COLD CLIMATE HOUSING RESEARCH CENTER
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Monitoring and Verification of Sustainable Northern Shelter Building Performance
Quinhagak Prototype House Final Report

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Monitoring and Verification of Sustainable Northern Shelter Building Performance *Quinhagak Prototype House Final Report*

Cold Climate Housing Research Center

written by

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NATIONAL RENEWABLE ENERGY LABORATORY

Figure 1. Quinhagak prototype house after a wind driven snow storm. The shape of the house sheds the wind and does not create large drifts in areas that would block the doors or windows.

CCHRC created the Sustainable Northern Shelter program in 2008 to help develop sustainable rural housing in northern climates. CCHRC designers work with local residents and housing authorities to develop homes that reflect the culture, environment, and local resources of individual communities. The designs emphasize energy efficiency, affordability, and durability. CCHRC has developed several prototype homes that can be easily and affordably reproduced throughout communities to provide much-needed housing. The first two prototype homes were built in Anaktuvuk Pass and Quinhagak.

Quinhagak

Quinhagak is a Yup'ik Eskimo village on the east shore of the Kuskokwim Bay, less than a mile from the Bering Sea coast. The temperature ranges from an average of 41° to 57°F (5 to 14°C) in the summer to 6° to 24°F (-14 to -4°C) in the winter. Figure 2 shows the exterior temperatures in Quinhagak for the past year. Quinhagak has a wet climate; it averages 22 inches of rain and 43 inches of snow a year (State of Alaska, 2011). Quinhagak experiences approximately 11,700°F·day heating degree days per year (compared to about 14,000 for Fairbanks and 6,500 for Chicago).

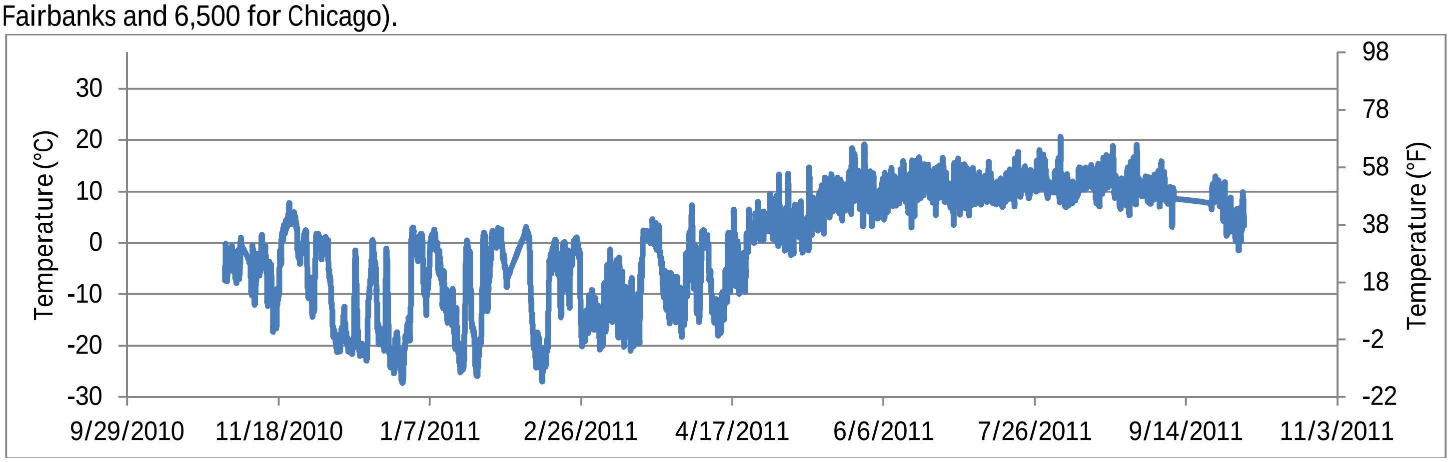

Figure 2. Exterior temperature in Quinhagak. Temperature ranges from -20 to 60°F (-28 to 15°C), but average about 32°F (0°C). The lapse in data in September 2011 is due to a network outage.

Quinhagak's housing stock is aging, and many homes have been compromised by extensive water infiltration, rot, and mold. Of particular concern are 55 homes from the 1970s that exhibit advanced structural damage and must be replaced.

