# RADIANT SLAB COOLING: A CASE STUDY OF BUILDING ENERGY PERFORMANCE

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## ABSTRACT

This paper introduces a case study of an existing multi-floor radiant slab cooling system through simulation and field measurements. *EnergyPlus* was selected based on a review of currently-available simulation programs. Real weather data were used and the model was calibrated with metered energy data. Simulated energy uses and indoor thermal conditions were compared with measured data to evaluate comfort conditions and operations. The exercise revealed problems in the existing *EnergyPlus* low-temperature radiant cooling/heating module and some uncertainties in the simulation model. Major problems in the control of the HVAC systems were identified, and remedial measures are proposed.

## INTRODUCTION

In Canada, most buildings have to be heated in winter and cooled in summer (Donnini *et al*. 1997). However, in many large commercial buildings, the interior zones require cooling in winter as well. Even in a cold climate, space cooling contributes 4% ~ 8% to annual energy use in commercial buildings (NRCan 2000). In recent years, radiant cooling technology has received increasing attention, especially in Europe. In North America, radiant cooling systems are still rare. It is often claimed that radiant systems both improve thermal comfort and increase energy efficiency (e.g. Imanari *et al*. 1999, Watson *et al.* 2002).

To investigate whether radiant cooling systems provides comfort and efficient operation, simulation and field measurements were used to investigate energy performance and thermal conditions at the University of Calgary's Information and Communications Technology (ICT) Building, which is equipped with radiant slab cooling and has operated since 2002.

## SIMULATING THE ICT BUILDING

### Selection of simulation programs

To analyze building energy performance with radiant slab cooling systems, whole building simulation results were compared with measured energy use and thermal conditions. A literature review of currently-available simulation programs for modeling radiant cooling systems was conducted. These programs include *ESP-r, TAS, TRNSYS, IDA ICE* and *EnergyPlus*.

Laouadi (2003) developed a semi-analytical model to simulate radiant heating and cooling systems within *ESP-r*. However, this model uses some simplifications such as the average specific heat for construction assemblies and the simplification may cause inaccurate results. Moreover, the validation of this model is limited to one zone (Weber *et al.* 2005).

*TAS* models the radiant system by defining a water cavity layer in the slab construction (Lee 2004). The simulated radiant slab only has an on-off control for the, and neither the slab temperature nor operation can be controlled based on the space temperature, which may lead to questionable results when analyzing annual building energy use.

Koschenz *et al.* (1999) developed a combined RC-conduction transfer model for *TRNSYS*, which is integrated into the multi-zone model of Type 56. But this model is not applicable to radiant panel systems and may not be accurate in simulating radiant slab systems when the pipe temperature fluctuation interval is less than 10 hours (Weber *et al*. 2005).

The *IDA ICE* program (Weber *et al.* 2005) can integrate an RC-network model to simulate radiant panel and radiant slab systems. But *IDA ICE* has a very small user base (Sahlin *et al.* 2003) and little literature has been published on results for radiant systems.

Strand *et al.* (2002) developed a radiant heating and cooling module for *EnergyPlus* based on the conduction transfer function method. To date, this module has some deficiencies when simulating combined radiant slab cooling and air systems: 1) the air temperature is the control parameter (instead of the operative temperature), and 2) the radiant system and air system can only be modeled in sequence instead of in parallel (Strand *et al*. 2005), which may differ from actual operating conditions in combined air and radiant systems.

The *EnergyPlus* radiant module was validated for a single zone radiant cooling system (Chantrasrisalai *et al*. 2003). Simulation results agreed well with the field measured data for both cooling energy use and indoor operative temperatures, but simulation results were sensitive to construction and system parameters. As well, the radiant system was the sole means of conditioning the space (i.e., there was no air system). According to DOE (2006), 31,000 copies of *Energyplus* have been downloaded.

Based on these results, the *EnergyPlus* program (Version 1.2.3) was selected for this study.

### The ICT Building

Calgary has annual heating and cooling requirements of about 5500 and 1000 degree days respectively. The ICT Building is a seven-storey 17,500 $m^2$ teaching and research facility located at the University of Calgary campus. The building has two main parts: the base and the tower. The tower (floors 2-7) includes laboratories, classrooms, faculty offices, and graduate student workstations. North and south service zones contain stairs, washrooms, and student lounges (Figure 1).

