QUALITY ASSURANCE AND COMMISSIONING PROCESS IN HIGH ENVIRONMENTAL PERFORMANCE (HEP) HOUSE IN NY STATE

by

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ABSTRACT

High Environmental Performance (HEP), a demonstration house in NY State, is an advanced, low energy house built to represent the state of the art in housing technology available in year 2006. In a process similar to that used by the Building America program, a team representing four areas of expertise went though the design review and construction process identifying options for integrating mechanical services (HVAC) with the building enclosure. To assist in the process of material selection some testing was also performed at the University. Thus, the process of analyzing material, component and subsystems performance was detailed and led to a few improvements in construction details.

This paper presents an overview of the process of QA and commissioning during construction for both the building envelope and HVAC. Included in the process are also measurements of VOC emissions, adjustment between natural air infiltration and mechanical ventilation, adjustment for large hood ventilation in the kitchen that is required by the code, assessment of distribution of air flows between different spaces of this large house (5,600 sq ft area). Since the house is a demonstration of our capabilities for predicting quality of indoor environment and energy conservation, a significant monitoring program has been designed and implemented.

1. BACKGROUND

The construction industry performs a lot of market studies and product testing. But does this testing predict long-term performance of a building? The linkage between the testing to qualify materials and components and the overall performance of the building is provided by the engineering experience and understanding of scientific principles. Without this linkage, material qualification alone is not sufficient to predict performance for the different climate and service conditions.

While this is easy to say, but how do we ensure that the quality assurance system would start with the conceptual design, and go through drawing development, actual construction and commissioning stages to deliver the performance that an architect had in the design intent. To avoid failures caused by a lack of communication between different groups of professionals to highlight the interactions between various subsystems, we need to institute a formal QA system that would alleviate most of these problems.

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Such a system, called Performance-Based Quality Assurance (PBQA) system and discussed by Lstiburek and Bomberg (1966 a and b) is applied to this case. It starts with a careful review of the design intent and examination if the drawings convey it in a clear fashion.

2. OBJECTIVE OF THE PAPER

As much as it is possible to specify objective in design, construction and commissioning of high performance house we wanted to achieve several goals:
1) compare airtightness of two tight building enclosure systems
2) compare air tightness during construction and after the house completion
3) compare total VOC introduced in the last phase of building construction (finishing, cleaning just before occupancy) with that after a few weeks of occupancy
4) compare energy use monitored over one year with that predicted

Since the monitoring is still ongoing, the last item is not discussed in the paper.

3. DESCRIPTION OF THE HOUSE

The house has a walk-out basement, living area and kitchen on the first floor and bedrooms and bathrooms on the second floor. A garage is attached to the end of the house. A bonus room has been constructed above the garage. Surface areas and volumes are listed in Table 1.

Table 1 – Surface Areas in ft^2

walls-outdoors	5924	walls-garage	216
roof-outdoors	3108	basement slab	2428
Bonus room			
walls-outdoors	480	roof-outdoors	1448
floor-garage	960	walls-bonus room	216
Bonus room	2888		
Total house area	14564		

Volume of the bonus room 8400 ft^3
Volume of the whole house 79408 ft^3

Figure 1. Back view of the house before the synthetic stucco application on the ICF blocks

4. QA CONSIDERATIONS IN THE DESIGN STAGE (i.e., ensuring that the design intent is clear)

During the design stage the whole team (builder, and three consultants dealing with HVAC, environmental considerations and building science) met several times to perform the selection process. Initially, each group reviewed the current experience form the low energy housing, Building America Program etc analyzing different options and proposing several selected solutions. In the next stage the full team carefully analyzed all possible solutions and selected two best options for each of the considered elements of the house. A cost benefit analysis was than performed by the builder and experts of the team leading to a final set of solutions that are briefly described below.

The house is located in wooded area, well sheltered from wind. Yet, the slope of the hill in front of the house created a risk of basement flooding – therefore an additional masonry protection wall was erected in front of the ICF foundation. The basic concept of the building enclosure included stress on continuity of heat, air and moisture control and led us to combine two different systems: the ICF and close cell spray polyurethane foam (SPF). While the ICF was used in the main p[art of the house, all roofs above the house and above the garage were designed as unvented cathedral ceilings using close cell spray polyurethane foam (SPF) insulation. Radiant floor with hydronic heating system were selected because of high efficiency of the boiler that is used for both heating and hot water supply.

4.1 Foundations

Typical concerns include: water seepage through the wall, floor drainage and soil ad-freezing to wall surfaces. There was no problem with seepage though ICF and drainage because the house is located on a sloped terrain and weeping tile can easily be drained to the wooded area. (The floor slab is placed on the bed of gravel and the weeping tile on the perimeter is protected with the crushed stone and filter cloth).

To avoid ad-freezing on the side exposed to the soil, the Insulated Concrete Forms (ICF) were first covered with a thin water proofing membrane (proprietary product supplied by the manufacturer of ICF) and protected by thin concrete blocks (concrete veneer) on the exposed part of the slope. With a drainage mat placed between masonry protection and waterproofing membrane a masonry veneer protection drawn a bit higher than a slope permits backfill with natural soil and is maintenance free.

4.2 ICF wall system

Typical environmental concerns include: thermal bridges, particularly at floor levels, and wall-window connections.

The manufacturer of ICF system is one of the industry leaders and provides the builder with well designed brackets, joist hangers and support plates (see Figure 2)

Figure 2: The selected ICF system provides brackets for hanging the joists (left) support plates (center) and bracing for corners (right side).

Figure 3 (a) Thermal insulation strip (extruded polystyrene) placed between the rough opening of the window and the concrete fill (left side). (b) Sealant foam application between the rough opening and the ICF blocks (right side).

