

Large Dynamic Thermal Labyrinth: A Step Towards Net Zero Energy Use in Acute Care Hospitals

*Paul Marmion and Ray Pradinuk, Stantec,
Andy Woods, Cambridge University,
Arash Guity, M+NLB USA;
Irfan Rehmanji, BC Hydro*

ABSTRACT

Buildings consume more than 30% of the total energy and 70% of the electricity produced in North America. Hospitals, with their high ventilation rates and predominantly 24/7/365 occupancy, consume approximately 4% of all energy consumed in the United States (EIA, 2006). A 60% fossil fuel energy reduction target is defined in the 2030 Challenge for 2010-2015 construction with net zero carbon targeted for 2030. While it has been shown in a number of studies and project applications that cutting the energy consumption in healthcare buildings by 60% is relatively easy to achieve using present day technology and good design practice, achieving the 2030 net zero carbon target is going to be significantly more difficult, requiring innovation and new approaches to healthcare building design. In our research effort, we have targeted an energy reduction of 80%. Achieving the additional 20% reduction would effectively half the amount of renewable energy required to meet the 2030 net zero target. We have called this additional 20% energy reduction the “innovation gap”.

Our funded research effort explored conventional and non-conventional energy conservation strategies that could be used in the design and operation of an Acute Care hospital’s inpatient unit (IPU) tower, achieving the targeted 80% energy savings as compared to a typical code compliant IPU building.

This paper focuses on the results of a non-conventional large dynamic thermal labyrinth energy conservation strategy, which was found to have contributed about half of the required “innovation gap” energy savings. The large dynamic thermal labyrinth research effort was undertaken in conjunction with Cambridge University in the UK. The studied thermal labyrinth used water based thermal mass which was found to be more cost effective and flexible as compared to a conventional concrete mass thermal labyrinth.

The conventional and non-conventional energy conservation strategies resulted in an almost 80% improvement over the ASHRAE 90.1 baseline for an IPU building located in Vancouver, British Columbia. The research team also modeled the same building and design strategies in the cold-dry climate of Edmonton and the hot-dry climate of Phoenix.

Background

There is a worldwide drive for new buildings in North America and Europe to be designed to operate as net-zero energy users. The European Union has already mandated that all public buildings are to be near-zero energy buildings by 2019 and that all new buildings are to be near-zero or net-zero by 2021. Policymakers and building design professionals in North America are recognizing that net-zero buildings will require both new energy policy and fundamental changes in building design, essentially a new building procurement mind-set. For example:

- ASHRAE Vision 2020 report (ASHRAE 2008) sets out requirements for developing the tools by 2020 to enable commercially viable net zero energy buildings by 2030.
- The AIA 2030 Challenge (AIA 2009) calls for incrementally reducing fossil fuel energy use, starting with a 50% reduction over existing building's energy use and increasing savings up to 2030, when new buildings will be carbon neutral.
- The California Public Utilities Commission has an energy action plan to achieve net zero energy for all new residential construction by 2020 and net zero for all new commercial construction by 2030.

It has become clear that for near-zero or net-zero energy targets to be economically viable, buildings will have to be configured to optimize built area, passive design, intrinsic material and configurational assets, such as day-lighting, thermal mass, high performance building envelopes, energy efficient lighting and high-performance HVAC systems. All of these energy reducing strategies should be implemented before considering the use of on-site or off-site renewable energy to make the final step to near-zero or net-zero energy. It is also understood that conventional energy saving strategies can only take the building so far and that new and innovative strategies are needed to take the building beyond the 60% threshold and as near-to-zero as possible. For the purpose of this research we labeled this as the 'innovation gap'. The desire to drive hospital buildings as close as possible to net-zero energy was the impetus for the "large dynamic thermal labyrinth" research effort with Cambridge University (UK).

Thermal mass labyrinths have been used for millennia, especially by the Persians and the Romans, and more recently in a number of modern building applications to modulate the inflow temperature of outdoor air, especially in summer when the labyrinth can lower the temperature of the incoming air during the day and warm the air during the night. In such usage, the day-warmed labyrinth warms cool nighttime air by releasing heat stored during the day. In doing so, the labyrinth is gradually cooled. The night-cooled labyrinth then cools warm daytime air by absorbing its heat, so is itself gradually warmed, completing the diurnal cycle. This simple continuous operation approach benefits buildings with consistent daytime cooling and night time heating requirements.

