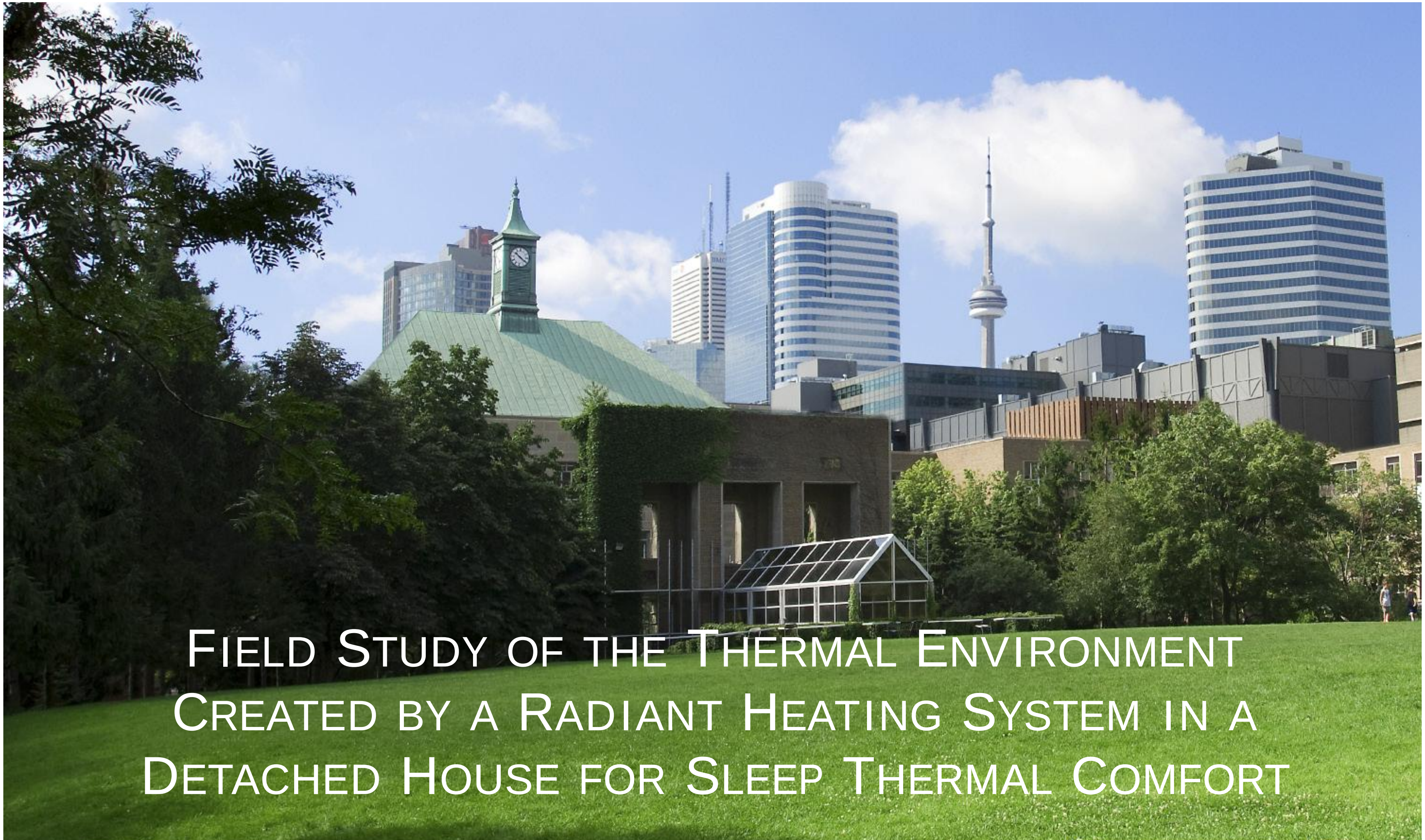


Field Study of the Thermal Environment Created by a Radiant Heating System in a Detached House for Sleep Thermal Comfort

