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Implementation of ASHRAE Guideline 36 Control Logic into Oak Ridge National Laboratory (ORNL)'s Flexible Research Platform (FRP)

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Electrification and Energy Infrastructures Division

IMPLEMENTATION OF ASHRAE GUIDELINE 36 CONTROL LOGIC INTO OAK RIDGE NATIONAL LABORATORY (ORNL)'S FLEXIBLE RESEARCH PLATFORM (FRP)

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EXECUTIVE SUMMARY

This report presents the initial field test procedure and results for ASHRAE Guideline 36 control logic. The US Department of Energy's Oak Ridge National Laboratory's (ORNL's) two-story Flexible Research Platform (FRP-2) was selected as a test building. The rooftop unit (RTU) system serves as the building's primary cooling system, and each variable air volume (VAV) box with an electric reheat coil serves as the building's heating system along with RTU gas furnace. In this study, the control for the RTU and VAV box adopted the practical control sequences from *ASHRAE Guideline 36-2018: High-Performance Sequences of Operation*. Each story of the FRP-2 building has 5 office zones (thermal zones), for a total of 10 zones.

To summarize, the Q2 milestone for the sensor impact evaluation project includes the following actions:

- Implement ASHRAE Guideline 36 control logic into the FRP-2 building
- Plan field testing
- Conduct initial field testing
- Perform field data analysis

The ORNL team implemented ASHRAE Guideline 36 control logic into the FRP-2 building and checked whether the control logic can communicate with the FRP-2 building and control the HVAC system as expected. The ORNL team confirmed that ASHRAE Guideline 36 control logic can communicate and with the FRP-2 building and control the system through three types of control logic tests as below.

- VAV control of ASHRAE Guideline 36 control logic test
- RTU control of ASHRAE Guideline 36 control logic test
- Entire ASHRAE Guideline 36 control logic test

After the control logic tests, the ORNL team conducted initial field testing. The FRP-2 building, especially the RTU and VAV boxes, operated well based on ASHRAE Guideline 36 control logic. The pattern of the supply air temperature and supply airflow rate from each VAV box and discharged air temperature from the RTU was consistent with the expected pattern of ASHRAE Guideline 36 control logic. The ORNL team will conduct more field tests and will complete them in the rest of FY 2022.

For the FY 2022 Q3 milestone, the ORNL team is developing other advanced control logics associated with new sensor types to demonstrate the robustness of this sensor impact verification and evaluation emulator.

1. INTRODUCTION

Sensors are critical components for controls in buildings. They collect desired information for input to controls for subsequent control actions. When sensors work in unhealthy or faulty conditions, the control benefits will be compromised regardless of the promising benefits of the controls [1]. For buildings, multiple components directly influence the sensor placement and deployment, such as sensor errors, sensor locations, sensor types, and sensor costs.

Figure 1 shows the overall research components for this project. Four sensor components are considered in this research, three of which were determined in FY 2021: sensor accuracy (sensor error), sensor type and control type. The sensor location was analyzed in FY 2022 Q1. In FY 2022 Q2, the US Department of Energy's Oak Ridge National Laboratory (ORNL) team implemented ASHRAE Guideline 36 control logic into the test building and conducted initial field testing. For this testing, the two-story Flexible Research Platform (FRP-2) at ORNL was selected as a test building. This report includes the following:

- Information on ASHRAE Guideline 36 control logic
- Information on the test building
- How to implement ASHRAE Guideline 36 control logic into the test building
- The field test plan
- The field data analysis

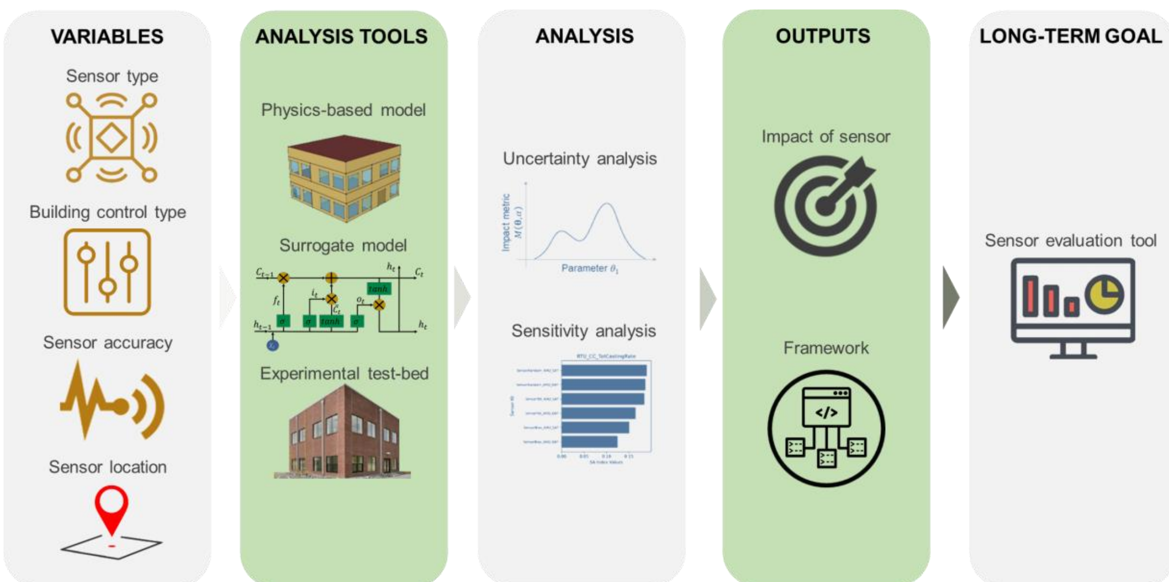


Figure 1. Overall research flow.

In FY 2022 Q3 and Q4, the ORNL team will develop an advanced control algorithm to compare different types of sensors with the ASHRAE Guideline 36 control algorithm. The ORNL team will also complete field testing and integrate sensor components into the emulator framework.

The goal in FY 2022 is to develop the framework for sensor impact analysis and verification to support sensor placement and configurations in building designs and analyses. The framework comprises the development of a physics-based emulator with sensor errors, sensor locations, and control sequences; large-scale simulations for sensor errors and sensor locations sampling to the controls on the cloud; the development of a surrogate model based on cloud simulation results for sensitivity analysis; and sensitivity and uncertainty analyses for the sensors and desired outputs (e.g., energy consumption, thermal comfort). This framework is extendable and scalable to other sensor factors, such as sensor types and costs. The ultimate goal of this research is to offer the sensor evaluation tool publicly.

2. ASHRAE GUIDELINE 36 CONTROL LOGIC FOR RTU AND SINGLE-DUCT VARIABLE AIR VOLUME SYSTEM

The installed HVAC systems in the FRP-2 building include the rooftop unit (RTU) in which cooling comes from a direct expansion cooling coil, and heating comes from a gas heating coil. Each floor of the FRP-2 building has 5 office zones, for a total of 10 conditioned zones. Each conditioned zone is served by a variable air volume (VAV) box with an electricity reheat coil. The air handling unit (AHU) connects all the zone VAV boxes and the RTU. Several control logics from ASHRAE Guideline 36 were investigated and defined for the RTU and VAV boxes.

1. Trim and respond (T&R) set point logic

   The first control logic is the T&R set point logic for the AHU. T&R logic resets set points of the pressure, temperature, or other variables on the AHU or plant side. T&R logic reduces the set point at a fixed rate until the zone thermal comfort is no longer satisfied, and then it generates the request to reset the set points. The set point is increased in response to a sufficient number of requests. By adjusting the importance of each zone's requests, the critical zones will always be satisfied. If there is not a sufficient number of requests, then the set point decreases at a fixed rate.

   The term *request* refers to a request to reset a static pressure or temperature set point generated by downstream zones or AHUs. These requests are sent upstream to the AHU or plant that supplies the zone or area that generated the request. Figure 2 shows an example of the T&R control provided by ASHRAE Guideline 36.

