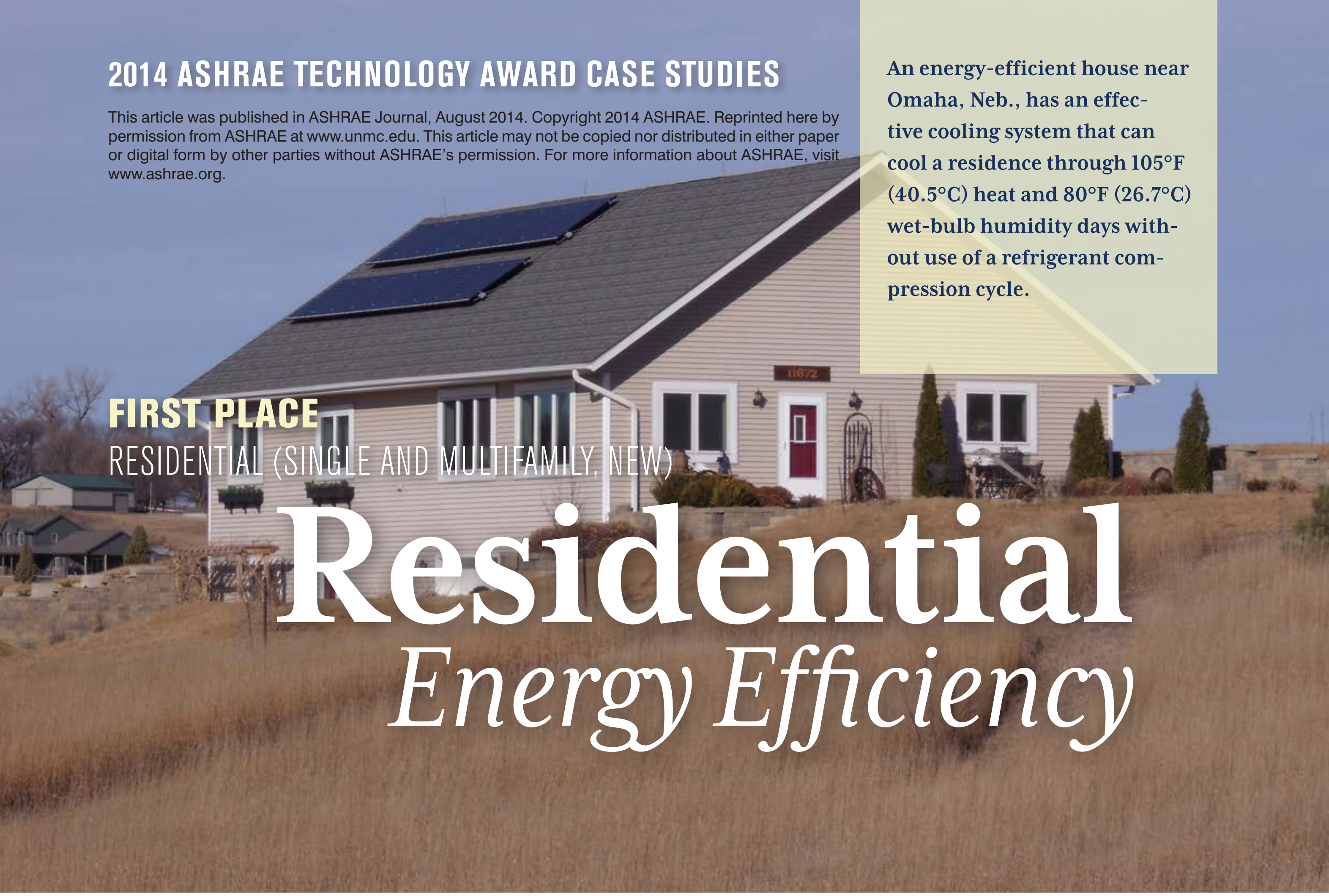

2014 ASHRAE TECHNOLOGY AWARD CASE STUDIES

An energy-efficient house near Omaha, Neb., has an effective cooling system that can cool a residence through 105°F (40.5°C) heat and 80°F (26.7°C) wet-bulb humidity days without use of a refrigerant compression cycle.

