



Lawrence Berkeley National Laboratory

Accuracy of HVAC Load Predictions: Validation of EnergyPlus and DOE-2 using FLEXLAB Measurements

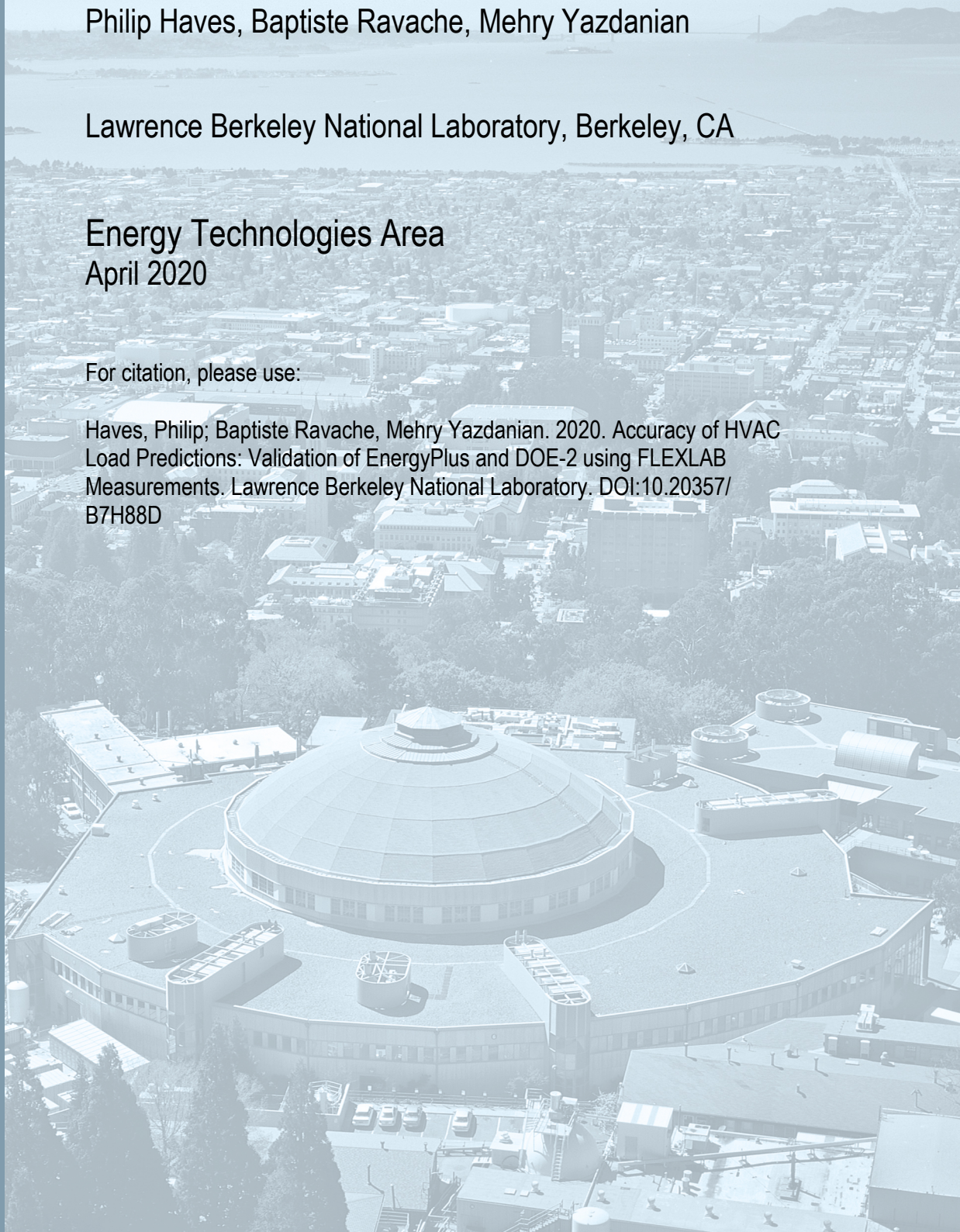
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Abstract

The aim of the project reported here was to better understand the level of accuracy of three building energy simulation (BES) engines ('engines') — EnergyPlus™, DOE-2.1e, and DOE-2.2 — by identifying and investigating significant deviations between the performance predicted by these engines and actual performance as measured in the FLEXLAB® test facility at Lawrence Berkeley National Laboratory (LBNL). The specific test conditions included some of those prescribed in ANSI/ASHRAE Standard 140 - Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Detailed measurements of FLEXLAB performance, including indoor temperatures and heat fluxes and air-flow and water flow rates and temperatures in the Heating, Ventilating and Air Conditioning (HVAC) system, together with hourly weather data, were recorded and used in analyzing the simulation results from EnergyPlus v8.8, DOE-2.2 v3.65 and DOE-2.1e v127. These engines are commonly used in the United States for building energy code compliance, federal, state, and utility incentives programs, as well as energy efficient design of new buildings and energy retrofit of existing buildings.

Seven conventional overhead mixing ventilation scenarios were tested and each engine was found to have a similar level of agreement with the measurements of space-level heating and sensible cooling loads. These results provide useful information regarding the accuracy of these engines in predicting the cooling and heating load elements of whole building energy performance. This information is intended for practitioners who are concerned about transitioning between simulation tools with different engines and for managers of utility programs leveraging these tools for evaluating and/or projecting measure savings to be incentivized under their programs.

The results of the comparisons of simulated and measured performance indicate that the predictions from all three engines are not significantly different. The 24-hour average value of the absolute mean bias indicates the likely magnitude of the error in any particular case. The average mean bias is reduced by cancelation of overprediction in one case by underprediction in another. The daytime absolute mean biases, which may be more important for both energy performance and occupant comfort, are ~6%, presumably because of the greater complexity involved in simulating in the presence of solar radiation.

EnergyPlus typically overpredicts the cooling load and/or underpredicts the heating load by ~1.5% and the DOE-2 engines typically underpredict the cooling load by approximately the same amount. The Root Mean Square Error is relatively more sensitive to shorter term variations in the difference between predicted and measured loads; the three engines have similar values, ~10%, suggesting that the uncertainties in their predictions of peak loads may also be similar in magnitude. The implication of these results is that users, both designers and program analysts, can use EnergyPlus, DOE-2.1e, or DOE-2.2 to model conventional commercial buildings equipped with overhead mixing ventilation with similar levels of confidence.

Further work is required to better understand the variability in the level of agreement between the engine predictions and FLEXLAB measurements, where a particular engine will agree well with FLEXLAB in some cases and not so well in others and another engine will agree or disagree in different cases. As the sources of this variability are identified and eliminated or reduced significantly, it is recommended that the experimental capabilities and methods developed in the study reported here should be applied to validating heating and cooling load calculations for spaces with different types of furniture and miscellaneous loads. These methods should then be applied to low energy space conditioning systems in EnergyPlus including, in particular, radiant slab and radiant ceiling panel cooling and heating systems and 'mixed mode' systems that combine mechanical cooling and natural ventilation systems, focusing on controls, including control of thermal mass.

The work reported here addresses the conventional method of heating and cooling occupied spaces; other methods, such as the use of radiant heating and cooling systems have the potential to provide equivalent occupant comfort, or better, with lower energy consumption. These systems are addressed more explicitly in EnergyPlus but there is a need for empirical validation to give users the same level of confidence in modeling these systems that they have, or should have, in modeling conventional systems, based on the results presented here.

Keywords: Whole building energy simulation, empirical validation, FLEXLAB, EnergyPlus, DOE-2

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Executive Summary

Introduction

Whole building energy simulation has been used to inform the design of new buildings, particularly commercial buildings, and to identify retrofit options for improving performance. As the need to improve building energy performance becomes ever more pressing as a result of the need to mitigate global climate change, there is a corresponding need to understand both the accuracy and limitations of whole building energy simulation programs. Until now, the only option for validating such programs has been to compare the predictions of different programs to each other. In 2016, the US Department of Energy (DOE) instigated a set of experimental studies at several National Laboratories, including LBNL, to generate measured data for use in the empirical validation of whole building energy simulation programs. The study reported here, supported by Southern California Edison, made use of these experimental measurements to validate the heating and cooling load predictions of three simulation programs that were developed in the United States with public funds and are currently used by building designers and utility program and policy analysts.

Project Purpose

The purpose of the project reported here was to better understand the level of accuracy of three building energy simulation (BES) engines ('engines') — EnergyPlus™, DOE-2.1e, and DOE-2.2 — by identifying and investigating significant deviations between the performance predicted by these engines and actual performance as measured in Lawrence Berkeley National Laboratory's FLEXLAB® test facility for specific test conditions, including some of those prescribed in ANSI/ASHRAE Standard 140 - Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. These engines are commonly used in the United States for building energy code compliance, federal, state, and utility incentives programs, as well as energy efficient design of new buildings and energy retrofit of existing buildings.

Project Process

Detailed measurements of FLEXLAB performance, including indoor temperatures and heat fluxes and air-flow and water flow rates and temperatures in the Heating, Ventilating and Air Conditioning (HVAC) system, together with hourly weather data, were recorded and used in analyzing the simulation results from EnergyPlus v8.8, DOE-2.2 v3.65 and DOE-2.1e v127.

Project Results

The results, summarized in Table 1, indicate that results from all three engines are not significantly different. The 24-hour average value of the absolute mean bias (column 2) indicates the likely magnitude of the error in any particular case. The average mean bias (column 3) is reduced by cancelation of overprediction in one case by underprediction in another. The daytime absolute mean biases, which may be more important for both energy performance and occupant comfort, are ~6%, presumably because of the greater complexity involved in simulating in the presence of solar radiation.

EnergyPlus typically overpredicts the cooling load and/or underpredicts the heating load by $\sim 1.5\%$ and the DOE-2 engines typically underpredict the cooling load by approximately the same amount. The Root Mean Square Error is relatively more sensitive to shorter term variations in the difference between predicted and measured loads; the three engines have similar values, $\sim 10\%$, suggesting that the uncertainties in their predictions of peak loads may also be similar in magnitude. The implication of these results is that users, both designers and program analysts, can use EnergyPlus, DOE-2.1e, or DOE-2.2 to model conventional commercial buildings equipped with overhead mixing ventilation with a similar level of confidence.

Table 1. Summary of Comparisons

| | Mean Absolute Error (Range Normalized), Averaged over all Cases (%) | Mean Bias Error (Range Normalized), Averaged over all Cases (%) | Root Mean Square Error (Range Normalized), Averaged over all Cases (%) |
|------------------------|---|---|--|
| EnergyPlus vs. FLEXLAB | 2.7 | 1.5 | 9.4 |
| DOE-2.1e vs. FLEXLAB | 3.4 | -1.5 | 11.2 |
| DOE-2.2 vs. FLEXLAB | 3.0 | -0.9 | 11.5 |

Project Recommendations

Further work is required to better understand the variability in the level of agreement between the engine predictions and FLEXLAB measurements, where a particular engine will agree well with FLEXLAB in some cases and not so well in others and another engine will agree or disagree in different cases. As the sources of this variability are identified and eliminated or reduced significantly, the experimental capabilities and methods developed in the study reported here should be applied to validating heating and cooling load calculations for spaces with different types of furniture and miscellaneous loads. These methods should then be applied to low energy space conditioning systems in EnergyPlus including, in particular, radiant slab and radiant ceiling panel cooling and heating systems and 'mixed mode' systems that combine mechanical cooling and natural ventilation systems, focusing on controls, including control of thermal mass.

The work reported here addresses the conventional method of heating and cooling occupied spaces; other methods, such as the use of radiant heating and cooling systems have the potential to provide equivalent occupant comfort, or better, with lower energy consumption. These systems are addressed more explicitly in EnergyPlus but there is a need for empirical validation to give users the same level of confidence in modeling these systems that they have, or should have, in modeling conventional systems, based on the results presented here.

Abbreviations and Acronyms

| | |
|----------|---|
| AHU | Air-handling unit |
| BES | Building Energy Simulation |
| BSDF | Bidirectional Scattering Distribution Function |
| CEC | California Energy Commission |
| CBECC | California Building Energy Code Compliance |
| CV(RMSE) | Coefficient of Variance of the Root Mean Squared Error |
| DOE | (US) Department of Energy |
| EEM | Energy Efficiency Measure |
| EMS | Energy Management System |
| FLEXLAB | Facility for Low-Energy eXperiments in Buildings |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IPMVP | International Performance Measurement and Verification Protocol |
| LBNL | Lawrence Berkeley National Laboratory |
| M&V | Measurement and Verification |
| MBE | Mean Bias Error |
| MPE | Mean Percentage Error |
| RNMBE | Range-Normalized Mean Bias Error |
| RMSE | Root Mean Square Error |
| RNRMSE | Range-Normalized Root Mean Square Error |
| SIPS | Structural Insulated Panel |
| TAG | Technical Advisory Group |
| UFAD | Underfloor Air Distribution |
| VFD | Variable Frequency Drive |
| WBES | Whole Building Energy Simulation |

1 Introduction

Whole building energy simulation engines are used to inform the design of utility programs and building energy codes and are increasingly used in the design of commercial buildings. Many analysts and designers use tools based on variants of the DOE-2 engine, which was first developed for the US Department of Energy in the 1970s. EnergyPlus™ is the Department of Energy's free, flagship building energy simulation engine and is intended to replace DOE-2. EnergyPlus has been selected by the California Energy Commission (CEC) to play a key role in Title-24, both in the analysis for updates and in the California Building Energy Code Compliance (CBECC) engine. Comparisons of cooling and heating load predictions made by EnergyPlus and DOE-2.2¹, the simulation engine in eQUEST², and DOE2.1e, the simulation engine in EnergyPro³ and VisualDOE⁴, have shown significant differences. (See Results below.) Resolution of these differences potentially has an important role to play in informing practitioners, program designers, and other stakeholders regarding their future use of EnergyPlus. In particular, for California and the IOUs to realize the potential of EnergyPlus to enable energy-efficient design and operation and Demand Response requires that stakeholders have confidence in the accuracy and robustness of EnergyPlus.

Comparisons of predictions from EnergyPlus, DOE-2.1e, and DOE-2.2 with measurements from Lawrence Berkeley National Laboratory's (LBNL) FLEXLAB® test facility (FLEXLAB, n.d.) have been conducted with the aim of determining which engine is more accurate. Significant deviations between building energy simulation's predicted performance versus actual performance as measured in FLEXLAB, at least for simple buildings, have been identified, starting with key test cases in ASHRAE Standard 140.

The significant differences between EnergyPlus predictions and the measurements will be shared with the rest of the EnergyPlus Development Team with the aim of rectifying any problems identified. Observed differences between the DOE-2 engines and the measurements have not been investigated in this project, partly because of resource constraints and partly because DOE-2.1e is no longer supported by US DOE and DOE-2.2 is proprietary. However, all findings involving significant differences in the load predictions from these engines will be communicated to the California Public Utilities Commission / Energy Division for their own evaluation and/or use.

A significant amount of project effort was applied to examining the differences between the predictions and the measurements, with the aim of identifying any errors or inconsistencies in the measurements. Explicit identification of errors in the engines is beyond the scope of the project, though apparent significant correlations between differences and experimental conditions have been noted and will serve as starting points for future investigations.

¹ DOE-2.2, produced by JJ Hirsch and Associates, is an extension of DOE-2.1e.

² eQuest is the user interface for DOE-2.2, also produced by JJ Hirsch and Associates.

³ EnergyPro is a user interface for DOE-2.1e, produced by EnergySoft.

⁴ VisualDOE is a user interface for DOE-2.1e, produced by Charles Eley and Associates, now part of NORESO

1.1 Background

1.1.1 EnergyPlus

EnergyPlus is the Department of Energy's flagship building energy simulation engine, replacing DOE-2, and is open source and distributed free-of-charge to the end-user. EnergyPlus enables the analysis of the energy, peak demand, water-use and renewables for more innovative and complex mechanical system and building designs. It makes fewer approximations and is more transparent; for example, EnergyPlus treats the following systems explicitly, without the need for the workarounds or simplifications required in DOE-2.1e or DOE-2.2:

- Radiant cooling and heating
- Underfloor air distribution (UFAD) and displacement ventilation
- Natural ventilation
- Window shading and blinds

DOE continues to fund extensions to EnergyPlus to support both low energy and conventional design for new construction and existing buildings. These extensions are open, documented, and made available in new public releases of EnergyPlus. Based on these and other considerations not detailed herein, EnergyPlus was selected by the CEC to play a key role in Title-24, both in the analysis for updates and in the CBECC-com compliance engine.

As indicated in Figure 1. EnergyPlus software componentsFigure 1, EnergyPlus implements detailed building physics for air, moisture, and heat transfer, including treating radiative and convective heat-transfer separately to support modeling of radiant systems and calculation of thermal comfort metrics. EnergyPlus also calculates lighting, shading, and visual comfort metrics. It supports flexible component-level configuration of heating, ventilation, and air conditioning (HVAC) systems and plant and refrigeration systems and includes a large set of HVAC and plant component models. EnergyPlus simulates sub-hourly time-steps to handle fast system dynamics and control strategies and has a programmable external interface for modeling control sequences and interfacing with other analyses.

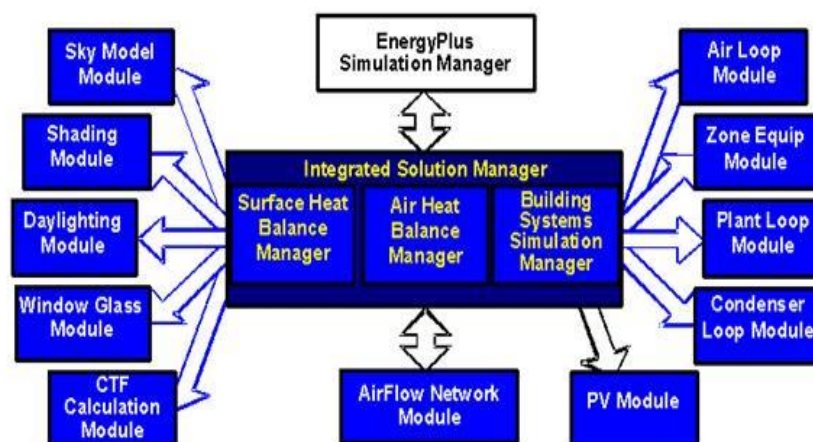


Figure 1. EnergyPlus software components

EnergyPlus can be accessed in a number of different ways:

- OpenStudio⁵: DOE's cross-platform collection of open source software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance
- Commercial user interfaces, intended primarily for designers, including:
 - DesignBuilder^{TM6}
 - Simergy^{TM7}
 - TraceTM-3D Plus⁸
- A suite of tools for editing input files (IDFEditor) and running simulations (EPLaunch) included in the EnergyPlus installation package

The results reported here were generated using EnergyPlus version 8.8.0.

1.1.2 DOE-2

DOE-2 is a freeware building energy analysis engine, developed more than 30 years ago, that continues to be a widely used and accepted engine that can predict the energy-use and cost for all types of buildings. DOE-2 uses a description of the building layout, constructions, usage, conditioning systems (lighting, HVAC, etc.) and utility rates provided by the user, along with weather data, to perform an hourly simulation of the building and to estimate utility bills⁹. DOE-2 performs hour-by-hour calculations with a sequential structure of Loads-Systems-Plant-Economics but does not solve the building envelope thermal dynamics simultaneously with the HVAC system operating performance.

The most widely used current DOE-2 engine is DOE-2.2, with eQUEST[®] as the graphical user-interface program⁹. eQUEST[®]'s features include schematic and design development building model creation wizards, an energy efficiency measure (EEM) wizard and a display module for graphical results. DOE-2.1e is a text-based engine, though users can also use a user-interface tool such as DrawBDL to enter the geometrical input of the building.

⁵ <https://www.openstudio.net/>

⁶ <https://designbuilder.co.uk>

⁷ <https://d-alchemy.com/>

⁸ <http://www.trane.com/commercial/north-america/us/en/products-systems/design-and-analysis-tools/analysis-tools/trace-3d-plus.html>

⁹ <http://doe2.com/doe2/>

2 Differences in Load Calculation Methods between DOE-2 and EnergyPlus

Differences in the calculation of HVAC loads by whole building energy simulation engines can arise for a number of reasons, including differences in:

1. Calculation methods: Heat Balance (EnergyPlus) vs. Weighting Factors (DOE-2)
2. Modeling of envelope heat transfer, including solar radiation
3. Modeling of thermal interaction between internal heat loads (lights, plug loads, occupants) and the air and surfaces
4. Modeling of the effect of changes in air temperature on heat transfer between the air and the interior surfaces, including surfaces bounding elements with significant heat capacity, due to set-point changes and unmet loads

There are significant differences in how EnergyPlus and DOE-2 treat #2, #3, and #4. EnergyPlus performs simultaneous heat balance calculation on each surface and room air, which is a more fundamental approach than the weighting factor approach used in DOE-2. The weighting factor approach effectively combines convective and long wave radiative heat transfer and involves other approximations.

2.1 Objectives

This project has several objectives. One is to assess results of previous comparisons of HVAC load predictions by EnergyPlus and DOE-2, including, but not limited to, ASHRAE Standard 140, identify the most significant differences, and repeat the comparisons with the most recent versions of three building energy simulation engines - EnergyPlus v8.8, DOE-2.1e v127 and DOE2.2 v3.65. Refer to the ASHRAE Standard 140 BESTEST Comparisons and Analysis of Prediction Differences section of this report for comparisons and analysis of prediction differences.

Another objective of this project is to perform a series of tests under different conditions in FLEXLAB and use the measurements obtained to compare and evaluate the ability of EnergyPlus, DOE-2.1e, and DOE-2.2 to predict sensible heating and cooling loads in a space subject to solar heat gains, internal heat gains, and varying temperature set-points.

The BESTEST test cases shown in Table 2 were used as a starting point in defining the FLEXLAB tests. (Refer to the Experiments section of this report.)

2.2 ASHRAE Standard 140 BESTEST Comparisons and Analysis of Prediction Differences

ASHRAE Standard 140-2011 Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs presents comparisons of EnergyPlus and DOE-2.1e and various other engines (though not DOE-2.2) for a number of different test cases, including annual and peak heating and cooling loads for high and low-mass buildings with and without night set-back/set-up (Figure 2). Differences between EnergyPlus v8.1 and DOE-2.1e of up to ~30% (for the case of annual cooling for a high-mass building) are documented.

Table 2. BESTEST Test Cases

| Test # | Building Type | Features Tested | Heating (H) and Cooling (C) set-points | Output |
|--------|---------------|-----------------------------------|--|----------------|
| 430 | Low-Mass | (No windows) | 20°C (H), 27°C (C) | Cooling Energy |
| 430 | Low-Mass | (No windows) | 20°C (H), 27°C (C) | Heating Energy |
| 600 | Low-Mass | (Windows base case) | 20°C (H), 27°C (C) | Cooling Energy |
| 600 | Low-Mass | (Windows base case) | 20°C (H), 27°C (C) | Heating Energy |
| 640 | Low-Mass | Night setback of zone temperature | 10°C (H) 23:00-07:00 20°C (H) 07:00-23:00 27°C (C) | Cooling Energy |
| 900 | High-Mass | (Windows base case) | 20°C (H), 27°C (C) | Cooling Energy |
| 900 | High-Mass | (Windows base case) | 20°C (H), 27°C (C) | Heating Energy |

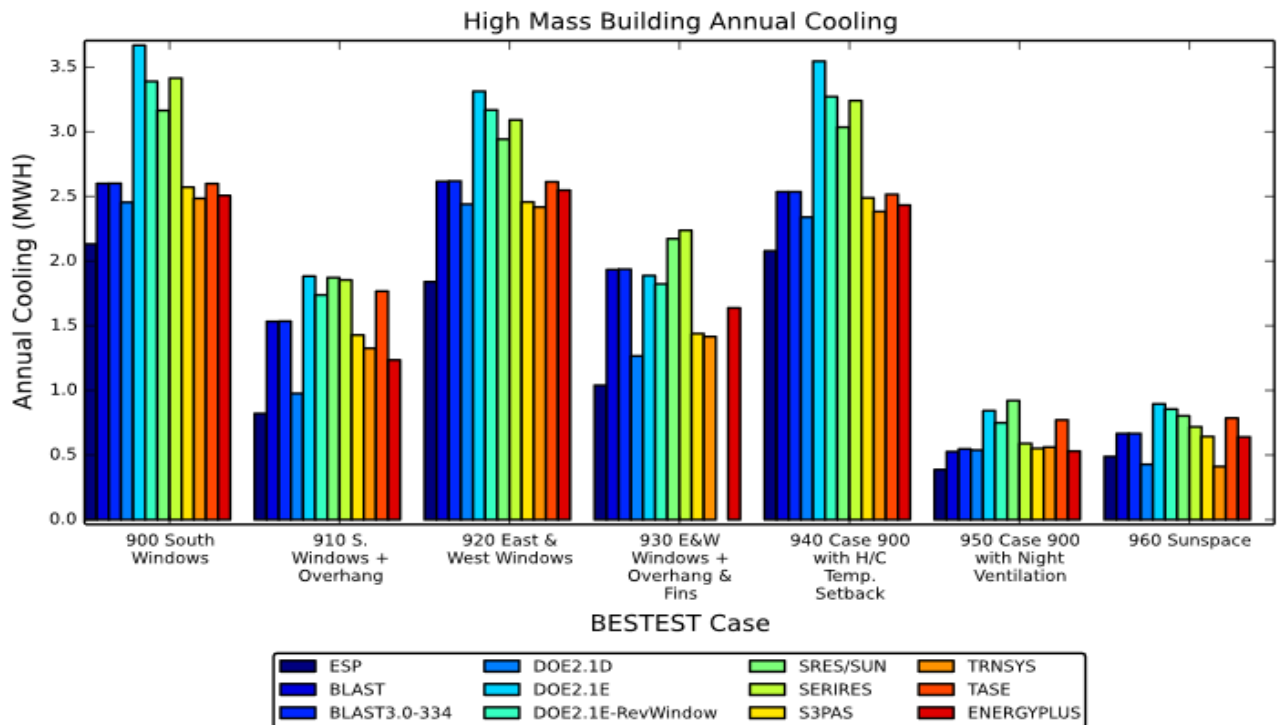


Figure 2. Example comparison of simulated annual cooling energy use between ENERGYPLUS and other tools

Figure 3, Figure 4 and Figure 5 illustrate the differences in the simulated cooling/heating loads between DOE-2.2 and EnergyPlus and between DOE-2.2 and DOE-2.1e. Cooling load is positive and heating load is negative and they are added algebraically each hour. (For

example, if there is cooling for part of a particular hour and heating for the remainder of the hour, there will be partial cancellation.) The horizontal lines in Figure 3 and Figure 4 indicate that the average difference in hourly load is 307 W in Case 600 vs. 172 W in Case 940. Case 600 has low thermal mass and constant zone temperature set-point whereas Case 940 has high thermal mass and variable zone temperature set-point. The distribution of differences at any particular time is also different; the distribution being wider in Case 600 (low-mass) than Case 940 (high-mass). Comparison of Figure 4 and Figure 5 indicates that the differences between DOE-2 and EnergyPlus are $\sim 5\times$ greater than the differences between DOE-2.1e and DOE-2.2.

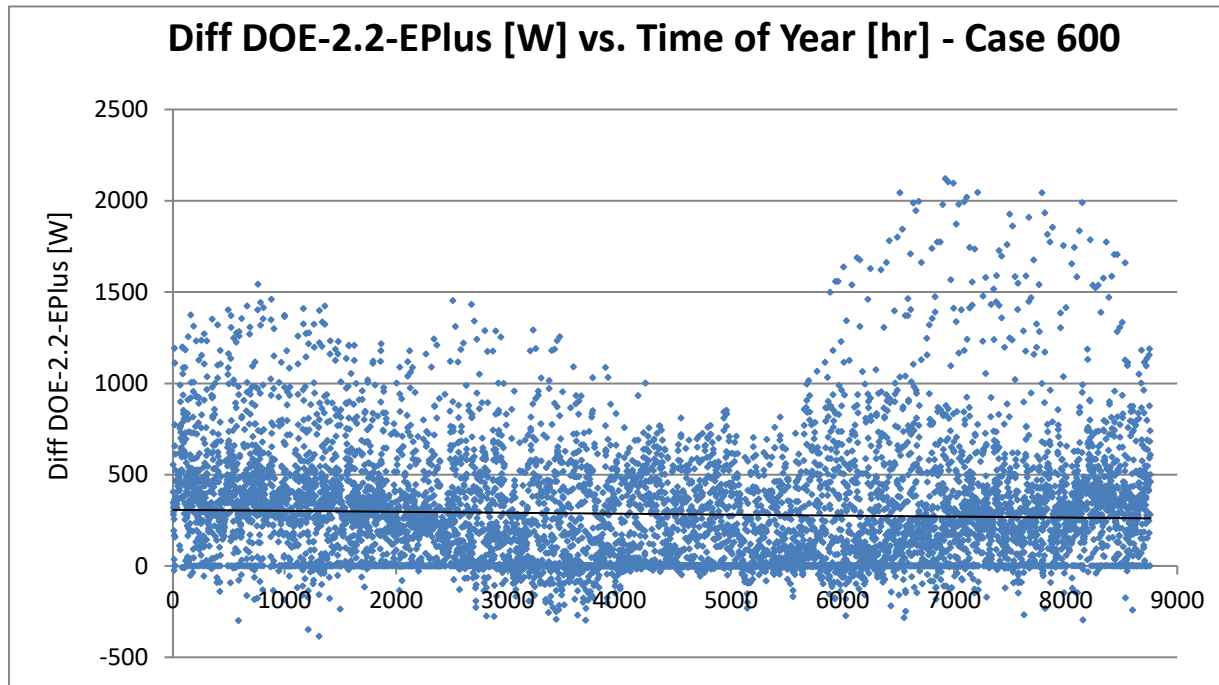


Figure 3. Differences in hourly cooling/heating load predictions between DOE-2.2 and EnergyPlus V8.5 for the Denver TMY used in BESTEST with low-mass construction and constant zone temperature set-point

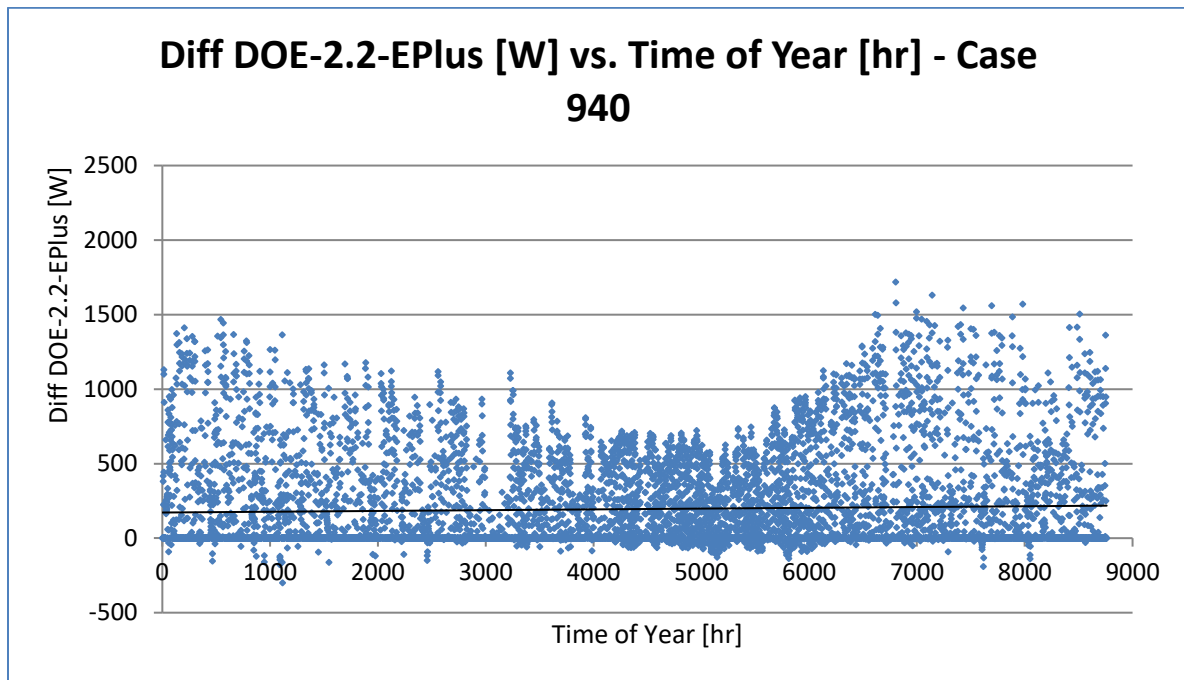


Figure 4. Differences in hourly cooling/heating load predictions between DOE-2.2 and EnergyPlus V8.5 for the Denver TMY used in BESTEST with high-mass construction and variable zone temperature set-point

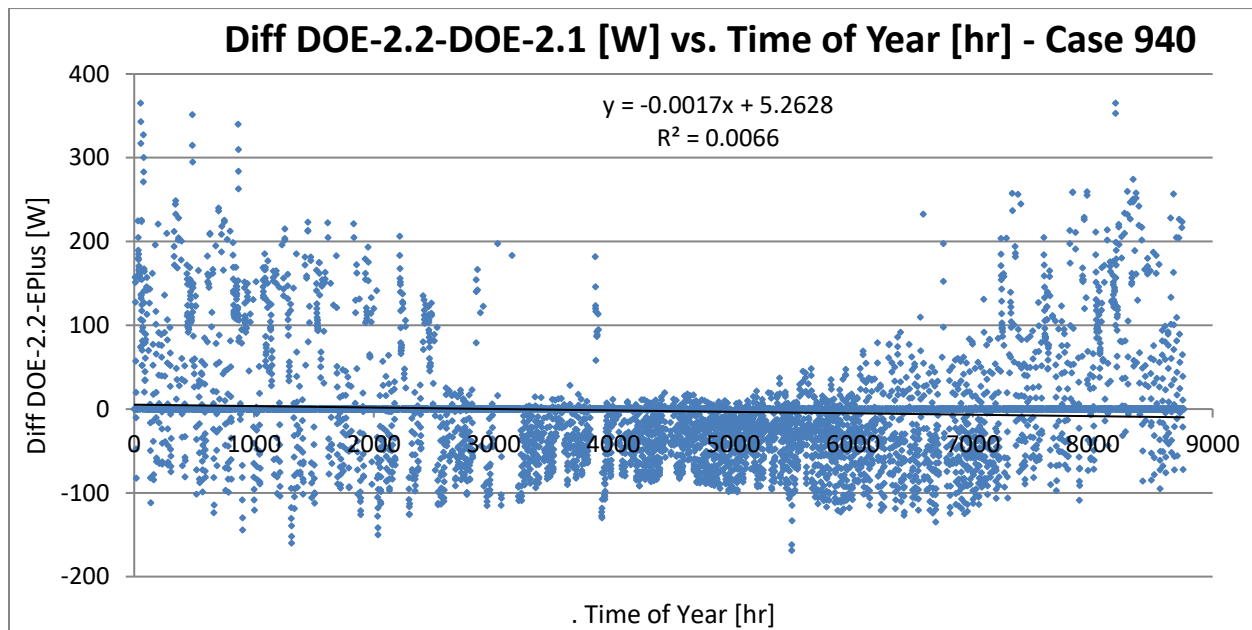


Figure 5. Differences in hourly cooling/heating load predictions between DOE-2.2 and DOE-2.1e for the Denver TMY used in BESTEST with high-mass construction and variable zone temperature set-point

Figure 6 shows the relationship between the differences between the inside temperature maintained by the HVAC system and the outside temperature read from the weather file for both DOE-2.2 and EnergyPlus. There is relatively good agreement between DOE-2.2 and EnergyPlus for Case 600 but the introduction of more thermal mass and greater variation in inside temperature in Case 940 result in a more complex relationship, with DOE-2.2 predicting lower inside temperatures than EnergyPlus for some significant fraction of the time.

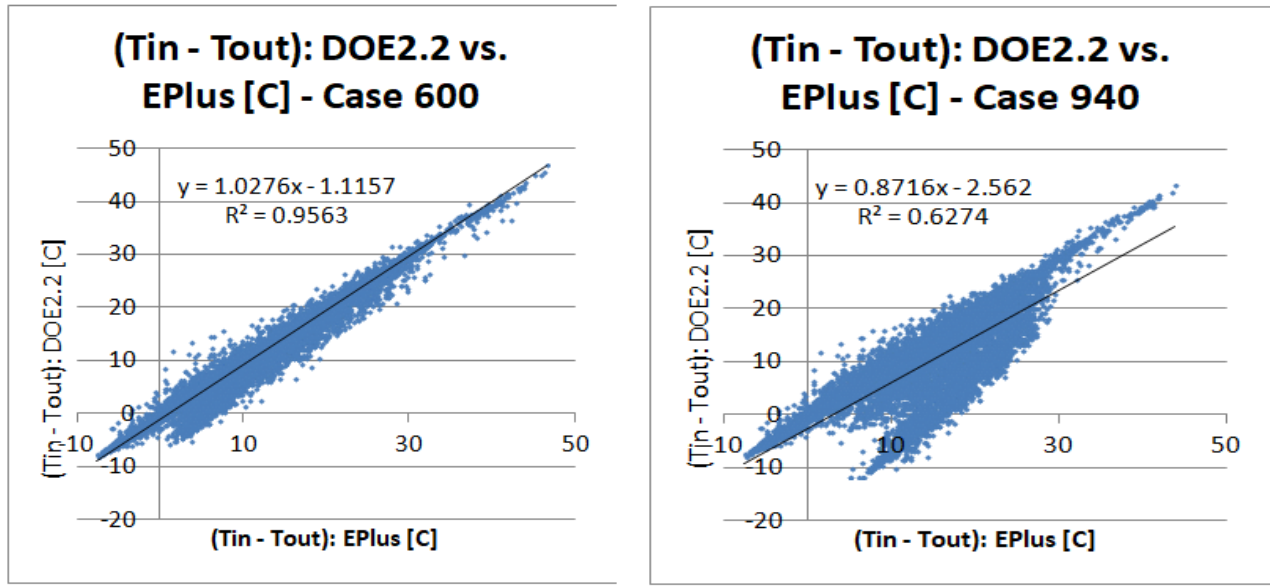


Figure 6. Inside – Outside temperature differences in DOE-2.2 and EnergyPlus for cases 600 and 940.

Figure 6 suggests that the differences between DOE-2.2 and EnergyPlus load predictions for Case 600 seen in Figure 3 cannot easily be explained by temperature effects. Figure 7 shows the incident insolation on the South-facing façade, as calculated by EnergyPlus. A modest correlation is evident for Case 600 ($R^2=0.18$); a somewhat stronger correlation ($R^2=0.31$) is seen for Case 940. This suggests that differences in the treatment of solar radiation may account for some modest fraction of the difference in load predictions. Further analysis is required in order to distinguish between the effects of differences in sky modeling, window transmission, and absorption by interior surfaces. The somewhat stronger correlation for Case 940 suggests that interior surface effects may be significant.

