof of a building. - Controlled indoor environment.</td>
<td>- Local weather station. - Data acquisition system. - Temperature and relative humidity sensors. - Pyranometers. - Heat flux sensors.</td>
<td>- Performance analysis of opaque and transparent building facades. - Performance of building enclosure elements integrated with HVAC systems.</td>
<td>[6]</td>
</tr>
<tr>
<td>Turin, Italy (45.07 °N)</td>
<td>Modular design with static wood structure and changeable separators exposed to outdoor environment with total dimensions of 10 m × 18 m × 2.7 m.</td>
<td>- Allows for installation and testing of 14 roof assemblies. - Integrated and individual data loggers recording data into a common server.</td>
<td>- Two weather stations. - Double air conditioning system with fixed indoor conditions. - Individual humidifiers. - Temperature and relative humidity sensors.</td>
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<td>[7]</td>
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<tr>
<td>Building Science Research and Test Unit (BSRTU)</td>
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<tr>
<td>Villach, Austria (46.6 °N)</td>
<td>Two identical test cells with the south wall facing the outdoor environment. Dimensions of each cell: (2.4 m × 4.2 m × 3.3 m), volume of 33 m³. Other sides are facing a guarded volume-controlled environment.</td>
<td>- Parallel testing of the same building envelope technology with different indoor air temperature setpoints. - Comparative tests and calorimetric tests.</td>
<td>- Integrated weather station. - Portable tripod with five air temperature sensors for indoor conditions at different heights in the cell. - Globe sensor to measure operative temperature. - Multi-sensor unit for temperature, relative humidity, and CO₂ concentration.</td>
<td>- Hydrothermal performance and durability of building components. - Wind-driven rain - Interaction of building components with indoor comfort.</td>
<td>[8]</td>
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<tr>
<td>Zero Energy Living Lab (ZEB)</td>
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<tr>
<td>Trondheim, Norway (63.4 °N)</td>
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<tr>
<td>Field Exposure of Walls Facility (FEWF)</td>
<td>Full-scale house facility exposed to outdoor conditions. The test bay has dimensions of 7.5 m wide × 3.2 m high</td>
<td>- The western façade allows for testing three test bays. - Change in air leakage is possible. - Indoor conditions can be changed to different scenarios. - Side-by-side comparison in attached rooms.</td>
<td>- Rain gauge measurement. - Automated 3D indoor environment measurement systems are used to sample spatially distributed IEQ parameters. - Moisture/temperature sensors. - Heat flux sensors. - Water detection tape.</td>
<td>- Hydrothermal performance of building wall systems (insulation, air, and vapour control layers) and retrofit strategies. - Lightweight and massive wall specimens - Energy use and IEQ.</td>
<td>[9]</td>
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<tr>
<td>Ottawa, Canada (45.2 °N)</td>
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<tr>
<td>Building Envelopes Outdoor Thermal Test (BEt3)</td>
<td>Square layout. Three test cells located within a 1.5 m distance</td>
<td>- Real-scale controlled lab environment (fixed conditions). - Central heating and cooling system- air-water heat pump.</td>
<td>- Sensors to measure indoor humidity, temperature, surface temperature, electrical absorbance, and energy calculation.</td>
<td>- Assessing thermal properties of building components.</td>
<td>[10]</td>
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<tr>
<td>Brescia, Italy (45.5 °N)</td>
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<tr>
<td>Multi Activity Test Room for Innovating\x (MATRIX)</td>
<td>The overall size of 6 m × 6 m × 5 m is divisible into two modules. The test room can rotate 360° on a horizontal plane.</td>
<td>-Façade elements with sizes up to 3 m × 5 m can be tested and changed using an automated system. -Thickness of the façade is changeable between 10–40 cm. -Two different heating and cooling systems for individual conditions.</td>
<td>-Standalone equipment for acoustical and lighting measurements.</td>
<td>-Testing building facades, small active systems integrated into the façade, and solar blinds. -Hygrothermal performance of envelope systems.</td>
<td>[11]</td>
</tr>
<tr>
<td>EGUZKI and ILARGI</td>
<td>Two rectangular separate test cells</td>
<td>-PASLINK test cells. -Vertical elements with sizes of 2.7 m × 2.7 m can be tested in the EGUZKI, while the horizontal ones can be tested in the ILARGI cell with a size of 3.7 m × 2.1 m. -The room is provided with an axial ventilator with an electrical heater.</td>
<td>-Local weather station. -Air temperature measurements at different points in the room. -230 heat flux-sensitive tiles.</td>
<td>-Testing vertical elements and horizontal building components.</td>
<td>[12]</td>
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<tr>
<td>NEXT Room</td>
<td>Rectangular space with dimensions of 10 m × 17 m × 4 m facing the outdoor environment on two sides. Located inside a laboratory.</td>
<td>-Radiant system on all surfaces, mechanical ventilation, and air conditioning system. -Artificial lighting systems for varying illuminance distribution, colours, and light dimming.</td>
<td>-Wearable devices for human-centred monitoring.</td>
<td>-Controlling the thermal, visual, and acoustic environments in indoor spaces. -Control of indoor pollutant concentration. -Virtual reality scenarios for indoor and outdoor condition replication.</td>
<td>[13]</td>
</tr>
<tr>
<td>Heritage energy Living Lab onsite (HeLLo)</td>
<td>The dimension of the box varies based on the size of the walls, grossly measured at: 2.5 m × 2.5 m × 4.01 m.</td>
<td>-Mobile base design using wheels. -Modular timber structure for size adjustments and assembly. -Non-invasive apparatus to connect the sensors to historical walls.</td>
<td>-2000 W Heating convector. - Two ultrasonic humidifiers. -T-RH combined sensors. -Infrared camera.</td>
<td>-Remote sensing technology for hygrothermal assessment of historical walls with minimum intervention. -Energy retrofit of heritage buildings.</td>
<td>[14]</td>
</tr>
<tr>
<td>FERRade Tool (FACT)</td>
<td>Two-floor building with dimensions of 7.8 m × 9.8 m × 8.34 m. The building is made of ten test cells.</td>
<td>-Allows for testing ten façade panels with a dimension of 2.3 m × 3.3 m.</td>
<td>-Fixed sensor systems.</td>
<td>-Building envelope testing for different façade thicknesses. -Renewable technologies and horizontal systems on the roof (solar panels, cool and green roof).</td>
<td>[15]</td>
</tr>
</tbody>
</table>