FIRST PLACE

RESIDENTIAL (SINGLE AND MULTIFAMILY, NEW)

Residential *Energy Efficiency*

BY DARREN DAGEFORDE, P.E., MEMBER ASHRAE

BUILDING AT A GLANCE

The Dageforde Residence

Location: Blair, Neb.

Owner: Darren & Karen Dageforde

Principal Use: Single Family Home

Includes: Three bedroom, 1.5 bath, kitchen, living, dining, laundry, exercise/game room, four-car garage

Employees/Occupants: Three

Gross Square Footage: 2,160 per floor (two floors)

Conditioned Space Square Footage: 2,922

Substantial Completion/Occupancy: May 17, 2011

Occupancy: 100%

In the rolling hills near Omaha, Neb., a new house demonstrates how to reset the bar in residential energy efficiency. This unassuming home operates at an annual energy use intensity of 13.2 kBtu/ft^2 (0.046 kWh/m^2), not including the effect of site-generated electricity. Contrary to conventional wisdom that higher efficiency costs more money, this home was actually constructed at a cost 16% less than an average custom-built home of comparable size in the area as predicted by nationally accepted cost estimating guides.

This estimate and costs includes appropriate corrections for self-performed work as well as site-generation electrical equipment.

Darren Dageforde is director of utilities and energy engineering at University of Nebraska Medical Center in Omaha, Neb.

ABOVE The living room entry has an abundance of natural lighting and dark tile to absorb the solar radiation.

LEFT The mechanical system is piped with PEX tubing. To minimize pressure losses, the tubing was installed with long sweeping bends instead of abrupt square fittings giving it the "tangled spaghetti" appearance.

The actual cost of the energy to cool this home for the entire summer of 2012, the hottest summer on record in Nebraska, was $3.72. This performance is a reduction of more than 95% from an average regional house, not including the energy benefit of site-generated energy. The summer of 2013 produced results that were 3% better than the previous year.

Technologies proven in the industrial, institutional, and commercial sectors have been brought together to take residential energy efficiency to a new level. In the 30 years of the award program, this is the only single-family residence ever awarded a First Place ASHRAE Technology Award.

A husband/wife team acting as the owner, designer, general contractor, mechanical subcontractor, and accountant ensured that every major detail was installed and constructed as the design intended. This singular authority made decision-making and quality accountability clear and concise while allowing the house to be built by traditional residential subcontractors using standard commercial materials.

The vision of the project was simple: create an extremely energy-efficient home with minimal maintenance and low utility costs at a reasonable budget. It had to look, feel, and function like a traditional residential home.

The goal was net zero; however, unreasonable financial commitments simply to achieve this goal needed to be avoided. The resulting design was an "A/C-less" (no traditional air-based furnace/cooling system), raised ranch home design. The basic home is a 36 ft × 60 ft (11 m × 18.3 m) rectangular floorplate, with 9 ft (2.7 m) ceiling height and a full walkout basement. Half of the basement is semi-finished living space and half is a four-stall (small standard car) garage and work area. Thirteen standard fiberglass frame, U = 0.29 Btu/ft^2·°F·h (1.64 W/K·m^2) low-E glass windows comprise 11% of the exposed wall area.

The skeleton of the structure consists of insulated concrete form walls (R-22, code minimum = R-19), flat ceilings (R-48 attic insulation, code minimum = R-39) with a standard wood truss rafter system. This construction is extremely tight with minimal air infiltration. The upper floor is a pan and joist reinforced concrete monolithic pour insulated concrete form system (R-26) comprised of a 4 in. (100 mm) slab, with radiant tubing, over 6 in. wide × 10 in. (150 mm × 250 mm) deep joists, 24 in. (610 mm) center to center. The basement floor is a 4 in. (100 mm) concrete slab on grade with radiant tubing over R-10 insulation. Installed on the south-facing roof is a total of 4.1 kW of photovoltaic panels.

Environmental conditioning is provided by hydronic radiant heated and cooled floor slabs. The radiant system uses the large mass of the insulated concrete flooring deck system (>110,000 lbs [50,000 kg] of concrete for the upper floor) to store and continuously distribute thermal energy to the occupied environment. The floor is topped with ceramic tile instead of traditional carpet to reduce any insulating effects of the flooring, minimizing the required temperature differential between the floor and the living environment.