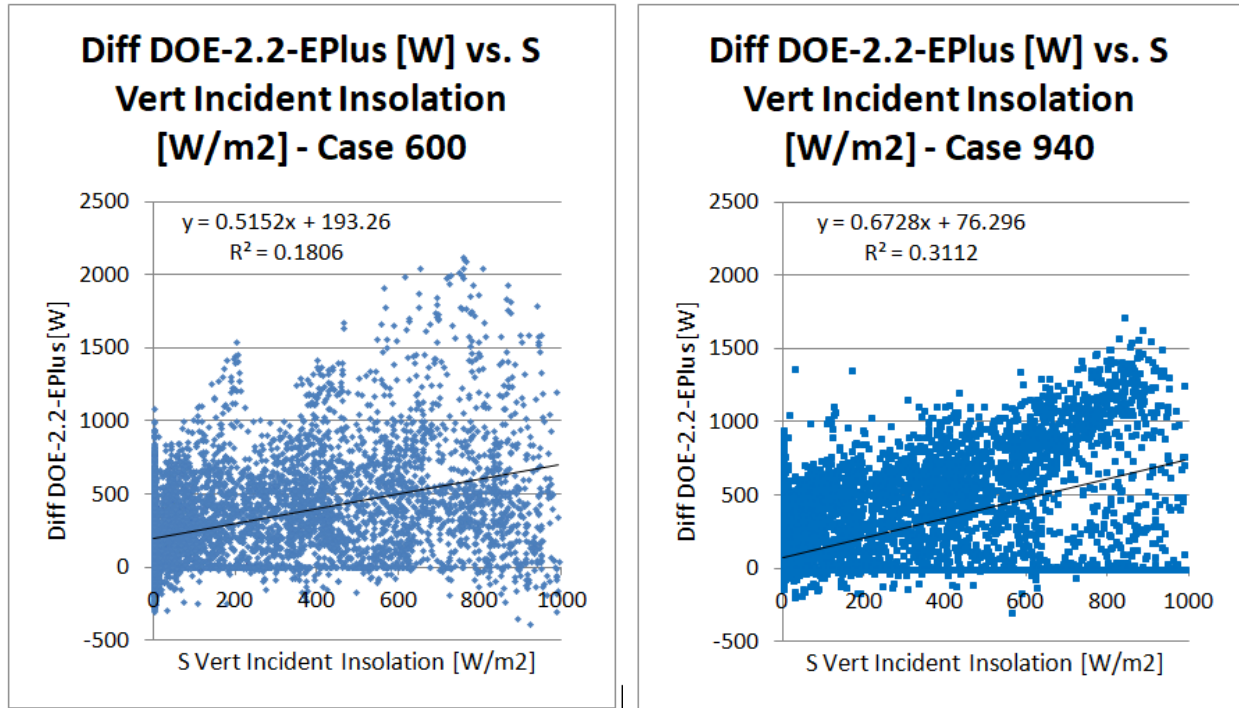


Figure 7. The relationships between DOE – 2.2 – EnergyPlus load prediction differences and the incident insolation on the South-facing façade, as calculated by EnergyPlus, for Cases 600 and 940.

2.3 Weather

2.3.1 Berkeley Weather Data

The measurements listed in Table 3 were made on site at FLEXLAB, by a weather station installed on the roof of Test Bed 2.

Table 3. Meteorological measurements made on site at FLEXLAB

| VARIABLE | UNIT | ACCURACY |
|---|------------------|--|
| Dry bulb temperature | °C | +/- 0.1 K |
| Dew point temperature | °C | +/- 0.2 K |
| Wind direction | Degrees | +/- 2° |
| Wind speed | m/s | +/- 1.5% |
| Global and Diffuse Horizontal Radiation Rate per Area | W/m ² | +/- 5% or +/- 10W/m ² (whichever is greater) |
| Global and Diffuse Horizontal Illuminance | klux | +/- 12% |
| Atmospheric pressure | mbar | +/- 1mbar |

The variables listed in Table 4 are computed, as they are required for the EnergyPlus weather file (EPW), which is then used to generate the weather file for DOE-2.1e and DOE-2.2.

Table 4. Calculated meteorological variables

| VARIABLE | UNIT | CALCULATION (OR SOURCE) |
|---|------------------|---|
| Sun azimuth and height angles | Degrees | Solar Hour Calculation (from oce R package (Kelley 2018)) |
| Direct Normal Radiation Rate Per Area | W/m ² | $\varphi_{direct,normal} = \frac{(\varphi_{global,horizontal} - \varphi_{diffuse,horizontal})}{\sin\left(\frac{\pi}{180} h_{sun}\right)}$ |
| Relative humidity | % | ASHRAE Handbook of Fundamentals 2013 Inputs: dry bulb and dew point temperatures |
| Opaque sky cover | Tenths | Random selection from a uniform distribution |
| Horizontal Sky Infrared Radiation Rate per Area | W/m ² | EnergyPlus V8.8 Engineering Manual Inputs: dry bulb and dew point temperatures and sky cover |

In the absence of a measurement of sky irradiance (due to a signal processing malfunction) or observational estimates of fractional cloud cover from a nearby weather station, the fractional opaque sky cover was selected hourly using a random number generator with a uniform probability distribution (which is the method used in the EnergyPlus Weather Converter for missing data). It was determined through simulations, using both minimum and maximum values for opaque sky cover, that the effect of the opaque sky cover (and the sky infrared radiation computed from it) on the results is insignificant. Figure 8 and Figure 9 show the effect of replacing the random sky cover by either a clear sky or completely cloudy sky in an EnergyPlus simulated case with an exposed window. A clear sky results in a heat

loss rate from the roof and the window that is on average 37.2 W greater than the random sky cover (i.e. less cooling required) and the completely cloudy sky results has a heat removal rate that is on average 37.4 W lower than the random sky cover.

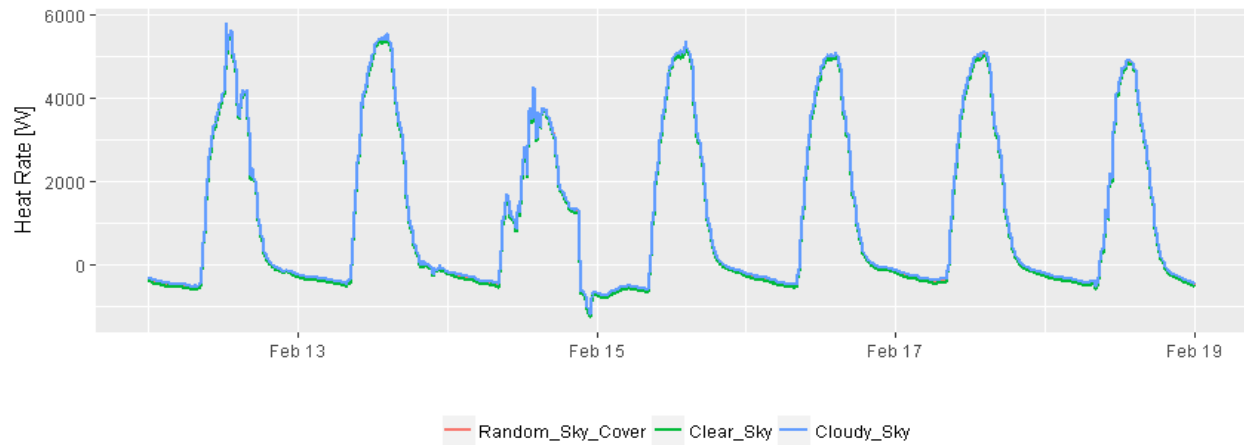


Figure 8. Comparison of Simulated Heat Rate when using Extreme Sky Cover (Clear and Cloudy) Against Random Sky Cover

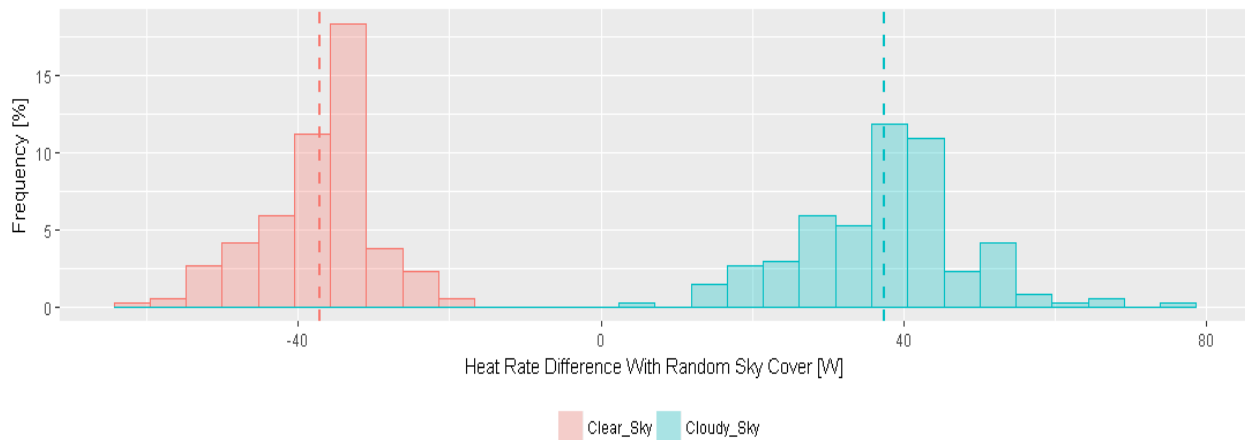


Figure 9. Error Distribution in Heat Rate when Using Extreme Sky Cover Against Random Sky Cover

The variables listed in Table 5 and Table 6 were measured or computed with a one-minute sample time and aggregated to ten-minute samples (for EnergyPlus simulation) or hourly (for DOE-2 simulation) EPW files. The aggregation is made by averaging all points before the step time, unlike the method used for aggregating input and output which averages all points around the step time. Aggregation before the step time was chosen to be consistent with standard hourly EPW and TMY3 weather files and the internal process in the simulation engines. Each variable was “cleaned” by replacing measured values that are physically infeasible. The following rules were applied in the creation of the weather file:

- The Solar Global, Diffuse, and Direct Irradiance should be equal to zero during nighttime (when the sun altitude is lower than zero).

- The Solar Diffuse Horizontal Irradiance should be less than or equal to the Solar Global Horizontal Irradiance. The diffuse value is reduced to the global value when this is not the case.
- The Dew Point Temperature should be less than or equal to the Dry Bulb Temperature. The Dew Point Temperature value is reduced to the Dry Bulb Temperature value when this is not the case.

In addition to the above rules, the measured and calculated variables that lay outside the pre-defined ranges listed in Table 5 were removed.

Table 5. Allowable ranges for meteorological measurements

| TYPE [UNIT] | MINIMUM | MAXIMUM |
|--------------------------------|---------|---------|
| Temperature [°C] | -5 | 100 |
| Speed [m/s] | 0 | No Max |
| Irradiance [W/m ²] | 0 | No Max |
| Direction [degrees] | 0 | 360 |
| Illuminance [klux] | 0 | No Max |
| Pressure [mbar] | 90000 | 200000 |

Any missing or removed data were replaced by interpolating between the closest two data points for that variable. The header for the EPW file, containing information on ground temperatures and location, was copied from the Oakland Airport TMY3 weather file. The hourly EPW file was then converted by the built-in weather converter in eQUEST to the BIN format used by DOE-2.1e and DOE-2.2.

2.3.1.1 Comparison of Berkeley and Denver BESTEST Weather Data

Table 6 shows a comparison of the weather characteristics of Berkeley, CA, represented by Oakland International Airport, and Stapleton International Airport, Denver, the weather station used as source of data for the BESTEST/ASHRAE Standard 140 simulation engine comparisons. (ASHRAE 1% design conditions are used to illustrate the differences between the two sites; there is no particular significance in the choice of 1% design conditions.)

Table 6. Comparison of the weather characteristics of Berkeley/Oakland, CA, and Denver, CO

| LOCATION | HEATING DEGREE DAYS BASE 18.3°C | COOLING DEGREE DAYS BASE 18.3°C | ASHRAE 1% HEATING DESIGN CONDITION [°C] | ASHRAE 1% COOLING DESIGN CONDITION – DRY BULB AND MEAN COINCIDENT WET-BULB TEMPERATURE [°C] |
|-------------|---|--|---|--|
| Oakland, CA | 1436 | 85 | 4.2 | 25.4 / 17.8 |
| Denver, CO | 3282 | 393 | -15.9 | 32.7 / 15.6 |

Figure 10 and Figure 11 show comparisons of the ambient dry bulb temperature and the global irradiance for Berkeley and for Denver. The Berkeley weather data were measured at the times indicated, which span the period of the tests reported in this report. The Denver

data were taken from the TMY weather file for Denver Stapleton Airport that was used in all the BESTEST comparisons presented in this report. There is substantial overlap in the weather conditions in spring and summer and significant overlap in the fall and winter, though Berkeley does not experience the low temperatures that occur in Denver in the winter. Comparison with indicates that substantial differences between the predictions of DOE-2 and EnergyPlus occur at weather conditions experienced in Berkeley, justifying the use of FLEXLAB to investigate these differences.

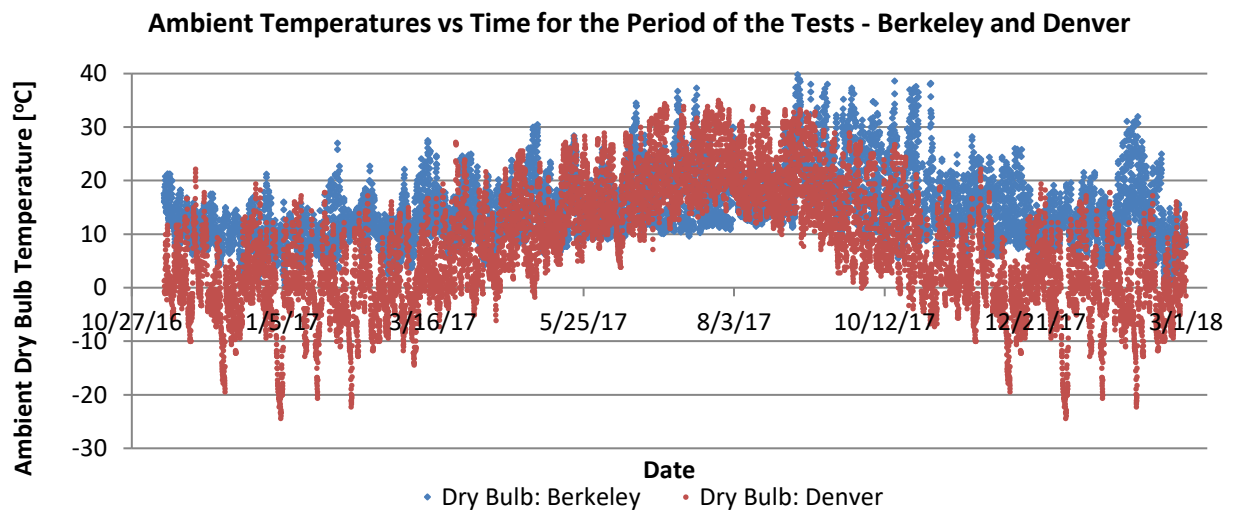


Figure 10. Comparison of the ambient dry bulb temperature for Berkeley and for Denver

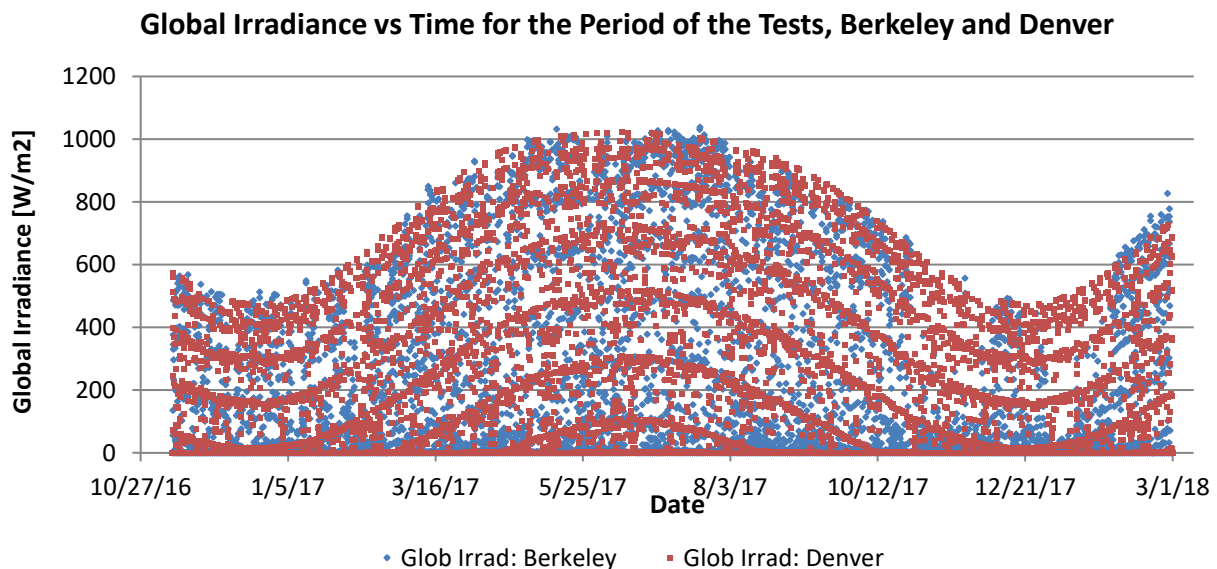


Figure 11. Comparison of the global irradiance for Berkeley and for Denver

2.4 FLEXLAB

The Department of Energy's FLEXLAB at Berkeley Lab is a flexible, physical building efficiency simulator. It allows users to test energy-efficient building systems individually or as an integrated system, under real-world conditions. FLEXLAB test beds can monitor and assess HVAC, lighting, windows, building envelope, control systems, and plug loads, in multiple combination. Users can test components and systems, compare alternatives, and perform cost-benefit analyses.

A general view of the four matched pairs of FLEXLAB test cells is shown in Figure 12 and a plan of the 3A and 3B test cells used in the work reported here is shown in Figure 13.



Figure 12. FLEXLAB test cells as viewed from Southwest

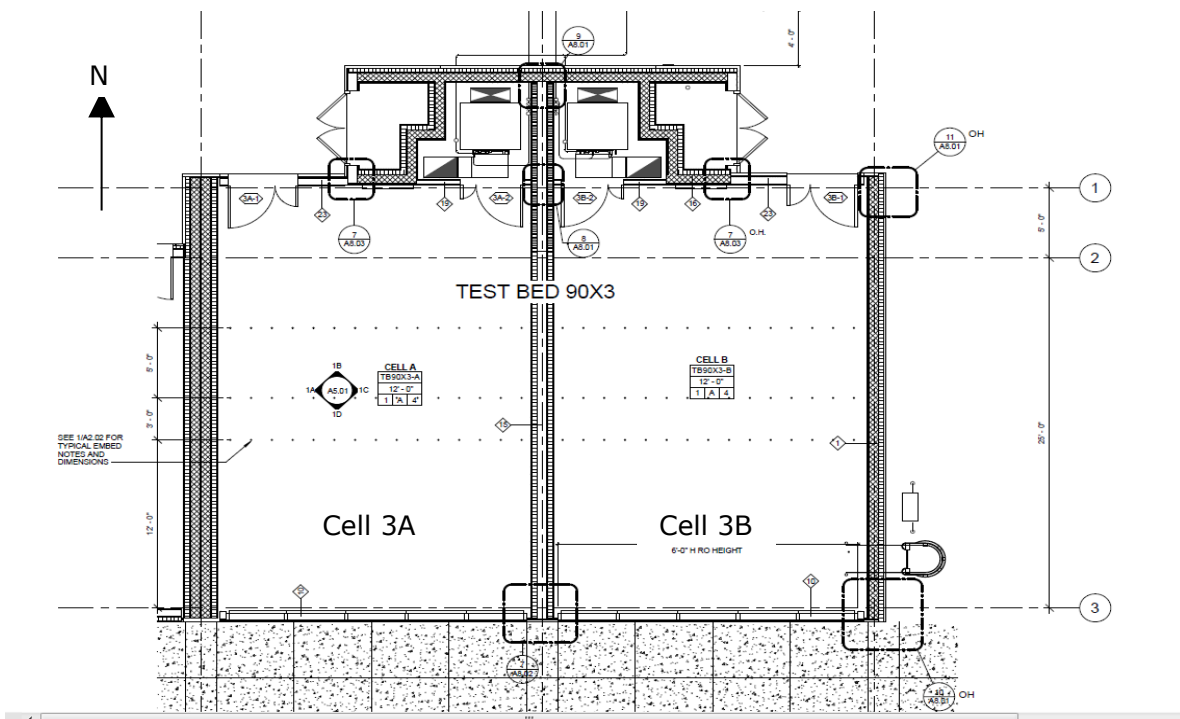


Figure 13. FLEXLAB Test Bed 3 (Cells 3A and 3B) – plan view

3 Technical Approach/Test Methodology

3.1 Laboratory Facility

The experiments were carried out in one of the four test beds that constitute the FLEXLAB test facility at LBNL [1], shown in Figure 14. The test bed used consists of a pair of matched cells (3A and 3B), each 30 ft. x 20 ft. x 16 ft. (9.14 m x 6.09 m x 4.88 m), equipped with a suspended ceiling placed at a height of 9 ft. (2.74 m) above the floor. The floor area of each cell is 600 ft² (59.3 m²). The south facade is reconfigurable, and the other surfaces are relatively highly insulated. (See below.) Each cell then effectively represents a single perimeter zone in a multistory, relatively deep plan building. Each cell includes its own air handling unit (AHU) with an economizer, hot water, and chilled water coils and supply fan. Each pair of cells has its own chilled water and hot water plant.

The thermal isolation resulting from the near adiabatic walls between adjacent cells allows their performance to be analyzed independently. Eight of the twelve experimental tests were conducted in Cell 3B (indicated by B in Figure 14).

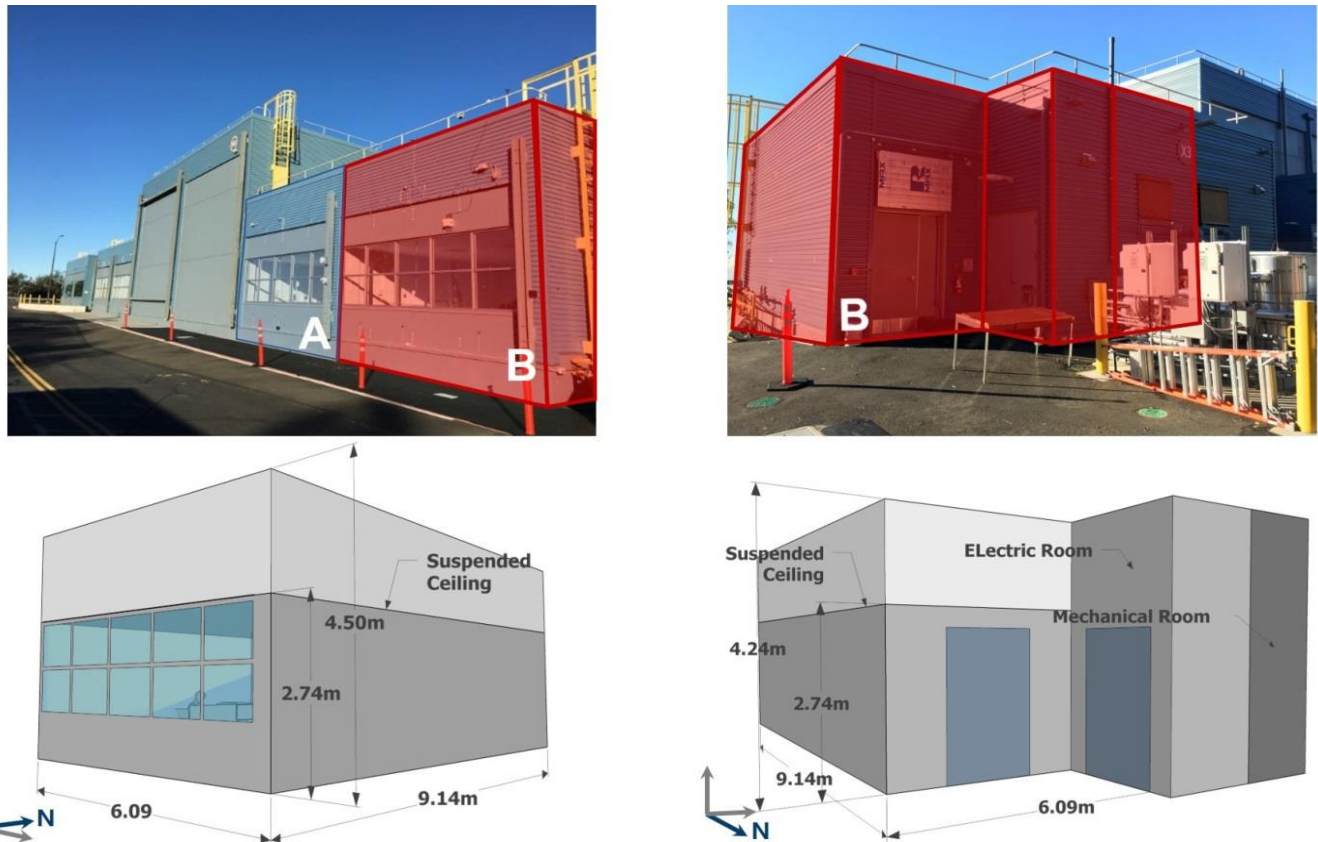


Figure 14. FLEXLAB Cell 3B

The south facade was configured with two rows of five single pane, clear glass windows, above a conventional stud wall with a heat transmission coefficient of 0.46 W/(m²K). The east facade has a heat transmission coefficient of 0.07 W/(m²K) and the partition wall between Cell B and Cell A, which bounds the west side of Cell B, has a heat transmission coefficient of 0.16 W/(m²K). The mechanical room and electrical room are located on the north side of the cell and provide a thermal buffer for ~60% of the north wall, the remainder of which has a heat transmission coefficient of 0.56 W/(m²K).

Thermal conditions in each test cell are maintained by a single zone AHU located in a mechanical closet on the north side of the cell. The AHU contains a hot water heating coil, a chilled-water cooling coil, a supply fan, and an economizer. The coils are supplied from a heating and cooling plant located to the north of the testbed that serves both test cells (3A and 3B). The economizer includes an outside air control damper and a recirculation control damper. The outside air damper was kept closed, and the outside air intake was kept sealed, while the tests were in progress. The AHU also includes an airflow measuring station in the supply duct, together with supply air, return air, mixed air and outside air temperature sensors. The coils were controlled by a cascaded control scheme in which the outer PI loop controls the zone temperature by setting the supply air temperature and the inner PI loop modulates the positions of the control valves on the coils. Some difficulties were experienced in tuning the controls across their operating range and the resulting zone temperature shows some undesired deviations from its set-point in some tests as a result.

3.2 Experiment Design, Analysis and Instrumentation

For the high priority ASHRAE Standard 140 test cases identified, the simulated building form was modified to one that can be re-created using FLEXLAB and the comparisons repeated to verify that the differences are still observed, even in the more moderate Berkeley climate. (Refer to Section 2.3 of this report.) Most of the ASHRAE Standard 140 test cases can be recreated in FLEXLAB, since FLEXLAB is approximately the same size (25 ft. x 20 ft. x 8 ft. for Standard 140 vs. 20 ft. x 30 ft. x 8-12 ft. for FLEXLAB). FLEXLAB only has windows in one façade, which faces south in the cells used in the work reported here.

The window and wall sizes and thermal characteristics were modified in simulation to match FLEXLAB. The low-mass cases were reproduced by adding insulation to the top side of the slab-on-grade floor and the high-mass cases were reproduced by exposing the slab. (Each floor slab in FLEXLAB has a continuous layer of rigid insulation separating it from the ground below and hence FLEXLAB is unable to treat slab-on-grade constructions.)

The initial test cell configurations used the full floor area of the cells as originally constructed and used the ceiling void as a plenum return. However, the results reported here were obtained using a modified cell configuration with a temporary north wall (partition), addition insulation above the drop ceiling and a ducted HVAC return, as described below.

Hardware for different experimental configurations included:

- Insulated floor (4" polyisocyanurate)
- Insulated window (2" polyisocyanurate)

Additional instrumentation (per cell) included:

- 150 surface temperature sensors:
 - Permanent interior and exterior sensors
 - Lower and upper surface of drop ceiling
 - Sensors on temporary insulation
- 28 air temperature sensors in four stratification trees

The permanent surface temperature sensor measurements and the infra-red thermography system were used to check for surface temperature inhomogeneities.

The infiltration rates under different conditions were measured using tracer gas. Measurements of the decay of the concentration in each space following periodic releases of

carbon dioxide indicate that rates are generally low - ~ 0.05 ACH under typical conditions, which may be attributed to the tight construction of FLEXLAB. For the tests reported here, each space was pressurized using a small fan to reduce the uncertainty in the zone heat balance due to infiltration. The space was pressurized to ~ 1 Pa (0.004 in water gauge) with respect to the north zone, whose pressure tracked that of the ceiling void and the ambient to better than 1 Pa.

The temperature of the injected air was measured, allowing the thermal effect of the pressurization on the zone heat balance to be determined. In all experiments conducted, the amount of heat introduced (or extracted) by the pressurization system is negligible compared to the total heat load of the cell. Figure 15 shows the heat rate introduced by the injection (i.e. pressurization) system compared to the total load of the cell for the period March 4-6, 2017. The mean of the ratio of the absolute values of the injection heat rate and the total load is 1.5%. Since this value is relatively small compared to other uncertainties and negative internal gains cannot be modeled in DOE-2, it was decided to ignore the injection heat rate.

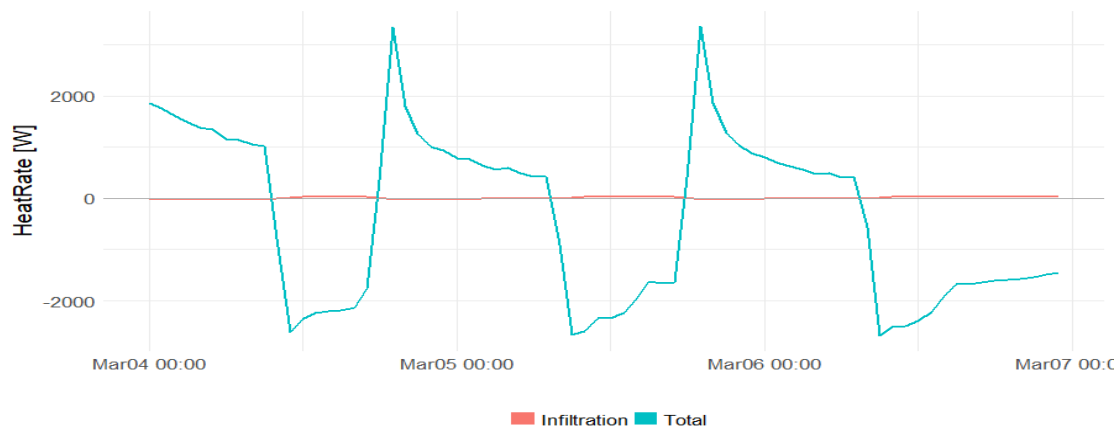


Figure 15. Infiltration and Cell Heat Rate for the period March 4 – 6, 2017

The initial experiments with a constant heating rate indicated thermal time constants of ~ 12 hours, which were thought to result, at least in part, from the heat capacity of the exposed joists and the HVAC air distribution equipment in the unmodified cell configuration. Since the complexity of these elements would make it difficult to model them explicitly, which would be necessary to represent the dynamics, it was decided to thermally isolate the upper part of the cell by installing a heavily insulated drop ceiling; this configuration was used in all further testing. Co-heating experiments showed only minor differences between the two cells – a further indication that the behavior of the cells was as expected.

A Technical Advisory Group (TAG) meeting was held at LBNL on July 18, 2016. The key recommendations from the TAG members regarding the configuration of FLEXLAB for further experiments in the project reported here were:

- Install single pane glazing in place of the double pane low-emissivity window system previously installed in order to increase the overall conductance to the ambient of the otherwise well-insulated remainder of the building envelope
- Add insulation to the top side of the drop ceiling (4.5" polyisocyanurate = R-25)
- Add a temporary north wall $\sim 6'$ from the structural wall (4.5" polyisocyanurate)
- Continue with insulation on the floor for the lo-mass experiments (4" polyisocyanurate = R-22)

The following modifications to the implementation of these measures were made on the instruction of LBNL Fire Protective Services:

- 7" batts of fire-treated denim insulation were substituted for the polyisocyanurate insulation immediately above the drop ceiling
- The 4.5" polyisocyanurate of the temporary north wall was lined on both sides with ½" gypsum wallboard. The side facing the main zone was painted with the same paint used for the other interior wall surfaces in FLEXLAB
- The 4" polyisocyanurate floor insulation was covered with ½" plywood and then with 26-gauge steel sheet, painted with the same grey paint used for the exposed floor slab

Figure 16 shows a north-south section of Testbed 3. The purpose of the drop ceiling insulation is to decouple the main zone from the complexities of the ceiling void, which would be very difficult to model if the ceiling void were part of the main zone. Similarly, the purpose of the temporary north wall is to decouple the main zone from the complexities of the structural north wall, the adjacent mechanical and electrical closets, and the main door.

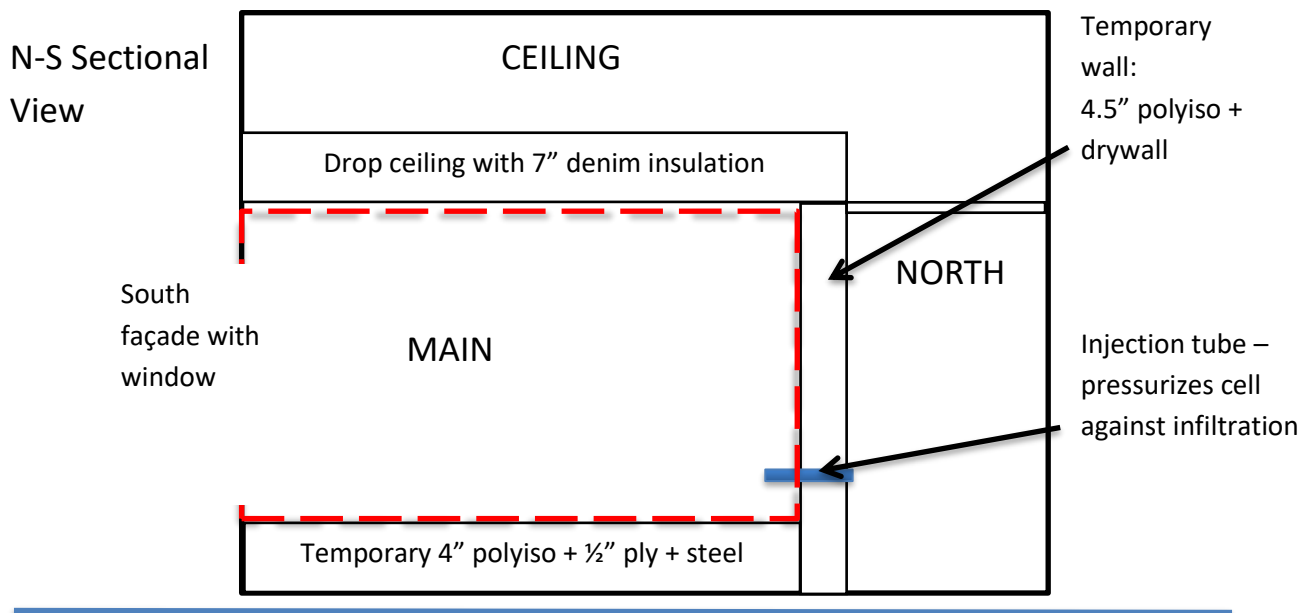


Figure 16. Diagrammatic north-south cross section of Testbed 3, modified as described above.

The properties of the opaque components of the envelope are detailed in Appendix B. The process of modeling of envelope components with two and three-dimensional heat flows is described in Appendix C. The process of modeling the windows and doors in DOE-2 and EnergyPlus is described in Appendices D and E.

3.3 Selection of Experimental Conditions

The simulation results reported in the Weather section indicate that the range of conditions encountered in Berkeley over the period of the tests described in this report (November 2016 to March 2018) give rise to significant differences between the predictions of DOE-2.1e, DOE-2.2, and EnergyPlus. These prediction differences occur for the key configurations corresponding to Case 600 (low thermal mass, constant inside temperature) and Case 940 (high thermal mass, varying inside temperature). As the tests proceeded, the

set-points for the inside temperature were selected to maximize the difference between the inside and outside temperatures, subject to the capacity of the heating and cooling systems.

3.4 FLEXLAB configuration and calibration

3.4.1 Instrumentation

Sixty-one temperature sensors were used to measure the surface temperatures of the walls, windows, floor, and ceiling with every surface having at least six temperature sensors, as shown in Table 7.

Table 7. Positions of the surface temperature sensors

| LOCATION | NUMBER OF TEMPERATURE SENSORS |
|--------------------------------|---|
| South wall | 2 thermistors on the wall, 9 thermocouples on the window and window frame |
| North wall | 9 thermistors |
| West wall | 12 thermistors |
| East wall | 12 thermistors |
| Drop ceiling | 6 thermistors |
| Floor (under the carpet tiles) | 9 thermistors |

Four vertical arrays of temperature sensors, fixed at seven different heights, were used to observe air temperature stratification, as shown in Figure 17. The heights of the temperature sensors on the vertical 'trees' follow ASHRAE Standard 55-2013[2], as shown in Table 8. Table 9 shows product and use information for the sensors used in the test cells.

Table 8. The heights of air temperature sensors on the stratification trees (according to ASHRAE 55-2013)

| HEIGHT ABOVE FLOOR | NOTES |
|--------------------|-----------------------------------|
| 4.0 in (0.1 m) | Ankle level |
| 11.8 in (0.3 m) | Knee level |
| 24.0 in (0.6 m) | Waist level for seated occupants |
| 43.0 in (1.1 m) | Head level for seated occupants |
| 67.0 in (1.7 m) | Head level for standing occupants |
| 86.6 in (2.2 m) | 20 in below the drop ceiling |
| 104.0 in (2.6 m) | 4 in below the drop ceiling |

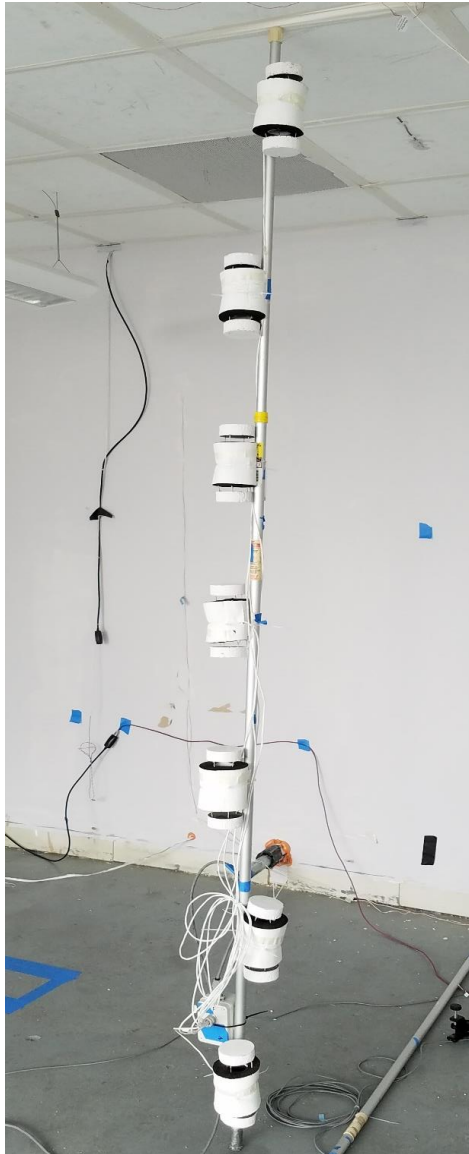


Figure 17. A vertical temperature sensor array

Each air temperature sensor was surrounded by a prototype radiation shield, made from pipe insulation and painted white to reflect solar radiation, as shown in Figure 18. The locations of the vertical trees are shown in Figure 19.