Prototype House

The CCHRC design team met with Quinhagak residents in November 2009 to discuss problems with their current housing and goals for the prototype house. The home, which was built in 2010, answers four major housing challenges: material shipping cost, operating cost, moisture mitigation and wind mitigation. From the initial meetings between village residents and the CCHRC design team, the following primary design goals were established:

1. Develop a building envelope that would lead to lower annual fuel usage and that could resist water-infiltration from wind-driven rain.

   The strategy for addressing this is now known as the "Quinhagak Wall", a continuous monolithic thermal envelope that includes a 3-inch thermal break in the walls and a 4-inch thermal break in the foundation. The walls of the prototype are comprised of 4-inch metal studs on the inside, a 3.5-inch plastic spacer in the middle, and a light-gauge angle-iron that holds the cladding (siding) 7.5 inches out from the inside of the stud. Spray foam is applied continuously to the foundations, walls, and roof, creating a monolithic envelope with no gaps. This wall assembly is simple and well insulated (R-40[1]). The prototype has a 1.5-inch vented airspace between the trusses and the roof sheathing that serves as both a drainage plane and a drying path if any wind-driven rain works its way into the roof. The roof is approximately R-50.

2. Address moisture and mold problems associated with rot that commonly cause upper respiratory infections in children and elders.

   In addition to reducing the amount of materials prone to mold growth (AC plywood sheathing in lieu of sheetrock, metal studs and joists in lieu of wood), the prototype also incorporates a heat-recovery ventilation system and a passive make-up air system in the home, which lowers interior moisture build up and brings in fresh air on a regular basis.

3. Develop a structural system that addresses the cultural preference for an open plan, while lessening the expense of shipping large structural members.

   The prototype has a raft-like foundation consisting of 10 inches of spray foam and embedded metal joists in an octagonal form. The prototype rests directly on an overbuilt gravel pad, unlike most homes in the village which are elevated on pile foundations. The floor joists are elevated off the ground with EPS foam board spacers, and polyurethane foam is sprayed through the joists directly on a geo-textile mat. This foundation provides an insulation value of R-60. Half-trusses spanning radially from a central hub allows for the roof bottom chords to remain in tension and the top chords in compression without the use of columns or point loads. Ordering half-trusses allowed the assembly to be shipped more economically.

4. Create a construction assembly that precludes the need for heavy equipment and reduces shipping costs for remote villages.

   Wall sections are created on a jig and then hand-carried and placed on the foundation. Trusses are also able to be set without a crane. This ability to assemble the building using only manpower is important in remote villages with limited access to heavy equipment.

5. Create a home that reflects the culture and daily activities of rural indigenous occupants.

[1] All R-values in this document are in imperial units of $ft^2 \cdot °f \cdot h/Btu$.

Members of the community were integrated into the design process, giving input from the first design meeting through construction. The resulting floor plan reflects the daily needs of community members.

The Quinhagak prototype house (Figure 1) was completed in November 2010, and the completion of the home demonstrates the achievement of the many of these short term goals (three through five). In order to determine if the house is meeting the goals about better efficiency and indoor air quality CCHRC has been monitoring the on-going performance of the house.

Since it was completed the house has been occupied for seven months. A family of five moved into the house on April 12, 2011. Due the financial difficulties, this first family moved out on June 10, 2011. A larger family of six moved in around July 13, 2011. The house is octagonal, which has a lower surface area-to-volume ratio than a rectangular model, significantly reducing the amount of surface area exposed to the cold. The heated portion of the house is 946 square feet. An unconditioned elaturaq, or arctic entry, is wrapped around two of the eight walls, further improving heating efficiency and protecting the home from wet winds. With the elaturaq the square footage of the house is 1080. In Quinhagak, wind direction changes seasonally and wind-driven moisture is one of the primary causes of failure in the existing housing stock.

Space Heating

The primary heat source in the home is a Toyotomi OM-22 Oil Miser Direct Vent Oil Heating System. The Oil Miser is AFUE rated to be 85% efficient, is thermostatically controlled, and has programmable temperature settings and a "shut-off" safety mode. The Toyotomi is rated to provide 8,000 to 22,000 BTU/hr. The secondary heat source is a Vermont Castings Dutchwest Wood Stove. The wood stove is intended to provide supplemental heat in the event that power is out or the Toyotomi is not operational.