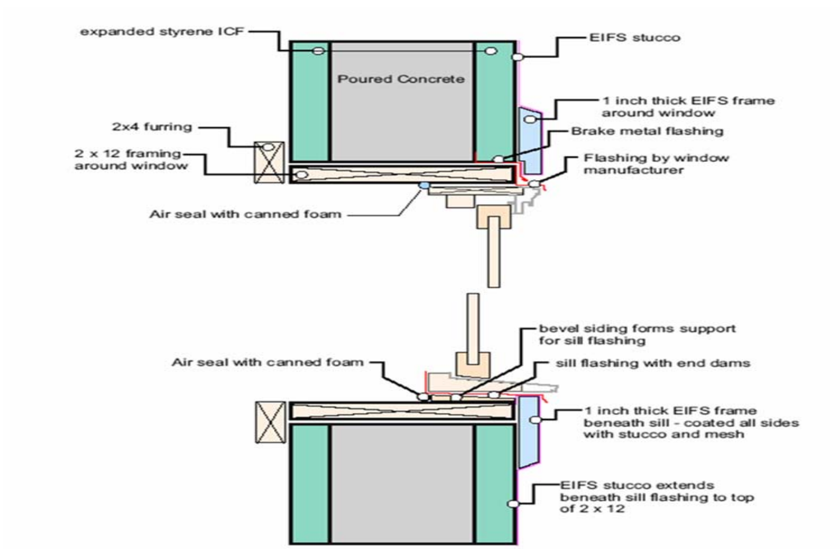

Figure 4 Schematic design of a window-wall interface

The thermal insulation strip (see Figure 3a) cuts the short circuit between the rough opening and the concrete fill in the ICF and reduces the thermal bridging around the window frame. Caulking applied to the rough opening (see Figure 3b) reduces possible infiltration of air between the ICF and rough opening.

Figure 4 shows a schematic design of a wall-window interface. Flexible flashing with end dams was selected. It was drawn on the an additional EIFS window frame, which in turn provided an additional protection for air leakage that might occur under the rough opening. A sealant foam was used on the other side of the rough opening i.e., between the window frame and the rough opening.

After performing air tightness measurements additional air tightening of the wall/window took place. As shown in Figure 4, a peel and stick flashing strip covers the whole surface under the window frame. Yet, after mounting of the window on the positioning shims and fastening it to the rough opening the gap is filled with sealant foam. The inner surface of the foam is cut flush and finished with a corner bead of wet caulk. Then, an additional wood strip, also placed on the sealant foam is added on the inside surface of the window trim. This strip, provides an additional air tightness measure should the foam develop cracks during long-term performance.

Figure 5 shows wall-roof connection where a peel and stick membrane is wrapped around the top surface of the ICF wall and anchored with the top plate. Spray polyurethane foam fills in full space above the wall. The soffit is unvented and EIFS lamina, joining through the freeze board to the exterior rim joist, provides a breathable but air tight enclosure under the roof.

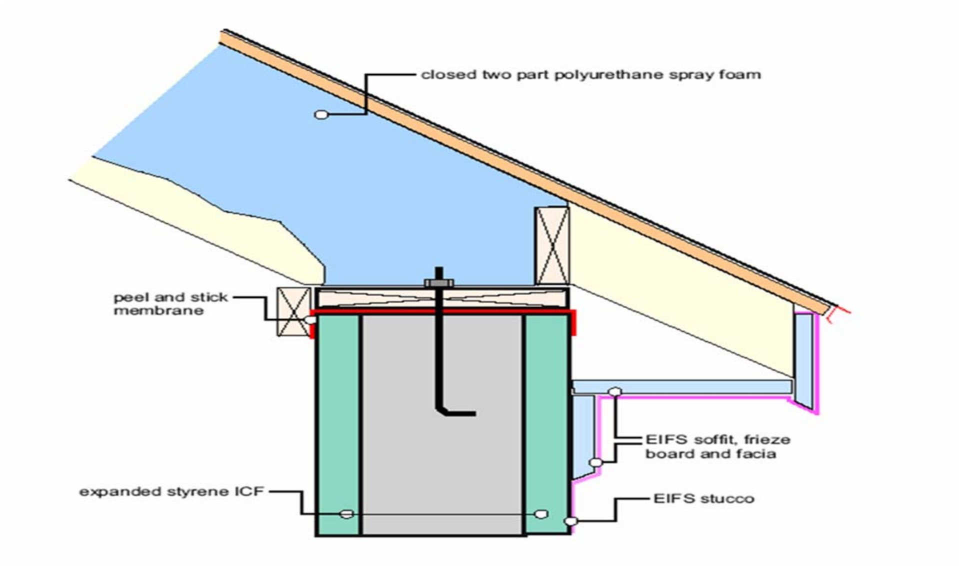

Figure 5 Schematic design of a wall –roof connection

One may wonder why we have selected unvented cathedral ceilings over the traditional ventilated roofs. The superiority of unvented Cathedralized ceilings has been discussed by Rudd (2005) for warm and mixed climate. In cold climates our concern was only condensation of water vapor and therefore we have selected medium density SPF type and having the whole roof space filled with this insulation. In this solution the sofitt plays only a decoration role.

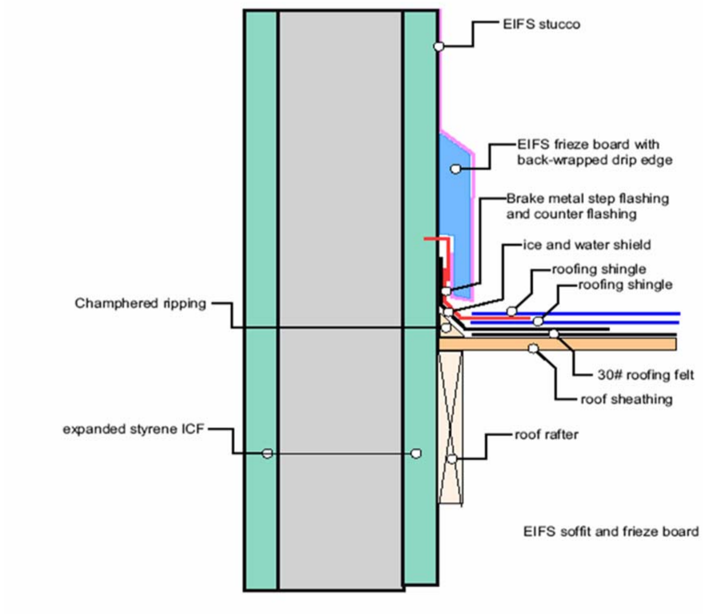

Figure 6 Schematic design of a wall – deck connection

Figure 6 shows a typical wall-deck connection where a counter flashing is made out of EIFS freeze-board.