Figure 18. Example of air temperature sensor with radiation shield

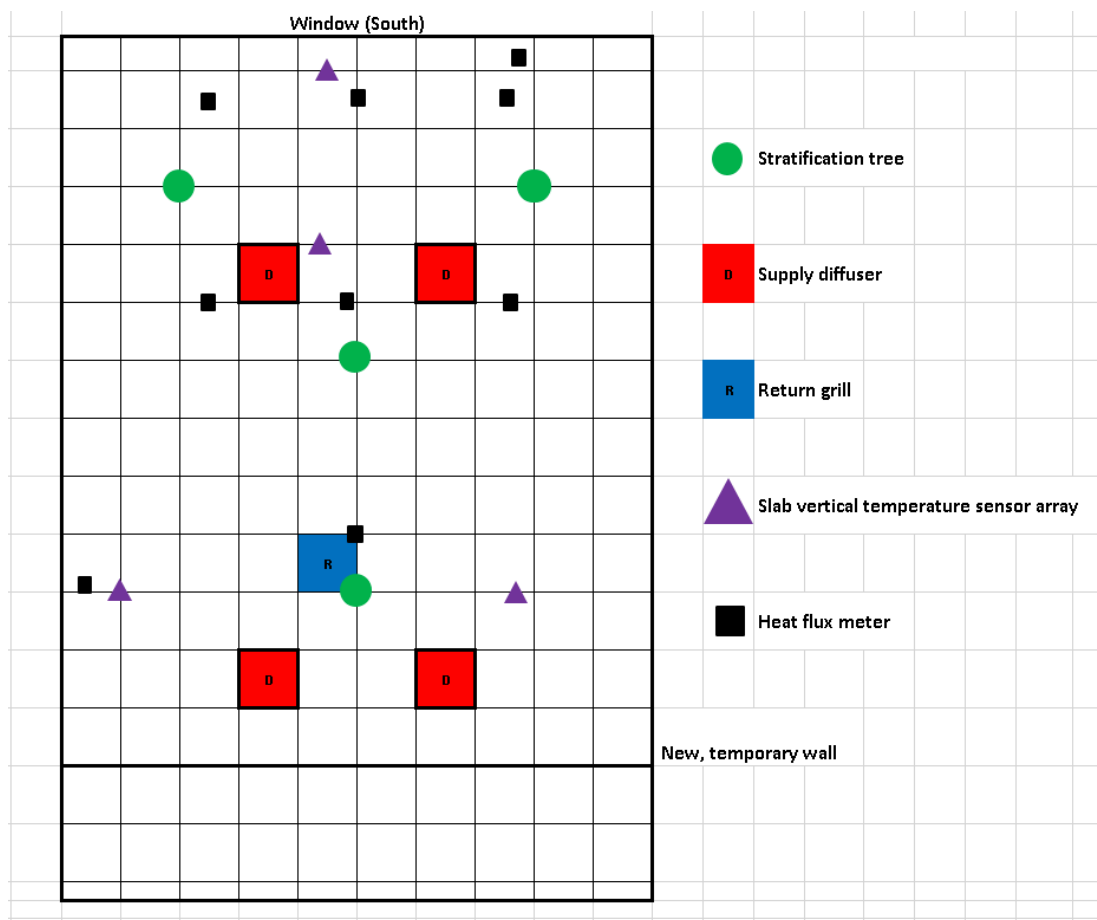


Figure 19. Locations of the temperature sensor vertical arrays and slab heat flux meters, shown on a 2 ft. x 2 ft. grid

Table 9. Sensor details

| SENSOR / PRODUCT | ACCURACY (SPEC.) | NUMBER | MEASURED VARIABLES |
|--|---|---------------|---|
| 10k Ω thermistor, US Sensor # PR103J2 | ± 0.05 K | ~ 100 | Surface temperature, air temperature, slab temperature |
| 30-gauge Type T thermocouple "Special Limits of Error, SLE", Omega Engineering | ± 0.5 K | ~ 15 | Window glazing, frame and mullion surface temperatures |
| Heat flux meter, FluxTeq PHFS-09e (majority) | 4% (based on our testing) | ~ 20 | Surface heat flow rate, walls, floor, ceiling, window glazing, frame and mullions |
| Pyranometer, Eppley SPP | $\pm 1\%$ | 2 | South facing vertical insolation |
| Pyranometer, Licor 200 | $\pm 3\%$ | 2 | Outside and inside window |
| Air flow station, Ebtron Advantage II, GTx116 with GP1 probes | $\pm 2\%$ (velocity only), area and placement \rightarrow $\pm 5\%$. In situ calibration against reference \rightarrow $\pm 4\%$ | 1 | Supply air flow rate |

All the sensors were sampled by the data acquisition system at an interval of one second and one-minute averages were then calculated for analysis purposes. Figure 20, Figure 21 and Figure 22 show the locations of the interior temperature sensors. Details of the locations of other sensors are presented in Appendix A – Locations of Sensors.

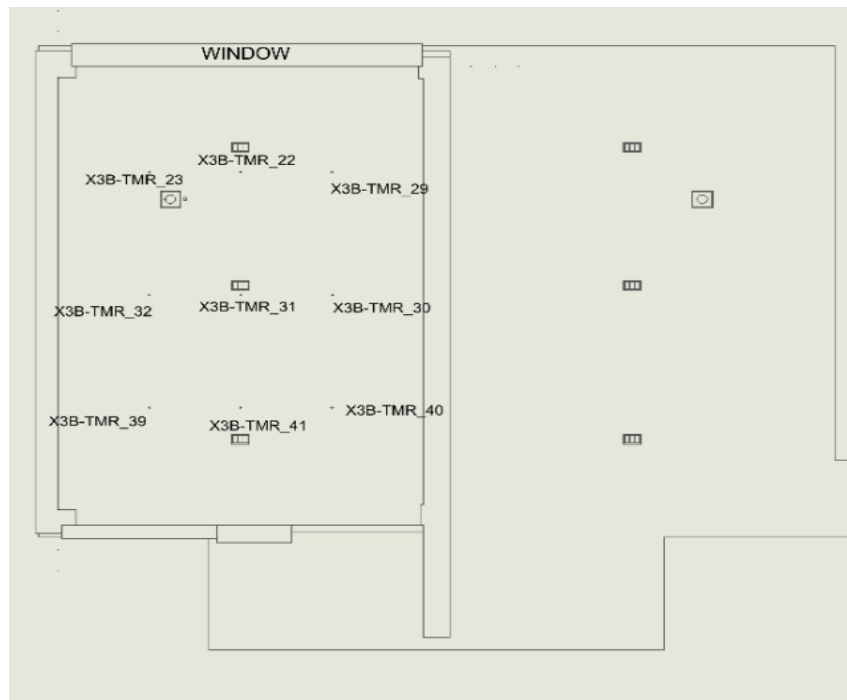


Figure 20. Floor thermistors

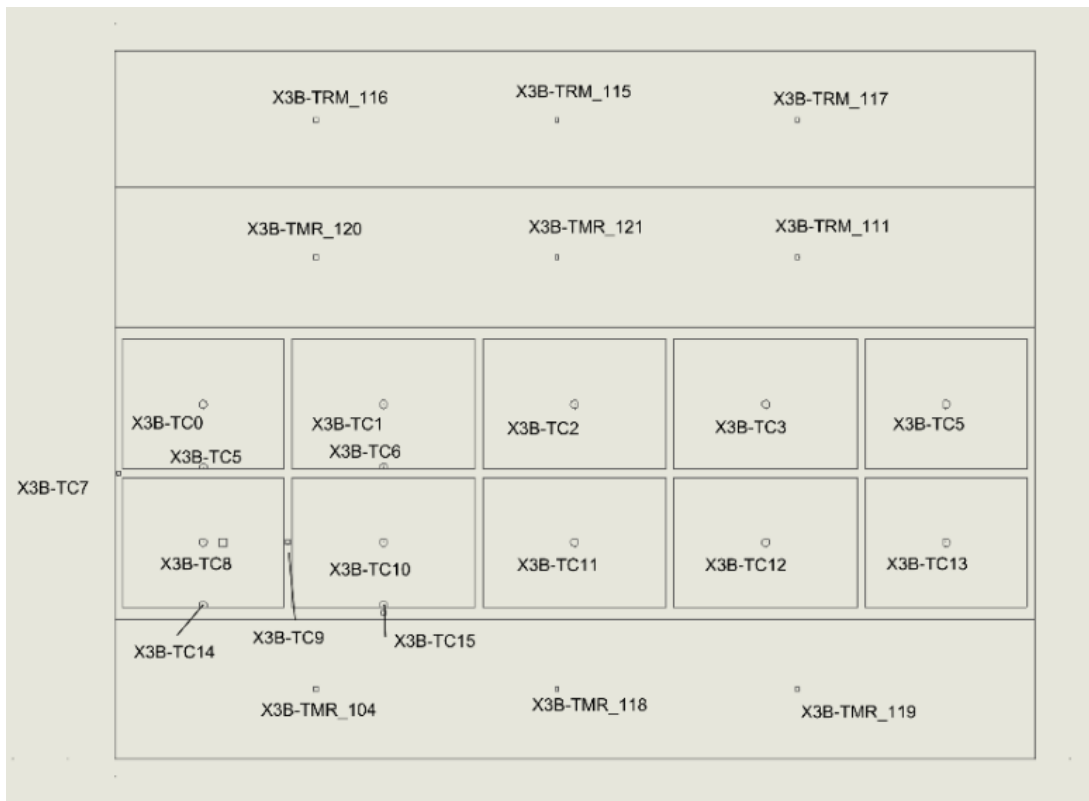


Figure 21. Thermistors on the South Wall/Windows

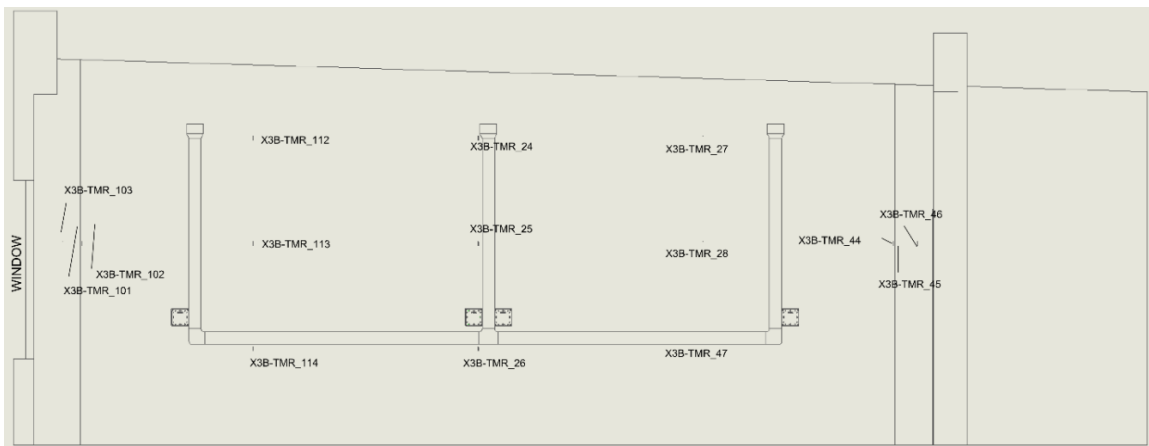


Figure 22. West Wall Thermistors

3.4.1.1 Calibration of sensors

- **Temperature sensors:** Multi-point temperature calibrations were performed in a stirred, thermostatically-controlled, water bath. An individual calibration curve was generated for each sensor.
- **Power meters:** Each electrical circuit in FLEXLAB has a separate measurement of power. The calibration of a statistical sample of these circuits was checked using a PLM1-PK power meter from Electronic Product Design, Inc., which had recently been checked by Power Standards Lab in Alameda, CA; measurements were all found to be better than 1% in real power.
- **Pyranometers:** The Eppley pyranometers used on the south façade were compared to each other and to other Eppley pyranometers used at LBNL. Differences were observed to be $\leq \sim 2\%$ over a range of angular distributions of irradiance.
- **Heat flux** at each interior surface was measured to enable future verification of consistency with the heat flux predicted by a high-fidelity finite difference model constructed using the known material layers of each envelope element. Special attention has been paid to losses from the floor slab to the ground through the continuous under-slab insulation, making use of the temperature sensors and heat flux meters buried in the slab during construction.

3.5 FLEXLAB Modeling

Testbed 3, consisting of Cells 3A and 3B, was modeled using three simulation engines: EnergyPlus, DOE-2.1E, and DOE-2.2. The EnergyPlus model was created using EnergyPlus V8.5 and the OpenStudio® SketchUp plug-in (see Figure 24) and subsequently upgraded to V8.8. The DOE-2.1e and DOE-2.2 models were created using DrawBDL and eQUEST.

3.5.1 Methodology

The simulation models went through several iterations in order to better represent FLEXLAB and also to streamline and minimize the number of runs. To create the models, the following simulation input categories were required:

- Environmental data, including ground temperature, and weather data
- Building geometry
- Building materials and constructions
- Windows and doors
- Building shading
- Internal gains
- HVAC system and temperature set-points

3.5.1.1 Environmental Data

Under-floor temperatures were measured using four vertical arrays of sensors, with thermistors spaced at 2" (50 mm) intervals between the top of the topping slab and the bottom of the structural slab. The temperature recorded by the sensor at the bottom of the structural slab was used as the ground temperature input. The weather data were imported via a weather file created based on measured weather data from the FLEXLAB weather station. Information from LBNL's main weather station and the LBNL Windows Test Facility (71T) weather station were used for consistency checking and to fill in gaps in the FLEXLAB data due to occasional instrumentation problems.

3.5.1.2 Building Geometry

The as-built drawings of FLEXLAB were used to build the simulation model. The three models were identical in terms of their representation of FLEXLAB, except in a few cases where there were limitations imposed by the two DOE-2 engines. These differences are discussed later in this report.

3.5.1.3 Building Material and Construction

To create the materials and constructions section of the input file, the following information was required:

- Construction Layers
- Conductivity of each layer
- Density of each layer
- Specific heat capacity of each layer

The constructions of the floors, ceilings, and walls are discussed separately, due to different levels of complexity.

3.5.1.4 Floor Modeling

Separate models were produced for the low-mass and high-mass configurations. The only difference between these two configurations was the construction of the floor. In the high-mass configuration, the topping slab was the top layer, with its top surface exposed to the space. In the low-mass configuration, the topping slab was covered with 4" (100 mm) of polyisocyanurate rigid board insulation covered with ½" (13 mm) plywood, which, for the 2017 and 2018 tests, was then covered with 26-gauge steel sheet, painted with the same grey paint that was used for the upper surface of the topping slab. The steel sheet was required for fire safety but was assumed to have no thermal effect. In both configurations, the outside surface is exposed to the ground and the temperature of this surface in the models was set to be the ground temperature for the month. The low-mass and high-mass floors were constructed as below. Thermal properties are given in Appendix B.

Low-mass Floor Construction:

| | |
|----------------|-------------------------------|
| Outside Layer: | HW CONCRETE 5" |
| Layer 2: | Slab Horizontal Insulation 5" |
| Layer 3: | Topping Slab 6" |
| Layer 4: | Polyiso 2" |
| Layer 5: | Polyiso 2" |
| Inside Layer: | Plywood 1/2" |

High-mass Floor Construction:

| | |
|----------------|-------------------------------|
| Outside Layer: | HW CONCRETE 5" |
| Layer 2: | Slab Horizontal Insulation 5" |
| Inside Layer: | Topping Slab 6" |

3.5.1.5

3.5.1.6 Ceiling Modeling

The drop ceiling was modeled as:

Outside Layer: Cotton Batt 7"

Inside Layer: Acoustic Tile 3/4"

The outside layer is exposed to the plenum. The material properties of each layer are shown in Table-B 1.

3.5.1.7 Wall Modeling

Whole building simulation engines can only model building components with continuous layers and one-dimensional heat transfer paths. In FLEXLAB, most of the walls, by area, were constructed from structural insulated panels (SIPS) in order to limit 2-D and 3-D heat flow paths to the corners, which also include boxed-in columns. It is not possible to model 2-D and 3-D heat flow paths directly in DOE-2 and EnergyPlus. For example, boxed-in steel columns consist of a highly conductive material surrounded by insulating material, creating a thermal bridge. The THERM software was used to model 2-D and 3-D heat transfer and develop 1-D approximations for use in simulation engines. THERM is a Microsoft Windows™-based computer tool that is part of the LBNL Windows Group software suite. Its heat transfer calculation is based on the finite-element method, which can model the complicated geometries of building products. The methodology to convert two-dimensional and three-dimensional to one-dimensional heat transfer path is described in Appendix C.

Table-B 1 shows the properties of the simple materials used in FLEXLAB. Table-B 2 shows the calculated properties of the equivalent layers. Table-B 3 shows the calculated R-values for the equivalent layers.

3.5.1.8 Window Modeling

EnergyPlus can model windows using the following methods:

1. Simple Model (U-value, Solar Heat Gain Coefficient, and Visible Transmittance)
2. Spectral Averages of the layers
3. Spectral Data for the Layers
4. BSDF (Bidirectional scattering distribution function) method

DOE-2, however, has fewer options for modeling windows:

1. Simple Model (U-value, Solar Heat Gain Coefficient)
2. Choice of glazing from the DOE-2 Window Library
3. Make a custom window and add it to the window library

To have a better comparison between DOE-2 and EnergyPlus, the best option for DOE-2 was chosen (option #3). For EnergyPlus, the window was modeled by defining the spectral averages of the layers (option #2). Both EnergyPlus and DOE-2 accept moveable insulation on the window that can be controlled with a schedule.

For some runs, the windows were covered with insulation. When the insulation was placed on the windows in FLEXLAB, it covered both the glazing and the frame. However, in both DOE-2 and EnergyPlus, when a moveable insulation element is placed on the window, it only covers the glazing and not the frames or mullions. To make the model to better match the actual configuration of the glazing, frame, and mullions, the following changes were made to the models:

- The ten windows in each cell were replaced with a single window. The area of this window is equal to the sum of areas of the ten windows.
- The frames and the mullions were moved into four additional areas of 'window' with the thermal and optical properties of the frame/mullions. These four 'windows' were placed above, below, and on the two sides of the main window (#1). The sum of the areas of these four glazings is equal to the sum of the areas of frames plus mullions. The new model is shown in Figure 24. WINDOW 7.4 was used to create the following window constructions, to be used in EnergyPlus and DOE-2 input files:
 - Laminate window
 - Insulated window
 - Frame window
 - Insulated frame window

Details regarding window modeling are given in Appendix D.

3.5.1.9 EnergyPlus window & insulation input

In EnergyPlus, the laminate construction was assigned to all windows and the option of shading control was added, where the shade has the construction of insulated window (#2). The shade is applied when the schedule allows. We also assigned the window with frame construction (#3) to the windows around the main window, representing the frame with the option of shading control, where the shade has the construction of insulated frame (#4). The shade is applied when the schedule allows. An annual schedule for shading that followed the exposed/insulated window schedules was created. This schedule takes values of 0 and 1, 0 for shade off, and 1 for shade on.

3.5.1.10 DOE-2 window & insulation input

In DOE-2, shading can be assigned to a window and is defined by two schedules, added to the Window object:

- Shading coefficient multiplier schedule
- Conductance multiplier schedule

These multipliers were calculated in such a way that, when they are multiplied by the shading coefficient and the conductance of the laminate and frame windows, they produce values equal to conductance and shading coefficient of the insulated window and insulated frame. An annual schedule for shading that followed the exposed/insulated window schedules was created. See Table-D 8 for the multipliers used in DOE-2 shading schedules.

3.5.1.11 Door Modeling

The doors in FLEXLAB have the following construction:

- Exterior door to the zone
 - Thermally insulated metal doors with thermally broken metal frames
- Exterior door to Electrical Room
 - Hollow metal doors with metal frames
- Interior door between the zone and the mechanical room
 - Thermally insulated metal doors with thermally broken metal frames

EnergyPlus input

To model the doors and door frames accurately, doors were modeled as glazing systems in EnergyPlus, using WINDOW 7.4 to calculate their thermal/optical properties. See Appendix E for the detailed modeling procedure used.

DOE-2 input

Due to the reduced effect of the exterior door heat flow on the total FLEXLAB heating and cooling load, in the last iteration of the DOE-2 model, the door construction was characterized by the effective U-value of the door.

3.5.1.12 Building Shades

The models included three external shading objects in front of the South façade to represent the steel frame attached to the wall to support exterior shading elements in other experiments. In addition, narrow overhangs and fins were added to the models to represent the external window reveal (i.e. the projection of the surrounding wall beyond the window frame). To capture the shading effect of FLEXLAB-X2, a large building shade on the West wall of Cell A was added to the models. (See Figure 23 and Figure 24)

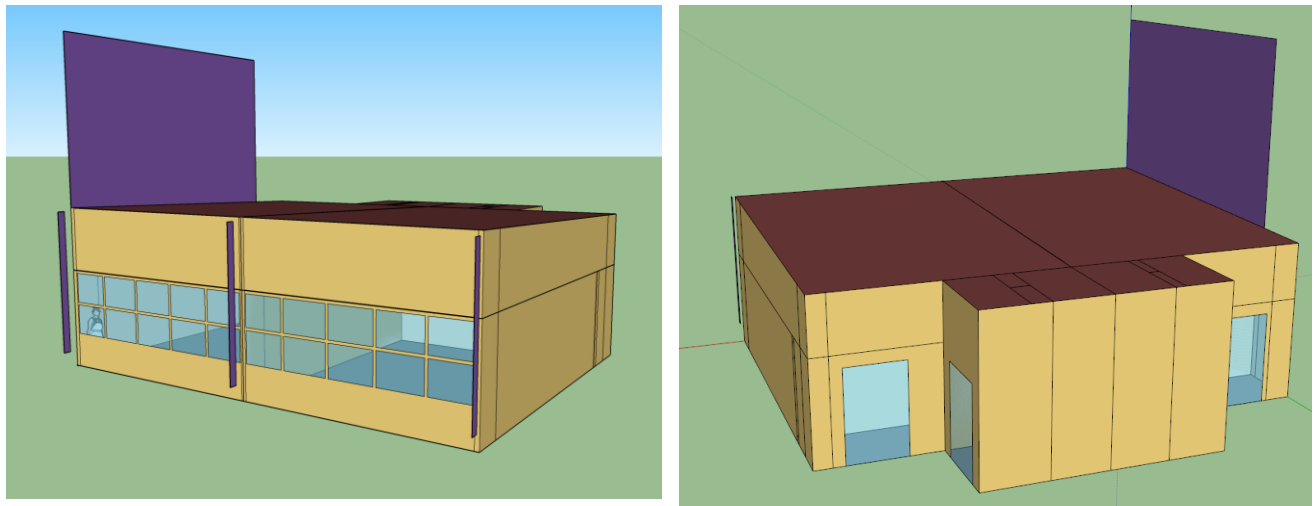


Figure 23. FLEXLAB-X3 Detailed Simulation Model (south façade left, north façade right)

3.5.1.13 Internal Gains

The internal gains varied by experiment. Annual schedules for lights and equipment loads were created, based on the power measurements in FLEXLAB. These schedules were applied to the internal gain objects to characterize their effects in the heating and cooling loads.

3.5.1.14 HVAC System and Temperature Set-points

The EnergyPlus model included an Ideal Load System object with a single temperature set-point thermostat assigned to each cell. The DOE-2 model used System=SUM with the proportional thermostat type and a throttling range of 0.1 K. A schedule of zone temperature set-points for the full period of the experiments was created from the average of the 28 air temperature measurements in the cell – four vertical arrays of seven shielded thermistors. This avoids the need for separate runs, each with their own warm-up period, for each of the 12 Cases.

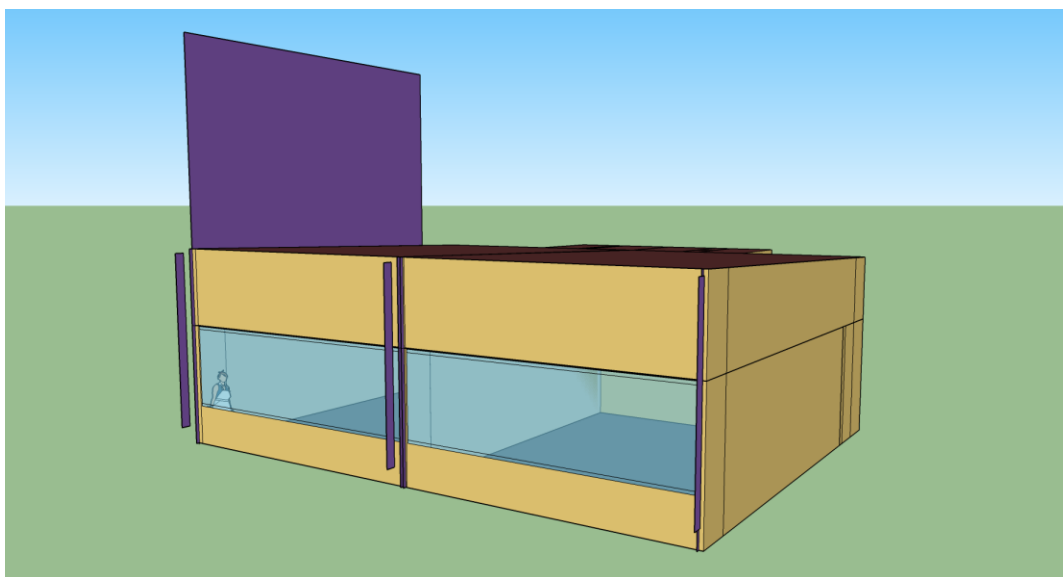


Figure 24. FLEXLAB Final Simulation Model

3.5.1.15 Simulation Parametric Run Procedure

The EnergyPlus parametric run procedure increased the flexibility of runs and provided the following capabilities:

- Inclusion of external files into the EnergyPlus input files.
- Selective acceptance of portions of the input.

Two parametric runs, one for low-mass and one for high-mass, were made in DOE-2.1e, DOE-2.2, and EnergyPlus. The schedules for internal gains and temperature set-points covered different experimental conditions. The details of setting up the parametric runs, and sample run files are shown in Appendix F.

3.5.1.16 DOE-2 Modeling Limitations

There were several instances where the limitations of the DOE-2 engines prevented the accurate modeling of the FLEXLAB and forced the simplification of the EnergyPlus model for the sake of consistency:

- The West wall of FLEXLAB-X3 Cell A consists of two sections, one exposed to the outside, and one a partition between Cell A of FLEXLAB-X3 and Cell B of FLEXLAB-X2, which was modeled as a wall with constant surface temperature of 21°C in EnergyPlus. DOE-2, however, does not have the option of modeling surfaces with a constant temperature. This section of the wall was modeled as adiabatic in DOE-2. To estimate the effects of this difference in modeling, a series of EnergyPlus sensitivity runs were performed, where the Cell A west wall surface temperature varied from 15°C to 40°C in the increments of 5 K. The case of an adiabatic wall was also run. The comparison between the adiabatic case and the constant surface temperature cases showed that the maximum difference in annual cooling was 0.6% and in heating was 3%.
- Each FLEXLAB cell was pressurized using a small fan to reduce the uncertainty in the zone heat balance due to infiltration. The temperature and the flow rate of the injected air were measured, allowing the thermal effect of the pressurization on the

zone heat balance to be determined. It was relatively straight forward to implement this process in EnergyPlus. The input object "OtherEquipment" was used; unlike other internal gain objects, it can accept either negative or positive values for heat gain. The supply temperature was input using a schedule and the flow rate with an Energy Management System (EMS) object. In DOE-2, however, implementing a negative heat gain would have required changing the lower limit of the equipment load object, which is hard-coded in DOE-2. If this change had been made, it would have required re-compiling the DOE-2 engine. In order to estimate the effect of this heat flow, two EnergyPlus sensitivity runs were made. In all experiments conducted, the amount of heat introduced (or extracted) by the pressurization system was ~1.5% of the total heat load of the cell and so the heat supplied through the injection tube was ignored, as discussed in the Experiment Design, Analysis and Instrumentation section.

3.5.1.17 Simulation Input

The following measurements were made in FLEXLAB and used as input for the models:

- Twenty-eight temperature sensors on four stratification trees in each cell were averaged to give the set-points for the zone temperatures in the models.
- All outlet power consumptions in each cell were summed and used as schedules for the internal loads in the model.
- All lights power consumptions in each cell were summed and used as schedules for the lights in the model.
- The pressurization air supply temperatures and flow rates were measured and used to calculate the input to an OtherEquipment internal gain object in EnergyPlus to determine the contribution of the injection air to the zone heat balance. As noted, the magnitude of this heat gain proved to be very small in relation to the total cooling and heating loads and was neglected.

For each run, the simulated zone temperature was compared to the measured average dry bulb temperature, which had been used as the zone temperature set-point, and good agreement was found consistently. The FLEXLAB and EnergyPlus 'zone' temperatures are dry bulb (air) temperatures. The zone temperature in DOE-2.1e and DOE-2.2 is technically an approximation to the operative temperature. However, it appears that most DOE-2 users treat the zone temperature as a proxy for the dry bulb temperature, one rationale being that, in multi-zone buildings with lightweight construction, the surface temperatures of the internal partitions and drop ceilings, at least, tend to follow the zone dry bulb temperature closely enough for most energy calculations and thermal comfort predictions.

4 Experimental Tests

FLEXLAB tests were performed for the high-mass and low-mass cases. The interior air temperature set-points, internal gain, and window insulation schedules were selected to excite different modes of operation. Sixteen scenarios were defined, consisting of all possible combinations of high-mass vs. low-mass, covered vs. exposed windows, constant or variable internal gains and constant or variable zone set-point temperatures. Tests were performed for six of these scenarios, selected to address different combinations of variable envelope conduction, window solar heat gain and charging/discharging of thermal mass, either singly or in combination, as shown in Table 10. Combinations for which adequate measurements were not obtained are shown greyed out. The rightmost column indicates the closest corresponding BESTEST; the BESTEST number scheme has been extended to indicate new variants in which the internal gains were varied diurnally.

The tests involved defining schedules of zone air temperature set-points and lighting and miscellaneous equipment switching in the data acquisition and control system. Test periods were typically three to five days, though, in some cases, operational problems resulted in the measurements for some part of the period being rejected.

The primary output for each test was a set of one-minute measurements of the supply and return air temperatures, measured at the supply diffusers and return grill, together with measurements of the supply air flow rate. Each of the temperature sensors in each cell – one in each of the four supply diffusers and three in the single return grill – was carefully calibrated as described in the Calibration of Sensors section of this document. In-situ cross-calibration was then performed to minimize the uncertainty in the supply-return temperature difference, which is estimated to be ~ 0.15 K (0.27 F). The airflow station in the supply duct was calibrated against two different reference airflow measurement systems and the resulting uncertainty is estimated to be $\leq 3\%$ across the range of flow rates used in the tests. When the supply-return temperature difference is ~ 5 K, the uncertainty in the measurement of cooling/heating load is then $\sim 5\%$.

Zone air temperature, surface temperature, and surface heat flux measurements were also collected. Each sensor was sampled once per second and one-minute averages were archived for use in visualization and analysis.

The initial intention was to use water-side measurements of the duties of the heating and cooling coils, together with the measured fan power, to determine the rate at which heat was added to, or removed from, the main test zone. (See Figure 16.) However, the following sources of uncertainty resulted in the decision to use a direct air-side measurement:

- **Fan power:** Direct measurement of the power supplied to the fan motor by the variable frequency drive (VFD) is uncertain/expensive because the harmonic content of the current. The VFD can be bypassed, but only at one fan speed; different fan speeds were used in the tests to minimize the uncertainty in the measurement of heating/cooling rate while maintaining adequate heating/cooling capacity.
- **Heat gains/losses:** Heat gains/losses through the (insulated) walls of the supply and return ducts that are significant enough to be very difficult to correct sufficiently, given the spatial and temporal variations in the temperature adjacent to the exterior surfaces of the ducts.

The simulation engines used the spatial average air temperature in the test zone as the time-varying zone temperature set-point. This temperature is the average of the readings of 28 sensors – four vertical arrays of seven individually-calibrated, shielded thermistors.

Table 10. Testing Scenarios

| SCENARIO : TEST | THERM MASS | WINDOW INSUL | INTERNAL GAIN (W) | ZONE TEMPERATURE | FAN SPEED (%) | TEST DATES | BEST-TEST |
|------------------------|-------------------|---------------------|--------------------------|-------------------------|----------------------|-------------------|------------------|
| 1 | Low | Yes | Constant | Constant | - | - | 430 |
| 2 | High | Yes | Constant | Constant | - | - | 800 |
| 3:01 | Low | No | 0 | 22°C / 22°C | 25 | Jul22-Jul26, 2017 | 600 |
| 3:02 | Low | No | 0 | 22°C / 22°C | 40 | Feb3-Feb5, 2018 | 600 |
| 3:03 | Low | No | 0 | 22°C / 22°C | Varies 10-50 | Feb7-Feb9, 2018 | 600 |
| 3:04 | Low | No | 0 | 22°C / 22°C | 50:8-18, 25:18-8 | Feb12-Feb18, 2018 | 600 |
| 3:05 | Low | No | 0 | 22°C / 22°C | 25 | Feb20-Feb23, 2018 | 600 |
| 4 | High | No | Constant | Constant | - | - | 900 |
| 5 | Low | Yes | Variable | Constant | - | - | 600 |
| 6:01 | High | Yes | 0/1440 W | 25°C / 25°C | 50→40→50 | Jul1-Jul3, 2017 | 800VIG |
| 7 | Low | No | Variable | Constant | - | - | 600VIG |
| 8 | High | No | Variable | Constant | - | - | 900VIG |
| 10 | High | Yes | Constant | Variable | - | - | 840 |
| 11:01 | Low | No | 0 | 30°C / 20°C | 50 | Nov12-Nov16, 2016 | 640 |
| 11:02 | Low | No | 0 | 30°C / 20°C | 50 | Nov24-Nov28, 2016 | 640 |
| 11:03 | Low | No | 0 | 30°C / 20°C | 50 | Nov30-Dec03, 2016 | 640 |
| 12:01 | High | No | 0 | 26°C / 22°C | 25 | Jul10-Jul14, 2017 | 940 |
| 13 | Low | Yes | Variable | Variable | - | - | 640VIG |
| 14:01 | High | Yes | 0/1440 W | 26°C / 22°C | 25 | Jul6-Jul10, 2017 | 840VIG |
| 15:01 | Low | No | 0/435 W | 30°C / 20°C | 25 | Dec15-Dec17, 2016 | 640VIG |
| 16 | High | No | Variable | Variable | - | - | 940VIG |

5 Results

Detailed comparisons of the measurements with the outputs from EnergyPlus, DOE2.2, and DOE-2.1e have been performed, and are shown in the next section. The primary comparison is in terms of the heating and cooling loads, measured in FLEXLAB by performing an air-side heat balance on the test cell, as discussed in the Experimental Tests section.

5.1 Comparisons Between EnergyPlus, DOE-2.2, DOE-2.1E and FLEXLAB

Figure 25 shows a standard set of plots and a summary table for the twelve test cases and Table 11 provides detailed comments on each case. The cases are presented in order of increasing complexity, starting with gentle transients (solar) to step changes in internal loads and/or zone temperature set-points. In several the variable set-point cases, there is substantial step change (5-10 K) in the zone air temperature set-point twice per day. The intention was to test the transient response of the simulation engines. However, in some cases, there was overshoot in the FLEXLAB zone air temperature control loop, which increased the higher frequency components of the response.

For each case, the comparisons between the simulation outputs (heat removal rate) from each of the three engines are presented, first as a time-series and then in cumulative/integrated form. The band around the measured heat removal rate line represents an estimate of the effect of the uncertainties in the supply-return air temperature difference and the air flow rate. The numerical values at the right-hand end of the cumulative plot can be used to obtain the mean bias error (MBE) by subtracting the simulation engine value from the FLEXLAB value.

The tables present two different but complementary metrics that characterize the case-by-case differences between the FLEXLAB measurements of heat removal rate and the predictions of DOE-2.1e, DOE-2.2 and EnergyPlus. The first metric is the Range-Normalized Mean Bias Error (RNMBE). The differences between hourly samples (*i*), of the simulation prediction (*s*), and the FLEXLAB measured value (*f*), are averaged for each test and normalized to the range of the FLEXLAB measurements for that test, as defined in Equation 1.

Equation 1. Calculation of the Range-Normalized Mean Bias Error

$$RNMBE = \frac{1}{\max(f) - \min(f)} * \frac{\sum s(i) - f(i)}{n}$$

This is in contrast to the mean percentage error (MPE), where the normalization is performed on every sample. In this case, the normalizing value in the denominator varies from sample to sample, thereby giving a different weight to each sample. Another consideration is the quantity to be used in the denominator; common choices are the mean value of *f*, the mean absolute value of *f* and the range of *f*. Since *f* can be either positive (cooling load) or negative (heating load), its mean value may be inappropriately small. The range was selected in preference to the mean absolute value since it better characterizes the simulation application. Since the mean of the actual differences, rather than the absolute differences, is calculated, fluctuations cancel out, yielding the underlying trend, or bias, for that test.

The second metric is the Range-Normalized Root Mean Square Error (RNRMSE). The square root of the average of the square of the difference between hourly samples of the simulation

prediction and the FLEXLAB measured value is normalized to the range of the FLEXLAB measurements for that test, as defined in Equation 2. Range normalization was selected for the reason described above for RNMSE.

Equation 2. Range-Normalized Root Mean Square Error

$$RNRMSE = \frac{1}{\max(f) - \min(f)} * \sqrt{\frac{\sum (s(i) - f(i))^2}{n}}$$

Fluctuations are accentuated; there is no cancellation of positive and negative errors and squaring the error gives more weight to outliers, which tend to occur more frequently during transients.

Normalized Mean Bias Error (strictly, Mean Bias) and the Coefficient of Variation of the Root Mean Square Error, both of which are normalized to the mean value rather than the range, are statistical metrics that have been adopted for use in the International Performance Measurement and Verification Protocol (IPMVP) and by ASHRAE Guideline 14P Measurement of Energy, Demand, and Water Savings to characterize how well a simulation model has been calibrated to measured data prior to use in a Measurement and Verification (M&V) exercise. This is a different situation to that of the work presented here, which does not involve calibrated simulation. In most situations, a simulation model constructed from as-built drawings and other design information is not be expected to be as accurate as a model that is calibrated with real measurements.