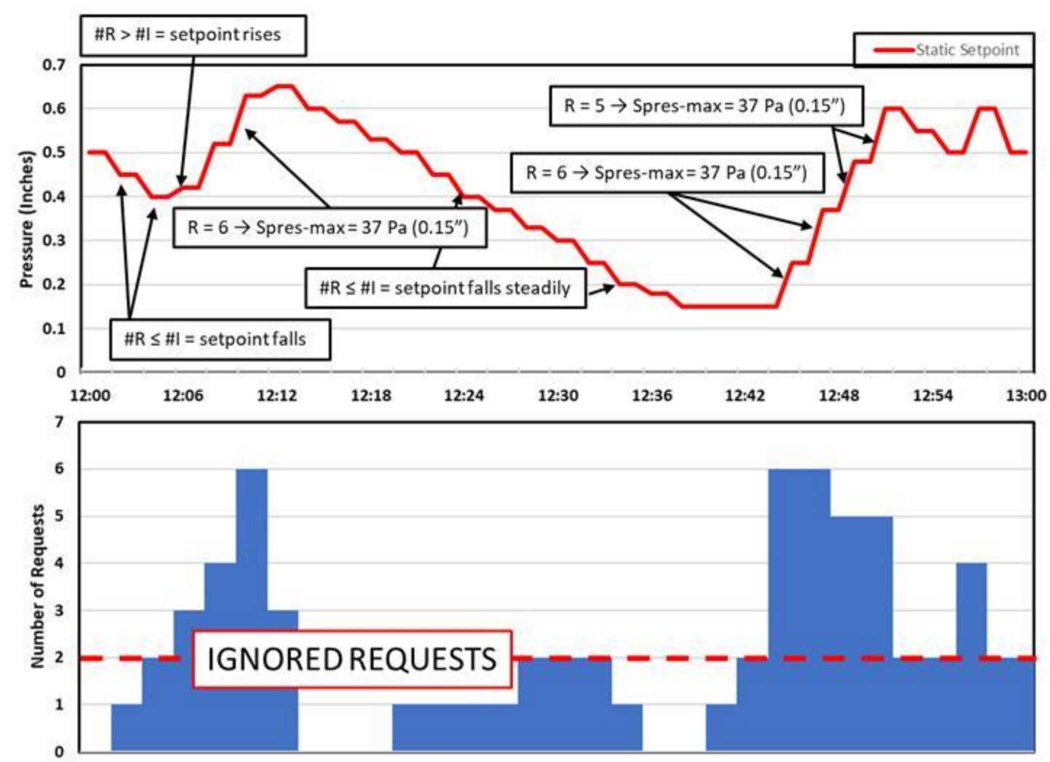


Figure 2. Example of the T&R control logic from ASHRAE Guideline 36 [2,3].

2. VAV box control logic

The VAV box control logic is the second control logic applied to the emulator. Figure 3 shows the control logic for the VAV box from ASHRAE Guideline 36. The control logic has three sections, which correspond to the heating mode, cooling mode, and deadband. The control logic uses the heating loop demand concept. Heating loop demand is the ratio (as a percentage) of actual required heating load of VAV box to the design heating capacity of the VAV box. Equation (1) describes how to calculate the heating loop demand.

$$Heating\ loop\ demand = \frac{Heating\ load\ of\ the\ VAV\ box}{Capacity\ of\ the\ VAV\ box} \times 100. \quad (1)$$

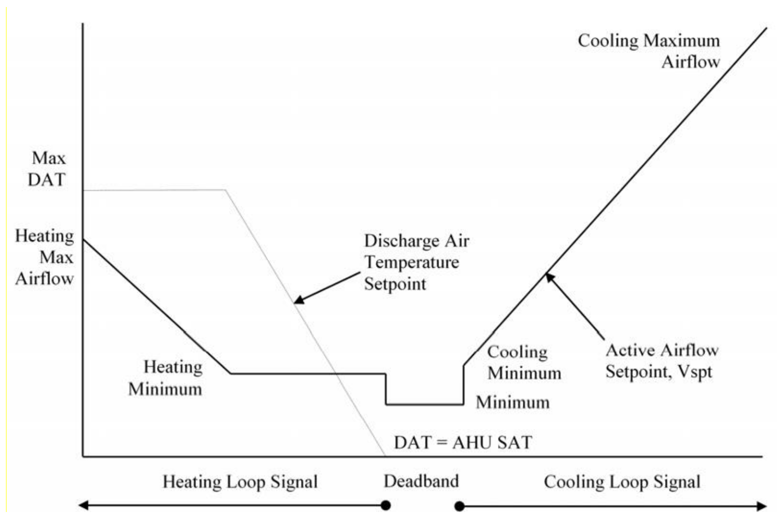


Figure 3. Control logic for VAV box from ASHRAE Guideline 36 [2,3].

3. Applied ASHRAE Guideline 36 control logic

Figure 4 shows the overall flow of the applied ASHRAE Guideline 36 control logic into the emulator. The gray box in Figure 4 indicates VAV box control logic, and the orange box indicates T&R control logic. Table 1 lists the nomenclature for ASHRAE Guideline 36 control logic.

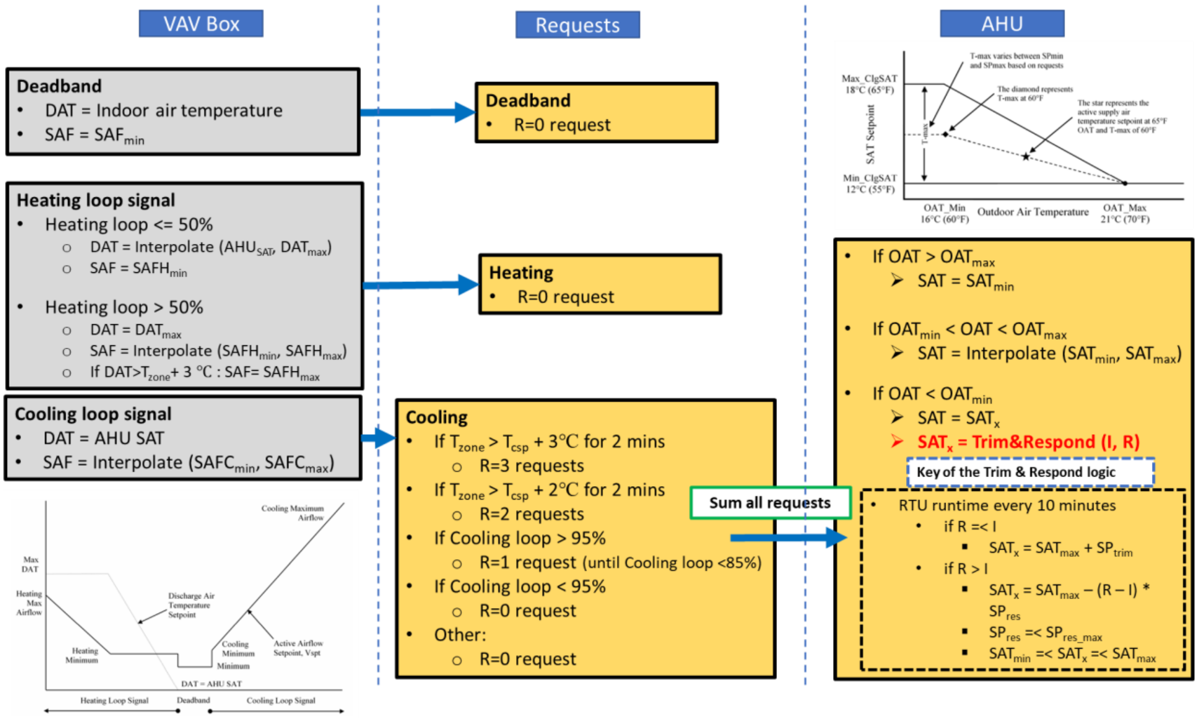


Figure 4. Overall flow of applied ASHRAE Guideline 36 control logic.
Abbreviation definitions are provided in Table 1.

