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Evaluation of Envelope Energy in a High-Performance Manufactured Home in California

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Evaluation of Envelope Energy in a High-Performance Manufactured Home in California

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List of Acronyms

FEMS	Frontier Energy Monitoring System
NREL	National Renewable Energy Laboratory
UA	thermal conductance (W/°F)

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Executive Summary

Frontier Energy performed a short-term field test and calibrated modeling of a Dvele standard-practice manufactured home located in Truckee, California, in late September 2022 (Figure ES-1). The primary objective was to characterize the in situ performance of the building envelope, with a focus on opaque wall and ceiling components that will be replaced with a vacuum-insulated panel assembly in an upcoming research project funded separately by the California Energy Commission. An additional objective was to evaluate the proposed methodology for comparing design predictions to actual envelope performance using co-heating combined with calibrated modeling under carefully controlled field test conditions, and refine the methodology if necessary for future field tests of envelope performance in manufactured homes.

Figure ES-1. Test house in Truckee, California

All report photos by the Frontier Energy research team

The home was a Roberts model that remained unoccupied for two weeks while Frontier staff performed blower door and co-heating tests in an effort to determine the heat loss coefficient. During the tests, circuits for all space-conditioning equipment, ventilation, plug loads, and lighting were turned off. All vents were taped over to minimize infiltration caused by duct leakage to the outside. Nobody was allowed to enter the building during the test period except when adjustments were made to the instrumentation. A multipoint blower door test was performed to quantify the effective leakage area. This approach helped to minimize the number of unknowns, and focus the test on the thermal performance of the building envelope.

The following key conclusions about the performance of the manufactured home and the test methodology were drawn from this project:

- The test house, representing builder standard practice, has a relatively tight building envelope, with an effective leakage area of about 6.7 in^2. In future tests, the water line to the washing machine, which likely contributed much of this leakage, should be sealed prior to testing.
- The “crawlspace,” which was actually just an open area where the chassis supporting the home was positioned, was well ventilated with uniform temperatures without skirting applied.
- Co-heating energy did not stabilize at any point during the test period, indicating that calibrated modeling will be necessary to calculate the total heat loss coefficient and component UAs.
- Calibrating solar gains in an EnergyPlus™ model for homes that are heavily shaded is extremely difficult in practice. Covering windows with a solar barrier is essential if the focus is on the performance of opaque envelope components.
- Tracer gas testing during the test period would be helpful to minimize the uncertainty of air infiltration as a function of weather conditions.
- The test period can be reduced from 15 days to 8 days without losing accuracy in model calibration. More diverse weather would likely help the calibration process, but four days of co-heating seems adequate, combined with one to two days of floating temperatures and one day at the beginning and one at the end for setup, blower door testing, equipment removal, and other activities.
- Based on the final calibrated model, the walls and ceiling appear to perform in accordance with design specifications.

1 Introduction

The overall heat loss coefficient in buildings plays a significant role in improving energy efficiency because it directly affects heating and cooling loads. However, frequent gaps in performance between a home's expected energy use and the actual energy use in operation highlight the need to identify and analyze the root causes of such disparities. Envelope materials and installation efficacy, coupled with occupancy behavior and equipment within the building, are known to be the main factors that influence this energy performance gap (Glasgo, Hendrickson, & Azevedo, 2017) (Halladay, 2012). In field test situations where the envelope is being investigated, the effects of occupancy and building equipment should be either removed as variables, applied in a controlled manner, or measured directly. This approach emphasizes the importance of evaluating uncertain properties of the building and helps identify areas with thermal shorts, air leaks, and poor insulation quality in the building that contribute to high energy loads and decrease the energy efficiency of the building.

Co-heating is a key test method for evaluating envelope thermal performance, and was an essential element to the Short-Term Energy Monitoring test protocol developed by the National Renewable Energy Laboratory (NREL) in the 1980s (Subbarao, Burch, Hancock, Lekov, & Balcomb, 1988), although more recent research has been limited. A European study conducted by Krstić and Domazetović examined co-heating in a laboratory setting where constant outdoor temperatures could be simulated, but it did not address protocols for in situ testing in the field under variable weather conditions (Krstić & Domazetović, 2020). This project examines whether co-heating can be used in a field test application to estimate the heat loss coefficient and disaggregate its components with sufficient accuracy to evaluate possible envelope performance deficiencies.

This document describes the execution of a series of short-term field tests and calibrated modeling to evaluate the heat loss coefficient of the building envelope in an energy-efficient manufactured home in Truckee, California. This baseline test was in support of a larger project funded by the California Energy Commission to evaluate manufactured homes with vacuum-insulated panels installed in the wall and roof assemblies.

1.1 Objective

For this project, Frontier Energy performed a series of short-term tests (co-heating and envelope leakage tests) and calibrated building simulation to evaluate the in situ heat loss coefficient of a baseline all-electric manufactured home constructed by Dvele. By carefully controlling as many uncertainties as possible, Frontier's objective was to "back out" the U-values of the ceiling and wall assemblies. If successful, the result would be an inexpensive methodology that allows sufficiently accurate disaggregation of the installed thermal conductance (UA) of individual envelope components, in particular the walls and ceiling where vacuum-insulated panels will be added for later tests. It is expected that the results from these studies will inform the development of advanced manufactured homes that will transform construction practices and further facilitate decarbonization of the building sector.

1.2 Test House Characteristics

The test house was a 400 ft^2, 1-story manufactured home with an interior loft built by Dvele (Roberts model). The house has a single bathroom and single bedroom, with a large common area serving as the living room, kitchen, and laundry. A 5-ft loft above the bedroom provides an additional sleeping/storage area.

Isometric views of the home and exterior dimensions are shown in Figure 1 and Figure 2. Photos of the actual test house are shown in Figure 3 through Figure 6.

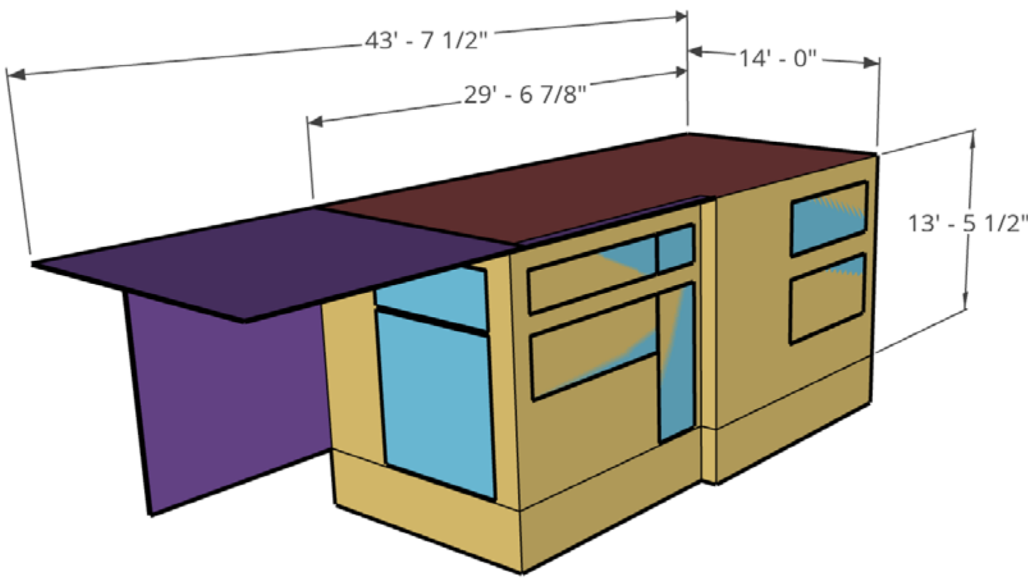


Figure 1. Front view of the Roberts model

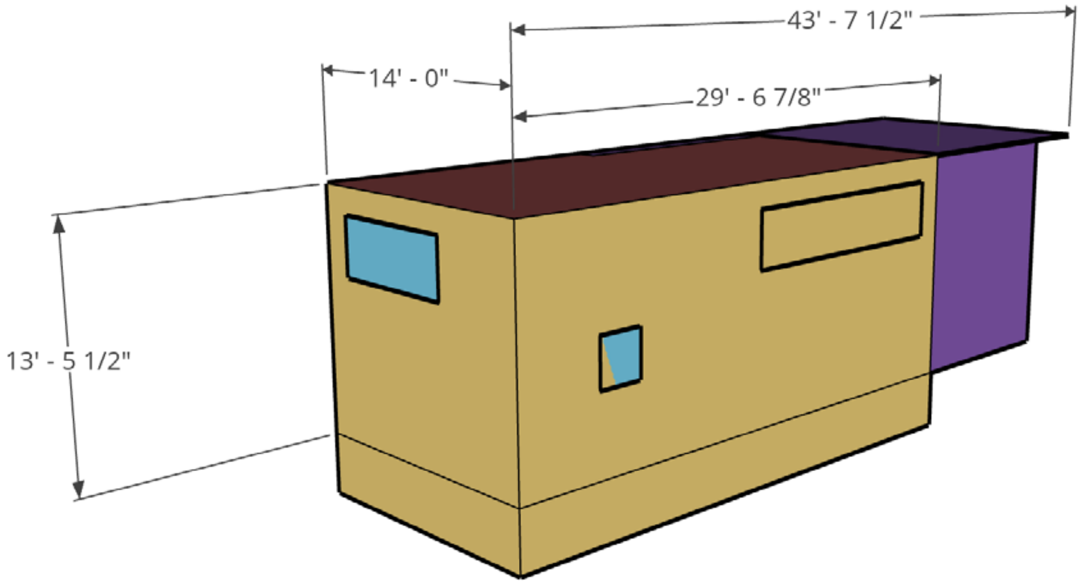


Figure 2. Back view of the Roberts model

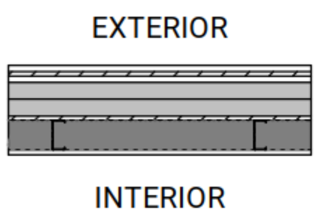
Figure 3. East side view of the test house

Figure 4. South side view of the test house (front)

Figure 5. West side view of the test house

Figure 6. North side view of the test house

Exterior walls were constructed with 3.5-in. deep, 16-in. on-center (o.c.) light-gauge steel framing. Insulation consisted of a 2-in. layer of R-17 foamboard sheathing and R-15 blown-in wall cavity insulation, totaling approximately R-25.5 for the assembly. For exterior wall assembly detail, see Figure 7.



EXTERIOR WALL ASSEMBLY

- EXTERIOR CLADDING: T&G WOOD PANEL SIDING
-1/2" PLYWOOD
- 3/4" RAINSCREEN
- (1) 2" LAYER KING KOOL THERM R-17
*FIELD JOINTS TREATED W/ PROSOCO JOINT & SEAM, TAPED W/ 6" HENRY BLUESKIN
- 1/2" PLYWOOD
- 350NF150 16" O.C. W/ KNAUF JETSTREAM BLOW IN BATT R15 HD
- 5/8" USG ECOSMART TYPE X DRYWALL

Figure 7. Exterior wall assembly

The roof was also light-gauge steel and had a low 1° slope with no attic. Ceiling insulation consisted of blown-in insulation to a depth of 6.5 in. at the shallowest point (R-19), 9 in. at the deepest point (R-26), and 4.5-in. thick structural insulated panels for the roof deck (R-15).