In effect, the purpose of the work reported here is to determine how accurate a carefully constructed simulation model is likely to be before any calibration, such as in the context of design for new construction. In particular, it is not appropriate to apply the acceptance criteria used in IPMVP and Guideline 14 for the adequacy of simulation model calibration to determine the adequacy of simulation engines in the context of the work presented here, since no calibration is involved. Three other confounding factors are:

- The operating conditions in the tests reported were deliberately designed to stress the engines. (For example, there was no dead-band between the heating and cooling set-points for the zone temperature.)
- The tests reported only address the heating and cooling loads in an occupied space and do not consider the performance of the HVAC system(s).
- The decision to normalize the calculated values of the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) to the difference between the maximum and the minimum value of the load - cooling and heating, was made to compare the uncertainty to the full-range of energy consumption rates that the building is predicted to encounter in a particular run. The corresponding metrics used in IPMVP and Guideline 14 are normalized to the mean absolute value and so are not directly comparable to the RNMSE and RNRMSE metrics used here.

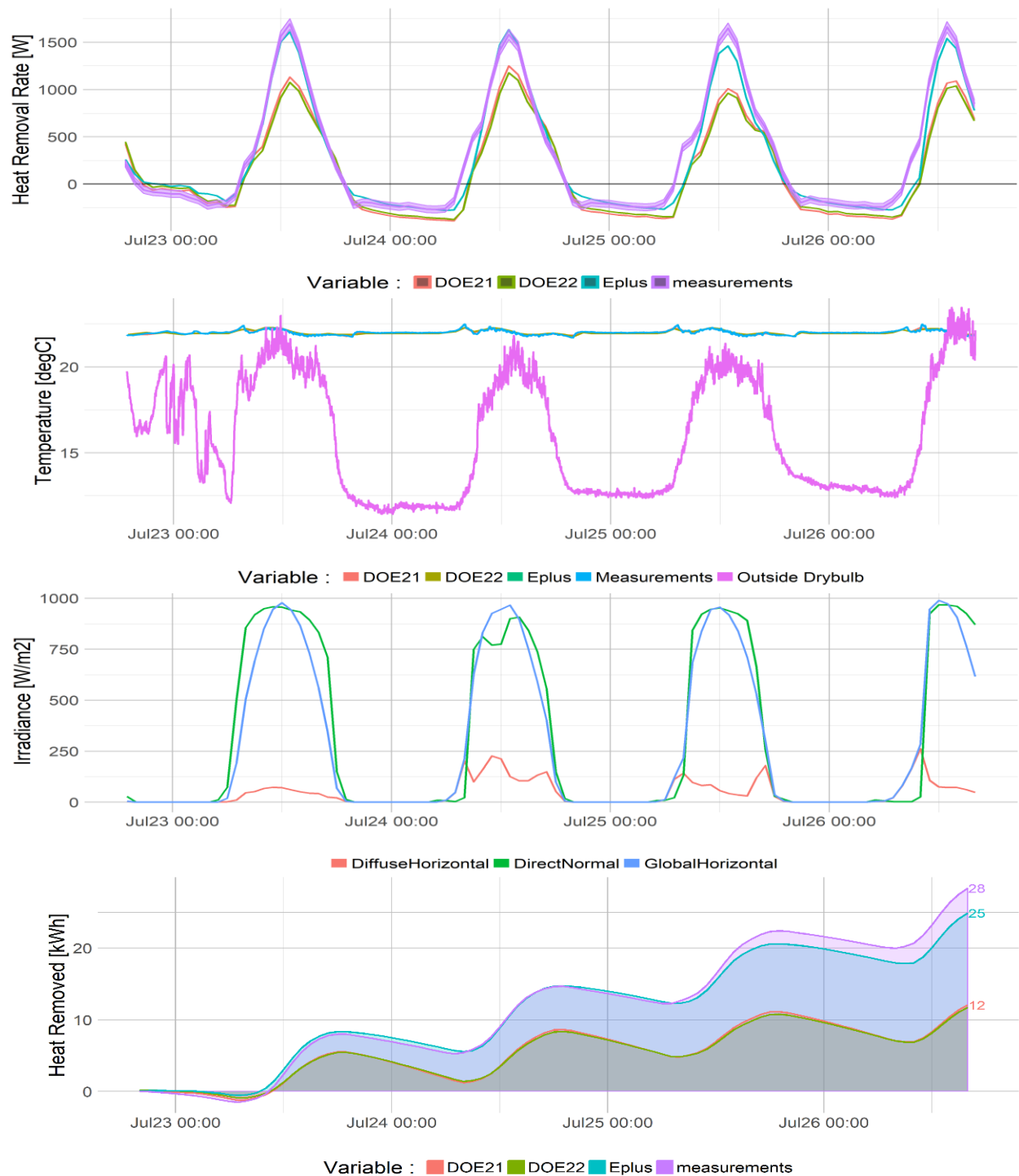
As will be discussed in more detail below, significant variation can be observed in the differences between the FLEXLAB measurements and the predictions of each simulation engine, as well as in the differences between the predictions of the three simulation engines; the test runs can be categorized as follows:

- Good agreement between all the engines and FLEXLAB (Cases 3:02, 3:04, 3:05)
- Good agreement between EnergyPlus and FLEXLAB but poorer agreement between the DOE-2 engines and FLEXLAB (Cases 3:01, 11:01, 11:02, 11:03, 15:01)

- Good or reasonable agreement between EnergyPlus and FLEXLAB and one of the two DOE-2 engines, but not both (Cases 3:03, 6:01)
- Poor agreement between FLEXLAB, EnergyPlus and the DOE-2 engines (Case 12:01)
- Reasonable agreement at night, hard to classify during the daytime (Case 14:01)

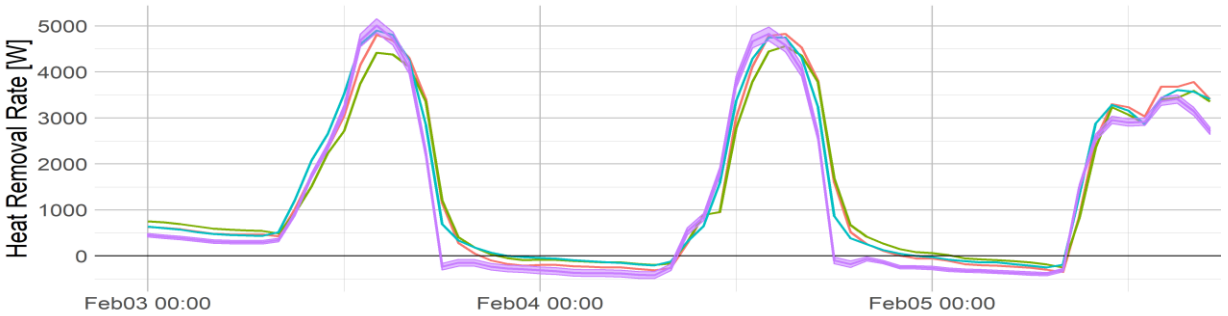
These patterns may be consistent between day and night or may be different between day and night. Better agreement is often observed at night, presumably because of the absence of solar radiation as a complicating factor.

Scenario 3:01: Low-mass, Exposed Windows, No Internal Gains, Constant Set-point (22 C)

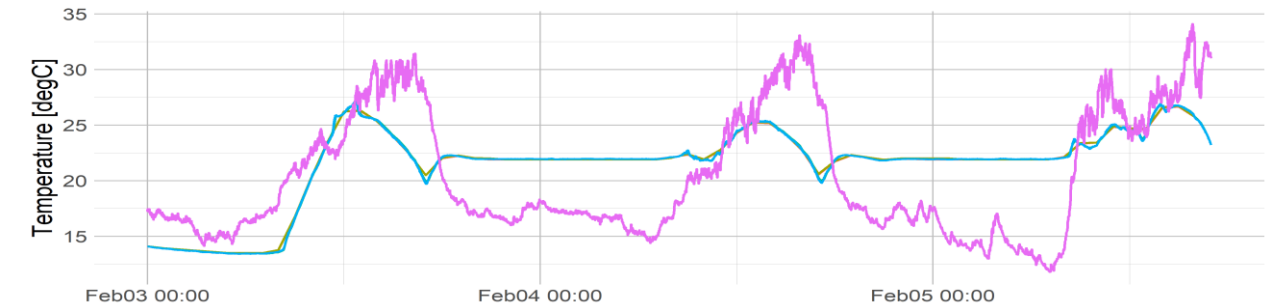


| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | -5.52% | -16.40% | -18.50% | 0.74% | -3.24% | -2.07% |
| RNRMSE | 8.18% | 19.20% | 21.20% | 3.18% | 5.53% | 5.01% |

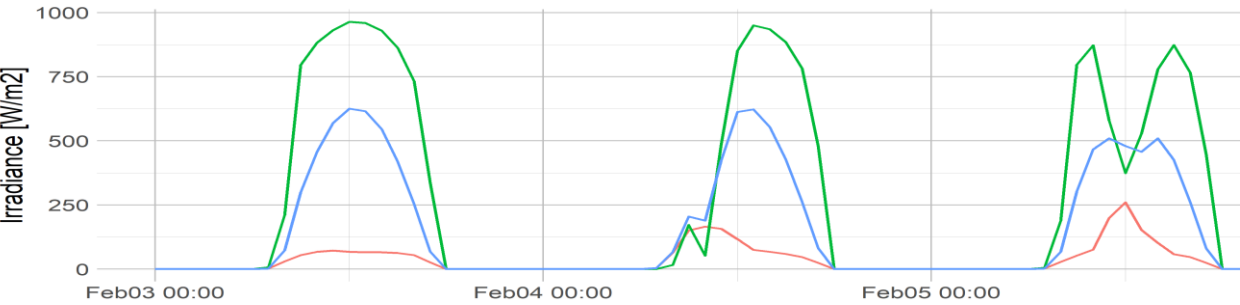
Scenario 3:02: Low-mass, Exposed Windows, No Internal Gains, Constant Set-point (22 C)



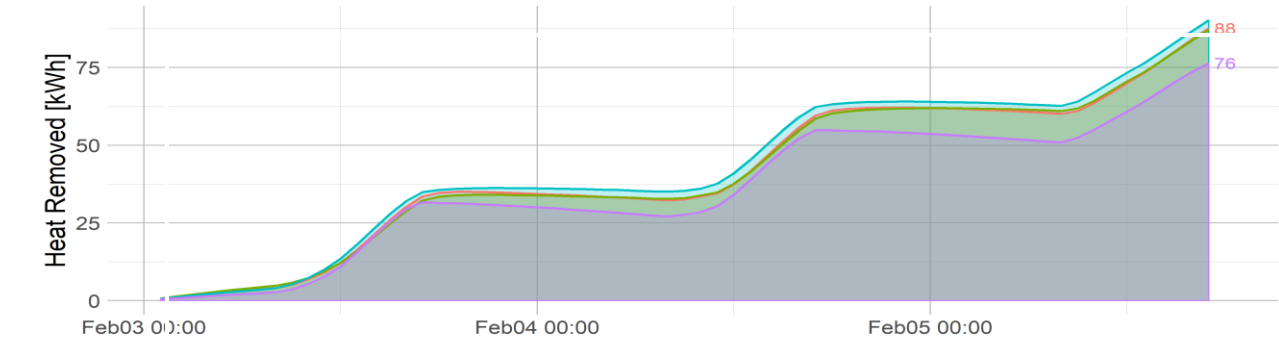
Variable : DOE21 DOE22 Eplus measurements



Variable : DOE21 DOE22 Eplus Measurements Outside Drybulb



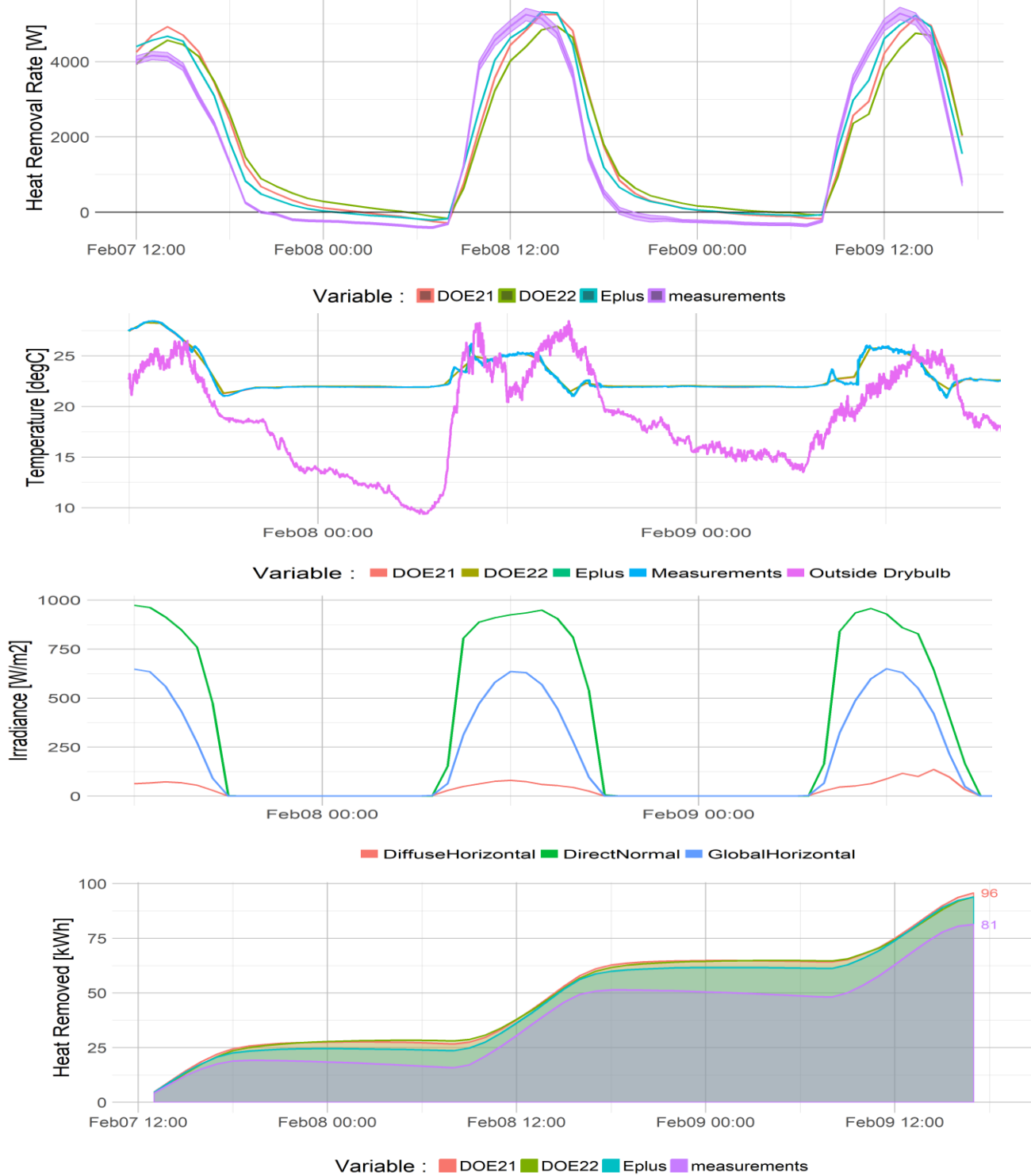
DiffuseHorizontal DirectNormal GlobalHorizontal



Variable : DOE21 DOE22 Eplus measurements

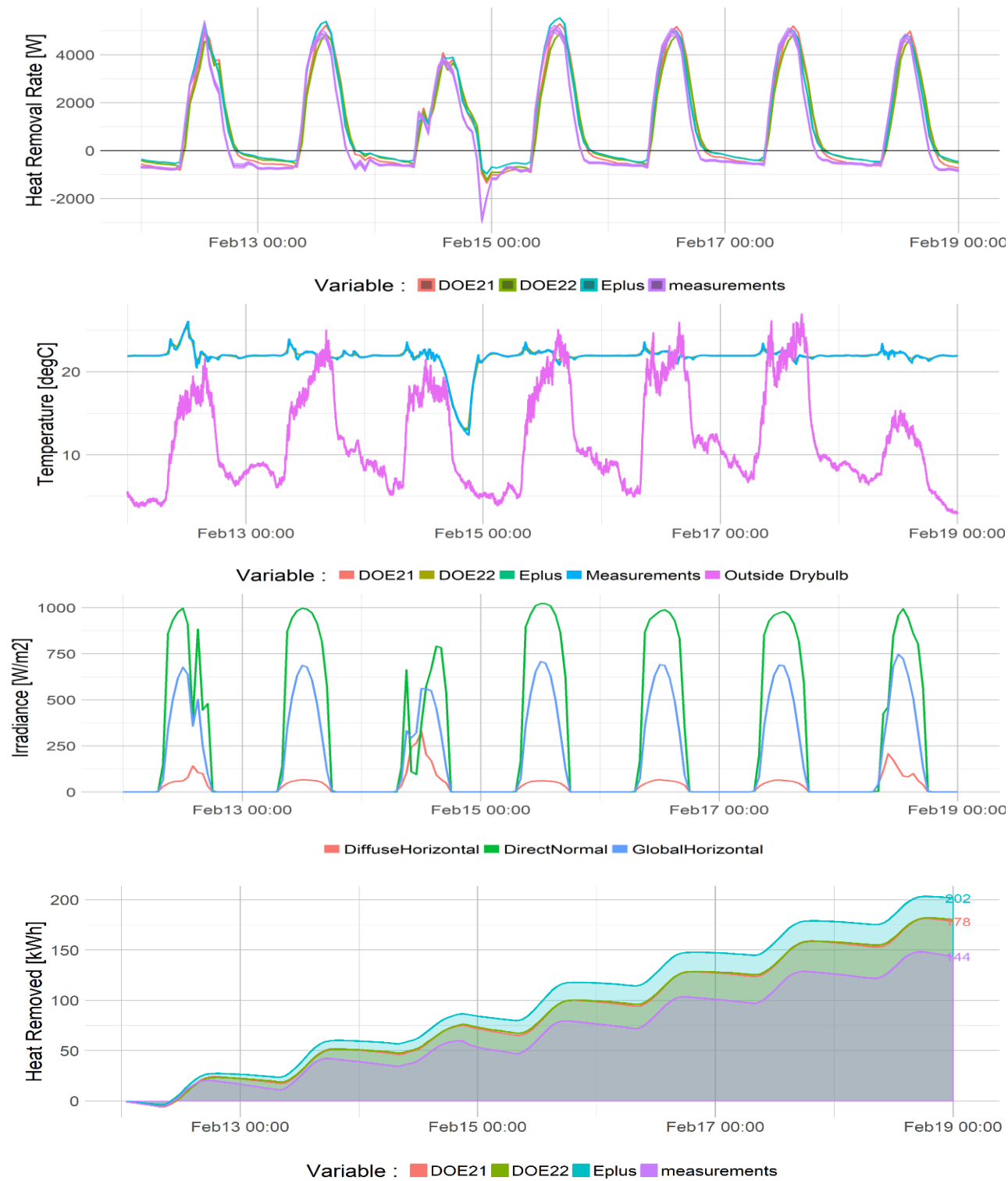
| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 2.39% | 1.26% | -1.55% | 5.17% | 4.77% | 6.94% |
| RNRMSE | 5.64% | 8.88% | 9.73% | 6.16% | 7.75% | 9.18% |

Scenario 3:03: Low-mass, Exposed Windows, No Internal Gains, Constant Set-point (22 C)



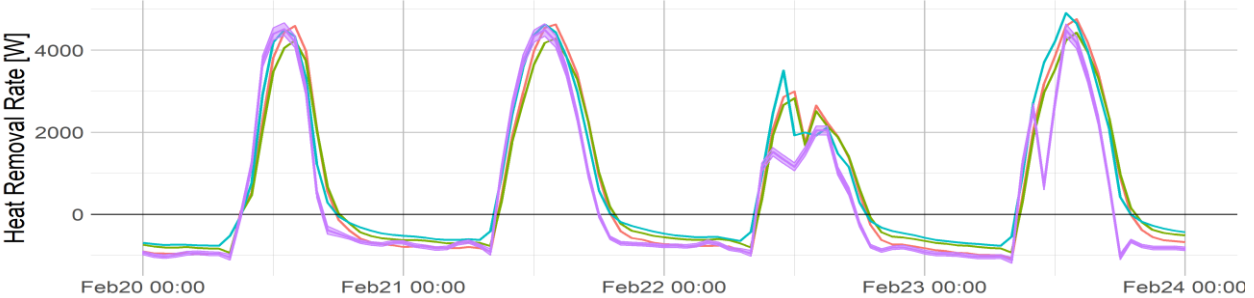
| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 2.23% | -1.24% | -5.09% | 6.04% | 7.62% | 10.10% |
| RNRMSE | 9.93% | 21% | 22.10% | 6.50% | 9.12% | 11.30% |

Scenario 3:04: Low-mass, Exposed Windows, No Internal Gains, Constant Set-point (22 C)

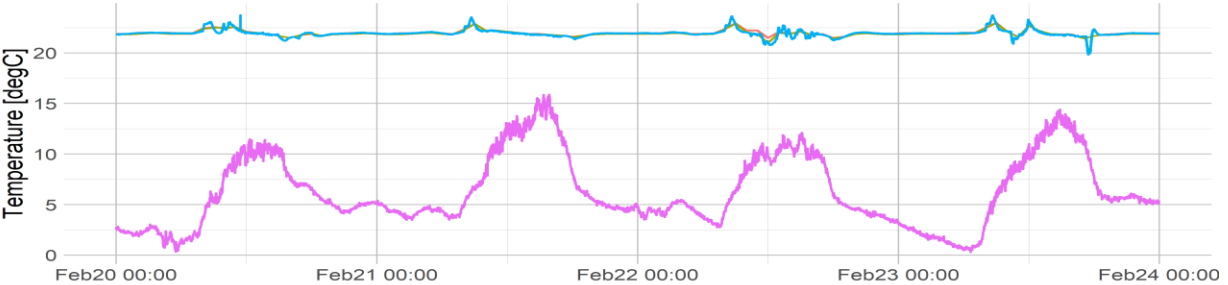


| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 3.28% | 1.47% | -0.78% | 4.91% | 3.28% | 5.11% |
| RNRMSE | 6.15% | 9.53% | 9.85% | 5.88% | 5.61% | 6.81% |

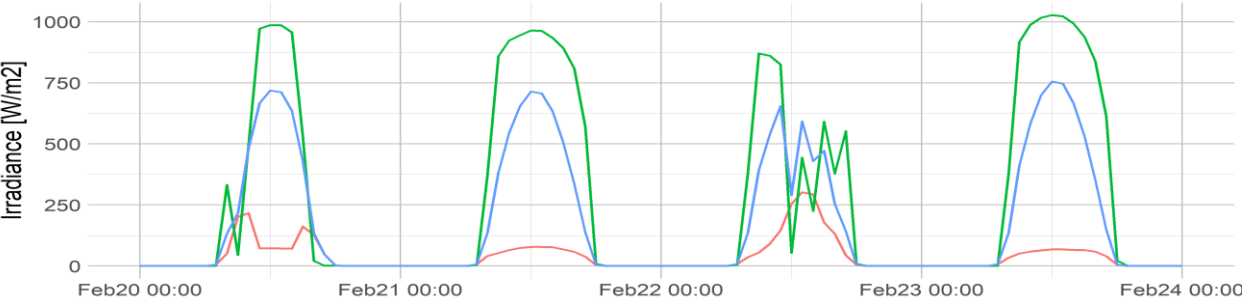
Scenario 3:05: Low-mass, Exposed Windows, No Internal Gains, Constant Set-point (22 C)



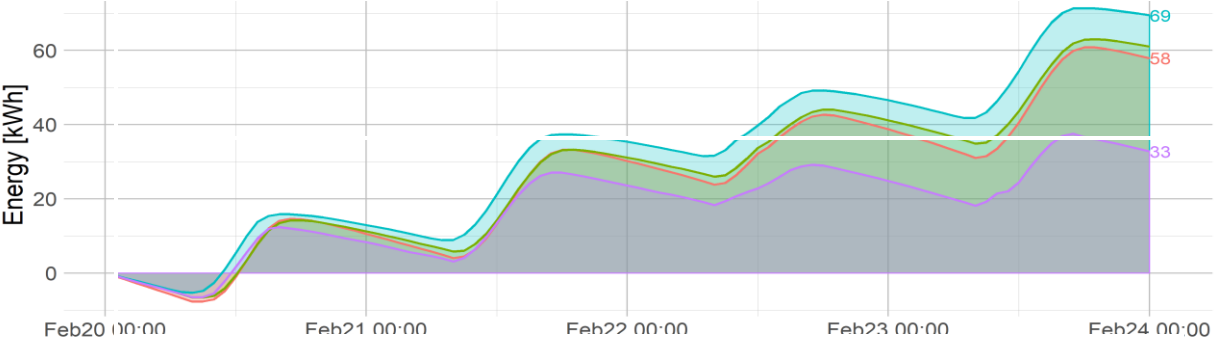
Variable : DOE21 DOE22 Eplus measurements



Variable : DOE21 DOE22 Eplus Measurements Outside Drybulb



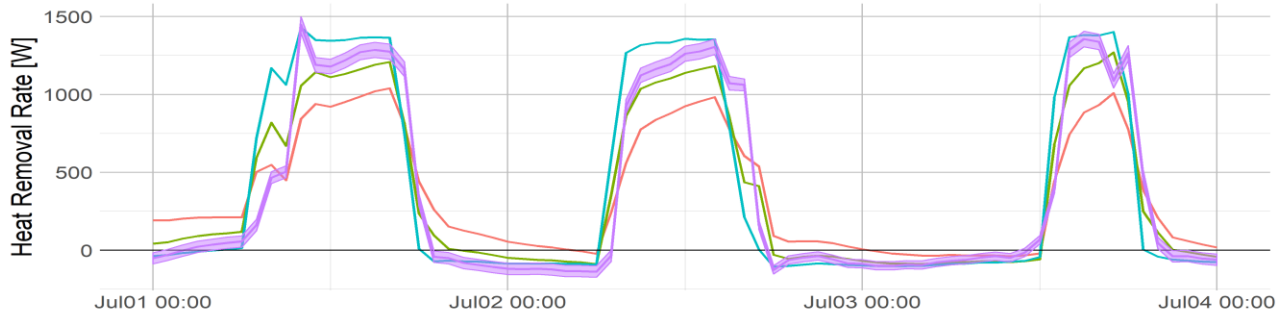
Variable : DiffuseHorizontal DirectNormal GlobalHorizontal



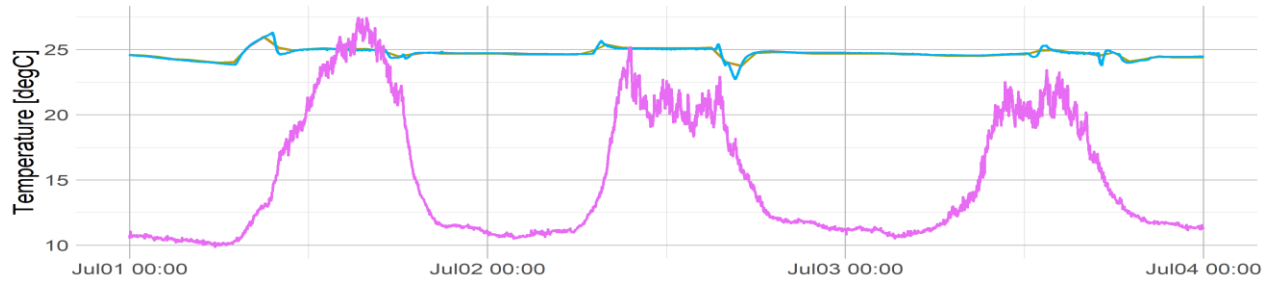
Variable : DOE21 DOE22 Eplus measurements

| | Day | | | Night | | |
|---------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMSE | 7.60% | 6.40% | 3.89% | 6.04% | 2.63% | 5.41% |
| RNRMSSE | 14.30% | 16.40% | 16% | 7.05% | 6.24% | 7.74% |

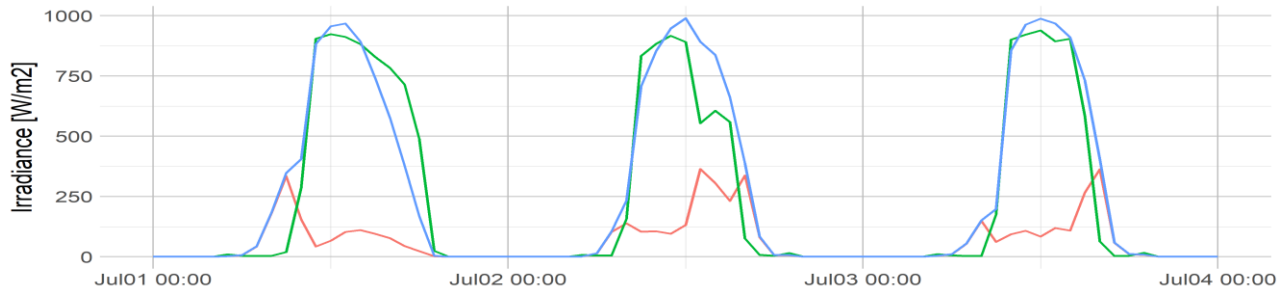
Scenario 6:01: High-mass, Covered Windows, Variable 1400 W Internal Gain, Const Set-point (25C)



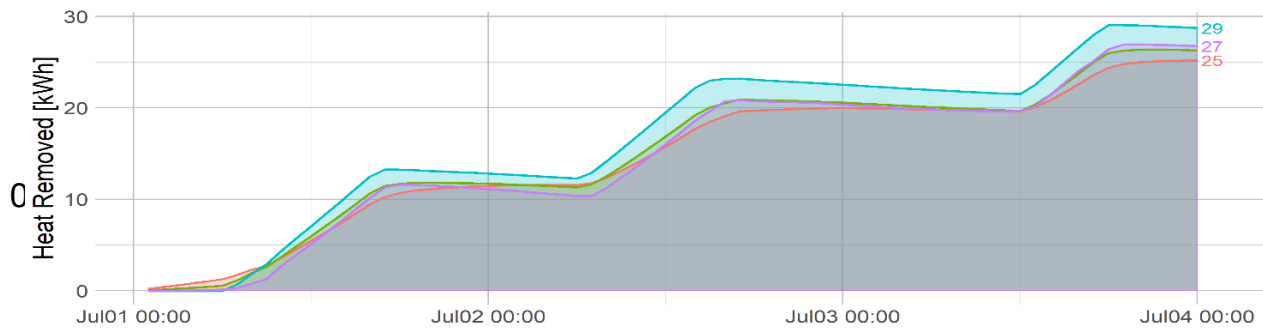
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements



Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ Measurements ■ Outside Drybulb



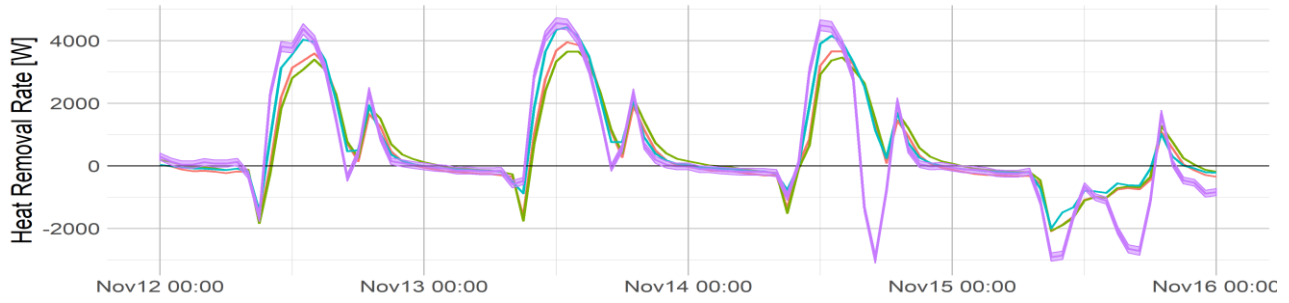
■ DiffuseHorizontal ■ DirectNormal ■ GlobalHorizontal



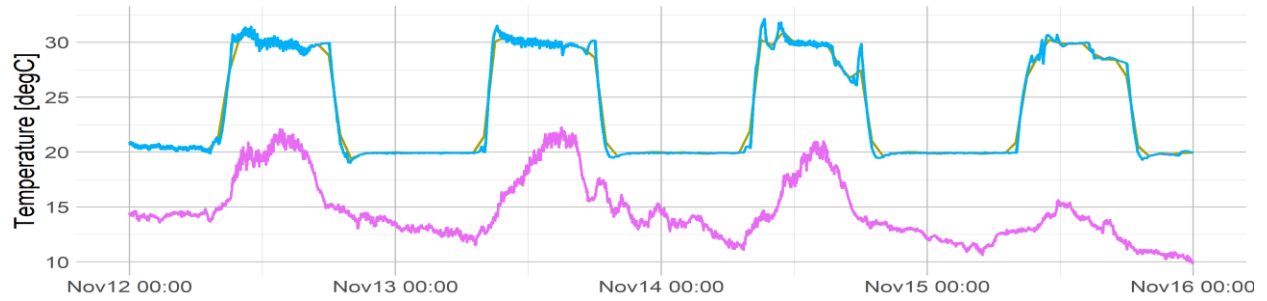
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements

| | Day | | | Night | | |
|---------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 4.30% | -14.20% | -4.88% | -0.32% | 7.95% | 2.84% |
| RNRMSSE | 18.50% | 19.40% | 13% | 10.20% | 11.10% | 7.57% |

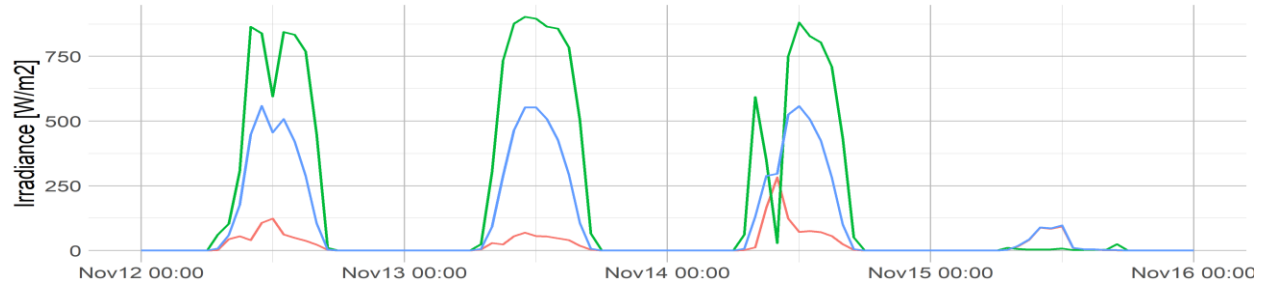
Scenario 11:01: Low-mass, Exposed Windows, No Int Gain, Var Set-point (20C / 30C) -Cell 3A



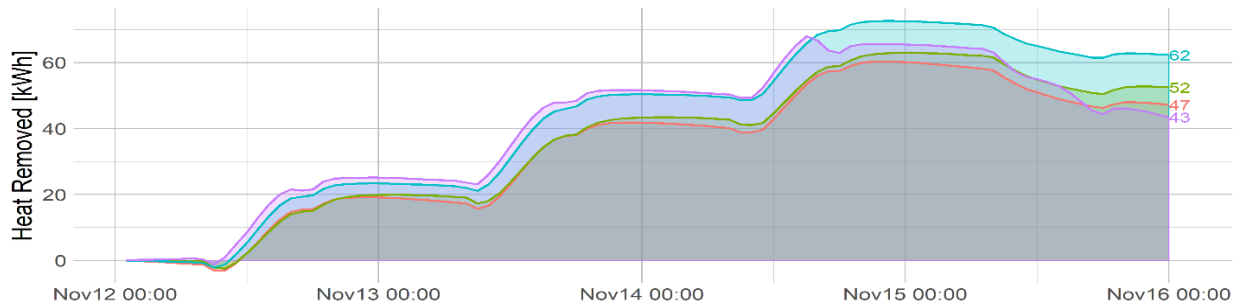
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements



Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ Measurements ■ Outside Drybulb



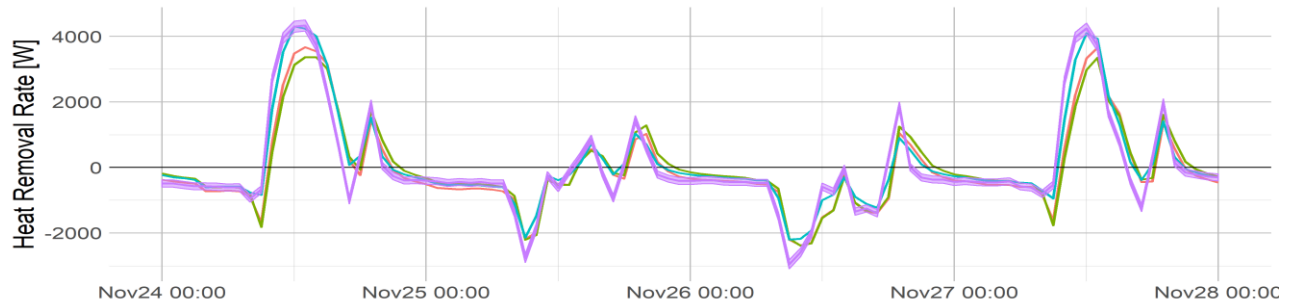
Variable : ■ DiffuseHorizontal ■ DirectNormal ■ GlobalHorizontal



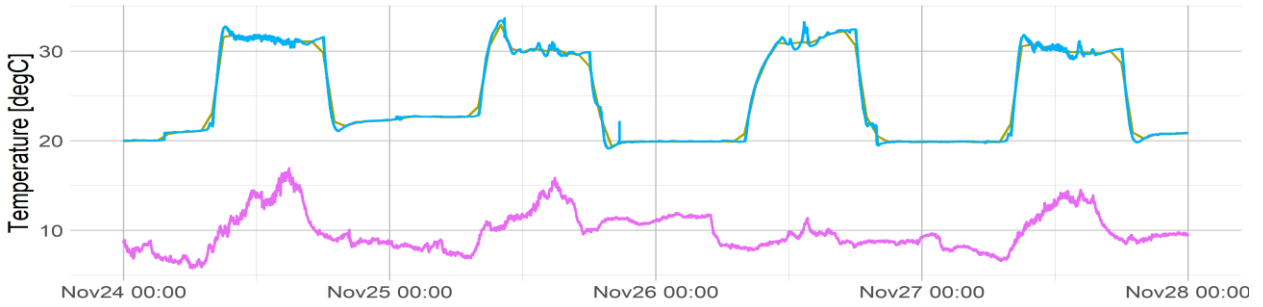
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements

| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 5.44% | 1.17% | -0.18% | 0.55% | 0.00% | 2.22% |
| RNRMSE | 13.50% | 18.10% | 19.60% | 3.84% | 4.12% | 4.85% |

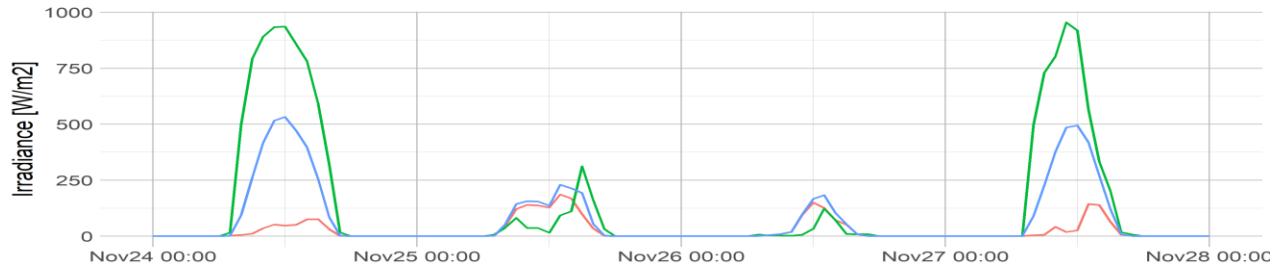
Scenario 11:02 Low-Mass, Exposed Windows, No Int Gain, Var Set-point (20C / 30C) - 3A