Three variable air volume (VAV) systems with terminal reheat serve the base. Another VAV system with reheat provides ventilation and heating/cooling to floors 2-7. Radiant panels offset heat loss in all perimeter areas. The radiant slab provides cooling in the tower except for the two service zones (Figure 1). The radiant slab cooling system circulates constant flow, 16 to 22 $^{o}C$ water in polyethylene pipes embedded in the concrete slabs. The chilled and hot water are provided by a campus system, with thermal meters to monitor the cooling and heating (including domestic hot water) energy uses in the ICT building.

Electricity is supplied via two transformers. One provides power for lighting and plug loads. The other provides power for fans, pumps, elevators and a nearby temporary building.

### Adjusting model inputs

Conditions such as occupancy patterns and lighting use were estimated and may thus cause differences between the measured and simulated results. The occupancy schedule, lighting schedule, and plug load (electrical equipment) schedule were adjusted to more closely represent the real situations. The main adjustments to the default schedules of Canada Model National Energy Code for Buildings (MNECB) (NRCan 1997) were: were: 1) the tower VAV system operates 24 hours per day, 2) the questionnaire results indicated that one third of participants in the interior zones worked during weekends; 3) about 30-40% of luminaires in the interior zones were activated outside the base schedule due to the lack of visible light switches; 4) most desktop computers were on "stand-by" or "log-off" instead of "off" during the unoccupied period. Desktops in the "turned on but not being used status" consume about 30-50% energy of the "on" mode (e.g. Sator, 2006; EU Energy Star, 2006).

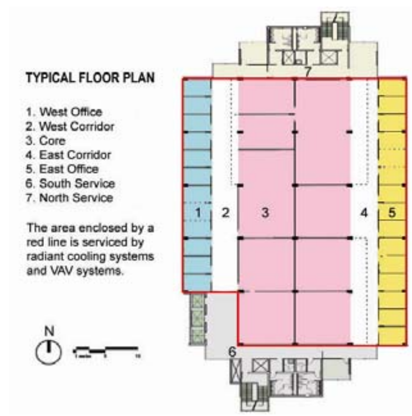


*Figure 1: Typical Floor Plan of ICT Building*

Another factor impacting building energy use is the operable windows in the ICT Building. It was found that some windows were kept open all day from April to October independent of the weather. As Calgary generally experiences 1640 heating degree hours during the period from April to October, the open windows could increase the outside air flow in the perimeter zones and the heating load of the building. The COMIS module was not adopted in simulating the air infiltration flow rates for two reasons: 1) the COMIS module generally cannot model simultaneous mechanical and natural ventilation (DOE 2005); 2) the number of opened windows and the size of each opening are unknown. As the detailed modeling of air infiltration rates with open windows is not the purpose of this research, the infiltration flow rates were approximated at 1.2 (June and August) and 1.4 (July) air changes/hour (ACH) (Wallace *et al.* 2002), gradually reduced to 0.2 ACH during the coldest months when it was observed that few windows were opened.

## Comparison of energy uses

Based on hourly real weather data and operating schedules adjusted to reflect actual conditions, the simulation model predicted annual cooling, heating (including domestic hot water heating), lighting & equipment energy usage with reasonable results for 2003 and 2004.

*Table 1: Measured vs. simulated energy uses*

| GJ | Meas. 2003 | Sim. 2003 | Meas. 2004 | Sim. 2004 |
|---|---|---|---|---|
| **Cooling** | 4997 | 4720 | 4037 | 4052 |
| **Heating** | 7300 | 7005 | 6771 | 6719 |
| **Lighting& Equipment** | 4323 | 4020 | 4060 | 4020 |

For 2003, simulated annual cooling energy use was roughly 5.5% lower than the metered amount (Table 1). The 2003 simulated annual heating energy use was about 4% lower than the metered quantity. For 2004, simulated annual cooling was only about 0.4% higher than metered data and simulated heating energy about 0.8% lower.

The 2003 simulated annual electricity use for lighting and equipment was about 7% lower than metered. For 2004, the simulated electricity use was about 1% lower than metered. The main difference is simulated electricity use exceeding metered use in July and August of 2003 (Figure 4). The electricity use in each of these months is about 30% higher than the monthly electricity use for lighting and equipment (about 335 GJ/month and varies between 300 GJ and 370 GJ). The reason is unknown to the authors. A possible explanation is the unexpected use of electrical equipment in the building because this building houses the Departments of Electrical Engineering and Computer Science.