Electrical Demand

The electrical appliances and fixtures were designed to be as energy efficient as target construction costs would allow. Of the regularly used electrical appliances the refrigerator, range, and the water heater have the highest power draw ratings. The combined lighting for the house only uses 536 W when all lights are on. The electrical appliances, fixtures, and lighting installed in the house are identified in Tables 1 and 2. This list does not take into account the additional electrical appliances that the occupants may have added.

Table 1. Quinhagak electrical appliances.

Appliance	Rated power specification
Toyotomi OM-22 – oil-fired heater	preheat = 275 W, burning = 46 W
Gould's BFO3s - water pump	990W
Bradford White 20 gallon - water heater	1500 W
Sanibest 013 - grinder pump	990 W
Hotpoint - electric range	10,100 W (@ 240V)
General Electric – refrigerator 16-18 CM	1650 W (maximum)
Venmar EKO 1.5 – HRV	98 W (maximum)

Table 2. Quinhagak light fixtures locations, types, and power consumption.

Location	No. of Fixtures	Number/Type Bulbs per Fixture	Total Rated Power
Kitchen	1	2/48"LED	30 W
Entry	2	2/48"LED	60 W
Bedroom	9	3/CFL	117 W
Bathroom	3	3/LED	108 W
Living room - can lights	13	1/LED	169 W
Outside	2	2/LED	52 W

Ventilation

Ventilation needs to meet several goals in a home: bringing in fresh air to maintain healthy interior living conditions, maintaining healthy interior moisture, and reducing the energy costs of maintaining comfortable living conditions in homes. The Quinhagak prototype house was designed to be very air tight with minimal air infiltration. This creates a warm house that requires less heating fuel than a conventionally constructed home. However, it also creates a house with very little fresh air entering. The lack of air movement though the building envelope creates the need for a mechanical ventilation system (Figure3) to maintain healthy air inside the house. The Quinhagak prototype house has a heat recovery ventilator (HRV), which uses blowers to pull cold outside air into the house, warm it with exiting heated inside air through an air-to-air heat exchanger, and distribute the fresh air around the house.

Figure 3. Quinhagak prototype house ventilation system. This high efficiency HRV is located in the mechanical room and circulates fresh air throughout the house.

Monitoring

Cold Climate Housing Research Center (CCHRC) is monitoring the prototype home in Quinhagak. The data collection systems are intended to help demonstrate operations of the prototype designs, evaluate the integration of various building systems, and recommend design improvements. Collecting data to help this process is critical to meeting the long-term objective: improve the quality of rural housing while reducing the costs for construction, maintenance, and energy.

Equipment and Methods

The Quinhagak prototype home monitoring system consists of a computer and two Labjack data loggers; a UE9 and a U6 (Figure 4). The UE9 is being used to watch for changes in the moisture content of the foam in the roof, walls and foundation of the house. The U6 is monitoring the house energy use and indoor air quality though an array of sensors embedded when the house was constructed (Table 3). The systems logs data from the sensors at five minute, hourly, and daily intervals, depending on the sensor type and location. The computer sends data back to CCHRC via a GCI WISP (wireless internet service provider) antenna network.

Table 3. Energy and ventilation sensors.

Sensor	Location	Purpose
Relative humidity	Living room and bedroom	Indoor air quality
Carbon dioxide (CO_2)	Living room and bedroom	Indoor air quality
Temperature	Living room, bedroom, and outside	Occupant comfort
Fuel level	On fuel tank	Energy use
Stove pipe temp	On stove pipe	Energy use
Current Transducer	HRV and bathroom fan	Ventilation use

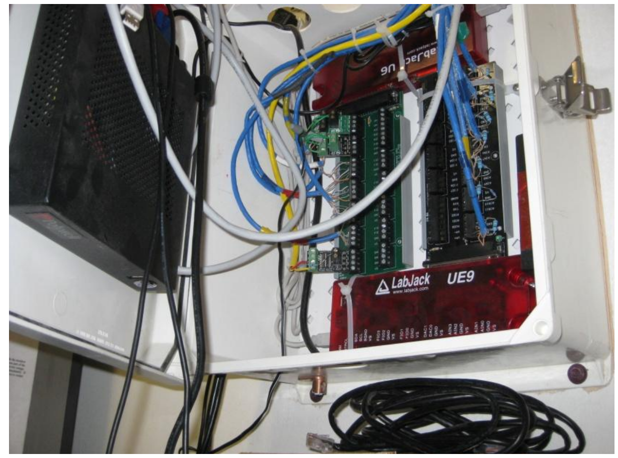

Figure 4. Quinhagak Datalogging System. The datalogging system fits in a small box in the mechanical room.