For our hospital application, with complex occupancy, ventilation and changing daily/seasonal heating and cooling requirements, we used a dynamic labyrinth control strategy. The dynamic labyrinth is only actively used to warm or cool the ventilation air whenever there is an energy benefit. When the labyrinth is not needed to warm or cool the ventilation air, the labyrinth is decoupled from the ventilation system. This allows the thermal mass to be warmed or cooled independently using wind assisted flushing towers to change the thermal mass storage temperature for use later to heat or cool the ventilation air.

Methodology

The team developed a conceptual layout for a prototypical 200-bed acute care hospital that would be efficient and provide daylight and view for the majority of patients and caregivers. The IPU component was developed from previous research on communication-rich cross-hall IPU layouts. It incorporates vertical air distribution - allowing reduced floor-to-floor heights, automatic exterior solar shading, displacement ventilation and a high-mass structure with thermally active surfaces. For the Pacific North West test hospital, a large thermal labyrinth was

located within the void generated by a base isolation seismic system, the extent of which was defined by the entire footprint of the hospital, including its multiple courtyards.

Figure 1: Typical Base Isolation Seismic System Used in the Pacific NW Test Hospital



Optimizing the efficiency of the thermal labyrinth was the primary focus of Cambridge University. They first developed numerical models to optimize the thermal storage capacity and the energy exchange surface areas, as well as an algorithm to determine when the ventilation air was to flow through or bypass the labyrinth. Using this information in conjunction with parameters such as the free volume generated by the base isolation system, the hospital's occupancy/ventilation requirements and site specific weather data, they determined the optimized air temperature leaving the thermal labyrinth over the course of a full year.

The dynamic labyrinth temperatures were then applied, along with other energy conservation measures, to modeling of the overall energy performance of the IPU component of the hospital.

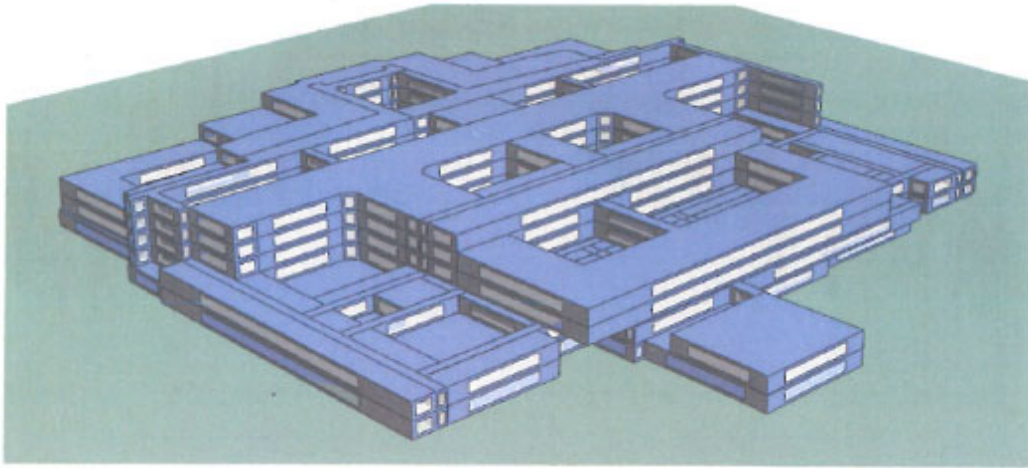
Test Hospital

Modern hospitals must achieve operational efficiency and flexibility, enhance communication within and between care teams, reduce energy consumption and above all be safe for both patients and staff. The test hospital developed for this study responds to these imperatives in part by organizing functions within three main blocks – ambulatory care, inpatient, and diagnostic – to allow systems to be rationalized to their specific needs.

The challenge for any integrated design approach is finding the optimal integration of systems with minimal impact on construction costs. The objective of this study is to provide the data to support strategies that have **broad applicability** across regions and can be implemented within the existing North American regulatory framework.