Figures 1 and 2 also show two outdoor test facilities recently built at the Norwegian University of Science and Technology (NTNU) in Trondheim (Norway) and Concordia University in Montreal (Canada), respectively. These facilities share multiple features that can be considered dominant factors for recent outdoor facilities, including multiple side-by-side façade modules to facilitate comparison and benchmark tests; internal compartmentalized rooms to test different set-points and internal loads; and roof tracks to test renewable energy technologies, including photovoltaic and solar thermal technologies. As evident, there is a large body of full-scale experimental test cells constructed in different climates that are directly exposed to outdoor conditions.

![Fig. 1. NTNU outdoor test cell in Trondheim (Norway).](image-url)
The review in Table 1 allows for a comprehensive analysis of requirements for a full-scale testing facility and proposes how they could be improved holistically.

In Canada, on the other hand, the focus of experimental performance evaluation has been on small-scale test cells or full-size research houses. However, the limitations of such small-scale testing and the lack of flexibility in full-size houses put demands on other test cell designs. Additionally, considering the diverse climatic variations in Canada, direct exposure to the outdoor environment is vital.

An innovative real-scale testing facility, BeTOP, is hence presented next. BeTOP test cell is an outdoor test cell facility located in Toronto, Ontario (Canada), to address the lack of such testing facilities in a cold continental climate to quantify the performance of building materials, components, and systems. In this paper, the design of the test cell, its characteristics, systems, and equipment are described with some indications of the type of studies that can be performed in this test cell.