4.3 Spray foam wall system

Closed-cell, soya-based spray foam was selected even though it aged thermal resistance was lower than that of traditional petroleum-based foam for two reasons: (1) to support the environment friendly product, (2) to evaluate the value of the air barrier technology provided by the spray polyurethane foams. The SPF was used in roof and walls surrounding the bonus room (see Figure 7). Laboratory testing and pilot foam application were performed to select the best available product on the market.

Figure 7 Room with walls and ceiling filled with the sprayed polyurethane foam

4.4 Cathedral ceilings

Cathedralized ceilings i.e., not finished with drywall but covered with a fire protective layer were originally planned but the price and need for different trades to apply the fire protective material, caused the builder to use the cathedral ceiling (i.e. finished with the drywall). Yet, as the raters above the bonus room were taller than others, there was an air space between SPF and drywall that was not filled with the foam. To examine if the air movement would affect the hygrothermal performance of the cathedral ceiling, this space will be monitored.

4.5 Heating system

While the radiant heating system may not offer any cost benefits over other heating systems it is generally considered a giving higher quality of the indoor environment. One may also assume some benefit of thermal mass which becomes a considerable benefit in winter season when the power failure occurs. In our case the decision was made to use high efficiency boiler and integrating the heating and hot water systems led to the selection of hydronic radiant floor system.

Extruded polystyrene insulation layer is placed on the concrete slab (Figure 8a) and the reinforcing wires together with the tubing of the floor heating system are placed (Figure 8b). They will be incorporated in the concrete overlay slab that is surface treated and finished with cutting groves to resemble flooring tiles. The reinforcing wires will be incorporated in the concrete overlay slab that is surface treated and finished with cutting groves to resemble flooring tiles.

On the main and second floor the tubing was placed on the subfloor, spaced with plywood strips and covered with hardwood flooring.

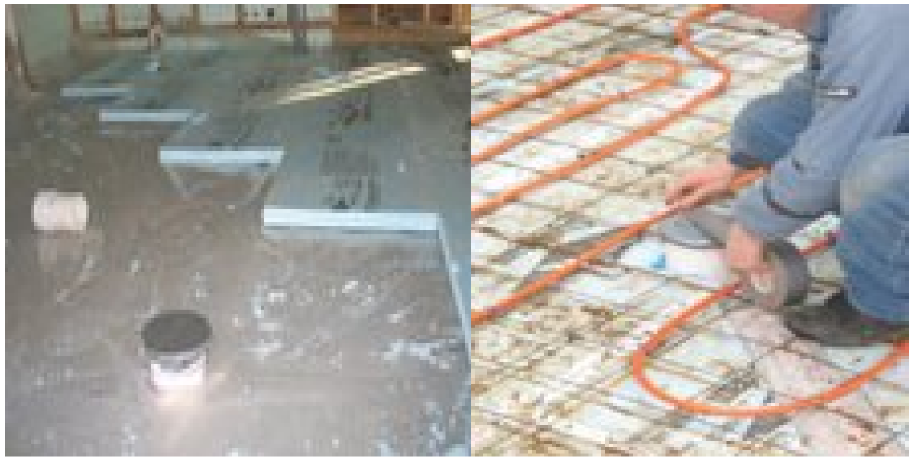

Figure 8. (a) Extruded polystyrene insulation layer is placed on the concrete slab (left side) and (b) the reinforcing wires together with the tubing of the floor heating system are placed (right side).

5. QA CONSIDERATIONS DURING THE CONSTRUCTION PROCESS

Clear drawings that highlight design intent are invaluable during the construction stage as they facilitate easy inspection process. Yet the main tool to control the quality of workmanship on site is the measurement of air tightness. To ensure the QA process was performed correctly the team members paid a weekly visit to the building site, taking pictures and inspecting critical details such as wall window junctions and even making some air-tightness measurements during construction. For instance a significant improvements of air tightness was observed when interior air seal was applied.

5.1 Air tightness of the building enclosure

Three different series of pressure testing were performed during the construction. Figure 9 shows the results of depressurizing the house with the door to the bonus room over the garage open and with the door to the bonus room sealed and taped with polyethylene film and tape. The distinction between the rest of the house and the bonus room is being made because the latter is insulated on all six sides using two part closed cell spray polyurethane foam in wall, roof and floor framing cavities, while the rest of the house is a combination of ICF and closed cell spray polyurethane foam (primarily ICF walls and spray foam roofs).

All doors and windows were closed. Intentional openings were taped off (e.g. chimney for temporary warm air furnace, hardware boreholes in doors). The tests shown in Figure 10 were conducted on May 8th, 2007. The wind was less than 5-10 mph from the WSW, the temperature was 70 to 73 degrees F, there was no precipitation and the barometric pressure was 30.16 inches mercury. The two tests were performed to see whether the bonus room added enough leakage area to make a difference in the test results. Although there is a slight difference it is in the wrong direction – the test with the bonus room blocked has a slightly larger leakage rate than with it open. The difference is not great and is within the repeatability of the test.

Table 2 provides airtightness results in a variety of units (e.g. leakage area, airflows at 50 and 75 Pascal and these units normalized to surface area). When normalizing to surface area all six sides of the enclosure were included – roofs, walls, and basement floor slab. The house is quite airtight existing airtightness standards (see Table 3). The HEP house is around ~~1.4~~ **1.22** in^2 **EqLA**/100 ft^2 enclosure and compares favorably with the Building America normalized EqLA of 2.5 in^2. In metric units the HEP house is around 2.46 m^3/hr.50/m^2 enclosure and compares favorably with the British best practice residential standard of 3 m^3/hr.50/m^2 enclosure.