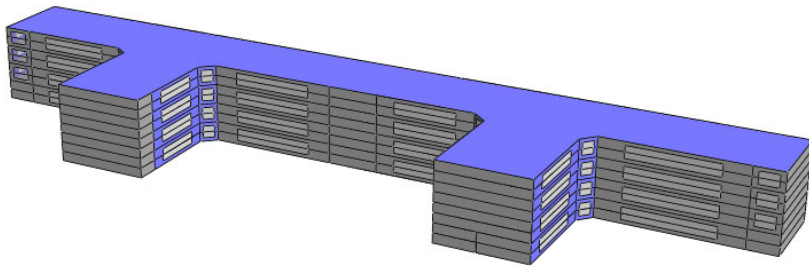
The test hospital is based on evidence-supported design principles and can be used as a virtual design tool for analyzing single or multiple energy conservation measures and comparing them to the ASHRAE 90.1 – 2007 baseline.

Figure 2: 50,000 m² (538,000 ft²) Test Hospital



Source: BC Hydro et al, 2011

Figure 3: 12,350 m² (132,900 ft²) Inpatient Unit (IPU) within the Test Hospital



The seismic requirements facing hospitals in the Pacific Northwest are among the highest in the world. The immediate post-event operability benefits of base-isolation type seismic systems are widely acknowledged, but there is an approximately 2-5% of total cost premium for a base isolation system over conventional seismic systems. The research investigated synergistic opportunities to explore how this costly requirement could be leveraged to reduce energy consumption and overall built area and volume (the base isolation system creates a 2.5 meter ‘walk-in space’ between entry level and a below grade parking level in the test hospital). The synergistic opportunities included using the walk-in space in the base isolation system to house mechanical ventilation equipment as well as the dynamic thermal labyrinth, and using vertical air distribution to reduce the total system air pressure drop and floor-to-floor height.

Figure 4: The Test Hospital Comprises 3 Blocks Separated by Courtyards and a Thermal Labyrinth between the Hospital and One Level of Underground Parking

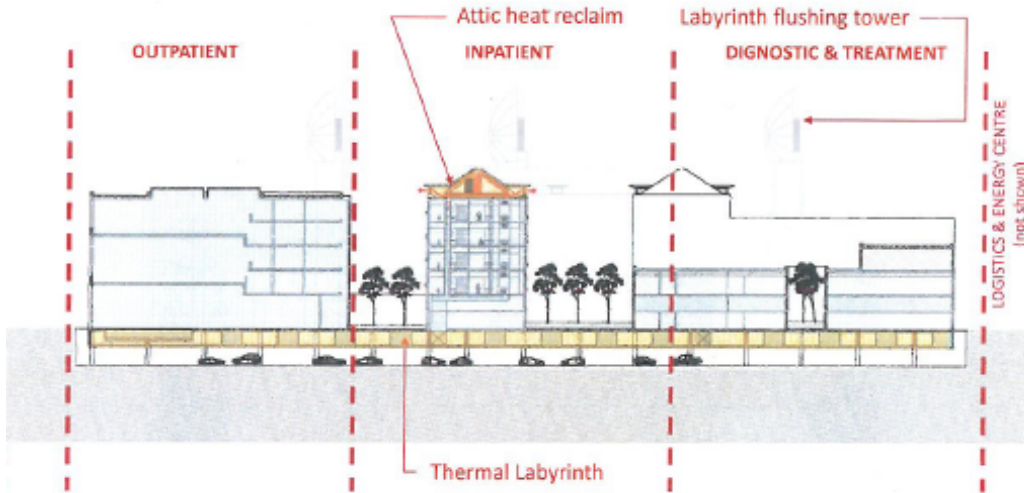
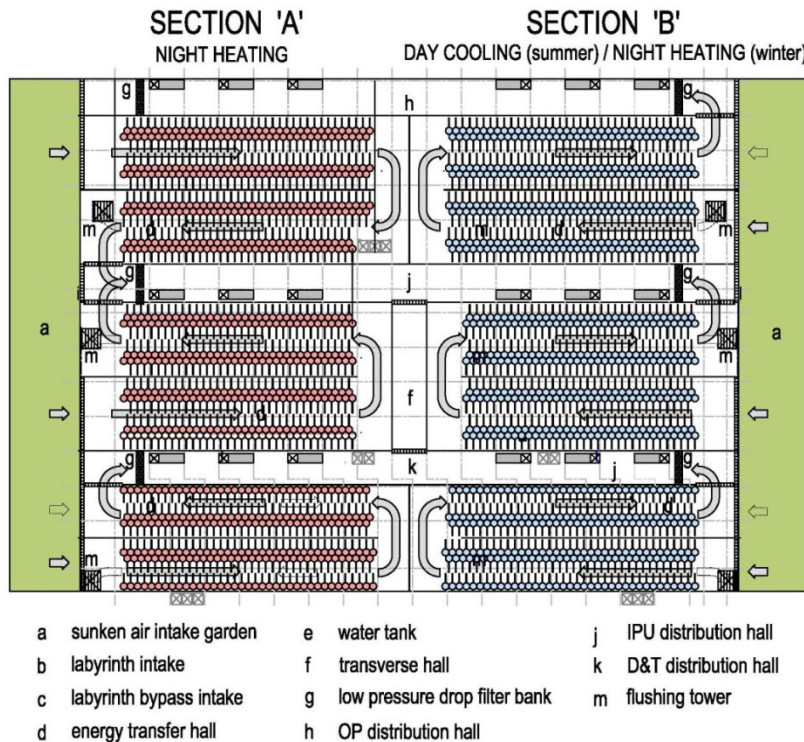