The home was installed on a well-ventilated chassis. The chassis was similar to a crawlspace, but more ventilated and not designed to be permanent. The floor consisted of 3.5-in. structural insulated panels with a graphite-enhanced polystyrene core, sandwiched between sheets of 5/8-in. oriented-strand board.

All windows were Aluplast Ideal 4000 Classicline windows with 0.29 U-value and 0.23 solar heat gain coefficient.

Mechanical systems included a 20-SEER, 10-HSPF, Mitsubishi minisplit heat pump with two ductless indoor heads (one in the kitchen/living room common area and one in the bedroom), five Lunos heat recovery ventilators (one at each end of the common area, one in the bathroom, one in the bedroom, and one in the loft), electric radiant heat in the bathroom floor, and point-of-use electric water heaters. None of the mechanical systems were in use during the short-term test.

2 Technical Approach

2.1 Disaggregation of Energy Losses

Disaggregation of the heat loss coefficient into specific components can theoretically be derived from the total heat transfer (Q_{tot}) to the building over a range of operating conditions, combined with known values wherever possible. The technical approach for this project focused on measuring, minimizing, or eliminating unknowns during the field test period, allowing isolation of the thermal performance of the walls and ceiling.

The amount of heat transfer across the building envelope is a function of several quantities including the insulation levels, thermal mass of the building, air infiltration, the temperature differential between inside and outside conditions, and thermal radiation. An energy balance of the building using interior surfaces as the control volume indicates the following primary contributors to heat transfer into and out of the home during the test period, as shown in Equation 1:

$$Q_{int} = Q_{ceiling,interior} + Q_{wall,interior} + Q_{window,interior} + Q_{floor,interior} + Q_{env,inf} + Q_{ducts} + Q_{vent} + Q_{mass} \quad (1)$$

Where:

- Q_{int} is the internal heat gain that arises from people and equipment (including co-heaters) within the building.
- $Q_{ceiling,interior}$ is the heat transfer from the interior to the ceiling.
- $Q_{wall,interior}$ is the heat transfer from the interior to the walls.
- $Q_{window,interior}$ is the heat transfer from the interior to the windows.
- $Q_{floor,interior}$ is the heat transfer from the interior to the floor.
- $Q_{env,inf}$ is the heat loss due to air infiltration.
- Q_{ducts} is the heat loss due to duct losses if ducts are present. For the Roberts model, this value is zero because there are no ducts for space conditioning.
- Q_{vent} is the heat loss due to the mechanical ventilation system, including both air exchange and conductive losses from the ducts.
- Q_{mass} is the thermal storage in the mass of the furnishings, fixtures, equipment, interior walls, and building envelope components inside and outside the home.

The control volume could also be drawn at the exterior of the building envelope, in which case the thermal mass of the walls, ceiling, and floor would be included in Q_{mass}, and envelope heat transfer terms would be at the exterior surface.

Most of these heat transfer terms were either eliminated, controlled, measured, or calculated during the field test period. Remaining terms were modeled beginning with manufacturer specifications and adjusted where necessary to match modeled results to field test data.

The internal gains (Q_{int}) in the home were very small because the home was unoccupied and all plug loads/equipment were turned off at the circuit breaker panel except for the space heaters that provided co-heating, along with related controls. The total electricity use of the manufactured home, including the co-heating system, was monitored directly, and it was assumed this energy was equal to the internal gains (i.e., none of the energy was on the exterior of the home).

The heat transfer across the ceiling ($Q_{ceiling,interior}$) was deduced using calibrated modeling, without changing known properties of the ceiling/roof construction. Likewise, the heat conducted across the wall ($Q_{wall,interior}$) was determined using calibrated modeling and known wall specifications. The heat transfer across the windows ($Q_{window,interior}$) included the effects of solar heat gain and radiation into the space. However, to mitigate the effects of radiative heat transfer, which can be challenging to model accurately even with a weather station, rigid insulation with a reflective coating facing the outside and a known R-factor of 7.7 was applied to the outside surfaces of all windows during part of the test so that heat losses from the windows would be limited to conduction. The floor heat transfer ($Q_{floor,interior}$), which is driven by floor assembly thermal properties, chassis ventilation, and ground coupling effects make the determination of losses through the floor very complicated. To address this, temperature sensors were placed in the crawlspace, and the calibrated energy model was used to estimate these losses.

The thermal mass of the furnishings (Q_{mass}), which was very difficult to determine empirically, was also obtained through model calibration. To assist with the calibration process for thermal mass, the temperature of the test home was allowed to float for 24-36 hours (ensuring a full range of outside thermal conditions) following several days of co-heating. There were no space-conditioning ducts in the house, so the Q_{ducts} term was zero. The heat loss through ventilation ducts (Q_{vent}) was minimized by covering the registers during the test. Envelope leakage area was determined from a multipoint blower door test according to ASTM E779-19: Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (ASTM, 2019), and heat transfer ($Q_{env,inf}$) was calculated using a calibrated EnergyPlus™ model based on measured leakage area and actual weather conditions during the test period, but uncertainty remains because actual leak sizes, locations, and response to wind and temperature can only be estimated.

2.2 Controls and Instrumentation

The co-heating system consisted of an array of space heaters placed throughout the home and programmed to maintain the internal temperature of the home at a setpoint at least 10°F above the forecasted outdoor temperature range for the period of the test. Other small interior sensible heat gains were present, including the monitoring system and standby losses from hardwired equipment, and the electricity for these loads were added to the space heater power to estimate total internal heat gain. This co-heating test was performed over approximately 14 days in Truckee, California, which is a relatively cold climate for California.[1] In late September, the outdoor temperatures were fairly warm, and co-heating at a temperature of 88°F, well above typical indoor conditions, was required to ensure the interior temperature was constant, and always warmer than the exterior.

The space heaters had built-in oscillating fans and were controlled using relays and aspirated thermocouples placed throughout the house. Each heater and thermocouple pair were able to operate independently to maintain an even temperature through the entire interior space. Figure 8 shows the approximate locations for the space heaters and aspirated thermocouples. Light green circles represent the aspirated thermocouples (dark green circle is the aspirated thermocouple in the loft). Red circles represent the space heaters (the orange circle represents the space heater in the loft), and blue triangles represent the range of oscillation.

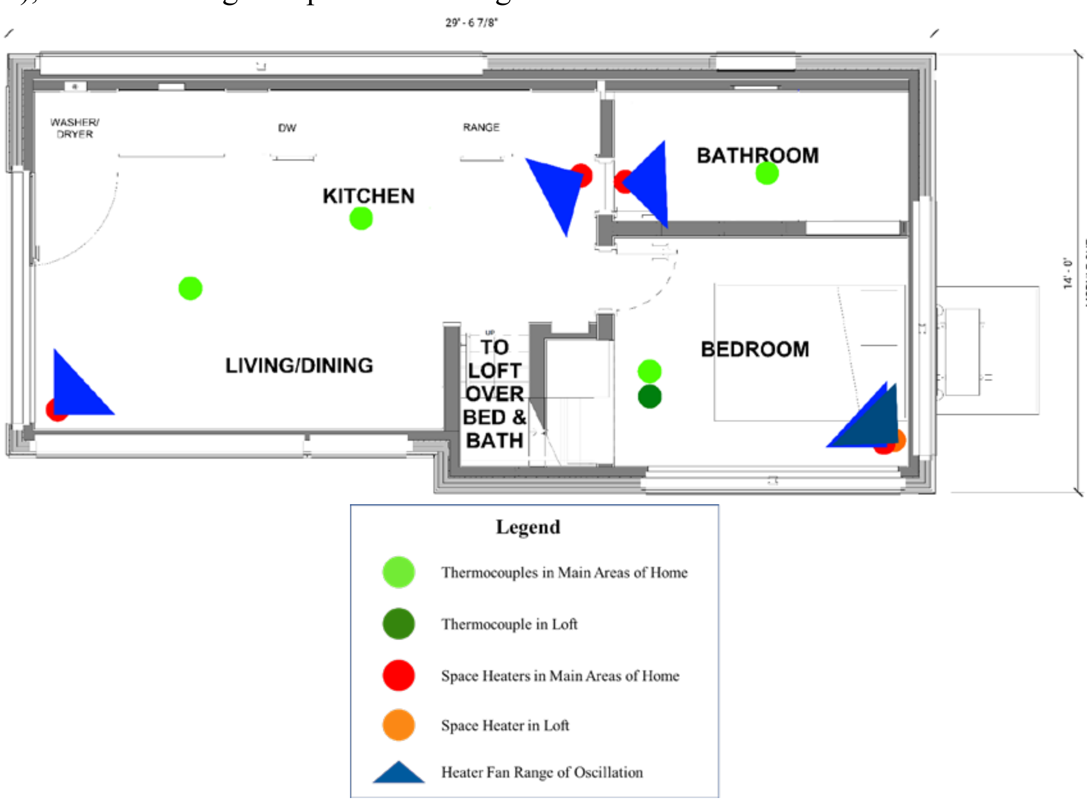


Figure 8. Layout of sensors and space heaters in the test home

[1] In 2021, °F heating degree days in Truckee, CA were 7184, over 2.8 times that of Sacramento, CA.

The short-term tests required active measurement and data collection of the manufactured home's envelope heat loss over a 2-week period. Table 1 details the relevant instrumentation that was used for data collection during the short-term tests, including sensor type, units, and accuracy. The five-zone co-heating system consisted of integrated electric space heater fan units with individual temperature controls. Calibration of the sensors used to obtain the measurements was verified before the start of the test. Depending on the nature of the measurement to be collected, some sensors were inside the home, and some were stationed outside the home with 120 VAC power and internet connection provided.

Table 1. Instrumentation for Short-Term Test

Location/ Purpose	Mfr/Model	Signal	Measurement	Measure-ment Range	Accuracy
Indoor Temperature	Omega TW SH STR 24 gauge	Type T Thermocouple	Temperature	-200 to 200°C (-328 to 392°F)	±0.5°C (±0.9°F)
Temperature Below Floor	Onset HOBO MX1101	Bluetooth Temperature/ Relative Humidity Sensor	Temperature and Relative Humidity	0 to 50°C (32 to 122°F) 1% to 90% Relative Humidity	±0.2°C (±0.4°F) ±02% Relative Humidity
Indoor Relative Humidity	Vaisala HMP110	Modbus RTU	Relative Humidity	0 to 100%	±1.5% Relative Humidity
Total Electricity Use	WattNode WND-WR-MB	Modbus RTU	True Root-Mean-Square Electrical Power	CT Dependent	0.5% (1% to 120% of CT rated current)
Outdoor Weather Conditions	Davis Instruments Vantage Pro 2 with Silicon Photodiode Pyranometer	Modbus RTU (via Ocean Controls KTA-282)	Temperature	-40 to 65°C (-40 to 149°F)	±0.5°C (±0.9°F)
			Relative Humidity	0 to 100%	±1%
			Solar Radiation (400 to 1,100 Nanometer Spectral Response)	0 to 1,800 W/m^2	±1 W/m^2
			Wind Speed	0 to 200 mph	±1 mph

The weather station was installed on the roof of the home, in the northeast corner approximately 14 feet off the ground where it would provide clean readings of wind and solar radiation (Figure 9). The station included monitoring of outdoor temperature, relative humidity, wind speed and direction, ultraviolet radiation, and total global radiation. A closer view of the weather station at the Davis Laboratory is shown in Figure 10.

