U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

# Evaluation of Crawlspace Retrofits in Multifamily Buildings

**Armin Rudd**
*Building Science Corporation*

September 2014

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Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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*Unless otherwise indicated, all tables were created by BSC.*

## Definitions

| | |
|---|---|
| ACH 50 | Air changes per hour at 50 Pascal test pressure ($hour^{-1}$) |
| AFUE | Annual fuel utilization efficiency |
| BSC | Building Science Corporation |
| CFL | Compact fluorescent lamp |
| cfm | Cubic feet per minute |
| DHW | Domestic hot water |
| EF | Energy factor |
| gpd | Gallons per day |
| gpm | Gallons per month |
| IRC | International Residential Code |
| kWh | Kilowatt-hour |
| nACH | Natural air changes per hour ($hour^{-1}$) |
| Pa | Pascal |
| PHFA | Pennsylvania Housing Finance Agency |
| RH | Relative humidity |
| SIR | Savings to investment ratio |
| TREAT | Targeted Retrofit Energy Analysis Tool |
| WRT | With respect to (used to reference pressure measurements) |

# Acknowledgments

Innova Services Corporation participated as a Building America partner on this project. Innova participants were Jeffrey Allegretti, Adam Blackburn, and Vaughan Piccolo.

# Executive Summary

In 2011 and early 2012, Building Science Corporation (BSC) collaborated with Innova Services Corporation on a multifamily community unvented crawlspace retrofit project at Oakwood Gardens in Lansdale, Pennsylvania. The actual retrofit work was funded by the Pennsylvania Housing Finance Agency. BSC provided design consulting services and pre- and post-retrofit evaluation, testing, and data monitoring. The U.S. Department of Energy Building America Program funded this work.

The existing condition was a vented crawlspace with an uninsulated floor between the crawlspace and the dwelling units above. The crawlspace was therefore a critically weak link in the building enclosure and was ripe for improvement. Saving energy was the primary interest and goal, but the greatest challenge in this unvented crawlspace retrofit project was working through a crawlspace bulk water intrusion problem caused by inadequate site drainage, window well drainage, foundation wall drainage, and a rising water table during rainy periods. Ideally, bulk water intrusion into the crawlspaces would be eliminated by addressing drainage before the unvented crawlspace retrofit begins with wall insulation and exhaust ventilation. The following steps were taken in this retrofit:

1. The crawlspace windows were blocked off and sealed against bulk water intrusion and air leakage to avoid moisture damage to the crawlspace framing and outside air bypass of the wall insulation. This brought the crawlspace into the building enclosure to maintain a stable warm temperature.
2. Exhaust ventilation was installed in the crawlspace, which pulled air from the dwelling units above to improve their air quality and to dry the crawlspace.
3. Sump pumps were strategically placed to keep the water table from rising enough to flood the concrete slab floor.

The post-retrofit crawlspace environmental conditions were better than they were before the insulation retrofit in addition to the improved energy performance. The moisture mitigation efforts had no effect on the overall energy savings, and savings to investment ratio. These measures were required to achieve adequate durability and better indoor air quality.

Annual energy savings based on the Targeted Retrofit Energy Analysis Tool model were expected to be about $4,000, and life cycle cost savings were expected to be about $36,000. The BEopt model showed that the crawlspace retrofit, the boiler upgrade for heating and domestic hot water, and compact fluorescent lamps individually and collectively saved energy and money. The combined improvements fell on the BEopt optimal curve and had average source energy savings of 18%.

A period of long-term post-retrofit monitoring was completed between March 2012 and July 2013. The main purpose of the long-term monitoring, and testing at the end of the monitoring period, was to track the crawlspace humidity conditions and the floor framing wood moisture content for a year after the unvented crawlspace retrofit. While the unvented crawlspace retrofit was effective in reducing heat loss, and the majority of the bulk water drainage problems had been resolved, the important finding was that some of the wood joists embedded in masonry

pockets behind the brick veneer were showing signs of moisture damage. A small airspace between the insulation and the joist was needed to allow the joist to adequately dry when it got wet from water passing through the brick veneer or from capillary uptake from the masonry unit. Brick leaks water, masonry units draw and hold water, and wood is both water absorptive and water sensitive. An airspace around the wood joists would keep the wood warmer and allow it to dry when it got wet, as it had for the last 40 years. This drying requirement reasoning was also influenced by having seen some pre-retrofit water staining at the ends of some wood joists, which indicated that the joists had been getting wet and drying, and tolerating that. Since it would not be possible to reliably determine which joists may become moisture damaged over time, a recommendation was made that the foam insulation be cut back ½ in. from around all the joists in all of the crawlspaces to increase drying of the joist ends. It was apparent that the risk of moisture damage to the wood joist ends far outweighed the energy penalty of the small area of uninsulated wall around the joists.

# 1 Introduction

Building Science Corporation (BSC) performed this research with Innova Services Corporation (Innova), a Philadelphia, Pennsylvania-based firm that works in various sectors of affordable housing, including construction project management, general contracting, and building retrofit services for the affordable housing industry.

Research on this multifamily retrofit was conducted at a group of buildings where federal retrofit funding was coming through the Pennsylvania Housing Finance Agency (PHFA) "Preservation Through Smart Rehab" Energy Efficiency Retrofits. The PHFA offers owners of multifamily affordable housing loans and grants to improve the energy efficiency of their buildings. The program, Preservation through Smart Rehab, approved a variety of building retrofits for Oakwood Gardens. Adam Blackburn was project manager, Multifamily Energy Solutions, for Innova.

The existing condition was a vented crawlspace with an uninsulated floor between the crawlspace and the dwelling units above. The crawlspace was therefore a critically weak link in the building enclosure and was ripe for improvement. BSC's particular experience in this area made this the appropriate focus of our efforts. BSC visited the Oakwood Gardens site with Innova.

Saving energy was the primary interest and goal, but the greatest challenge in this project was working through a crawlspace bulk water intrusion problem caused by inadequate site drainage, window well drainage, foundation wall drainage, and a rising water table during rainy periods.

## 1.1 Oakwood Gardens Background

The buildings are located at Oakwood Gardens, 421 E. Main St., Lansdale, PA 19139.

| | |
|---|---|
| Owner: | Oakwood Gardens Associates |
| Prop. Mgmt.: | Gross & Quade Management Co. |
| Size: | 8 Two-Story Buildings, 48 Units, 45,500 ft$^2$ |
| Age: | Approximately 70 years old |
| Structure: | Concrete block foundation walls, wood-framed above-grade walls, brick veneer cladding, wood-framed floors and roof |
| Occupancy: | Families with rent subsidies |
| Utilities: | Direct-metered electricity for each apartment is paid by the occupant. Separate electricity metering for common areas, all delivered oil (which serves only the central mechanical systems), and water are paid by the building management. |


**Figure 1. Oakwood Gardens, Lansdale, Pennsylvania, entrance sign (L) and front of Building D (R)**


**Figure 2. Oakwood Gardens apartments, aerial view (L) and back of Buildings A and B (R)**


Figure 3. Oakwood Gardens site rendering

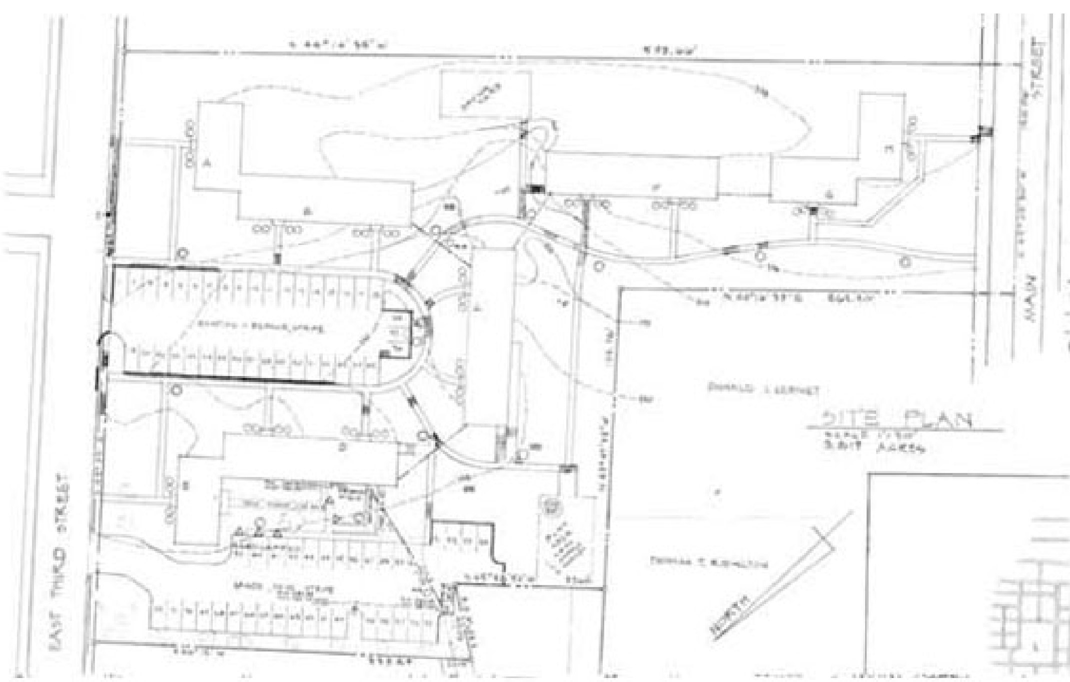


Figure 4. Oakwood Gardens site plan showing layout of the building

# 2 Overall Project Retrofit Plan

## 2.1 Oakwood Gardens Energy Audit by MaGrann Associates

MaGrann Associates conducted a detailed audit of the Oakwood Gardens complex for the PHFA in December 2009 (MaGrann 2009). The work for this retrofit project was constrained by programmatic limitations: energy cost savings measures were required to meet cost-effectiveness requirements to be funded under various government programs. These requirements included a minimum savings to investment ratio (SIR) of 1.0 for the U.S. Department of Energy and 0.6 for PHFA.

Table 1 shows a description of all the measures evaluated by the MaGrann audit. Table 2 shows the predicted energy performance. All the recommended improvement measures were evaluated using the Targeted Retrofit Energy Analysis Tool (TREAT) software – a software tool for energy analysis and building modeling. The red text of improvement measures in Table 1 and Table 2 draws focus to the measures related to the crawlspace work since those measures were the only efforts BSC became fully involved with for this project. Referring to Table 2, the Annual Cost Savings and the Life Cycle Savings for the crawlspace air sealing and wall insulation retrofit were $3,960 and $36,493, respectively.
MaGrann also analyzed previous utility data. Figure 5 shows “House” electricity consumption data for the period from April 2008 to June 2009. “House” consumption includes all common areas and pumps for the central heating plant. Figure 6 shows in-unit “Apartment” electricity consumption data (including those for window cooling units if they had any) for December 2007 to November 2008. The data show that approximately 72% of the total community’s electricity is consumed in the dwelling units, while 28% is consumed in the common spaces and central plant (MaGrann 2009).

The central heating plant uses oil to heat water for space heating and domestic hot water (DHW). Figure 7 shows that oil consumption peaks at about 2,300 gal/month in winter, and is about 900 gal/month in summer. The central plant fuel was switched from oil to gas. Figure 9 shows the before and after boiler retrofit photos.

Figure 8 shows the average site water consumption in gal/day by month, which is consistently 6,000–7,000 gal/day. Annual water use for the community totals about 2.3 million gal, at a cost of $9,670. This converts to an average use of 132 gal/apartment/day. According to HUD data, this is about 11% lower than a typical multifamily complex of this size (MaGrann 2009).

The text that follows, relative to the crawlspace/basement wall insulation, was taken from the audit conducted by MaGrann Associates in 2009:

> The foundations for the eight buildings in the community are a mix of basements and enclosed crawl spaces. None of the foundation walls, floor assemblies over the basements, or floor assemblies over the crawl spaces are insulated. Additionally, there is no band joist insulation installed in any of the buildings in the community. These uninsulated areas of the foundations allow heat to be easily transferred between the conditioned buildings and the exterior.

Recommended Actions: Install 1 in. of Thermax rigid insulation in the band joists between the basement or crawlspace of each building and the first floor to limit conductive heat transfer between these spaces and the exterior of the buildings. Insulate the basement and crawl space walls that are exposed to ambient air from the sill plate down to at least 2 ft below grade with 1 in. of Thermax rigid insulation.

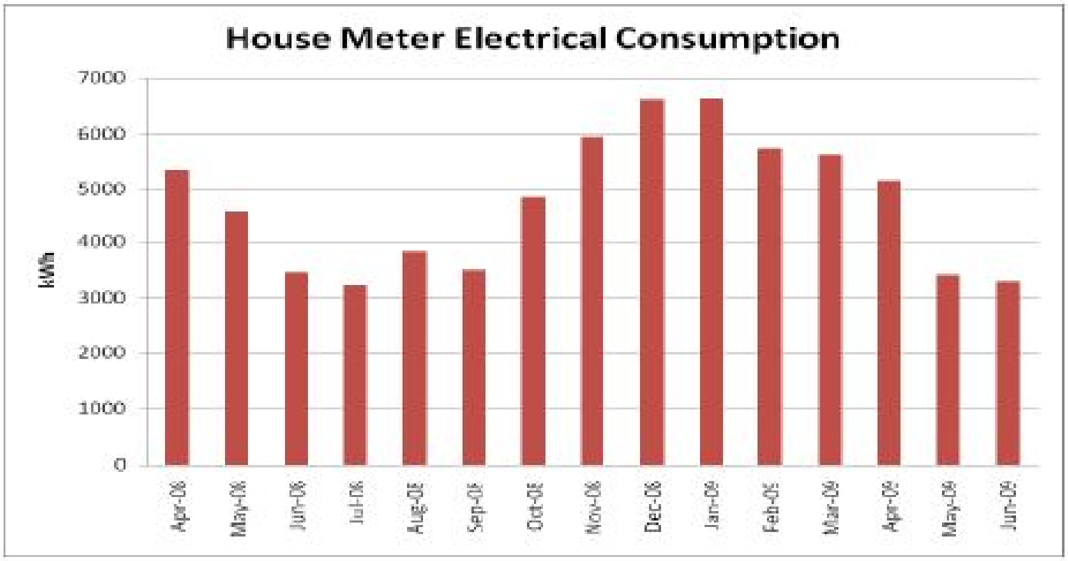


**Figure 5. Previous year of metered electricity consumption paid for by the owner**

(MaGrann 2009)

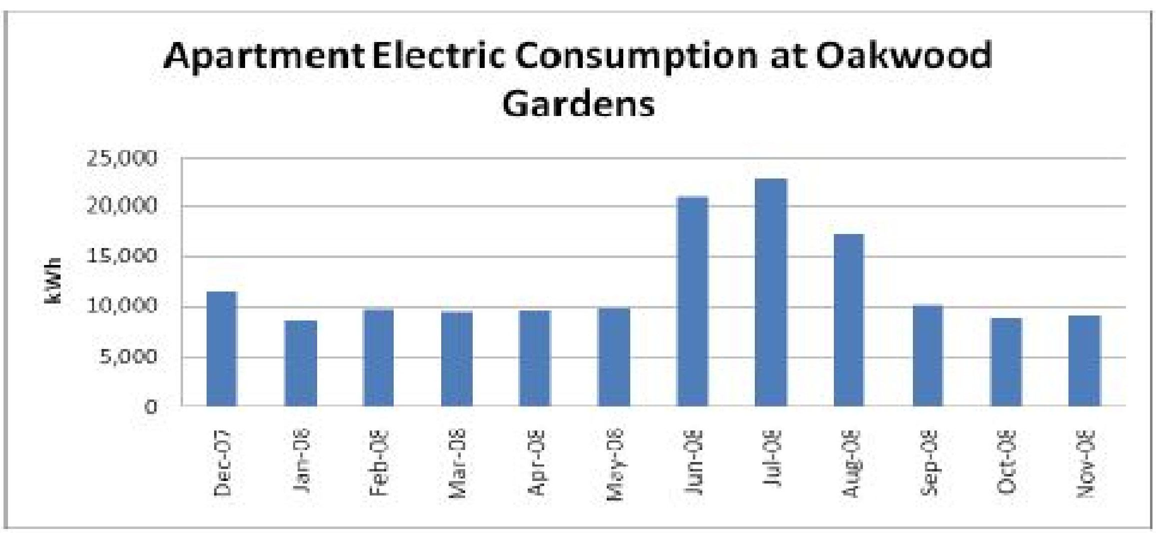


**Figure 6. Previous year of all electricity consumption in the apartment (including that for window cooling units if they had any) paid for by the tenants**

(MaGrann 2009)

**Table 1. Description of All Evaluated Measures in the MaGrann Audit (December 2009)**

| Category | Upgrade Measure | Savings Benefit | Notes and Assumptions |
|---|---|---|---|
| **Air Leakage** | Air seal foundations and band joist areas | Owner and Tenant | Assumes a 3% infiltration reduction |
| **Air Leakage** | Exterior door weather stripping | Owner and Tenant | Assumes a 3% infiltration reduction |
| **DHW** | Temperature sensor on return | Owner | Assumes an 8% reduction in DHW fuel consumption |
| **DHW** | Replace all lavatory aerators with 1.5-gpm models | Owner | |
| **DHW** | Replace all showerheads with 2.0-gpm models | Owner | |
| **DHW** | Boiler replacement | Owner | Includes cost of control upgrade |
| **DHW** | Insulate pipes for DHW | Owner | Insulation improvement modeled as R-2 |
| **Envelope** | Insulate foundation band joist areas | Owner and Tenant | 1-in. Thermax, R-6.5 |
| **Envelope** | Insulate and weather strip attic accesses | Owner and Tenant | Includes improved R-value and a 1% infiltration reduction |
| **Envelope** | Isolate upper attic from lower attic | Owner and Tenant | Adds the full R-value of blown-in insulation currently installed in upper attic |
| **Envelope** | Insulate foundation walls | Owner and Tenant | 1-in. Thermax, R-6.5 at a depth of 4 in. down from the sill plate |
| **Envelope** | Replace foundation windows | Owner and Tenant | |
| **Envelope** | Replace wooden exterior doors | Owner | 1% infiltration reduction |
| **Health and Safety** | Install bath exhaust fans with timer controls | Tenant | |
| **Heating** | Zone controls on stairwell heaters | Owner | Savings based on 1% infiltration reduction and 1° thermostat set point reduction |
| **Heating** | Variable frequency drive on main circulator pump | Tenant | Variable frequency drive calculator |
| **Heating** | Fuel switch to natural gas | Owner | Assumes $1.40/therm gas rate, savings based on annual fuel consumption following upgrades |
| **Heating** | Boiler replacement | Owner | Includes heating pipe insulation savings and cost, and control upgrade cost |
| **Lighting** | T8 replacements in mechanical room, offices, laundry | Owner | Includes occupancy sensors in laundries, maintenance office, and storage rooms |
| **Lighting** | T8 replacements in stairwells | Owner | |
| **Lighting** | In-unit compact fluorescent lamps | Tenant | Includes linear fluorescent lighting upgrades in kitchens |
| **Lighting** | Compact fluorescent lamps (CFLs) in common areas | Owner | |