Figure 5: Thermal Labyrinth Plan View Showing Air Paths



The IPU layout developed for this study provided dedicated vertical supply and exhaust shafts for each inpatient room. This eliminated the potential for cross contamination between rooms, the need for sound dampers, and almost all horizontal ductwork and associated crossovers. It also allowed for a reduced floor-to-floor height of 3.6 meters. The lower floor-to-floor height reduced construction cost, increased daylight penetration, and allowed concrete floor slabs to be made ‘thermally active’ using low-grade energy for low-temperature heating and

high-temperature cooling. The decoupling of heating and cooling from ventilation in turn allowed the use of displacement ventilation in the IPU and other non-critical areas.

Thermal Labyrinth Analysis and Results

As stated above, thermal labyrinths have been used for thousands of years to modulate the inflow temperature of the air, especially during the summer when the labyrinth can lower the temperature of the incoming air during the day and warm the air during the night.

As far as we are aware, there has not been a significant study of the potential benefits of heat storage in a dynamic thermal labyrinth in winter conditions, even though there are still substantial swings in temperature between the day and night. The application is very different from the conventional labyrinth in that during the winter, the dynamic thermal labyrinth uses the warmest day time temperature to warm the labyrinth, using a decoupled flushing system and active air flow control strategies. The warmed labyrinth is then used to pre-heat the night-time ventilation air required for the 24/7 areas within the hospital, including IPU. With diurnal temperature differences of 5 to 10°C in winter, significant pre-heating of night time ventilation air can be achieved using dynamic control of the labyrinth.

In our study we have assumed that the air flow through the labyrinth is actively controlled based on the real time labyrinth and outside air temperatures as well as the actual and predicted use of the hospital. Three modes of air flow through the labyrinth are employed (see Figure 5):

- Air flowing slowly through the labyrinth to air handling equipment distribution halls serving each of the functional blocks
- Air flowing directly in to the air handling equipment distribution halls bypassing the labyrinth
- Air flowing through the labyrinth at higher air speeds generated by wind assisted flushing towers (bypassing the air handling equipment distribution hall)

Cambridge University researchers used the test hospital model and weather data to optimize the benefits of using water storage tanks as a thermal media in the labyrinth. They developed mathematical models that accounted for changes in air temperature, air flow rates, radiator surface area and water tank temperatures over the course of the year for each successive 24-hour period and mode of operation. Using the model, the researchers were able to develop the parameters critical to determining the optimum length of pipe for the heat exchanger, the water circulation rate, and the size of water tanks that balanced the need for winter pre-heating and summer pre-cooling. It was determined that 300 x 4m³ (141 ft³) water tanks, interconnected in 30 clusters of 10 tanks was optimal, with each cluster of tanks having a reversible water pump to circulate the water from the tanks to their respective heat exchange. This rationalized the number of water pumps required, and enabled use of more substantial pumps that circulate about 1 l/s (16 usg/min) through the heat exchange pipes. The reversible pumps allow the pumping of stratified water in the storage tanks from either the top of the tanks (for heating) or from the bottom of the tanks (for cooling). The pumps would also allow the tanks to be deployed sequentially, depending on demand, mode of operation, and tank temperatures.