The data monitoring system used to control the co-heating system and measure the indoor and outdoor thermal conditions is shown in Figure 11. The space heaters and aspirated thermocouples for the bedroom and loft are shown in Figure 12 and Figure 13, respectively. The test rig for monitoring temperature stratification is shown in Figure 14. The HOBO temperature and relative humidity sensors installed in the chassis area under the home are shown in Figure 15.

Figure 9. Weather station installed on top of the test home

Figure 10. Davis Vantage Pro 2 weather station

Figure 11. Monitoring and control system at the test home

Figure 12. Space heater, controller/watt node, and aspirated thermocouple in the downstairs bedroom

Figure 13. Space heater, controller/watt node, and aspirated thermocouple in the loft

Figure 14. Thermocouple array for measuring thermal stratification (left) and aspirated thermocouple (center) in the main living area

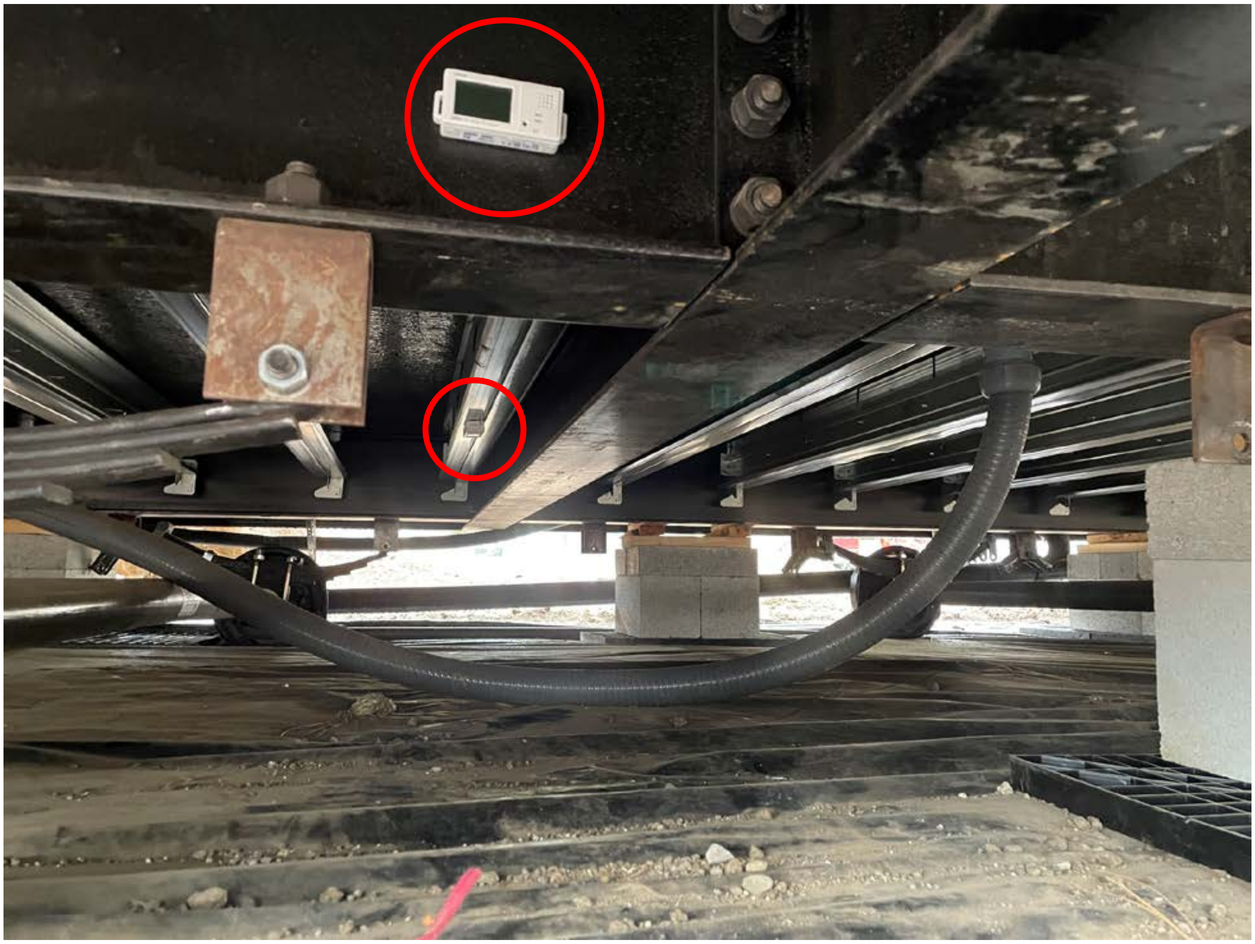


Figure 15. Onset HOBO temperature and relative humidity sensors near perimeter and center of chassis area

The Frontier Energy Monitoring System (FEMS) shown in Figure 16 automated data collection, data checking, and any daily analysis or calculations using monitored data. The FEMS produced a spreadsheet that was updated daily and included tabular summaries of electricity consumption, weather conditions, and indoor and outdoor temperatures. The FEMS performed automated data quality checks to identify malfunctioning equipment or sensors on a daily basis and notify team members of potential issues, such as one heater using significantly less energy than the others or interior temperatures above the co-heating set point. The FEMS also produced interactive daily timeseries plots for human review. These timeseries plots were backed up regularly and made available to the project team on Frontier's SharePoint site. As insights into system performance were gained over time, further quality assurance measures were added to diagnose other potential issues such as someone entering the home during the test or using one of the exterior power outlets.

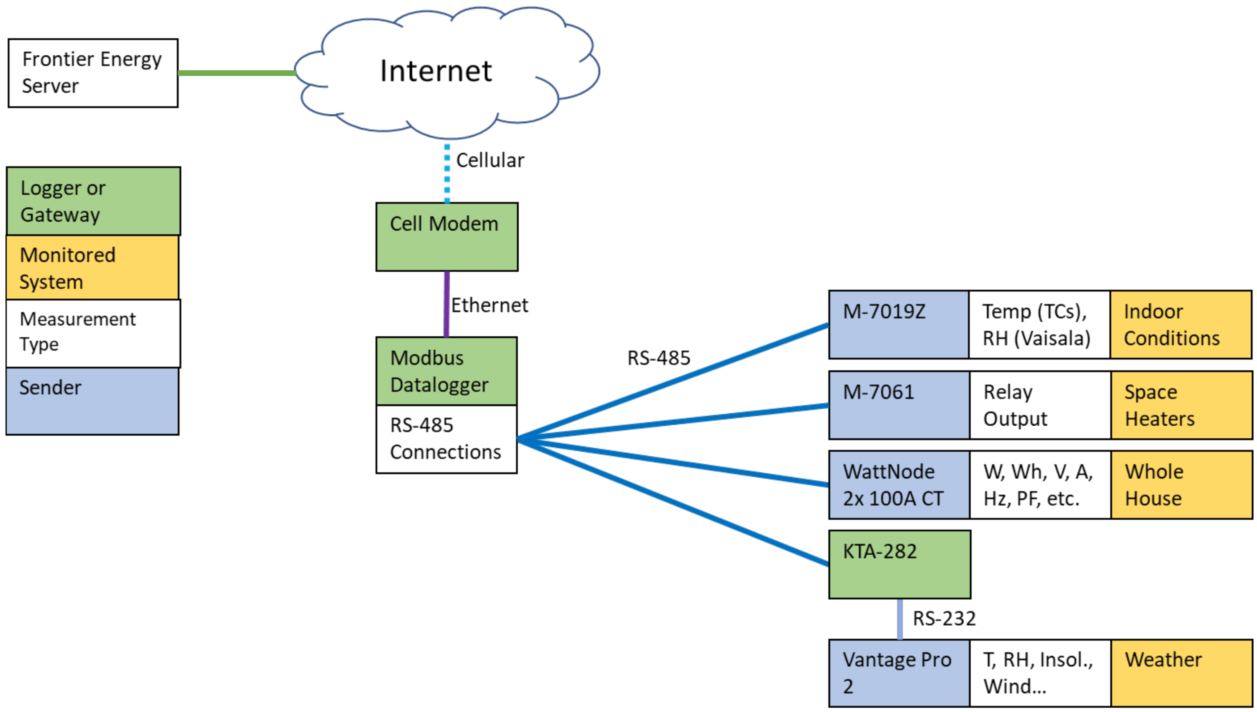


Figure 16. Diagram of the Frontier Energy Monitoring System

2.3 Test Schedule

The tests were performed from September 19 through October 3, 2022.

Pre-Test Activities

Prior to the field test, several action items were performed as preparatory steps. These steps included:

- Selection and purchasing of equipment (funded by the California Energy Commission).
- Verification of blower door calibration.
- Datalogger programming.
- Mock-up test in laboratory.
- Work with Dvele and property manager to ensure home would be fully operational and nobody would enter the home during the test period.

On-Site/Remote Activities

The following steps outline the order of test operations performed during the 2-week field test period.

1. Starting at 9 a.m. on the first day of the test:
    a. Turn off heat pump and mechanical ventilation.
    b. Seal registers/exhaust vents.
    c. Install two Onset HOBO temperature/relative humidity dataloggers in chassis space, midway between the ground and the floor of the house, one near the middle of the house and the other 2 ft inside the outer perimeter of the space.
    d. Install weather station.
    e. Install and set up co-heating system.
    f. Turn off all circuit breakers except those for co-heating.
    g. Make sure blinds are open.
    h. Install watt nodes for whole-house electricity monitoring.
    i. Verify on-site functionality of instrumentation and controls.
    j. Verify remote communication.
    k. Take photos of house exterior, interior, under floor, equipment nameplates, and EnergyGuide labels.
    l. Leave site and begin test period.
2. At midnight on Day 7, 32 hours prior to the second site visit, remotely turn off the heaters and allow the home to cool down.
3. Midway through the test period (Day 8), visit the site to change several test conditions. The site visit procedures include:
    a. Perform multipoint blower door tests, both pressurized and depressurized.
    b. Cover windows with rigid insulation to block radiation into the home and minimize conductive losses.
    c. If necessary, adjust the co-heat setpoint temperature. (Not necessary because the weather forecast was similar to the first week)
    d. Verify that nothing changed inside the home, including vent covers, breaker positions, heater positions and orientations, etc. (Nothing had changed, but the space heater and fan in the loft was reactivated after failing to operate during the first week, resulting in slightly lower temperatures in the loft, and two heaters/fans were moved to provide better air circulation.)
    e. Turn the heaters back on and resume testing.
4. At midnight on Day 14, 32 hours prior to the third site visit, remotely turn off the heaters and allow the home to cool down.
5. On the final day of the test (Day 15), the following steps are performed:
    a. Remove instrumentation.
    b. Retrieve Onset temperature/relative humidity dataloggers.
    c. Turn HVAC and circuit breakers back on.
    d. Leave home as it was found on Day 1.