## Simulation model calibration and verification

With numerous variables in the simulation model as well as complicated systems and time-varying operating patterns in the actual building, uncertainties exist in simulation. Simulation models provide better quality data when calibrated using metered energy use, which is especially important when used for evaluating energy conservation measures (ECMs). Either hourly or monthly data can be employed for calibration (IPMVP 2002). In this case, only monthly data were available. The comparison of metered and simulated energy uses in 2003 and 2004 is graphed in Figures 2, 3 and 4.

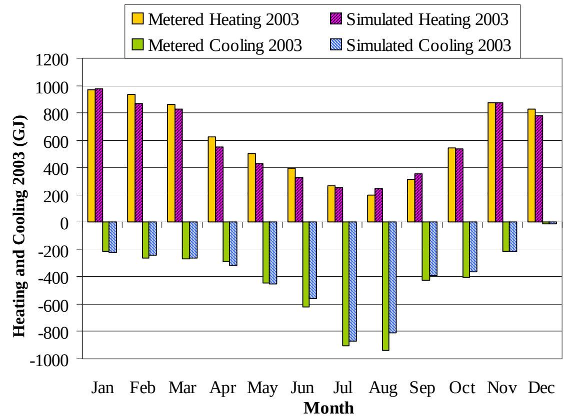


*Figure 2: Metered and simulated monthly heating and cooling energy uses for 2003*

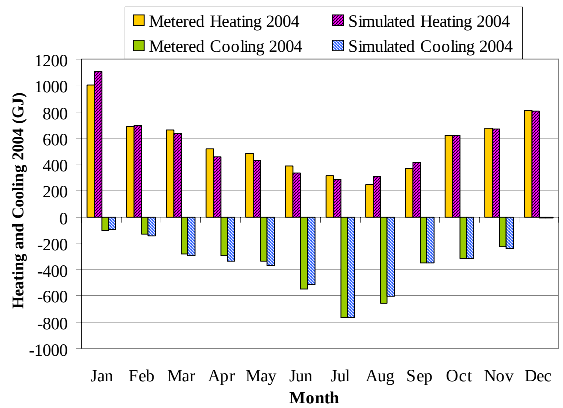


*Figure 3: Metered and simulated monthly heating and cooling energy uses for 2004*

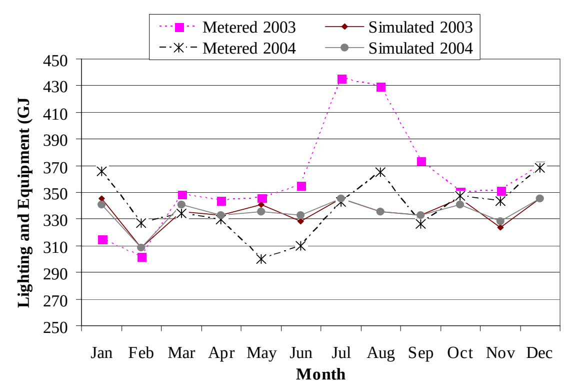


*Figure 4: Metered and simulated monthly electricity uses for lighting and equipment in 2003 and 2004.*

The International Performance Measurement and Verification Protocol (IPMVP 2002) and the US DOE measurement and verification guidelines (DOE 2000) provide guidance for the calibration of simulation models. Calibration indices include error (ERR) and coefficient of variation of the root-mean-squared-error

(CV(RMSE)). The evaluation criteria are listed in Table 2.

*Table 2: Criteria for monthly data calibration*

| INDEX | IPMVP | FEMP |
|---|---|---|
| $ERR_{month}$ | 20% | 15% |
| $ERR_{year}$ | --- | 10% |
| $CV(RMSE_{month})$ | 5% | 10% |

As monthly differences in measured and simulated energy uses may cancel each other, resulting in a smaller annual ERR, the combination of EER and CV(RMSE) can be used to determine how well the simulation model predicts the building energy uses (DOE 2000). The calibration results for 2003 and 2004 are listed in Table 3. Generally the calibration results of 2004 are slightly better and basically meet the criteria prescribed in the FEMP (DOE 2000).