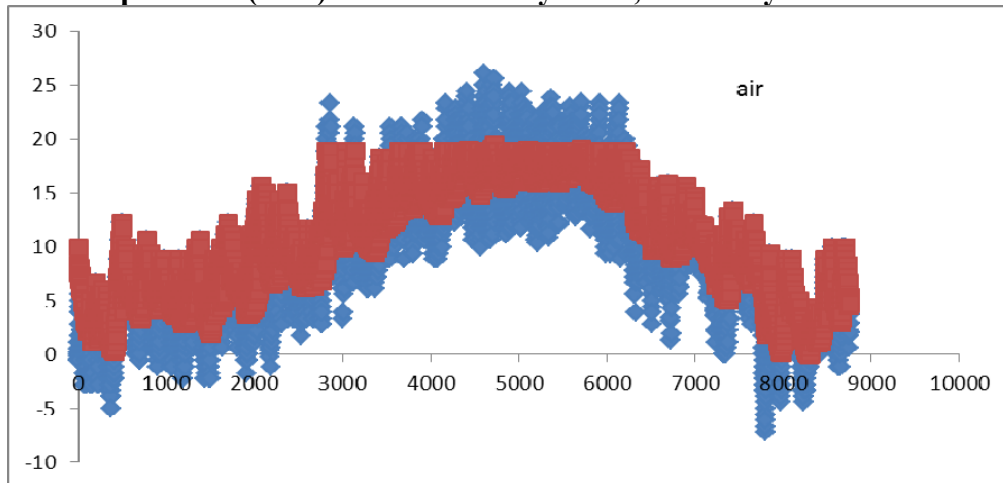
For the IPU, the assumed ventilation system is a mixed mode system using displacement ventilation. The displacement ventilation system requires a constant supply air temperature of

19°C. The labyrinth control strategy optimizes the use of the thermal storage and outside air cooling and heating capacity to minimize the required supplementary heating and cooling from the hospitals heating and cooling plant.

Figure 6 shows the variation of the outside air temperature through the year in Vancouver (blue) and the inflowing air temperature leaving the labyrinth and entering the hospital air handling systems (red). It is seen that there is substantial cooling benefit in the summer and heating benefit throughout the year e.g. as stated above, the night-time cold outside temperatures are buffered by the diurnal heating of the labyrinth during the day, therefore providing an energy benefit for summer cooling and winter heating.

For the IPU in Vancouver, Cambridge University’s analysis shows the average increase in inflowing temperature in cold external conditions is 1.9 °C (3.5°F) saving about 406 MWh/yr preheat while the average cooling in the summer is 3.4 °C (6.1°F) with a saving of about 99 MWh/yr cooling load. Note that the cooling demand is quite localized in time while the pre-heating is used all year round owing to cool night-time temperatures throughout the year.

Figure 6: Variation of the Inflowing Air Temperature from the Plenum (red) and the Outside Air Temperature (blue) in Vancouver ‘y’ Axis, for Every Hour of the Year ‘x’ Axis



The study examined how the outside air temperature, labyrinth thermal mass temperature and hospital usage varied for every hour of the year to optimize the operation of the dynamic thermal labyrinth. Figures 7 and 8 show the temperature of the outside air (blue), temperature of the air leaving the labyrinth/entering air handling system (red) and first water tank in the labyrinth (green) as a function of time for hours 550-600 during the year, which correspond to late winter, and for hours 4400 to 4450, corresponding to the middle of summer. The figures also show the mode of operation (orange squares), where a value 0 corresponds to bypass mode (outside air directly flows into the air handling plenum), a value 1 corresponds to winter preheat and a value 2 is summer cooling (see the right “y” axis).

As can be seen, on the summer day, there is an extensive period of pre-cooling through the middle of the day, extensive intervals of pre-heating at night owing to the cold night temperatures, and the bypass mode use is relatively small.

Figure 7: Temperature of Labyrinth (green), Outside Air Temperature (blue) and Air Temperature Leaving the Labyrinth (red) as a Function of the Hour during the Year, for a Winter Scenario. Orange Boxes Illustrate the Operation of the System (right y-axis)