A day-by-day breakdown of the two-week test period is provided in Table 2. Green cells indicate on-site activities in Truckee. Yellow indicates a change in operating conditions performed remotely.

Table 2. Day-by-Day Test Schedule

Date (2022)	Activities
Monday, Sept. 19	On-site: Arrival (9 a.m.); turn off heat pump and ventilation; seal vents; install testing equipment and sensors; verify functionality and communication
Tuesday, Sept. 20	Remote monitoring
Wednesday, Sept. 21	Remote monitoring
Thursday, Sept. 22	Remote monitoring; initial check of model compared to measured data
Friday, Sept. 23	Remote monitoring; interim review with NREL
Saturday, Sept. 24	Remote monitoring
Sunday, Sept. 25	Remote monitoring; remotely turn off heaters
Monday, Sept. 26	On-site: Arrival (9 a.m.); perform blower door test; cover windows; verify conditions; resume co-heating test; implement changes based on initial calibration and NREL review meeting
Tuesday, Sept. 27	Remote monitoring
Wednesday, Sept. 28	Remote monitoring
Thursday, Sept. 29	Remote monitoring
Friday, Sept. 30	Remote monitoring
Saturday, Oct. 1	Remote monitoring
Sunday, Oct. 2	Remote monitoring; remotely turn off heaters
Monday, Oct. 3	On-site: Arrival (9 a.m.); remove instrumentation; turn on HVAC and circuit breakers

2.4 Model Calibration

EnergyPlus was used for all modeling activity to allow maximum flexibility when performing the energy analysis. The initial base case model, which was mostly consistent with the physical specifications of the test house, was provided by GTI Energy. The adjustments to match the final house design and the calibration process were performed as part of this NREL-funded project. Actual measured and controlled conditions, including weather, effective leakage area, and internal gains (other than co-heating) were used as fixed inputs to the model. For weather values that were required by EnergyPlus but could not be measured using the portable weather station (primarily detailed solar radiation data), Actual Meteorological Year data from White Box[2] for the nearest permanent weather station (Truckee-Tahoe, approximately 2 miles away) were used.

[2] http://weather.whiteboxtechnologies.com/

Key calibration points that we attempted to match included co-heating energy, crawlspace temperature, and interior temperature while co-heating is disabled. Variables that were available for adjustment during the calibration process included crawlspace/chassis space ventilation rate, ground coupling, thermal mass of furnishings, and most importantly, wall and ceiling thermal conductance (UA).

2.5 Desired Outcomes

Specific desired outcomes of the tests were:

- Determine leakage area in the building envelope through the performance of a multipoint blower door test in accordance with ASTM E779-19 (ASTM, 2019).
- Measure heat gains and losses as a function of weather conditions through the performance of a short-term co-heating test.
- Disaggregate the effective U-value of wall and roof assemblies from other components of envelope thermal conductance, air infiltration, solar gains, and energy storage through calibration of field test data with an EnergyPlus model of the home. Alternatively, confirm that the in situ performance of the envelope assembly matches the specifications as designed and modeled.

3 Project Results

The final results for this project included key findings from the short-term test, the detailed changes to modeling inputs necessary for adequate calibration, and the impact on calibration accuracy for potential simplifications to the test plan.

Observations of the test house include the following:

- The home was fully finished except the skirting around the chassis area/foundation was not yet installed. This could have a significant effect on the crawlspace temperature measurements.
- There was a slight difference in glazing area on the east side compared to the original specifications.
- The water line for the clothes washer was open, allowing more infiltration than would be expected after occupancy when the line would be filled with water. This was not discovered until late in the test, and at that point the team decided it was not vital for the purpose of model calibration because the blower door test would have captured the infiltration through the water line, but the effect should be considered when comparing vacuum-insulated panel homes to the base case in future tests.

3.1 Blower Door Test

The multipoint blower door test was performed in accordance with ASTM Standard E779–19 using Tectite Software provided by the Energy Conservatory for "Minneapolis Blower Door" systems. Adjustments were made for lower air density and viscosity at the high altitude in Truckee (5,817 ft). The pressurization test report is shown in Figure A-1 in the Appendix, followed by the depressurization test report in Figure A-2.

The logarithmic curve fit was very strong (over 99% correlation coefficient) for both the pressurization and depressurization tests. The estimated effective leakage area was 6.8 in^2 based on the pressurization test, and 6.6 in^2 for the depressurization test. This value was somewhat higher than the true effective leakage area would be during normal operation because, as noted, the clothes washer pipe was not sealed off. The average of 6.7 in^2 was used in the calibrated EnergyPlus model.

3.2 Co-Heating Test

Weather conditions during the test period are shown in Figure 17 through Figure 20. After two cold days to begin the test, the temperature became more consistent with seasonal norms for late September in Truckee. The low temperature was 42°F, the high was 78°F. Although more daily diversity in temperature would have been helpful for model calibration, consistent weather provided a better opportunity to estimate the heat loss coefficient directly from test data because the thermal mass effects would roughly cancel out. Colder temperatures would have allowed a more realistic interior control point for co-heating, but as long as continuous heating was required, higher temperatures were satisfactory. Wind speeds were mild for most of the test period, generally less than 2 mph except for two days that exceeded 4 mph around noon. Again, some additional windy days would have allowed better calibration of infiltration effects, but calm winds also help limit the number of variables at play. Solar radiation measurements indicated very sunny days throughout the test period, except the first two days which were cloudy and cold. There is clear indication of shading from nearby trees during parts of the day. Sunny days are generally easier to replicate in the building model, but the shading effects remained too complex for reliable modeling of solar gains.