9th Nordic Symposium on Building Physics

Christopher Leung & Dr. Hua Ge

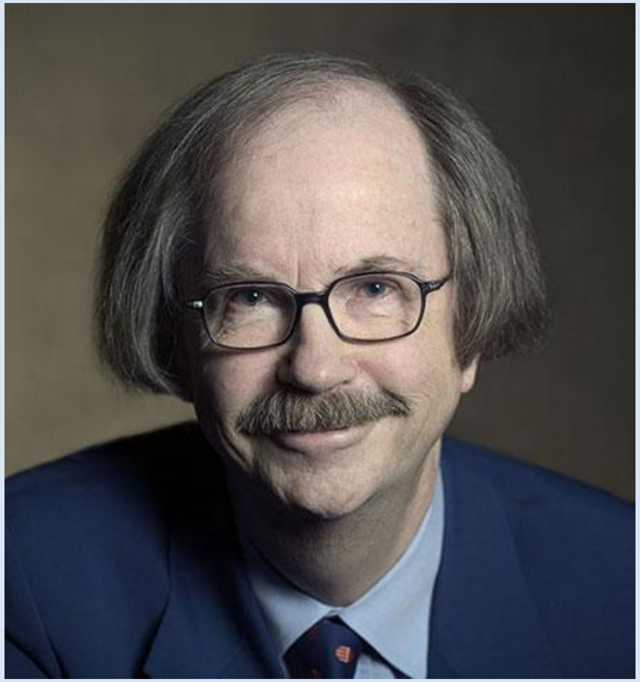
Ryerson University

Introduction

- We sleep a significant portion of our lives
- But sleep thermal comfort have not really been investigated or defined

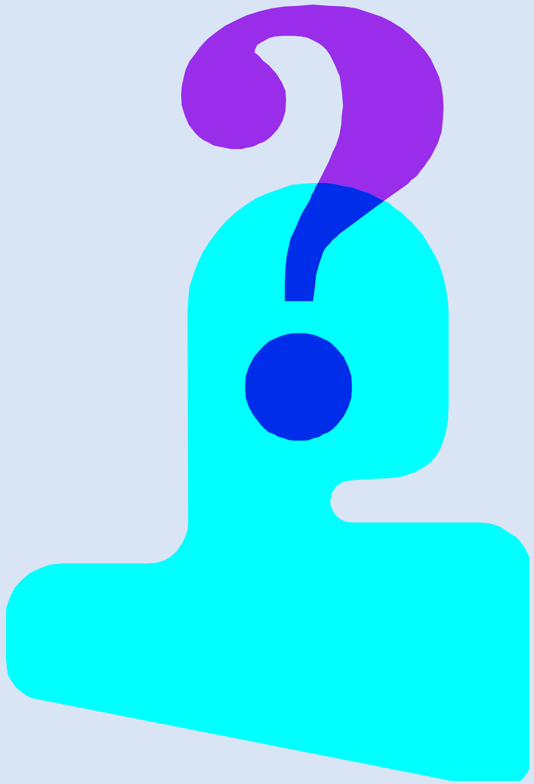
Established Standards

- ASHRAE 55:Thermal environmental conditions for human occupancy
  - Definition of thermal comfort: *The condition of mind that expresses satisfaction with the thermal environment*
- ISO 7730: Ergonomics of the thermal environment
- Both radiant thermal condition criteria is based on P.O. Fanger’s Work



Definition of Thermal Comfort

- ASHRAE 55 especially excludes the sleep condition
- What is sleep thermal comfort:
  - Sleep is unconscious, how can the mind express or how do we record satisfaction?
- Existing research in thermal comfort: neutral heat balance method (Fanger, Gagge)



Comparison Between Asleep and Awake

Asleep	Awake
Reclined or laid down	Standing or seated
Reduced metabolism rate $<40\ W/m^2$	Varied metabolism rate $>60\ W/m^2$
Generally higher clothing value - blanket	Generally lower clothing value
Unconscious thermal regulation and incapable of controlling the environment	Conscious thermal regulation and active participation in controlling the environment

SLEEP THERMAL COMFORT

- Given the differences between sleep and awake conditions, existing thermal comfort research is not entirely applicable
- Some research into thermal comfort of sleeping bags is applicable:
  - Goldman 1988, Holand 1999, McCullough 1994, Hartog et al 2001
- This current research will borrow from psychology: Sleep Quality and Sleep Efficiency – function of sleeping time, REM, S3 and S4 of sleep
  - Bischof et al 1993, Candas et al 1982, Lack et al 2008

Why – Radiant Heating and Sleep?