Table 1. Nomenclature for ASHRAE Guideline 36 control logic

Abbreviation	Definition
DAT (°C)	Discharged air temperature (each VAV box)
DAT_{max} *(°C)*	Maximum discharged air temperature
AHU SAT (°C)	AHU supply air (SA) temperature
SAT_{max} *(°C)*	Maximum SA temperature
SAT_{min} *(°)*	Minimum SA temperature
SAT_x *(°C)*	Adjusted SA temperature based on the requests
OAT (°C)	Outdoor air (OA) temperature
OAT_{max} *(°C)*	Maximum OA temperature
OAT_{min} *(°C)*	Minimum OA temperature
SAF (m^3/s)	SA flow (each VAV box)
SAF_{min} (m^3/s)	Minimum SA flow
$SAFC_{min}$ (m^3/s)	Minimum SA flow for cooling
$SAFC_{max}$ (m^3/s)	Maximum SA flow for cooling
$SAFH_{min}$ (m^3/s)	Minimum SA flow for heating
$SAFH_{max}$ (m^3/s)	Maximum SA flow for heating
Heating loop (%)	Heating load/capacity of the VAV box
Cooling loop (%)	Cooling load/capacity of the direct expansion cooling coil
T_{csp} *(°C)*	Cooling set point temperature
T_{zone} *(°C)*	Indoor air temperature (each zone)
R	Number of requests from zones/systems
I	Number of ignored requests
SP_{trim}	Trim amount
SP_{res}	Number of responses
SP_{res_max}	Maximum number of responses per time interval

The control logic starts from the VAV box and links with the T&R control logic. Control logic for the VAV box can be divided into three sections:

a. In the heating mode, when the heating loop is less than or equal to 50%, the discharged air (DA) set point temperature of the VAV box is increased from the RTU supply air (SA) temperature to the maximum DA set point temperature of the VAV box, and the minimum SA flow rate is maintained. When the heating loop is greater than 50%, if the DA temperature of the VAV box is greater than the indoor air (IA) temperature plus 3°C, then the SA flow rate of the VAV box is increased from the minimum SA flow rate to the maximum SA flow rate while maintaining the maximum DA set point temperature of the VAV box.

b. In the cooling mode, the DA temperature of the VAV box is the same as the RTU SA temperature because no option exists to decrease the SA temperature using the VAV box. Therefore, VAV box control is linked with T&R control in the cooling mode as the VAV box control should refer the RTU SA temperature. The four cooling SA set point temperature reset requests are as follows:

- If the IA temperature exceeds the indoor cooling set point temperature by 3°C for 2 min and after the suppression period resulting from an RTU SA set point temperature change via the T&R control, then send three requests.

- Else if the IA temperature exceeds the indoor cooling set point temperature by 2°C for 2 min and after the suppression period resulting from an RTU SA set point temperature change via the T&R control, then send two requests.

- Else if the cooling loop is greater than 95%, then send one request until the cooling loop is less than 85%.

- Else if the cooling loop is less than 95%, then send no request.

In terms of the SA flow rate in the cooling mode, the SA flow rate of the VAV box is increased from the minimum SA flow rate to the maximum SA flow rate as the cooling loop is increased.

c. In the deadband, when neither heating nor cooling are needed, the SA flow rate is set to the minimum SA flow rate, and the DA temperature of the VAV box is set to the RTU SA temperature.

After requests are received from the VAV box control logic, requests are used for the T&R control to reset the RTU SA set point temperature in the emulator. When the outdoor air (OA) temperature is higher than the maximum OA set point temperature (21°C), the RTU SA temperature is set to the minimum RTU SA set point temperature (12°C). When the OA temperature is lower than the minimum OA set point temperature (16°C), the RTU SA temperature is set to maximum RTU SA set point temperature (18°C). If the OA temperature is between the minimum and maximum OA temperature when the OA temperature is increased, the RTU SA temperature is increased linearly from the minimum RTU SA set point temperature to the maximum RTU SA set point temperature. For T&R control, following ASHRAE Guideline 36, fewer than two requests are ignored.

3. TEST BUILDING

ORNL's FRP-2 is a two-story lightweight commercial building that represents a typical small to medium office building built in the 1980s in the United States. Considering the significance of the existing building sector, the ORNL team selected this building to evaluate the impact of sensors on small to medium office buildings. The FRP-2 building has 10 conditioned zones and a staircase with a 0.4 m thick exterior wall as shown in Figure 5. The FRP-2 building is an unoccupied research apparatus in which occupancy is emulated by process control of lighting, humidifiers for human-based latent loading, and a heater for miscellaneous electrical loads. The 44 kW RTU conditions the zones with an AHU and VAV boxes as shown in Figure 6. To observe the effects of the VAV control logic in the heating mode, the main gas heating system turns off, and only VAV boxes operate for the heating mode.

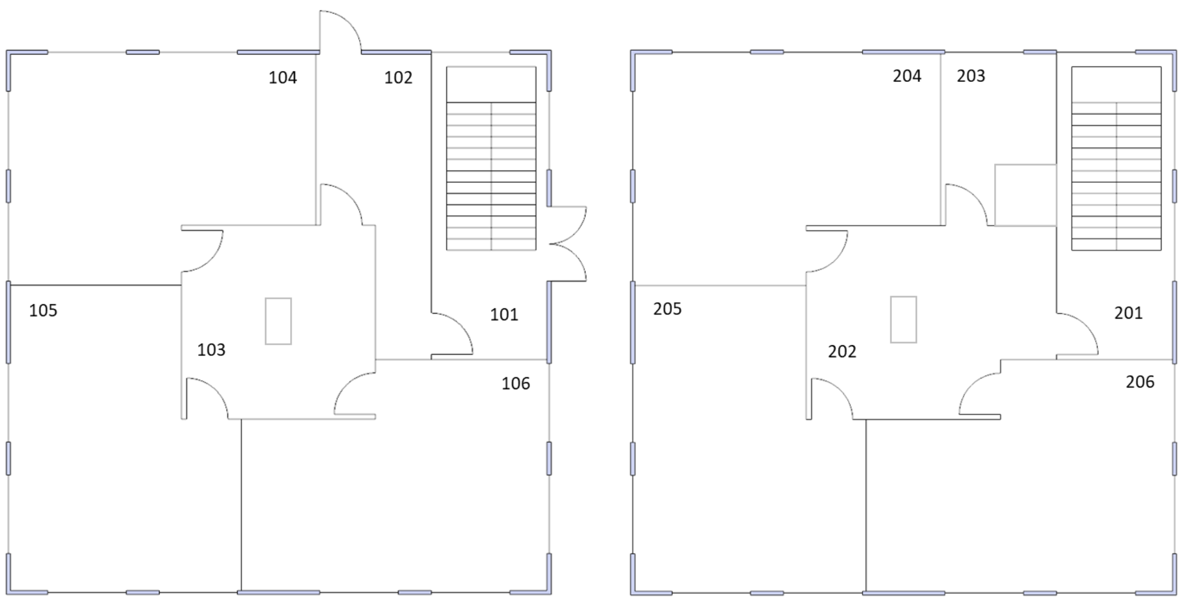


Figure 5. Floor plan of the FRP-2 building.

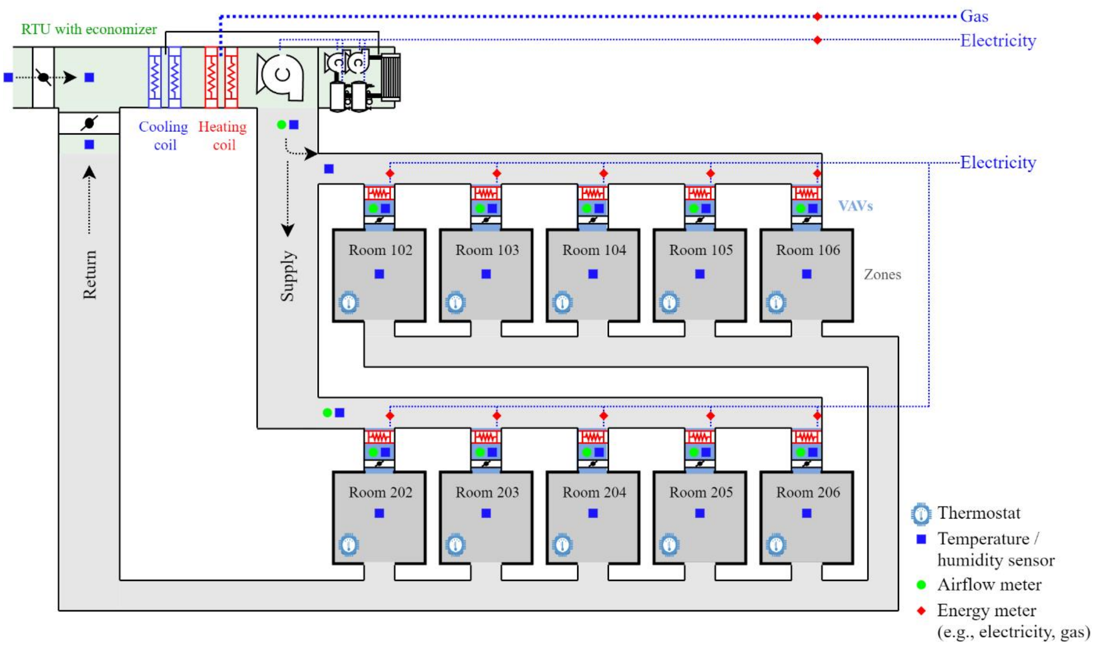


Figure 6. HVAC system and current measurements of the FRP-2 building.