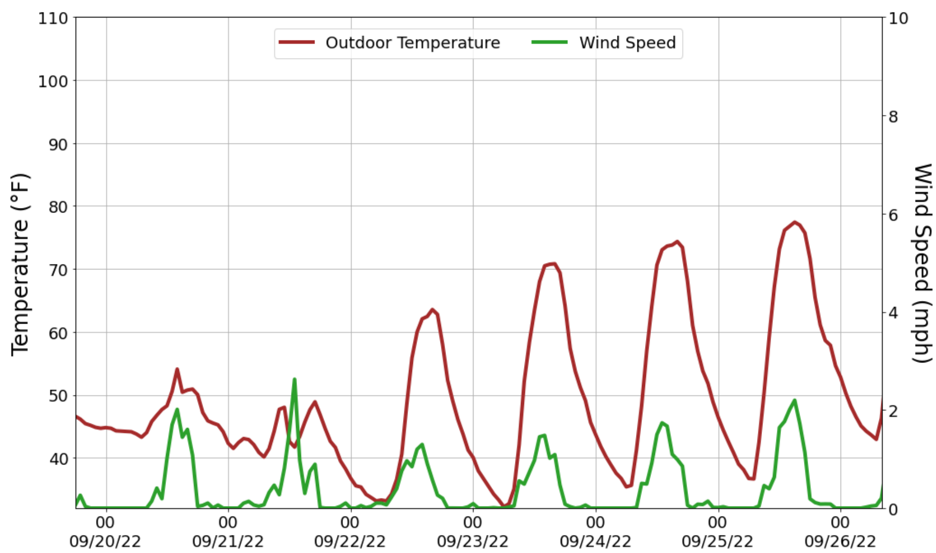


Figure 17. Outdoor temperature and wind speed during Week 1

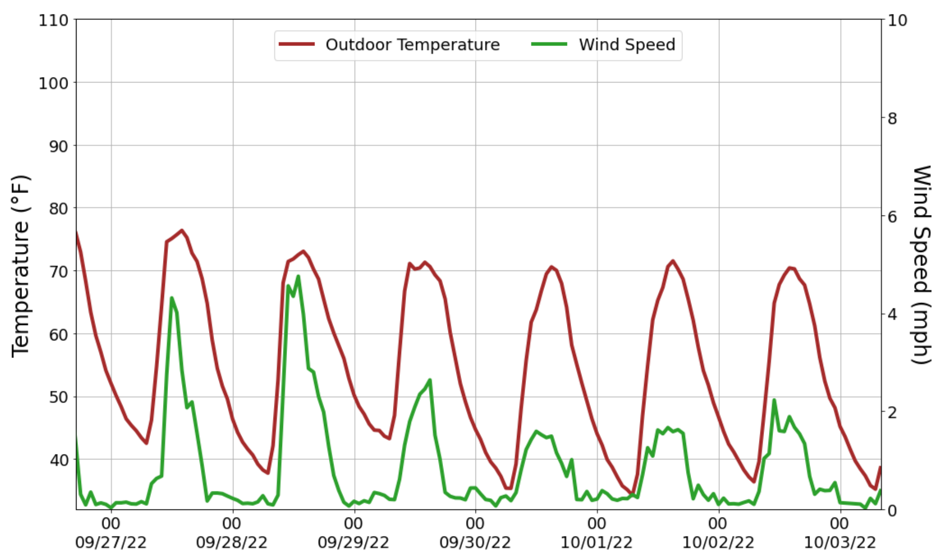


Figure 18. Outdoor temperature and wind speed during Week 2

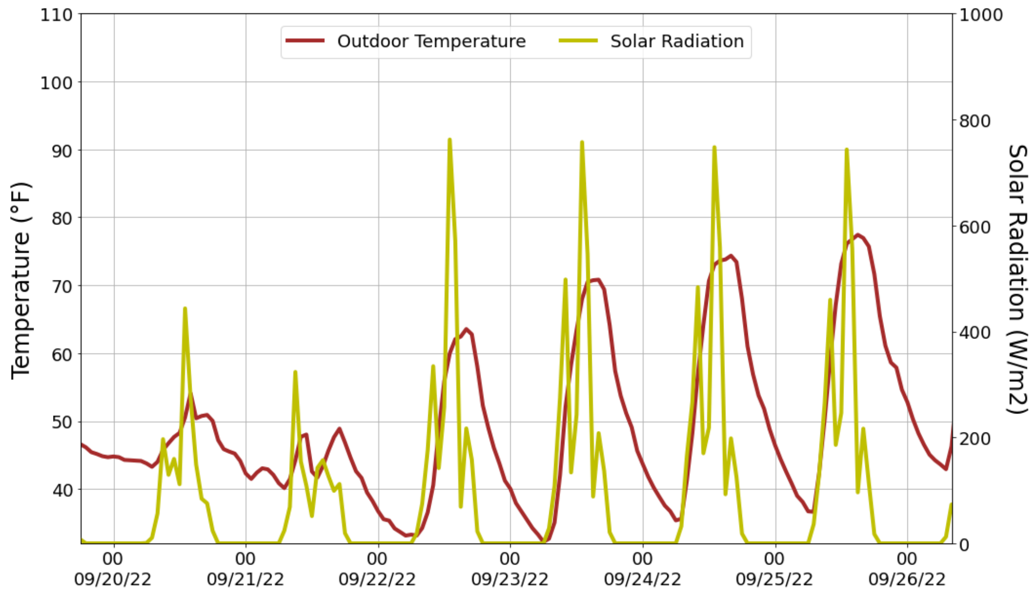


Figure 19. Outdoor temperature and total global solar radiation during Week 1

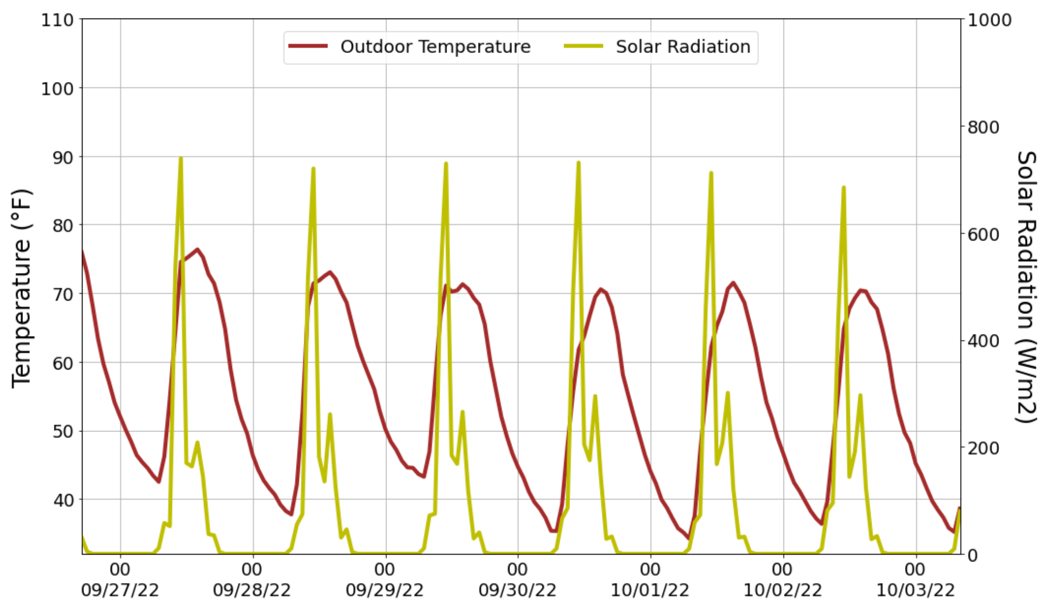


Figure 20. Outdoor temperature and total global solar radiation during Week 2

Indoor, outdoor, and average crawlspace temperatures during Week 1 and Week 2 are shown in Figure 21 and Figure 22, respectively. A co-heating set point of 89°F was used for the first five days of each week, followed by a 32-hour period where the heaters were turned off and the interior temperature was allowed to float.

During the first week, the heater in the loft area was inadvertently left disconnected from the controller during a troubleshooting process late on the first day, resulting in the loft remaining 2°F cooler than the rest of the space, making the use of a single-zone EnergyPlus model less reliable. The space remained well mixed during the "floating" period, which was intended to assist with calibration of thermal mass in the EnergyPlus model. The “crawlspace” (actually an open area where a chassis supports the house) temperature was comparable to the outdoor temperature, with 5°–10°F damping of temperature extremes and a warmer average temperature. The crawlspace temperature was different enough that it had to be treated as a buffer space in the model.

Prior to beginning the second week of testing, the loft heater was reconnected and the windows were covered with R-7.7 foam insulation with foil facing to minimize solar gains and simplify the calibration process during that period. The interior temperatures were more uniform during the second week, and the morning spike in interior temperature due to solar gains observed during Week 1 disappeared, most clearly shown during the floating period. These improvements made model calibration more viable during the second week. No issues with data communication, malfunctioning sensors, or visitors entering the home were encountered during the test period.

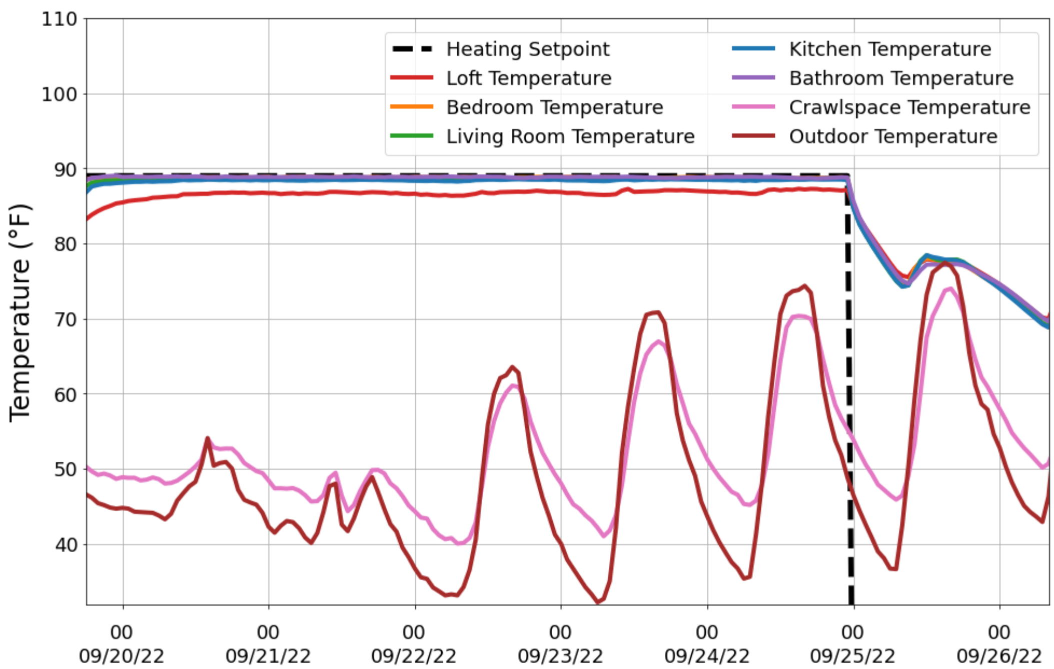


Figure 21. Indoor, outdoor, and crawlspace temperatures during Week 1

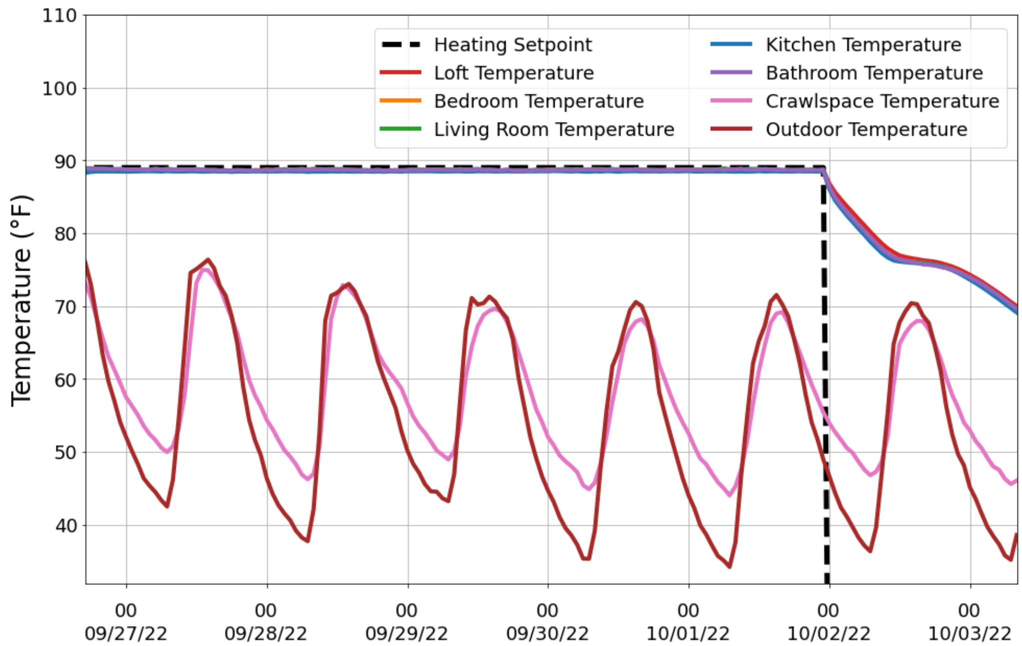


Figure 22. Indoor, outdoor, and crawlspace temperatures during Week 2

Co-heating energy—which was the sum of the heater energy, the auxiliary electric loads for the monitoring equipment, and any small electric base loads that could not be turned off at the circuit panel—is shown in Figure 23 and Figure 24 for Week 1 and Week 2, respectively. As expected, the co-heating energy increased when outside temperature decreased, with some time delay due to thermal mass and fluctuations during periods of high solar gain due to shading and sun angle. The co-heating energy was generally smaller and more stable during the second week, due to the combined effect of insulating the windows and minimizing solar gains. During the floating periods at the end of each week, the co-heating energy was very close to zero, with only monitoring equipment operating along with a small amount of standby power. The outside temperature never remained constant long enough during the day or at night to allow the thermal mass to stabilize. As a result, the building heat loss coefficient could not be measured directly, and calibrated modeling was necessary to estimate total heat loss coefficient in addition to individual component thermal conductance (UA) values.