2 BeTOP: a new test cell in Toronto

2.1 Scope

BeTOP, which stands for Building efficiency: Testing, Operation, and Performance, is a test cell for advanced building systems and material performance evaluation. The design of the test cell aimed to allow the investigation of the dynamic interactions between building enclosure components, indoor environments, and mechanical systems for Canadian buildings. BeTOP allows for conducting studies on new and existing building systems such as:

- Investigating the hygrothermal behaviour of new systems in an outdoor setting: the enclosure in BeTOP allows researchers to assess condensation issues and measure in-situ thermal properties of systems affected by variable weather conditions.
- Performing aging tests on new building systems in the Canadian climate: in this regard, reducing the thermo-physical performance of the investigated panels over time requires continuous analysis of the recorded data to assess changes with respect to the lab characterization results.
- Studying exterior and interior enclosure systems exposed to dynamic outdoor conditions while testing different HVAC regimes. The assessment uses quantitative analysis of several physical parameters in the building enclosure and the indoor room of BeTOP.
- Assessing energy-related performance and indoor comfort acoustics and lighting levels.
- Testing new building enclosure systems impacts the cells' indoor hygrothermal and energy demand.
- Assessing the synergies between innovative building systems and different HVAC systems.

Furthermore, BeTOP allows for a comparative assessment of eight full-scale wall components in a simultaneous manner, including opaque and transparent building systems. The size of each wall component further allows for testing multiple components in one opening area. BeTOP comprises two modules separated by an internal partition, allowing for different controllable indoor conditions in each half. In addition to the primary comparative experimental testing of building components, analytical evaluation of thermo-physical and hygrothermal parameters is also possible in BeTOP.

2.2 Location and Climate

BeTOP is located on the campus of Toronto Metropolitan University in the core of the city of Toronto, Canada (43.65 °N, 79.38 °W), as shown in Fig. 3. Toronto is classified under the Dfa and Dfb climate zones based on the Koppen climate classification system and Zone 6 of the ASHRAE climate zones. Toronto is situated near Lake Ontario, one of the five major North American lakes, which has a critical impact on the weather.

Fig. 3. BeTOP test cell location in Toronto, Ontario, Canada.
32 °C. Periods of low temperature are further enhanced by the effect of high wind speeds, which could be as high as 54 km/hr. Conversely, in the cooling season, air temperature ranges between an average of 17 °C to 26.6 °C daily, while it could also reach as high as 39 °C. High air temperatures recorded with considerable relative humidity could create significant comfort and health issues in buildings during the summer season.

2.3 Test cell design characteristics

BeTOP is a customized modular test cell facility that allows for the flexible inclusion of different enclosure components, indoor materials, and building systems. The test cell was built by RDH Building Science Laboratories and designed based on the PASSYS-PASLINK and PASLINK EEIG networks [16]. Figures 4 and 5 show the axonometric view and the floor plan, respectively. The total area covered by the test cell is approximately 45 m², subdivided into two test rooms and a vestibule. The test rooms are identical in design and dimensions and separated by a partition wall that allows for different conditions to be created.

![Axonometric view of the BeTOP test cell facility.](image)

The volume of each room is 42 m³. As shown in Fig. 5, this test cell allows for the simultaneous testing of eight façade modules and two large ceiling modules that are directly exposed to the exterior environmental conditions. The modular design of BeTOP allows for easy removal and integration of different façade systems. The dimension of each façade opening is 1.3 m × 2.55 m, and each ceiling opening is 1.8 m × 1.8 m. It must be noted that two windows are currently installed on one of the façade modules facing east and west.