More than 200 sensors—including zone temperature and relative humidity, supply and return air temperature, relative humidity, airflow rate, and power measurements—were installed in the FRP-2 building. The field data were collected by the data logger (CR 3000) and the building automation system (BAS) installed in the FRP-2 building. The installed BAS is the Metasys, which can control the building via the programming in the BAS. Figure 7 and Figure 8 show the information on the RTU and VAV in the BAS. The values in the figures update with real-time actual field data automatically.

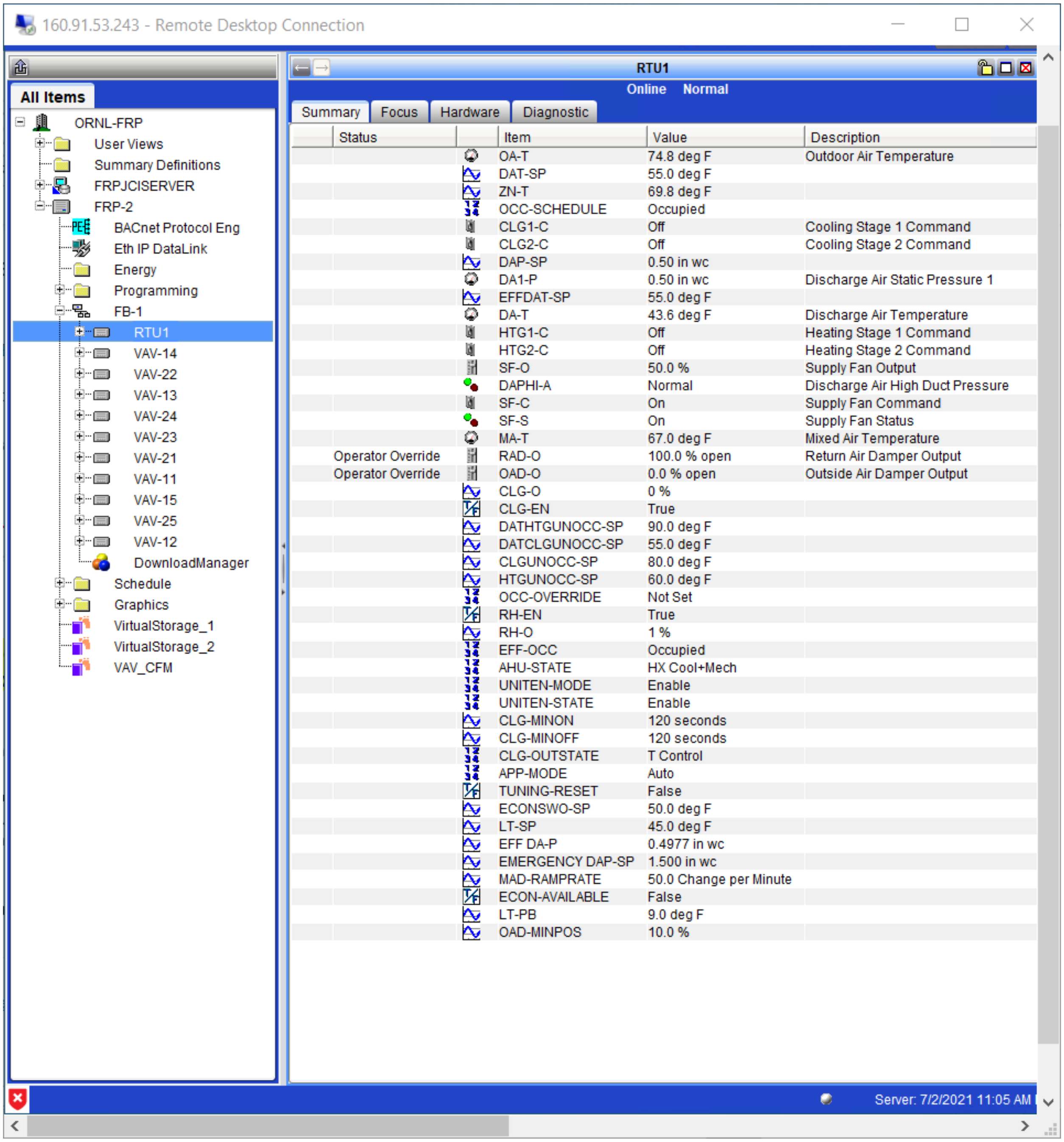


Figure 7. Information on the RTU in the BAS.

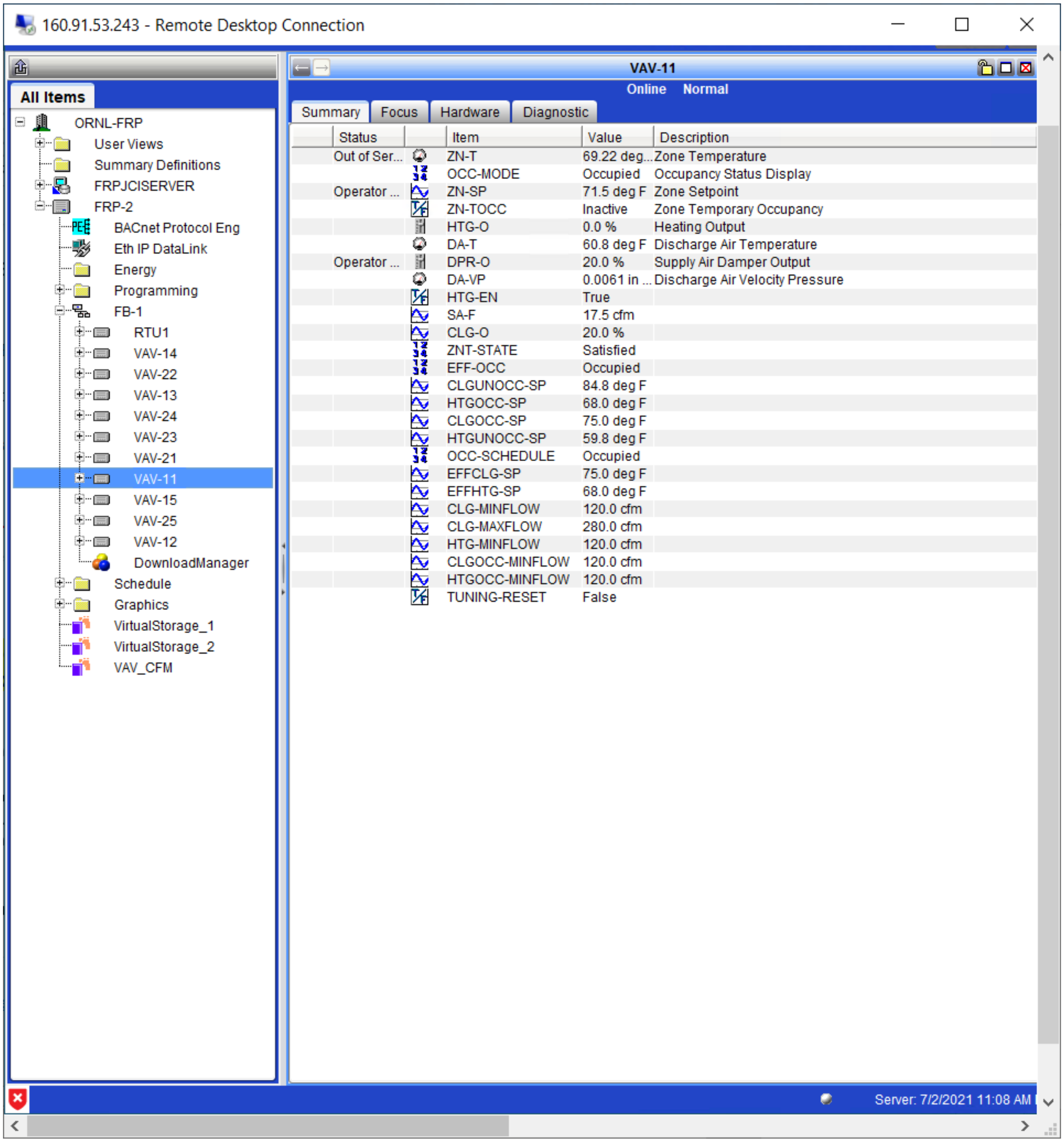


Figure 8. Example of the information on the VAV box in the BAS.

