ASHP Test Settings

This document summarizes detailed settings regarding each test scenario for the ASHP testing. The settings of the **Default** cases are shown in detail. For variation cases, settings that are different from the **Default** cases are highlighted.

1 Test Settings Overview

1.1 Default

1.1.1 Test Day Selection

The selected test days below represent a **typical summer** day in each location, respectively.

Location	Date (TMY3)	Peak (standard time)	Non-peak (standard time)
Atlanta	8/26	13:00-18:00	0:00-13:00, 18:00-24:00
Buffalo	7/2	10:00-16:00	0:00-10:00, 16:00-24:00
New York	6/26	11:00-19:00	0:00-11:00, 19:00-24:00
Tucson	8/28	13:00-19:00	0:00-13:00, 19:00-24:00

1.1.2 Simulation Settings

Item	Detail
EnergyPlus model standard	ASHRAE 90.1-2004
Occupancy	Perimeter_ZN_1: 7
Occupant behaviors	4 (57 %) occupants care energy saving with 80 % restriction probability.
Other modifications	Temperature Capacity Multiplier of the selected zones in the EnergyPlus model are set to 8 to better represent the damping effect of internal thermal mass in typical buildings.

1.1.3 GEB Scenario

GEB Scenario	Description	The method of determining zone temperature setpoint
Efficiency	Persistently low energy us minimizes demand on grid resources and infrastructure.	No reset
Load shedding	Reduce energy consumption by turning off or lowering the device's power during peak periods.	Relax 2 °F in the peak period
Load shifting	Load shifting can be achieved by storing heat in advance using zone air during off-peak periods and releasing it during peak periods.	Non-TES case: see 2.1 TES case: see 1.9
Load modulating	Load modulating requires the system power to be variable in response to changes in the power grid. However, the ASHP is a two-speed system, therefore, there is no load modulating case for ASHP testbed.	NaN

1.1.4 Control Strategy

Item	Default setpoint	Reset strategy
Zone Temperature	Occupied (5am – 10pm): 68 °F – 78 °F; Unoccupied/setback (12am – 5am, 10pm – 12am): 55 °F – 90 °F	**Eff**: No reset **Shed**: 70 °F – 80 °F during peak **Shift**: Rule-based schedule determined by preliminary simulation (see 2.1)

1.2 Variation: Extreme Summer (ExtrmSum)

1.2.1 Test Day Selection

The selected test days below represent an **extreme summer** day in each location, respectively.

Location	Date (TMY3)	Peak (standard time)	Non-peak (standard time)
Atlanta	7/8	13:00-18:00	0:00-13:00, 18:00-24:00
Buffalo	7/16	10:00-16:00	0:00-10:00, 16:00-24:00
New York	7/10	11:00-19:00	0:00-11:00, 19:00-24:00
Tucson	8/16	13:00-19:00	0:00-13:00, 19:00-24:00

1.2.2 Simulation Settings

See 1.1.2.

1.2.3 Control Strategy

See 1.1.3.

1.3 Variation: Typical Shoulder (TypShldr)

1.3.1 Test Day Selection

The selected test days below represent a **typical shoulder** day in each location, respectively.

Location	Date (TMY3)	Peak (standard time)	Non-peak (standard time)
Atlanta	4/29	NA	0:00-24:00
Buffalo	3/12	NA	0:00-24:00
New York	10/16	11:00-19:00	0:00-11:00, 19:00-24:00
Tucson	10/7	5:00-9:00, 16:00-20:00	0:00-5:00, 9:00-16:00, 20:00-24:00

Due to the absence of peak hours, shedding and shifting cases are not tested under the typical shoulder conditions in Atlanta and Buffalo.

1.3.2 Simulation Settings

See 1.1.2.

1.3.3 Control Strategy

See 1.1.3.

1.4 Variation: Extreme Winter (ExtrmWin)

1.4.1 Test Day Selection

The selected test days below represent an **extreme winter** day in each location, respectively.

Location	Date (TMY3)	Peak (standard time)	Non-peak (standard time)
Atlanta	NA	NA	NA
Buffalo	NA	NA	NA
New York	NA	NA	NA
Tucson	1/2	5:00-9:00, 16:00-20:00	0:00-5:00, 9:00-16:00, 20:00-24:00

Due to the absence of peak hours, shedding and shifting cases are not tested under the extreme winter conditions in Atlanta.

1.4.2 Simulation Settings

See 1.1.2.

1.4.3 Control Strategy

See 1.1.3.

1.5 Variation: Model Predicted Control (MPC)

1.5.1 Test Day Selection

See 1.1.1.

1.5.2 Simulation Settings

See 1.1.2.