**Table 2. Predicted Energy Performance of Recommended Improvement Measures**

(MaGrann 2009)

| | Measures | Installed Costs ($) | Annual Electricity Savings (kWh) | Annual Oil Savings (Therms) | Annual Water/ Sewer Savings (Gal) | Annual Cost Savings ($) | Payback (Years) | SIR | Life Cycle Savings ($) | Years for Life Cycle Cost |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Isolate upper and lower attics | 4,456 | 2,395 | 1,100 | 0 | 2,277 | 1.96 | 10.02 | 40,174 | 30 |
| **2** | Recirculation control | 481 | 933 | 110 | 0 | 383 | 1.26 | 9.50 | 4,092 | 15 |
| **3** | Zone controls for stairwell radiators | 2,441 | –8 | 1,484 | 0 | 2,521 | 0.97 | 8.81 | 19,065 | 10 |
| **4** | Common Area CFLs | 248 | 2,632 | –64.1 | 0 | 444 | 0.56 | 8.21 | 1,785 | 5 |
| **5** | Variable frequency drive recirculating pumps | 2,260 | 5,982 | 0 | 0 | 1,526 | 1.80 | 6.64 | 12,737 | 15 |
| **6** | Air seal foundations and band joists | 1,915 | –23 | 336 | 0 | 546 | 3.51 | 5.59 | 8,781 | 30 |
| **7** | Low-flow aerators and showerheads | 11,277 | 0 | 2,544 | 721,824 | 7,212 | 1.56 | 3.98 | 33,656 | 7 |
| **8** | Insulate band joist areas | 9,936 | 0 | 762 | 0 | 1,295 | 7.67 | 2.56 | 15,454 | 30 |
| **9** | Heating condensing boiler | 46,660 | 0 | 5,354 | 0 | 9,102 | 5.13 | 2.33 | 61,997 | 15 |
| **10** | In-unit lighting upgrade | 13,478 | 24,814 | –576 | 0 | 3,240 | 4.16 | 2.05 | 14,157 | 10 |
| **11** | Office, shop, laundry, storage t8 | 5,833 | 4,616 | –39 | 0 | 903 | 6.46 | 1.85 | 4,948 | 15 |
| **12** | Insulate foundation walls | 39,196 | | 2,008 | 0 | 3,414 | 11.48 | 1.71 | 27,712 | 30 |
| **13** | Insulate and weather strip attic access | 3,342 | 73 | 151.2 | 0 | 269 | 12.40 | 1.58 | 1,939 | 30 |
| **14** | Door weather stripping | 547 | –8 | 108 | 0 | 182 | 3.01 | 1.52 | 285 | 5 |
| **15** | Insulate DHW piping | 4,298 | 712 | 122.7 | 0 | 330 | 13.04 | 1.14 | 606 | 20 |
| **16** | DHW condensing boiler | 45,342 | 3 | 2,370 | 0 | 4,030 | 11.25 | 1.06 | 2,763 | 15 |
| **17** | Fuel switch to natural gas | 51,573 | 0 | 0 | 0 | 2,749 | 18.76 | 0.79 | –10,675 | 20 |
| **Architectural and Engineering Fees** | | 9,500 | All individual measure installation cost estimates include allowances for general condition (6%), fees (2%), and overhead (6%) | | | | | | | |
| **Building Permits** | | 1,946 | | | | | | | | |
| **Contingency (10%)** | | 24,328 | | | | | | | | |
| **Total Package** | | 252,783 | 42,122 | 15,771 | 721,824 | 40,152 | 6.30 | 1.35 | 89,721 | 10 |

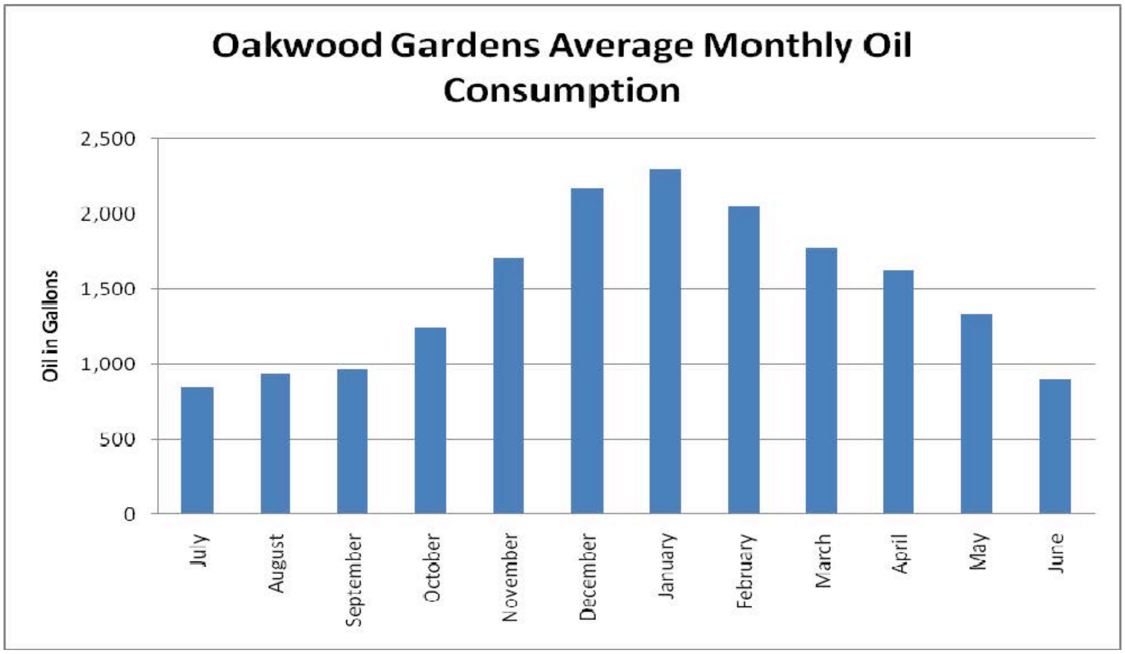


**Figure 7. Average monthly oil consumption by the central heating plant providing hot water for space heating and DHW**

(MaGrann 2009)

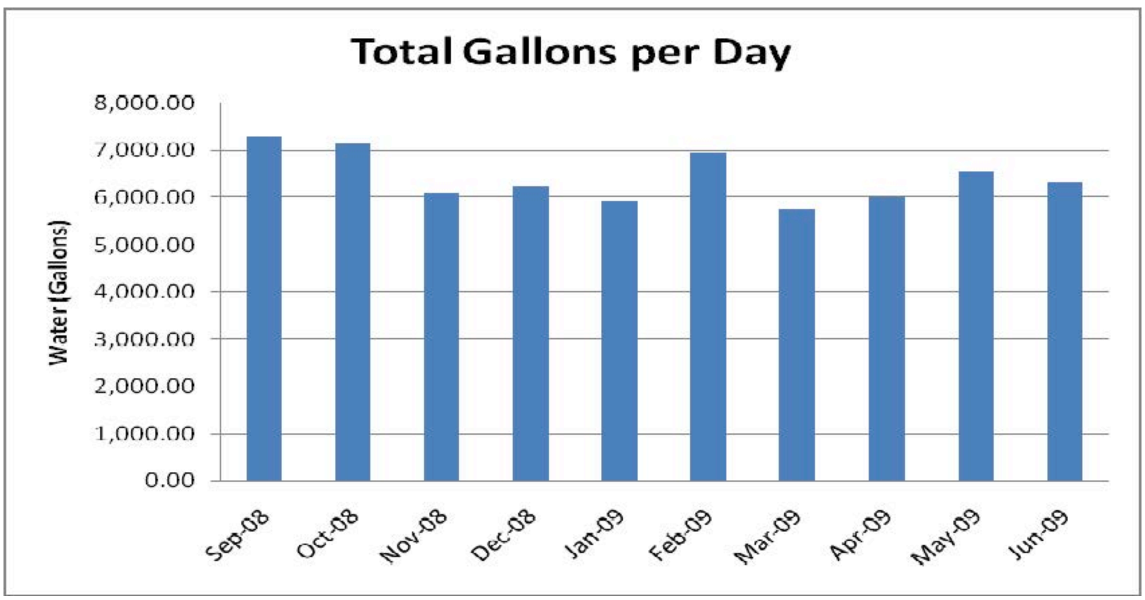


**Figure 8. Average monthly site water consumption in gpd**

(MaGrann 2009)

**Figure 9. Atmospheric boilers (L) were replaced with condensing sealed-combustion boilers (R)**

## 2.2 Initial Building Science Corporation Site Visit to Oakwood Gardens With Innova

After exchanging electronic information and holding a follow-up conference call, a meeting between Innova and BSC was held at the Innova offices in Philadelphia on June 13, 2012. The Oakwood Gardens project was identified as the best project for BSC to provide technical support to Innova. It would allow evaluation and documentation of a multifamily community retrofit project in which the crawlspaces under the buildings would be sealed and the exterior stem walls insulated. That same afternoon, BSC visited the Oakwood Gardens site with Innova.

After evaluating the condition of some of the crawlspaces and the site, BSC recommended that the crawlspace windows and window wells be sealed against bulk water intrusion and air leakage (Figure 11). The crawlspaces ranged from wet to mostly dry, going from a shallow at-grade to a deeper crawlspace with about 3 ft of above-grade wall, respectively. All crawlspaces had concrete slab floors, but wet mud and some standing water were prevalent in some. Wet or damp slabs and concrete block walls were evident in others. For financial reasons, a major foundation drainage upgrade was not an option. Considering the mud on top of the concrete slab in the crawlspace, the condition of the window wells, and the site drainage conditions, BSC believed that blocking water intrusion through the window wells was the first best affordable option for trying to manage the crawlspace water/moisture problem.

**Figure 10. Project team discussions near a window well behind Buildings B and A; the at-grade crawlspace inside was wet and muddy**

**Figure 11. Evidence indicating bulk water intrusion through the crawlspace windows**

## 2.3 Research Questions

Crawlspace foundations are not common in all regions of the United States but they are common in many regions. Crawlspace bulk water intrusion, rising ground water table, and inadequate soil water vapor control issues are all too common as well. In order to ensure durability and indoor air quality in existing building retrofit programs, this research project evaluated and addressed these problems in one multifamily project. The key research questions with relevance to Building America goals follow:

1. What are the real-world challenges in pursuing energy savings through improving crawlspace foundations?
2. Where does crawlspace insulation improvement fall in the order of optimal energy savings in multifamily retrofit work?
3. What is the best approach to crawlspace retrofit when bulk water intrusion is evident?
4. What is the best approach to crawlspace retrofit when wood joists are embedded in concrete block foundation walls with brick veneer cladding?

## 2.4 Unvented Crawlspaces Background

Unvented crawlspaces are International Residential Code (IRC) approved (section R408.3) (IRC 2009). Crawlspaces can be constructed such that the interior grade is higher than the exterior grade, as in Figure 12, or lower than the exterior grade, as in Figure 13, which is effectively no different than a "short basement." For an unvented crawlspace, the foundation wall is insulated rather than the floor cavity above, turning the crawlspace into semi-conditioned space (Lstiburek 2009). Any mechanical equipment, ductwork, wiring, piping, etc., in that space, are then in a semi-controlled, mild environment. That eliminates heat gain and heat loss inefficiency issues, makes equipment last longer, and makes maintenance or repair easier because working conditions are more comfortable.

The IRC Code provision follows:

> **R408.3 Unvented crawl space.** Ventilation openings in under-floor spaces specified in Sections R408.1 and R408.2 shall not be required where:
>
> 1. Exposed earth is covered with a continuous Class I vapor retarder. Joints of the vapor retarder shall overlap by 6 inches (152 mm) and shall be sealed or taped. The edges of the vapor retarder shall extend at least 6 inches (152 mm) up the stem wall and shall be attached and sealed to the stem wall; and
> 2. One of the following is provided for the under-floor space:
>    2.1. Continuously operated mechanical exhaust ventilation at a rate equal to 1 cubic foot per minute (0.47 L/s) for each 50 square feet (4.7m2) of crawlspace floor area, including an air pathway to the common area (such as a duct or transfer grille), and perimeter walls insulated in accordance with Section N1102.2.9;
>    2.2. Conditioned air supply sized to deliver at a rate equal to 1 cubic foot per minute (0.47 L/s) for
>    each 50 square feet (4.7 m2) of under-floor area, including a return air pathway to the common area (such as a duct or transfer grille), and perimeter walls insulated in accordance with Section N1102.2.9;

2.3. Plenum in existing structures complying with Section M1601.5, if under-floor space is used as a plenum.

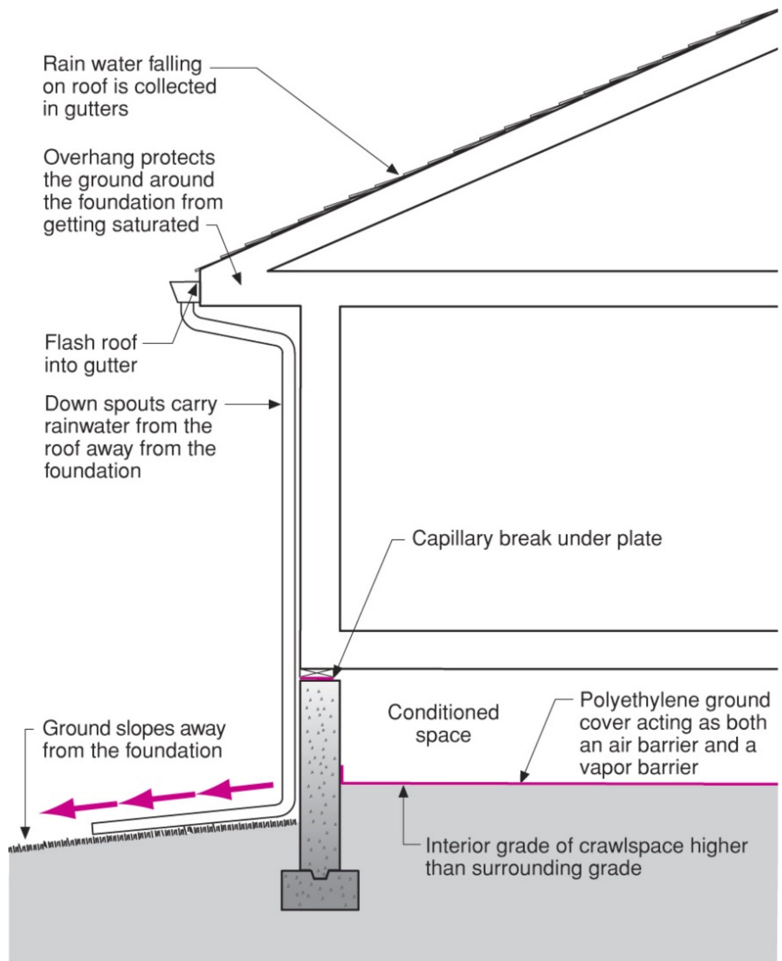


**Figure 12. Conventional crawlspace section drawing where interior grade is higher than exterior grade**

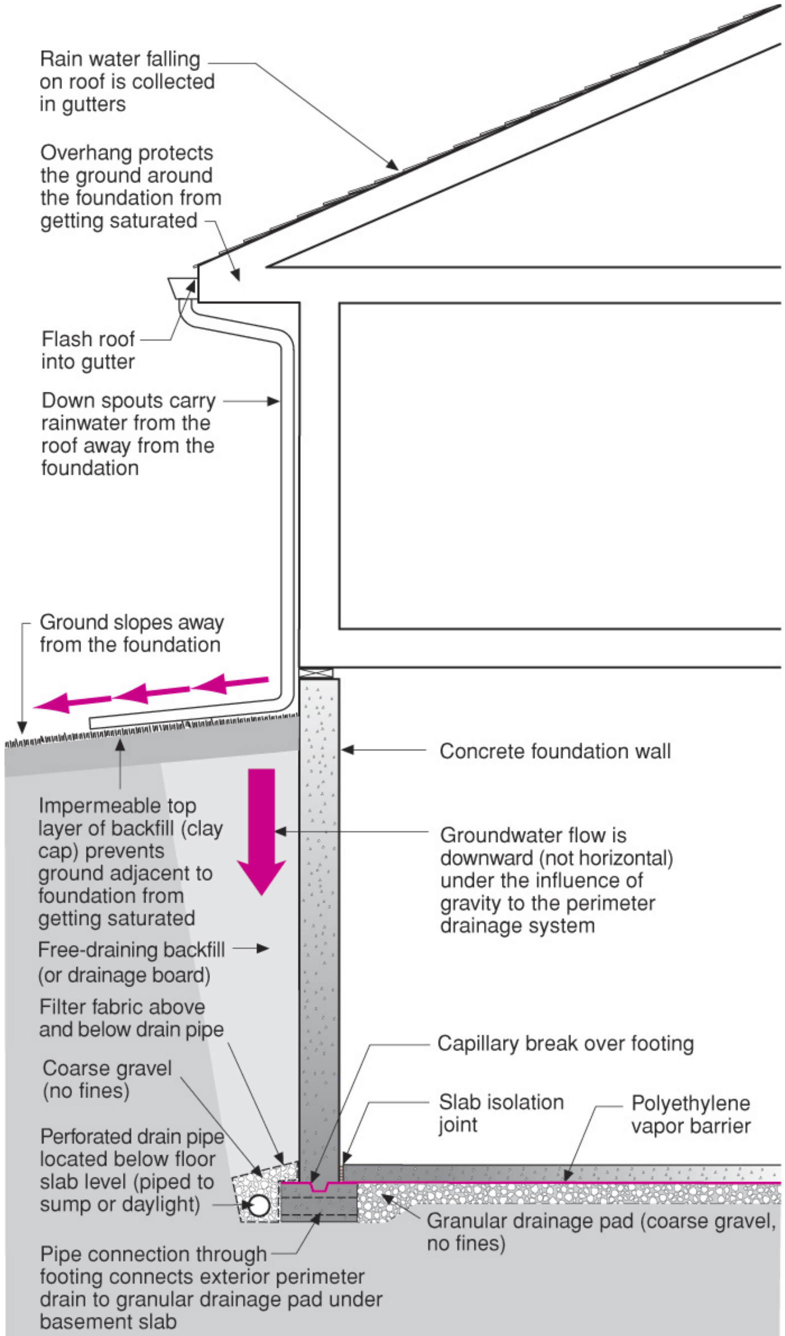


**Figure 13. Conventional basement or crawlspace section drawing where interior grade is below exterior grade**

Figure 14 is a section drawing of the "as-built" crawlspace after the wall insulation retrofit; Figure 15 shows what would have been a recommended best practice design from the beginning.