*Table 3: ICT error statistics for 2003 and 2004*

| Year | Index | Coolin g | Heating | Electricity for Lighting & Equipment |
|---|---|---|---|---|
| 2003 | $ERR_{year}$ | 3.1% | 2.4% | 6.2% |
| | $CV(RSME_{month})$ | 10.8% | 7.9% | 11.9% |
| 2004 | $ERR_{year}$ | 1.7% | 0.6% | 0.7% |
| | $CV(RSME_{month})$ | 7.2% | 8.5% | 5.8% |

As shown in Figure 4, the unexpected higher July and August 2003 electricity use for lighting and equipment directly increased the difference between metered and simulated electricity use and also increased the difference in cooling energy use.

### Verification when radiant cooling was inactive

Illustrated in Figures 2 and 3, the cooling energy use in December was only 11.5 GJ and 8.2 GJ for 2003 and 2004, significantly lower than other months (Figures 2 and 3). Further investigation revealed that the radiant slab cooling system of the ICT Building only ran about 1.5 days and in December 2003, and 1 day in December 2004. The simulated radiant cooling energy uses were 11.8 GJ in 2003 and 8.4 GJ in 2004. As well, it was also found that the radiant slab cooling system only ran about half a month in January and February 2004. Accordingly, the metered and simulated cooling energy uses are about half of those in January and February of 2003 (Figures 2 and 3). The simulation model predicted monthly cooling energy use very well for these months, based on actual operating schedules of the radiant cooling systems.

### Actual cooling energy use

The hot and chilled water for heating and cooling is provided by campus network with thermal meters recording water temperatures and flow rates. However, the chilled water (around 5 $^{o}$C) during the cold months did not come from the chillers but directly from the Bow River nearby the university campus.

The information from campus infrastructure shows that the chillers which supply the chilled water generally stop during the period of November to March of the next year. This means that the cooling energy is free except the energy use in pumps and fans for these five months. The actual cooling energy uses are 4022 GJ in 2003 and 3274 GJ in 2004.

## MEASUREMENT OF INDOOR THERMAL CONDITIONS

### Comparison of indoor climate conditions

As Chantrasrisalai *et al.* (2003) showed, even though the simulated energy uses match metered energy data, simulation results may contain errors. It is necessary to compare the actual and simulated temperatures, especially operative temperatures.

An east side private office and an interior computer laboratory were chosen as field measurement locations. The simulated temperature trends in the interior zone and the east zone during the daily cycle were similar to the measured values for August, 2004 (Figures 5-8).

Similar measurements were conducted in a west side private office and the same interior computer laboratory during December 2004 and January 2005. It was found that simulated temperature trends in both rooms were in reasonable agreement with measurement results (Figures 9-12).

As the indoor temperatures were only measured in a few spaces, the measured data may not represent the average temperature in the building. In both summer and winter of 2005, transverse measurements were taken in the interior spaces of the ICT Building. The measured air temperatures at interior spaces ranged from 20.6 to 24 $^{o}$C with an average of 22.3 $^{o}$C for both summer and winter seasons (St.Dev.=0.75 $^{o}$C). The operative temperatures varied between 20.3 and 23.6 $^{o}$C with an average value of around 22 $^{o}$C in both winter (St.Dev.=0.68 $^{o}$C) and summer (St.Dev.=0.78 $^{o}$C). The temperatures in the computer laboratory were close to the average air temperature of interior spaces.

In January 2006, a transverse investigation was conducted to check the temperatures in perimeter offices. By inspecting the temperature setpoints and displayed temperature on thermostats, it was found that the average setpoint temperature and displayed air temperature were both around 23 $^{o}$C (St.Dev.=1.1 $^{o}$C), indicating that the temperature in the measured office was roughly representative of the temperature trends in perimeter offices in winter.

**Discussion**

Generally the east side office reached the highest temperature at 0900 in summer (Figures 5-6). Even equipped with radiant cooling systems and low-E glazing, the indoor mean radiant temperature still exceeded 28 $^{o}$C and the operative temperature reached the upper comfort limit of 27 $^{o}$C while the outdoor dry-bulb temperature was about 19 $^{o}$C. This reveals that solar radiation has a very important effect on the indoor temperature in summer, indicating the requirement for control of solar radiation in perimeter offices. The space air temperature remained above 21 $^{o}$C all day. However, due to the thermal mass of the concrete slab, "coolness" stored in the slab may result in low indoor temperatures at night. The simulation results showed that the air temperature in perimeter offices dropped to around 18-19 $^{o}$C on summer nights unless heat was supplied by the reheat coils in air systems.