4. IMPLEMENTATION OF ASHRAE GUIDELINE 36 CONTROL LOGIC INTO THE TEST BUILDING

To deploy ASHRAE Guideline 36 control logic to the existing BAS in the FRP-2 building, the input and output variables of the optimal control algorithm had to be clearly identified. Figure 9 shows the overall framework of the data communication between the control algorithm and test building. All input variables should consist of data that can be collected via the BAS or data logger or directly input to the control logic (e.g., system capacity, maximum airflow rate, cooling/heating set point). For the output variables, checking whether override is possible in the BAS is necessary. Output of the control algorithm must be sent to the BAS, and the building is subsequently controlled by the control signal from the control algorithm. Input variables can be obtained from the data logger or through the BAS; however, the output must be sent to the BAS because the data logger can only store the data.

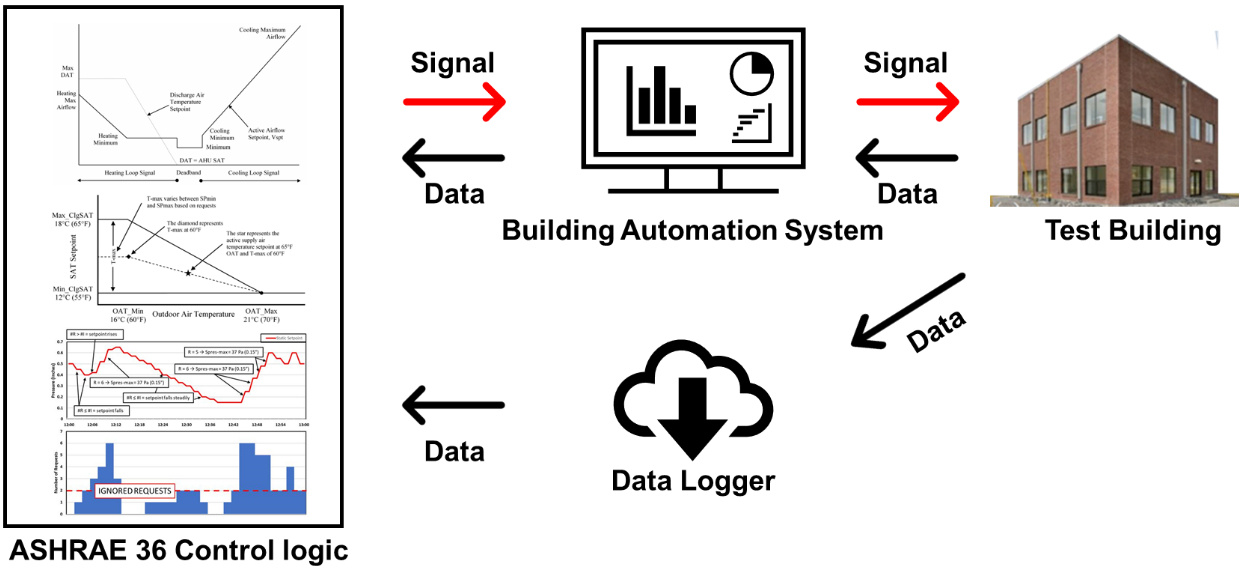


Figure 9. Overall framework of the data communication between the control algorithm and test building.

To connect the ASHRAE Guideline 36 control algorithm to the existing BAS in the FRP-2 building, a Python library for the BACnet is required [4]. After the BAC library is installed, the BACnet version is supposed to be checked. In the case of the BACnet, there is a connectable Python version depending on the BACnet version, which is why checking the version of the existing BACnet and matching the Python version is important. After the BACnet version and Python version are matched, information that is required to connect between the control algorithms is developed using the Python program and the test building.

Required information includes the following:

- IP address used by the BAS
- Sensor ID of data used as input variables
- Sensor ID for overriding control signal
- Control algorithm logic

For the input variable, the sensor ID must be entered correctly. Notably, even for the same type of data, the sensor ID used in the BAS and the sensor ID of the data logger are different. Therefore, correctly inputting the sensor ID of the data to be retrieved is crucial.

For the output variable, checking whether the data to be overwritten are controllable in the actual building is necessary. For example, there are generally two types of data on IA temperature in the BAS: set point temperature and current temperature. In the case of the set point temperature, data overriding is possible. Meanwhile, in the case of the current temperature, the current room temperature can be checked but cannot be directly changed by the control. Therefore, checking whether the variable to be controlled by the control algorithm is controllable within the BAS is necessary.

The optimal control algorithm and input variables are all connected by the sensor ID. The values of input variables are brought to the control algorithm via the bacnet.read function, and the signal is sent to the BACnet via the bacnet.write function so that the building is controlled [4].

As explained previously, various factors need to be checked before connecting the optimal algorithm to the actual building.

- First, checking whether all input variables used in the control algorithm are directly input into the control algorithm is crucial, as well as checking whether data can be loaded to the BAS or the data logger.

- Second, to override outputs to the BAS, checking whether the data are controllable is necessary. This is possible in a simulation study; however, when applied to an actual building, the limitations of the existing BAS must be clearly determined to ensure efficient control of the building. For example, when one wants to control the fan airflow, if fan airflow data are collected from the data logger not from the BAS, then fan airflow cannot be overwritten. Since the data logger only can store the data, cannot control the building, controlled variable need to be collected by BAS.

- Third, the IP address used by the BAS and the sensor IDs of input and output variables need to be known.

- Fourth, checking field data collection intervals is imperative. The control signal interval should be the same as the data collection interval. For example, if data are stored at 1 min intervals and control is performed at 30 s intervals, checking whether the control is well-implemented will be difficult. Similarly, if data are stored at 1 min intervals and the control is performed at 2 min intervals, additional work may be needed to delete data in the uncontrolled time zone.

Figure 10 shows the data communication between ASHRAE Guideline 36 control logic and the test building. The ORNL team defined values, which are the fixed values, in ASHRAE Guideline 36 control logic. Field data were collected by the BAS and a data logger. ASHRAE Guideline 36 control logic received some field data, such as supply air temperature from RTU and VAV boxes, and supply airflow rate from VAV boxes, from the BAS. ASHRAE Guideline 36 control logic received other field data from the data logger, including the IA temperature, IA relative humidity, SA relative humidity of the VAV boxes and RTU, and SA flow rate from the RTU.

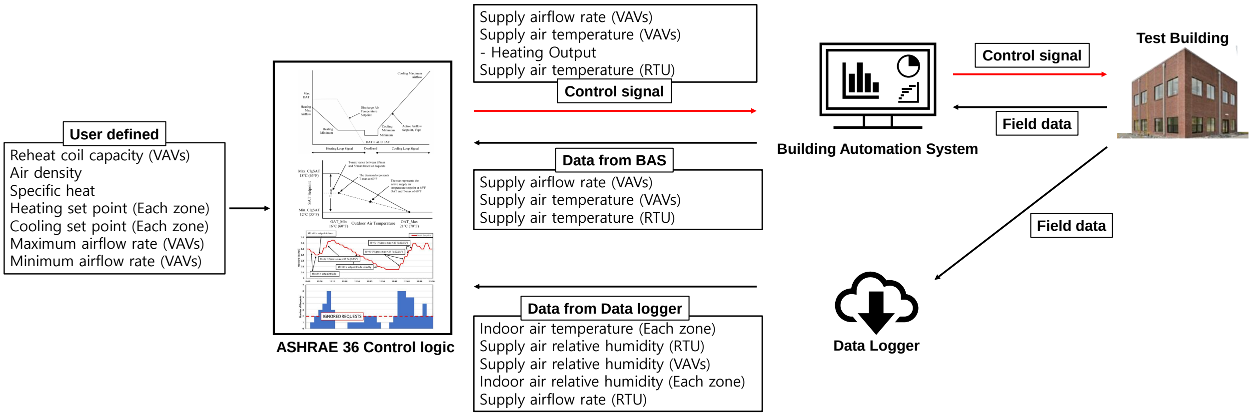


Figure 10. Data communication between ASHRAE Guideline 36 control algorithm and test building.

ASHRAE Guideline 36 control logic sends control signal, which is calculated by received field data and user-defined values, to the BAS. The control signal consists of three different types of data as follows:

- SA flow rate from each VAV box
- SA temperature from each VAV box
- SA temperature from the RTU

The SA flow rate cannot be overwritten directly to the BAS, which is why the ORNL team overrode the control signal of SA flow rate from each VAV box to the values of the maximum and minimum airflow rate of each VAV box by using the programming in the BAS. The ORNL team generated fake sensor IDs to override the value of the SA flow rate from the VAV box. The fake sensor ID (VAV_SAF_zone number) is shown on the left side of Figure 11. Figure 11 shows how to override the VAV box SA flow rate to the BAS. After fake sensor IDs were generated, they were linked with the minimum and maximum airflow rate. By controlling the minimum and maximum airflow rate of the VAV box, the VAV box worked as the control signal from the control algorithm.