Due to the continuous and even heat flow of the large mass floor system, the floor temperature is typically in the 72°F to 77°F (22°C to 25°C) range, requiring a supply water temperature in the 77°F to 86°F (25°C to 30°C) range for heating. This supply temperature is ideal for heat pumps, especially geothermally coupled systems. The radiant heating system is driven from a two-speed, 5 ton (17.8 kW) water-to-water heat pump (operating only as a 2.5 ton [8.9 kW] unit) connected to five 200 ft (61 m) deep closed loop geothermal wells as the heat source. This water-to-water geothermally coupled system is approximately 40% more efficient than traditional residential water-to-air geothermally coupled systems that

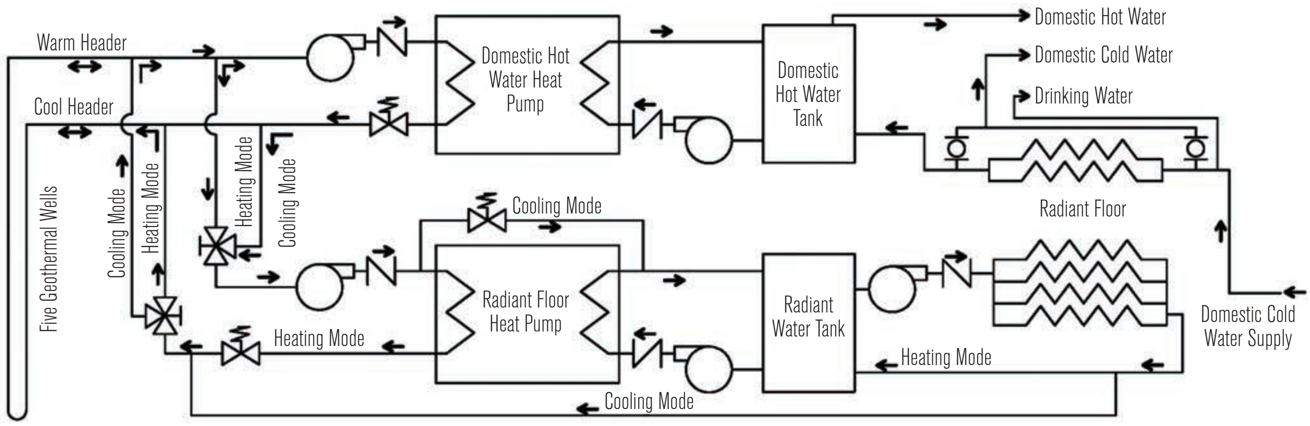

FIGURE 1 Geothermal and heat pump flow diagram.

require around 110°F (43°C) supply air temperatures. Due to the non-traditional requirements of the control system and the desire to automatically gather large volumes of data, a small programmable logic computer controls all of the mechanical systems.

Several large, low-E windows face south. The roof eave overhang is specifically designed to provide full window shading in the summer and full sun in the winter. During the heating season, the passive solar gain raises the living area temperature up to 4.5°F (2.5°C) above normal with much of the thermal energy absorbed by the dark-colored tile into the floor mass. This thermal surge will carry elevated temperatures until very late in the evening without any supplemental heating from the heat pump system.

Domestic hot water is generated by a 3 ton (10.5 kW), two-speed water-to-water heat pump (operating only as a 1.5 ton [5.3 kW] unit) also served from the geothermal well system. All domestic hot water is preheated via independent tubing in the upper floor structure. In the summer, this design provides free cooling for the home and free preheat for the water. In the winter, the radiant floor heat pump, due to much lower lift requirements, operates at least twice as efficiently as the domestic water heat pump. Preheating domestic water with the radiant heat pump system results in significantly reduced total energy consumption for domestic hot water heating as compared to a single heat pump for water heating.

Home cooling as initially conceived was to be provided by direct circulation of cool geothermal well water through the radiant floor system, a very efficient and cost-effective means of cooling. Nonetheless, even more efficient options were developed during the house design process. With the exception of dedicated drinking water, in the cooling season all domestic cold water (40°F to 70°F [4.5°C to 21°C]) from the local municipal water supply is routed via dedicated PEX tubing through the floor slab to extract free cooling by increasing the water temperature up to near 74°F (23.3°C), the temperature of the floor.