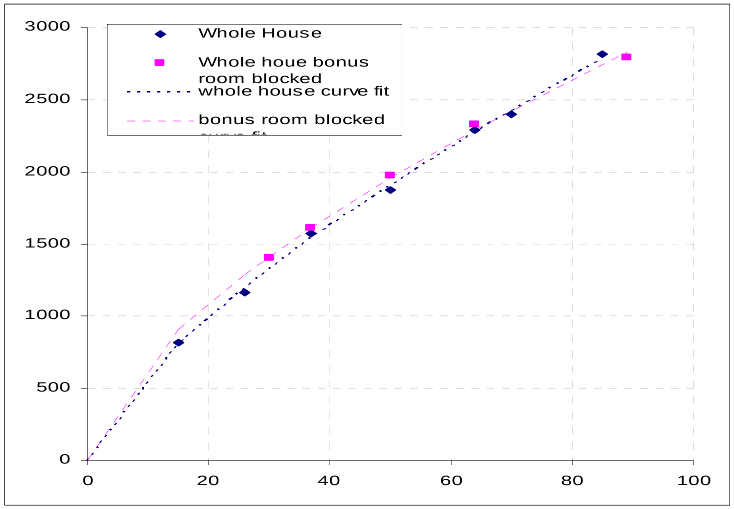

Figure 9 Measured Q [cfm] vs DP [Pa] curves for whole house tests

Note: Curve fit In the first series of tests was poor and a leakage path through unsealed penetration for a few electrical cables was found. After the sealing of this connection results became more consistent as shown in Figure 9.

5.2 Measurement of airtightness in the bonus room

The bonus room proved to be too airtight to be reliably tested using a fan door. A Fantech in-line centrifugal blower and a six inch diameter iris ring damper flow station was used to pressure test the room. At 960 square feet of floor space the bonus room is actually the size of a fairly large apartment. The test was conducted on May 18th, 2007. The windows in the bonus room were closed. Windows and a door in the main house were open. The test apparatus was set-up in the door between the main house and the bonus room. The bonus room was pressurized during the test. The wind was less than 5 mph, the temperature was 52 degrees F, there was no precipitation and the barometric pressure was 30.24 inches mercury.

When the leakage area is normalized to the exposed surface area the bonus room is very airtight – 0.3 in^{2}ELA/100ft^2 enclosure and 0.61 in^{2}EqLA/100ft^2 enclosure.

With the room pressurized to around 48 Pascal relative to outside a smoke bottle was used to test joints and penetrations for air leakage (see Figure 10). The windows themselves were quite airtight, with no leakage at the operating hardware or weather stripped sash. Air leaked behind the gypsum board at every penetration. The pressure drop over the gypsum board was around 1.7 Pascal, indicating that the foamed roof, wall and floor assemblies provide the air barrier. No effort was made to air-seal the gypsum board to the framing, window jambs or electric outlets so it is not a surprise that it is not the primary air barrier.

Figure 10 Search for the leaks from pressurized room with the smoke bottle and light to observe the smoke path.

5.3 Results of airtightness measurements and criteria.

Table 2 Airtightness of the whole house and bonus room

	Whole house	Bonus room	Criteria
C	117.6	11.1	
n	0.712	0.728	
R^2	0.998	0.998	
ELA4 (in^2) =	89.5	8.67	
CFM50 =	1907	192.4	
ACH50pa =	1.44	1.37	
m^3/hr.50/m^2 enclosure =	2.39	1.22	British ATTMA residential 3
LPS75/m^2 enclosure =	0.89	0.45	
CFM50/100ft^2 enclosure =	13.09	6.66	
in^2ELA/100ft^2 enclosure =	0.62		EEBA, LEED multi-family

		0.30	**1.25**	
$in^2EqLA/100ft^2$ enclosure =	1.22	0.61	Building America, **EFL** Platinum 2.5	.

Tightness criteria for four residential programs are included for comparison. The British Air Tightness Testing Measurement Association (ATTMA) Standard TS1 contains air tightness criteria for a number of building types. For single family residences it is 3 $m^3/hr.50/m^2$ enclosures. The Energy Efficient Builder's Association (EEBA) and the Leadership in Energy and Environmental Design (LEED 2.2) include target enclosure requirements of 1.25 $in^2ELA/100ft^2$ enclosures. The Building America program and Environments for Living, Platinum target tightness level is 2.5 $in^2EqLA/100ft^2$ enclosure. The HEP house exceeds the target tightness levels of all these programs.

5.5 Measurements of Indoor Air Quality

Indoor air quality measurements were made before and after occupancy. Four indoor air contaminant and environmental variables were measured continuously (temperature, humidity, carbon monoxide and carbon dioxide). Volatile Organic Compounds (VOC), formaldehyde and acetaldehyde samples were collected on two days – pre-occupancy: 12/11/07 and post occupancy 2/06/08. Tracer decay measurements were used to estimate ventilation rates during the VOC sampling. Short term (3 day) radon measurements were made using charcoal canisters beginning on 12/11/07.

Ventilation Rates

Tracer decay analysis was used to estimate the ventilation rate of the Master Bedroom and the Bonus Room over the garage during the time the VOC samples were collected. The results are shown in the following Table 3.

Table 3: Ventilation rates measured in the HEP house

Air change rate during VOC testing, [air changes per hour]		
Date and external temperature	Master Bedroom	Bonus Room
Dec 10, 2007 (28 ^oF)	0.18	0.02
Feb 6, 2008 (30 ^{o} F)	0.16	0.02

The central ventilation system was operated continuously during the sampling period. This provides a measured fan flow of around 130 cfm, which for this house translates to 0.1 ACH. Applying the fan door test results and the weather conditions for the test days to ventilation models (Kronval, Shaw and LBL) results in stack and wind driven infiltration rates between 0.06 and 0.09 ACH. The combined fan powered and natural infiltration is in line with the ventilation rates measured using the tracer decay analysis.