With fixed temperature setpoints and relatively stable internal loads, the indoor temperatures of interior zones were stable and unrelated to the outdoor temperatures. The computer laboratory air temperature remained at around 22 $^{o}$C and the mean radiant temperature varied between 20 $^{o}$C and 22 $^{o}$C (Figures 7-8). In winter, interior zones experienced similar temperatures to those in summer, as interior zones require cooling all year (Figures 11-12). For the real building, it was found that reheat coils were activated in the interior areas to prevent overcooling throughout the year. However, these maintained the air temperature at 22 $^{o}$C instead of allowing it to fall to 21 $^{o}$C.

In December 2004, the air temperature in the measured west side perimeter office was maintained above 23 $^{o}$C all day along (Figure 11). It is obviously that there was no temperature setback control during vacant times.

Through the combined simulation and field measurement of indoor thermal conditions, the following major problems were identified with the control of building mechanical systems: 1) the core zones were overcooled and the reheat coils in the air systems were activated all year; 2) operation of radiant cooling systems during the winter in the perimeter zones wastes energy; 3) temperature setback should be used in the perimeter zones during unoccupied times in winter.

## CONCLUSIONS

Comparison of 1) simulated and measured energy uses in 2003 and 2004 and 2) simulated and measured indoor temperature trends showed that *EnergyPlus* represented the ICT Building thermal and energy performance with reasonable accuracy. However, some uncertainties and problems exist in the simulation model:

1) Two models were used to represent the building, one for the base and one for the typical tower floor to avoid convergence problems in *EnergyPlus*. The results were then aggregated. The tower was modeled as a single floor, and the results were multiplied after simulation, because the radiant module does not work correctly with zone multipliers in current version (Witte 2005).
2) The EnergyPlus low-temperature radiant cooling/heating module (version 1.2.3) may not correctly allocate cooling loads between the air and radiant cooling systems (see introduction), especially in the part-load period (e.g. in the evening).
3) The *EnergyPlus* low-temperature radiant cooling/heating module lacks control of the supply-return water temperature range.
4) The actual supplied water temperature for the radiant slab cooling systems was unavailable and may differ from the simulated supplied water temperature.
5) The impact of operable windows on air infiltration rates could only be approximated by variation of monthly air infiltration rates.
6) Fixed schedules were used for internal loads (occupants, lights, equipment) due to lack of detailed information.

With limited information of building design and operation, to simulate a complicated building like the ICT which incorporates a variety of environmental control systems, operable windows, combined with central control and user-override control, it is reasonable to expect that simulated results slightly differ from the metered data.

Through this case study, it was found that even though radiant cooling has the potential to improve energy efficiency, attention must be paid to the control of radiant cooling systems and coordination with air systems to avoid conflicts. Through simulation and measurements, the major problems in the design and operation of building can be identified. With calibrated simulation, cost-effective energy conservation measures can be proposed to improve building energy performance based on current operation control.

## ACKNOWLEDGMENT

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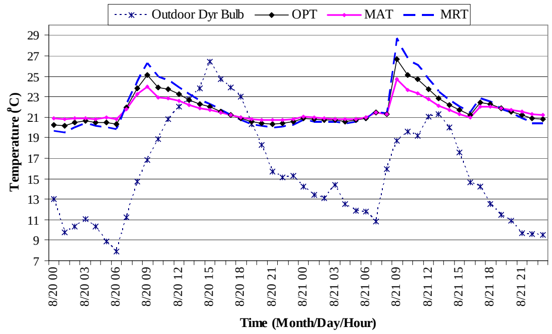