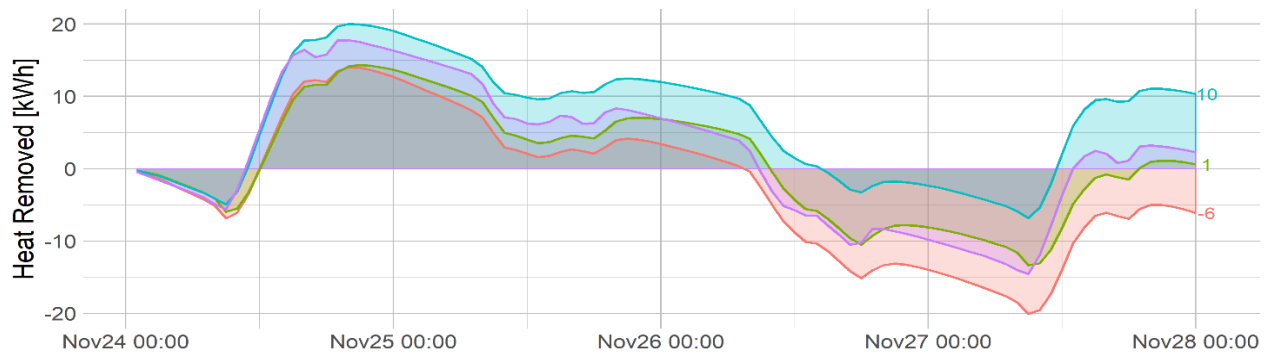
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements



Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ Measurements ■ Outside Drybulb



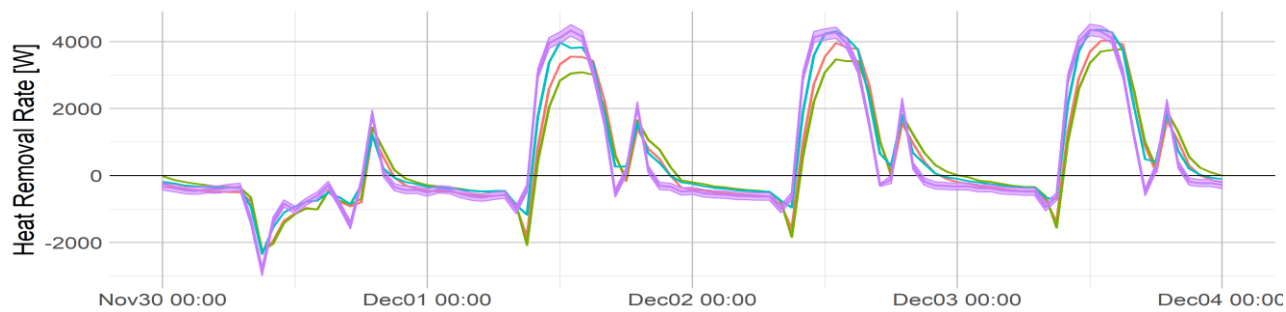
■ DiffuseHorizontal ■ DirectNormal ■ GlobalHorizontal



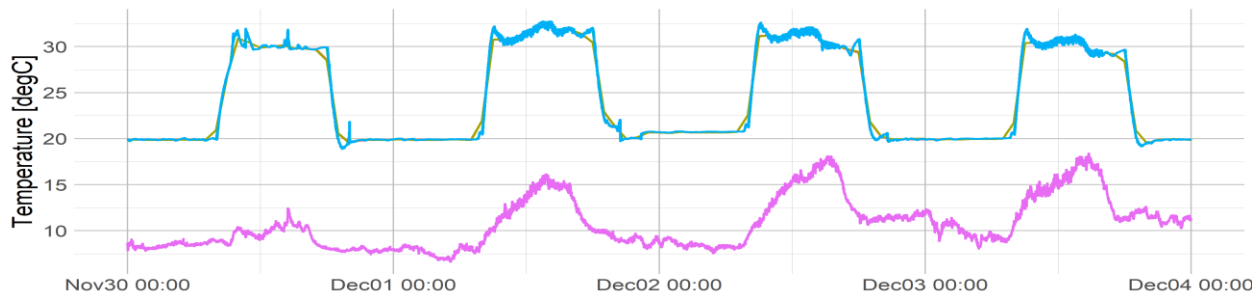
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements

| | Day | | | Night | | |
|---------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMSE | 2.13% | -1.58% | -2.59% | 0.50% | -0.88% | 1.49% |
| RNRMSSE | 7.13% | 11.30% | 12.90% | 3.39% | 4.60% | 5.09% |

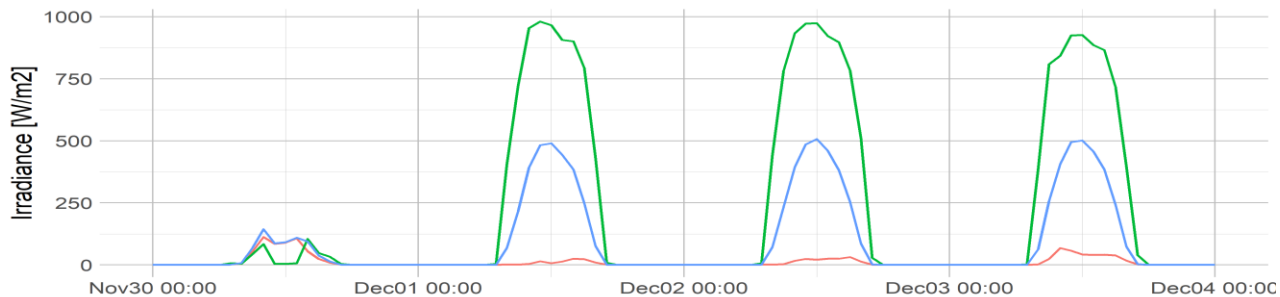
Scenario 11:03: Low-mass, Exposed Windows, No Int Gain, Var Set-point (20C / 30C) - 3A



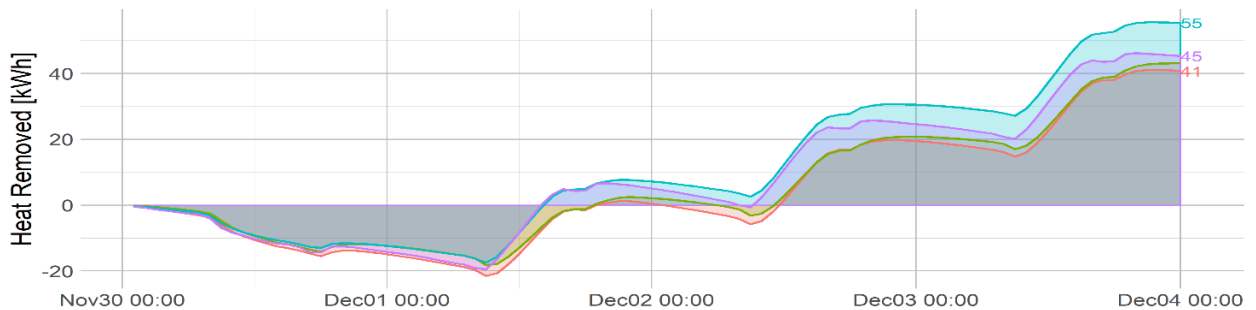
Variable : DOE21 DOE22 Eplus measurements



Variable : DOE21 DOE22 Eplus Measurements Outside Drybulb



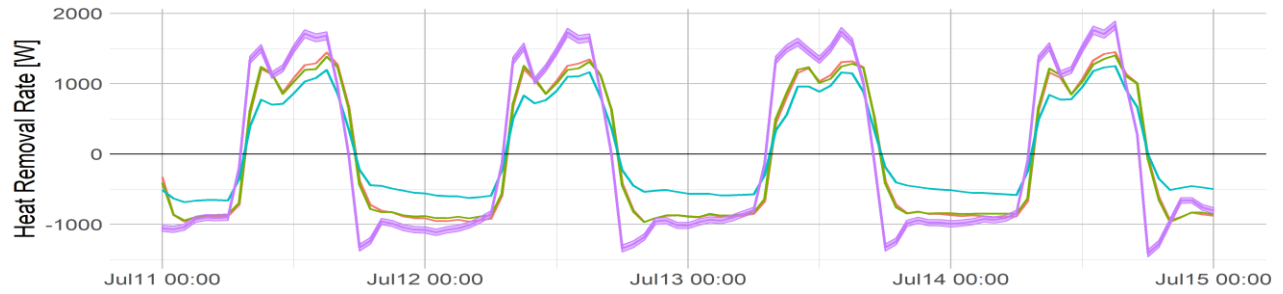
DiffuseHorizontal DirectNormal GlobalHorizontal



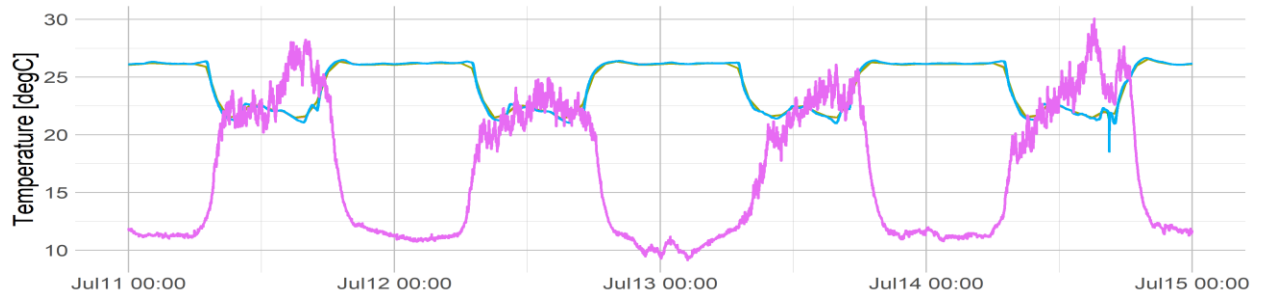
Variable : DOE21 DOE22 Eplus measurements

| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 0.53% | -2.79% | -5.56% | 2.13% | 0.88% | 3.44% |
| RNRMSE | 7.36% | 12.80% | 15.50% | 3.65% | 4.25% | 5.67% |

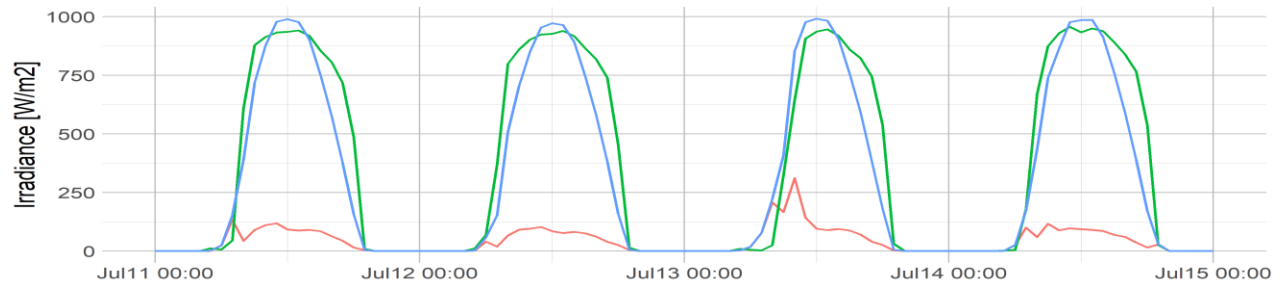
Scenario 12:01: High-mass, Exposed Windows, No Int Gain, Var Set-point (22C / 26C)



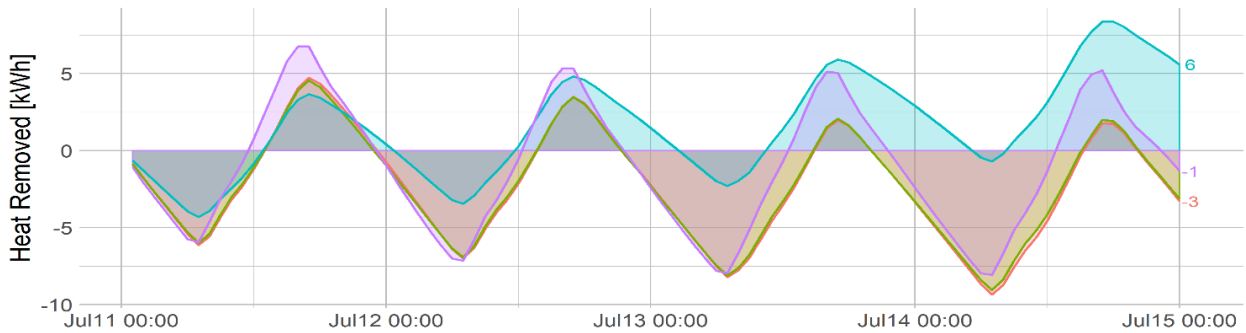
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements



Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ Measurements ■ Outside Drybulb



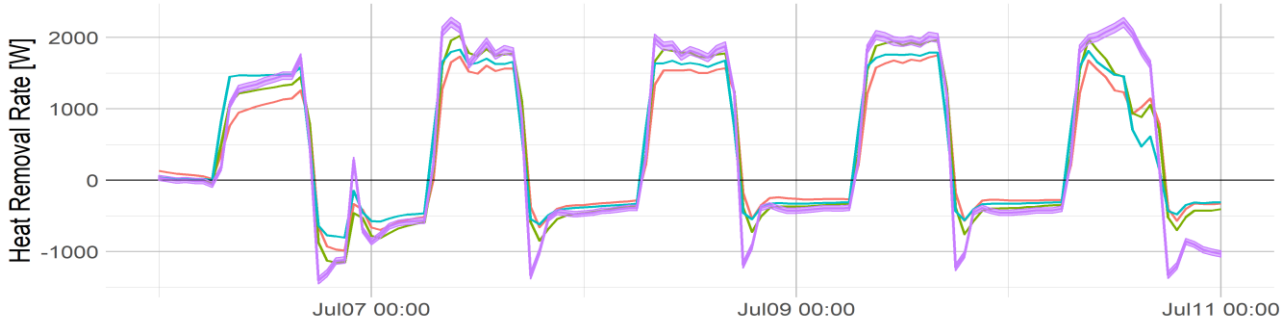
■ DiffuseHorizontal ■ DirectNormal ■ GlobalHorizontal



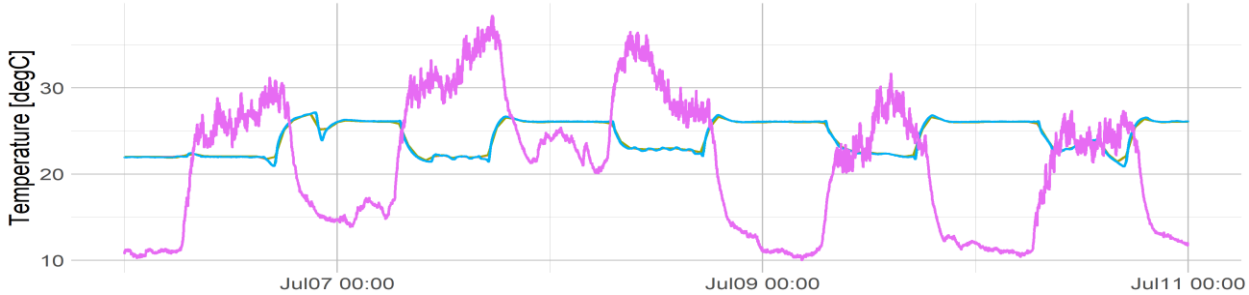
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements

| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | -13.60% | -6.79% | -7.15% | 12.90% | 4.10% | 4.40% |
| RNRMSE | 17.30% | 13.90% | 14% | 15.70% | 11.50% | 11% |

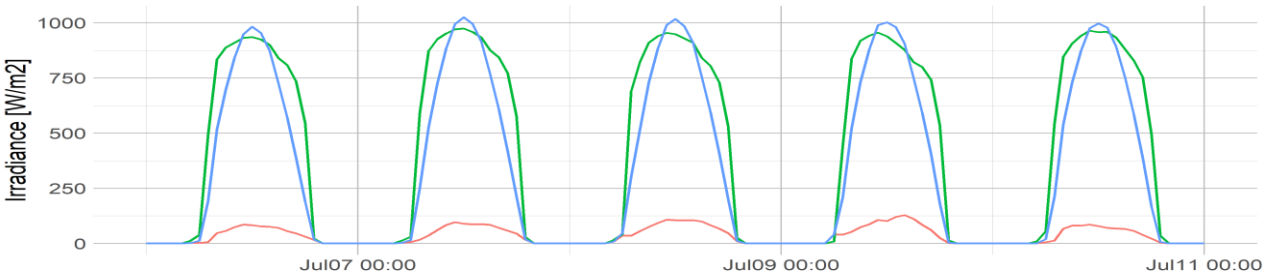
Scenario 14:01: High-mass, Covered Windows, Var 1440 W INT Gain, Var Set-point (22C / 26C)



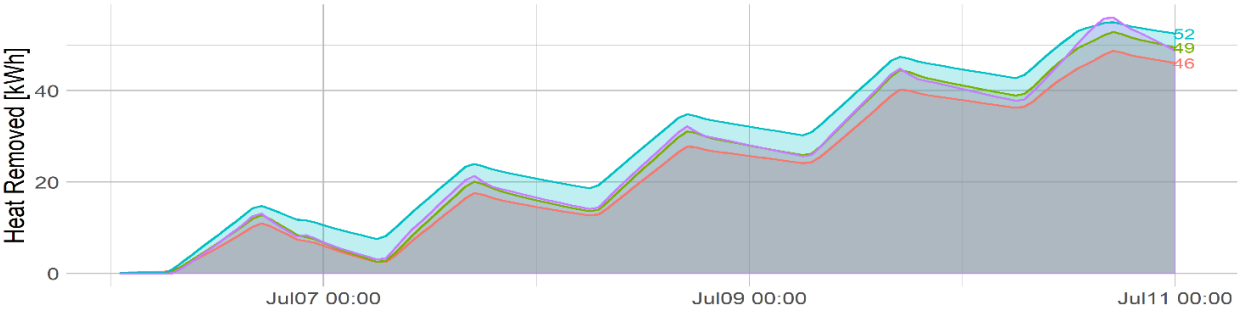
Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements



Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ Measurements ■ Outside Drybulb



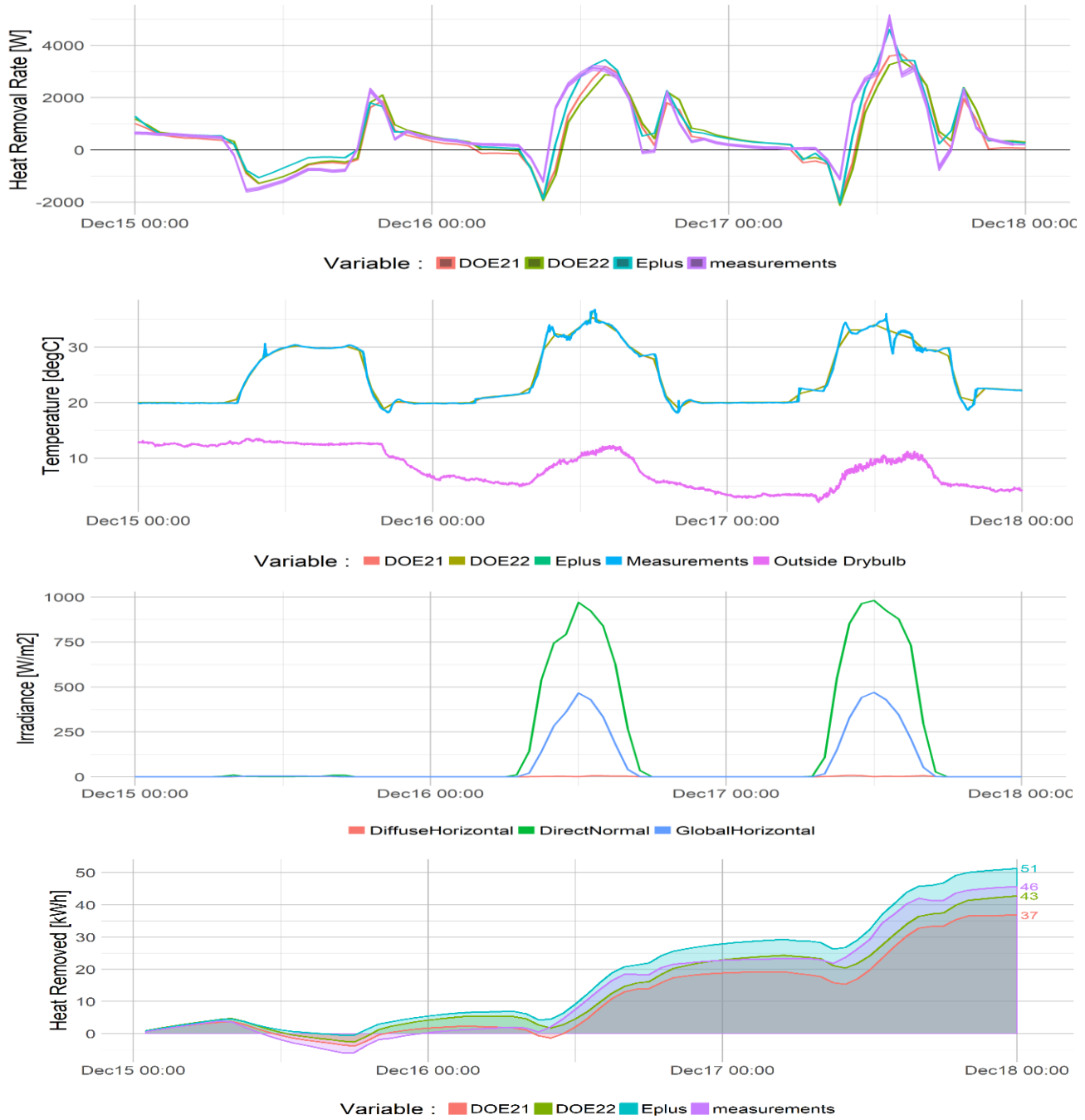
■ DiffuseHorizontal ■ DirectNormal ■ GlobalHorizontal



Variable : ■ DOE21 ■ DOE22 ■ Eplus ■ measurements

| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMSE | -6.88% | -9.55% | -3.89% | 6.31% | 5.72% | 3.03% |
| RNRMSE | 11.20% | 12.50% | 8.61% | 9.58% | 9.64% | 7.70% |

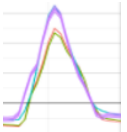
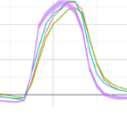
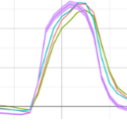
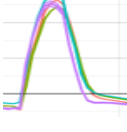
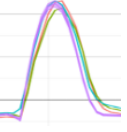
Scenario 15:01: Low-mass, Exposed Windows, Var 800 W Int Gain, Var Set-point (20C / 30C) - 3A



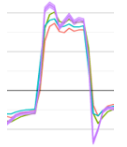
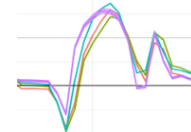
| | Day | | | Night | | |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| | EplustoMeas | DOE21toMeas | DOE22toMeas | EplustoMeas | DOE21toMeas | DOE22toMeas |
| RNMBE | 1.20% | -2.28% | -3.72% | 1.37% | -1.44% | 1.75% |
| RNRMSE | 8.94% | 13% | 15.10% | 3.79% | 4.01% | 4.64% |

Figure 25. Graphical representations of the twelve test cases

Table 11. Comments on the Tests

| SCENARIO: TEST | FLEXLAB | DOE-2.1E | DOE-2.2 | ENERGYPLUS | GENERAL COMMENTS, UNRESOLVED DIFFERENCES |
|-------------------|---|--|---|--|---|
| 3:01 | Data/control good except night of Jul22/23. | Cooling ~500 W low during the day, high heating at night. | Cooling ~700 W low during the day, high heating at night. | Cooling ~300 W low during the day, high heating at night. | At night, engines agree better with each other than with F/L.  |
| 3:02 | Zone temp set-point not met; solar heat gain is high because sun angle is low in Feb, causing too high a cooling load for the HVAC. | Lags F/L during afternoon fall, otherwise good agreement day and night. | Lags F/L during afternoon fall; low cooling during day and slightly low heating at night. | Lags F/L during afternoon fall, good agreement during day and slightly low heating at night. | DOE-2.1e and EP agree during day; fairly good agreement at night.  |
| 3:03 | Zone temp set-point not met; solar heat gain is high because sun angle is low in Feb, causing too high a cooling load for the HVAC. | Lags F/L during morning rise and afternoon fall, otherwise good during day and low heating at night. | Lags F/L during morning rise and afternoon fall, low cooling during day and low heating at night. | Lags F/L during morning rise and afternoon fall, otherwise good during day and low heating at night. | Anomalous response on first day. Engines agree during day; low heating at night.  |
| 3:04 | Increased fan speed during day (50% vs 25% at night) increases cooling capacity enough to meet set-point. | Good agreement during day and night, with afternoon lag. | Good agreement during day, a bit low at night, afternoon lag. | Good agreement during day, a bit low at night, afternoon lag. | Engines agree during day, low at night, with afternoon lag.  |
| 3:05 | Low ambient temperature increases window heat-loss sufficiently to meet cooling load at 25% fan speed. | Good agreement during day and night, with afternoon lag. | Slightly low during day and night, with afternoon lag. | Good agreement during day, low at night, with afternoon lag. | Engines agree during day, low at night, with afternoon lag.  |

| | | | | | |
|-------|--|--|--|--|---|
| 6:01 | Temporary offset in zone air temperature sensors resulted in effective set-point of 25 C. | Daytime cooling low, cooling or low heating at night. | Daytime cooling and nighttime heating agree. | Agrees at night, daytime cooling slightly high. | Daytime: EnergyPlus good, DOE-2.1e low.  |
| 11:01 | One sunny, one partly sunny, one partly cloudy and one cloudy day. Poor temperature control when set-point changes by 10 K. Cell 3A. | Daytime cooling low, nighttime heating agrees well. Rise and fall responses delayed. | Daytime cooling low, nighttime heating agrees well. Rise and fall responses delayed. | Agrees well with FLEXLAB apart from the transients on the cloudy day (Nov 15). | All engines agree well with FLEXLAB at night and agree well during the day apart from the sharpest transients and the DOE-2 delays.  |
| 11:02 | Two moderately clear and two cloudy days. Poor temperature control when set-point changes by 10 K. Cell 3A. | Daytime cooling low, nighttime heating agrees well. Rise and fall responses delayed. | Daytime cooling low, nighttime heating agrees well. Rise and fall responses delayed. | Agrees well apart from some transients. | All engines agree with FLEXLAB at night and agree during the day apart from the sharpest transients and the DOE-2 delays.  |
| 11:03 | One cloudy and three moderately clear days. Poor temperature control when set-point changes by 10 K. Cell 3A. | Daytime cooling low, nighttime heating agrees well. Rise and fall responses delayed. | Daytime cooling low, nighttime heating agrees well. Rise and fall responses delayed. | Agrees well apart from some transients; rise and fall responses delayed. | All engines agree with FLEXLAB at night and agree during the day apart from the sharpest transients and the DOE-2 delays.  |
| 12:01 | Four sunny days. Somewhat poor temperature control. Cell 3A. | Daytime cooling and nighttime heating agree well apart from some transients. | Daytime cooling and nighttime heating agree well apart from some transients. | Slightly under-predicts cooling and significantly under-predicts heating. | No delays. Main feature is EnergyPlus significantly under-predicts heating relative to both FLEXLAB and the DOE-2 engines.  |

| | | | | | | |
|-------|---|--|--|---|---|---|
| 14:01 | Three clear days. | Agrees very well with FLEXLAB. | Cooling is high on Jul 7, 8 and 9. | Cooling is high on Jul 6. | Generally good agreement, esp. at night, apart from poor response to the sharpest major transients. |  |
| 15:01 | One completely overcast day followed by two clear days. Poor temperature control when set-point changes by 10 K. Cell 3A. | Agrees quite well with FLEXLAB, except for delay in daytime rise and fall – cooling and heating. | Agrees quite well with FLEXLAB, except for delay in daytime rise and fall – cooling and heating. | Daytime cooling agrees well with FLEXLAB; daytime heating on Dec 15 is low. | Generally good agreement, apart from the morning delays. |  |

5.1.1 Data Analysis

Figure 26, Figure 27 and Table 12 show the values of the range-normalized mean bias error (RNMBE) and the range-normalized root mean square error (RNRMSSE) between the predictions of each engine and the FLEXLAB measurements, aggregated over daytime and nighttime, for each of the 12 cases. The average of the RNMBE values for all the cases provides an indication of the overall bias, with cancellation between over-prediction and under-prediction of different cases. The Absolute Average values are averages of the absolute values of the RNMBE for each case and so there is no cancellation of over-prediction and under-prediction between the different cases, making these values a better indication of the uncertainty in any particular run and, by extension, in a set of runs of the same model as part of a design project. The uncertainties in the tables are standard deviations of the populations

The average of the RNRMSSE values for all the cases provides an indication of the variability of the error for all the cases. Because the value of RNRMSSE is always positive for each run, there is no cancellation when the values for the different cases are averaged. The relatively large values of RNRMSSE – averaging ~10% - indicates that there can be significant variation at the hourly level. Some of the larger values may not be representative of real operation, in that large simultaneous step changes in the internal gain and the zone temperature set-point were made in some runs to create 'stress cases'.

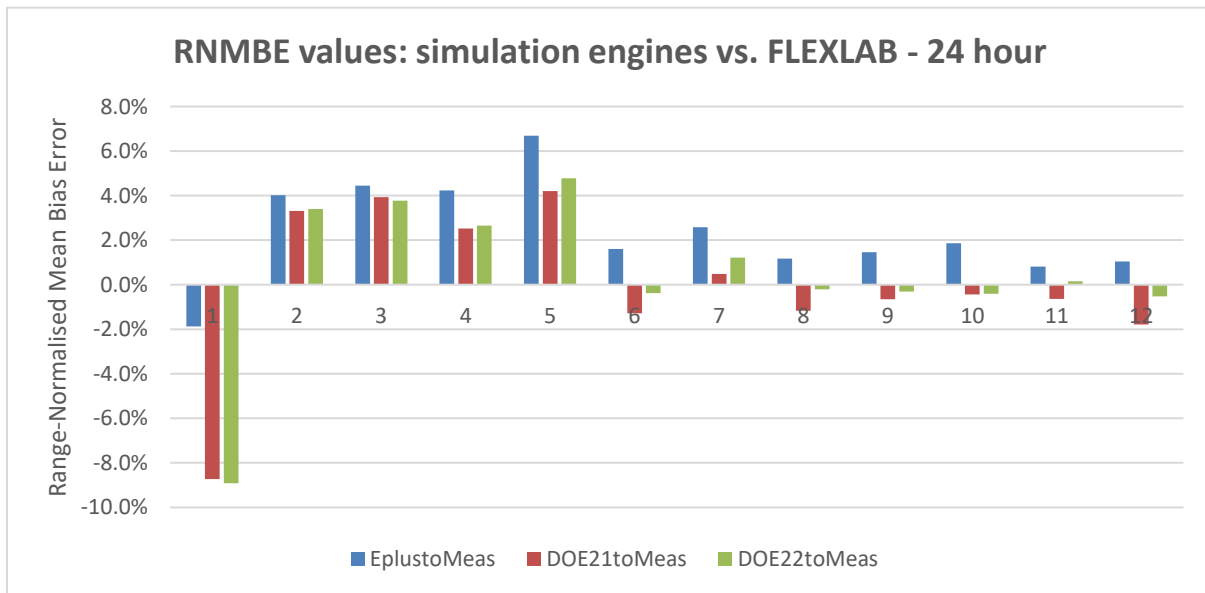


Figure 26. RNMBE values: simulation engines vs. FLEXLAB - 24 hour

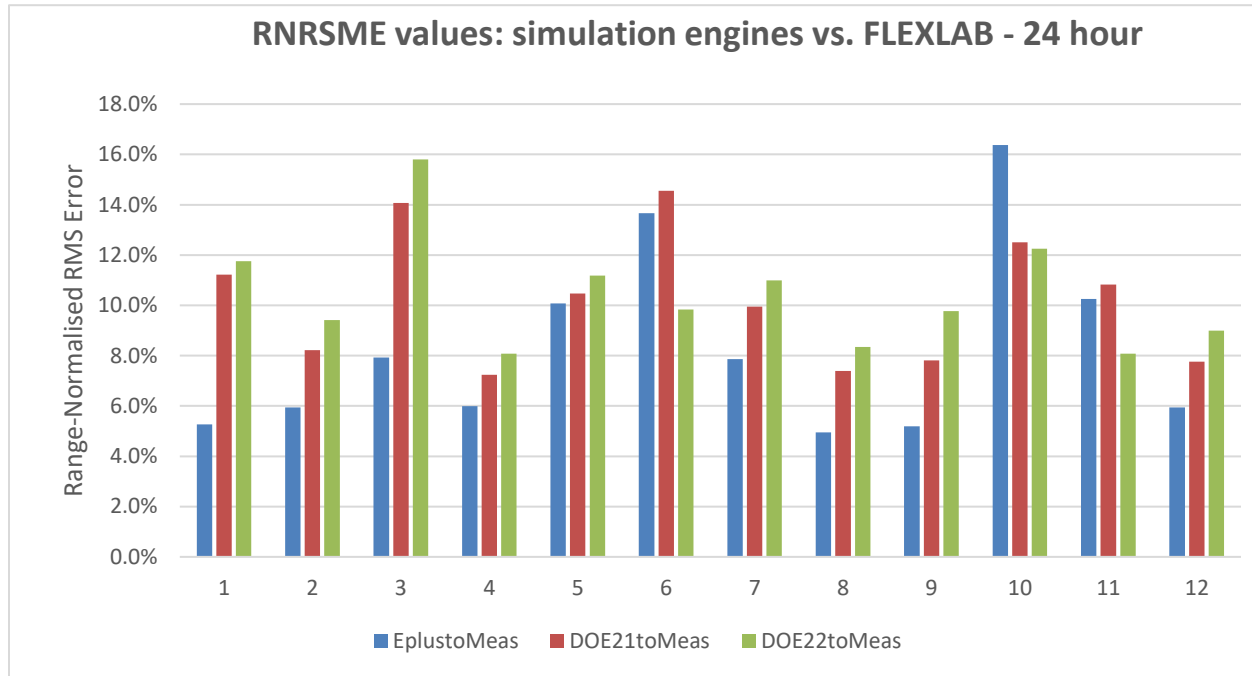


Figure 27. RNRSME values: simulation engines vs. FLEXLAB - 24 hour

Table 12. RNMBE and RNRMSSE values – simulation engines vs. FLEXLAB – 24 hour

| SCENARIO: | ----- RNMBE ----- | | | ----- RNRMSSE ----- | | |
|-------------------------|-------------------|-----------------|-----------------|---------------------|------------------|------------------|
| RUN | EPLUSTOMEAS | DOE21TOMEAS | DOE22TOMEAS | EPLUSTOMEAS | DOE21TOMEAS | DOE22TOMEAS |
| 3:01 | -1.87% | -8.72% | -8.92% | 5.26% | 11.23% | 11.76% |
| 3:02 | 4.01% | 3.31% | 3.40% | 5.94% | 8.22% | 9.41% |
| 3:03 | 4.45% | 3.93% | 3.77% | 7.93% | 14.07% | 15.80% |
| 3:04 | 4.23% | 2.53% | 2.66% | 5.99% | 7.24% | 8.08% |
| 3:05 | 6.69% | 4.20% | 4.78% | 10.07% | 10.47% | 11.18% |
| 6:01 | 1.61% | -1.28% | -0.38% | 13.66% | 14.56% | 9.83% |
| 11:01 | 2.59% | 0.49% | 1.22% | 7.87% | 9.95% | 11.00% |
| 11:02 | 1.18% | -1.17% | -0.21% | 4.95% | 7.39% | 8.34% |
| 11:03 | 1.46% | -0.65% | -0.31% | 5.20% | 7.81% | 9.77% |
| 12:01 | 1.86% | -0.44% | -0.41% | 16.37% | 12.50% | 12.25% |
| 14:01 | 0.81% | -0.64% | 0.15% | 10.26% | 10.83% | 8.08% |
| 15:01 | 1.04% | -1.79% | -0.53% | 5.94% | 7.76% | 9.00% |
| Average | 2.3±2.1% | 0.0±3.3% | 0.4±3.4% | 8.3±3.5% | 10.2±2.6% | 10.4±2.2% |
| Absolute Average | 2.6±1.7% | 2.4±2.3% | 2.2±2.5% | | | |

Figure 28 and Figure 29 show the values of the RNMBE between the predictions of each engine and the FLEXLAB measurements, separated by daytime and nighttime respectively, for each of the 12 cases. Table 13 shows the values of the RNMBE between the predictions of each engine and the FLEXLAB measurements, separated by daytime (8:00-18:00) and nighttime (18:00-8:00), for each of the 12 cases.