1.5.3 Control Strategy

Item	**Default setpoint**	**Reset strategy**
Zone Temperature	Based on MPC decisions (see 2.1)	NA

1.6 Variation: High Performance Building (STD2019)

1.6.1 Test Day Selection

See 1.1.1.

1.6.2 Simulation Settings

Item	**Detail**
EnergyPlus model standard	ASHRAE 90.1-2019
Occupancy	Perimeter_ZN_1: 7
Occupant behaviors	4 (57 %) occupants care energy saving with 80 % restriction probability.
Other modifications	Temperature Capacity Multiplier of the selected zones in the EnergyPlus model are set to 8 to better represent the damping effect of internal thermal mass in typical buildings.

1.6.3 Control Strategy

See 1.1.3.

1.7 Variation: Dense Occupancy (DenseOcc)

1.7.1 Test Day Selection

See 1.1.1.

1.7.2 Simulation Settings

Item	**Detail**
EnergyPlus model standard	ASHRAE 90.1-2004
Occupancy	Perimeter_ZN_1: 11

Occupant behaviors	6 (55%) occupants care energy saving with 80% restriction probability
Other modifications	Temperature Capacity Multiplier of the selected zones in the EnergyPlus model are set to 8 to better represent the damping effect of internal thermal mass in typical buildings.

1.7.3 Control Strategy

See 1.1.3.

1.8 Variation: Energy Saving Behaviors (EnergySave)

1.8.1 Test Day Selection

See 1.1.1.

1.8.2 Simulation Settings

Item	**Detail**
EnergyPlus model standard	ASHRAE 90.1-2004
Occupancy	Perimeter_ZN_1: 7
Occupant behaviors	9 (82 %) occupants care energy saving with 90 % restriction probability
Other modifications	Temperature Capacity Multiplier of the selected zones in the EnergyPlus model are set to 8 to better represent the damping effect of internal thermal mass in typical buildings.

1.8.3 Control Strategy

See 1.1.3.

1.9 Variation: Thermal Energy Storage (TES)

1.9.1 Test Day Selection

See 1.1.1.

1.9.2 Simulation Settings

Item	**Detail**
EnergyPlus model standard	ASHRAE 90.1-2004
Occupancy	Perimeter_ZN_1: 7
Occupant behaviors	4 (57 %) occupants care energy saving with 80 % restriction probability.
Other modifications	Temperature Capacity Multiplier of the selected zones in the EnergyPlus model are set to 8 to better represent the damping effect of internal thermal mass in typical buildings. The walls and ceiling of the tested zone are coated with an additional wall layer that contains phase change material (PCM). The PCM chosen for each location is different. Specifically: **Atlanta**: SP26E **Buffalo**: SP26E **New York**: SP26E **Tucson**: SP29Eu

	The parameters of the PCM wall layers specified in the EnergyPlus models are summarized in Table 1-1.

Table 1-1 EnergyPlus Objects for Phase Change Material

Name	EnergyPlus Objects
SP26E	Material, SP26E, !- Name MediumRough, !- Roughness 0.015, !- Thickness {m} 0.5, !- Conductivity {W/m-K} 1600, !- Density {kg/m3} 2000; !- Specific Heat {J/kg-K} MaterialProperty:PhaseChangeHysteresis, SP26E, !- Name 180000, !- Latent Heat during the Entire Phase Change Process {J/kg} 0.5, !- Liquid State Thermal Conductivity {W/m-K} 1500, !- Liquid State Density {kg/m3} 2000, !- Liquid State Specific Heat {J/kg-K} 0.190, !- High Temperature Difference of Melting Curve {deltaC} 25.833, !- Peak Melting Temperature {C} 3.415, !- Low Temperature Difference of Melting Curve {deltaC} 0.5, !- Solid State Thermal Conductivity {W/m-K} 1600, !- Solid State Density {kg/m3} 2000, !- Solid State Specific Heat {J/kg-K} 0.501, !- High Temperature Difference of Freezing Curve {deltaC} 24.303, !- Peak Freezing Temperature {C} 2.857; !- Low Temperature Difference of Freezing Curve {deltaC}
SP29Eu	Material, SP29Eu, !- Name MediumRough, !- Roughness 0.015, !- Thickness {m} 0.5, !- Conductivity {W/m-K} 1600, !- Density {kg/m3} 2000; !- Specific Heat {J/kg-K} MaterialProperty:PhaseChangeHysteresis, SP29Eu, !- Name 200000, !- Latent Heat during the Entire Phase Change Process {J/kg} 0.5, !- Liquid State Thermal Conductivity {W/m-K} 1500, !- Liquid State Density {kg/m3} 2000, !- Liquid State Specific Heat {J/kg-K} 2.631, !- High Temperature Difference of Melting Curve {deltaC} 27.110, !- Peak Melting Temperature {C} 1.497, !- Low Temperature Difference of Melting Curve {deltaC} 0.5, !- Solid State Thermal Conductivity {W/m-K} 1600, !- Solid State Density {kg/m3} 2000, !- Solid State Specific Heat {J/kg-K} 4.941, !- High Temperature Difference of Freezing Curve {deltaC}

	25, 0.00003;	!- Peak Freezing Temperature {C} !- Low Temperature Difference of Freezing Curve {deltaC}

1.9.3 Control Strategy

See 1.1.3.