- Working as a HVAC designer/consultant, several client asked: Why did they wake up in the middle of the night with a cold sweat?
- HVAC systems were radiant heating
- Only males responded to having this issue
- Only occurs when it is near the design conditions outdoors – i.e. HVAC system operating at maximum capacity

Research Objective and Methodology

- Research objective:
  - Focus is on establishing sleep thermal comfort from a radiant ceiling heating system
  - Secondary focus is on potential energy savings of operating the system in reduced output mode during the hours of sleep
- Research Methodology
  - Development of a simple model for sleep thermal comfort
  - Experimental data collection in a building where the occupant have complained about sleep thermal comfort
  - Comparison of model and experimental data

Development of Sleep Thermal Model

- Two types of thermal model are widely used:
- Single node model
  - Treat body as a single mass of flesh
  - Was used to model people whom are awake and for sleeping bags (Goldman 1988, Holand 1999, McCullough 1994, Hartog et al 2001)
  - Suggested and used by ASHRAE Fundamentals 2009 and ISO 11079
- Two node model
  - Treat body as two concentric mass of flesh
  - Widely used to model awake people
  - Used by researcher like: KSU, Pierces and Gagge

Developing of Sleep Thermal Model Cont'

- Model for this research is based on the single node model:
  - Radiant: Stefan-Boltmann's law
  - Convection: ASHRAE Fundamentals for free convection over a cylinder
  - Conduction: Fourier's law
  - Latent heat loss: Respiration at 8.7 L/min @ 34°C leaving (Cain et al, 1990)

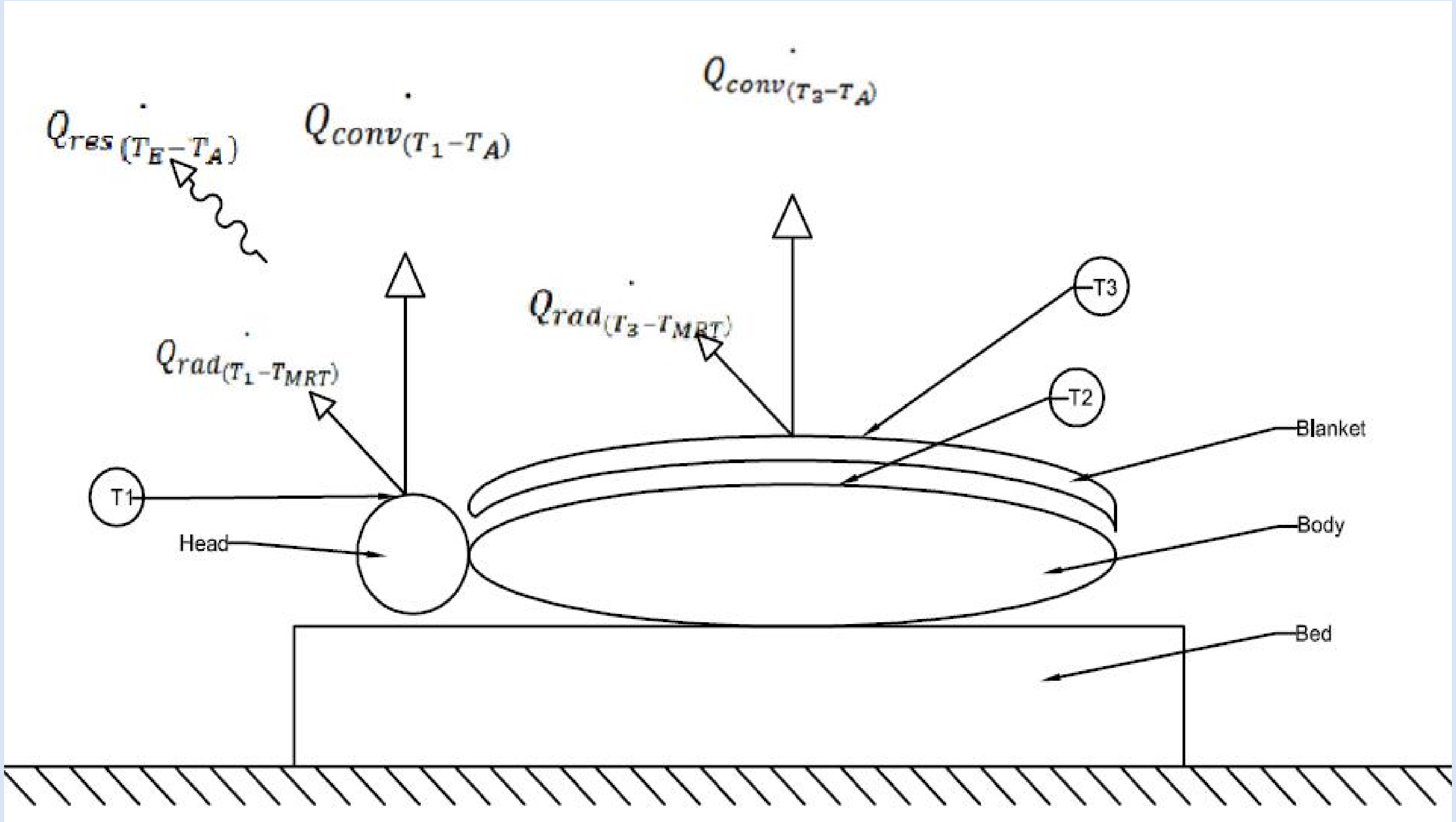
The Assumptions For This Heat Balance Model