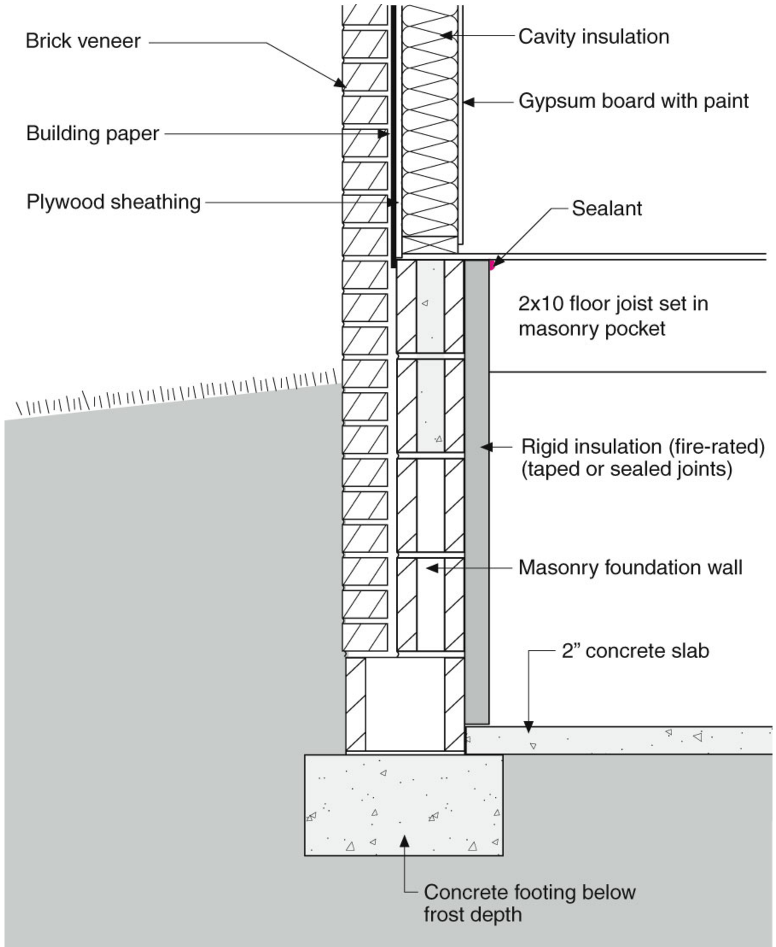


**Figure 14. Section drawing of the “as-built” crawlspace wall after the wall insulation retrofit**

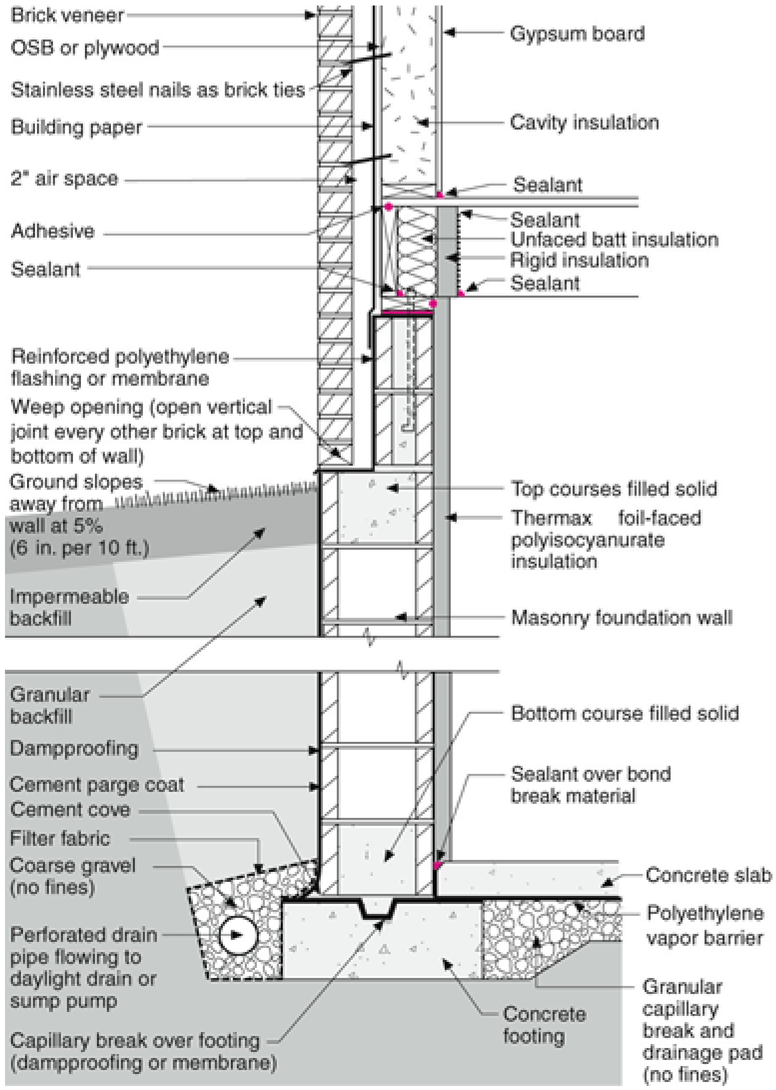


**Figure 15. Section drawing of what would have been a recommended appropriate design from the beginning**

Design professionals sometimes argue that the floor above the crawlspace, rather than the crawlspace walls, should be insulated. That may be true in many cases, but in this case it would have been a disaster for the durability of wood framing in the crawlspace. If the floor above the crawlspace were insulated instead of the walls, the crawlspace would have become colder than it had been for much of the year, raising the relative humidity (RH), and resulting in mold and rot in a short time. The wet crawlspaces at Oakwood Gardens survived as well as they did because they were kept warm with heat from the dwelling units above. Keeping the crawlspaces even warmer with heat from above, by insulating the walls to reduce heat loss, is clearly the right way to go.

Another important component of this project relates to some uncertainty about fully insulating around water-sensitive wood joists embedded into water-absorptive concrete block, as shown in Figure 16. Additional work was done to track the wood joist ends over time and determine whether insulating the band area tight to the wood joists embedded in the masonry wall is a recommended practice.

**Figure 16. Water-sensitive wood joists embedded into water-absorptive concrete block**

## 2.5 Amended Crawlspace Retrofit Scope

After the initial site visit, BSC recommended that blocking off and sealing the crawlspace windows against air infiltration and bulk water intrusion would be necessary to make the unvented crawlspace retrofit effective. Innova then sent out new bid request language and details (Figure 17) relative to the crawlspace insulation and air sealing improvement measure, on June 17, 2011, as follows:

> Add/Alternate Scope Items and Scope Clarifications:
>
> a. Insulate the interior face of the basement and crawlspace walls from the sill plate down to floor slab with 1” (one inch) Thermax rigid insulation.
>
> b. Block below-exterior grade crawlspace windows with ½” Durock panel. Wrap panel in peel-and-stick impermeable membrane. Affix to surrounding masonry with masonry anchors, screws and washers. Apply caulk seal at interior where panel meets window opening and at exterior where panel meets brick cladding. Backfill window pits with loose stone fill.

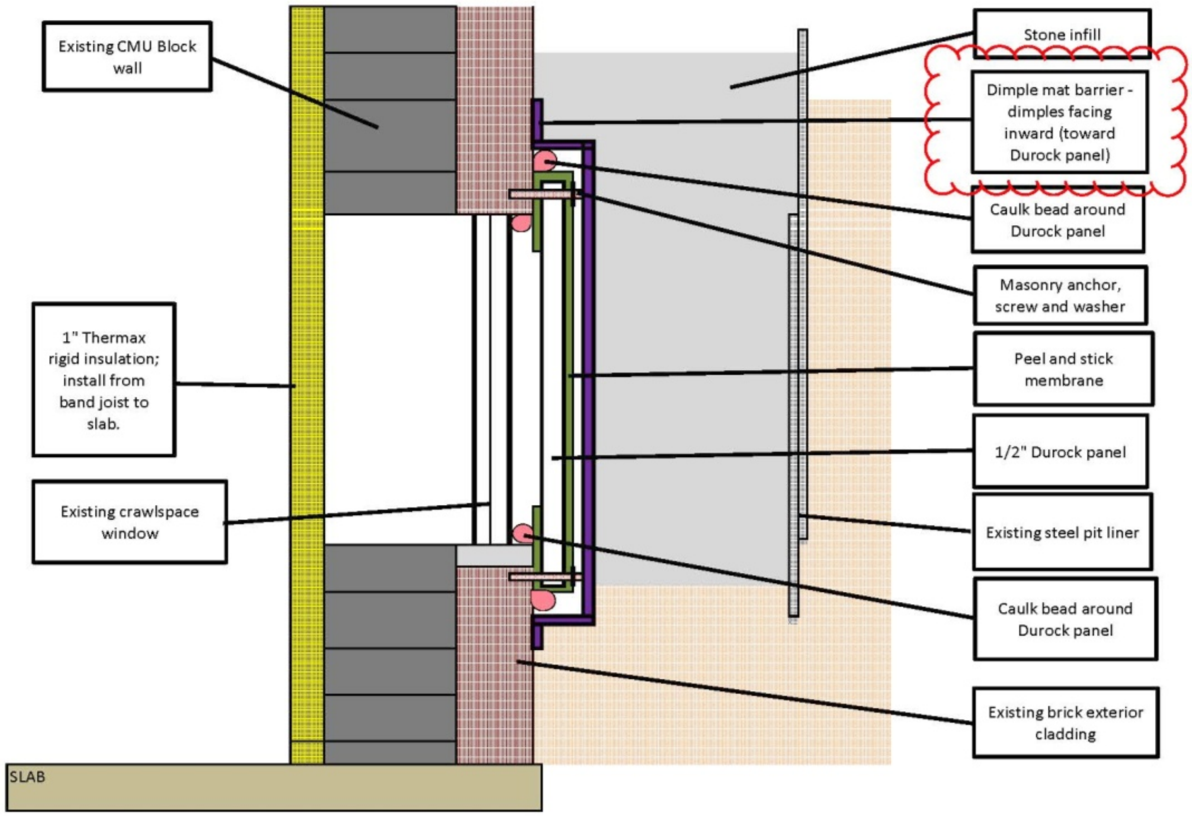


**Figure 17. Window well retrofit detail that went out with the Innova bid request, for sealing the crawlspace windows against water intrusion and air leakage**

## 2.6 Unvented Crawlspace Exhaust Ventilation

After the exterior crawlspace windows were blocked and sealed off (all of which were air leaky and some of which were allowing bulk water intrusion to the crawlspaces), and after the interior wall insulation part of the unvented crawlspace retrofit was completed, controlled mechanical exhaust ventilation of the crawlspace was installed. This system is shown schematically in Figure 18. The under-slab polyethylene vapor barrier shown in Figure 18 is best practice but not part of the existing condition. A drawing of the installed exhaust ventilation system is shown in Figure 21. The floor interface between the crawlspace and the dwelling units above was leaky compared to the insulated and sealed foundation walls (Figure 19); thus, exhaust ventilation of the crawlspace would preferentially draw air from the dwelling units above, helping to further dry the crawlspaces and improve air quality in the dwellings.

With relatively airtight crawlspace walls, air from the dwelling units will be drawn through leakage in the floor. That will reduce the crawlspace humidity, potentially reduce radon gas concentration in the crawlspace, and potentially improve air quality in the dwelling units. The reasons are both because of slightly increased dwelling air exchange with outdoors and because of keeping contaminated air from the crawlspace from moving upward into the dwelling units. The existing dwellings did not have designed whole-building mechanical ventilation. The rated power draw of the inline exhaust fan used for each crawlspace was 21.2 W, for a total annual energy consumption of less than 200 kWh. This consumption was not later factored back into the savings predictions made by the MaGrann TREAT analysis, but its impact would be small.

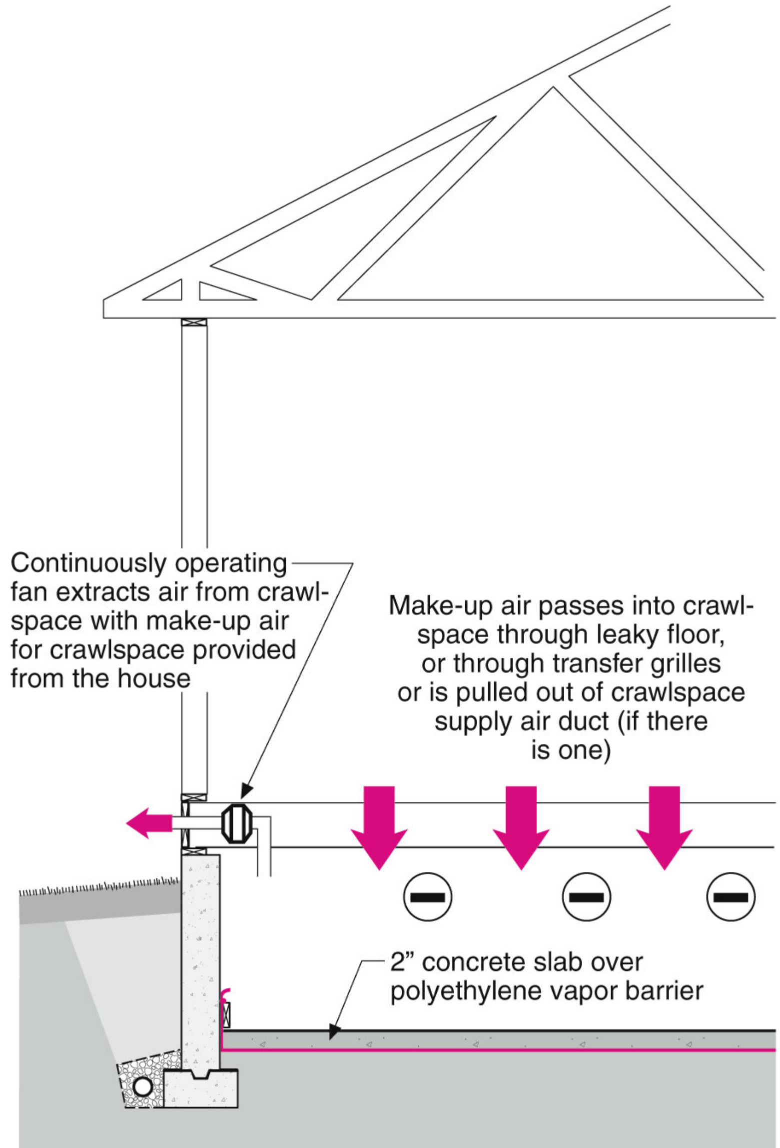


**Figure 18. Unvented crawlspace exhaust ventilation schematic**

**Figure 19. Example of air leakage to unit above but well-sealed foundation wall**

In this case, crawlspace exhaust ventilation does double-duty, meaning that depressurization of the crawlspace would primarily draw air from the units (having drier air than the crawlspace), with unit replacement air coming from outside by infiltration, which could improve air quality in the units and tend to dry the crawlspace at the same time. But, of course, the drying potential of ventilation has its limitations. In situations where crawlspaces are not experiencing standing water, ventilation and dehumidification will likely control humidity better than before an unvented retrofit. However, with the repeating standing water, means to eliminate the water source must be applied in addition to the weaker tools of ventilation and dehumidification. Because extensive reworking of foundation drainage was out of the question (cost-wise), sealing off the windows at the exterior was the first best option to mostly eliminate the bulk water problem and eliminate air bypass around the insulation. Then in some cases, sump pumps would also be needed where high water table events caused water to rise through cracks in the slab. Evidence of that can be seen in Figure 20, where the wettest parts were along the seams in the slab.