2 Control Algorithms

2.1 Rule-based Load Shifting Preconditioning Schedule

Similar to the approach a real building operator would take, a simulated ASHP model was used to determine the rule-based control strategy for load-shifting cases. The optimal preconditioning schedule, including setpoints for precooling or preheating and their respective durations, was determined through an exhaustive search method. Candidate setpoints range from 68 °F to 78 °F in 1 °F increments, and preconditioning durations range from 0.5 hours to 8 hours in 0.5-hour increments.

		Default	ExtrmSum	TypShldr	ExtrmWin	STD2019	TES
Atlanta	T_{spt_pre}	76 °F	76 °F	NA	NA	76 °F	76 °F
	Duration	0.5 h	0.5 h	NA	NA	0.5 h	0.5 h
Buffalo	T_{spt_pre}	77 °F	75 °F	NA	NA	77 °F	77 °F
	Duration	0.5 h	0.5 h	NA	NA	0.5 h	0.5 h
New York	T_{spt_pre}	77 °F	77 °F	77 °F	NA	77 °F	77 °F
	Duration	5 h	3 h	4.5 h	NA	5 h	5 h
Tucson	T_{spt_pre}	77 °F	76 °F	77 °F	77 °F	77 °F	77 °F
	Duration	1 h	1.5 h	0.5 h	0.5 h	1 h	1 h

Note: 1) T_{spt_pre} is the precooling setpoint 2) Duration is the preconditioning duration before the peak period according to the TOU price structure; 3) No TypShldr for Atlanta and Buffalo cases as there are no peak pricing period. And no ExtrmWin for Atlanta, Buffalo, and New York cases as the system limitation.

2.2 Model Predicted Control

The controllable variables u for this system is the zone air temperature setpoints $T_{z,s}$. The decision variable U at time step t for the optimization-based controllers is a sequence of the controllable variable u over the prediction horizon N as shown below.

$$U^t = [u^t, u^{t+1}, \dots, u^{t+N-1}] \tag{1}$$

The MPC formulations are shown as follows, where the objective function of load shifting is shown in Eq. (2), and the objective function of energy efficiency and load shedding are shown in Eq. (3).

$$\min_{U^t} \quad \sum_{k=0}^{\mathrm{N}-1} p^{t+k} P^{t+k} \Delta t + \omega \left|\left|\Delta T_{z,s}^{t+k}\right|\right|^2 \tag{2}$$

$$s.t.$$

$$\min_{U^t} \quad \sum_{k=0}^{\mathrm{N}-1} P^{t+k} \Delta t + \omega \left|\left|\Delta T_{z,s}^{t+k}\right|\right|^2 \tag{3}$$

$$s.t.$$

$$\dot{q}_l^{t+k} = f_l\left(T_{z,s}^{t+k}, y\right) \tag{4}$$

$$\dot{q}_l^{t+k} \le \bar{\dot{q}}_{hp}^{t+k} \tag{5}$$

$$P^{t+k} = \sum_{i=0}^{n} \alpha_i \left(\dot{q}_l^{t+k}\right)^i + \sum_{i=0}^{m} \beta_i \left(T_{s,in}^{t+k}\right)^i \tag{6}$$

$$\Delta T_{z,s}^{t+k} = T_{z,s}^{t+k} - T_{z,s}^{t+k-1} \quad (7)$$
$$T_{z,s}^{t+k-1} = T_z^{t-1} \quad (8)$$
$$\underline{T}_{z,s}^{t+k} \leq T_{z,s}^{t+k} \leq \overline{T}_{z,s}^{t+k} \quad (9)$$

where p is the electricty price, P is the power consumed by the heat pump system, and Δt is the control interval of the predictive controller, i.e., 15 min. ω is a weight, and $\Delta T_{z,s}$ is the zone air temperature setpoint changes. $\dot{q}_l$ is the thermal load in the zone and can be predicted from a thermal network resistance and capacitance (RC) model and system speed mode y. The power of the heat pump system P is represented as a polynomial function of $\dot{q}_l$, system speed mode y, and source side inlet temperature $T_{s,in}$. $\underline{x}$ and $\overline{x}$ are the lower and upper bounds of the variable x. The zone air temperature setpoints $T_{z,s}$ sent to ASHP is back calculated based on the optimized system speed mode y and the ASHP's local speed control logic.