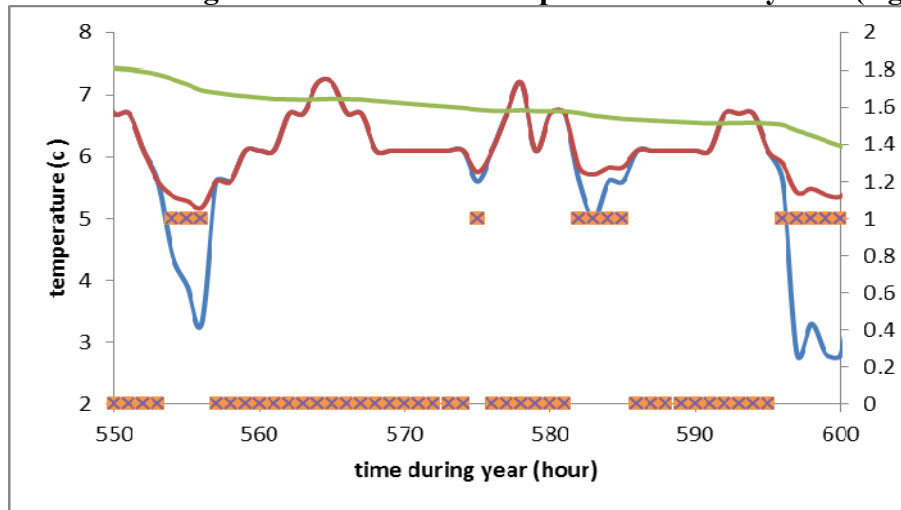
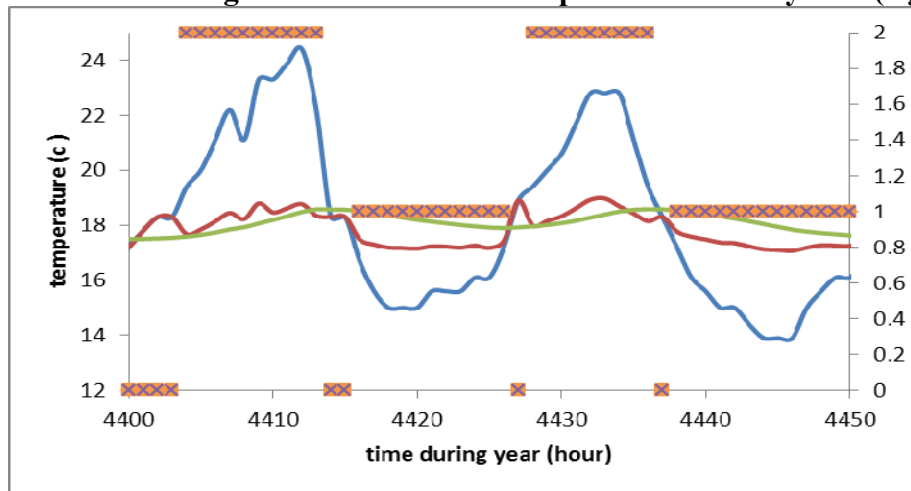


Figure 8: Temperature of Labyrinth (green), Outside Air Temperature (blue) and Air Temperature Leaving the Labyrinth (red) as a Function of the Hour During the Year, for a Summer Scenario. Orange Boxes Illustrate the Operation of the System (right y-axis)



In summary, the Cambridge University research considered the potential benefits of the thermal labyrinth's energy storage and exchange for both winter and summer conditions. The novel strategy uses the warmer day temperatures to pre-heat the labyrinth for use at night in pre-heating the night ventilation air; this is shown to provide comparable or greater energy savings than the conventional summer pre-cooling use of the labyrinth, dependent on the ratio of the day to night ventilation rates.

The results from Cambridge Universities study were provided to the energy modelers (M+NLB) to be used as their modified outside air temperature for use in the IES Virtual Environment V6.4 energy modeling of the IPU.

Inpatient Unit Energy Study

The test building model described in this article was developed in Integrated Environmental Solution's Virtual Environment (IES VE) v6.4 energy modeling software. A model based on the prescriptive parameters of ASHRAE standard 90.1-2007 was developed in order to provide a baseline to which proposed strategies could be compared and savings quantified. Simulations for this study were performed using Vancouver, BC climatic data. The simulations performed energy analysis to test the following **ECMs** (Energy Conserving Measures) on the test model:

Table 1: ECM Descriptions

	ECM Description	Discussion
ECM 1	Daylighting	Daylighting controls are used extensively throughout the IPU rooms, allowing reductions in lighting power throughout the year
ECM 2	Automatic Solar Shading	Automatic exterior solar shading devices reduce room cooling loads and help eliminate hot spots on the floor which may diminish displacement ventilation effectiveness.
ECM 3	High Efficiency HVAC System	Displacement ventilation system provides low velocity air at elevated supply temperatures 17.2- 20°C (63 - 68 °F), saving fan energy as well as cooling energy required to temper the air. Modular heat pumps with reduced heating hot water supply temperature 49°C (120 °F) and elevated chilled water supply temperature 12.2°C (54 °F) allowing increased efficiency. Decoupled hydronic heating/cooling at zone level using thermally active radiant slab system
ECM 4	Thermal Labyrinth	A thermal labyrinth with water-based thermal storage tanks naturally preconditions entering outside air. A combination of bypass and mixing dampers allows optimized entering air conditions (with a mixed air temperature target of 17.2- 20°C (63 - 68 °F) while minimizing necessary air tempering at the air handling unit.
ECM 5	Hybrid Natural Ventilation	IPU rooms take advantage of a hybrid natural ventilation strategy by allowing outside air to directly enter the space when the following conditions are satisfied: outside air temperature is between 15.5 and 27°C (60 and 80 °F); room air temperature is above 20°C (68 °F) and below 23.5°C (74 °F). When these conditions are satisfied, supplied airflow is reduced from 4 to 2 ACH, and mechanically controlled louvers open to allow untempered outside air directly into the spaces
ECM 6	Heat Recovery	Modular heat pumps with integral heat recovery capture waste heat from cooling cycle to precondition heating hot water and DHW, significantly reducing heating energy required between April and October when cooling load is prevalent.

Results for the individual ECMs are listed in Table 2 below for each of the three locations simulated, followed by the annual energy use intensity by end-use category for Vancouver BC (Figure 9).

Table 2 Annual Saving for the ECMs for the IPU, Vancouver BC

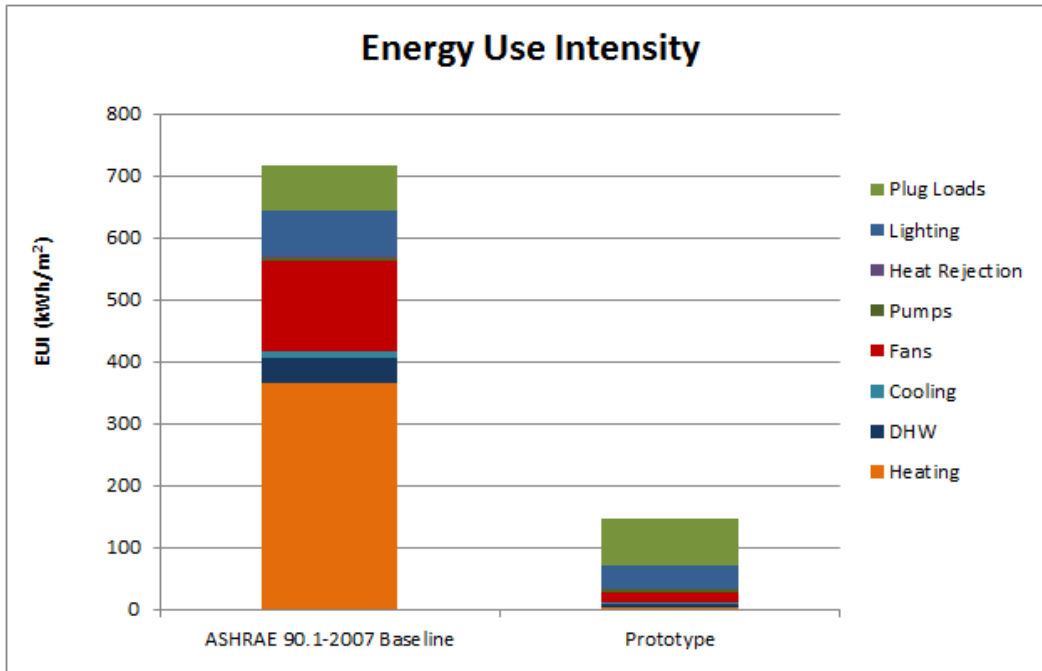
ECM#	ECM Description	Electricity Savings	Electric Demand Savings	Natural Gas Savings	Energy Cost Savings	Total Energy Savings
		kWh	kW	therms	\$	ekWh/m2
ECM 1	Day lighting	114,470	0	0	\$6,800	9
ECM 2	Automatic Solar Shading	11,120	2	0	\$661	1
ECM 3	High Efficiency HVAC System	4,300,370	77	0	\$255,468	348
ECM 4	Thermal Labyrinth (note #1)	505,000	102	0	\$30,000	41
ECM 5	Hybrid Natural Ventilation	31,800	6	0	\$1,889	3
ECM 6	Heat Recovery	14,140	0	1,028	\$2,630	4

Note 1; ECM #4 is the primary focus of this paper, the calculated energy savings as determined by Cambridge University is in the order of 505 MWh/yr, which translates to an energy saving of about \$30,000/ yr.