**Figure 20. Crawlspace photo showing wetness at seams in the concrete slab (L) and (R), and floor drain backup (L)**

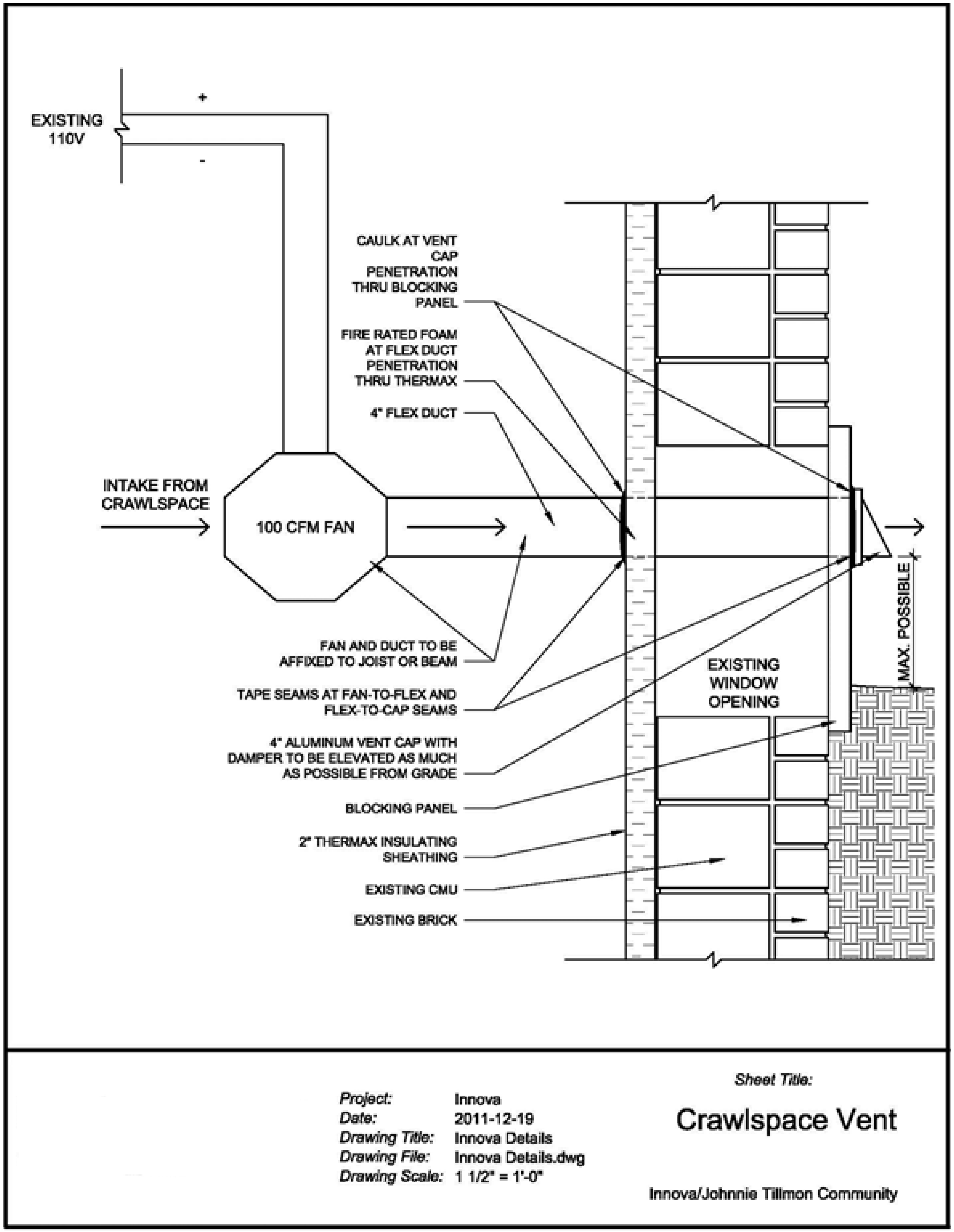


**Figure 21. Drawing of the unvented crawlspace exhaust ventilation system design**

## 2.7 Sump Pump for Bulk Water Removal Where Needed

The first line of defense against bulk water intrusion was to cover and seal the crawlspace windows from the outside; however, onsite observations after heavy rains revealed a continued potential for standing water in the crawlspaces.

Installing crawlspace exhaust ventilation is a low-energy strategy that significantly reduces the risk of contaminated air moving from the crawlspaces into the units. It also stands a good chance of returning the crawlspace humidity level to no more than it was before the crawlspace retrofit, or better. However, in some crawlspaces, exhaust ventilation may still not be adequate to remove enough moisture evaporating in the crawlspace because bulk water rises from below the slab. In this case adding dehumidification would likely not be sufficient either, and the operating cost would be high. Rather, a sump pump should be installed in the crawlspaces that are chronically wet. The 2-ft to 3-ft deep plastic sump pits are to be perforated with drilled holes in the bottom so that as the water table rises the water will be removed before it reaches the bottom of the slab. This was done in four of the nine crawlspaces, in Buildings B and E.

# 3 Pre-Retrofit Testing

The pre-retrofit conditions of the crawlspace conditions were evaluated by monitoring temperature and RH in two of the eight crawlspaces. BSC programmed four battery-powered temperature and RH data loggers and sent them to Innova with instructions for installation in two crawlspaces. Innova installed two data loggers in the crawlspace of Building B under the apartments 5–8, which was thought to be representative of the wettest conditions. Innova installed the remaining two data loggers in the crawlspace of Building E, which was thought to be representative of the driest conditions (however, this crawlspace flooded at times).

BSC made a site visit to Oakwood Gardens on September 7, 2011 to retrieve the first set of temperature and RH data before the crawlspace retrofit project began, to seal the window wells against bulk water intrusion and air leakage. Then 1-in. thick Thermax insulation was applied to the interior of the foundation walls. Analysis of the collected data showed very high moisture conditions in the often flooded crawlspaces (see Section 4).

## 3.1 Temperature and Relative Humidity Monitoring

During a rainy period BSC researchers arrived to download the pre-retrofit temperature and RH data in the crawlspaces, and found that both were flooded (Figure 22). Conditions were such that the data loggers in the crawlspace of Building B could not be accessed (Figure 23). The data loggers were accessible in the crawlspace of Building E, and plots of the conditions are shown in Figures 25 to 27.

**Figure 22. Temperature and RH data logger (L); standing water in crawlspace (R)**

**Figure 23. Inaccessible Building B crawlspace (L), and Building E crawlspace (R) with standing water during a rainy period**

The conditions of the crawlspace exterior, the windows and window wells, and the site drainage characteristics were observed and documented from the exterior for the entire eight-building project. In general, the windows were leaky or broken, the window wells were loaded with debris and showed evidence of holding water and passing water through the windows, and site drainage was a problem around the back of Buildings A and B and where the tops of some window wells were at grade (Figure 11). Most roof water was conducted to an underground storm water drain system; however, in one case (Figure 24) it was dumping on the ground next to the crawlspace foundation wall.

**Figure 24. Roof gutter downspout not piped to storm drain system allowing water intrusion to crawlspace**

# 4 Short-Term Post-Retrofit Performance Testing and Observations

BSC conducted post-retrofit testing of the Oakwood Gardens project on March 19, 2012. Measurements were taken and observations made in the crawlspaces or basement of each of the eight apartment buildings. The individual measurements are recorded in Table 3.

## 4.1 Temperature and Relative Humidity Measurements

Air temperature measurements showed that the crawlspaces were maintaining temperatures in the 70°–80°F range, which was similar to the living spaces above, many of which had windows open on the unusually warm testing day.

Air RH measurements showed that the crawlspaces had generally elevated humidity levels, which was understandable because some slabs were wet. However, there was no standing water, as had been the case in the past.

Surface temperature measurements of the insulated unvented crawlspace walls ranged from about 77°F at the top to about 70°F at the bottom. The center-of-slab and edge-of-slab surface temperatures were generally the same as or about 2°F lower than the top-of-wall and bottom-of-wall temperatures, respectively.

## 4.2 Air Temperature and Relative Humidity Monitoring

Pre-retrofit and post-retrofit monitoring (up to the day of post-retrofit testing) of the air temperature and RH in two crawlspaces (Buildings B and E) was conducted. Outdoor temperature and RH data were taken from a nearby airport.

As points of reference when looking at Figures 25 through 27:

- The crawlspace foundation wall insulation retrofit work was done between October 10, 2011 and December 12, 2011.
- The crawlspace window blocking and sealing was done between December 5, 2011 and December 14, 2011.
- The crawlspace exhaust ventilation retrofit work was done between February 27, 2012 and March 2, 2012.
- The sump pump retrofit work for Buildings B and E was done between February 29, 2012 and March 2, 2012.

Figure 25 shows that the air dry bulb temperature between the two crawlspaces did not differ much, because in each case it was moderated by the earth temperature and by the uninsulated floor connection to the apartments above. The crawlspaces were not purposely vented to outside, but they tracked ambient temperature on a moderated basis until the insulation retrofit took place, after which the crawlspace temperature remained steadier.

Figure 26 shows that the RH between the two crawlspaces tracked very closely at an elevated level, between 70% and 85%, from June to September before the crawlspace retrofit was started. The month between the middle of August and the middle of September was also a historically rainy period. After that, the crawlspaces started drying out with the receding water table and drier ambient conditions. However, November was again wet, and the crawlspace insulation and window blocking retrofit closed that moisture in. As winter progressed, the crawlspaces were drying out again, and stabilized around the time of the exhaust ventilation system and sump pump installations in late February to early March. The Building B crawlspace was always the wettest and most flooded at times, which is evident in that the Building B crawlspace stabilized at about 60% RH, or about 20% RH higher than the Building E crawlspace.

Although RH is dry bulb temperature dependent, dew point temperature indicates air moisture level independent of dry bulb temperature. As shown in Figure 27, the crawlspace dew point temperature of 75°F remained elevated above the summer outdoor dew point temperature for most of the period before the crawlspace retrofit. That was due to bulk water intrusion, wet slabs, and frequent standing water in the crawlspaces. Only when the unvented crawlspace retrofit was complete—with blocked windows, insulated walls, exhaust ventilation, and sump pumps in the wettest locations—did the crawlspace dew point temperatures stabilize at acceptable levels. The Building E crawlspace dew point temperature of about 50°F is quite acceptable, but we hope that the Building B crawlspace continues to trend downward to avoid condensation on the steel I-beams and cool slab edges.

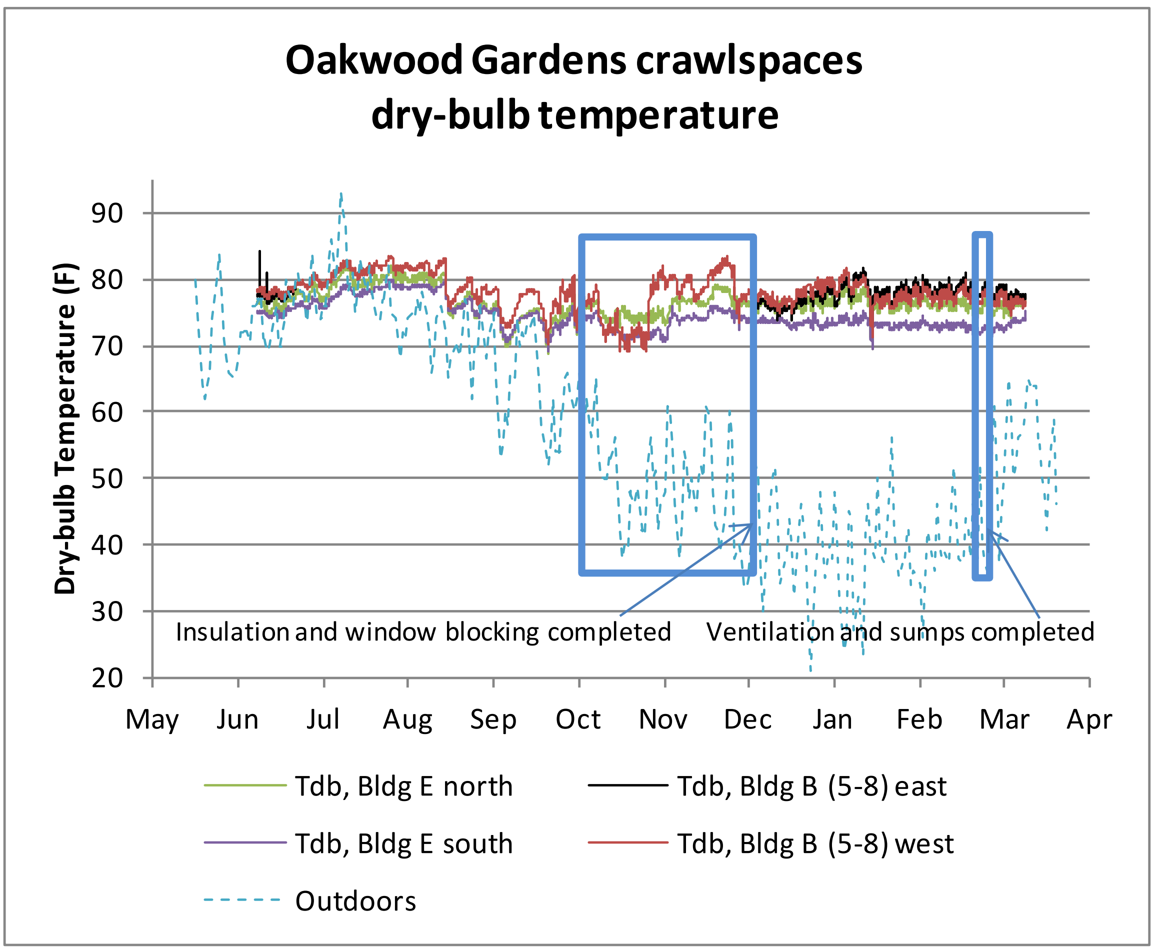


**Figure 25. Pre-retrofit and post-retrofit monitoring of crawlspace air dry bulb temperature**

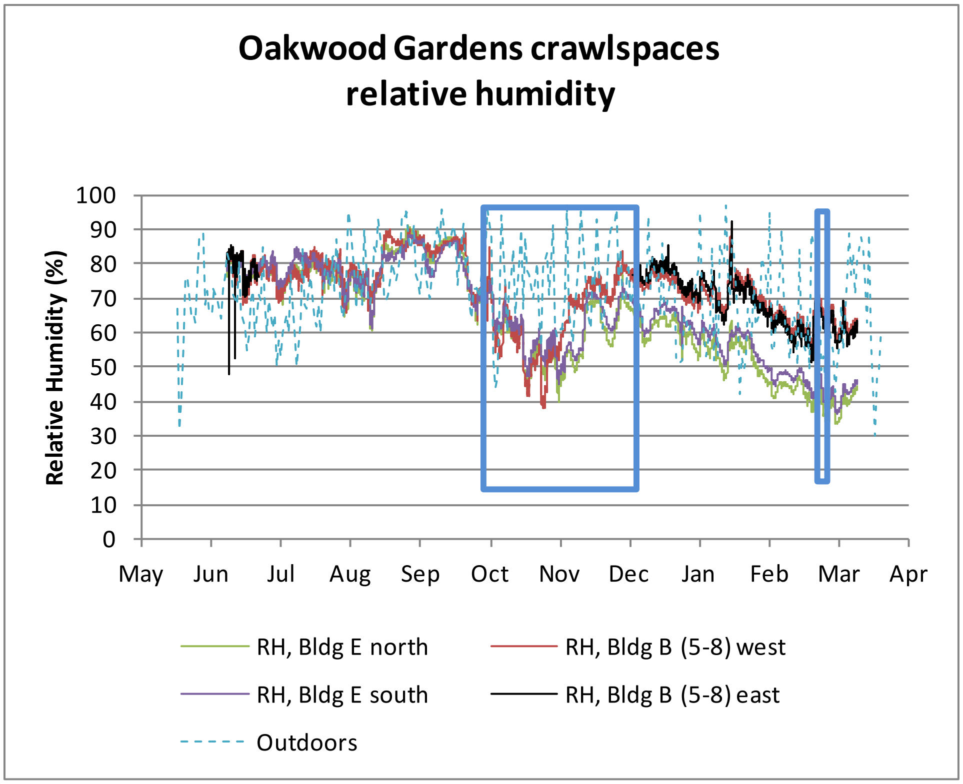


**Figure 26. Pre-retrofit and post-retrofit monitoring of crawlspace air RH**

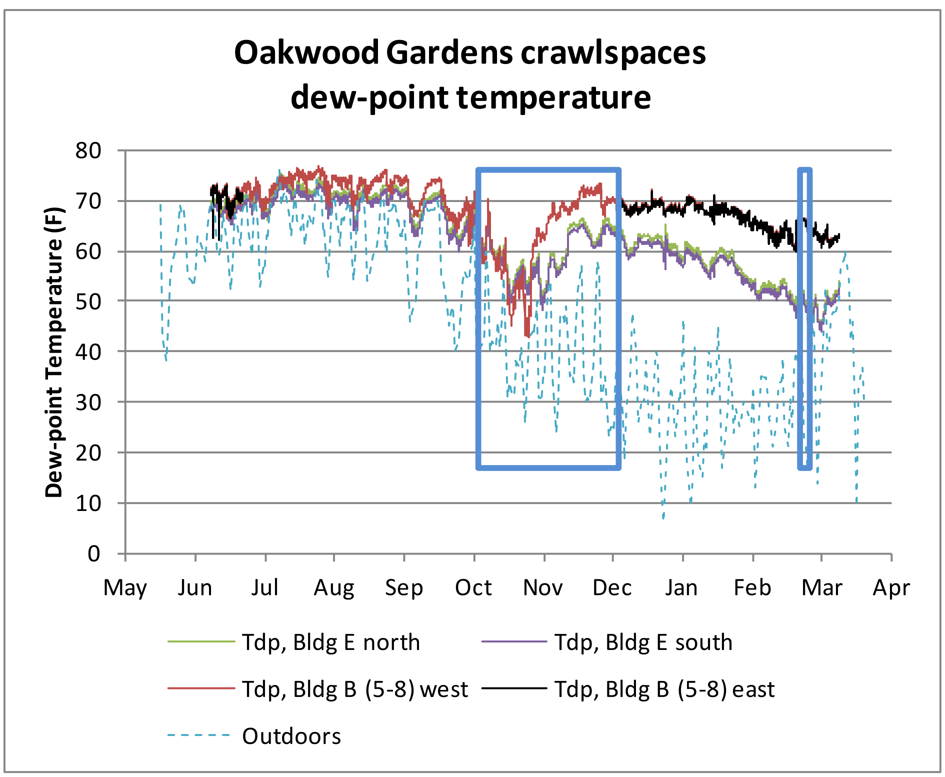


**Figure 27. Pre-retrofit and post-retrofit monitoring of crawlspace air dew point temperature**

On the day of post-retrofit testing, a temperature and RH data logger was left in each of eight crawlspaces (Figure 28) and one basement. These data loggers will take and record measurements each 3 hours for the next 496 days. This will allow careful tracking of the conditions in the crawlspaces over different seasons and rain events.