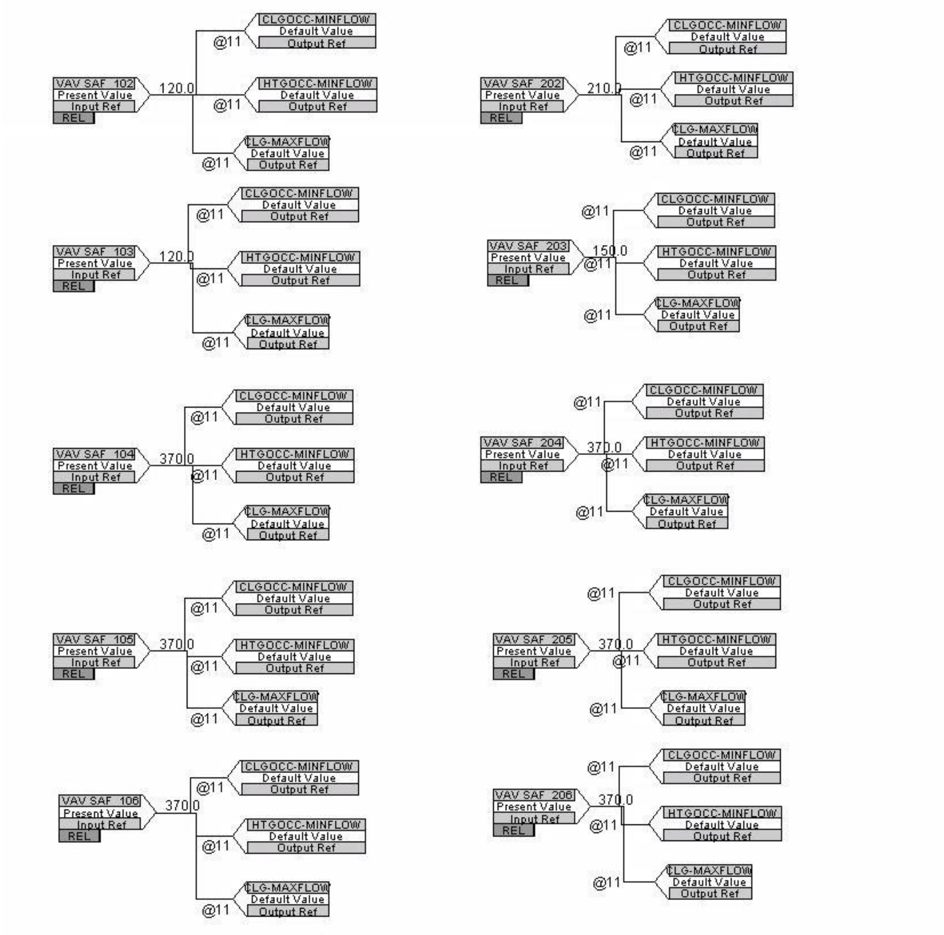


Figure 11. How to override the VAV box SA flow rate to the BAS.

The SA temperature from the VAV box cannot be overwritten because it changes based on the heating output of the VAV box. To override the SA temperature from the VAV box, in this test, the ORNL team generated fake sensor IDs (VAV_SAT_zone number) and linked fake sensor IDs with the heating output of the VAV box as shown in Figure 12. Figure 12 shows how to override the VAV box SA temperature to the BAS. To send the heating output signal, the ORNL team calculated the value of the heating output using the SA temperature of the VAV box.

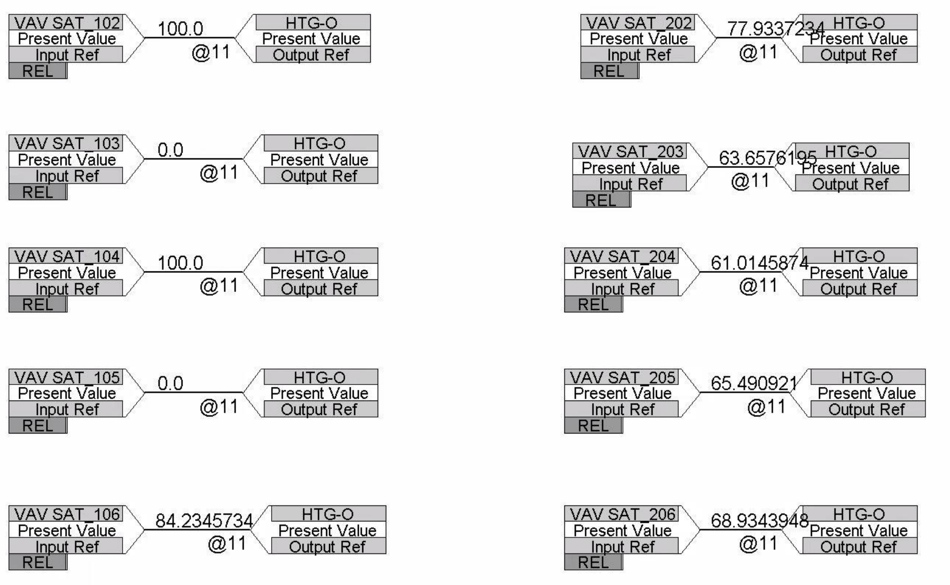


Figure 12. How to override the VAV box SA temperature to the BAS.

Figure 13 shows the relationship between the SA temperature from the VAV box and the heating output of the VAV box. The heating output of the VAV box is 0% when the VAV box does not work. When the VAV box does not work, the SA temperature is the same as the SA temperature from the RTU. When the maximum SA temperature from the VAV box is needed, the heating output of the VAV box is 100%. The maximum SA temperature from the VAV box is the same as the threshold. Threshold in Figure 13 is determined by ASHRAE Guideline 36 control logic. The two thresholds in ASHRAE Guideline 36 control logic are as follows [2]:

- Threshold 1: Heating set point temperature plus 11°C
- Threshold 2: IA temperature plus 3°C

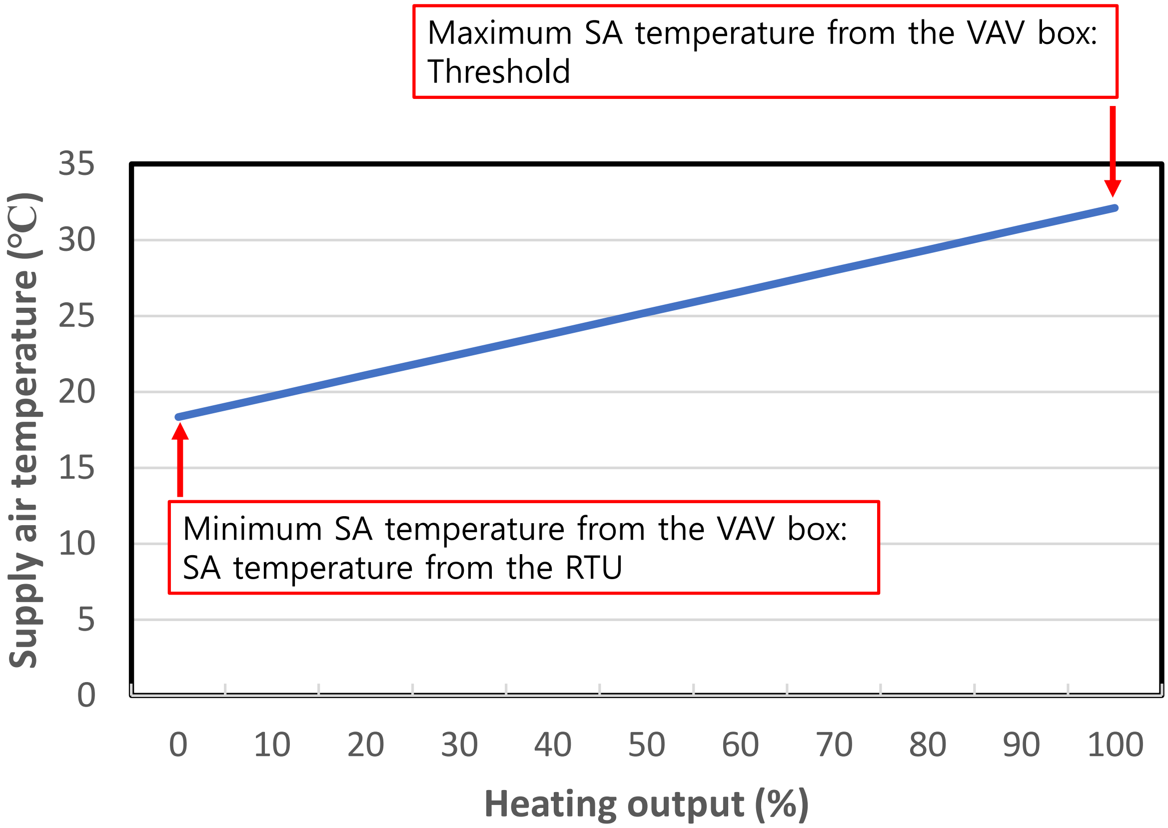


Figure 13. Relationship between SA temperature and heating output.