VOC results

Total Volatile Organic Compound (TVOC) concentrations were initially highest in the Bonus room over the garage, second highest in the kitchen and lowest in the master bedroom. TVOC was reduced between the first and second sampling at all three locations where pre and post occupancy sampling was conducted. In the second set of samples the bonus room levels were about cut in half but remained the highest. The kitchen levels plummeted by a factor of five making it the test area with the lowest TVOC. The master bedroom levels were about cut in half. It is not surprising that the bonus room has the highest concentrations considering the ventilation rate is eight or nine times lower than the master bedroom.   It is expected that the building related VOC sources decreased between the first and second sample sets. During the first set of samples sources from wet applied products were present in the house - cleaning and touch-up painting were occurring. Emission rates for many materials rapidly decrease after initial installation (e.g. paints, varnishes, adhesives, carpet systems). However new sources of VOCs were introduced when the owners moved their belongings and furnishings into the house. With the exception of formaldehyde the reduction in building related emissions appears to have had a bigger impact on VOC levels than the introduction of belongings.

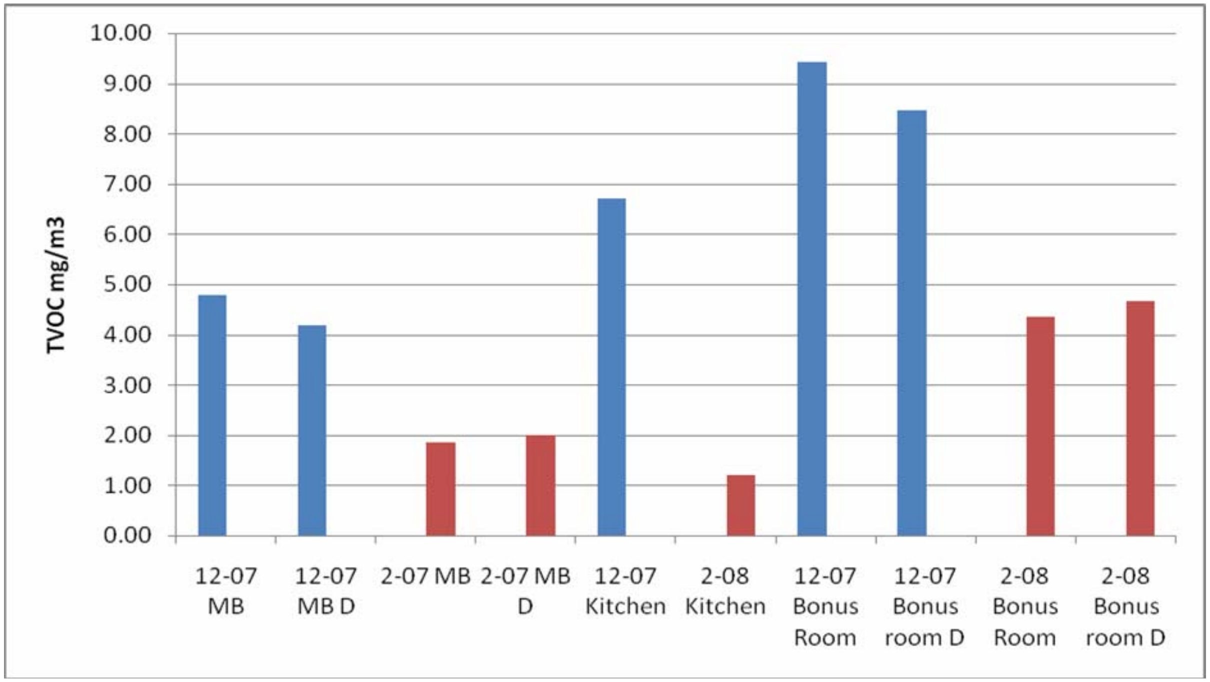

Figure 11: TVOC sampling in different location before and after occupancy.

The results of the VOC sampling are shown for each sampling location in Figures 11 (Master Bedroom), 12 (Kitchen) and 13 (Bonus room over garage). Dozens of VOCs were found at measureable levels at one or more locations during the pre or post sampling. Twenty major identified compounds are reported in the graphs. Each of the twenty is listed on the horizontal axis of all three graphs. The pre-occupancy samples are the left-most bars for each VOC. They are followed by the post occupancy results. For some compounds results from a study of VOCs in a National Research Council (NRC) study of newly constructed pre-occupancy Canadian house (Zhang et al 2000) and results from a study in 150 existing single and multi-family residences (mean and maximum concentrations) are included for comparison. Note that the HEP House is newly constructed. VOCs from building materials are expected to be found at higher concentrations in newly constructed buildings than in existing buildings. VOC emissions from furnishings are more dependent on the age of the furnishings and the materials from which they were made. Some new furniture was used in furnishing the HEP house and the dataset from the 150 existing houses may well include some with new pieces of furniture. Occupant related sources should be similar, with the exception of contaminants related to tobacco smoke.

Some observations:

All the compounds found during the first sample were reduced in the kitchen except for D-Limonene which remained at the same levels.
The following compounds were reduced in all three locations:

- DECANE
- D-LIMONENE
- 2-PROPANOL, 1-(2-METHOXY-1-METHYLETHOXY)
- 2-PROPANOL, 1-(2-METHOXYPROPOXY)-
- UNDECANE
- 2-PYRROLIDINONE, 1-METHYL-
- DODECANE
- ETHANOL, 1-(2-BUTOXYETHOXY)-
- BENZENE, 1,3-BIS(1,1-DIMETHYLETHYL)-
- PROPANOIC ACID, 2-METHYL-, 2,2-DIMETHYL-
- PROPANOIC ACID, 2-METHYL-, 3-HYDROXY-2,4

The compounds with higher molecular weights had the greatest reductions (from Ethanol down).
The only compounds found in the first samples that showed an increase between the first and second sample were in the Bonus room over the garage: Hexanal, P-xylene and D-limonene showed around a 10% increase.

Three compounds that were not present in the December samples appeared in the February samples:

- 2-Propanol, 1-(1-methylethoxy)- (found in cleaners, paints, scatter rugs)
- Ethylbenzene (found in varnishes and wooden furniture)
- Decamethylcyclopentasiloxane (found in personal care products, soaps and alternative dry cleaning)

These three compounds were not found in the Canadian new house project. This provides some evidence that they associated with occupant related sources.