**Figure 28. Example of the temperature and RH data logger left in each crawlspace to record data for the next year**

## 4.3 Wood Moisture Content Measurements

Wood moisture content was measured at two places along a 2 × 10 wood floor joist running from the center of the crawlspace to the outside wall. The first location was in the center of the joist span in the center of the 10-in. side of the floor joist. These measurements ranged from 6.3% to 9.6% moisture content by weight. As expected, the wood moisture content was higher in the crawlspaces with higher air RH. The second measurement location was taken near the end of the joist close to the wall insulation in the center of the 10-in. side of the floor joist. Each wood joist rested directly on the concrete masonry unit foundation wall, in a pocket with concrete block on all sides except the top, which was in contact with the wood board subfloor (Figure 16). So the moisture content of the joist at that location was expected to be higher because of capillary uptake and possible wetting from water penetrating the brick veneer. However, the measurements showed that the wood moisture content near the end of the joist was only 1 to 2 percentage points higher than that in the field of the joist, with a non-problematic maximum measurement of 11.2%. Even so, knowing that the wall insulation and air sealing have reduced the capacity for drying at the end of the wood joist in the masonry pocket, as an extra measure of caution, we intend to monitor the condition of these joists over the next year.

**Table 3. Post-Retrofit Testing Results for Eight Buildings at Oakwood Gardens**

| Building | A | B | B | C[a] | D[b] | E | F[c] | G | H |
|---|---|---|---|---|---|---|---|---|---|
| Under Apartments | | (1–4) | (5–8) | (1–4) | (5–8) | | (5–8) | | |
| **Crawlspace Air Conditions** | | | | | | | | | |
| Dry Bulb Temperature (°F) | 70 | 75 | 76 | 80 | 80 | 75 | 77 | 77 | 75 |
| RH (%) | 56 | 78 | 68 | 49 | 37 | 46 | 43 | 47 | 47 |
| Dew Point Temperature (°F) | 55 | 67 | 65 | 59 | 52 | 53 | 53 | 56 | 54 |
| **Pressure Difference (Pa)** | | | | | | | | | |
| Common Area WRT Outside | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Crawlspace WRT Outside | 0 to –0.5 | 0 to –0.3 | 0 to –0.5 | 0 | 0 to –0.7 | –0.1 to –0.3 | 0 to –0.5 | 0 | 0 to –0.6 |
| Crawlspace WRT Common Area | 0 to –0.5 | 0 to –0.3 | 0 to –0.5 | 0 | 0 to –0.7 | –0.1 to –0.3 | 0 to –0.5 | 0 | 0 to –0.6 |
| **Floor Joist Wood Moisture Content (%)** | | | | | | | | | |
| Field of Joist Near Center of Crawlspace | 7.5 | 8.4 | 9.6 | 6.3 | 6.9[d] | 7.5 | 6.3 | 7.6 | 6.7 |
| End of Joist Next to Wall Insulation | 7.0 | 10.3 | 11.2 | 8.0 | N/A | 8.8 | 6.9 | 8.6 | 7.5 |
| **Concrete Slab Temperatures (°F)** | | | | | | | | | |
| Center of Slab in Center of Crawlspace | 73 | 74 | 75 | 79 | 80 | 75 | 78 | 75 | 75 |
| Edge of Slab at Foundation Wall | 68 | 68 | 69 | 72 | 74 | 70 | 70 | 70 | 68 |
| **Wall Temperature at Interior of Insulation (°F)** | | | | | | | | | |
| High | 73 | 75 | 77 | 79 | 79 | 74 | 79 | 78 | 77 |
| Mid | 72 | 73 | 76 | 77 | 75 | 72 | 76 | 77 | 76 |
| Low | 70 | 70 | 71 | 74 | 72 | 69 | 72 | 72 | 72 |
| Crawlspace Exhaust Airflow (cfm)[e] | 64 | 58 | 57 | 70/100 | N/A | 54/93 | 69/102 | 69/104 | 63/99 |

[a] Building C had a full basement on the north end under apartments 5–8, which was the central plant boiler room and maintenance room. That part was not tested. The separate crawlspace under apartments 1–4 was tested.
[b] Building D had a full basement. The part under apartments 1–4 was an office and laundry with exhaust. The part under apartments 5–8 was a tenant storage area. Both parts were connected by an open door during testing.
[c] Building F had a full basement on the east end, under apartments 1–4, with laundry and exhaust. That part was not tested. The separate crawlspace under apartments 5–8 was tested.
[d] There were no exposed joists in the Building D basement, so the wood moisture content was taken from other wood framing in that space.
[e] The first number is with the Alnor flow hood pressed up to the wall with the exhaust hood directing air toward the bottom side of the flow hood. The second number is with the flow hood tipped down away from the wall so the air jetting out of the exhaust hood flowed toward the middle of the flow hood. Where the second measurement was possible (because of space available to tip the flow hood down), it is thought to be the more accurate airflow measurement. Despite the uncertainty in measuring the airflow, the Fantech FR100 fan was likely moving its rated airflow of about 100 cfm in all cases. The 4-in. diameter ducts were short with smooth bends. Based on the measured airflow and the Fantech performance data, the fans were operating at an external static pressure of about 0.3 in. w.c.

### 4.4 Exhaust Ventilation System Measurements

Exhaust airflow was measured with a flow hood where the air exited the wall cap. This measurement was best taken where there was sufficient distance between the wall cap and the ground to tip the flow hood down such that the downward flow of exhaust air moved through the center of the flow hood. Where that was possible, the airflow measurement compared well to the expected rated airflow of the fan, in the range of 100 cfm. Where that was not possible, the flow hood was simply pressed against the wall, and the airflow measurement was generally in the range of 65 cfm.

Pressure differential measurements made with the crawlspace exhaust fans on showed that the crawlspaces were at a slight negative to no pressure differential with respect to outside because of the 100 cfm of installed exhaust ventilation.

### 4.5 Post-Retrofit Observations

The most significant challenges to this project were dealing appropriately with bulk water intrusion into the crawlspaces in the PHFA and the property owner's cost constraints. A great deal of observation and photo documentation was done both before and after the unvented crawlspace retrofit work was done. Figures 29 through 35 describe the most important post-retrofit observations.


**Figure 29. Finished view of the crawlspace window blocking retrofit to eliminate that bulk water intrusion (L); note the foundation drainage mat protecting the waterproof membrane (R)**

**Figure 30. Crawlspace window well blocking and sealing on the back sides of Buildings A and B (L); note the sloped sealant to shed water at the top of the blocking panel (R)**

**Figure 31. Crawlspace foundation wall insulation fit well and sealed at edges and penetrations (L); some crawlspace conditions remained wet but drying, with exhaust ventilation throughout and sump pumps in critical locations (R)**

**Figure 32. Condensation showing on cold I-beam at exterior wall of humid (70% RH) crawlspace (December 2011)**

**Figure 33. Unvented crawlspace exhaust ventilation fan and ducting to outside wall cap**

**Figure 34. Sump pump installation; sides of sump pit are perforated with drilled holes, but perforating the bottom would be better; concrete debris and mud left in sump should be cleaned out to allow pump impeller to work freely.**

**Figure 35. Sump pump water discharged into the roof drain water system**

# 5 Long-Term Post-Retrofit Performance Monitoring, Testing, and Observations

Eight multifamily crawlspaces were retrofitted where the existing condition was a vented crawlspace with an uninsulated floor between the crawlspace and the dwelling units above. The crawlspace was therefore a critically weak link in the building enclosure energy performance and was ripe for improvement. All eight vented crawlspaces were retrofitted to unvented crawlspaces by sealing off the windows/window wells from the outside, insulating the crawlspace walls, installing controlled exhaust ventilation in the crawlspace, and installing sump pumps in critical locations in some of the crawlspaces. Saving energy was the primary interest and goal, but the greatest challenge in the unvented crawlspace retrofit project was working through crawlspace bulk water intrusion problems caused by inadequate site drainage, window well leakage, inadequate foundation wall drainage, and rising water table coming up through cracks in the concrete slab during rainy periods. If those wet conditions were not fully resolved, the wood structure and the air quality in the apartments above could suffer.

After retrofitting of the eight crawlspaces was complete, temperature and RH data loggers were left in place to help monitor the long-term success of the project. This was important because of the previous wet crawlspace conditions. Questions remained about the long-term risk of insulating and tightly sealing around wood floor joists embedded in masonry units behind brick façade. The concern was that the wood joist ends, being prone to water uptake from the masonry unit due to capillarity and from water leakage through the brick façade, could suffer from reduced drying potential. The reduced drying potential would come from the joist ends being colder and having less air exposure to the warm crawlspace due to tightly fitted and sealed wall insulation.

A data logger measuring air dry bulb temperature and relative humidity was installed in each of the eight crawlspaces. To track an unmodified reference condition, a data logger was also installed in a not-retrofitted walk-out basement under Building D, which housed a laundry and storage lockers.

A period of post-retrofit, long-term monitoring was completed between March 2012 and October 2013. The main purpose of the long-term monitoring and testing at the end of the monitoring period was to track the crawlspace humidity conditions and the floor framing wood moisture content for a year after the unvented crawlspace retrofit. The main points of interest were:

- The long-term resolution of bulk water problems addressed by the crawlspace retrofits as they related to crawlspace air humidity and potential fungi effecting the durability of the wood floor framing and air quality in the apartments above
- The long-term durability of the wood floor framing as it related to the wood floor joists being embedded in the exterior masonry wall behind brick façade.

## 5.1 Wood Moisture Content Measurements

The author's original recommendation was that the crawlspace wall insulation not be fit or sealed tight to the wood joists which were sitting in a masonry pocket behind the brick cladding. A ½-in. airspace was recommended to be left around the wood joist. The main reasoning was that brick leaks water, masonry units hold water, and wood is water absorptive. An airspace around the wood joists would let the wood dry out as it had for the last 40 years. That reasoning was also influenced by having seen some water staining at the ends of some wood joists, which indicated that they were getting wet and drying, and tolerating that. As it turned out, however, the installers did a beautifully perfect job of fitting and sealing the insulation around the wood joists (refer to Figure 31). Rather than go back and change that, it was decided to monitor the crawlspace conditions for a year and return to make observations of the wood joist conditions and moisture content.

As an evaluation reference point, typical wood moisture content values are listed in Table 4 for various wood treatments and conditions.

**Table 4. Typical Wood Moisture Content Values Relative to Various Treatments or Conditions**

| Wood Treatment or Condition | Typical Wood Moisture Content |
|---|---|
| Kiln Dried Cabinet Grade Wood; Plywood/OSB Sheathing out of the Factory or Under a Roof in the Sun | 6%–7% |
| Kiln-Dried Then AirDried Framing Lumber | 10%–12% |
| Air-Dried Wood | 12%–14% |
| Wood at 85% Equilibrium RH | 16% |
| Wood at Fiber Saturation | 28% |

Referring to the October 2013 measurements listed in Table 5 when measured near the center of the crawlspace the joists were generally in a good range of 7%–11% moisture content. When measured at the end of the joists near the wall insulation most of the joists were in good condition at 9%–13% moisture content, but some were in bad condition. In crawlspace B(5-8), which also was the only crawlspace where the exhaust ventilation fan had been turned off, some visibly wet floor joist ends were found at 40% moisture content (refer to Figure 36). The bottom of those joist ends were starting to get soft with decay, and on which yellow and white fungi were growing. In comparison, when measured near the center of that crawlspace, the joists were at a safe 14% moisture content. At another location in that crawlspace, 20% moisture content was measured at the joist ends. The March 2012 measurements showed the same joists, both at the end and center locations, to be at 10%–11% moisture content.

Only a sampling of the floor joists were inspected, typically about five joists opposite from the crawlspace access, which was the same protocol used in the March 2012 testing.

While the unvented crawlspace retrofit was effective in reducing heat loss, and the majority of the bulk water drainage problems had been resolved, the important finding was that some of the wood joists embedded in masonry pockets behind the brick veneer were showing signs of moisture damage. The earlier recommended small airspace between the insulation and the joist was needed to allow the joist to adequately dry when it got wet from water passing through the brick veneer or from capillary uptake from the masonry unit. Since it would not be possible to reliably determine which joists may become moisture damaged over time, a recommendation was made that the foam insulation be cut back ½ in. from around all the joists in all of the crawlspaces to increase drying of the joist ends. It was apparent that the risk of moisture damage to the wood joist ends far outweighed the energy penalty of the small area of uninsulated wall around the joists.


**Figure 36. Wet floor joists coming out of insulated masonry wall, measuring 40% moisture content and showing fungi growth and decay**

**Table 5. Field Measurements of Dry Bulb and Dew Point Temperature, RH, Wood Moisture Content, and Exhaust Ventilation Fan Status Taken in Both October 2013 and March 2012**

| Year | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Building | A | A[1] | B | B[2] | B | B[3] | C | C[4] | D | D | E | E[4] | F | F[6] | G | G[7] | H | H[8] |
| Under Apartments | | | 1–4 | 1–4 | 5–8 | 5–8 | 1–4 | 1–4 | 5–8 | 5–8 | | | 5–8 | 5–8 | | | | |
| **Crawlspace Air Conditions** | | | | | | | | | | | | | | | | | | |
| Dry Bulb Temp. (°F) | 70 | 77 | 75 | 75 | 76 | 76 | 80 | 75 | 80 | 76 | 75 | 76 | 77 | 76 | 77 | 76 | 75 | 75 |
| RH (%) | 56 | 73 | 78 | 76 | 68 | 81 | 49 | 83 | 37 | 69 | 46 | 78 | 43 | 77 | 47 | 73 | 47 | 70 |
| Dew Point Temp. (°F) | 55 | 68 | 67 | 67 | 65 | 70 | 59 | 70 | 52 | 65 | 53 | 69 | 53 | 68 | 56 | 67 | 54 | 66 |
| **Floor Joist Wood Moisture Content (%)** | | | | | | | | | | | | | | | | | | |
| Field of Joist Near Center of Crawlspace | 8 | 9 | 8 | 10 | 10 | 14 | 6 | 9–10 | 7 | 7–8 | 8 | 8–9 | 6 | 9–10 | 8 | 9–11 | 7 | 8–9 |
| End of Joist Next to Wall Insulation | 7 | 9 | 10 | 12 | 11 | 20–40 | 8 | 10–12 | N/A | N/A | 9 | 9–10 | 7 | 9–13 | 9 | 10–12 | 8 | 9–13 |
| **Concrete Slab Temperature (°F)** | | | | | | | | | | | | | | | | | | |
| Center of Slab in Center of Crawlspace | 73 | 76 | 74 | 75 | 75 | 75 | 79 | 79 | 80 | 81 | 75 | 76 | 78 | 76 | 75 | 75 | 75 | 74 |
| Edge of Slab at Foundation Wall | 68 | 73 | 68 | 73 | 69 | 74 | 72 | 77 | 74 | 78 | 70 | 75 | 70 | 73 | 70 | 73 | 68 | 72 |
| **Wall Temperature at Interior of Insulation (°F)** | | | | | | | | | | | | | | | | | | |
| High | 73 | 78 | 75 | 76 | 77 | 76 | 79 | 79 | 79 | 82 | 74 | 77 | 77 | 77 | 78 | 77 | 77 | 76 |
| Mid | 72 | 75 | 73 | 76 | 76 | 75 | 77 | 79 | 75 | 80 | 72 | 77 | 76 | 76 | 77 | 76 | 76 | 75 |
| Low | 70 | 75 | 70 | 74 | 71 | 75 | 74 | 77 | 72 | 78 | 69 | 75 | 72 | 74 | 72 | 74 | 72 | 72 |
| **Crawlspace Exhaust Fan Running?** | | | | | | | | | | | | | | | | | | |
| | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | N/A | N/A | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

[1] Foil tape coming loose in some places on crawlspace insulation boards. Conditions: looked good and smelled good.
[2] Sump pump filled with approx. 3 in. of water. Damp around drain. Smelled like cat (otherwise fine). Some water seepage around foundation edge. Dampness under scrap insulation boards lying on the slab. Looked good except for a few damp/wet spots, most around debris on ground. No standing water. Floor dirty with mud and leftover debris.
[3] Sump pump filled with approximately 5 in. of water. Sump pump was not working at full capacity. It took approximately 20 seconds for sump pump to evacuate the accumulated water. Impeller may be clogged. Quite a few damp sections on floor, but no standing water. Crawlspace exhaust fan was turned OFF. We turned it back on and it worked fine. Some floor joists visibly wet where they went into the insulation before the masonry wall pocket (40% moisture content at bottom of joist, 16% near middle and top of joist). Some of those joists were rotting and growing fungi at the bottom where they sat on the masonry unit. Went around the perimeter and found a few more joists that were 20% moisture content at the bottom and 17% in middle. Crawlspace smelled generally dirty/damp.
[4] Conditions: Good, looked good and smelled good.
[5] One joist was 18% moisture at top and 20% at bottom. Condition: Smells good, looks good. Conditions were very good. Sump pump had approximately 5 in. of water (took 3–4 seconds to evacuate).
[6] Conditions: Very good
[7] Moisture is under control. Smells like cigarette smoke (so that indicates that the exhaust fan is working to draw stale air from the dwelling units). Conditions: Very good.
[8] Conditions: Very Good to Excellent

## 5.2 General Crawlspace Observations

There was no mold odor in any of the crawlspaces. The crawlspaces were ranked from good to excellent in terms of areas of slab dampness. Most of the dampness was found under pieces of insulation board left lying on the slab floor. (These were initially used by the crawlspace retrofit workers to stay off the water and mud in the early stages of the project.) It was recommended that the crawlspaces be cleared of debris and dried mud, which was up to ½ in. thick in some places. This would reduce the water holding capacity and earth odors in the crawlspaces should they still get water at times.

With a few relatively minor exceptions (Figure 37) there was no standing water. Operation of all the sump pumps was verified, although one pump was probably clogged because it pumped water very slowly compared to the others.

In one crawlspace, a strong cigarette smoke odor coming down was an indication that the crawlspace exhaust fan was working as intended to draw air from the apartments above.