- Existing Literature
  - Sleep is complex, 4 stages of sleep, vasculatory rhythms, thermal regulatory cycles
  - No direct research into the “average” person; existing research focus on sleep disorders, elderly, soldiers and athletes
  - Simplified documentation of thermal environment, i.e. only a simple air temperature measurement
- Assumptions
  - Steady state for the entire period of sleep – unless the thermal environment is for one person and that there is a monitoring system on that person, the HVAC system have to one condition

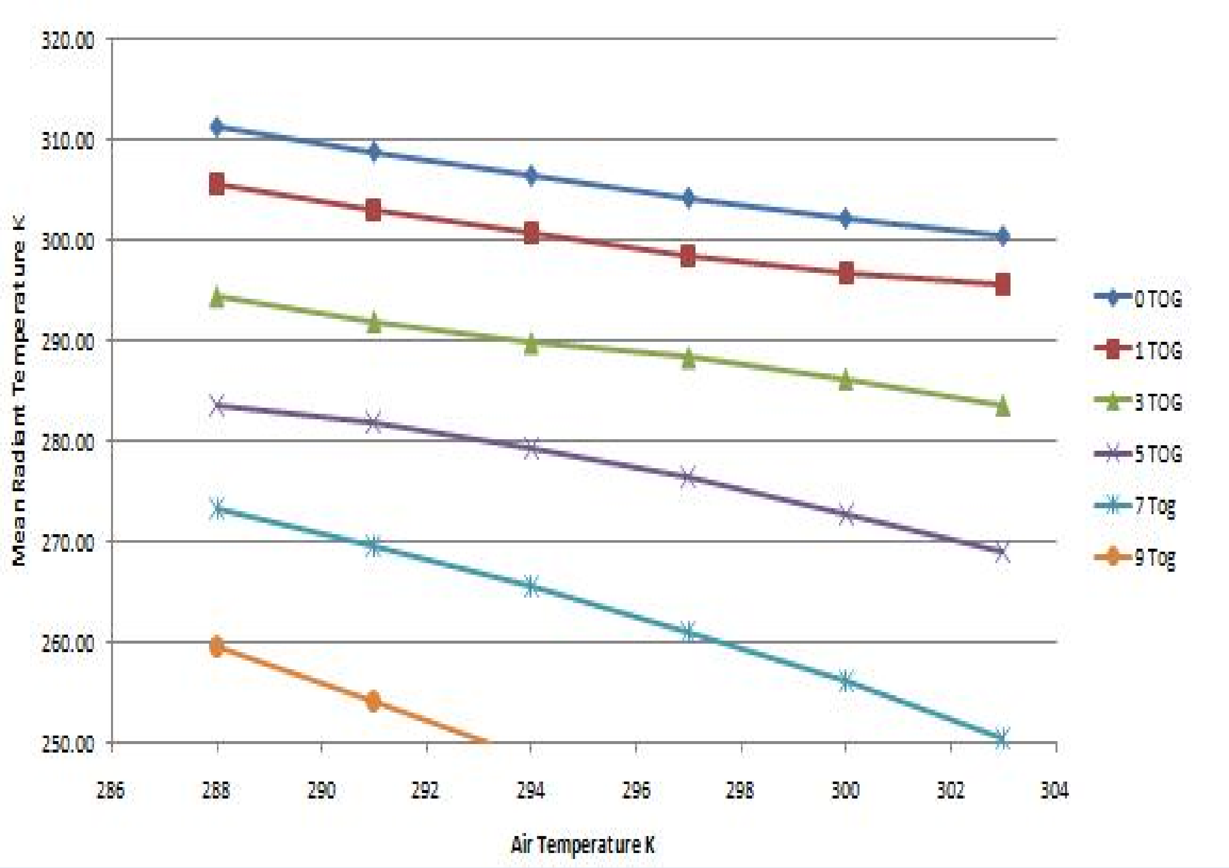
Boundary Conditions

- Skin temperature:
  - Neutral heat balance: 32°C for soldiers' sleeping bags (Goldman)
  - Neutral heat balance: 31.5°C for athletes' sleeping bags (KSU)
  - Neutral heat balance Europe: 32.8°C for athletes' sleeping bags (EN13573)
  - Sleep quality study: 32.5 °C (Bischof et al)
- Body heat loss rate:
  - 34.9 W/m^2 to 43.5 W/m^2 with body heat deficit (Goldman)
  - 36 W/m^2 with body heat gain (Bischof et al)

HEAT BALANCE MODEL DIAGRAM



HEAT BALANCE CALCULATION RESULTS

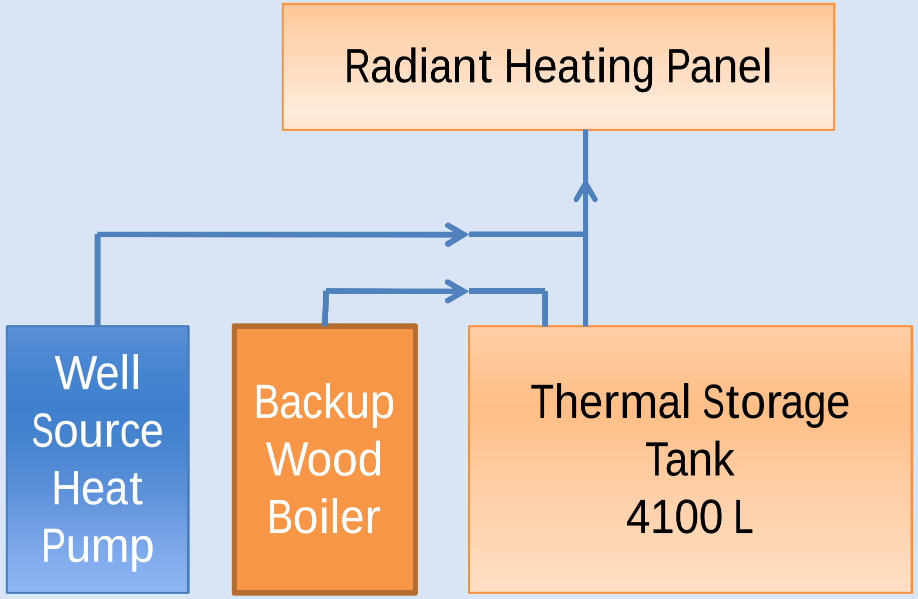


- 1 Clo = 1.55 Tog
- All season blanket = 3 to 5 Tog
- Suggest overheating if operative temperature (average of air temperature and MRT) > 16˚C