The following compounds found in the HEP House are commonly found in building materials (e.g. paints, caulks, adhesives, polishes, varnishes, sealants, plastics, rubber or vinyl flooring), furnishings (e.g. scatter rugs, wooden furniture) cleaning products or as fragrance (e.g. deodorizers, cleaning products):

- N-butanol 71-36-3
- Toluene 108-88-3
- Ethylbenzene 100-41-4

- P-xylene 106-42-3
- Alpha pinene 80-56-8
- Decane 124-18-5
- D-limonene 5989-27-5
- Undecane 1120-21-4
- 2-PYRROLIDINONE, 1-METHYL- 872-50-4

Eight compounds were found in both the NRC new house study and the HEP House. Three compounds - Toluene, P-xylene, Hexanal - were found at higher levels in the HEP house tests than in either the new house tests. One compound, D-Limonene was found at similar concentrations in both the HEP house and the NRC new house study. Four compounds – alpha-pinene, Decane, Undecane and Dodecane - were found at similar or lower levels in the HEP House than in the NRC new house study.
Eleven compounds were found in both the HEP House samples and the 150 house study reported by Zhang et al (2003). In the second set of HEP samples Toluene, Hexanal and propanoic acid, 2 methyl-,3 are significantly higher in the HEP House. The other six compounds are near the reported means and significantly below the reported maximums.

More detailed information is provided in Figures 12, 13 and 14 where compounds measured at different locations are specified

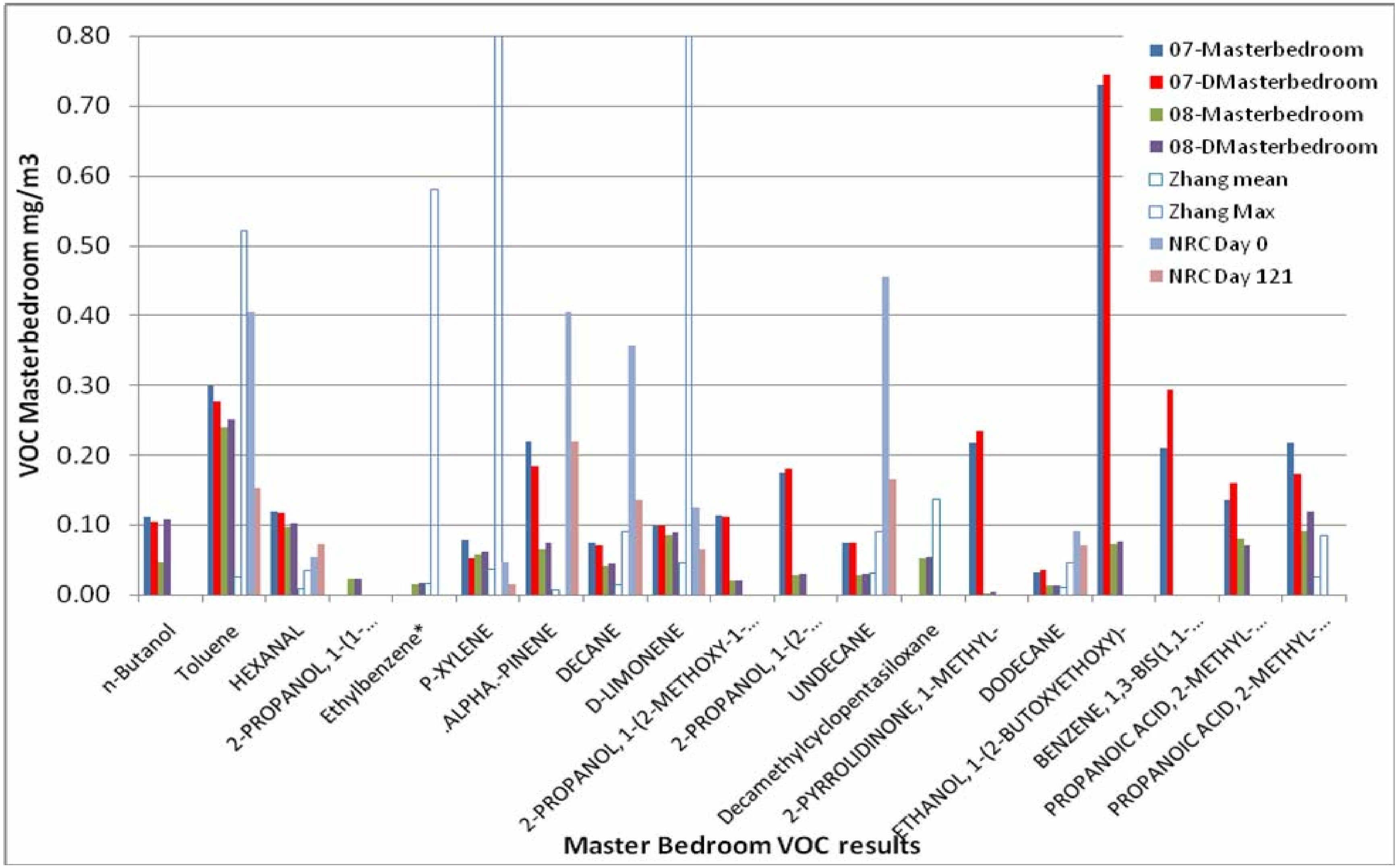

Figure 12. VOC results from measurements performed in Master Bedroom.