Next, heat is recovered from the floor mass to the domestic hot water system via swapping valves on the geothermal system. As shown in the flow diagram in *Figure 1*, this change allows the domestic hot water heat pump to bypass the geothermal system and take heat directly from the home via the radiant floor and delivering the heat to the domestic hot water. Since the floor operates up to 20°F (11°C) above the geothermal well temperatures, this design is over 30% more efficient than direct geothermal coupling for the domestic hot water system and it provides almost free cooling to the house.

Because the large mass of the floor system acts as a thermal storage reservoir, and it takes multiple hours to actually change the floor temperature a single degree, the typical energy recovery timing problems due to generation not coinciding with load usage are eliminated. Therefore, using domestic hot water provides home cooling that will be stored until it is needed. If any additional cooling is needed, the control system will circulate cool water from the geothermal wells directly through the radiant slab. To prevent overcooling, if the cooling load is sufficiently satisfied, the domestic heat pump will automatically swap back to the geothermal wells for its heat source.

Indoor Air Quality

Indoor air quality to this home is provided via a geothermally conditioned 100% fresh air supply system.

Advertisement formerly in this space.

Outdoor fresh air is drawn underground through a 160 ft (49 m) long, 8 in. (203 mm) diameter, 22 gauge steel duct (PVC coated for corrosion resistance) buried between 5 ft and 13 ft (1.5 m and 4 m) deep in a trench of wet sand and sloped toward the house. In the summer, approximately 100 cfm (47 L/s) of hot, humid air is drawn into the duct and cooled/dehumidified to saturation at 60°F (15.6°C) or lower, via a small Energy Star rated fan (ASHRAE design 97°F [31.6°C] DB, 78°F [25.6°C] WB). Condensation is trapped and drained at the house entrance. The air is pulled through a MERV 8 filter and delivered near the floor to the occupied space while the bathroom exhaust fan is operated to exhaust air from the space. In the summer this system actually provides the first stage of home cooling. Similarly, in the winter 45°F to 55°F (7.2°C to 12.8°C) air is supplied for environmental contamination control as well as preheating the outside air to minimize the load on the heating system (ASHRAE design –3°F [–19.4°C]). Carbon dioxide levels as measured within the living space very seldom exceed 1,200 ppm and are routinely maintained less than 1,000 ppm. The calendar year 2012 averaged 778 ppm CO_2. Given the region's atmospheric CO_2 levels average around 350 ppm and that ASHRAE research references 700 ppm above atmospheric as typically acceptable criteria (350 + 700 = 1,050 ppm), the data indicates that the house is, on average, adequately to over-ventilated.

Relative humidity levels are maintained within the 30% to 65% comfort range specified in ASHRAE Standard 62.1. In the dead of winter, relative humidity averages 41% without supplemental humidification. In the summer, 65% and lower relative humidity is nearly always recorded. Humidity control deviations were generally related to large groups/tours and occupants simply opening windows. The dryer vent and the geothermal fresh air makeup are the only envelope design penetrations not positively isolated to prevent uncontrolled infiltration. The toilet exhaust vents are isolated with inexpensive motor operated soft seat dampers when not in use, eliminating these leakage paths. Not isolating the fresh air makeup allows the home to "breathe" only tempered air, minimizing the effect of wind pressurization and leakage on thermal comfort and humidity control.

Ultimately, indoor air quality is a relative term measured by the satisfaction of the occupants. The three occupants of the house all agree that the indoor air quality is outstanding. With no carpeting, there are very few places to trap allergens and there is very little dust or particulate debris being transported and deposited

TABLE 1 2012–13 annual total energy consumption of Dageforde home. The gross square footage of the main floor is 2,160, and the net conditioned space is 2,922 ft^2.