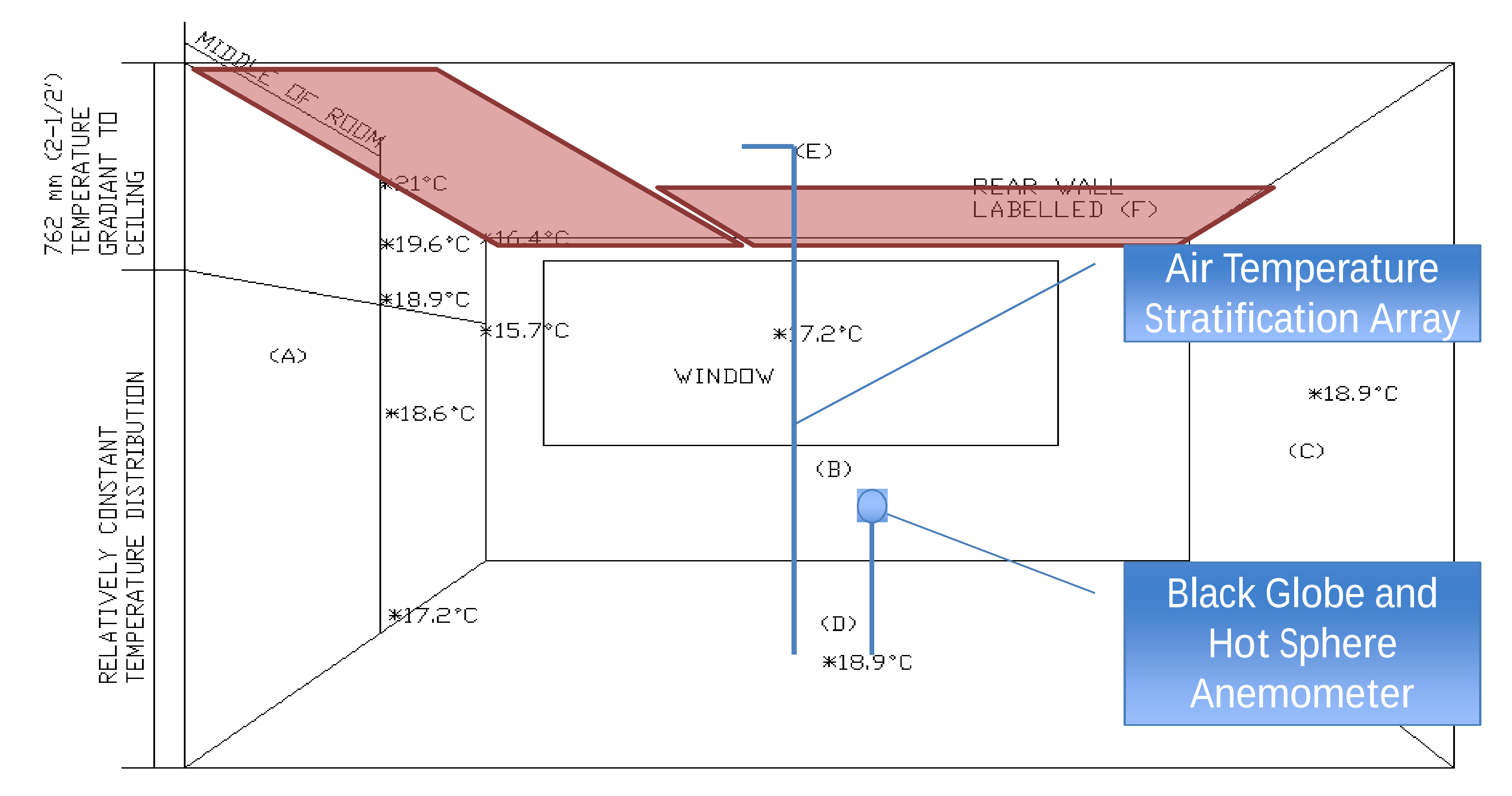
Experiment Site

- Site is single family home located in Caledon Ontario Canada
- Floor area is around 560 m^2, volume is around 2,400 m^3
- Sprayed concrete hydronic radiant heating system
- Triple low-E Argon RSI 1.2 windows
- RSI 6.2 walls.