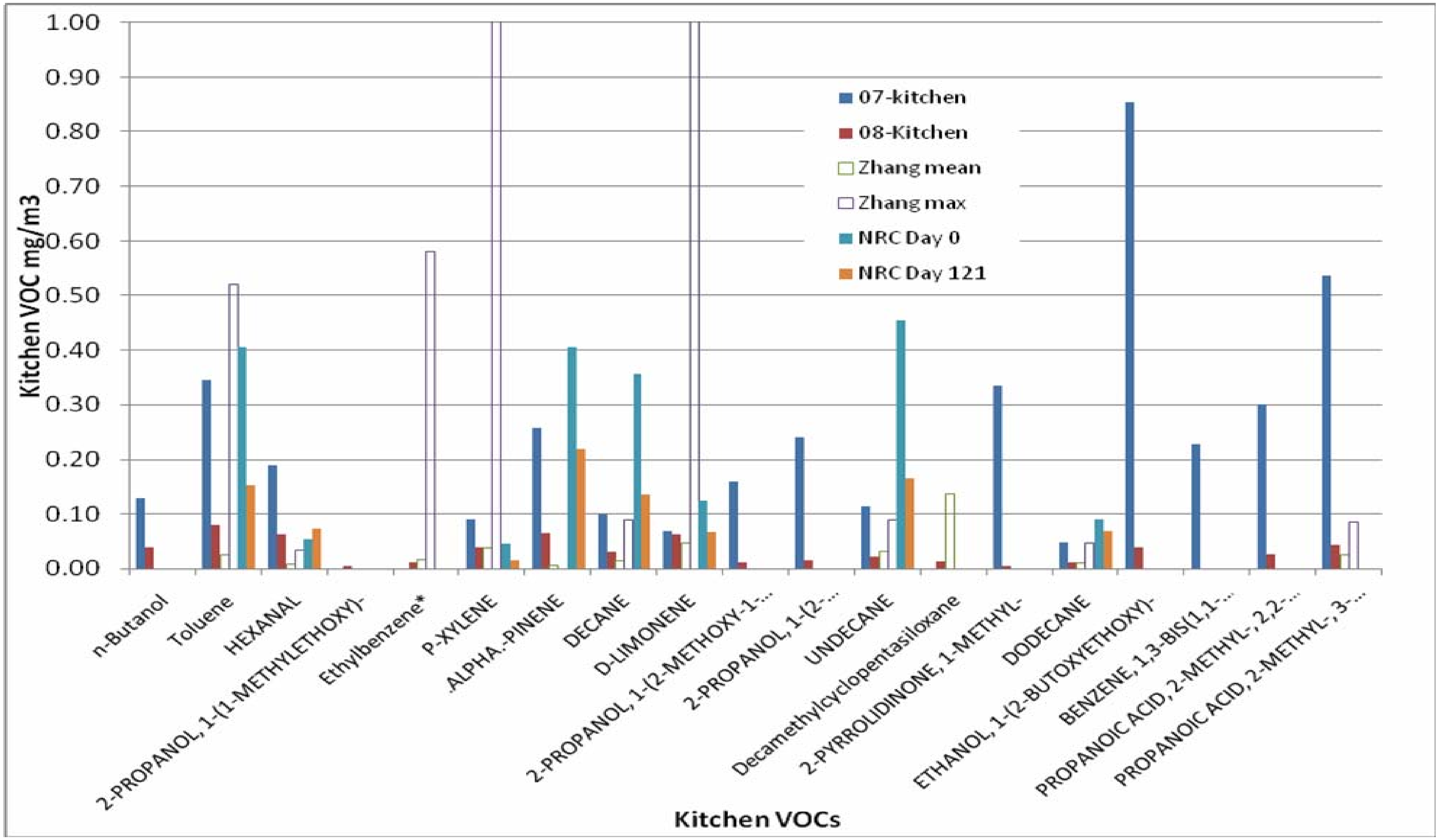

Figure 13. VOC results from measurements performed in Kitchen.

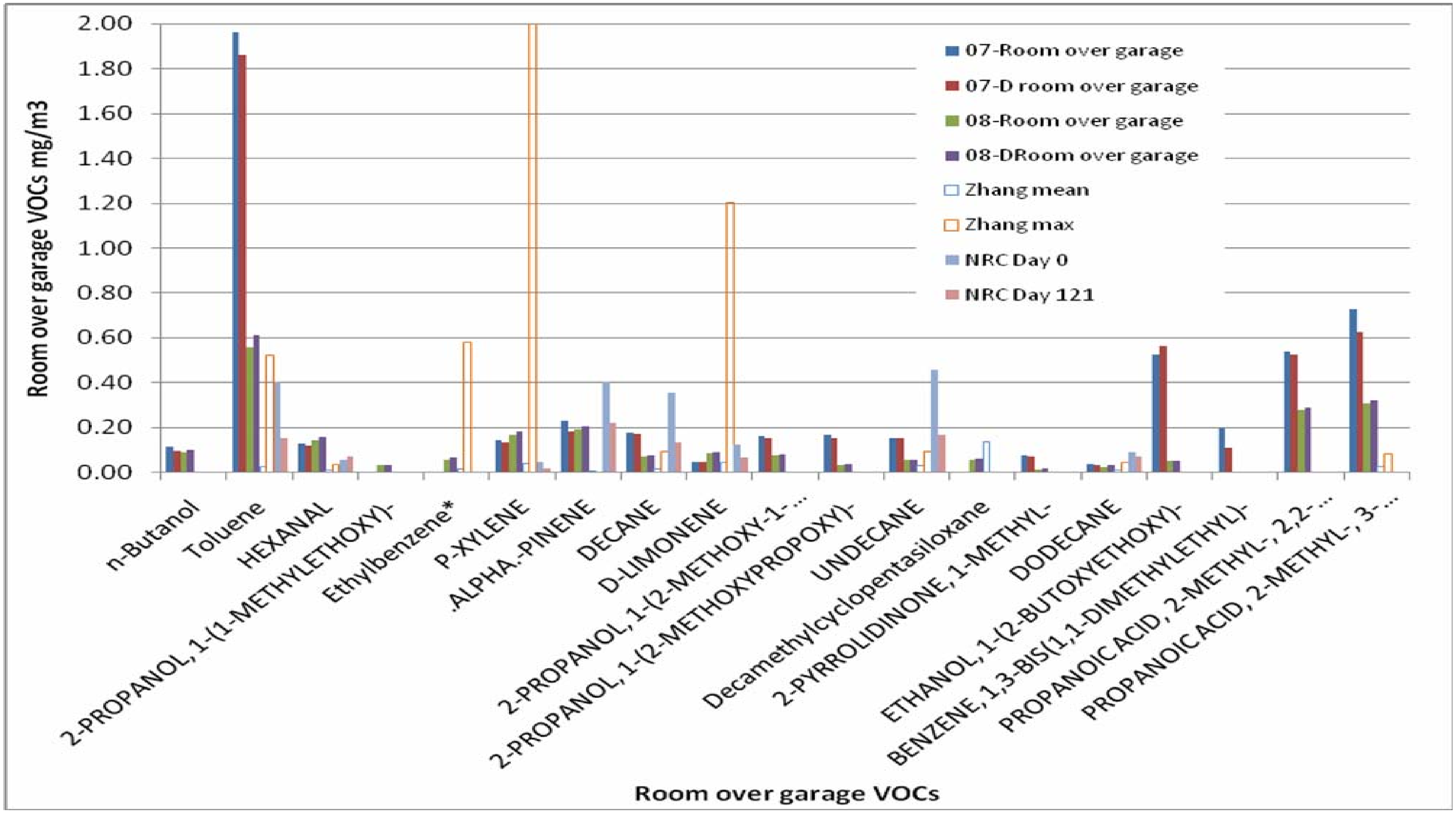

Figure 14. VOC results from measurements performed in Bonus room (over garage) insulated with Spray Polyurethane Foam.