Fluctuating power and outages in the WISP network have caused problems with the data system at times leading to gaps in the data. Extended power outages have run down the battery system twice, requiring hard reboots of the system. The WISP antenna requires a hard reboot every time the village power fluctuates. Due to the remote location of the system getting the system rebooted involves some delays. The lower Kuskokwim area is in line to get high speed internet access over the next year, which will greatly enhance the data monitoring system and the response time.

All of the sensors provide an analog signal which is converted via an open-source Python program to useable data. The humidity, temperature and CO_2 are all self-explanatory, providing average conditions in the house at regular intervals. The current readings from the HRV and fans are used to estimate the total power use of the ventilation system. By using a voltage of 110V, this system overestimates the total power consumption slightly by ignoring the power factor and fluctuations in the incoming voltage.

The fuel level and stove pipe temperature readings are used to determine the heating demand of the house. A thermocouple on the stove pipe records when the woodstove is fired. Monitoring for sharp temperature increases in the pipe provides a simple on/off signal for the woodstove. That on/off signal can be used to estimate how much fuel the woodstove is offsetting. The fuel level sensor is actually a pressure transducer placed at the outlet of the fuel storage tank. As the level of fuel in the tank changes the sensor records the changes in the pressure at the bottom. The pressure reading is divided by the specific weight of heating fuel (0.379 lb/in^2) to get the height of the fuel in the tank. The volume is then determined using the height of fuel and the dimensions of the tank. The hourly estimate of the fuel volume allows for the calculation of the fuel taken from and added to the tank.

In addition to the sensor data, CCHRC is working with the local electric company Alaska Village Electric Cooperative (AVEC) to study the whole-house electrical usage. AVEC has been providing CCHRC with the monthly meter readings.

Ventilation Analysis

The air quality in a home is complicated to monitor and involves several parameters that need to be carefully balanced. The optimum humidity zone for human health is between 40% and 60% relative humidity (Sterling, 1985). This optimum band minimizes bacteria growth and virus spread that will occur at both very low and very high humidity; it also minimizes fungi and dust mites that thrive in high humidity. The optimum zone also reduces respiratory infections that come from low humidity and asthma that can be caused by very low and very high humidity. However, the optimum humidity zone for human health is not optimum for building health and the high humidity levels are detrimental to building durability. Relative humidity of 40% in the interior space can mean 80% or higher relative humidity inside the wall cavity depending on outside air temperature and wall construction. In an effort to balance healthy people and healthy buildings the recommended interior relative humidity is 30% to 50% for Alaska (Seifert, 2007).

In addition to having healthy humidity levels, changing the air in the house for fresh air is also important. A tight home does not have the air exchange with the outside that the older leaky homes do. This allows for the build-up of stale air in the house. The stale air can have a noticeable odor from cooking and human activities and can harbor higher concentrations of volatile organic compounds (VOCs) that may off gas from furniture, carpet, tile, and other items in the home. Carbon dioxide (CO_2) concentration is a marker that is simple to monitor and gives a good indication of air exchange. ASHRAE (2007) specifies that maintaining a steady state CO_2 level less than 700 parts per million (ppm) above ambient should ensure that sufficient fresh air is supplied to the space.