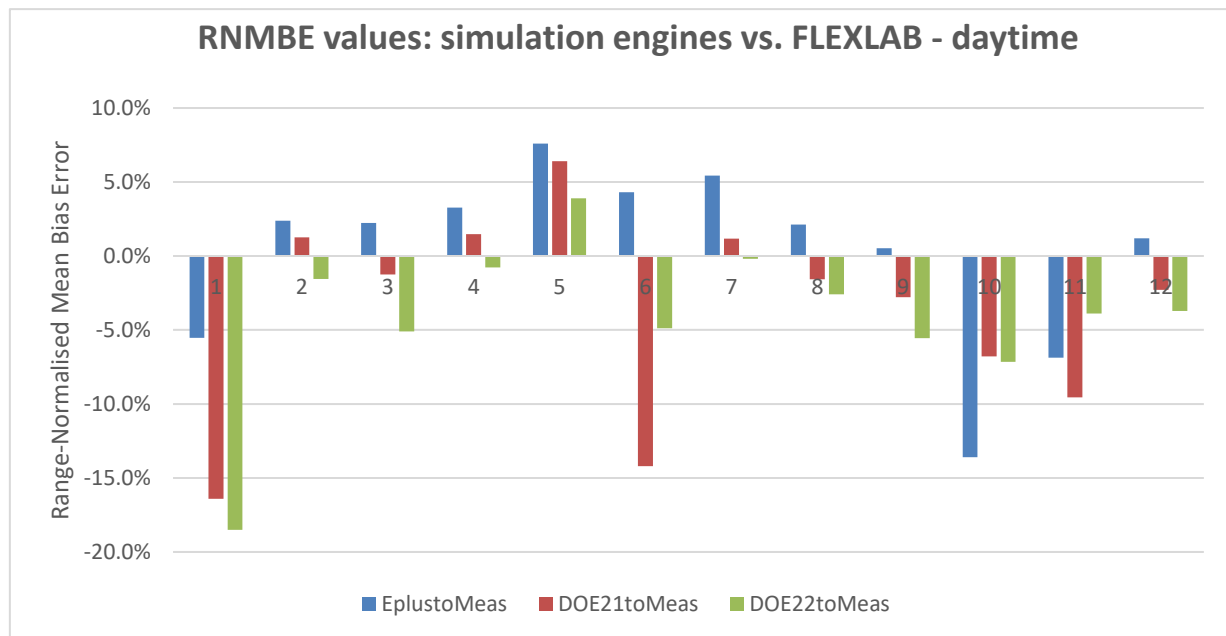


Figure 28. RNMBE values: simulation engines vs. FLEXLAB – daytime

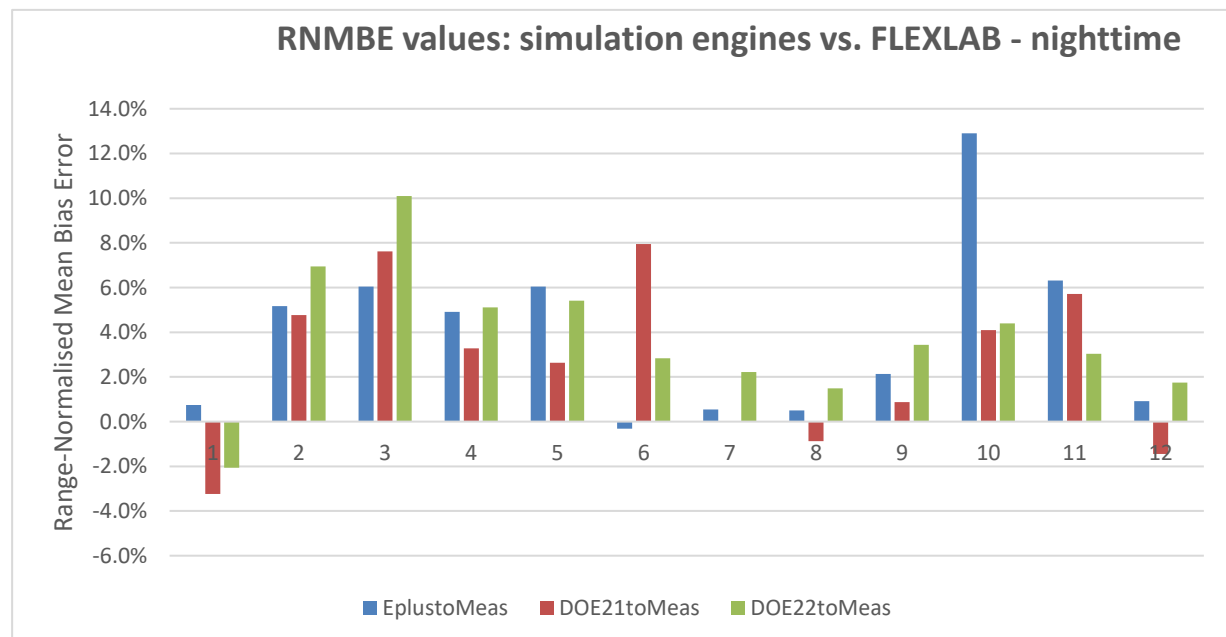


Figure 29. RNMBE values: simulation engines vs. FLEXLAB - nighttime

Table 13. RNMBE values for daytime and nighttime

| SCENARIO: | DAY | | | NIGHT | | |
|-------------------------|-----------------|------------------|------------------|-----------------|-----------------|-----------------|
| RUN | EPLUSTOMEAS | DOE21TOMEAS | DOE22TOMEAS | EPLUSTOMEAS | DOE21TOMEAS | DOE22TOMEAS |
| 3:01 | -5.52% | -16.40% | -18.50% | 0.74% | -3.24% | -2.07% |
| 3:02 | 2.39% | 1.26% | -1.55% | 5.17% | 4.77% | 6.94% |
| 3:03 | 2.23% | -1.24% | -5.09% | 6.04% | 7.62% | 10.10% |
| 3:04 | 3.28% | 1.47% | -0.78% | 4.91% | 3.28% | 5.11% |
| 3:05 | 7.60% | 6.40% | 3.89% | 6.04% | 2.63% | 5.41% |
| 6:01 | 4.30% | -14.20% | -4.88% | -0.32% | 7.95% | 2.84% |
| 11:01 | 5.44% | 1.17% | -0.18% | 0.55% | 0.00% | 2.22% |
| 11:02 | 2.13% | -1.58% | -2.59% | 0.50% | -0.88% | 1.49% |
| 11:03 | 0.53% | -2.79% | -5.56% | 2.13% | 0.88% | 3.44% |
| 12:01 | -13.60% | -6.79% | -7.15% | 12.90% | 4.10% | 4.40% |
| 14:01 | -6.88% | -9.55% | -3.89% | 6.31% | 5.72% | 3.03% |
| 15:01 | 1.20% | -2.28% | -3.72% | 0.92% | -1.44% | 1.75% |
| Average | 0.3±5.7% | -3.7±6.5% | -4.2±5.2% | 3.8±3.7% | 2.6±3.5% | 3.7±2.9% |
| Absolute Average | 4.7±3.5% | 5.4±5.1% | 4.8±4.6% | 3.9±3.6% | 3.5±2.5% | 4.1±2.4% |

Figure 30 and Figure 31 show the values of the RNRSMSE between the predictions of each engine and the FLEXLAB measurements, separated by daytime and nighttime respectively, for each of the 12 cases. Table 14 shows the values of the RNRSMSE between the predictions of each engine and the FLEXLAB measurements, separated by daytime (8:00-18:00) and nighttime (18:00-8:00), for each of the 12 cases.

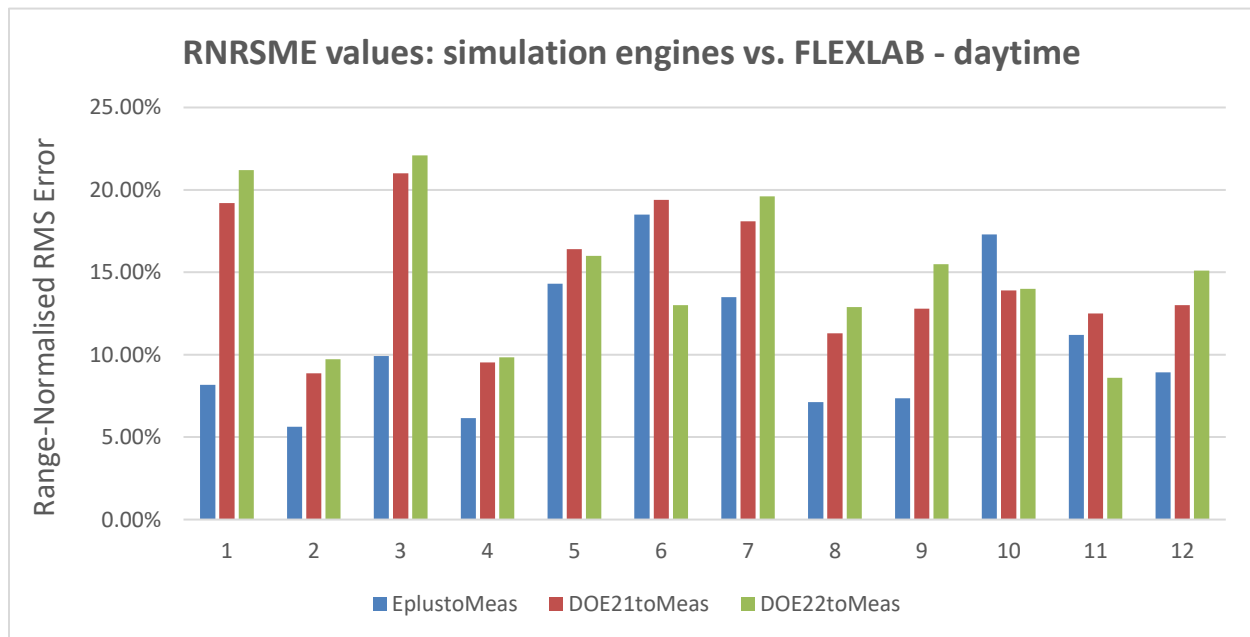


Figure 30. RNRSMSE values: simulation engines vs. FLEXLAB – daytime

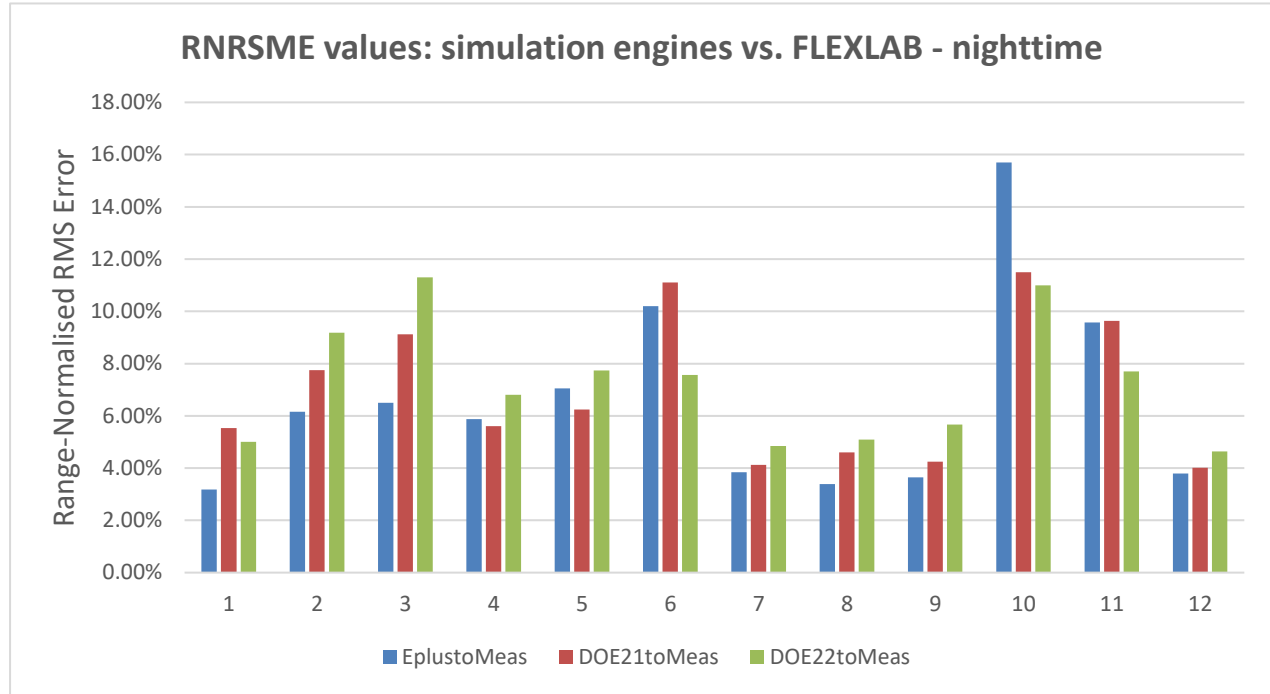


Figure 31. RNRSME values: simulation engines vs. FLEXLAB – nighttime

Table 14. RNRMSSE values for daytime and nighttime

| SCENARIO: | ----- DAY ----- | | | ----- NIGHT ----- | | |
|----------------|------------------|------------------|------------------|-------------------|-----------------|-----------------|
| RUN | EPLUSTOMEAS | DOE21TOMEAS | DOE22TOMEAS | EPLUSTOMEAS | DOE21TOMEAS | DOE22TOMEAS |
| 3:01 | 8.18% | 19.2% | 21.20% | 3.18% | 5.53% | 5.01% |
| 3:02 | 5.64% | 8.88% | 9.73% | 6.16% | 7.75% | 9.18% |
| 3:03 | 9.93% | 21.00% | 22.10% | 6.50% | 9.12% | 11.30% |
| 3:04 | 6.15% | 9.53% | 9.85% | 5.88% | 5.61% | 6.81% |
| 3:05 | 14.30% | 16.40% | 16.00% | 7.05% | 6.24% | 7.74% |
| 6:01 | 18.50% | 19.40% | 13.00% | 10.20% | 11.10% | 7.57% |
| 11:01 | 13.50% | 18.10% | 19.60% | 3.84% | 4.12% | 4.85% |
| 11:02 | 7.13% | 11.30% | 12.90% | 3.39% | 4.60% | 5.09% |
| 11:03 | 7.36% | 12.80% | 15.50% | 3.65% | 4.25% | 5.67% |
| 12:01 | 17.30% | 13.90% | 14.00% | 15.70% | 11.50% | 11.00% |
| 14:01 | 11.20% | 12.50% | 8.61% | 9.58% | 9.64% | 7.70% |
| 15:01 | 8.94% | 13.00% | 15.10% | 3.79% | 4.01% | 4.64% |
| Average | 10.7±4.3% | 14.7±3.8% | 14.8±3.9% | 6.6±3.6% | 7.0±2.7% | 7.2±2.2% |

6 Discussion

As presented in Table 12, both the steady state/low frequency deviations between the engine predictions and FLEXLAB measurement, as indicated by RNMBE, and the high frequency deviations, as indicated by RNRMSE, vary significantly from test to test. These deviations are shown in Figure 26 and Figure 27. In addition, Table 12 indicates that, in general, any systematic bias in the engines is quite small; EnergyPlus exhibits a barely significant bias of $2.3 \pm 2.1\%$ towards overprediction of cooling load, possibly with an element of underprediction of heating load. The corresponding values for the DOE-2 engines are not significant. The quasi-steady-state variability from run-to-run for EnergyPlus, as indicated by the average of the absolute values of the bias errors (RNMABE) is only slightly significant ($2.6 \pm 1.7\%$), while corresponding values for the DOE-2 engines are barely significant.

The response to transients, as indicated by the root-mean-square error (RNRMSE), is also quite similar for all three engines, i.e. 8-10%. This is despite the use of a relatively short time-step (10 min) in EnergyPlus and a one-hour time-step in DOE-2.1e and DOE-2.2. In contrast to the mean bias errors, these values are all greater than three standard deviations, indicating that the errors in the transient responses of the engines are more significant than the quasi-static errors.

There is a significant difference in behavior between the daytime period and the nighttime period. Table 14 indicates that the average value of RNMBE for all engines and all tests is -4.4% during the day and 2.7% during the night and the corresponding values of RNRMSE, presented in

Table 14, are 13.7% and 8.5%. These differences indicate that there are greater bias errors, and greater transient deviations, during the day. It seems probable that these are caused by solar gain, though the number of insulated window tests is not great enough to allow solar effects to be separated from, for example, the effect of other transients occupying a larger fraction of the shorter time interval (10 hours vs. 14 hours).

Several cases in the day-night variations in both RNMBE and RNRMSE, illustrated in Figure 28, Figure 29, Figure 30 and Figure 31, exhibit significant cancellation between substantial errors, of opposite sign for day and night. Cases 12:01 and 14:01 are the most significant. The EnergyPlus daytime average bias error of 0.3% is substantially smaller than the daytime average absolute bias error of 4.7%, indicating substantial cancellation between positive and negative bias errors for different cases during the daytime. By contrast, the daytime average bias error for the DOE-2 engines is -3.7%, which is not much smaller than the daytime average absolute bias error of 5.4%, indicating only modest cancellation between positive and negative bias errors for different cases during the daytime. Conversely, the nighttime average bias errors fall in the range 2.6% - 3.8%, only slightly smaller than the nighttime average absolute bias errors of 3.5% - 4.1%, indicating modest cancellation between positive and negative bias errors for different cases during the nighttime.

The practical significance of the difference between the daytime and nighttime results is that both energy consumption and the importance of thermal comfort are greater during the daytime, giving greater significance to the daytime results and diminishing the importance of the 24-hour average results for buildings with typical occupancy.

Preliminary results obtained during the project indicated significantly greater errors than those presented above, which benefited from more extensive calibration over the life of the project. Suggestions of possible causes were made by members of the Technical Advisory Group; these included:

- Limitations of the models of long wave infra-red radiation from the sky; EnergyPlus uses a model developed by Clark and Allen (1976), which is based on observations of a narrower range of climates than the Berdahl and Martin (1984) model used in DOE-2. A sensitivity test was performed using EnergyPlus in which the emissivity of the roof was changed from the default value of 0.9 to zero and no perceptible difference in the nocturnal heating load was observed, confirming that the ~350 mm (14 in.) of polyurethane and polystyrene insulation in the roof of FLEXLAB provides effective isolation of the ceiling void from the ambient conditions. That said, the different sky models will predict different values of long wave irradiance incident on the window, and this may account for some part of the modest differences between the engines in their predictions of nighttime load observed in some of the cases with uncovered windows. However, as noted in the Introduction section of this report, it is beyond the scope of this project to determine the causes of differences in the predictions of the engines or differences between these predictions and the FLEXLAB measurements.
- The default window model in DOE-2 is different than the more recent default model in EnergyPlus. However, changing the default window model used with the DOE-2 engines to a model that is more like that used in EnergyPlus resulted in somewhat greater differences in the heating and cooling loads predicted by the DOE-2 engines and EnergyPlus; this indicates that window model is unlikely to be the cause of the observed differences.

In the initial stages of the analysis presented in this report, it was observed that, in terms of cooling/heating load, the response of EnergyPlus to substantial step changes in the internal heat gain or the zone temperature set-point appeared underdamped compared to the transient responses of FLEXLAB and the DOE-2 engines. Investigation determined that this effect was driven by the use of the "CeilingDiffuser" interior convection model in EnergyPlus, rather than the default "TARP" interior convection model. Under the range of conditions prevailing in most of the tests, the CeilingDiffuser model predicts significantly greater values of the interior surface convection coefficient than does the TARP model or the default fixed values used in DOE-2. The TARP model was used to generate the EnergyPlus results presented in this report and response can be seen to be overdamped relative to FLEXLAB in some cases (For example, 12:01 and 14:01, though not in others). Trials were made using the Beausoleil-Morrison hybrid model (Beausoleil-Morrison, 2000) included as an option in EnergyPlus, which combines the momentum-driven CeilingDiffuser model with the buoyancy-driven TARP model, but no reduction in the differences between the EnergyPlus and the FLEXLAB transient responses was observed.

Not enough data were obtained for the high-mass cases to be able to separate the effect of high-mass and low-mass. In particular, it is not possible to assert that the high-mass cases have higher values of RNMSE, though the data are not inconsistent with the high-mass cases having higher values of RNMSE. Additional high-mass runs are required for more definitive statements to be made.

7 Conclusions

The differences between the cooling and heating load predictions of EnergyPlus and the DOE-2 engines and the FLEXLAB measurements are generally relatively small for the conditions in the tests described in this report. The averages of the magnitudes of the hour-by-hour differences are $\sim 2.5\%$ of the range over several 24-hour periods. The daytime averages, which may be more important for both energy performance and occupant comfort, are $\sim 5\%$, presumably because of the greater complexity involved in simulating in the presence of solar radiation.

The 24-hour and daytime systematic bias errors are in the range $-4.2\% - 2.3\%$; in each case, the corresponding standard deviation exceeds the average mean bias error, so it is not possible to make statements about the magnitudes, or even the signs, of the average mean bias errors, particularly since the individual values do not appear to be normally distributed.

Given the limited nature of the cases studied, these results do not support the hypothesis that there is any significant difference in the ability of the three engines to predict heating and cooling loads in spaces with conventional overhead air supply for mixing ventilation. The results of this study, and the conclusions stated above, may not be fully applicable to spaces with furniture or sources of internal heat gain with different characteristics to those used in the study. The results, and conclusions, do not apply to other methods of space conditioning, such as radiant heating and cooling, UFAD, displacement ventilation, and natural ventilation.

8 Recommendations

As a result of this study, the following recommendations are made.

- Users and other stakeholders should be informed, through different forms of training, and through dissemination of this report, that DOE-2.1e, DOE-2.2 and EnergyPlus generally produce very similar heating and cooling load predictions for conventional overhead mixing ventilation systems. The choice of tool should be driven by other factors, including:
 - Modeling features – envelope, lighting, HVAC, renewables ...
 - User support
 - Any need for sub-hourly time-steps to track demand and model demand response
 - Execution speed
 - Ease of use, including preference for available user interfaces
 - Anticipated future features
- It would be beneficial to perform additional experiments for the scenarios with limited numbers of runs, in particular, the high-mass scenarios. These additional runs should be performed with:
 - Additional sensors found to be useful, based on the analysis of the runs reported.
 - Recalibrated existing sensors, to mitigate sensor drift and to take advantage of incremental improvements in calibration techniques over the course of the project reported.
 - Longer measurement periods, including quasi-real-time checking of heat balances and consistency with model predictions.
- The experiments discussed in this report for empty spaces with overhead mixing ventilation should be extended to address more realistic room configurations, including:
 - Furniture, including cubical dividers
 - Thermal manikins, to provide realistic thermal plumes and radiative/convective splits
 - Luminaires with different heat emission characteristics, e.g., up-lighters and down-lighters
 - Realistic power consumption / heat emission from computers programmed to produce more heat during work times vs. break times
 - The effect of ceiling fans on stratification and the heat storage characteristics of high-mass elements

- In each case, a key objective is to determine whether the accuracy of simulation engines is impaired by any of these non-ideal elements.
- The experimental capabilities and methods developed in the study should be applied to validating heating and cooling load calculations for low-energy space conditioning systems in EnergyPlus, including:
 - Radiant heating and cooling systems, particularly radiant slab floors, and radiant panel ceilings
 - Mixed-mode systems that combine mechanical cooling and natural ventilation systems, focusing on controls, including control of thermal mass
 - UFAD and displacement ventilation systems
- Verify the ability of EnergyPlus to predict peak load and simulate demand response strategies and events. Experimental methods should be developed for both day-ahead and short notice events. The experiments should compare the effect of high-mass vs. low-mass construction on the impact of HVAC curtailment or temperature set-up on thermal comfort.

9 Appendices

9.1 Appendix A – Locations of Sensors

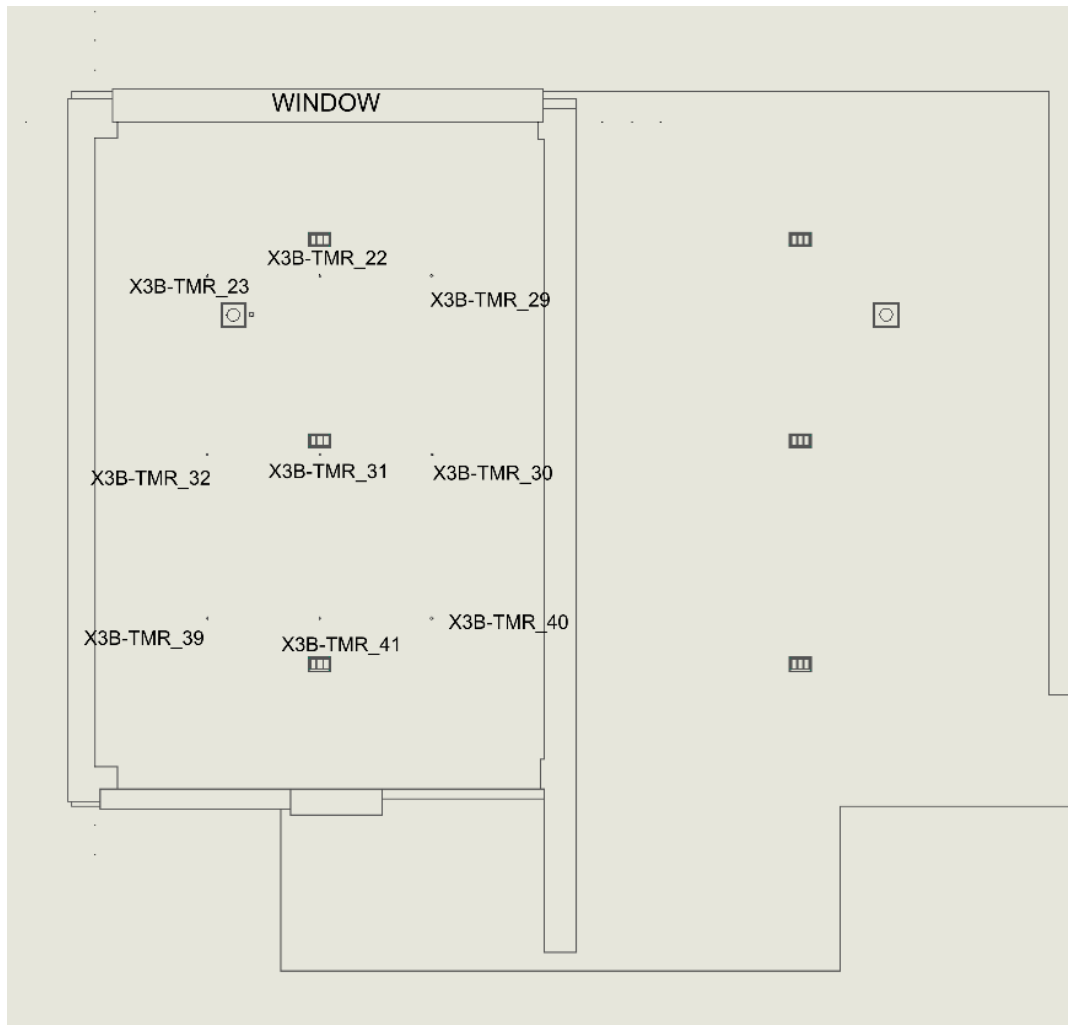


Figure-A 1. Floor Thermistors

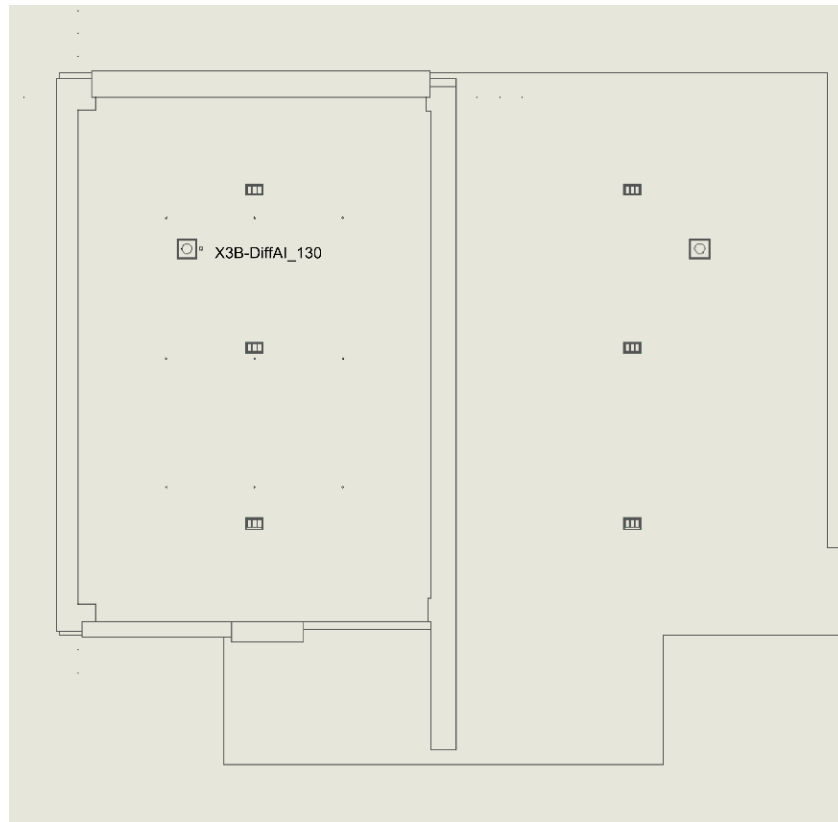


Figure-A 2. Floor Heat Flux Meters

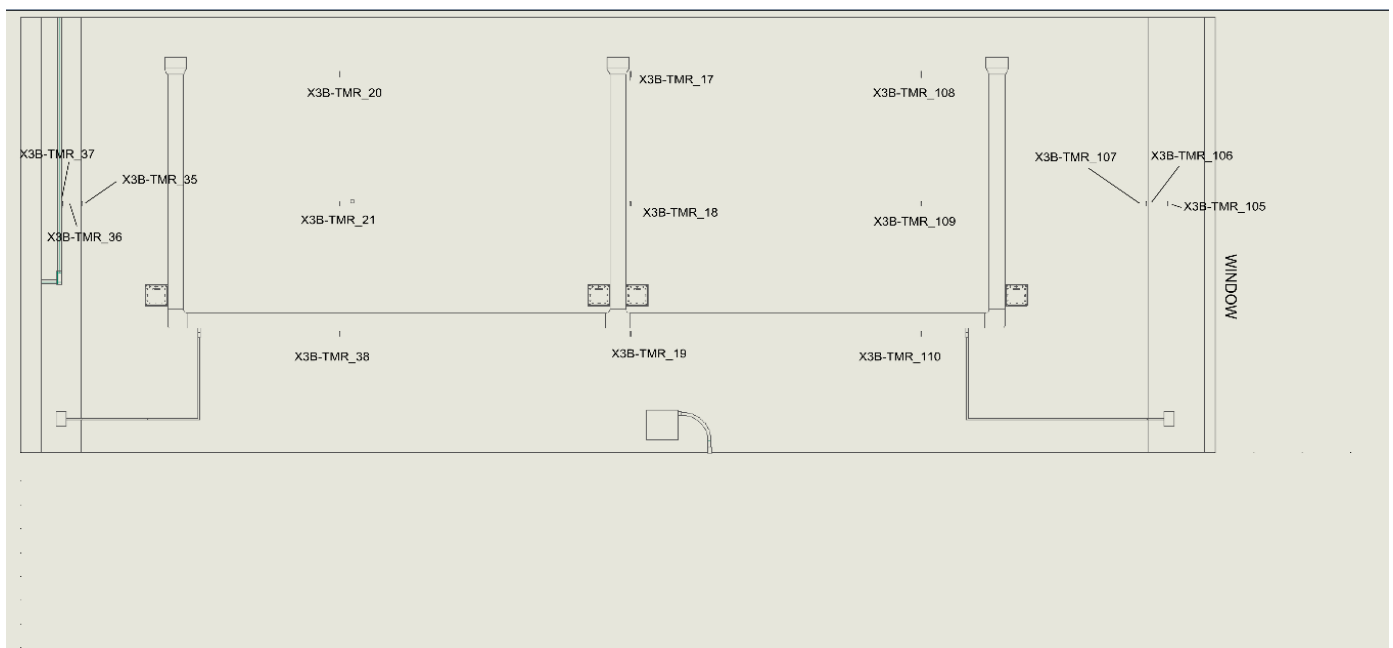


Figure-A 3. East Wall Thermistors

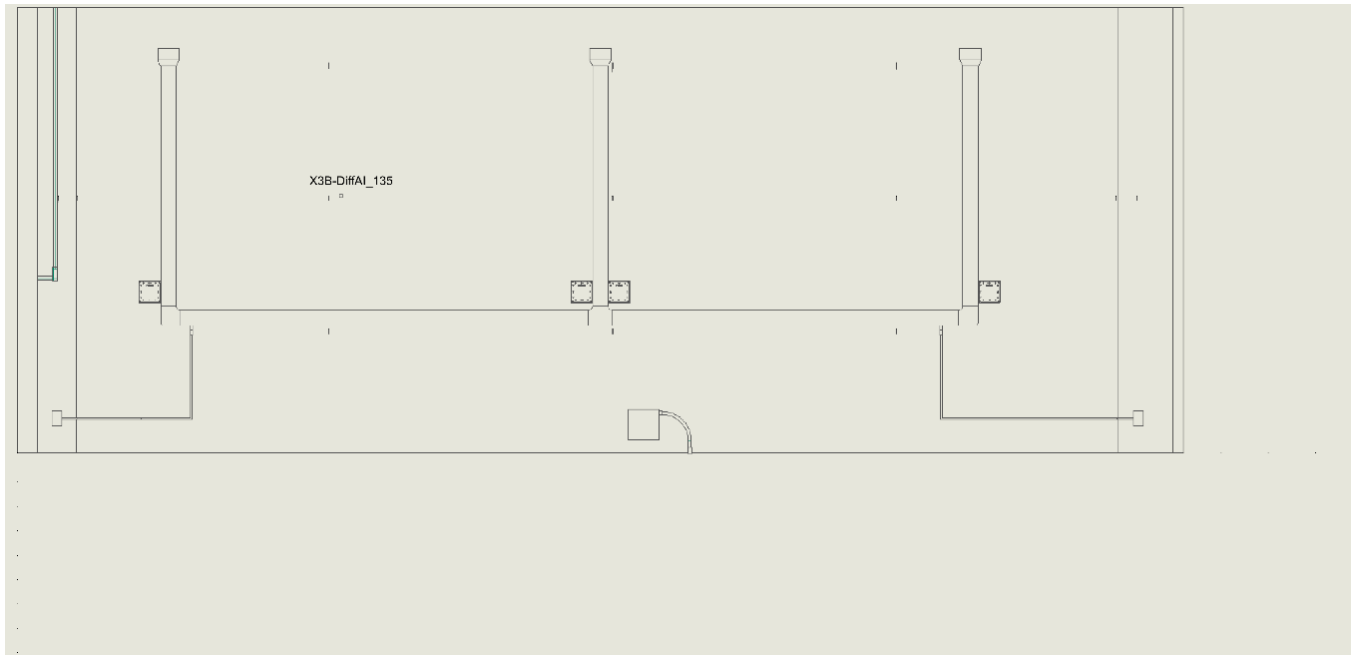


Figure-A 4. East Wall East Wall Heat Flux Meters

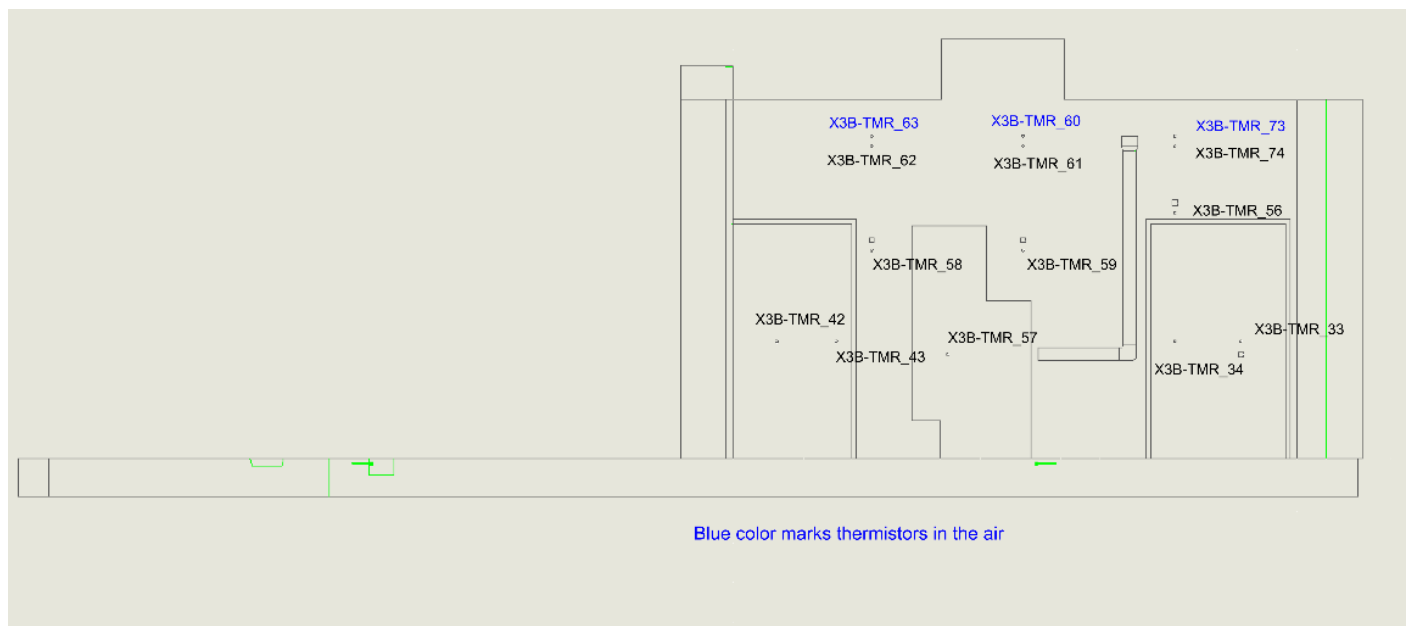


Figure-A 5. North Wall Thermistors

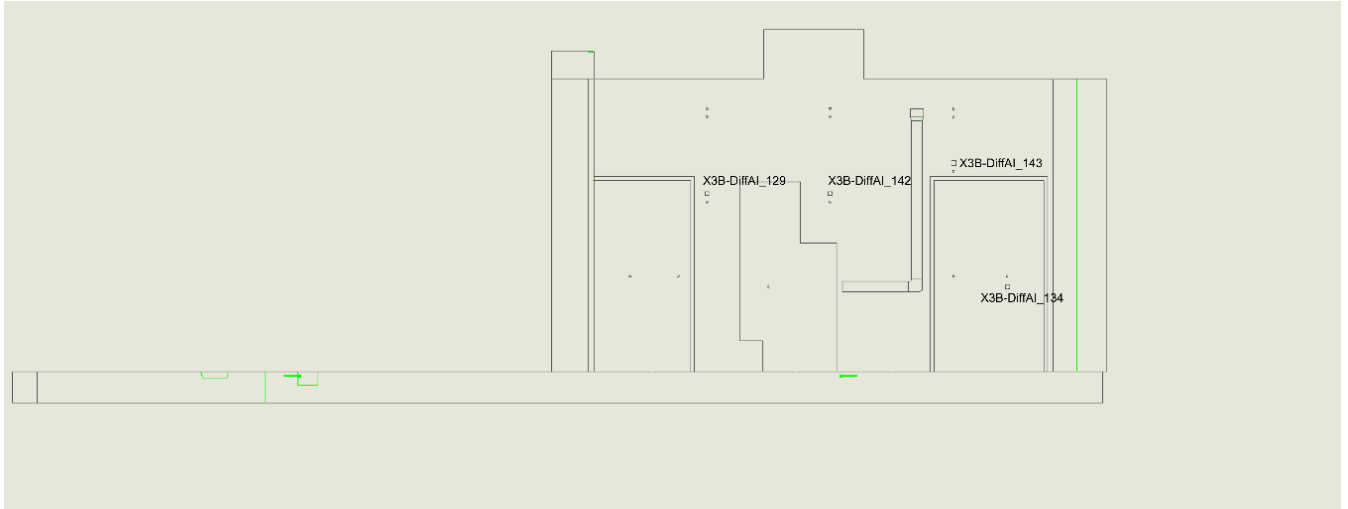


Figure-A 6. North Wall Heat Flux Meters

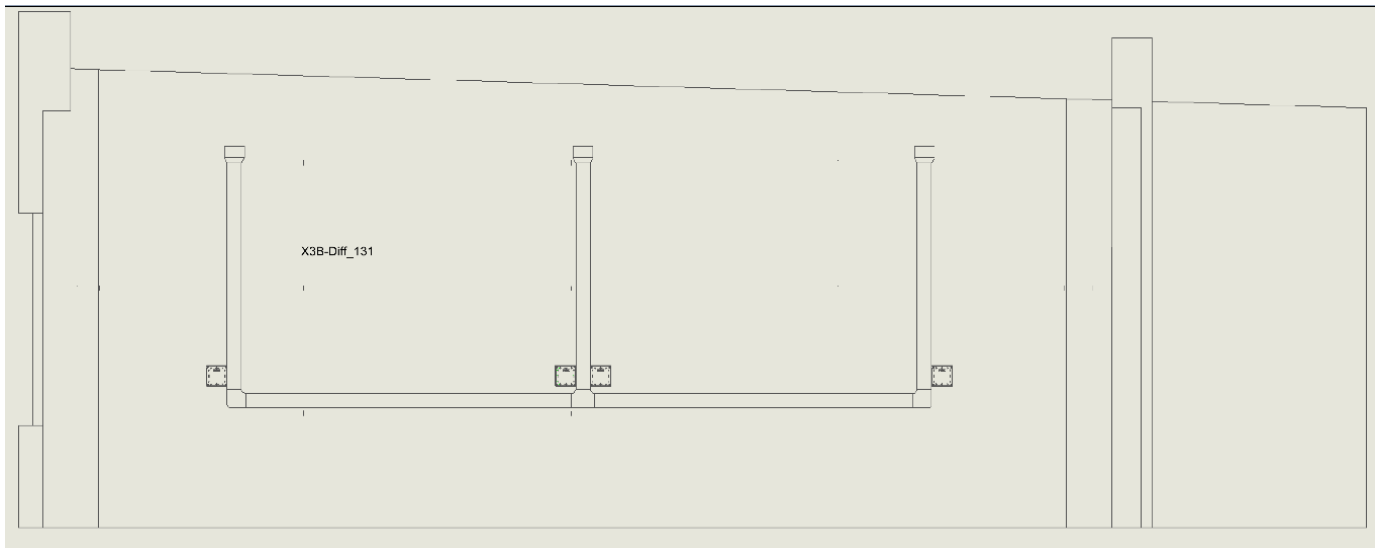


Figure-A 7. West Wall Heat Flux Meters



Figure-A 8. South Wall Heat Flux Meters

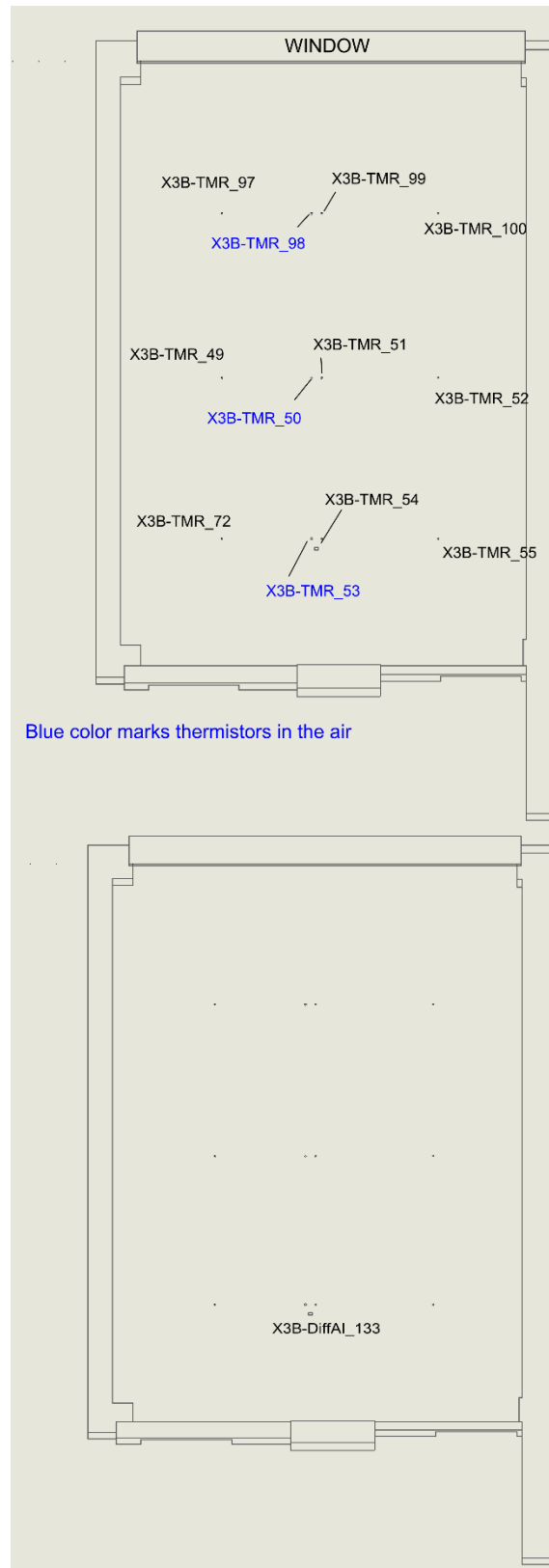


Figure-A 9. Ceiling Thermistors (top) and Ceiling Heat Flux Meter (bottom)