From 0% to 50% heating signal, the maximum SA temperature from the VAV box is the same as "Threshold1." From 51% to 100% heating signal, the maximum SA temperature from the VAV box is the same as the lower value between "Threshold 1" and "Threshold 2" [2]. The ORNL team calculated the heating output of the VAV box based on the SA temperature from the VAV box by using Eq. (2). T_{inlet} is the inlet air temperature of the VAV box, which is the same as the SA temperature from the RTU. T_{outlet} is the outlet air temperature of the VAV box, which is the same as the SA temperature from the VAV box.

$$Heating\ output\ (\%) = 100 - \left(\frac{100}{Threshold - T_{inlet}}\right) \times (Threshold - T_{outlet}) \tag{2}$$

Figure 14 shows how to override the RTU SA temperature to the BAS. Because the RTU SA temperature can be overwritten, the RTU DA temperature is overwritten directly.

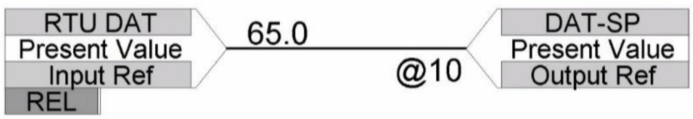
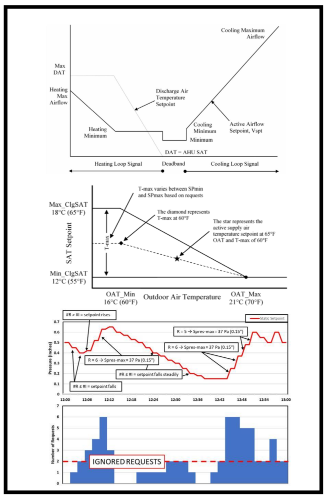


Figure 14. How to override the RTU SA temperature to the BAS.

5. INITIAL FIELD TEST DATA ANALYSIS

The ORNL team conducted initial field testing. Figure 15 shows the initial test plan. Before the initial testing, the ORNL team performed logic testing to check whether ASHRAE Guideline 36 control logic can communicate with the test building. The VAV control of ASHRAE Guideline 36 control logic was tested on February 1 and 2, 2022, and the RTU control of ASHRAE Guideline 36 control logic was tested on February 23, 2022. The ORNL team tested the entire ASHRAE Guideline 36 control logic on March 11, 2022.

ASHRAE 36 Control logic



Field test schedule

- **Logic test**
  - VAV control: 02/01/22 – 02/02/22
  - RTU control : 02/23/22
  - VAV and RTU control: 03/11/22
- **Initial test**
  - 03/15/22 11 a.m. – 03/18/22 9 a.m.
  - 03/25/22 10 a.m. – 03/25/22 10 p.m.
  - Test setting

Heating set point	21°C
Cooling set point	23.9°C

- 03/18/22 11 a.m. – 03/18/22 6 p.m.
- 03/25/22 11 p.m. – 03/28/22 7 a.m.
- Test setting

Heating set point	23.9°C
Cooling set point	26.7°C

- 03/31/22 8 p.m. – 04/01/22 8 a.m.
- Test setting

Heating set point	26.7°C
Cooling set point	29.4°C

Test Building

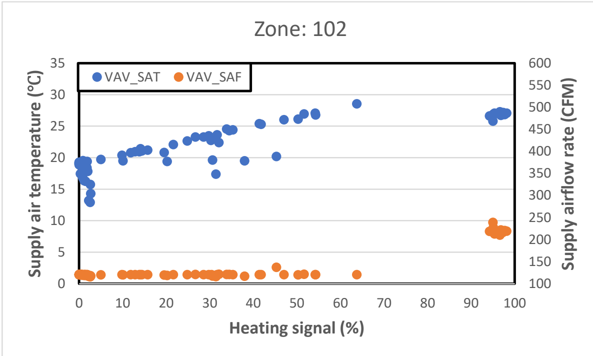
Figure 15. Initial field test plan.

After confirming that ASHRAE Guideline 36 control logic can communicate with the test building, the ORNL team conducted initial field testing from March 15 to April 1, 2022.

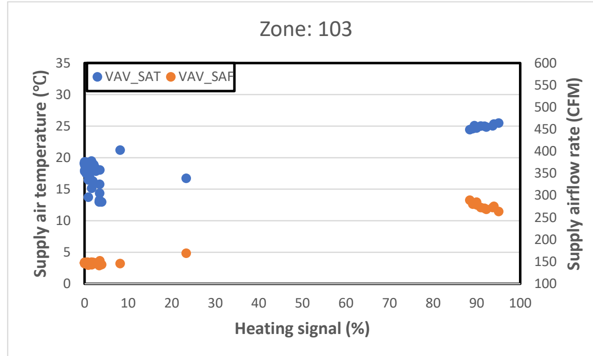
From March 15 to 18, 2022, the heating set point temperature was 21°C and the cooling set point temperature was 23.9°C. Because of the warmer outdoor conditions, it was challenging to test the VAV heating control logic. Therefore, on March 18, and from March 25 to 28, 2022, the ORNL team increased the heating and cooling set point temperature to 23.9°C and 26.7°C, respectively, to increase the heating load of the building to test the VAV heating control logic.

Also, the ORNL team conducted final round of field test from March 31 to April 1, 2022. The ORNL team increased the heating setpoint temperature and cooling setpoint temperature to 26.7°C and 29.4°C respectively.

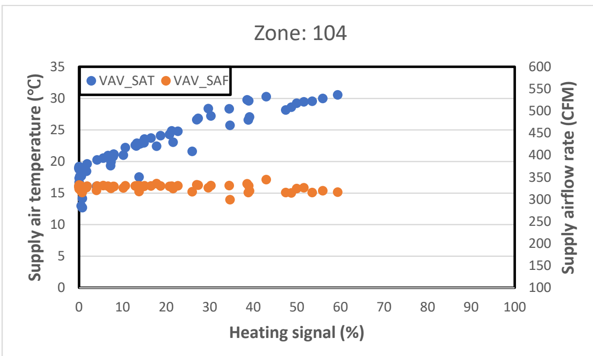
Figure 16 shows the field data analysis for the VAV control logic. SA temperature and SA flow rate in Figure 16 are the data from each VAV box. As shown in Figure 17, the pattern of the SA temperature trend is consistent with the pattern of ASHRAE Guideline 36 control logic. As the heating signal increased, the SA temperature increased. The SA flow rate was set as the minimum airflow rate of each VAV box under 50% of heating signal. When the heating signal was greater than 50%, then the SA temperature was set as the maximum SA temperature, and the SA flow rate increased as the heating output increased.