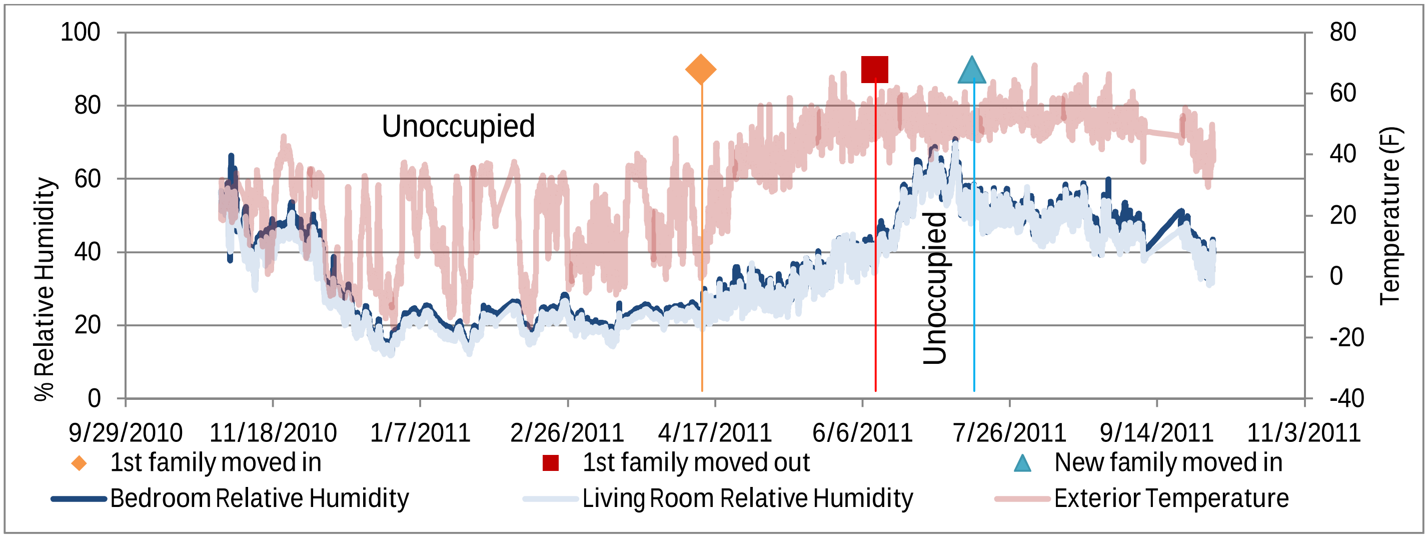

Figure 5. Interior Humidity and Exterior Temperature. As the exterior temperatures drop so does the interior humidity because the colder air in the winter maintains less moisture.

Another consideration when introducing fresh air in the winter is to need to keep the house warm. Using mechanical ventilation by an HRV allows for fresh air entering to be heated by the warm air exiting. This lowers heating demand and makes the house more comfortable. However, the HRV heat exchanger does not recover the moisture from the exiting air. Keeping CO_2 levels low while maintaining humidity in a healthy range can be conflicting goals, especially in the winter when fresh air introduced into the house will contain very little moisture. On particularly cold days the interior humidity can drop drastically (Figure 5). Thus far in the Quinhagak prototype house the humidity during occupation has been between 20% and 50% and variable with the seasons. Figures 5 and 6 demonstrate the difficulty of balancing air exchange with healthy humidity. The CO_2 levels in the house should remain below 1050 ppm (350 ppm ambient from unoccupied house data plus 700 ppm), yet they are exceeding 1500 ppm on several occasions, indicating that more air exchange would be beneficial. However, the humidity is in the healthy range and more air exchange would lower the humidity possibly out of the healthy range. A full winter of occupancy will provide a better understanding of the humidity and CO_2 levels and allow for fine tuning the HRV controls to approach the optimum balance for healthy indoor air quality.