Hot Water

Last update

Thu, Apr 16, 2015, 10:02:44 AM (3 seconds ago)

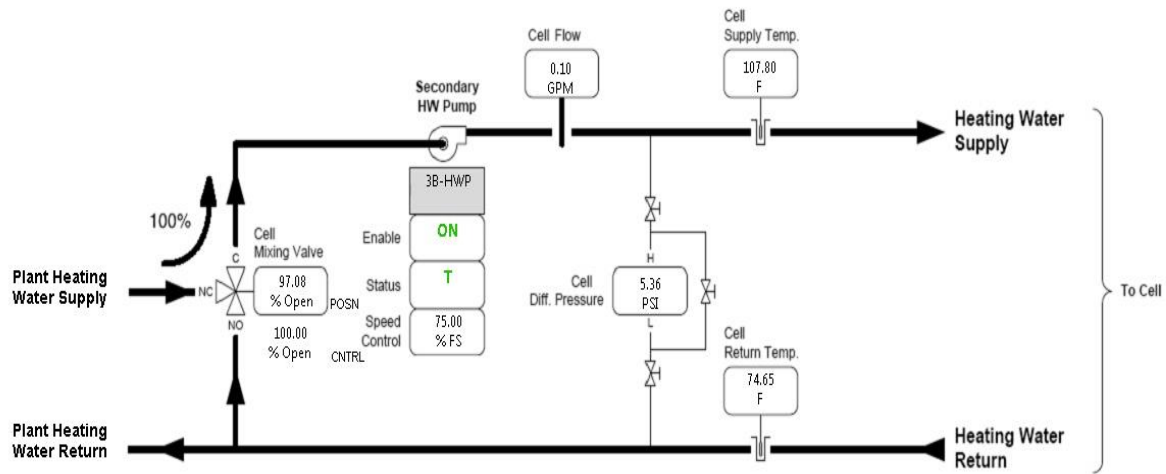


Figure-A 10. Primary Hot Water Circuit

Chilled Water

Last update

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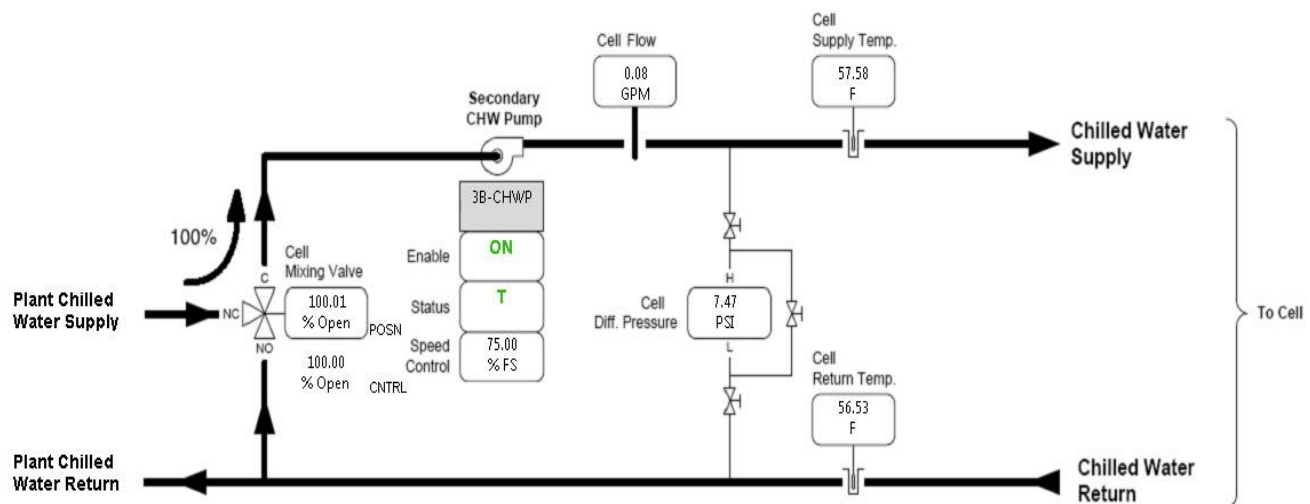


Figure-A 11. Primary Chilled Water Circuit

Air Handler

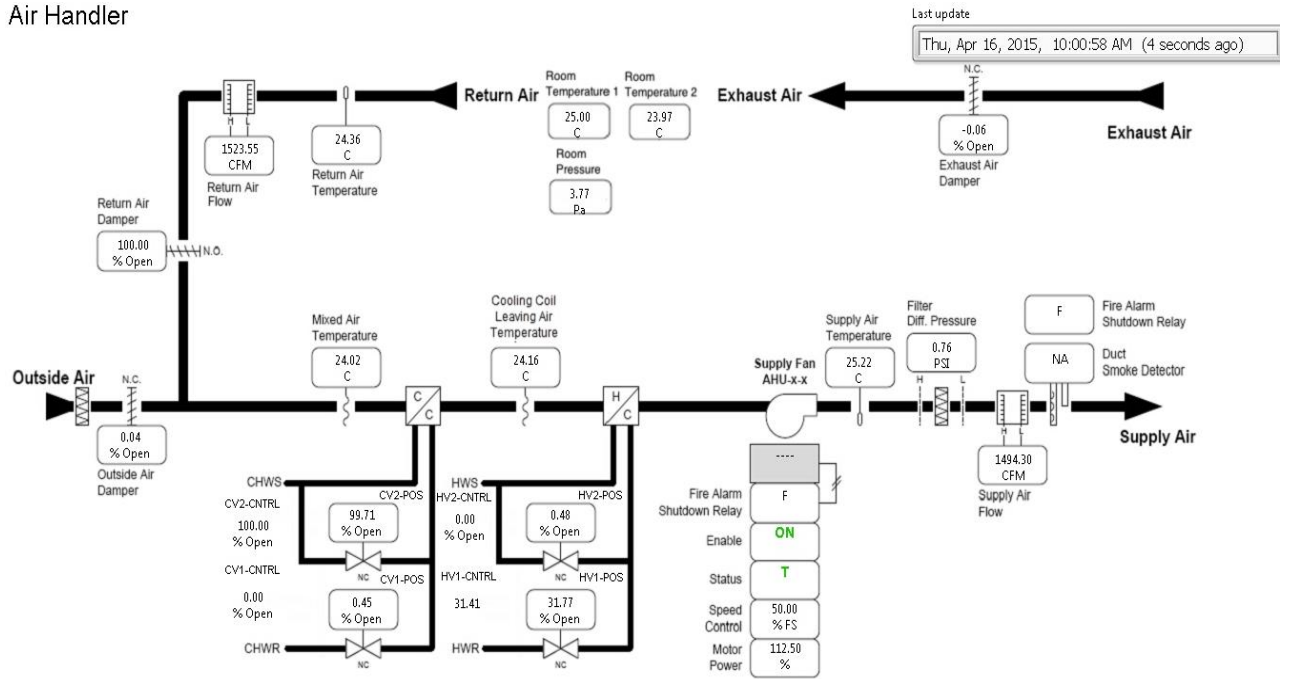


Figure-A 12. Air Loop

9.2 Appendix B – Properties of opaque envelope components

Table-B 1. Properties of materials used in FLEXLAB

| MATERIAL | ROUGHNES S | THICKNESS (M) | CONDUCTIVITY (W/M-K) | DENSITY (KG/M3) | SPECIFIC HEAT (J/KG-K) | THERMAL ABSORPT ANCE | SOLAR ABSORPT ANCE | VISIBLE ABSORPT ANCE |
|--|-----------------------|------------------------------|---------------------------------|----------------------------|---------------------------------------|-------------------------------------|-----------------------------------|-------------------------------------|
| Topping Slab 6" | Rough | 0.1524 | 1.95 | 2087 | 900 | 0.9 | 0.65 | 0.65 |
| Slab Horizontal Insulation 5" | Smooth | 0.127 | 0.035 | 265 | 1300 | 0.9 | 0.65 | 0.65 |
| HW CONCRETE 5" | Rough | 0.127 | 1.311 | 2240 | 836.8 | 0.9 | 0.7 | 0.7 |
| Metal Panel 0.0433 | Medium Smooth | 0.0011 | 62 | 7580 | 485 | 0.9 | 0.5 | 0.5 |
| Plywood 1/2", 3/4", 1.125" | Medium Smooth | 0.0127, 0.0191, 0.0286 | 0.115 | 545 | 1213 | 0.9 | 0.5 | 0.5 |
| Gypsum Board 5/8", 1/2" | Medium Smooth | 0.0159, 0.0127 | 0.16 | 801 | 837 | 0.9 | 0.69 | 0.63 |
| Cement Board 0.65" | Medium Smooth | 0.0165 | 0.597 | 1922 | 837 | 0.9 | 0.5 | 0.5 |
| SIP 7.25" | Medium Smooth | 0.1842 | 0.038 | 29 | 1210 | 0.9 | 0.5 | 0.5 |
| R20 Ins Board 4" | Medium Smooth | 0.1016 | 0.037 | 29 | 1213 | 0.9 | 0.5 | 0.5 |
| R3.8 Ins Board 3/4" | Medium Smooth | 0.0191 | 0.035 | 29 | 1213 | 0.9 | 0.5 | 0.5 |
| R13 Insulation Board 7.5" | Medium Smooth | 0.1905 | 0.039 | 48 | 1318 | 0.9 | 0.5 | 0.5 |
| Acous Tile 3/4" | Medium Smooth | 0.0191 | 0.057 | 288 | 1331 | 0.9 | 0.2 | 0.2 |
| Spray-on Insul | Rough | 0.2413 | 0.0324 | 68.71 | 1558 | 0.9 | 0.12 | 0.7 |

| MATERIAL | ROUGHNES S | THICKNESS (M) | CONDUCT TIVITY (W/M-K) | DENSITY (KG/M3) | SPECIFIC HEAT (J/KG-K) | THERMAL ABSORPT ANCE | SOLAR ABSORPT ANCE | VISIBLE ABSORPT ANCE |
|--------------------------------|-----------------------|--------------------------|---------------------------------------|---------------------------------|---------------------------------------|-------------------------------------|-----------------------------------|-------------------------------------|
| Roof Decking 1/2" | Medium Smooth | 0.0127 | 0.13 | 850 | 1300 | 0.9 | 0.12 | 0.7 |
| Polyiso 2" | Medium Smooth | 0.0508 | 0.0220 | 31.65 | 1500 | 0.9 | 0.5 | 0.5 |
| Polyiso 2.25" | Medium Smooth | 0.0572 | 0.0186 | 31.65 | 1500 | 0.1 | 0.3 | 0.3 |
| Additional Insulation 6" | Medium Rough | 0.1524 | 0.023 | 40 | 1500 | 0.9 | 0.7 | 0.7 |
| Cotton Batt 7" | Medium Smooth | 0.178 | 0.059 | 1480 | 1307 | 0.2 | 0.5 | 0.5 |

Table-B 2. Calculated Properties of Equivalent Layers **

| | | CONDUCTIVITY [W/M-K] | DENSITY [KG/M3] | SPECIFIC HEAT [J/KG-K] |
|--|----|-------------------------|--------------------|---------------------------|
| K Wall South Corner | K1 | 0.035 | 109.2 | 1276 |
| | K2 | 0.046 | 111.3 | 1278 |
| | K3 | 0.042 | 853.6 | 1300 |
| K Wall North Corner | K1 | 0.055 | 109.2 | 1276 |
| | K2 | 0.065 | 111.3 | 1278 |
| | K3 | 0.052 | 874.9 | 1312 |
| K Wall Middle Section | K1 | 0.0504 | 48.3 | 1228 |
| J Wall South Corner | K1 | 0.0465 | 105.1 | 1273 |
| | K2 | 0.096 | 873 | 1109 |
| | K3 | 0.292 | 694 | 1287 |
| J Wall North Corner | K1 | 0.0565 | 619.6 | 1010 |
| | K2 | 0.184 | 747.9 | 1599 |
| H Wall South Corner | K1 | 0.046 | 75.3 | 1250 |
| | K2 | 0.0488 | 297.9 | 1411 |
| | K3 | 0.066 | 1428.2 | 1044 |
| H Wall North Corner | K1 | 0.0503 | 107.1 | 1274 |
| | K2 | 0.0635 | 89.6 | 1261 |
| | K3 | 0.1160 | 563.7 | 968 |
| South Wall | K1 | 0.174 | 105.9 | 1312 |
| North Wall - Exterior Door Wall Section | K4 | 0.136 | 80.1 | 1314 |

| | | CONDUCTIVITY [W/M-K] | DENSITY [KG/M3] | SPECIFIC HEAT [J/KG-K] |
|--|----|-------------------------|--------------------|---------------------------|
| North Wall – Adjacent to Electrical Room | K1 | 0.2050 | 270 | 1300 |
| | K2 | 0.0418 | 72.9 | 1249 |
| North Wall – Adjacent to Mechanical Room | K5 | 0.371 | 79.4 | 230 |

** - The layer naming convention is as below:

K wall is the exterior wall on the East side of Cell B.

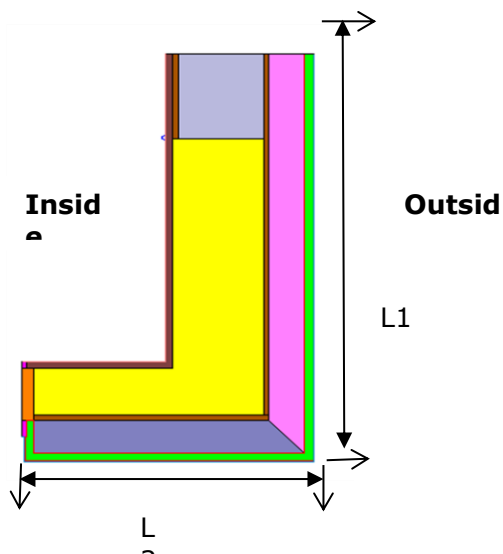
J wall is the interior wall separating Cell A and Cell B.

H wall is the interior wall between Cell A and FLEXLAB-X2.

Table-B 3. Wall section Calculated R values

| WALL SECTION | LENGTH [M] | CALCULATED U-VALUE [WATTS/M2-K] | CALCULATED R-VALUE [M2-K/WATTS] | NOTES |
|-----------------------|-------------------|--|--|--|
| K-Wall South Corner | 0.898 | 0.210 | 4.75 | K-Wall refers to East Wall. |
| K-Wall North Corner | 0.888 | 0.235 | 4.26 | K-Wall refers to East Wall. |
| K-Wall Middle Section | 2.438 | 0.133 | 7.54 | K-Wall refers to East Wall. |
| J-Wall South Corner | 0.717 | 0.256 | 3.91 | J-Wall refers to Wall between Zone A and B. |
| J-Wall North Corner | 0.706 | 0.113 | 8.86 | J-Wall refers to Wall between Zone A and B. |
| J-Wall Middle Section | 0.236 | 0.091 | 10.99 | J-Wall refers to Wall between Zone A and B. |
| H-Wall South Corner | 0.72 | 0.168 | 5.95 | H-Wall refers to Wall between Zone A and X2. |

| WALL SECTION | LENGTH [M] | CALCULATED U-VALUE [WATTS/M2-K] | CALCULATED R-VALUE [M2-K/WATTS] | NOTES |
|---------------------------|------------|---------------------------------|---------------------------------|--|
| H-Wall North Corner | 2.134 | 0.171 | 5.86 | H-Wall refers to Wall between Zone A and X2. |
| H-Wall Middle Section | 0.271 | 0.062 | 16.04 | H-Wall refers to Wall between Zone A and X2. |
| South Wall Middle Section | 0.905 | 0.439 | 2.28 | |
| North Wall (N2-N3) | 0.725 | 0.378 | 2.64 | See Drawing in sheet "North Wall Drawing". |
| North Wall (N4-N5) | 1.57 | 0.119 | 8.40 | See Drawing in sheet "North Wall Drawing". |
| North Wall (N6-N7) | 0.542 | 1.444 | 0.69 | See Drawing in sheet "North Wall Drawing". |



Total Length from the final THERM model = $L_1 + L_2 = 0.898 \text{ m}$

THERM calculated heat flow between inside and outside = 7.371 W/m

Inside/Outside $\Delta T = 39 \text{ K}$

Calculated U-value = $7.371 / [0.898 * 39] = 0.210 \text{ [W/m}^2\text{-K]}$

Figure-B 1. K-Wall South Corner U-value Calculation

9.3 Appendix C - Modeling of Envelope Components with Two- and Three-dimensional Heat Flows

9.3.1 Process of modeling of envelope components with two- and three-dimensional heat flows

9.3.1.1 Two-dimensional component modeling

Converting a two-dimensional to one-dimensional heat flow is done in multiple steps, which are listed below:

1. Use THERM software to create a detail model of each wall section from detail architectural drawing.
2. Calculate the heat flow through the modeled section using THERM.
3. Step-by-step, replace sections of the model with uniform layers and set the conductivity of the newly created equivalent layers such that the heat-flow through the model stays the same as the original model (step 2 above). The conductivity of the equivalent layer is therefore calculated in this step.
4. Calculate the density and specific heat of each equivalent layer by calculating the area weighted average of the original section that the layer is replacing.

See Figures C-1 to C-3 for an example of two-dimensional component modeling for the south-east corner of Cell B, without the additional insulation on the east wall. All components used in this section are shown in Figure C-2. The full model, drawn in THERM, is shown in Figure C-3.

9.3.1.2 Three-dimensional component modeling

Converting a three-dimensional, thermal bridging component to one-dimensional is more complicated. Thermal bridging is usually caused by structural components, combined with discontinuities in thermal insulation. It can be easily identified in places where highly conducting components are passing through the exterior thermal insulation in multi-layer wall assemblies. Thermal bridges provide a path of higher conduction through the insulation, allowing for more heat to bypass the building thermal barrier. These thermal pathways often have strong multi-dimensional characteristics. Using the THERM software, which is part of the WINDOW software suite developed by LBNL, the heat-flow is calculated in both vertical and horizontal paths and then combined to calculate the one-dimensional equivalent heat flow. The multi-layer thermal bridging layers are then replaced by a single equivalent layer which produces the same heat flow. The methodology to create an equivalent layer using THERM and then calculate the effective U-value is as follows:

1. Calculate the horizontal heat-flow for left, right, and middle section of the wall (3 values).
2. Calculate the vertical heat-flow for top and bottom of the wall section (2 values).
3. Combine the 5 U-values to produce the overall equivalent U-value.
4. Using THERM, define a new material with the U-value calculated in step 3.

The calculation of equivalent U-value from horizontal and vertical U-values is described in Curcija (2012). Figure C-4 shows the sections of the wall for which U-values were calculated.

9.3.1.3 Conductivity of the equivalent layers

The conductivity of the equivalent layer is calculated by THERM software, when multiple layers are replaced by a single layer.

9.3.1.4 Density and Specific Heat of the equivalent layers

The density and the specific heat of the equivalent layer are the area weighted averages for all the layers that the equivalent layer is replacing. The following is an example of calculation for an equivalent layer, replacing layers of wood, R20, R4.2, and Aerogel insulation, Plywood, Air, and Steel, with different thicknesses:

Wood

Density = 559 [Kg/m³]
 Specific Heat = 1630 [J/Kg-K]
 Area = 259.12 [inch²]

R20 Insulation

Density = 29 [Kg/m³]
 Specific Heat = 1213 [J/Kg-K]
 Area = 80.8 [inch²]

R4.2 Insulation

Density = 48 [Kg/m³]
 Specific Heat = 1318 [J/Kg-K]
 Area = 69.77 [inch²]

Aerogel

Density = 150 [Kg/m³]
 Specific Heat = 840 [J/Kg-K]
 Area = 2.9 [inch²]

Plywood

Density = 545 [Kg/m³]
 Specific Heat = 1213 [J/Kg-K]
 Area = 8.67 [inch²]

Air

Density = 1 [Kg/m³]
 Specific Heat = 1 [J/Kg-K]
 Area = 31.69 [inch²]

Steel

Density = 7580 [Kg/m³]
 Specific Heat = 485

$$\begin{aligned} \text{Density of Equivalent Layer K3} &= [(259.12 \times 559) + (80.8 \times 29) + (69.77 \times 48) + \\ &\quad (2.9 \times 150) + (8.67 \times 545) + (31.69 \times 1) + \\ &\quad (35.5 \times 7580)] / \\ &\quad (259.12 + 80.8 + 69.77 + 2.9 + 8.67 + 31.69 + 35.5) \\ &= 869.9 \text{ [Kg/m}^3\text{]} \end{aligned}$$

Specific Heat of Equivalent Layer K3 = [(259.12*1630) + (80.8* 1213) + (69.77*1318) + (2.9*840) + (8.67*1213) + (31.69*1) + (35.5*485)] / (259.12+80.8+69.77+2.9+8.67+31.69+35.5) = 1315.4 [J/Kg-K]

Figure-C 1 shows the architectural drawing of Cell A south-west corner detail. (The south-east corner of Cell 3B is a mirror image, reflected about the N-S axis. and also includes 6" of polyisocyanurate insulation and 0.5" of gypsum wall board on the east wall.)

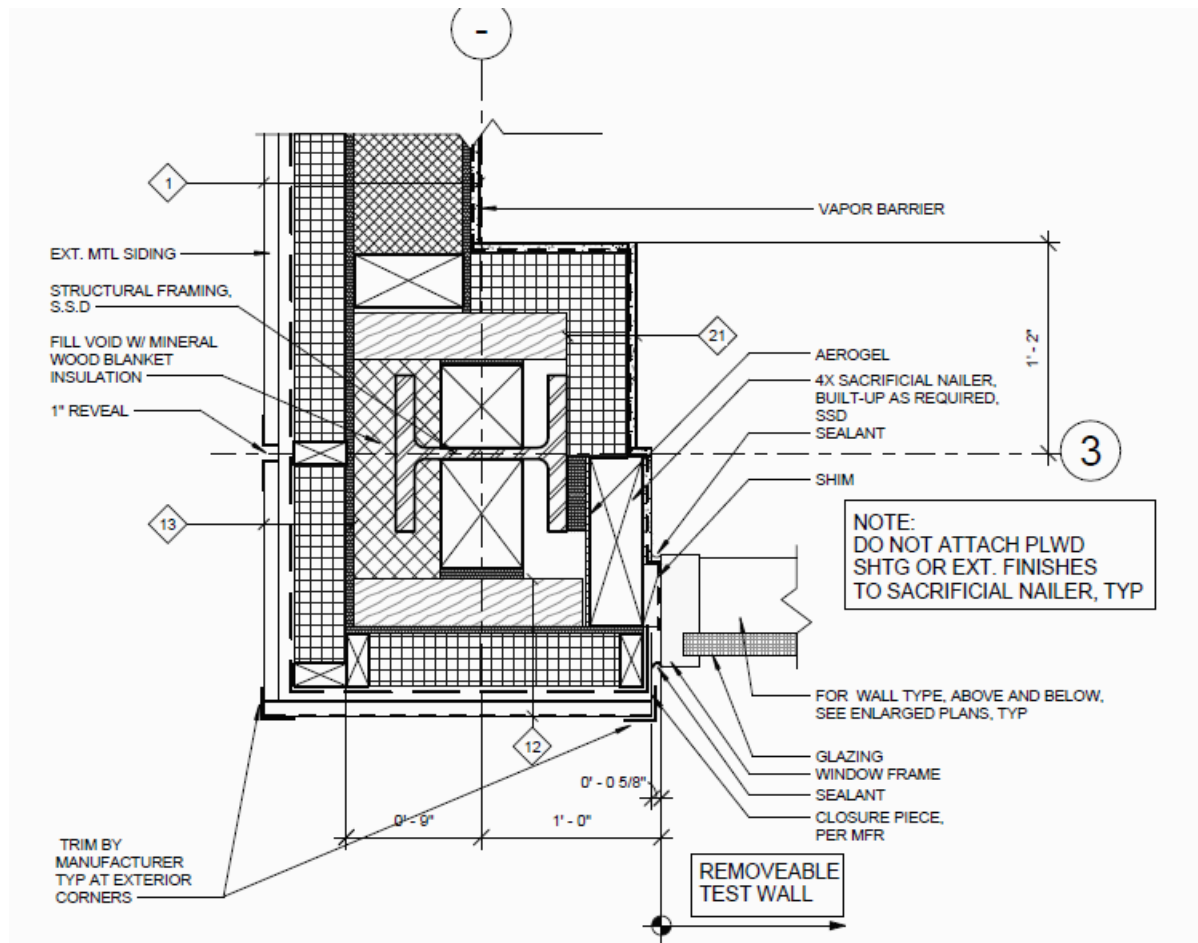


Figure-C 1. Architectural drawing of Cell A South-West corner detail

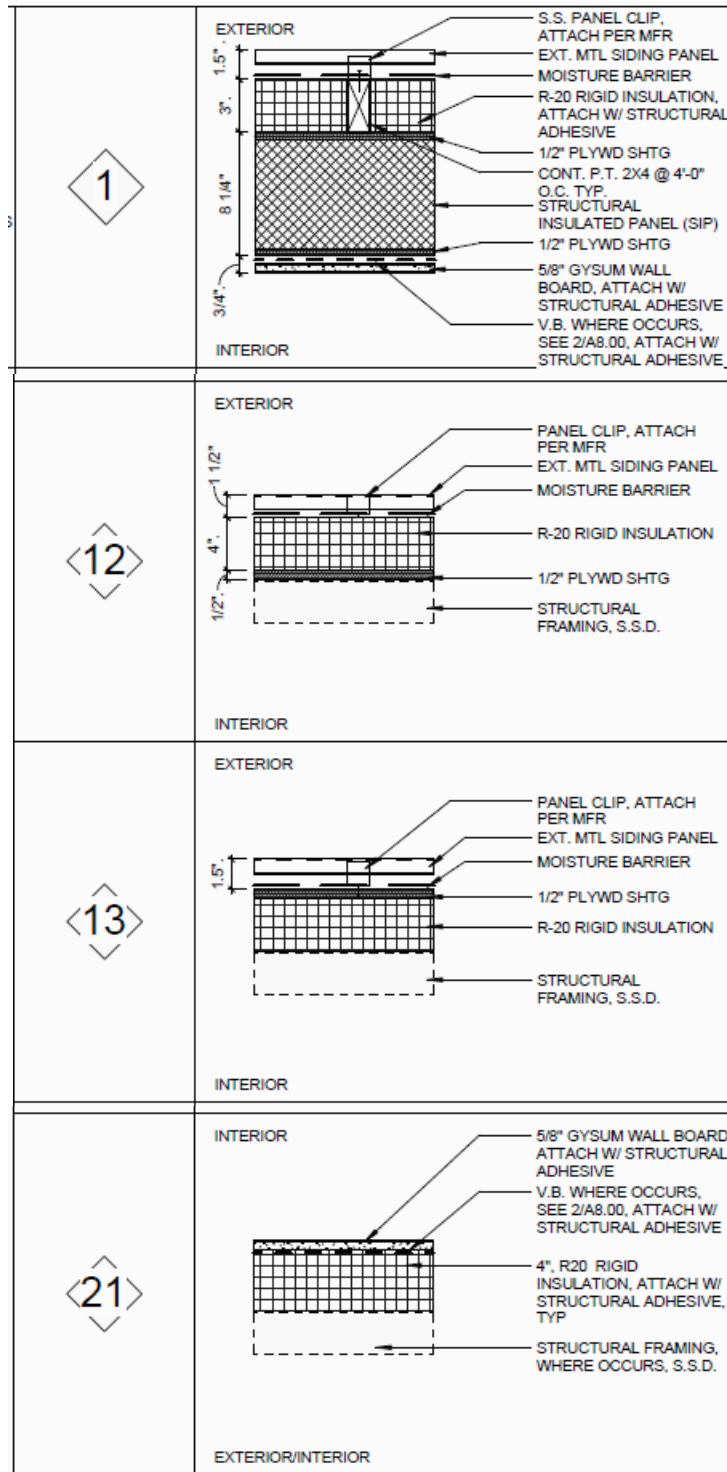


Figure-C 2. Detail Architectural Drawing of the Wall Section Referred to in Figure-C 1

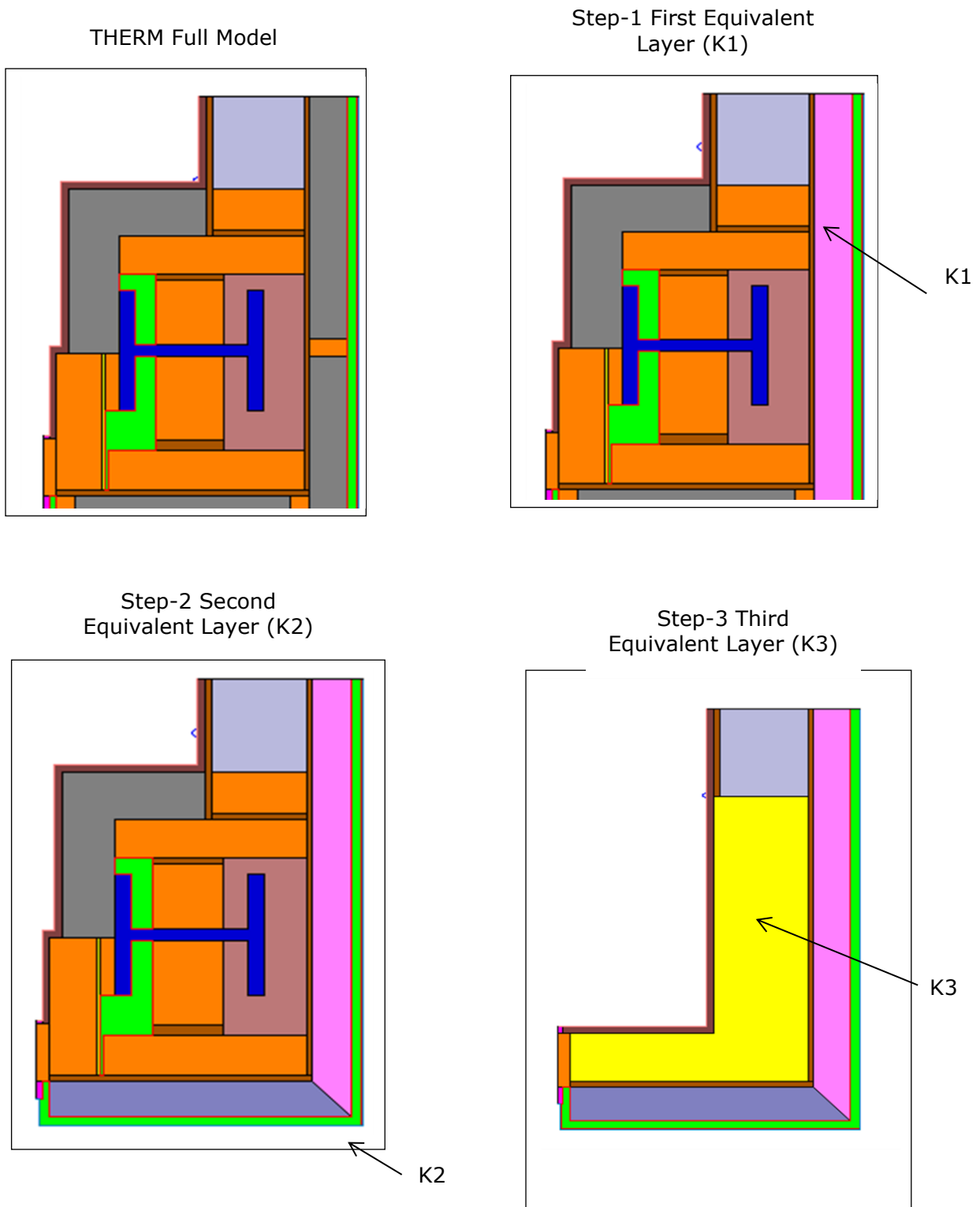
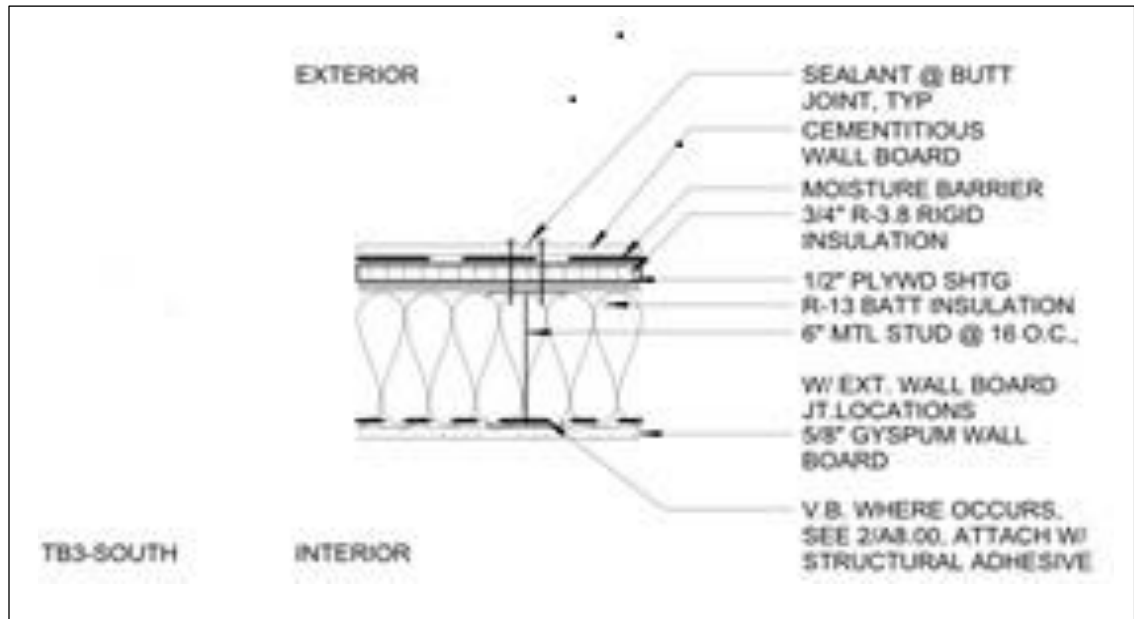
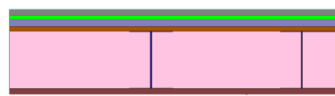


Figure-C 3. FLEXLAB-X3 South-East Corner Wall - steps in creating the equivalent layers for the two-dimensional heat flow paths



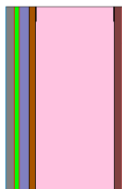
Horizontal Left Section



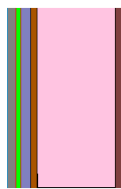
Horizontal Right Section



Horizontal Middle Section



Vertical Top Section



Vertical Bottom Section



Equivalent Layer K1

Figure C-3. The resulting 1-D layers

9.4 Appendix D - Window Modeling

9.4.1 Creating window input for EnergyPlus and DOE-2 using WINDOW 7.4

The following steps were used to calculate the properties of the glazing systems in both EnergyPlus and DOE-2:

1. Chose a single layer from the WINDOW glass library. The properties of this layer closely matched the properties of the laminate glass used in FLEXLAB.
2. Created a new layer in the WINDOW glass library. The properties of this layer matched those of the temporary insulation used in FLEXLAB to cover the windows for particular tests.
3. Created a new layer in the WINDOW glass library. The properties of this layer matched those of the frame used in FLEXLAB.
4. Created a glazing system with a single layer, using the layer in #1. The construction of this glazing system was used as the exposed window construction.
5. Created a glazing system with double-layers, with the laminate layer in #1 as the outer layer and the insulation layer in #2 as the inner layer, separated by a 5 cm (2 in) gap. The construction of this glazing system was used as the insulated window construction.
6. Created glazing system with a single-layer, using the layer in #3. The construction of this glazing system was used as the exposed frame construction.
7. Created a glazing system with double layers, with the frame layer in #3 as the outer layer and the insulation layer in #2 as the inner layer, separated by a 5 cm (2 in) gap. The construction of this glazing system was used as the insulated frame construction.
8. Added four Windows, with glazing systems created in steps 4 through 7, above, to the WINDOW 7.4 window library and calculated the center-of-glazing thermal properties (U-value, SC, SHGC) for each window.
9. Produced a WINDOW-generated DOE-2 report for the windows in step #8. The reports are text files that are used in the DOE-2 input file.