The indoor conditions in the BeTOP test rooms are fully controllable. Multiple systems provide heating and cooling to the rooms to include different mechanisms of heat exchange and study different microclimatic controls in each room, affecting indoor thermal comfort and performance of building materials. The primary heating and cooling system in BeTOP include two air-source heat pumps (one for each room). The second heating system is a hydronic radiant floor system that can be activated upon demand. The hydronic system’s hot water is provided by a high-efficiency condensing gas boiler installed inside one of the rooms. Based on the demands of specific experimental tests, standalone humidifiers or dehumidifiers are positioned.

![Floor plan of BeTOP test cell facility including all systems and components.](image)

The indoor room temperature set points can be controlled automatically or through schedules to start and stop the operation of the air-source heat pump system. Additionally, the system provides the option to distribute the air in the room by activating the fan mode without any heating or cooling. The mechanical systems provide conditions within the range of 15 °C to 30 °C and relative humidity of 25% to 80%.

![Data acquisition (left) and Mechanical (right) systems.](image)

Different measuring and data collection systems have been embedded in the BeTOP test cell, identical in each test room. The first measurement device is a weather station installed on the roof of the test cell. The parameters that can be measured using the weather station include air temperature, relative humidity, rainfall, wind speed, wind direction, diffuse, and global solar radiation on different exposures. The weather station is connected to the data acquisition system in both test rooms. The data acquisition system uses a 13 Bit auto-ranging for up to 500 analog channels to record different sets of measurements. Each cell is provided with the original configuration of 300 sensors to monitor different performance parameters in different locations in the room and on the surface of the enclosure system. Figure 6 shows a diagram of the measurement tools and data logging systems. The data logging systems provide a flexible arrangement of the many sensors. Table 2 also reports the specifications of the sensors installed.
Table 2. List of the sensors installed in BeTOP.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Parameter</th>
<th>Range/Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photometer</td>
<td>Outdoor illuminance</td>
<td>0 – 200 ± 0.6 klux</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Horizontal irradiance</td>
<td>0 – 2000 W/m² ± 3-8%</td>
</tr>
<tr>
<td>Thermocouple Type T</td>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Thermistor</td>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Photometer</td>
<td>Horizontal workplace</td>
<td>0 – 15 klux ± 3%</td>
</tr>
<tr>
<td>HDR Camera</td>
<td>Luminance distribution</td>
<td>0 – 100,000 cd/m² ± 5%</td>
</tr>
<tr>
<td>Plate heat meter</td>
<td>Heat flux</td>
<td></td>
</tr>
<tr>
<td>Anemometer</td>
<td>Airflow</td>
<td></td>
</tr>
<tr>
<td>Flow meter</td>
<td>Water flow rate</td>
<td>0 – 10 GPM ± 1%</td>
</tr>
<tr>
<td>CO₂ Sensor</td>
<td>Room air change rate / CO₂ levels</td>
<td>0 – 30000 ppm ± 5%</td>
</tr>
<tr>
<td>Globe thermometer</td>
<td>Mean radiant temperature</td>
<td>-40 – 100 ± 0.2°C</td>
</tr>
<tr>
<td>Velocity sensor</td>
<td>Air velocity</td>
<td>0.015 – 6 m/s</td>
</tr>
<tr>
<td>Hygrometer</td>
<td>Relative humidity</td>
<td>10 to 90% ± 2.5%</td>
</tr>
</tbody>
</table>

2.4 Construction

The construction was completed off-site, and the prefabricated unit was moved to the final location and installed on concrete footings. Figure 7 shows photos of the test cell’s delivery and construction.

Fig. 7. BeTOP delivery and construction.

Figures 8 and 9 show the construction details of BeTOP. The wall assembly is comprised of a metal stud wall and 4” external insulated metal panels. The floor assembly is constructed of hollow structural section joists at 24” of center, while the roof assembly is built using at least 10” of rigid insulation. The blank panels are constructed of structural insulation. Attention was paid to minimizing thermal bridging and air leakage paths through the building enclosure.

Fig. 8. Floor connection detail.

Fig. 9. Roof Connection detail.