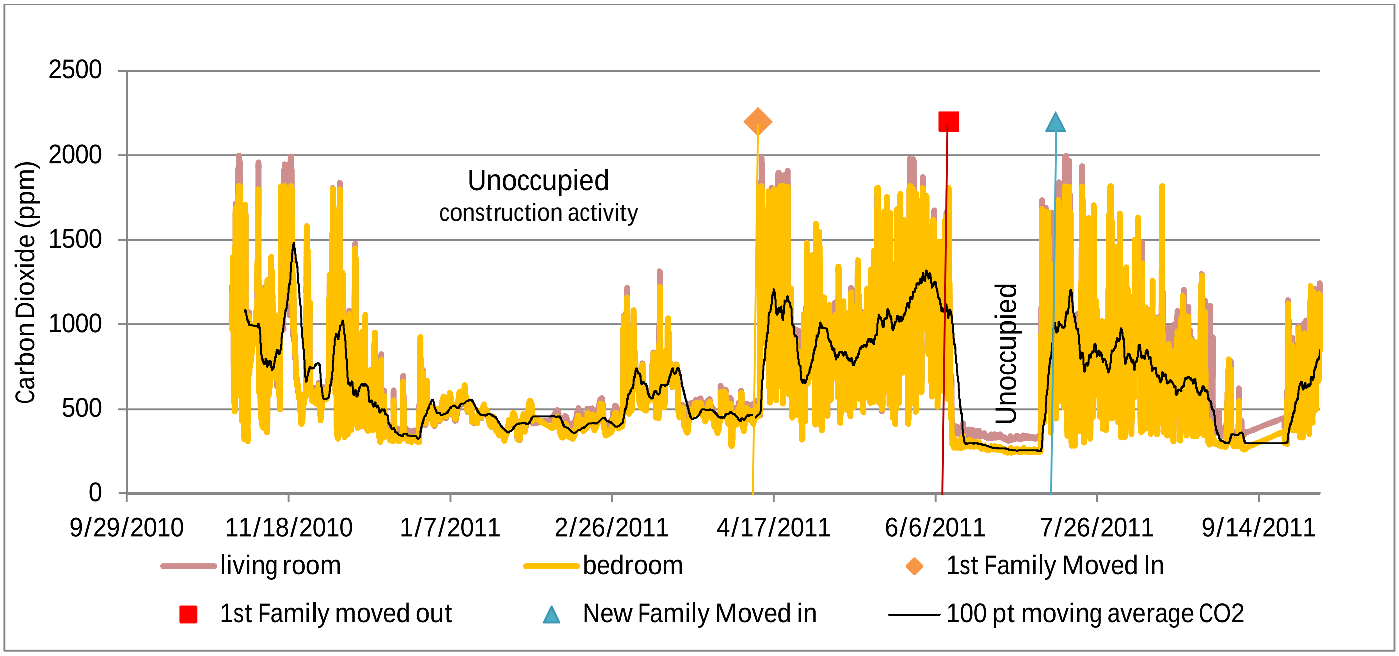

Figure 6. Interior carbon dioxide levels for the Quinhagak prototype house. The CO_2 levels fluctuated quite a bit in the first ten months as construction wrapped up and people moved in and out.

The HRV and a booster fan in the bathroom are the main electrical components of the ventilation system. The HRV has its own controller which offers a variety of options (control based on interior humidity and outside temperature or on/off cycles for fractions of an hour). The controller is in the living space and can be adjusted by the occupants at any time. In ten months of operation the HRV and bathroom fan used 195 kWh of electrical energy. For comparison, a television on 3 hours a day will use about 264 kWh a year (California Energy Commission, 2011)

Heating Demand

Typical home heating usage in rural Alaska is not well known. Estimates from a survey of 10 homes in Quinhagak, built in the 1970's and retrofitted with more insulation in the 1990's put fuel usage at 110 gallons per month (Housing Analysis, 2009). It is assumed that this estimate is for winter months, putting the 6 months of winter use at 660 gallons; Quinhagak has year-round heating requirements (A. Cooke, personal communication, December 15, 2011). The 2009 Alaska Housing Assessment puts Quinhagak in its rural 2 category which is defined as a median house size of 1056 square feet that consumes an average of 880 gallons of heating fuel a year (Alaska Housing Finance Corporation, 2009). These estimates compare well to each other when summer usage is taken into account.

The tight envelope of R-40 insulation should make the heating load for the house around 35 MMBtu for the year (AkWarm 2.1.2.1[2]). The model estimates that the house will use 88 gallons of #2 diesel oil. When the model is compared to the actual use for the first thirteen months (see table 4, next page) it slightly underestimates the fuel use. However, the model was done in the design phase of the project and it not accurate for the prototype home as it is built and the home has not been occupied for a full year.

[2] AkWarm 2.1.2.1 is the energy modeling program for Alaska Housing Finance Corporation's BEES and energy retrofit programs.

Table 4. Estimated fuel usage by date

Occupancy	Dates	Gallons
Unoccupied	November 7, 2010 to March 7, 2011	30[3]
First family moved in April 12, 2011	March 7, 2011 to May 2, 2011	42[3]
Second family moved in July 13, 2011	May 2, 2011 to August 21, 2011	29
Second family	August 21, 2011 to October 13, 2011	16
Second family	October 13, 2011 to December 21, 2011	54
Total since construction	November 7, 2010 to December 21, 2011	171

Figure 7 shows the temperature inside the prototype and the house occupancy for the first year. The most consistent interior temperature has been from July 13 until early October when the new family has been consistently in the house and kept the heater on. During construction and before occupancy the temperatures in the house fluctuated quite a bit and do not allow for an accurate estimate of fuel use for the house. Further monitoring of the occupied house will provide a better understanding of the house fuel use.