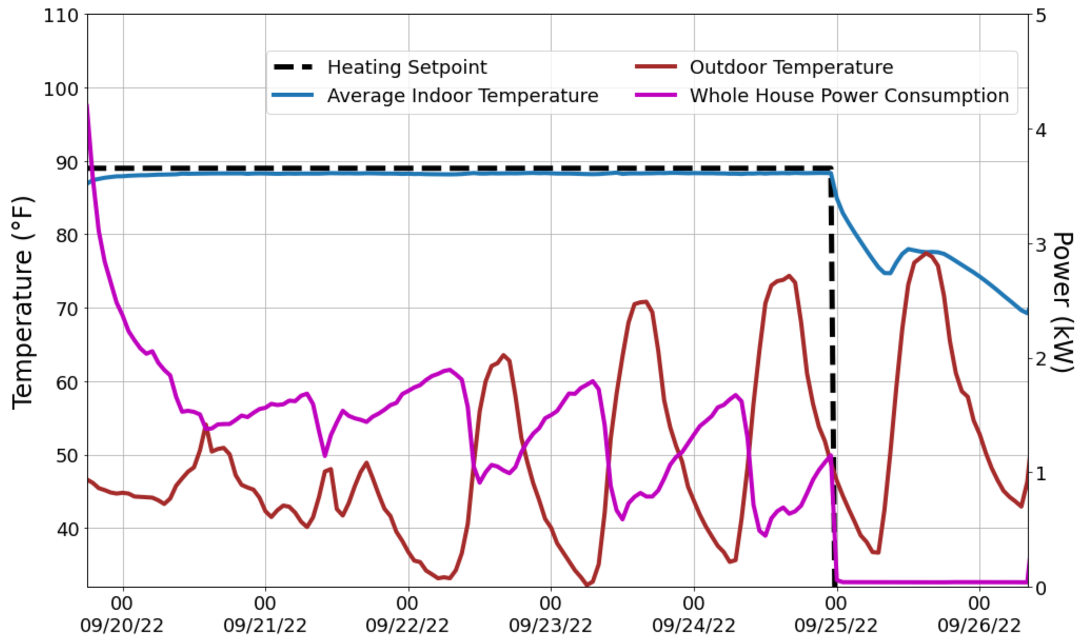


Figure 23. Co-heating energy during Week 1

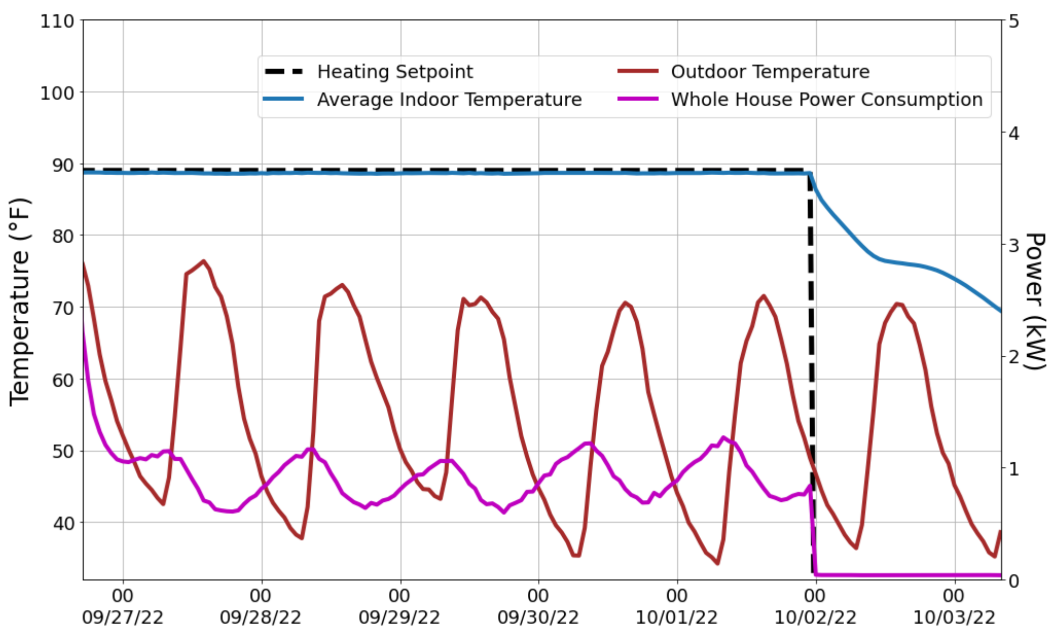


Figure 24. Co-heating energy during Week 2

Additional temperature and relative humidity readings are shown in Figure 25 through Figure 28 for Week 1 and Week 2, respectively. Thermal stratification within the space was generally limited to 2°–3°F during Week 1, while the floor was 4°–6°F cooler than higher points in the space, except when the sun was directly striking it late in the morning. Stratification was greatly mitigated during Week 2 when the windows were covered, and was also smaller when the space heaters were turned off. Indoor relative humidity remained at 30%–35% throughout the test period, but this value is not very meaningful due to the lack of latent loads and artificially high indoor temperature.

The two temperature readings in the crawlspace (one in the middle and one near the perimeter) were very similar, indicating that one sensor would probably be adequate for future tests, although the addition of skirting could affect this conclusion. The crawlspace relative humidity approached 90% at times early in the test when it was cold and wet outside, but remained below 70% following several days of sunny, dry weather. Moisture potential could become a concern once skirting is added, but the current data shows the crawlspace relative humidity remaining within reasonable limits.