**Figure 37. Example of debris and mud, holding moisture in crawlspace (L); example of small area of standing water at slab edge and foundation wall (R)**

## 5.3 Temperature and Relative Humidity Measurements

In October 2013, at the same time the temperature and RH data loggers were retrieved, one-time measurements of air temperature and RH, insulated wall temperature, and slab temperature were taken in the crawlspaces. Those results are shown in Table 5 listed beside the same measurements made in March 2012. The October 2013 crawlspace temperature conditions were generally similar to those in March 2012, but the crawlspaces were significantly more humid due to the recent rains that had occurred. The most humid crawlspace was B(5-8) in which someone had gained access to the crawlspace and turned off the exhaust ventilation fan. The fan was turned back on and it functioned properly. The maintenance staff did not have an explanation for why or how the fan had been turned off.

## 5.4 Temperature and Relative Humidity Monitoring

The data loggers recorded air dry bulb temperature and RH data from March 19, 2012 to July 28, 2013, with the exception of Building A, in which the data logger malfunctioned and stopped recording on October 11, 2012. Air dew point temperature was calculated from dry bulb temperature and RH. The sample interval was 3 hours. Time traces of these data are shown in Figure 44 to Figure 52.

The unvented crawlspace dry bulb temperature was generally 70°–90°F with the higher temperatures being in the winter heating season. Referring to Table 6 and Figure 39, the dry bulb temperature was 75°–80°F, 44% of the time. It is likely that the apartments maintained high heating set points, and heat loss from the central plant hot water piping in the crawlspaces contributed to the elevated crawlspace temperatures. This shows the energy saving value of insulating the crawlspace walls instead of the floor over the crawlspace, capturing the hot water piping losses inside the thermal boundary instead of losing them to the vented crawlspace.

**Table 6. Unvented Crawlspace Dry Bulb Temperature Frequency by Building and Averaged Across the Buildings**

| Dry Bulb Temp. Range (°F) | A | B (1–4) | B (5–8) | C | D | E | F | G | H | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|
| 50–55 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 55–60 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 60–65 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 65–70 | 0% | 0% | 0% | 0% | 0% | 1% | 1% | 1% | 5% | 1% |
| 70–75 | 32% | 26% | 25% | 3% | 1% | 38% | 33% | 36% | 75% | 30% |
| 75–80 | 67% | 58% | 38% | 43% | 26% | 61% | 29% | 58% | 20% | 44% |
| 80–85 | 1% | 14% | 34% | 46% | 59% | 0% | 31% | 5% | 0% | 21% |
| 85–90 | 0% | 0% | 2% | 9% | 13% | 0% | 6% | 0% | 0% | 3% |
| 90–95 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| >95 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

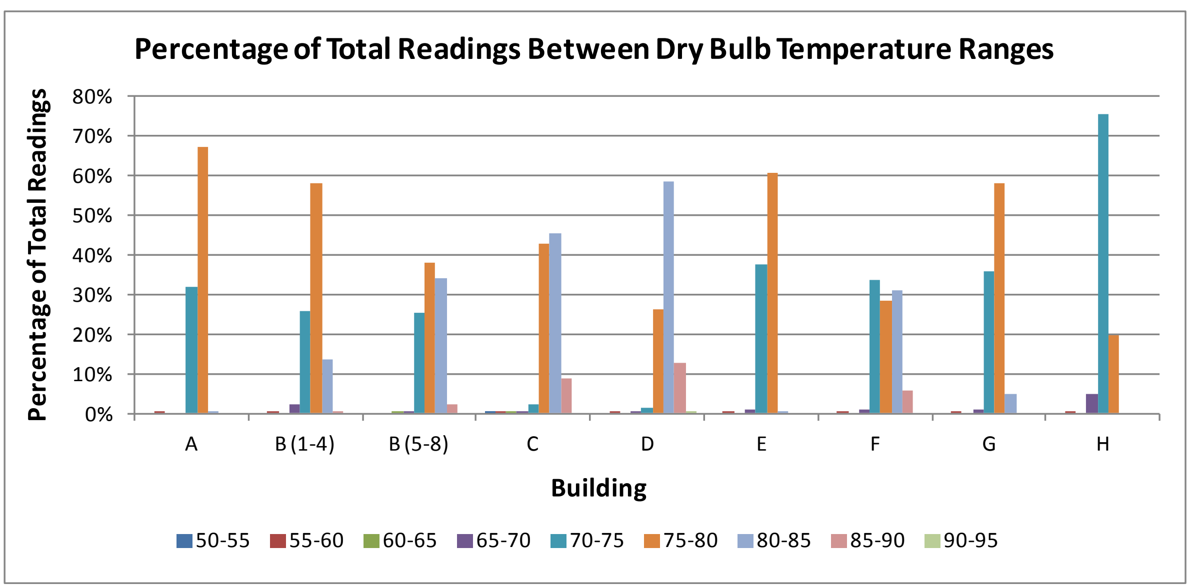


**Figure 38. Unvented crawlspace dry bulb temperature ranges by building**

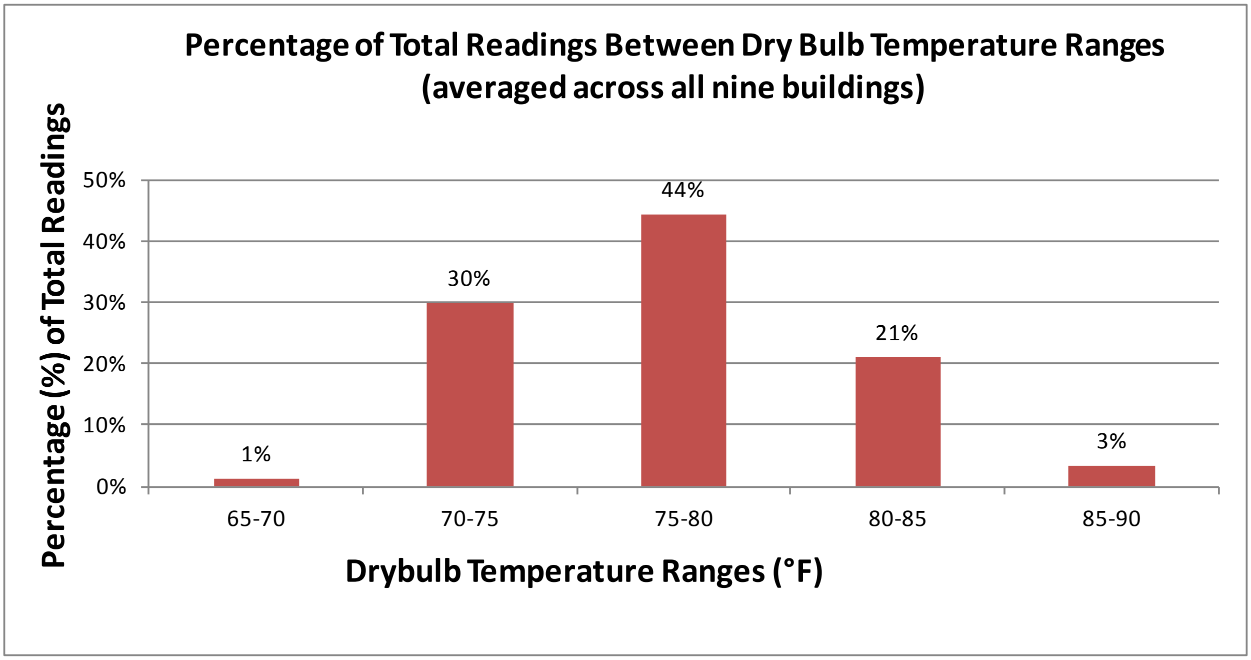


**Figure 39. Dry bulb temperature ranges averaged across all nine buildings**

RH in the unvented crawlspaces ranged from about 25% in the winter to about 80% in the peak summer. Some RH excursions went above 80% with rain events and in the crawlspace under Building B(5-8) where the exhaust ventilation fan had been inadvertently turned off. This showed that the exhaust ventilation strategy of drawing air from the units above through the crawlspace and exhausting to outside was effective in removing crawlspace moisture due to water and moisture coming up through the slab. This also showed that the bulk water drainage problem was largely solved by sealing off the window wells and adding sump pumps, but an even more complete permanent solution to the problem of moisture gain from below the slab would be to scrape the existing concrete slab clean, caulk all slab joints with polyurethane caulk, then install a minimum 6 mil polyethylene vapor barrier over the slab and sealing it to the side walls, foundation piers and any penetrations. For protection, the vapor barrier could also be covered with a 2-in. thick concrete slab, but that cost may be prohibitive.

**Table 7. Unvented Crawlspace RH Frequency by Building and Averaged Across the Buildings**

| RH Range (%) | A | B (1–4) | B (5–8) | C | D | E | F | G | H | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|
| 20–25 | 0% | 0% | 0% | 3% | 37% | 2% | 17% | 0% | 1% | 7% |
| 25–30 | 2% | 0% | 0% | 18% | 10% | 13% | 14% | 8% | 16% | 9% |
| 30–35 | 10% | 1% | 0% | 13% | 5% | 13% | 9% | 13% | 14% | 9% |
| 35–40 | 4% | 5% | 4% | 9% | 6% | 12% | 7% | 10% | 10% | 8% |
| 40–45 | 5% | 9% | 9% | 7% | 6% | 7% | 5% | 11% | 7% | 7% |
| 45–50 | 5% | 11% | 9% | 6% | 8% | 9% | 5% | 6% | 7% | 7% |
| 50–55 | 7% | 11% | 9% | 4% | 12% | 8% | 4% | 6% | 5% | 7% |
| 55–60 | 9% | 9% | 7% | 7% | 9% | 8% | 5% | 3% | 5% | 7% |
| 60–65 | 17% | 8% | 9% | 8% | 7% | 9% | 8% | 3% | 10% | 9% |
| 65–70 | 30% | 7% | 6% | 12% | 0% | 9% | 6% | 9% | 8% | 10% |
| 70–75 | 11% | 14% | 5% | 8% | 0% | 6% | 6% | 11% | 6% | 7% |
| 75–80 | 0% | 12% | 10% | 4% | 0% | 3% | 7% | 15% | 11% | 7% |
| 80–85 | 0% | 7% | 15% | 0% | 0% | 0% | 5% | 5% | 2% | 4% |
| 85–90 | 0% | 8% | 11% | 0% | 0% | 0% | 0% | 0% | 0% | 2% |
| 90–95 | 0% | 0% | 5% | 0% | 0% | 0% | 0% | 0% | 0% | 1% |
| 95–100 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

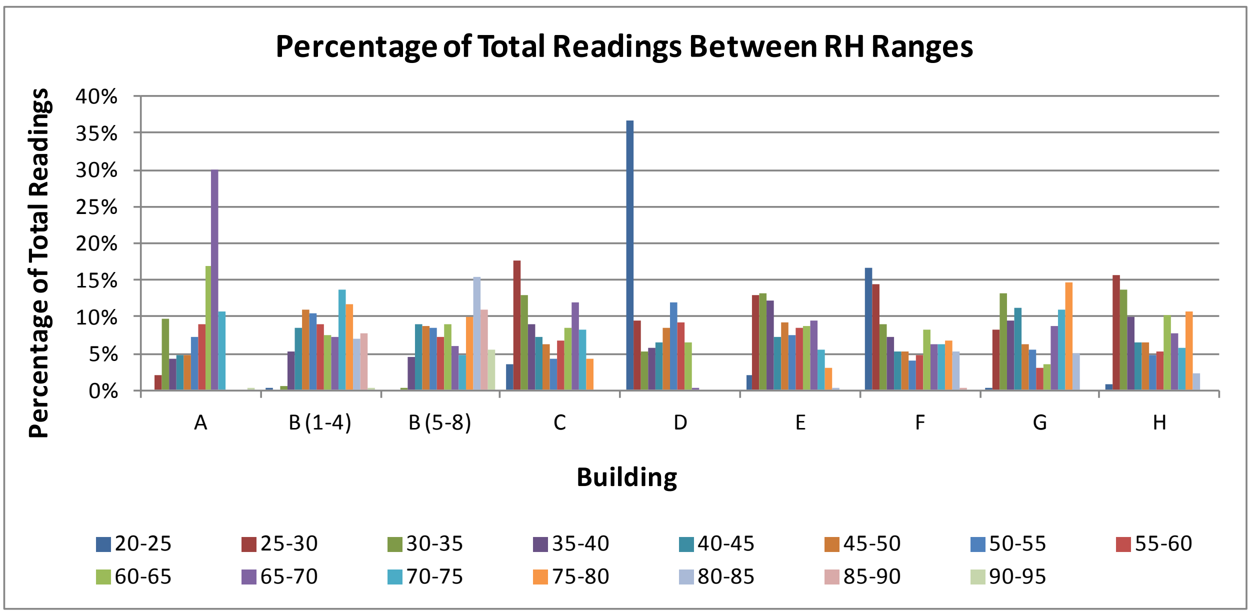


**Figure 40. Unvented crawlspace RH ranges by building**

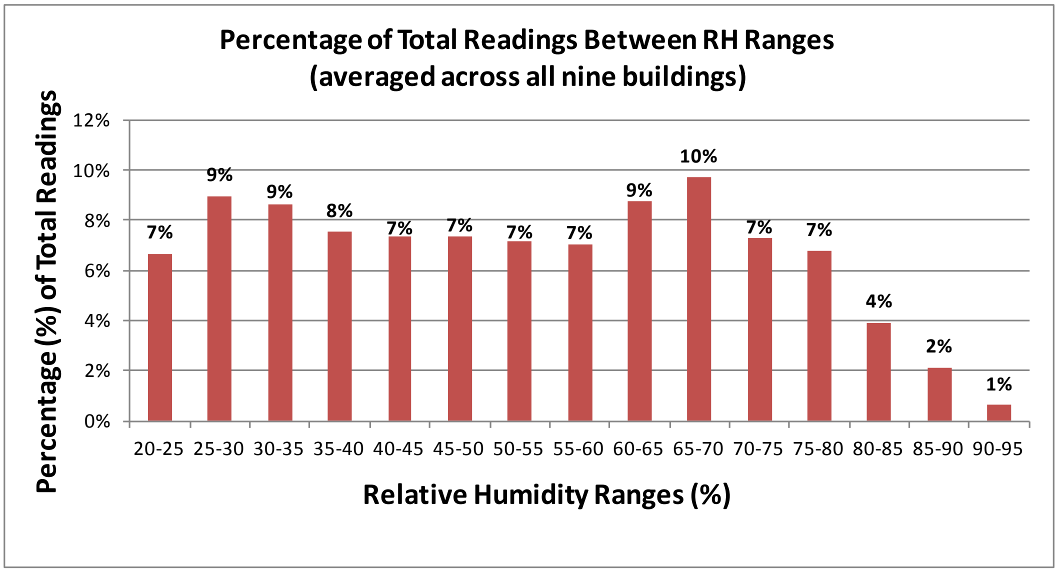


**Figure 41. RH ranges averaged across all nine buildings**

The dew point temperature data shown in Table 8, Figure 51, and Figure 52 are useful for seeing the moisture conditions independent of dry bulb temperature. With the apartments above the unvented crawlspaces being conditioned with window air conditioners, a dew point temperature of 60°F or lower could be expected. However, the dew point was going up to 70°F a significant amount of time in most of the crawlspaces (19% of the time averaged across the buildings). This is due to unwanted moisture coming up through the concrete slab, which had no continuous vapor barrier over the soil. In the crawlspace under Building B(5-8), where the exhaust ventilation fan had been turned off, the crawlspace dew point temperature range was 70°–75°F 18% of the time (refer to Table 8 and Figure 42).