Table 3: Annual Energy Consumption per End-Use and Energy Use Intensity (EUI) for the Inpatient Tower, Located in Vancouver BC, Edmonton and Phoenix

End Use Energy (kWh/m ²)	VANCOUVER		EDMONTON		PHOENIX	
	ASHRAE 90.1-2007 Baseline (kWh/m2)	Test (kWh/m2)	ASHRAE 90.1-2007 Baseline (kWh/m2)	Test (kWh/m2)	ASHRAE 90.1-2007 Baseline (kWh/m2)	Test (kWh/m2)
Space Heating Energy	364	2	426	16	213	0
DHW Energy	40	5	40	7	40	1
Space Cooling Energy	11	4	10	3	60	53
Fan Energy	148	16	148	16	148	21
Pump Energy	6	6	5	6	14	15
Heat Rejection Energy	3	0	2	0	10	0
Lighting Energy	71	37	71	37	71	37
Plug Load Energy	75	75	75	75	75	75
Total Energy EUI (kWh/m2)	718	146	777	161	630	203

Figure 9: Energy Use Intensity (EUI) for the ASHRAE Baseline and the Proposed Design by System Component in Vancouver BC



Conclusions

As stated above, present day best practice design can relatively easily achieve 60% energy reduction as compared to code compliant design practice. To achieve 80% energy reduction it was necessary to employ a number of innovative design solutions over and above present day “best practice” design. The Dynamic Thermal Labyrinth and the integration of the thermal labyrinth with the natural/hybrid ventilation system provided the required additional energy savings, to take the design from 60% to the targeted 80% energy savings. It is clear from this study that integrated design is essential and that the building configuration, envelope, structure, and the mechanical and electrical systems have to be designed to minimize the energy use and at the same time collect, reuse and store any excess energy for future use.

The ECM’s cannot be considered in isolation in that they all work in an integrated and synergistic manner to achieve the overall energy savings.

Having stated this, the focus of this research was on the optimization of the thermal labyrinth. The optimization included: active/inactive flow; flushing using wind assisted flushing towers; water thermal storage; pumped energy exchange; and “real time” control strategies to improve the energy storage and energy transfer capabilities of the labyrinth.

The energy savings for the Vancouver IPU labyrinth, as calculated by Cambridge University is in the order of 505 MWh/yr (406 MWh/yr preheat energy reduction and 99 MWh/yr mechanical cooling energy reduction). This translated to an energy cost saving of approximately \$30,000/yr.

In addition to the reduction in operating energy, the thermal labyrinth eliminates the need for mechanical cooling in the IPU air handling system i.e. the air temperature leaving the thermal labyrinth is never higher than the required displacement ventilation system supply air temperature.

From a costing analysis that was undertaken as part of the BC Hydro study, the cost premium for the thermal labyrinth (air intakes, wind assisted flushing towers, dampers, controls, tanks, piping, pumps etc.) was in the order of \$800,000 CDN which would give a simple payback in the order of 26 years (it should be noted that the cost premium does not include the cost of the seismic base isolation system).

Areas requiring further research include:

- Expanding the scope to include the full acute care hospital
- Optimize the labyrinth performance by utilization of “forward thinking” control and minimize the built volume needed to accommodate on-site thermal storage
- Explore design of the main components of a labyrinth–air path configuration, storage medium and energy transfer mechanism– to optimize efficiency and/or achieve 100% passive operation
- Explore on-site thermal storage and direct energy transfer systems to optimize synergies between the main components of the hospital as a whole

Although further research is required, this study provides strong evidence that an integrated approach to healthcare facility design with an active thermal labyrinth can result in significant improvements in energy consumption in a range of climatic zones.

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Keywords

Thermal Labyrinth, Mixed mode ventilation, Buildings, Hospitals, Inpatient units, green, energy, health, net zero.