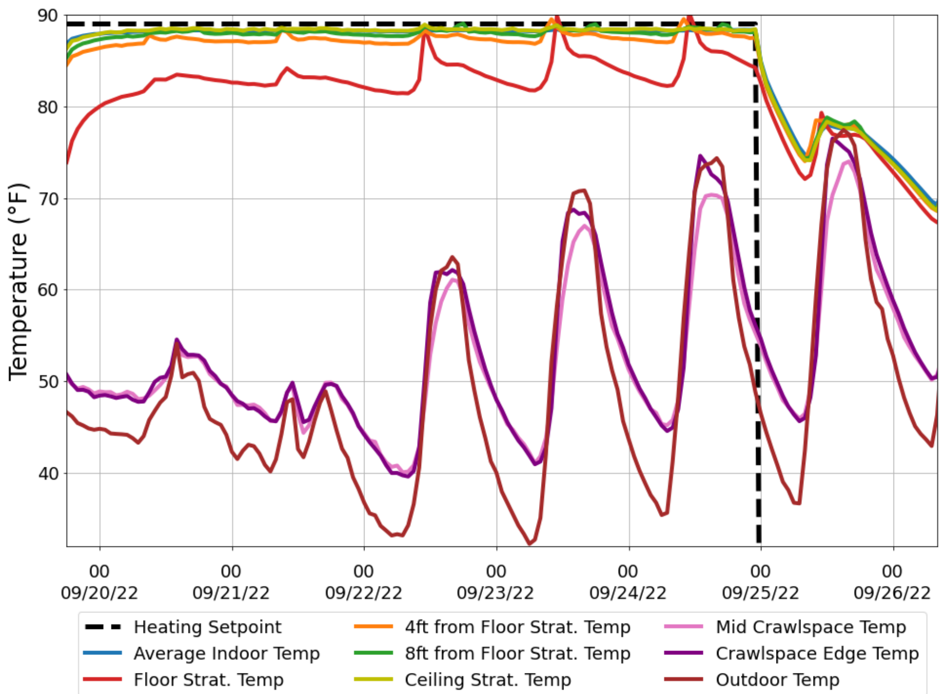


Figure 25. Miscellaneous temperature readings during Week 1

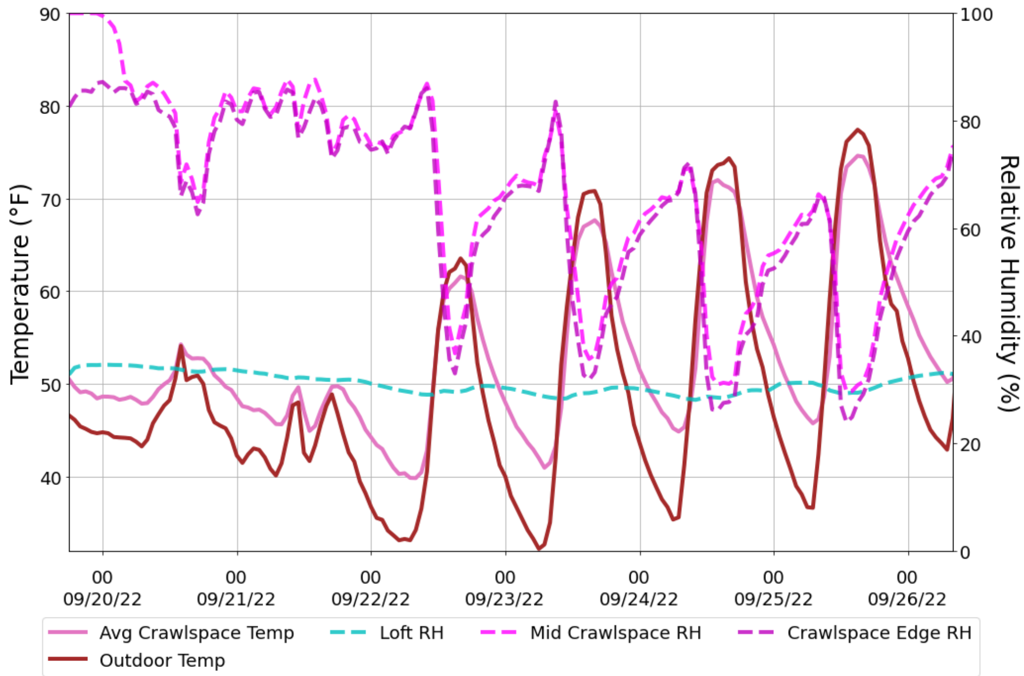


Figure 26. Relative humidity readings during Week 1

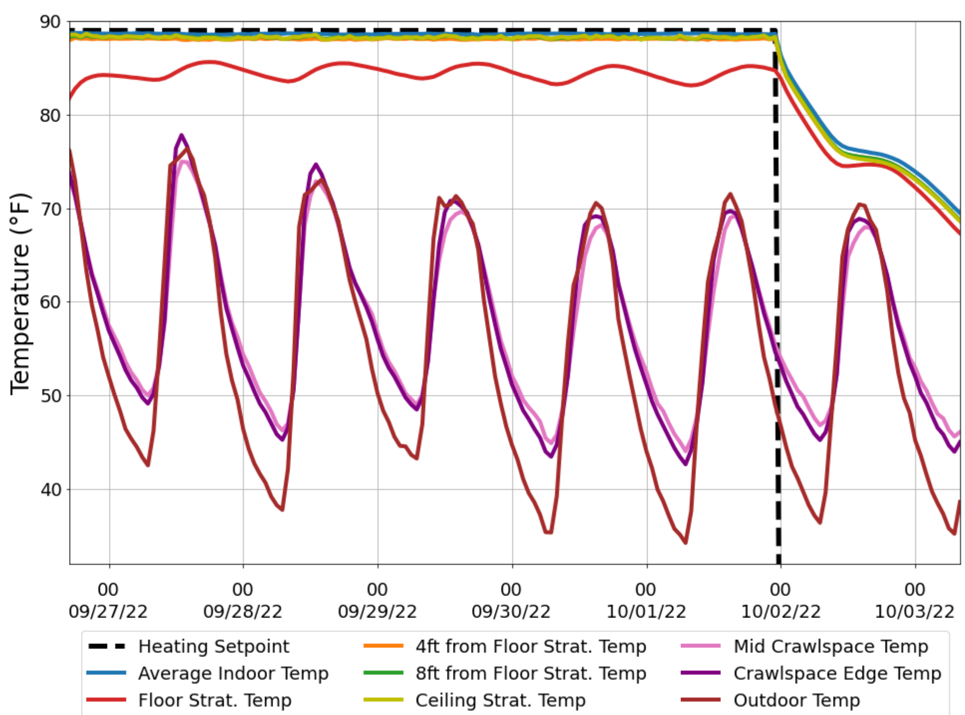


Figure 27. Miscellaneous temperature readings during Week 2

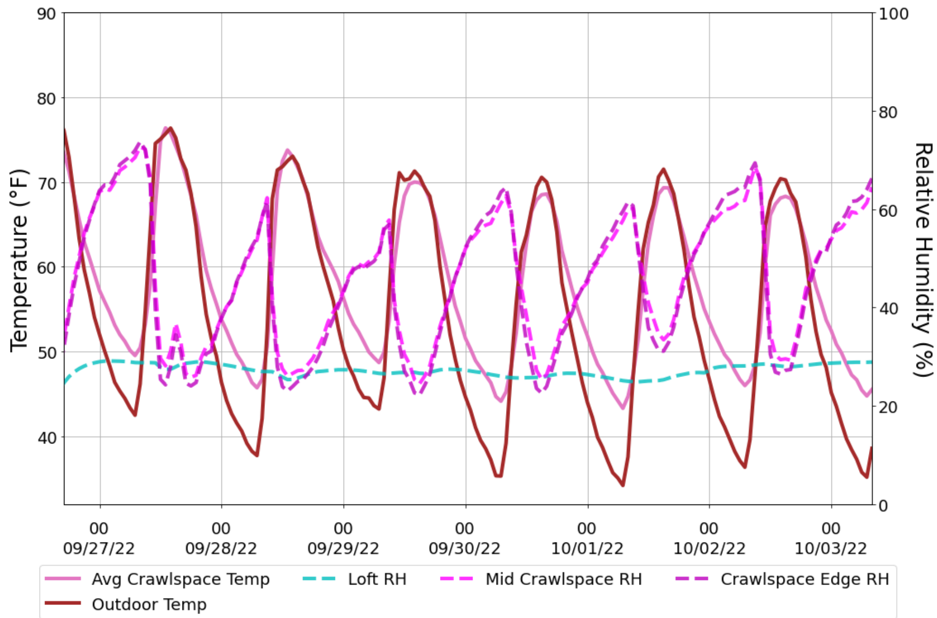


Figure 28. Relative humidity readings during Week 2

3.3 Model Calibration

Initial modeling results using construction specifications combined with actual operating conditions as well as measured leakage area and weather conditions are presented in Figure 29. Although average values for all metrics were relatively consistent between the monitored and modeled data, the interior of the home was clearly much less responsive to weather changes than the model predicted. This strongly suggested that the initial estimate of thermal mass was far too low, and possibly the rate of heat transfer to and from the thermal mass was too high in the model. Conversely, the crawlspace temperature responded more quickly to weather changes than the model predicted, suggesting that the ventilation rate was much higher in reality than initial assumptions.

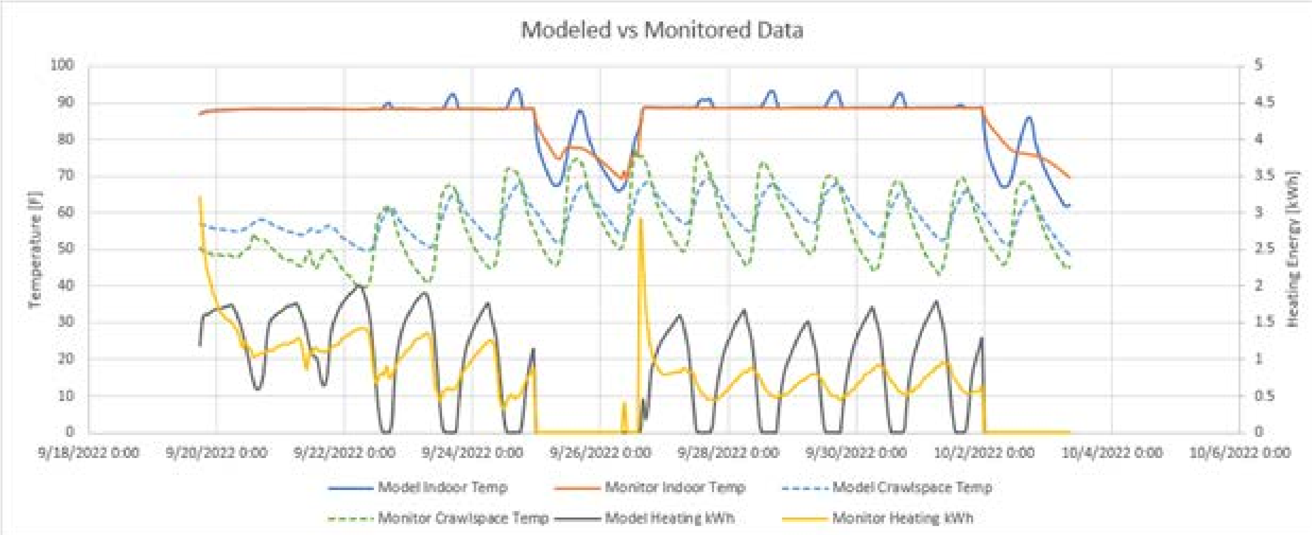


Figure 29. Initial comparison of modeled results to measured data prior to calibration

The calibration process included the model adjustments described in Table 3. In addition to these parameters, which were fairly uncertain and were adjusted within a reasonable range to better match measured field data, there were several modifications based on specific test measurements and corrections to issues identified in the original model, which was developed under another project. These include a correction to the floor and ceiling assemblies, use of measured air temperature in the crawlspace/chassis space instead of modeling infiltration and ground coupling, air infiltration based on the multipoint blower door test, a correction to building orientation, changes to one of the window areas to match the actual house, and a correction to the window properties published by the manufacturer. These model corrections were not part of the primary focus of this project, which was to calibrate uncertain modeling inputs that could not be measured accurately in the field, and to determine if the test method could provide enough confidence in the disaggregated envelope U-values that in situ performance issues could be quantified.

It became apparent early in the process that the solar gains would be nearly impossible to match because of the complex shading from nearby trees. The team also decided that the crawlspace temperature would be imposed on the model based on direct measurements, to remove the complex interactions between air infiltration and ground coupling. Our primary interest was in the performance of the opaque areas of the thermal envelope and not the thermal performance of the crawlspace. The important remaining parameters for calibration were the interior thermal mass, air infiltration, roof absorptivity and emissivity, the combined U-value of the windows and foam insulation covering them, and the effective U-values of the floor, ceiling, and opaque walls. Table 3 shows the parameters that were ultimately modified in the final calibrated model.

Table 3. Modeling Input Adjustments During Calibration Process

Parameter	Changes Made
Temperature capacity multiplier	Changed from 0 to 10
Roof shingle material	Changed from .25 reflectance to .55
Effective graphite-enhanced polystyrene floor insulation	Changed from R-15 to R-17.7
Glass window (covered)	Changed U-value to .111, solar heat gain coefficient to .02

Figure 30 compares key measurements with the results of the final calibrated model. We did not attempt to calibrate the model during the first week because of the complicated shading provided by nearby trees and homes, along with the interior temperature nonuniformity caused by one of the space heaters not working. We therefore focused on the second week, where we were able to match the average envelope UA within 4% (21.4 W/°F in the model compared to 22.2 W/°F based on measurements) during the consistent weather period from Sept. 28 to Oct. 1. The maximum and minimum heating requirements also matched very closely, indicating the UA in the model was very accurate. Thermal mass in the final model also caused the floating temperatures to match measured data very closely from Oct. 2 to Oct. 3.

The wall and ceiling U-values were not changed from their nominal design specifications, because there was no indication from the calibration process that these components performed better or worse than expected. The house seemed to respond to outdoor temperature cycling more slowly than the model predicts, but overall thermal mass and UA seem accurate. Possible explanations could be the heat transfer rate to and from thermal mass, the proportion of thermal mass that is inside the house versus outside, and inaccurate modeling of air infiltration (e.g., crack size and location) as a function of weather. We will consider additional measurements or tests that could be performed using the vacuum-insulated panel prototypes to shed light on this difference between modeled and measured thermal response times. Tracer gas testing would have shed light on the responsiveness of the house to infiltration drivers such as temperature and wind speed, but was not affordable within the scope of this project. However, it may be necessary in future tests to minimize the uncertainty of infiltration as a function of weather.

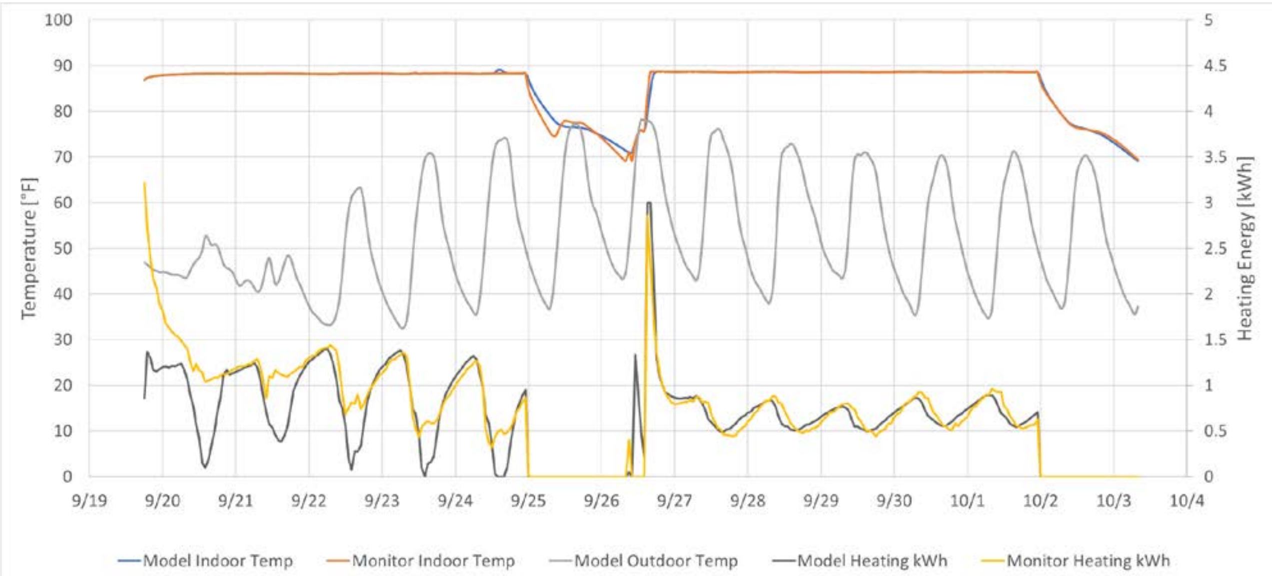


Figure 30. Final comparison of modeled results to measured data after calibration

Using the results of model calibration, we examined several potential modifications to the test schedule and protocols for short-term testing of envelope heat loss coefficient:

- Covering windows with a radiant barrier that has a known U-value is essential for minimizing solar gains that proved nearly impossible to model accurately. The first week of testing is therefore unnecessary.
- At least two days were necessary to achieve stable response to outside air temperature during the co-heating process, at which point another three days of co-heating seem adequate. Five days of co-heating seem to be appropriate.
- The final 32 hours of floating temperatures with co-heating disabled proved vital for successfully calibrating thermal mass.
- Including time for instrumentation and blower door testing, plus duct blaster testing needed for the overall home performance evaluation, an eight-day short-term test period is recommended for future tests.