3 Research activities

Since its construction in 2021, some experimental campaigns have already been completed in BeTOP. The first experimental test aimed at testing a full-scale ventilated building façade system. In this study, a full-scale climate-responsive and ventilated building façade prototype was installed in place of one of the blank wall modules of Room 2 of BeTOP facing south (Fig. 10). The façade was designed to respond to the flow of heat and airflow using daily and seasonal responses by integrating different components, including phase change materials (PCMs), ventilation module with embedded heat recovery, and dynamic insulation.

Fig. 10. Innovative façade module integrating ventilation.
Full details on the characteristics of this façade are described in [17] and [18]. To conduct the experimental tests, 40 sensors were installed to measure temperature, heat flow, and airflow changes. Thermistors and thermocouples were positioned inside the façade module, on different surfaces, and inside the room at different locations to measure air and surface temperature. Digital anemometers were attached to the façade to measure the fresh airflow provided to the room from the façade and the return air leaving the room. Heat flux meters were attached to the surface of the façade to measure heat flow through the façade under the variable operation of the façade. All the sensors were attached to the main data acquisition system in BeTOP, in addition to one of the individual data loggers provided.

The second test cell regarded radiant panels with PCM surrounding the pipes and used to enhance building heating/cooling flexibility. Full details on the characteristics of this façade are described in [19] and [20] and shown in Figure 11.

The BeTOP test cell facility, in addition to testing enclosure systems, allows for the testing of building systems. A test is now underway to evaluate the performance of a ground source heat pump (GSHP) system under controlled environmental conditions. The GHSP system has been designed to address heating and cooling loads in buildings (Fig.11). This system was coupled with thermal energy storage to improve the system's stability and increase its efficient heating and cooling. Phase change materials integrated with nanoparticles were used as the primary thermal storage medium. Nanoparticles were added to improve the thermophysical properties of the PCMs, the efficiency of the entire system, and the economic feasibility in the macro-scale. Prior to the experimental tests, a numerical model was built and validated for using PCM in ground source heat pump systems by evaluating the effect of adding PCMs to the heat exchange.

![Fig. 11. Scaled down prototype of the NanoPCM integrated GSHP installed and tested in BeTOP.](image)

### 4 Conclusions

BeTOP is a full-scale test cell facility that will help drive lab research and innovations in the construction industry. Buildings are mandated to increase their energy efficiency and sustainability and thus must benefit from different technologies to achieve intended targets. Advanced building systems and materials are one of the fastest growing areas to enhance building performance and sustainability, creating significant new business opportunities. This paper discussed the possible approaches to investigate experimentally and in-field systems that improve energy performance, sustainability, and indoor environmental quality in buildings. In the case of the BeTOP test cell facility located in the city of Toronto, the challenge of the seasonal and annual performance of new building technologies must be addressed considering the climatic conditions in this city. While numerical studies could provide an understanding of how systems can be applied in buildings and larger scopes, experimental testing of new systems is critical in evaluating the actual performance of a system in operation.

The BeTOP test cell represents the necessary step to test new building technologies developed in the lab to be investigated in an outdoor enclosure, supporting the overall objective of bringing new technology solutions to the market to help with energy efficiency. Remarkably, considering the different scales of tests that can be performed in BeTOP, ranging from material scale to component and room-scale tests, a more extensive range of
technologies could be tested. As discussed, in BeTOP, performance evaluation of building enclosure components, building mechanical systems for heating, cooling, ventilation, and surface applied materials can be performed. The two identical rooms in BeTOP allow for comparative testing of new systems or simultaneous testing of different technologies. While the measurement sensors and data acquisition system provide the means to monitor indoor environmental quality, building enclosure parameters, and outdoor conditions and further additions could enhance the capabilities of this test cell facility. Additionally, incorporating monitoring systems for the mechanical space conditioning systems to measure the energy consumption to heat and cool each room is necessary to provide data for studies focused on energy savings measures.

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