*Figure 5: Measured temperature trends in an east side private office*

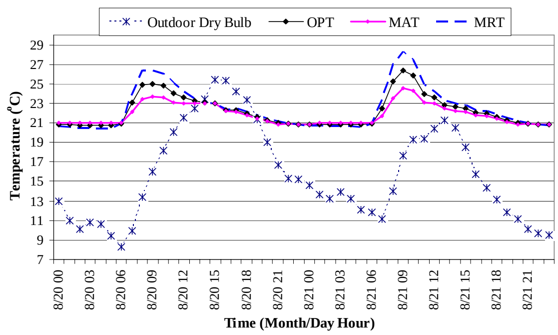


*Figure 6: Simulated east zone temperature trends*

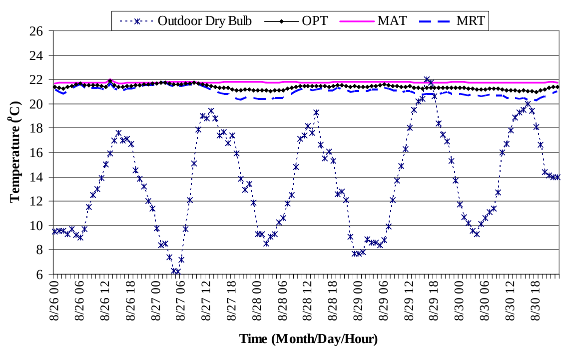


*Figure 7: Measured temperature trends in an interior computer lab*

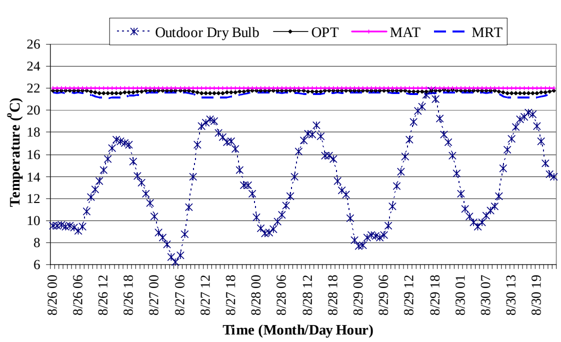


*Figure 8: Simulated core zone temperature trends*

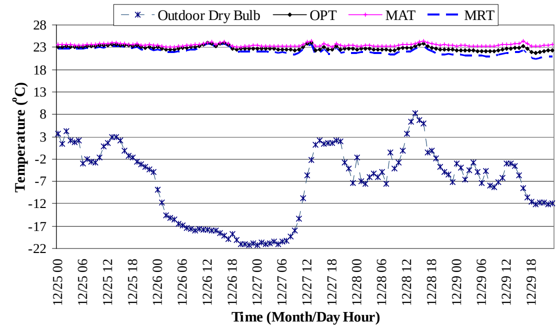


*Figure 9: Measured temperature trends in a west side private office*

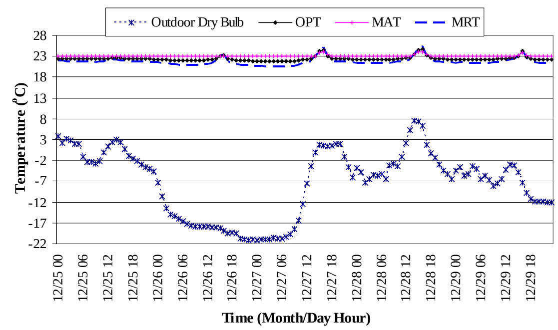


*Figure 10: Simulated west zone temperature trends*

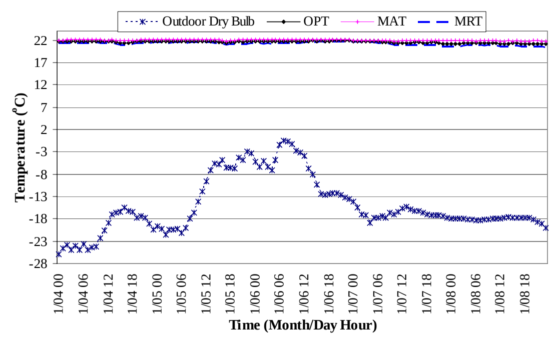


*Figure 11: Measured temperature trends in an interior computer lab*

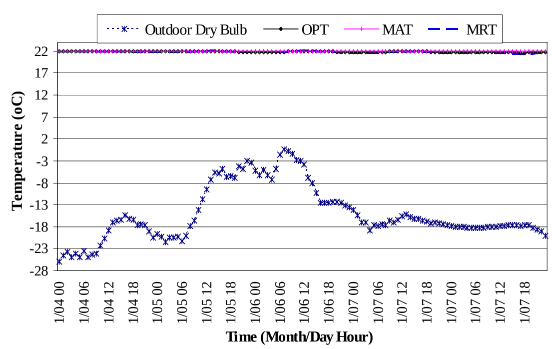


*Figure 12: Simulated core zone temperature trends*