4 Conclusions

Several important conclusions regarding the performance of the manufactured home and the sufficiency of the test methodology for disaggregating heat loss coefficient could be drawn from the short-term test results and subsequent model calibration:

- The test house, representing builder standard practice, has a relatively tight building envelope, with an effective leakage area of about 6.7 in^2. In future tests, the water line to the washing machine, which likely contributed much of this leakage, should be sealed prior to testing.
- All openings, including heat recovery ventilators, were well sealed prior to testing.
- Once all five co-heaters were operating, the interior temperature remained well mixed at the desired set point.
- The "crawlspace," which was actually just an open area where the chassis supporting the home was positioned, was well ventilated with uniform temperatures without skirting applied.
- There were no large hardwired loads drawing electricity during the test.
- Co-heating energy did not stabilize at any point during the test period, indicating that calibrated modeling will be necessary to calculate the total heat loss coefficient and component UAs.
- There was no evidence anyone entered the home during the two test periods.
- There were no gaps or major outliers in the monitored data.
- Calibrating solar gains in an EnergyPlus model for homes that are heavily shaded is extremely difficult in practice. Covering windows with a solar barrier is essential if the focus is on the performance of opaque envelope components.
- Tracer gas testing during the test period would be helpful to minimize the uncertainty of air infiltration as a function of weather conditions.
- The test period can be reduced from 15 days to 8 days without losing accuracy in model calibration. More diverse weather would likely help the calibration process, but four days of co-heating seems adequate, combined with one to two days of floating temperatures and one day at the beginning and one at the end for setup, blower door testing, equipment removal, and other activities.
- Based on the final calibrated model, the walls and ceiling appear to perform in accordance with design specifications.

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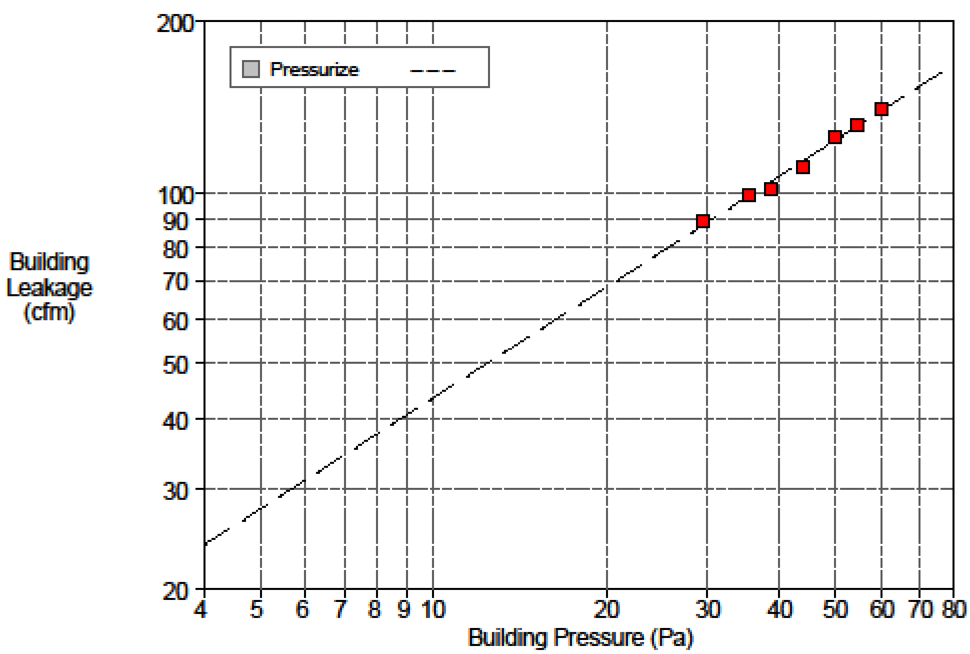
Appendix: Blower Door Test Results

Figure A-1. Pressurized blower door test results

Date of Test: 9/26/2022 Test File: VIP pressurize
Technician:
Project Number: VIPS pressurize
Customer: Building Address:

Test Results at 50 Pascals:	
cfm50 Airflow	123 (+/- 2.4 %)
ACH50	2.00
cfm/ft² (Floor Area)	0.4009
cfm/ft² (Surface Area)	0.0796
Leakage Areas:	12.7 in² (+/- 13.1 %) Canadian EqLA @ 10 Pa or 0.0082 in²/ft² Surface Area 6.8 in² (+/- 21.1 %) LBL ELA @ 4 Pa or 0.0044 in²/ft² Surface Area
Building Leakage Curve:	Flow Coefficient (C) = 9.7 (+/- 33.3 %) Exponent (n) = 0.650 (+/- 0.088) Correlation Coefficient = 0.99309
Test Standard:	E779-10
Test Mode:	Pressurization



Date of Test: 9/26/2022 Test File: VIP pressurize
Technician:
Project Number: VIPS pressurize
Customer: Building Address:

Test Results at 50 Pascals:

cfm50 Airflow	123 (+/- 2.4 %)
ACH50	2.00
cfm/ft² (Floor Area)	0.4009
cfm/ft² (Surface Area)	0.0796

BUILDING LEAKAGE TEST Page 3 of 4

Date of Test: 9/26/2022 Test File: VIP pressurize

Pressurization Test:

Environmental Data

	Indoor Temperature (°F)	Outdoor Temperature (°F)	Altitude (ft)
Pre-Test	75.0	77.0	
Post-Test	75.0	77.0	
Average	75.0	77.0	5817.0

Data Points - Automated Test (TTE 5.0.8.4)

Nominal Building Pressure (Pa)	Baseline adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (cfm)	Adjusted Flow (cfm)	% Error	Fan Configuration
0.0	n/a	n/a				
60.5	60.1	**74.1**	135	140	0.5	Ring 2
55.1	54.6	**66.0**	127	132	0.9	Ring 2
50.2	49.8	**59.2**	121	125	1.4	Ring 2
44.2	43.8	**47.1**	107	111	-1.8	Ring 2
39.1	38.7	**39.0**	98	101	-3.3	Ring 2
35.9	35.4	**37.4**	96	99	0.3	Ring 2
29.8	29.4	**30.6**	86	89	2.2	Ring 2
0.8	n/a	n/a				

Deviations from Standard ASTM E779-10 - Test Parameters

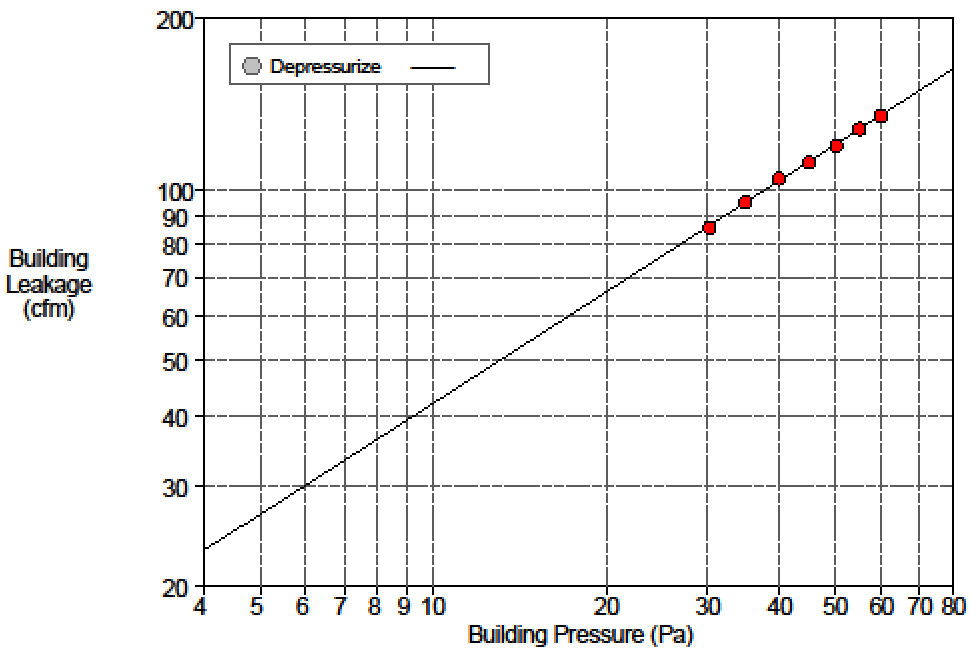
- Depressurization test not included.

Figure A-2. Depressurized blower door test results

Date of Test: 9/26/2022 Test File: VIPS depressurize
Technician:
Project Number: VIPS
Customer: Building Address:

Test Results at 50 Pascals:

cfm50 Airflow	120 (+/- 0.7 %)
ACH50	1.95
cfm/ft² (Floor Area)	0.3891
cfm/ft² (Surface Area)	0.0772
Leakage Areas:	12.3 in² (+/- 3.9 %) Canadian EqLA @ 10 Pa or 0.0079 in²/ft² Surface Area 6.6 in² (+/- 6.2 %) LBL ELA @ 4 Pa or 0.0042 in²/ft² Surface Area
Building Leakage Curve:	Flow Coefficient (C) = 9.4 (+/- 9.7 %) Exponent (n) = 0.652 (+/- 0.026) Correlation Coefficient = 0.99941
Test Standard:	E779-10
Test Mode:	Depressurization



BUILDING LEAKAGE TEST Page 2 of 4

Date of Test: 9/26/2022 Test File: VIPS depressurize

Building Information

Volume (ft^3)	3696
Surface Area: (ft^2)	1552
Floor Area: (ft^2)	308
Height (ft)	12
Year of Construction	

Equipment Information

Type	Manufacturer	Model	Serial Number	Custom Calibration Date
Fan	Energy Conservatory	Duct Blaster B		-
Micromanometer	Energy Conservatory	DG700	34179	1/12/2022

BUILDING LEAKAGE TEST Page 3 of 4

Date of Test: 9/26/2022 Test File: VIPS depressurize

Depressurization Test:

Environmental Data

	Indoor Temperature (°F)	Outdoor Temperature (°F)	Altitude (ft)
Pre-Test	75.0	77.0	
Post-Test	75.0	77.0	
Average	75.0	77.0	5817.0

Data Points - Automated Test (TTE 5.0.8.4)

Nominal Building Pressure (Pa)	Baseline adjusted Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (cfm)	Adjusted Flow (cfm)	% Error	Fan Configuration
-0.3	n/a	n/a				
-60.2	-60.1	68.5	130	135	0.1	Ring 2
-55.2	-55.1	61.3	123	128	0.1	Ring 2
-50.4	-50.2	53.6	115	119	-0.7	Ring 2
-45.2	-45.0	46.9	107	112	-0.3	Ring 2
-40.1	-39.9	41.2	100	105	1.0	Ring 2
-35.0	-34.9	34.1	91	95	0.2	Ring 2
-30.4	-30.2	27.9	82	86	-0.5	Ring 2
0.0	n/a	n/a				

Deviations from Standard ASTM E779-10 - Test Parameters

- Pressurization test not included.

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