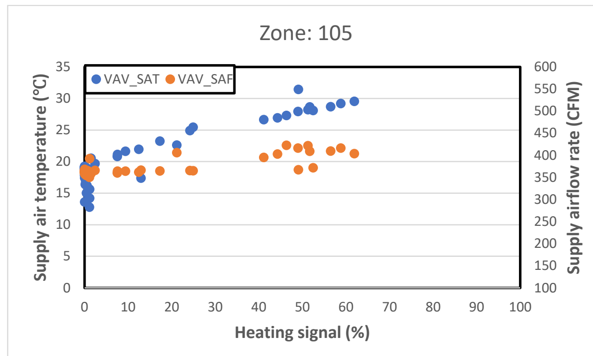
(a) Zone 102



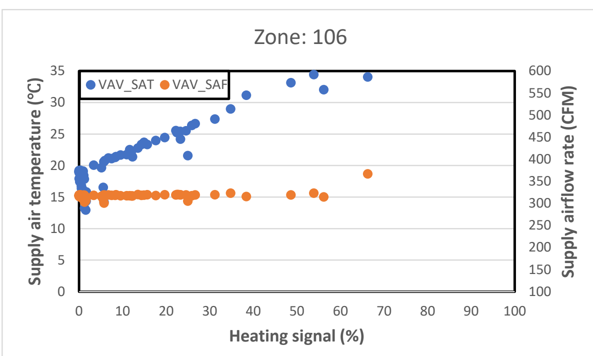
(b) Zone 103



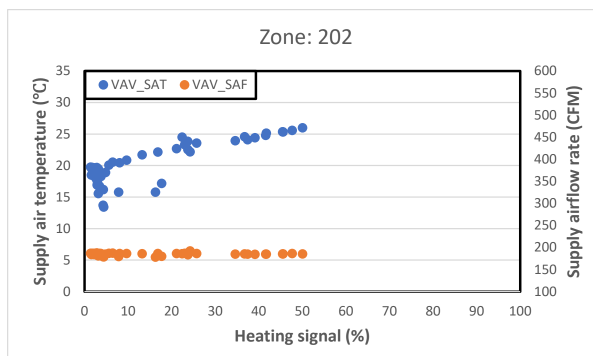
(c) Zone 104



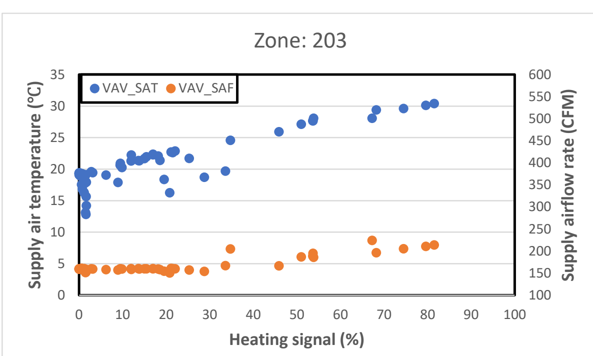
(d) Zone 105



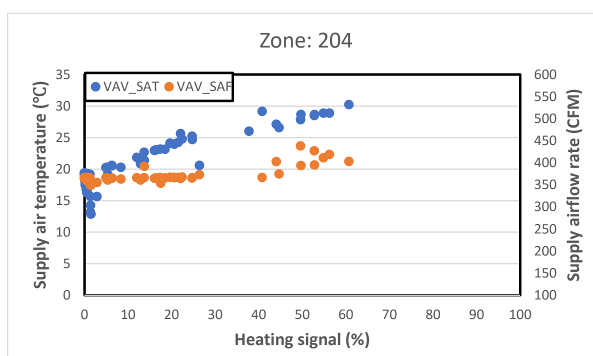
(e) Zone 106



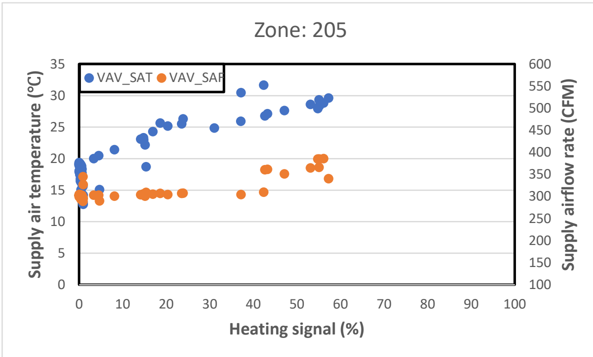
(f) Zone 202

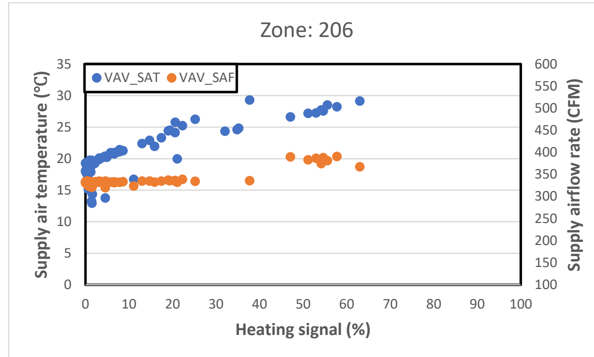


(g) Zone 203



(h) Zone 204





(i) Zone 205 **(j) Zone 206**

Figure 16. SA temperature and SA flow rate from VAV boxes in each zone.

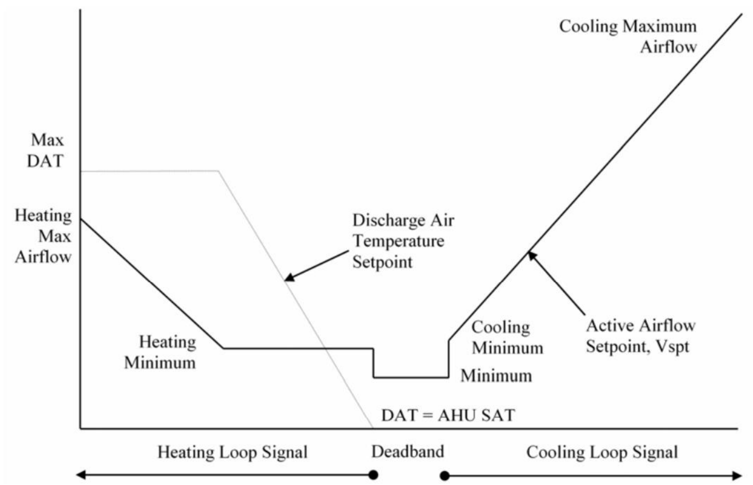
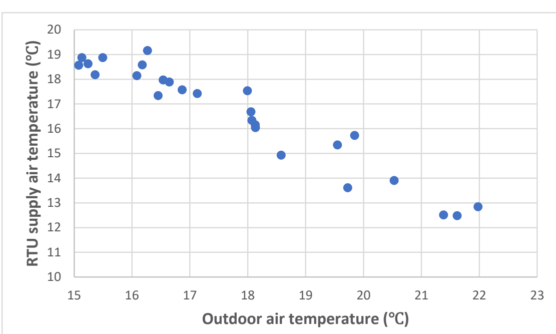
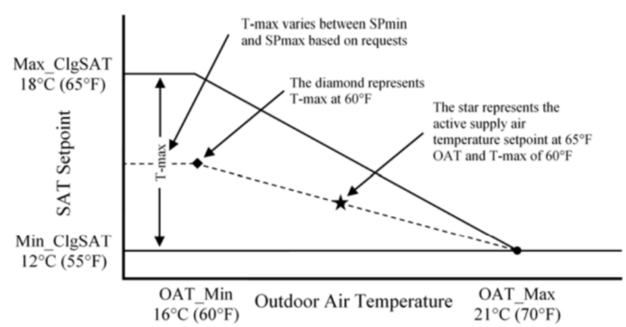


Figure 17. Control logic for VAV boxes from ASHRAE Guideline 36 [2].

Another control logic, SA OA reset control was tested as well. Figure 18 shows the pattern of the RTU SA temperature and SA temperature reset diagram [2]. The pattern of the RTU SA temperature is consistent with the SA temperature reset diagram, which is provided by ASHRAE Guideline 36.





(a) Pattern of the RTU SA temperature **(b) SA temperature reset diagram [2]**

Figure 18**. Pattern of the RTU SA temperature and SA temperature reset diagram.**

6. CONCLUSIONS

This study includes the results from the initial field test analysis from the implementation of ASHRAE Guideline 36 control to ORNL's FRP-2 building.

For the initial field test, ORNL's FRP-2 building was selected as a test building. The RTU system serves as the building's primary cooling system, and each VAV box with an electric reheat coil serves as the building's heating system along with the RTU gas furnace. The control for the RTU and VAV box adopted the practical control sequences from *ASHRAE Guideline 36-2018: High-Performance Sequences of Operation*.

The ORNL team implemented ASHRAE Guideline 36 control logic into the FRP-2 building and checked whether ASHRAE Guideline 36 control logic can communicate with the FRP-2 building and the control the system as expected.

With successful deployment of control, the ORNL team conducted several logic tests on February 1 and 2, 2022; February 23, 2022; and March 11, 2022. Then, the ORNL team conducted initial field testing from March 15 to April 1, 2022.

As demonstrated by the initial field testing, the FRP-2 building, especially the RTU and VAV boxes, was successfully operated based on ASHRAE Guideline 36 control logic. The pattern of the SA temperature and SA flow rate from each VAV box and DA temperature from the RTU was consistent with the pattern of ASHRAE Guideline 36 control logic.

For the rest of FY 2022, the ORNL team will complete impact analysis of sensor types for a selected advanced control logic, complete field testing, and integrate sensor components to the emulator framework.

7. REFERENCES

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