The WINDOW calculated properties are shown in Tables D-1 through D-7.

1. EnergyPlus Window Input

Layer-by-layer average properties were calculated using the WINDOW program. In early versions of the input file, the layers were defined using bidirectional scattering distribution function (BSDF) data and then with wavelength-specific data for multiple spectral bands. Comparison of the annual cooling and heating predictions showed very little difference between the three methods, for the type of window used in FLEXLAB. The spectral average method was therefore used to characterize the glazing layers.

2. DOE-2 Window Input

DOE-2.1E and DOE-2.2 use different methods of reading in window properties, using the report files generated in #9.

2.a – DOE-2.1E

1. Find the file w4lib.dat in the Data folder, where DOE-2.1E is installed.
2. Paste the WINDOW DOE-2.1 output report (#9) at the end of file W4lib.dat.
3. Copy the file W4lib.tmp to the root library where the DOE-2 input file is located.
4. When creating windows in DOE-2, assign the glazing ID that was chosen when creating these windows in WINDOW to G-T-C (For example, G-T-C = 1900). This ID number is found in the DOE-2 report file, generated by the WINDOW program. The DOE-2 program first looks for glazing with the appropriate ID number (e.g., 1900) in DOE-2 window library. If it can't find it, it looks in W4lib.dat.

2.b - DOE-2.2

DOE-2.2 does not use the file W4lib.dat. If eQUEST is used to make the DOE-2.2 runs, the DOE-2 reports generated by WINDOW can be imported into the eQUEST window library and then assigned to the window. **A word of caution: the latest version of WINDOW (7.4) uses a different header for the DOE-2 output file which causes eQUEST to crash. eQUEST can only import a DOE-2 report from Window 4 or Window 5. The header needs to be manually changed to match the WINDOW 4/5 header.** Below is an example:

- a. WINDOW 4/5 header
Window 5.2 v5.2.12 DOE-2 Data File : Multi Band Calculation
- b. WINDOW 7.4 header
BERKELEY LAB WINDOW v7.4.8.0 DOE-2 Data File : Multi Band Calculation

• If DOE-2.2 runs are done outside of eQUEST, the following steps have to be taken to import the WINDOW-generated DOE-2 report into the input file:

- a. Generate the WINDOW program DOE-2 report file, in the same way as was done for DOE-2.1E.
- b. Put the DOE-2 report file in the folder Document\equest 3-65 Data\Window. (It is the Window folder under the root folder where eQUEST is installed.)
- c. In eQUEST, open a fresh (default) eQUEST model, go into detail mode and Save it.
- d. Go to Tools and select the Import Window4/5 Report File option.
- e. Find your DOE-2 report file and import it.
- f. Assign the new glazing to a window in your model.
- g. Save the default eQUEST file.
- h. Go into resulting .inp file, created by eQUEST (#7 above), copy the relevant glazing data section and paste it into the DOE-2.2 input file. The following is a sample of DOE-2.2 window section with the pasted glazing data:

- "FlexlabLaminateWindow" = GLASS-TYPE-CODE
DESCRIPTION = *FlexlabLaminateWindow*
NLAYER = 1
TSOL = (0.735, 0.734, 0.732, 0.726, 0.715, 0.693, 0.648,
0.547, 0.329, 0, 0.656)
TVIS = (0.886, 0.886, 0.885, 0.882, 0.874, 0.855, 0.807,
0.69,
0.429, 0, 0.808)
ABS-1 = (0.194, 0.182, 0.185, 0.189, 0.195, 0.201, 0.206,
0.205, 0.183, 0, 0.193)
RBSOL-HEMI = 0.14
RBVIS-HEMI = 0.144
SHDCOF = 0.81
PANES-TIR = (0, 0, 0, 0, 0)
PANES-EMIS-F = (0.84, 0, 0, 0, 0)
PANES-EMIS-B = (0.84, 0, 0, 0, 0)
PANES-THICK = (5.8, 0, 0, 0, 0)
PANES-COND = (108.5, 0, 0, 0, 0)
FILMS-COND = (30.84, 3.29, 7.25)
U-CENTER = 5.67
PANES-ID = (1808, 0, 0, 0, 0)

..

Table-D 1. FLEXLAB Laminated Glass properties

| Thickness meters [INCH] | TSOL | RSOL _F | RSOL _B | TVIS | RVIS _F | RVIS _B | TIR | EMIS _F | EMIS _B | Cond W/m-K (BTU/HR-FT-F) |
|-------------------------------|-------|-------------------|-------------------|-------|-------------------|-------------------|-----|-------------------|-------------------|--------------------------------|
| 0.0058 [0.227] | 0.735 | 0.07 | 0.07 | 0.886 | 0.08 | 0.08 | 0 | 0.84 | 0.84 | 0.625 [0.361] |

Table-D 2. FLEXLAB Insulation Layer properties

| Thickness meters [INCH] | TSOL | RSOL _F | RSOL _B | TVIS | RVIS _F | RVIS _B | TIR | EMIS _F | EMIS _B | Cond W/m-K (BTU/HR-FT-F) |
|-------------------------------|------|-------------------|-------------------|------|-------------------|-------------------|-----|-------------------|-------------------|--------------------------------|
| 0.0508 [2] | 0.0 | 0.84 | 0.84 | 0.0 | 0.84 | 0.84 | 0 | 0.84 | 0.84 | 0.022 [0.013] |

Table-D 3. FLEXLAB Frame Layer properties

| Thickness meters [INCH] | TSOL | RSOL_F | RSOL_B | Tvis | Rvis_F | Rvis_B | TIR | EMIS_F | EMIS_B | Cond W/m-K (BTU/HR-FT-F) |
|--|-------------|-------------------------|-------------------------|-------------|-------------------------|-------------------------|------------|-------------------------|-------------------------|---|
| 0.064 [2.5] | 0.0 | 0.84 | 0.84 | 0.0 | 0.84 | 0.84 | 0 | 0.84 | 0.84 | 88.75 [51.279] |

Table-D 4. FLEXLAB Laminated Window Center of glazing properties

| Thickness meters [INCH] | U-value W/m2-k (BTU/HR-F2-F) | SC | SHG C | Tvis |
|--|---|-----------|------------------|-------------|
| 0.0058 [0.227] | 5.512 [0.971] | 0.912 | 0.793 | 0.886 |

Table-D 5. FLEXLAB Insulated Window Center of Glazing properties

| Thickness meters [INCH] | U-value W/m2-k (BTU/HR-F2-F) | SC | SHG C | Tvis |
|--|---|-----------|------------------|-------------|
| 0.107 [4.227] | 0.364 [0.064] | 0.081 | 0.071 | 0.0 |

Table-D 6. FLEXLAB Frame Window Center of Glazing properties

| Thickness meters [INCH] | U-value W/m2-k (BTU/HR-F2-F) | SC | SHG C | Tvis |
|--|---|-----------|------------------|-------------|
| 0.064 [2.5] | 5.7 [1.019] | 0.053 | 0.046 | 0.0 |

Table-D 7. FLEXLAB Insulated Frame Center of Glazing properties

| Thickness meters [INCH] | U-value W/m2-k (BTU/HR-F2-F) | SC | SHG C | Tvis |
|--|---|-----------|------------------|-------------|
| 0.164 [6.49] | 0.365 [0.064] | 0.003 | 0.003 | 0.0 |

Table-D 8. DOE-2 Shading Schedule Conductance and Shading Coefficient Multipliers

| GLAZING | SHADING SCHEDULE CONDUCTANCE MULTIPLIER | SHADING SCHEDULE SHADING COEFFICIENT MULTIPLIER |
|----------------|--|--|
| Laminate | 0.066 | 0.089 |
| Frame | 0.064 | 0.056 |

9.5 Appendix E – Modeling Opaque Envelope Components with Moveable Insulation

9.5.1 Doors

9.5.1.1 Door Specifications

There are three doors in each FLEXLAB cell, located as shown in Figure-E 1:

- Exterior door to the North Zone
- Exterior door to the Electrical Room
- Interior Door between the North Zone and the Mechanical Room

The exterior and the interior doors to the zones are thermally insulated hollow steel doors, filled with polyurethane. They have thermally broken steel frames.

The exterior door to the mechanical room is a hollow steel door with a steel frame. There are steel stiffeners placed 6" apart along the length; there is fiberglass insulation along the seam edges. However, since this door opens to an unconditioned space, the insulation was ignored and the door modeled as a hollow steel door. Figure E-2a is from the architectural drawings which display the door types.

9.5.1.2 Frames Specifications

The frames are hollow metal frames. The frames on the doors to the zone, both exterior and interior, are thermally broken, while the frame used with the exterior door to the electrical room is a regular, non-thermally broken frame. Figure E-2b is the architectural drawing of the frame. Figures E-2c and E-1d are from the manufacturers data sheet and show the detail of the thermally broken frame.

Table–E1 displays the properties of the doors and frames.

9.5.1.3 Modeling the Doors

EnergyPlus modeling of doors is very simple and does not consider thermal mass and the effect of door frames. In FLEXLAB, doors are metal and some are thermally insulated. Frames are also thermally broken in the doors that open to the zones. In order to capture these effects, the doors were modeled as (opaque) glazings with frames. Window 7.4 and THERM 7.3 were used to create models of the frames, the door and the whole door including frames. The properties of the whole door were calculated using WINDOW and an EnergyPlus report was created that is included in the EnergyPlus input file. The following procedure was used to model doors:

1. Create the frame model in THERM.
2. Create the door as a glazing system in WINDOW.
3. In THERM, add the door created in WINDOW to the frame.
4. Import the frame from THERM into Window.
5. In Window, create the whole door by adding the frames to the glazing system.
6. Calculate the properties of the whole door in Window.
7. Create an EnergyPlus report in Window, which is added to EnergyPlus input file.

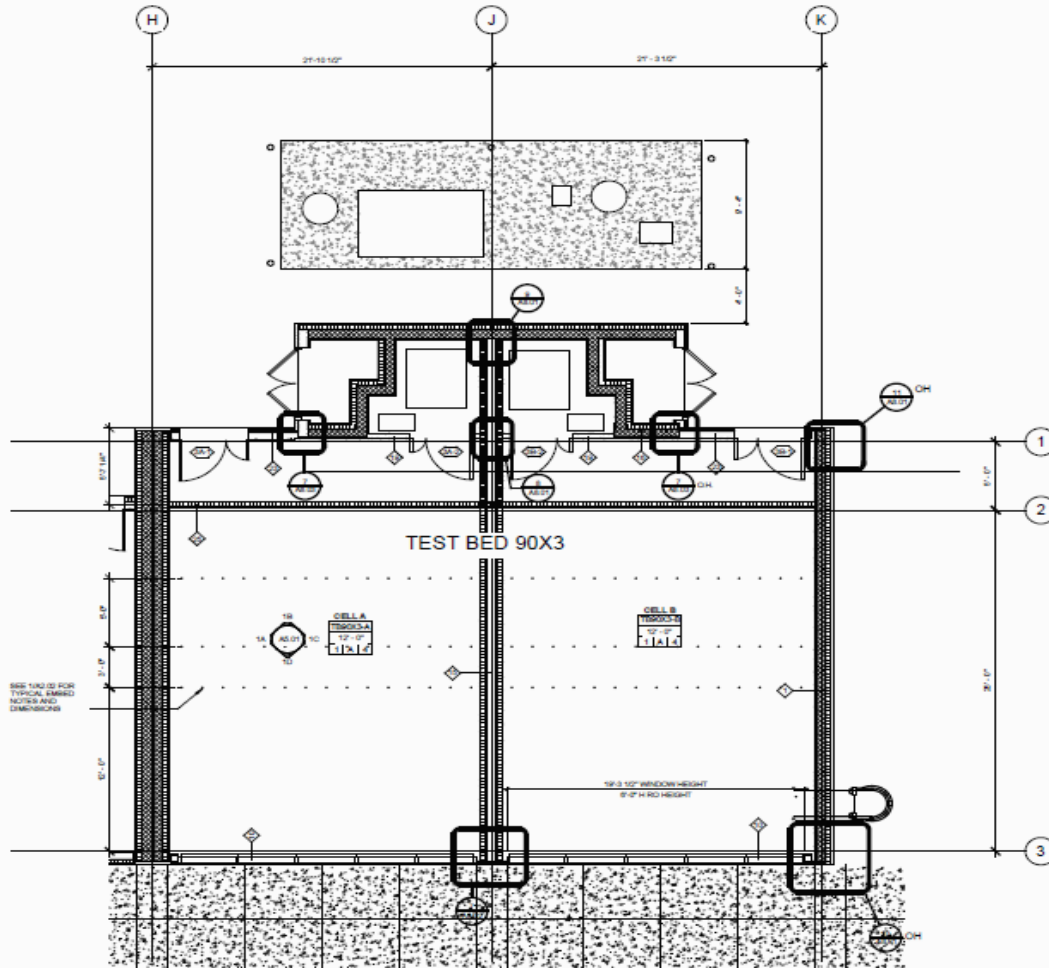


Figure-E 1. Schematic Drawing of Flexlab-X3

DOOR TYPES

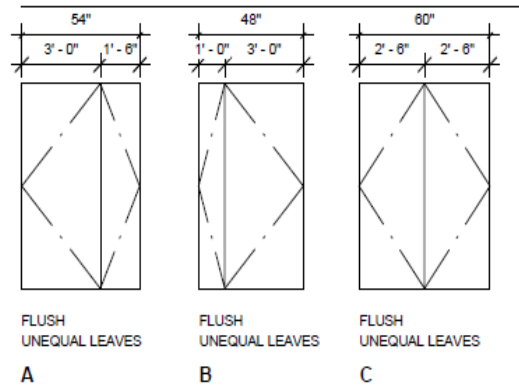


Figure-E 2a. Door Types

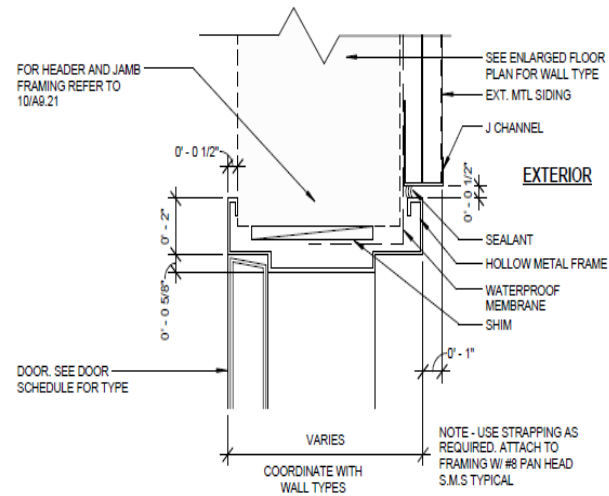


Figure-E 2b. Architectural Drawing of the frame

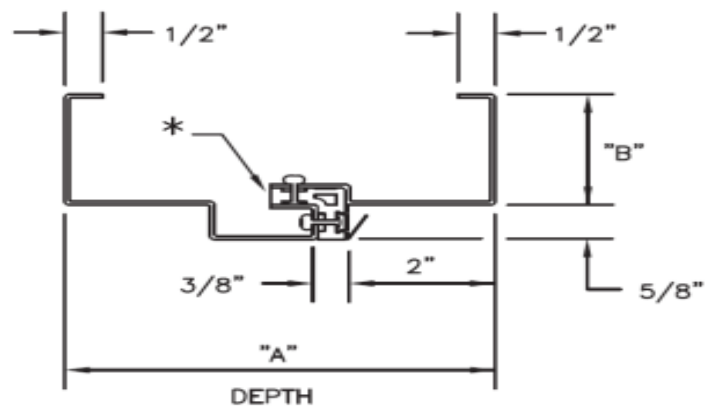


Figure-E 2c. Thermally broken metal frame from manufacturer's data sheet



Figure-E 2d. Detail drawing of the thermally broken metal frame

Table-E 1. FLEXLAB Doors

| OPENINGS | | | FRAMES | | | | | DOORS | | | |
|-----------------------------|----------|----------------|------------------|---------------------|------------------|------|----------|------------------|---------------------|-----------------|-----------------|
| LOCATION | TYPE | SIZE | TYPE | MATERIAL | PROFILE | JAMB | HEADFACE | TYPE | MATERIAL | SERIES | TYPE |
| Exterior to Zone | Exterior | 4' 6" x 7' 10" | HMF ¹ | A60-14 ³ | SQT ⁶ | 2" | 2" | HMD ² | A60-16 | HE ⁸ | A ¹⁰ |
| Zone to Mechanical Room | Interior | 4' 0" x 7' 10" | HMF | A60-16 ⁴ | SQT | 2" | 2" | HMD | CRS-16 ⁵ | HE | B ¹¹ |
| Exterior to Electrical Room | Exterior | 5' 0" x 7' 10" | HMF | A60-14 | SQ ⁷ | 2" | 2" | HMD | A60-16 | MS ⁹ | C ¹² |

Key

1-HMF, hollow metal frame

2-HMD, hollow metal door

3- A60-14, galvanized steel, 14 gauge

4- A60-16, galvanized steel, 16 gauge

5- CRS-16, rolled steel, 14 gauge

6- SQT, thermally broken frame

7- SQ, Non-thermally-broken frame

8- HE, hollow metal door, filled with polyurethane insulation

9- Hollow metal door

10, 11, 12 – See Figure E-2a for door types

9.6 Appendix F - Running EnergyPlus, DOE-2.1e and DOE-2.2

The EnergyPlus and DOE-2 input files were parameterized to allow different cell configurations to be selected during a single long run. For example, window insulation could be added or removed, based on a schedule.) The exception to this flexibility was high-mass vs. low-mass, since only purely resistive components, such as insulation, can be added or removed without changing the stored thermal energy. Different simulation runs, each with their own warm-up, are required when transitioning between high-mass and low-mass.

9.6.1.1 EnergyPlus parametric run procedure

The EnergyPlus Runs Folder Structure is shown in Figure-F 1.

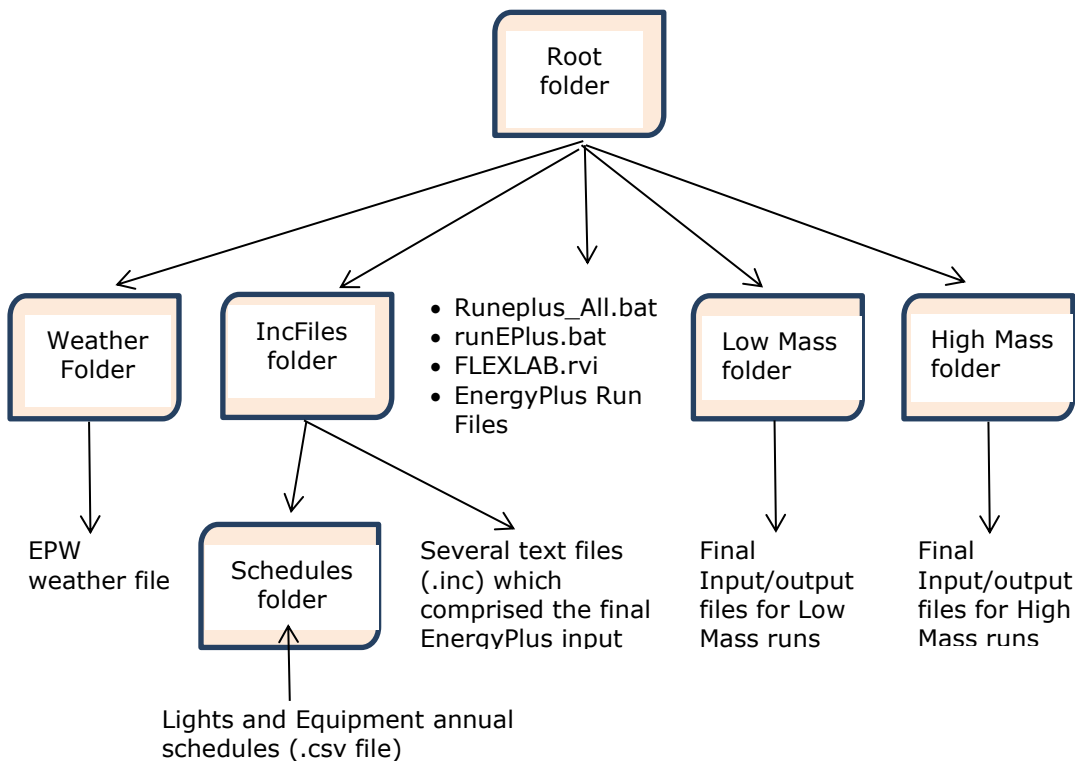


Figure-F 1. EnergyPlus Runs Folder Structure

The EnergyPlus runs were performed by executing a DOS batch file, "Runeplus_All.bat". This file executes a second batch file "runEPlus.bat" and provides input for the run options.

The file "runEPlus.bat" performs the following steps:

1. Takes input from the file "Runeplus_All.bat".
2. Creates the EnergyPlus imf file. This file includes Input Macros.
3. Runs EPMacro.exe file to create the final idf file.
4. Runs EnergyPlus.
5. Runs ReadVarseso.exe to create the hourly results.

6. Renames the generic EnergyPlus output file with an appropriate name for the run and copies the Input/Output files into the appropriate folder for better organization.

9.6.1.2 Description of the folders and files

RootDir folder - includes the following folders and file:

- **Runeplus_All.bat file:** Executes another batch file, "runEPlus.bat", and feeds input variables to this file. The user edits this file to make different EnergyPlus runs.
- **RunEPlus.bat file:** Creates the EnergyPlus macro file from user input (.imf), runs EPMacro on the imf file to create the final EnergyPlus input file (.idf), runs EnergyPlus by executing the EnergyPlus.exe, runs ReadVarsESO.exe file to create the hourly data from user selected variables, renames the input/output files to the appropriate names, and copies input/output files to the appropriate folders.
- **IncFiles folder:** Includes the main body of the input file, the location include file, and the schedules folder.
- **Weather folder:** Includes the FLEXLAB-measured weather data (EPW file).
- **Low-Mass folder:** Includes the final input/output of the low-mass runs.
- **High-Mass folder:** Includes the final input/output of the high-mass runs.
- **FLEXLAB.rvi file:** Contains the names of the hourly report variables. This file is read by ErasVarsESO.exe file to create the hourly output file.

The following files are needed to make and run Energyplus (exe, dll, idd):

- **IncFiles folder (#3 above):** Includes the following files and folders.
- **EnergyPlus-FLEXLAB-X3-2017.inc:** Main body of the idf file.
- **General.inc:** A section of idf that most likely not changed in each run, contains general run information.
- **ParamCalc.inc:** Performs calculation on some input variables.
- **Berkeley.inc:** Location section of the idf file.
- **Schedules folder:** Contains the annual FLEXLAB-measured heating/cooling set-points, lighting, and plug load schedules, used in the EnergyPlus run.

9.6.1.3 Sample file listing

"Runeplus_All.bat" sample file to run for Low-mass case.

```
Rem ----- runEPlus.bat -----
Rem ***** Low Mass 2017 *****

call runeplus.bat Berkeley LowMass berkeley_FLEXLAB_weather_2017_12142017 Eplus-FLEXLAB-X3-
2017 EplusSched_2017TillSep22_10min_COR

Rem ***** High Mass 2017 *****

Rem call runeplus.bat Berkeley HighMass berkeley_FLEXLAB_weather_2017_12142017 Eplus-FLEXLAB-
X3-2017 EplusSched_2017TillSep22_10min_COR
```

Runeplus.bat sample file.

```
rem runEPlus.bat

SET yTempNwall_FT=5.6
SET Infile=%4

SET Loc=%1
SET Mass=%2

CD IncFiles

copy Schedules\%5.csv ..\input_file_Hourly.csv

IF %2 == LowMass echo ##set1 SlabConst_ID 3 > UserInput.txt
IF %2 == HighMass echo ##set1 SlabConst_ID 1 > UserInput.txt

echo ##set1 yTempNwall_FT 5.6 >> UserInput.txt
echo ##set1 RunType %2 >> UserInput.txt

copy UserInput.txt + ParamCalc.inc + General.inc + %Loc%.inc + %4.inc ..\in.imf

CD ..
rem pause

EPMacro.Exe

COPY in.imf %2\%2_%4.imf
COPY out.idf in.idf
COPY out.idf %2\%2_%4.idf
DEL epl*.csv
DEL in.*
DEL *.end
DEL *.imf
DEL *.audit
DEL *.mtd
DEL *.shd
DEL *.mdd
DEL *.mtr
rem DEL *.rdd
DEL *.dxf
DEL *.bnd
```

```
DEL *.eso
DEL *.err
DEL *.audit
DEL *.out
DEL *.eio
DEL *.log
DEL out.idf
DEL in.imf
DEL *.ini
DEL *.htm

: End
```

The following is the description of each command:

- *set yTempNwall_FT=5.6*

Set the variable "yTempNwall" to 5.6. This is the distance of the from North wall to the temporary wall.

- *set Infile=%4*

Set the variable "Infile" to "plus-FLEXLAB-X3-2017".

- *set Loc=%1*

Set the variable "Loc" to "Berkeley".

- *set ExpDate=%2*

Set the variable "Mass" to "LowMass".

- *cd IncFiles*

Change folder to "IncFiles" folder.

- *copy Schedules\%5.csv .\input_file_Hourly.csv*

Copy the file "EplusSched_2017TillSep22_10min_COR" in Schedule folder to the RootDir file "input_file_Hourly.csv".

- *IF %2 == LowMass echo ##set1 SlabConst_ID 3 > UserInput.txt*

If second input is equal to "LowMass", write "##set1 SlabConst_ID 3" to the file UserInput.txt.

- *IF %2 == HighMass echo ##set1 SlabConst_ID 1 > UserInput.txt*

If second input is equal to "HighMass", write "##set1 SlabConst_ID 1" to the file UserInput.txt.

- *echo ##set1 yTempNwall_FT 5.6 >> UserInput.txt. >> UserInput.txt*

Write "##set1 yTempNwall_FT 5.6" to the file UserInput.txt.

- *echo ##set1 RunType %2 >> UserInput.txt*

Write "##set1 RunType LowMass" to the file UserInput.txt.

- *copy UserInput.txt + ParamCalc.inc + General.inc + %Loc%.inc + %4.inc ..\in.imf*

Concatenate the files UserInput.txt, ParamCalc.inc, General.inc Berkeley.inc, and plus-FLEXLAB-X3-2017 into the file "in.imf" in RootDir.

- *CD ..*

Change foldet to RoodDir (move one folder up).

- *EPMacro.Exe*

Run EpMacro.

- *COPY in.imf %2\%2_%4.imf*

Copy the file "In.imf" to the RootDir\LowMass\LowMass_ EnergyPlus-FLEXLAB-X3-2017.imf.

- *COPY out.idf in.idf*

- *COPY out.idf %2\%2_%4.idf*

Copy the file "out.idf" to LowMass\LowMass_ EnergyPlus-FLEXLAB-X3-2017.idf.

- *Copy Weather\%3.EPW In.EPW*

Copy the file "berkeley_FLEXLAB_weather_2017_12142017" from the folder rootdir\Weather folder to the file rootdir\in.EPW.

- *EnergyPlus.exe*

Run EnergyPlus.exe.

- *Copy eplusout.err %2\%2_%4.err*

Copy the file "eplusout.err" to "LowMass\LowMass_ EnergyPlus-FLEXLAB-X3-2017.err".

- *Copy eplustbl.csv %2\%2_%4_Table.csv*

Copy the file "eplusout.csv" to "LowMass\LowMass_ EnergyPlus-FLEXLAB-X3-2017_Table.csv.err".

- *ReadVarsESO.exe FLEXLAB.rvi*

Run the program ReadVarESO.exe with the input file "FLEXLAB.rvi".

- *Copy eplusout.csv %2\%2_%4.csv*

Copy the file eplusout.csv to "LowMass\LowMassEnergyPlus-FLEXLAB-X3-2017_.csv".

- *DEL epl/*.csv*
- *DEL in.**
- *DEL *.end*
- *DEL *.imf*
- *DEL *.audit*
- *DEL *.mtd*
- *DEL *.shd*
- *DEL *.mdd*

- *DEL *.mtr*
- *DEL *.rdd*
- *DEL *.dxf *.TMP*
- *DEL *.bnd*
- *DEL *.eso*
- *DEL *.err*
- *DEL *.audit*
- *DEL *.out*
- *DEL *.eio*
- *DEL *.log*
- *DEL out.idf*
- *DEL in.imf*
- *DEL *.ini*
- *DEL *.htm*
-

: End

Delete all the files that are no longer needed

9.6.2 DOE-2 Parametric Run Procedure

The DOE-2.2 Runs Folder Structure is shown in Figure-E 4.

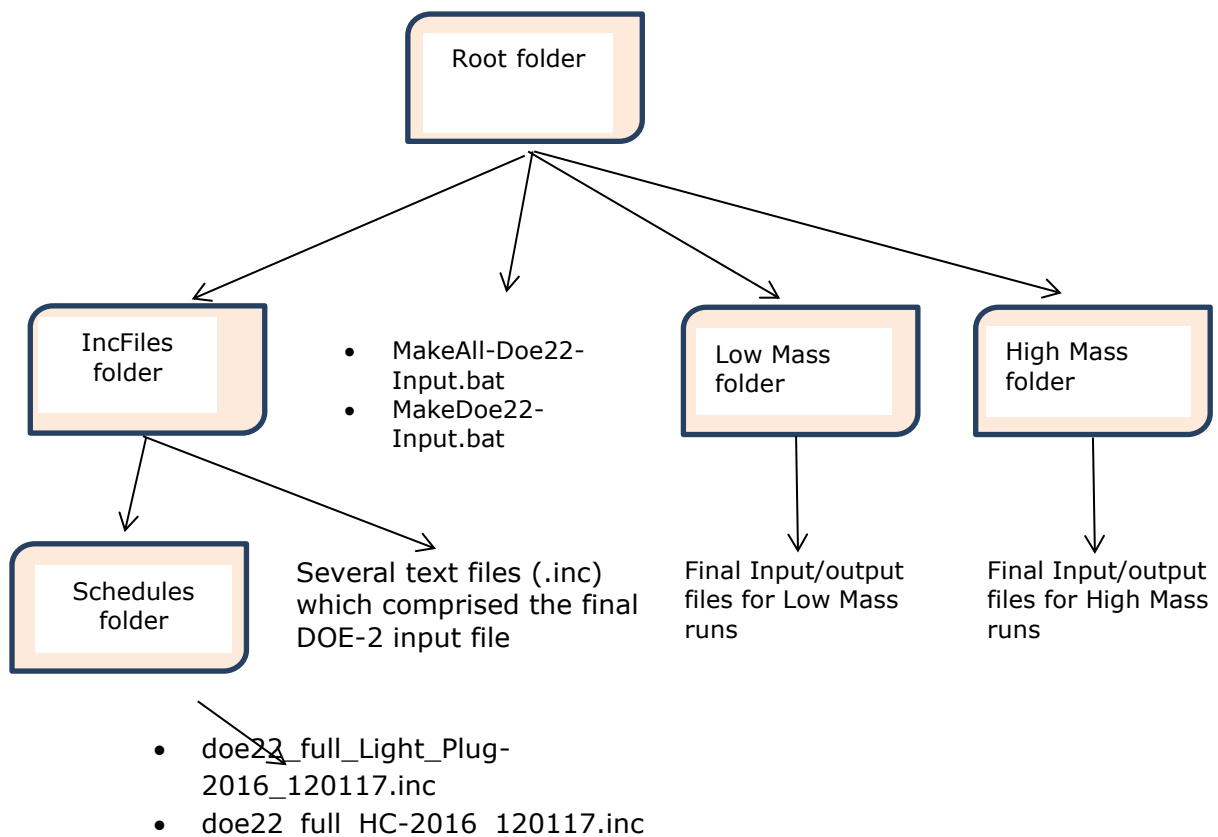


Figure-E 4. DOE-2.2 Runs Folder Structure

The DOE-2 input file is created by executing a DOS batch file "MakeAll-Doe22-Input.bat". This file executes a second batch file, "MakeDoe22-Input.bat", and provides input for the run options.

The file MakeDoe22-Input.bat does the following:

1. Takes input from MakeAll-Doe22-Input.bat file.
2. Creates the .inp file, needed to make DOE-2 runs.
3. When the DOE-2 input file is created, the file "WinDOE-2.exe" (DOE-2.2 Windows executable) is executed. This interactive program prompts the user for the location of input file and the weather file and makes the simulation run. The results are the SIM file (monthly and annual simulation results) and hourly results.

9.6.2.1 Description of the Folders and Files

- **RootDir folder:** Includes the following folders and file:
- **MakeAll-Doe22-Input.bat file:** Executes another batch files, MakeDoe22-Input.bat and feeds input variables to this file. User edits this file to make different DOE-2 runs.
- **MakeDoe22-Input.bat file:** Creates the DOE-2 input file.
- **IncFiles folder:** Includes the main body of the input file, the location include file, and the schedules folder.
- **LowMass folder:** Includes the final input/output of the low-mass runs.
- **HighMass folder:** Includes the final input/output of the high-mass runs.
- **IncFiles folder (#3 above):** Includes the following files and folders.
- **DOE-22-Flexlab-X3-2017.inc:** Main body of the input file (.inp).
- **Schedules folder:** Contains the annual FLEXLAB-measured heating/cooling set-points, lighting, and plug load schedules, used in DOE-2 run.

9.6.2.2 Sample File Listing

"MakeAll-Doe22-Input.bat" sample file to run for Low-Mass case.

```
rem ***** 2017 CELL A *****
rem ----- Low Mass 2017 -----
call MakeDoe22-Input LowMass DOE-22-FLEXLAB-X3-2017-OneOvhFinSB doe22_full_Light_Plug-2017
doe22_full_HC-2017_COR LamWin
rem ----- High Mass 2017 -----
rem rem call MakeDoe22-Input HighMass DOE-22-FLEXLAB-X3-2017-OneOvhFinSB
doe22_full_Light_Plug-2017 doe22_full_HC-2017_COR LamWin
```

"Make-Doe22-Input.bat" sample file:

```
cd IncFiles

set in_out_Dir=%1
set base_file=%2
set Inc_file=%2.inc
set final_input=%1_%base_file%.inp

echo INPUT..          > UserInput.txt
echo. >> UserInput.txt
echo ##showdetail >> UserInput.txt
echo ##set1 RunType %1      >> UserInput.txt

if %5==LamWin echo ##set1 WinType "LamWin" >> UserInput.txt
if %5==InsWin echo ##set1 WinType "InsWin" >> UserInput.txt

if %1==LowMass echo ##set1 Floor_Const "Floor-SLAB_3_Construction" >> UserInput.txt
if %1==HighMass echo ##set1 Floor_Const "Floor-SLAB_1_Construction" >> UserInput.txt

copy UserInput.txt + %Inc_file% ..\%in_out_Dir%\%final_input%

rem ----- Delete old schedule files before copying new ones -----

Copy Schedules\%3.inc C:\DOE-22\DLL48y\Sched22_Light_Plug.inc
Copy Schedules\%4.inc C:\DOE-22\DLL48y\Sched22_HC.inc

Del UserInput.txt
cd ..
```

The following is the description of each line in the Make-Doe22-Input.bat:

- `cd IncFiles`

Go down to to "IncFiles" folder.

- `set in_out_Dir=%1`

Set the variable "in_out_Dir" to "LowMass".

- `set base_file=%2`

Set the variable "base_file" to "DOE-2.2-FLEXLAB-X3-2017".

- `set Inc_file=%2.inc`

Set the variable "Inc_file" to "DOE-2.2-FLEXLAB-X3-2017.inc".

- `set final_input=%1_%base_file%.inp`

This command creates the final input name. It sets the variable "Final_Input" to "LowMass_ DOE-2.2-FLEXLAB-X3-2017.inp".

- `echo INPUT.. > UserInput.txt`

Write "INPUT.." to the file UserInput.txt (create a new file "UserInput.txt and start writing to the file".

- *echo. >> UserInput.txt*

Write a blank line to the file UserInput.txt (skip a line – done for easy reading of the file).

- *echo ##showdetail >> UserInput.txt*

Write “##showdetail..” to the file UserInput.txt.

- *echo ##set1 RunType %6 >> UserInput.txt*

Write “##set1 RunType 900” to the file UserInput.txt.

- *if %5==LamWin echo ##set1 WinType "LamWin" >> UserInput.txt*

If Input #5 to this file is LamWin, then Write “##set1 WinType LamWin” to the file UserInput.txt.

- *if %5==InsWin echo ##set1 WinType "InsWin" >> UserInput.txt*

If Input #5 to this file is InsWin, then Write “##set1 WinType InsWin” to the file UserInput.txt.

- *if %1==LowMass echo ##set1 Floor_Const "Floor-SLAB_3_Construction" >> UserInput.txt*

If second input to this file is LowMass, then Write ##set1 Floor_Const “Floor-SLAB_3_Construction” to the file UserInput.txt.

- *if %1==HighMass echo ##set1 Floor_Const "Floor-SLAB_1_Construction" >> UserInput.txt*

If second input to this file is HighMass, then Write ##set1 Floor_Const “Floor-SLAB_1_Construction” to the file UserInput.txt.

- *copy UserInput.txt + %Inc_file% ..\%in_out_Dir%\%final_input%*

Copy the file “UserInput.txt” to the top of the file “rootdir\IncFiles\DOE-2.2-FLEXLAB-X3-2017.inp” and put the file in the folder “rootdir\LowMass\” and rename it to “LowMass_ DOE-2.2-FLEXLAB-X3-2017.inp”.

- *Copy Schedules\%3.inc C:\DOE-2.2\DLL48y\Sched22_Light_Plug.inc*

Copy the file “Schedules\doe22_full_Light_Plug-2017.inc to the file “C:\DOE-2.2\DLL48Y\Sched22_Light_Plug.inc”.

- *Copy Schedules\%4.inc C:\DOE-2.2\DLL48y\Sched22_HC.inc*

Copy the file “Schedules\doe22_full_HC-2017.inc to the file “C:\DOE-2.2\DLL48Y\Sched22_HC.inc”.

- *Del UserInput.txt*

Delete the file `UserInput.txt`.

- `cd ..`

Go back one folder up to *rootdir*.

References

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