WSHP Test Settings

This document summarizes detail settings regarding each test scenario for the WSHP 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 Simulation Settings

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, due to WSHP local controller, direct manipulation of the VFDs is not	NaN

	feasible. And because the local controller of the WSHP is quite complex, it is hard to develop an additional controller to manipulate the zone temperature setpoint to track the frequency modulated power signal. So, therefore, there is no load modulating case for WSHP testbed.	

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	1/7	NA	0:00-24:00
Buffalo	2/6	16:00-19:00	0:00-16:00, 19:00-24:00
New York	2/6	11:00-19:00	0:00-11:00, 19:00-24:00
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 contain phase change material (PCM). The PCM chosen for each location is different. Specifically: **Atlanta**: SP25E2 **Buffalo**: SP25E2 **New York**: SP25E2 **Tucson**: SP26E 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
SP25E2	Material, SP25E2, !- 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, SP25E2, !- 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} 2.404, !- High Temperature Difference of Melting Curve {deltaC} 24.179, !- Peak Melting Temperature {C} 3.498, !- 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} 0.604, !- High Temperature Difference of Freezing Curve {deltaC} 22.827, !- Peak Freezing Temperature {C} 3.194; !- Low Temperature Difference of Freezing Curve {deltaC}
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}

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 WSHP model is 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, is 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	77 °F	NA	NA	77 °F	77 °F
	Duration	1 h	1 h	NA	NA	1.5 h	1 h
Buffalo	T_{spt_pre}	77 °F	77 °F	NA	74 °F	77 °F	77 °F
	Duration	1.5 h	1.5 h	NA	1.5 h	3.5 h	3.5 h
New York	T_{spt_pre}	74 °F	74 °F	74 °F	69 °F	77 °F	77 °F
	Duration	1 h	1 h	2 h	1 h	4 h	4 h
Tucson	T_{spt_pre}	77 °F	77 °F	77 °F	69 °F	77 °F	77 °F
	Duration	1 h	1 h	1 h	1 h	1 h	1 h

Note: 1) T_{spt_pre} is the precooling setpoint for the cooling cases (Default, ExtrmSum, TypShldr, and STD2019), or the preheating setpoint for the heating case (ExtrmWin); 2) Duration is the preconditioning duration before the peak period according to the TOU price structure; 3) No TypShldr, ExtrmWin for Atlanta and TypShldr for Buffalo cases as there are no peak pricing period.

2.2 Model Predicted Control

The MPC takes the grid signals, disturbance predictions, and system measurements as inputs and generates optimal setpoints for the system, i.e., zone air temperature setpoint $T_{z,s}$. The optimization variables x for the MPC include the compressor and fan speed ratio y, a zone temperature slack variable ϵ, the WSHP cooling capacity $\dot{q}_{hp}$, and the power consumed by the WSHP P. The optimization vector X at time step t for the MPC is a sequence of the optimization variables x over the prediction horizon N as shown below:

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

The MPC formulations are shown as follows, where the objective function of load shifting is shown in Eq. (1), and the objective function of energy efficiency and load shedding are shown in Eq. (2).

$$\min_{X^t} \sum_{k=0}^{\mathrm{N}-1} \omega_1 |p^{t+k} P^{t+k} \Delta t| + \omega_2 |\epsilon^{t+k}|^2 + \omega_3 |x^{t+k} - x^{t+k-1}| \tag{2}$$

$$\min_{X^t} \sum_{k=0}^{\mathrm{N}-1} \omega_1 |P^{t+k} \Delta t| + \omega_2 |\epsilon^{t+k}|^2 + \omega_3 |x^{t+k} - x^{t+k-1}| \tag{3}$$

$$P^{t+k} = y^{t+k} \left(\gamma_1 \left(T_z^{t+k} T_{w_{in}}^{t+k} \right) + \sum_{j=0}^{n} \alpha_j (T_z^{t+k})^j + \beta_j \left(T_{w_{in}}^{t+k} \right)^j \right) \tag{4}$$

$$\dot{q}_{hp}{}^{t+k} = y^{t+k} \left(\gamma_2 \left(T_z^{t+k} T_{w_{in}}^{t+k} \right) + \sum_{l=0}^{m} \alpha_l (T_z^{t+k})^l + \beta_l \left(T_{w_{in}}^{t+k} \right)^l \right) \tag{5}$$

$$\begin{bmatrix} \frac{dT_z^{t+k}}{dt} \\ \frac{dT_{w_e}^{t+k}}{dt} \\ \frac{dT_{w_i}^{t+k}}{dt} \end{bmatrix} = A \begin{bmatrix} T_z^{t+k} \\ T_{w_e}^{t+k} \\ T_{w_i}^{t+k} \end{bmatrix} + B \begin{bmatrix} T_{oa}^{t+k} \\ \dot{q}_{conv_i}^{t+k} \\ \dot{q}_{hp}^{t+k} \\ \dot{q}_{sol_e}^{t+k} \\ \dot{q}_{rad\,i}^{t+k} \end{bmatrix} \tag{6}$$

$$T_{w_{in}}^{t+k} = f\left(\dot{q}_{hp}^{t+k}\right) \tag{7}$$

$$T_z^{t+k} - \epsilon^{t+k} \leq \underline{T_z}^{t+k} \tag{8}$$

$$T_z^{t+k} + \epsilon^{t+k} \geq \overline{T}_z^{t+k} \tag{9}$$

$$\underline{y}^{t+k} \leq y^{t+k} \leq \overline{y}^{t+k} \tag{10}$$

$$\underline{e}^{t+k} \leq e^{t+k} \leq \overline{e}^{t+k} \tag{11}$$

$$T_z^{t+k} = T_{z,s}^{t+k} = u^{t+k} \tag{12}$$

where p is the electricity price, and Δt is the control interval of the predictive controller, i.e., 15 min. ω_{1-3} are the weights of the optimization multi-objective function. T_z is the zone temperature which can be predicted from the thermal network resistance and capacitance (RC) model illustrated in Figure 22. $T_{w_{in}}$ is the water temperature entering the WSHP which is calculated using the same formulation as the HIL single U-tube ground loop heat exchanger model (GLHE). $\underline{g}$ and $\overline{g}$ are the lower and upper bounds of any variable g.