**Table 8. Unvented Crawlspace Dew Point Temperature Frequency by Building and Averaged Across the Buildings**

| Dew Point Temp. Range (°F) | A | B (1–4) | B (5–8) | C | D | E | F | G | H | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|
| 20–25 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 25–30 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 30–35 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| 35–40 | 0% | 0% | 0% | 0% | 2% | 7% | 1% | 0% | 13% | 3% |
| 40–45 | 6% | 0% | 0% | 2% | 31% | 19% | 22% | 9% | 18% | 12% |
| 45–50 | 10% | 1% | 0% | 27% | 21% | 18% | 21% | 18% | 13% | 14% |
| 50–55 | 11% | 8% | 3% | 16% | 10% | 14% | 12% | 19% | 13% | 12% |
| 55–60 | 19% | 23% | 16% | 13% | 11% | 13% | 12% | 14% | 16% | 15% |
| 60–65 | 33% | 35% | 23% | 17% | 14% | 14% | 18% | 20% | 18% | 21% |
| 65–70 | 20% | 24% | 39% | 22% | 11% | 13% | 14% | 20% | 9% | 19% |
| 70–75 | 0% | 8% | 18% | 3% | 0% | 1% | 0% | 0% | 0% | 3% |
| 75–80 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
|---|---|---|---|---|---|---|---|---|---|---|