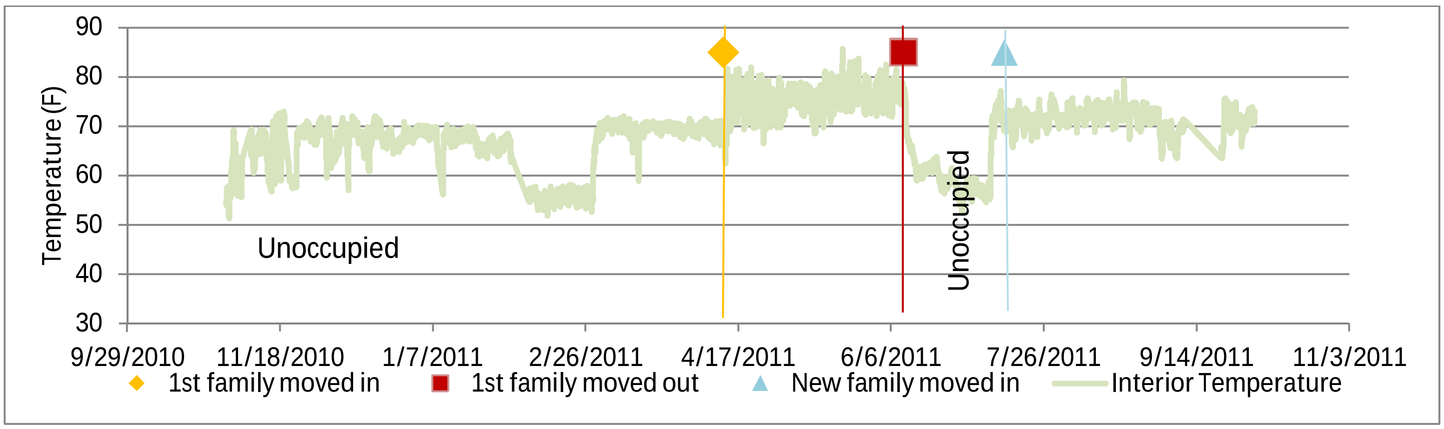

Figure 7. Interior temperature and occupancy patterns. This graph shows the interior temperatures and the house occupancy. Another year of data will give provide a better understanding of the house's energy performance.

Electrical Demand

Home electrical usage is strongly a function of occupant behavior. Quinhagak was designed with the most efficient appliances that were affordable within the construction budget. So far two different families have lived in the house and their electrical use has been very different (Figure 8). The initial family was in the house from early April to early June, the electrical demand for the two months they were in the house averaged 475 kWh per month. The new family moved in during late July, their monthly use has averaged 225 kWh, less than half of the previous family. However, both families used less monthly electricity than the average Alaskan household of 661 kWh/month (U.S. Energy Information Administration, 2009).

[3] Fuel data is estimated prior to May 2, 2011 due to a broken fuel level sensor.