Formaldehyde and Acetaldehyde

Formaldehyde and acetaldehyde samples were collected on 12/11/07 and on 2/06/08. Intially formaldehyde levels were between 40 and 55 ug/m^3. The kitchen and a secondary bedroom were the highest. Formaldehyde levels in the NRC new house study exceeded 60 ug/m^3 for most of the study period. Hodgson and Levin (2003) report a geometric mean of 39 ug/m^3 and maximum of 76 ug/m^3 in a study of newly constructed residences. However the formaldehyde levels increased between the first and second samples to the point they are outside the levels reported by Hodgson and Levin (2003). The increase is particularly high in the master bedroom where levels are slightly over double what was measured in December. There are two published guidelines for formaldehyde in residences: the Canadian recommendation of 61 ug/m^3 and the California Air Resources Board value of 33 ug/m^3. It is believed that the increase in formaldehyde levels in the master bedroom may be the result of furniture placed in the room between sample sets.

Acetaldehyde levels in the intial samples ranged between 15 and 20 ug/m^3. Hodgson and Levin report a geometric mean of 25 ug/m^3 and a maximum of 77 ug/m^3. Acetaldehyde levels showed minor increases in the second samples in the master bedroomand the kitchen but tripled in the bonus room over the garage. The levels in the kitchen and master bedroom are 25ug/m3 the same as the geometric mean reported by Hodgson and Levin. The levels the room over the garage approach the maximum reported by Hodgson and Levin.

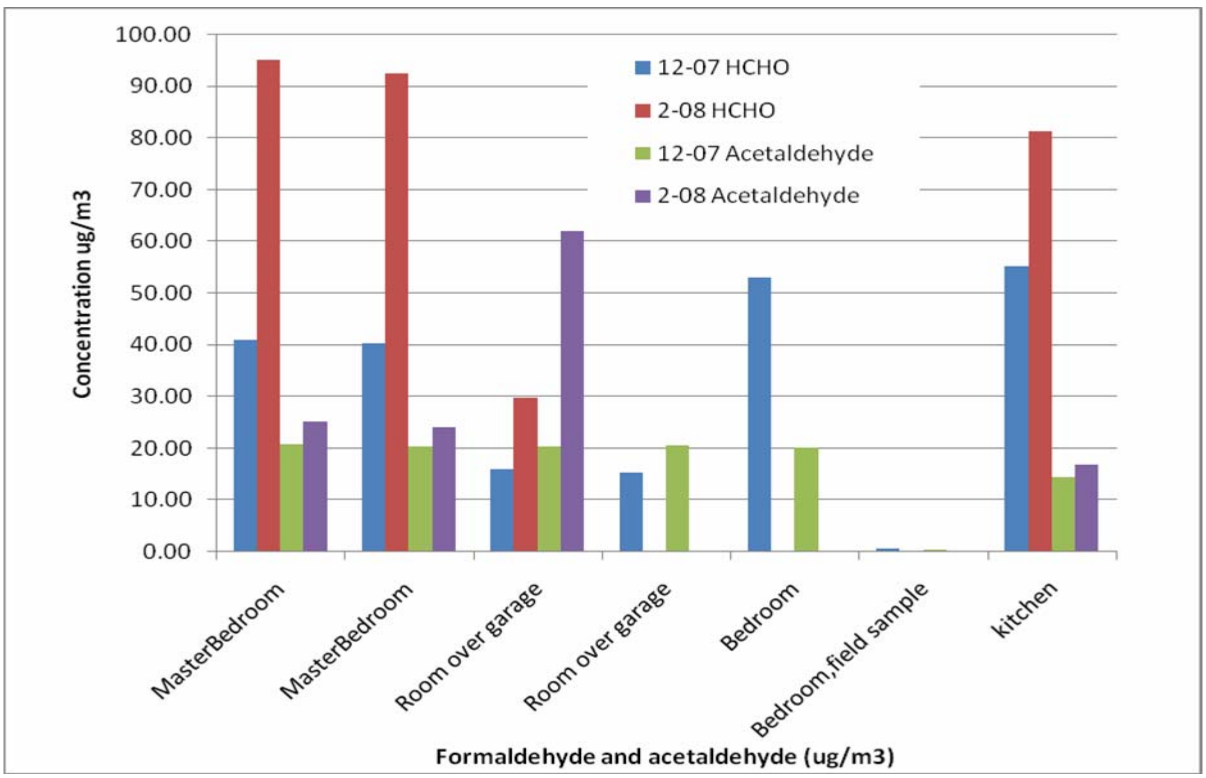

Figure 15. Concentration of aldehyde before and after occupancy

6. Conclusions

The following conclusions can be drawn from the above reported study

1) Developing separate drawings of each detail was helpful in the construction process
2) Performing air tightness tests during the construction was helpful to find leaks and increase the level of airtightness
3) Airtightness achievable on larger buildings is similar to that achievable on small but may require more attention during design stage and QA testing during construction
4) Both ICF and SPF systems permit achieving a very high level of airtightness
5) No difference in VOC was observed in space enclosed by SPF than that by ICF
6) There may be a need for increased ventilation right before occupancy to reduce effect of the last moment painting and cleaning
7) The introduction of the furniture had a very significant effect on aldehyde concentration

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