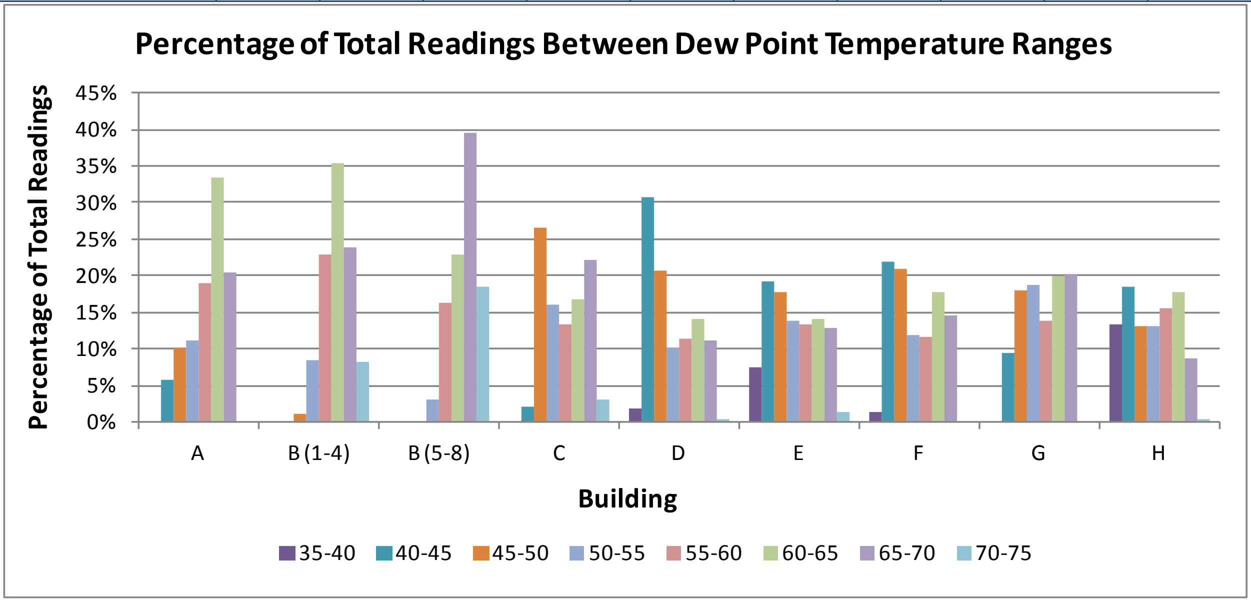


**Figure 42. Unvented crawlspace dew point temperature ranges by building**

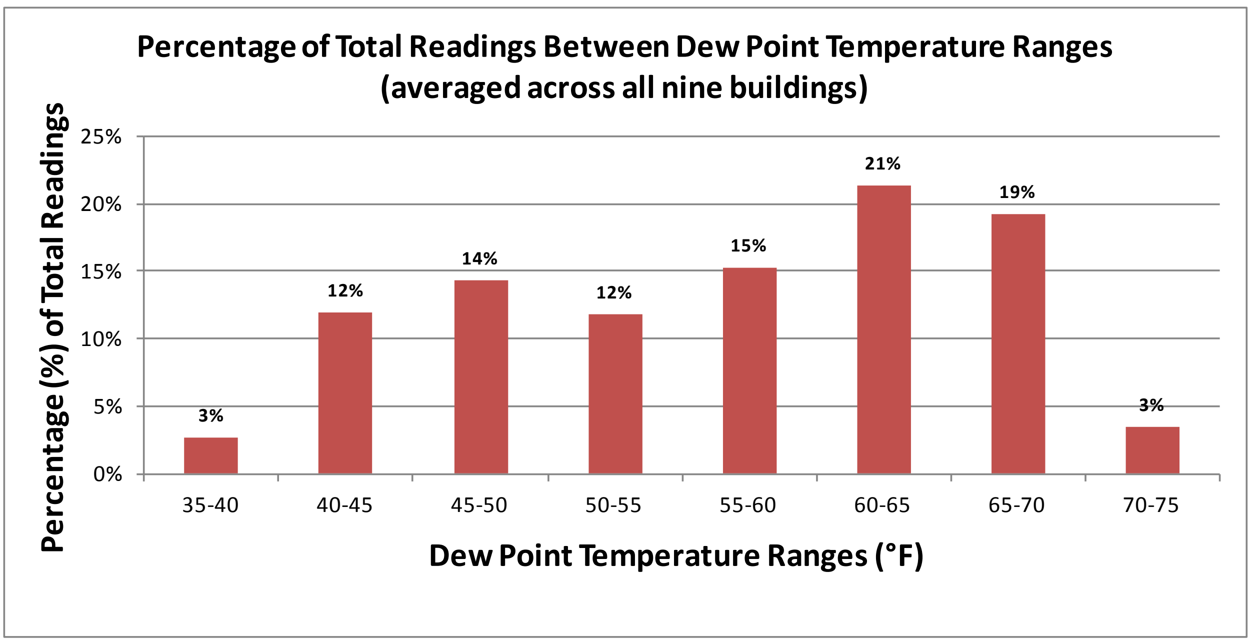


**Figure 43. Dew point temperature ranges averaged across all nine buildings**

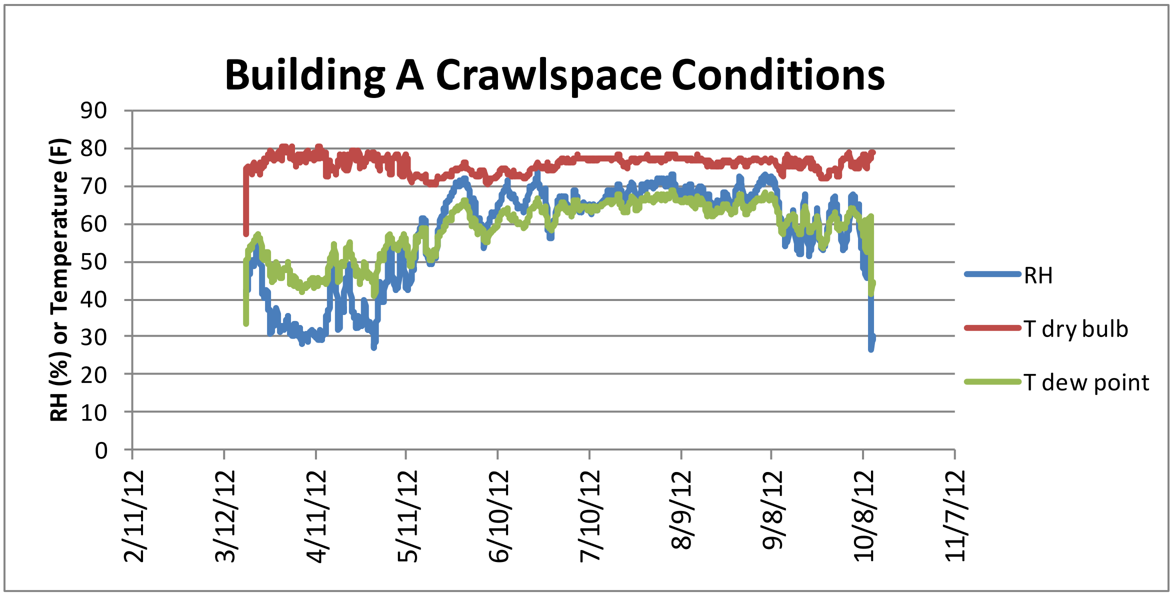


**Figure 44. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building A**

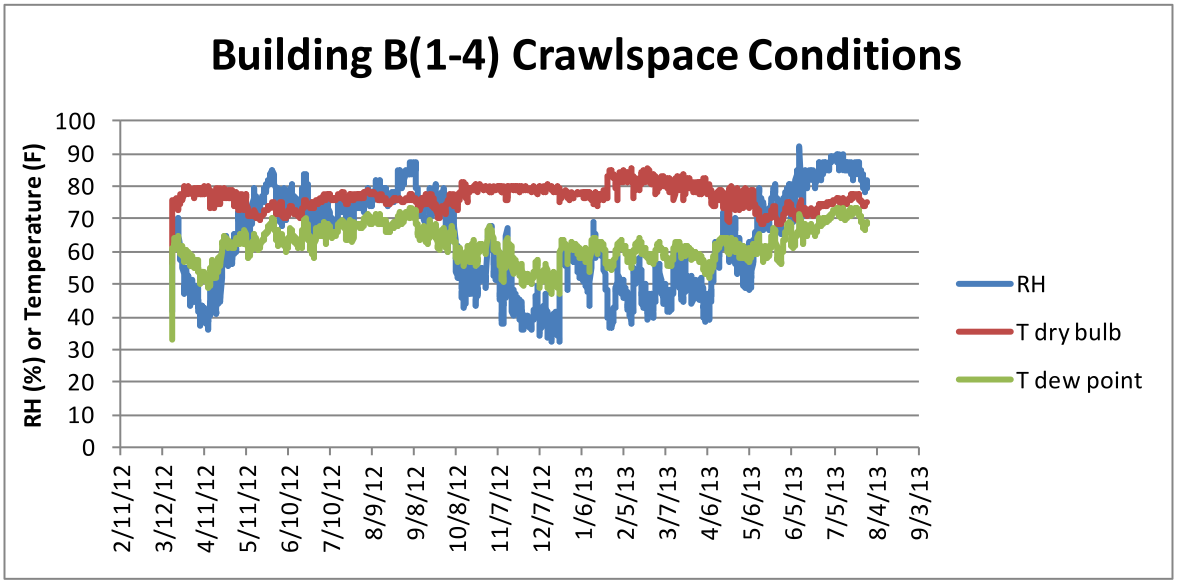


**Figure 45. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building B(1-4)**

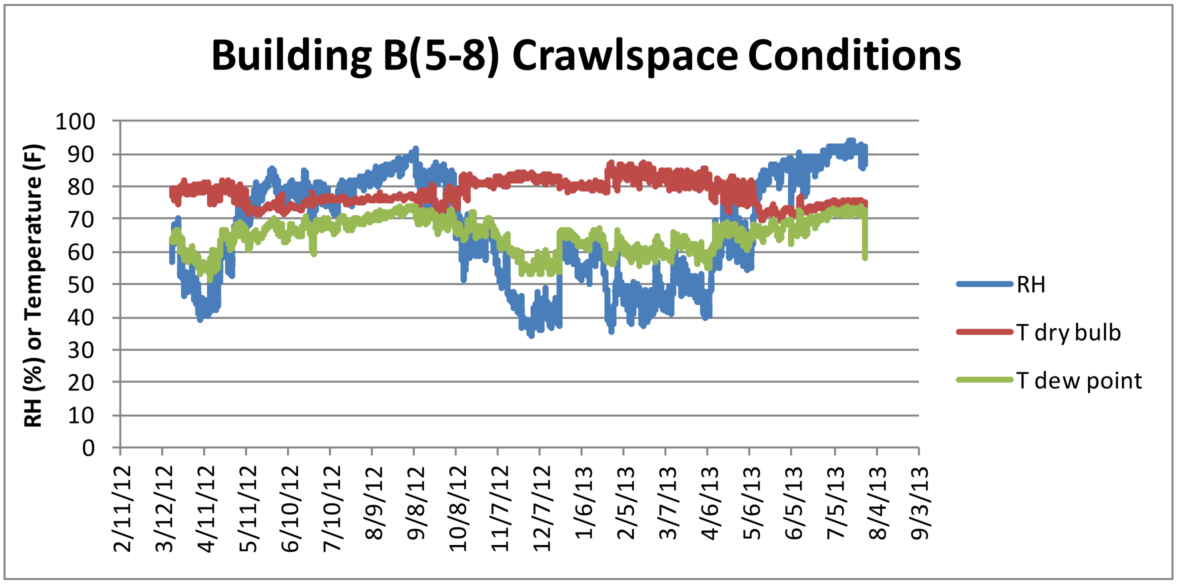


**Figure 46. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building B(5-8)**

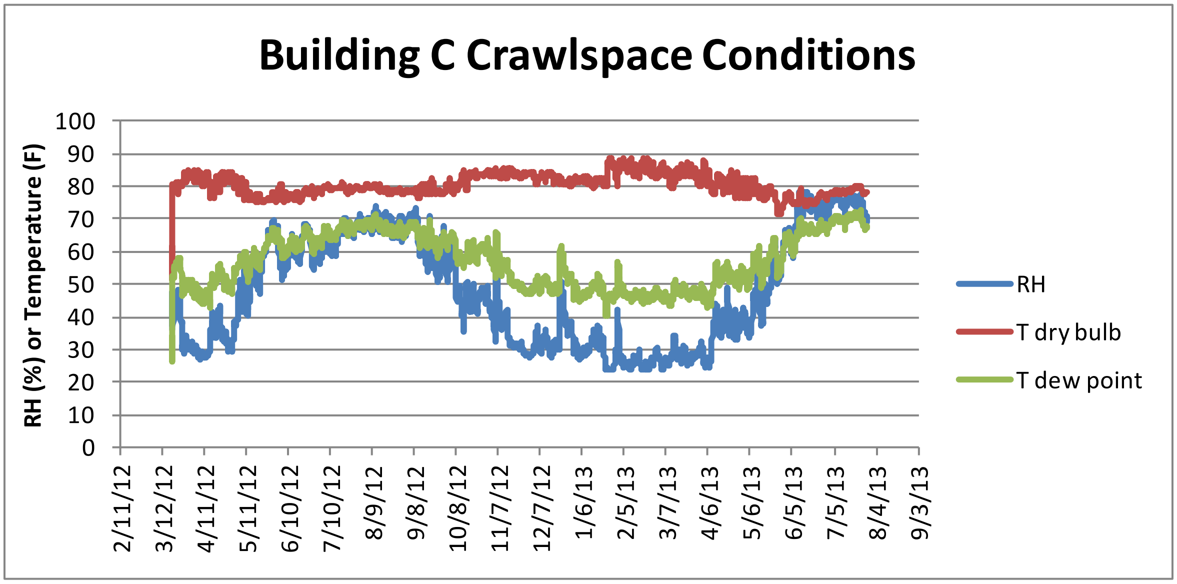


**Figure 47. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building C**

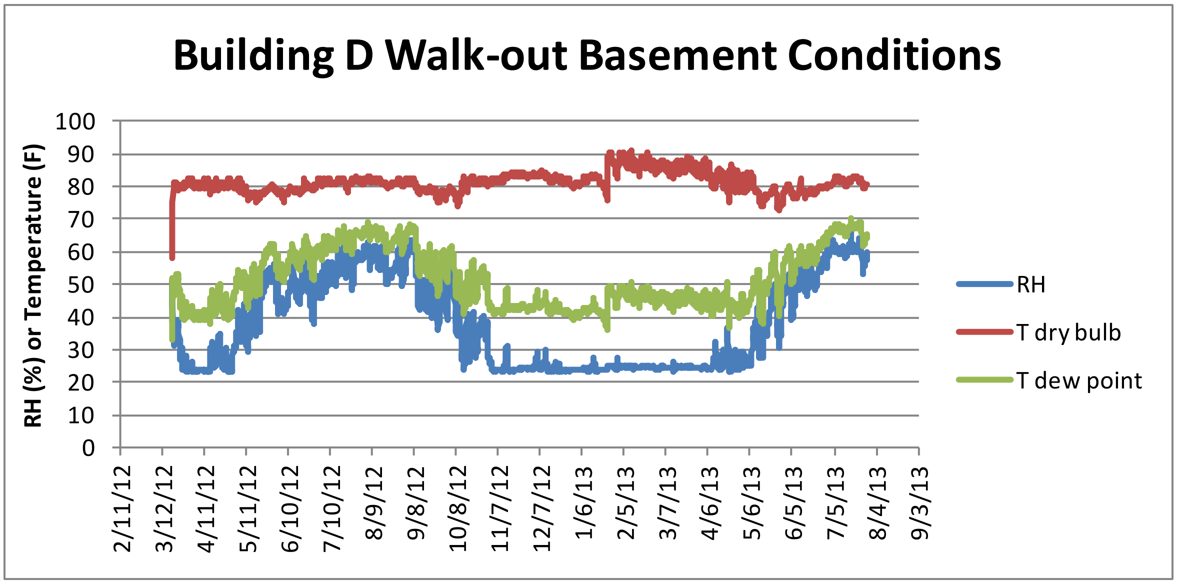


**Figure 48. Monitored temperature and RHy conditions in the non-retrofitted walk-out basement under Building D**

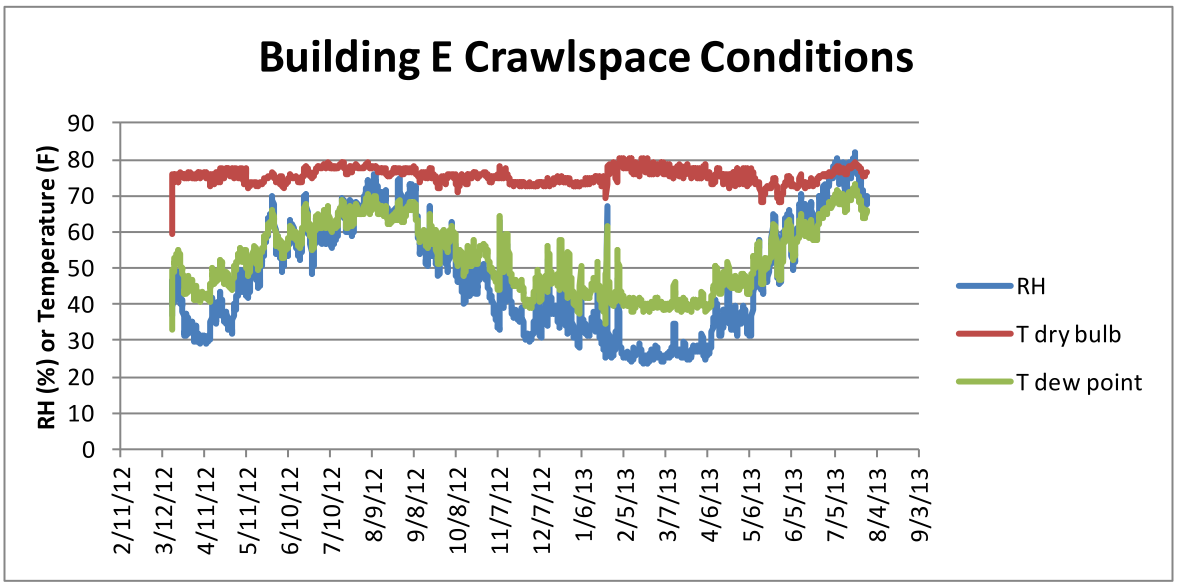


**Figure 49. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building E**

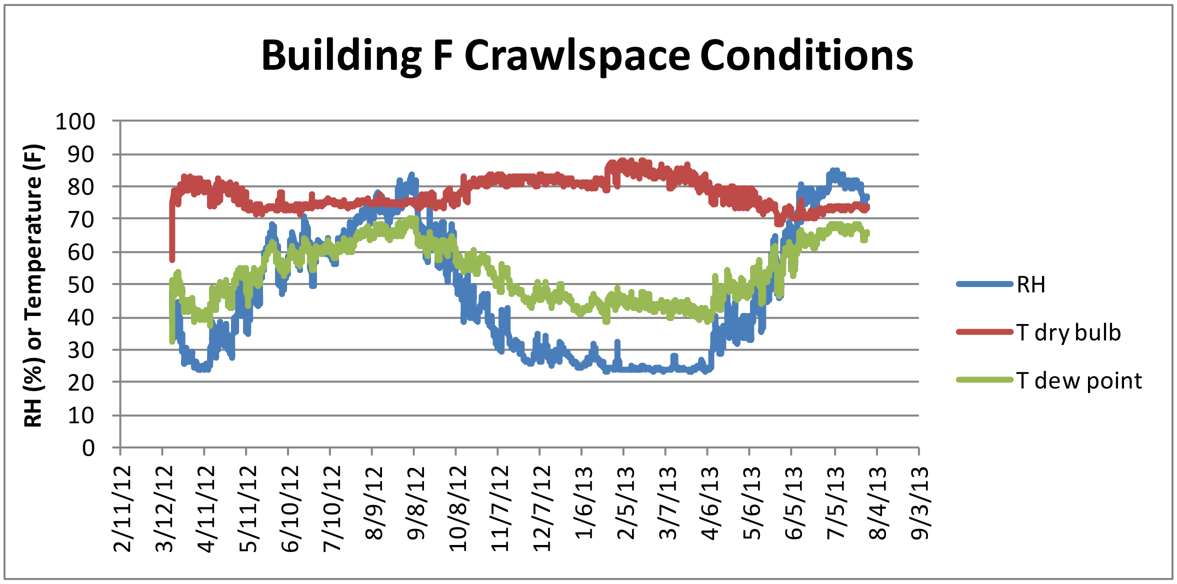


**Figure 50. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building F**

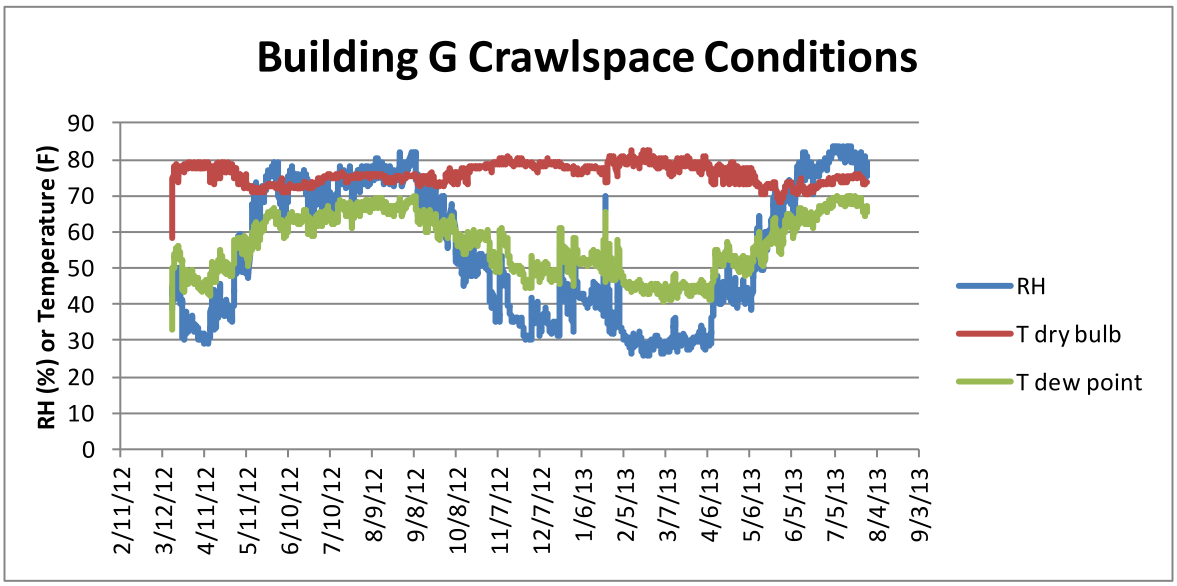


**Figure 51. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building G**

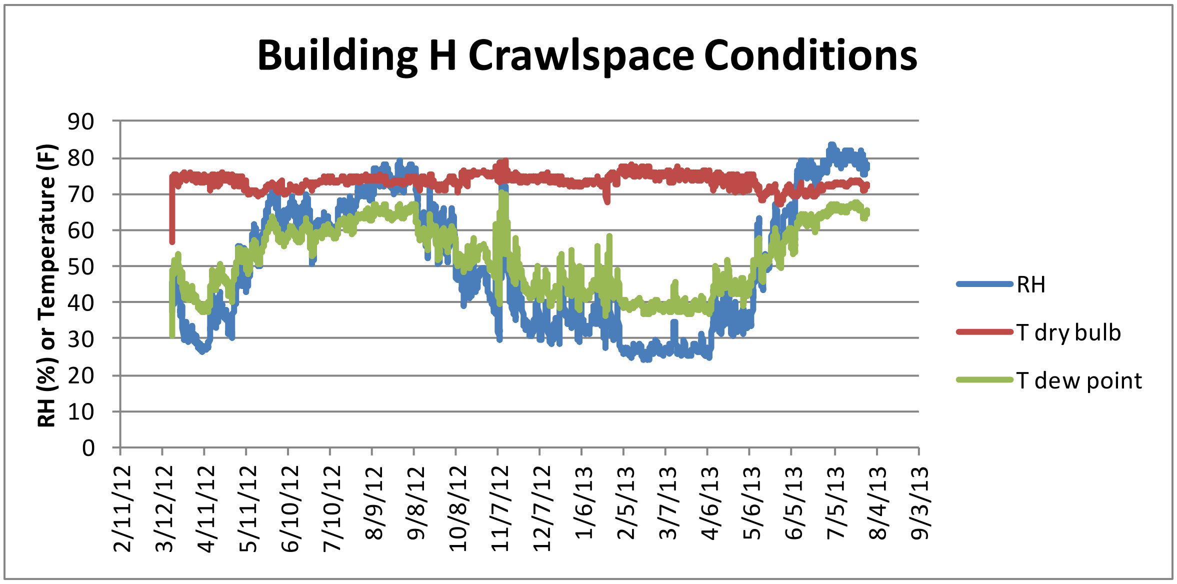


**Figure 52. Monitored temperature and RH conditions in the retrofitted unvented crawlspace under Building H**

# 6 BEopt Modeling

## 6.1 Improvement Analysis

The BEopt model simulates a single apartment with two bedrooms, the most common unit type at Oakwood Gardens. The pre- and post-retrofit model inputs are described in Table 4 and the BEopt modeling results are shown in Figure 36. The pre-retrofit crawlspace ventilation rate was taken from BEopt defaults. The post-retrofit rate was calculated at 0.5 ACH, from the flow hood measurements reported in Section 5.4. The infiltration improvement is an estimate, reflecting only the scope of work in the crawlspace.

**Table 9. Pre- and Post-Retrofit BEopt Model Inputs**

| Building Characteristic | Pre-Retrofit | Post-Retrofit |
|---|---|---|
| Crawlspace Insulation | None | R-5 |
| Crawlspace Ventilation (ACH) | 2 | 0.5 |
| Unit Infiltration (nACH) | 0.85 | 0.82 |
| Space Heating | Oil, 80% AFUE[a] | Gas, 95% AFUE |
| Domestic Water Heating | Oil, 0.62 EF[b] | Gas, 0.95 EF |
| Lighting | Benchmark | 80% fluorescent hardwired |

[a] AFUE = annual fuel utilization efficiency

[b] EF = energy factor

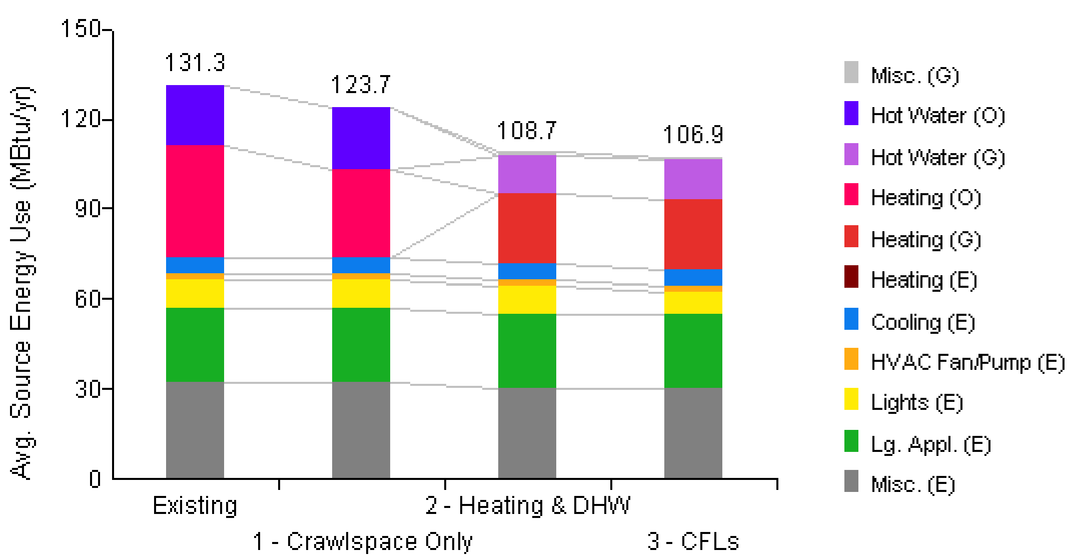


**Figure 53. BEopt model results for as-designed condition and selected alternatives for a representative apartment**

## 6.2 Optimization Analysis

Improvement options included in the BEopt optimization mode are listed in Table 5. The first (best value) step in the optimization was replacing the existing oil boiler with a condensing gas boiler. The last few measures taken in the optimization (the least cost-effective) were upgrading to an ENERGY STAR refrigerator, and upgrading the crawlspace insulation from 1 in. (R-5) to 1.5 or 2 in. These are all measures that were excluded from the actual retrofit by the cost-benefit analysis shown previously in Table 2. MaGrann (2009) recommended that ENERGY STAR refrigerators be installed at wear-out.

**Table 10. Improvement Options Included in the BEopt Optimization Model**

| Component | Options for Optimization |
|---|---|
| **Crawlspace** | Uninsulated, 2 nACH<br>R-5 on walls, 0.5 nACH<br>R-7.5 on walls, 0.5nACH<br>R-10 on walls, 0.5 nACH |
| **Unit Infiltration** | 0.85 nACH<br>0.82 nACH |
| **Refrigerator** | Standard, top freezer<br>ENERGY STAR, top freezer |
| **Lighting** | Benchmark<br>40% fluorescent, hardwired<br>60% fluorescent, hardwired<br>80% fluorescent, hardwired<br>100% fluorescent, hardwired |
| **Space Heating** | Oil, 80% AFUE<br>Oil, 85% AFUE<br>Oil, 95% AFUE<br>Gas, 95% AFUE |
| **Domestic Water Heating** | Oil, 0.62 EF<br>Oil, 0.66 EF<br>Gas, 0.59 EF<br>Gas, .0.67 EF<br>Gas, 0.82 EF<br>Gas, 0.96 EF |

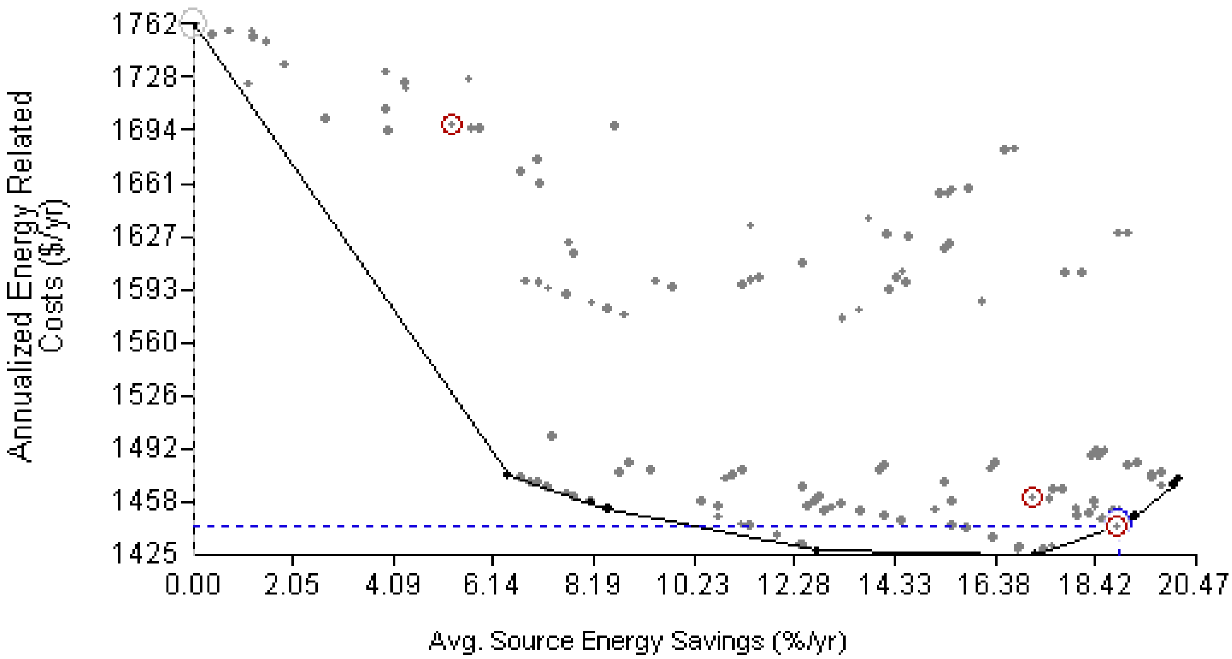


**Figure 54. BEopt optimization chart indicating the three improvements done at Oakwood Gardens in red circles**

Although all the improvements done at Oakwood Gardens save energy and money, the BEopt optimization applies them in a different order, so the first two red circled points are not on the optimal cost curve. The first circle from the left represents the crawlspace retrofit, the middle circle adds the heating and DHW system improvement, and the far right circle is back on the optimal curve and combines all three improvements (crawlspace, mechanicals, and lighting).

# 7 Conclusions

Saving energy was the primary goal of the builder partner's original multifamily community project, but in cooperation with the builder, this specific project drew focus on the crawlspace air sealing and wall insulation measures. The existing condition was a crawlspace that could be vented via window well windows, with an uninsulated floor between the crawlspace and the dwelling units above. The greatest challenge in this crawlspace retrofit project was working through the bulk water intrusion problem caused by inadequate site drainage, window well drainage, foundation wall drainage, and a rising water table during rainy periods. Bulk water intrusion into the crawlspace must be eliminated by addressing drainage before retrofit to an unvented crawlspace proceeds with wall insulation and exhaust ventilation.

The crawlspace windows were blocked off and sealed against bulk water intrusion and air leakage. This was to avoid moisture damage to the wood floor framing and outside air bypass of the wall insulation. In addition to improved energy performance, the crawlspace post-retrofit environmental conditions were improved since:

- The crawlspace now remains at a stable warm temperature because it is inside the building thermal enclosure.
- The exhaust ventilation pulls air from the dwelling units above to improve their air quality and dry the crawlspace.
- The blocked windows do not allow rainwater to flood the crawlspace.
- The strategically placed sump pumps resist the rising water table from flooding the concrete slab floor.

Annual energy savings based on the TREAT model were expected to be about $4,000, and life cycle cost savings were expected to be about $36,000. The BEopt model showed that the crawlspace retrofit, the boiler upgrade for heating and DHW, and CFLs individually and collectively saved energy and money. The combined improvements fell on the BEopt optimal curve and had average source energy savings of 18%.

A period of long-term post-retrofit monitoring was completed between March 2012 and July 2013. The main purpose of the long-term monitoring, and testing at the end of the monitoring period, was to track the crawlspace humidity conditions and the floor framing wood moisture content for a year after the unvented crawlspace retrofit. While the unvented crawlspace retrofit was effective in reducing heat loss, and the majority of the bulk water drainage problems had been resolved, the important finding was that some of the wood joists embedded in masonry pockets behind the brick veneer were showing signs of moisture damage. A small airspace between the insulation and the joist was needed to allow the joist to adequately dry when it got wet from water passing through the brick veneer or from capillary uptake from the masonry unit. A recommendation was made that the foam insulation be cut back one-half inch from around all the joists in all of the crawlspaces to increase drying of the joist ends. It was apparent that the risk of moisture damage to the wood joist ends far outweighed the energy penalty of the small area of uninsulated wall around the joists.

## References and Bibliography

ASHRAE (2010). *ANSI/ASHRAE Standard 62.2-2010: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Advanced Energy (2005). Field Study Final Report: A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South. Raleigh, NC: Advanced Energy.

Advanced Energy (2012). Closed Crawl Spaces: An Introduction to Design, Construction and Performance. Raleigh, NC: Advanced Energy.

Bianco, M.D.; Wiehagen, J.; Wood, A. (2013). "Energy Efficient Crawlspace Foundation Retrofit: Mixed Humid Climate." Upper Marlboro, MD: NAHB Research Center. January. Accessed January 1, 2014: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/crawlspace_found_retrofit.pdf.

BSC (2004). Conditioned Crawl Space Construction, Performance and Code. Somerville, MA: Building Science Corporation. Accessed January 1, 2014: http://www.buildingscience.com/documents/bareports/ba-0401-conditioned-crawlspace-construction-performance-and-codes.

BSC (2009). "Info-512: Crawlspace Insulation." Building Science Corporation. Accessed May 18, 2011: http://www.buildingscience.com/documents/information-sheets/crawlspace-insulation.

Dickson, B. (2013). "Guide to Closing and Conditioning Ventilated Crawlspaces." IBACOS, Inc. Pittsburg, PA. January. Accessed January 1, 2014: http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ventilated_crawlspace_guide.pdf.

IRC (2009). "International Residential Code." International Code Congress.

MaGrann Associates (2009). "Multi-Family Building Performance Audit: Oakwood Gardens."

Rudd, A. (2012, 2013). "Initial Evaluation of Crawlspace Retrofits in Multifamily Buildings." Somerville, MA: Building Science Corporation, final report submitted April 2012, final NREL editing January 2013.

Straube, J.F.; Burnett, E.F.P. (2005). Building Science for Building Enclosure Design, Building Science Press: Westford, MA.

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