Simplified HVAC Heat Flow Schematic



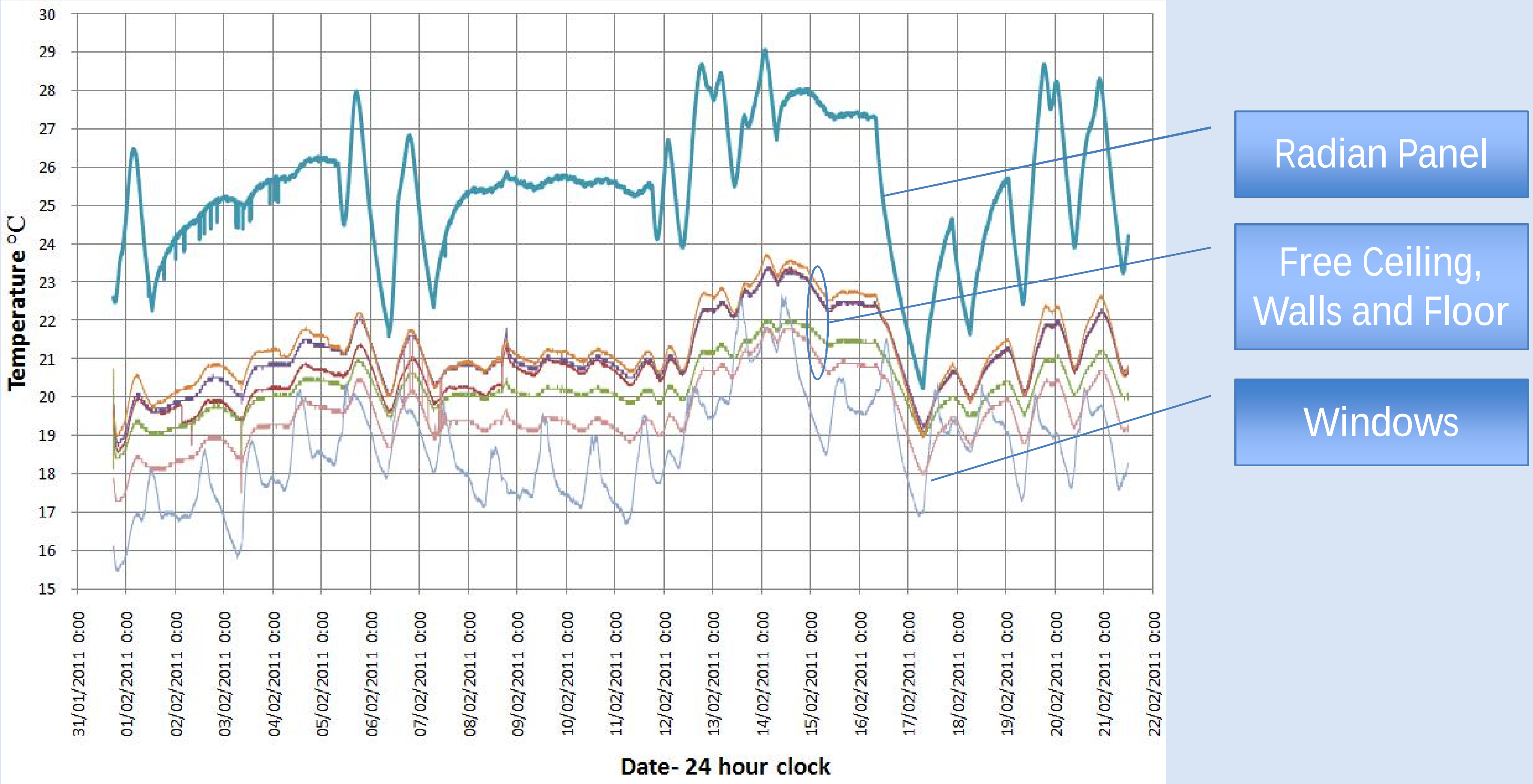
Experiment Setup



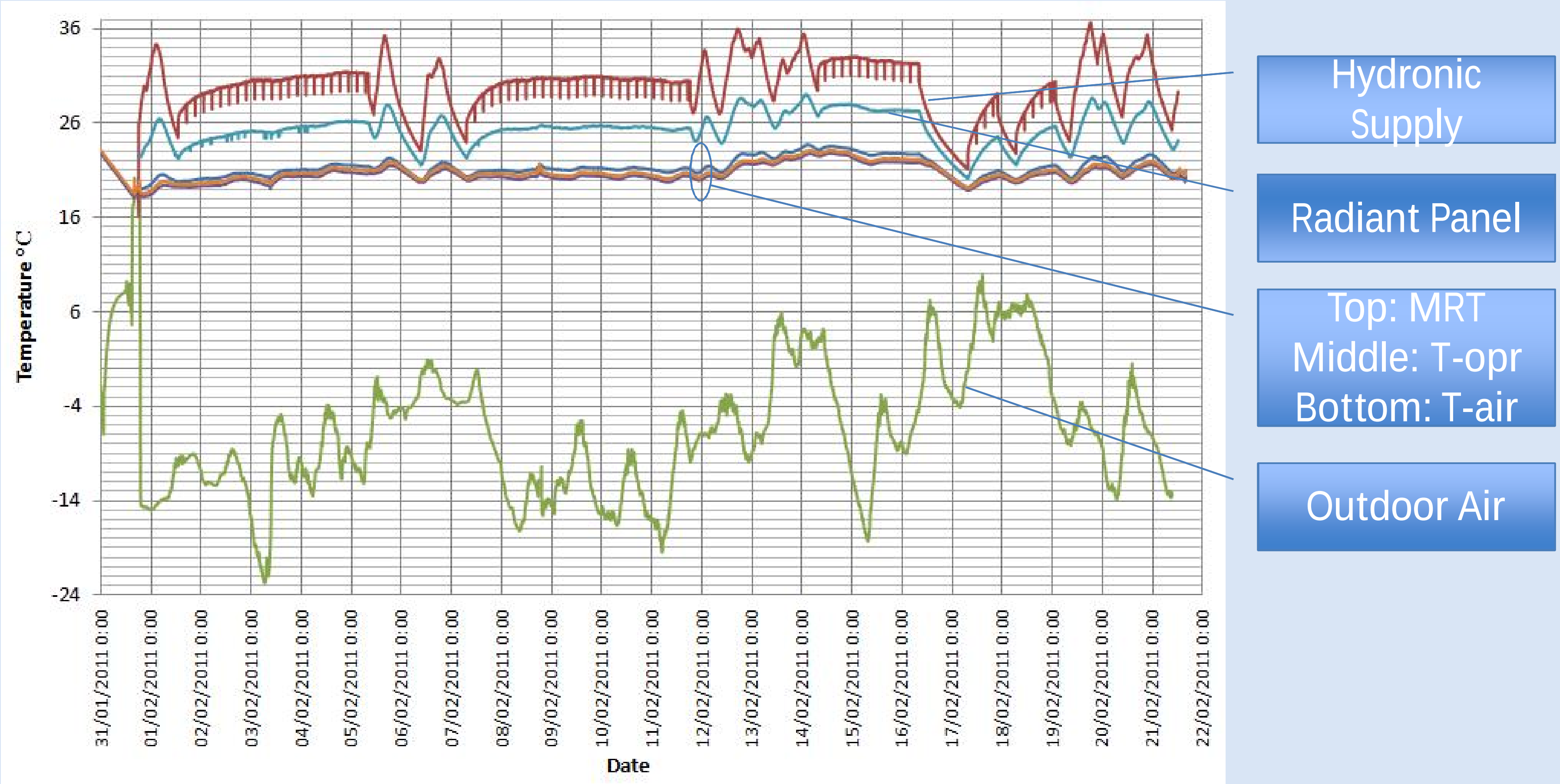
SENSORS AND MEASUREMENTS

Measurement	Sensors	Deployed Amount
Mean Radiant Temperature	Black Globe Thermometer and Hot Sphere Anenometer	1
Surface Temperatures	Type T thermocouple surface temperature sensors	19
Air Temperature Stratification	Type T thermocouple radiant shielded temperature sensor	5
Relative Humidity	Relative humidity probe	1
Outdoor relative humidity and temperature	Micro weather station	1

WALL SURFACE TEMPERATURE COMPARISON



Wall Surface Temperature Comparison



EXPERIMENT RESULTS

- Maximum rate of change for operative temperature is approximately 1 °C/6 hours: less than ASHRAE 55 limit of 3.3 °C/4 hours
- Radiant asymmetry within ASHRAE 55 requirements
- The operative temperature was between 19°C and 25°C, regardless of outdoor temperature -24°C to 10°C
- Higher than the operative temperature calculated for comfortable sleep
- The mean air velocity is measured at 0.021 m/s.
- Relative humidity is between 21% to 37%
- The air temperature did not lag the MRT significantly and is approximately 1°C lower than the MRT

Experiment Results Summary

- This radiant heating system considered comfortable under existing standards for an awake person
- The operative temperature recorded is higher than what is calculated for comfortable sleep
- Possible reduction of operative temperature down to 16°C with a 5 TOG blanket. – Potential energy savings?

LIMITATIONS

- Limitations
  - Existing system is radiant ceiling system in heating (during winter), research may not apply to wall and floor system; or as in cooling
  - The test building have a superior envelope to typical buildings and will not be representative of other buildings
  - Small scale experiment will not produce concrete comprehensive results

Conclusion and Future Work

- Conclusion
  - Existing knowledge have significant gaps in sleep thermal comfort
  - Developed a simple model to determine the desired thermal environment for sleep
  - Field measurement shows that recorded operative temperature is higher than desired
- Future Work
  - Experimental studies with statistically significant demographic to establish sleep thermal comfort criteria.
  - Controlled lab test with volunteers and thermal manikin
  - Bridging scientific knowledge from psychology, physiology and engineering with multidiscipline research teams
  - Calculation of potential energy savings of reduction of operative temperature during sleep