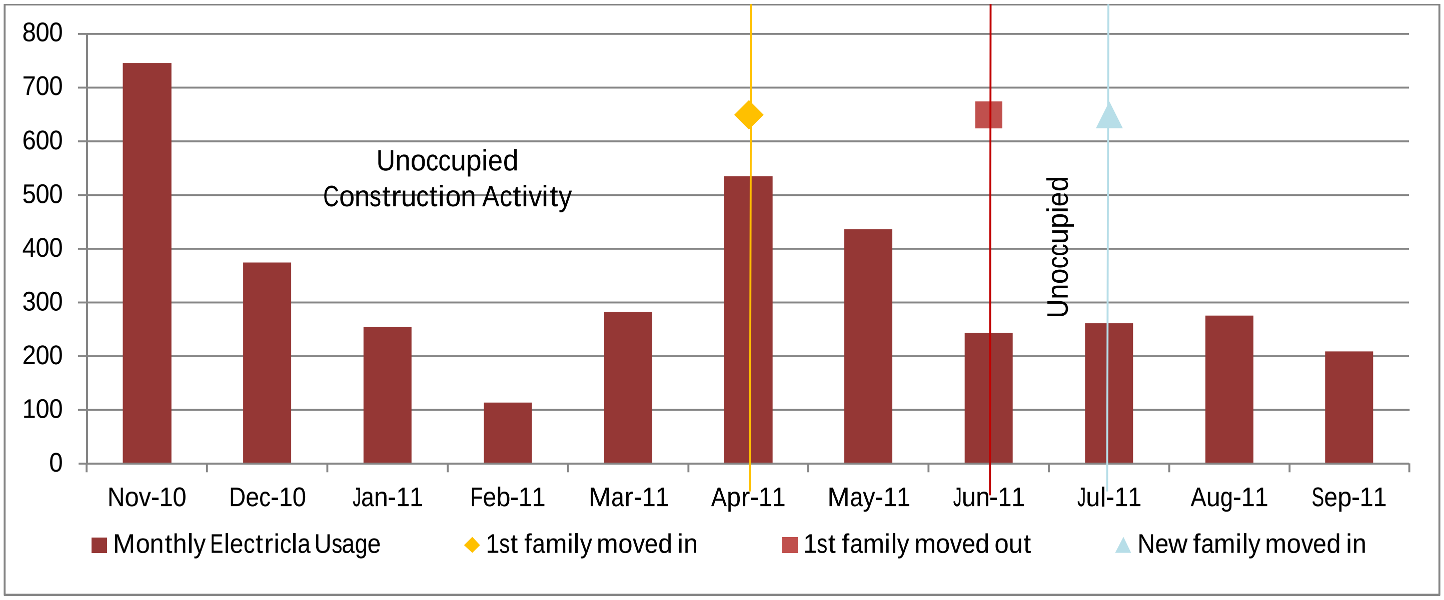

Figure 8. Electrical demand for the Quinhagak prototype house. The house was occupied for most of April, May, July, August and September.

General House Performance

House construction took a six person crew about seven weeks to complete. The crew was able to raise the house supports without the use of heavy machinery (Figure 9).

The two main post construction callbacks on the house were completed in September 2011. A direct make-up air vent was added to the woodstove to prevent back drafting caused by the very tight envelope. In addition, horizontal ground insulation added around the base of the house to protect the foundation from frost jacking and to divert run off away from the house.

Figure 9. The roof system. The trusses were small enough that the six person crew was able to raise them without heavy machinery.

The house has weathered a few strong coastal storms handily. A blowing snow storm in December 2010 allowed the house to demonstrate its ability to handle blowing snow. Figure 1 shows the exterior of the house after the blowing snow, notice the complete lack of drifts around the house; compare that to t truck sitting in the front yard (Figure 10).

Both families that have lived in the house have been pleased with the warmth and clean air inside the house. The village of Quinhagak plans to build more homes based on many of the techniques tested in this project.

Figure 10. Quinhagak truck after a coastal storm. This vehicle was sitting in front of the prototype house during the December 2010 storm.

Conclusions

So far there is only a partial picture of how the house performs, with such a short occupancy period. However, this limited information shows promise, in terms of meeting the original design goals. The preliminary data puts the house's annual heating fuel consumption of 171 gallons a year at 19% of a typical rural home of 880 gallons per year (Alaska Housing Finance Corporation, 2009). A full year of data with consistent occupancy is needed to get a more accurate assessment of how the house actually performs, but the actual number is not expected to change by much.

The ventilation system is doing an adequate job of maintaining healthy indoor air, but that system is much more difficult to assess without a full year of occupancy. So far, the relative humidity has been in the healthy range of 30 to 50% with the house occupied. The CO_2 levels have fluctuated drastically, but are better than the 1994 study that recorded CO_2 levels in Quinhagak from1100 to 3500ppm (Brooks, 1994). A winter's worth of occupancy will allow for a better assessment of the indoor air quality.

Though HRVs have been slow to be adopted in rural Alaska, its use in this prototype home with its better air quality and low heating and electrical costs could prove to be a good demonstration of an effective way to ventilate rural homes.

In order to determine how the house is meeting the long term goals of energy efficiency and indoor air quality, CCHRC plans to continue to monitor the home though June 2012. Early results with half a year of occupancy indicate that the home is achieving the goals of energy efficiency and healthy indoor air; a full year of data will help inform decisions on the next generation of homes for Quinhagak.

Partners

The following organizations collaborated to help design, build, and study the prototype house in Quinhagak:

- Native Village of Kwinhagak, Housing
- Alaska Housing Finance Corporation
- US Department of Energy, National Renewable Energy Laboratory (NREL)
- Rural Community Development Consultants
- ThotPro Engineering
- Ventilation Solutions
- Star Electric
- U.S. Department of Housing and Urban Development (HUD)
- The house residents

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