DOES NOT INCLUDE SOLAR PANEL IMPACT	ACTUAL 2012	ACTUAL 2013	REGIONAL AVERAGE*		KANSAS/NEBRASKA AVERAGE HOUSE**		EUI
	KWH	KWH	KWH	2012%	KWH	2012%	KBTU/FT^2
COOLING	93	90	967	10	1,348	7	0.11
HOME HEATING***	4,461	7,196	20,457	22	16,471	27	5.21
WATER HEATING	2,104	1,982	7,278	29	6,594	32	2.46
VENTILATION	146	145	N/A	N/A	N/A	N/A	0.17
OTHER LIVING USES	4,451	3,728	9,379	47	7,825	57	5.20
TOTAL	11,255	13,141	38,081	30	32,239	35	13.15
SITE ENERGY PRODUCED	6,770				Net Energy Consumed	4,485	5.24

*Regional average based on 2009 U.S. EIA Residential Consumption Survey for average Midwest home, 2,500 to 3,000 ft^2, three household members, gas heat and gas water heater.

**Average house in Nebraska and Kansas uses gas heat and gas water heating and is much smaller than the regional average.

***A freon leak was discovered in the heat pump in the fall of 2013 that significantly reduced system performance. Correction of the leak returned the expected high performance.

TABLE 2 2012 energy production, consumption, cost and CO_2 generation.

PURCHASES AND PRODUCTION	KWH	TOTAL ENERGY USED FOR	KWH	CO_2 METRIC TONS	AVERAGE HOME CO_2
TOTAL KWH PRODUCED PVA	6,770	HOME COOLING	93	0.07	0.68
TOTAL KWH PURCHASED	4,485	HOME HEATING	4,461	3.15	3.50
TOTAL ELECTRIC SUPPLY	11,255	FRESH AIR MAKEUP	146	0.10	0.00
TOTAL CONNECTION CHARGE	$143.83	HOME HOT WATER	2,104	1.48	1.24
TOTAL ENERGY CHARGE	$409.57	OTHER MISC. LIVING	4,451	3.14	6.62
TOTAL ELECTRICAL COST	$553.40	TOTAL ELECTRICITY USED	11,255	7.94	8.42
ACTUAL ENERGY PURCHASED	4,485	ANNUAL CO_2 – TOTAL ENERGY PURCHASE		3.16	13.29*

*Includes electricity and natural gas to an average home.

anywhere in the home from a traditional air-handling system.

Using radiant cooling systems, a space temperature setpoint of 75°F (23.9°C) borders on too cold in the summertime and would be comparable to an air-cooled system thermostat setting 3°F to 5°F (1.7°C to 2.8°C) cooler. The large thermal mass of the floor provides outstanding temperature control and stability with rapid recovery. Recorded temperatures indicate that room temperatures very seldom exceed 1.5°F (1°C) negative deviation from the desired setting in both the summer and winter. Positive deviations in the winter can be as high as 5°F (2.8°C) warmer due to uncontrolled passive heating and 1.5°F (1°C) cooler in the summer during nighttime no-load conditions.

Energy Efficiency

Eighteen grid-connected photovoltaic solar panels on the roof generate 4.1 kW of onsite electricity. The system size was based on maximizing payback from current utility rates. These panels provide enough energy to supply the heating, cooling, and domestic hot water heating needs of the home or more than 60% of the total energy consumed. Due to the extremely low energy consumption of the equipment required to cool the home, more than 67% of the energy produced in the summertime is exported to the utility grid during the peak daytime hours. Most of the energy in the home is consumed by evening lighting and morning water heating for bathing, laundry and cooking. This design reduces the utility peak demand and increases the load during non-peak time, a win-win situation for both the utility company and the homeowner.

As can be seen in *Table 1,* this home has demonstrated a 65% to 70% reduction in annual energy use from an average home in the region, ignoring the effects of site generation. Actual domestic hot water heating energy requirements were reduced to 18% of the owner's previous home's load, which used a gas water heater.

The typical grid production of electricity on average generates more than four times more carbon dioxide per unit of usable discharge energy than the simple burning of natural gas for heating; therefore, this home's carbon footprint is only 40% smaller than the typical regional home if site generated energy is not included as shown in *Table 2*. When the effects of the PV array are included, the home shows a 76% reduction on the carbon footprint from an average house in the region.

Conclusion

This project created a cost-effective cooling system that can cool a residence through 105°F (40.5°C) heat and 80°F (26.7°C) wet-bulb humidity days without use of a refrigerant compression cycle. Ironically, recovering this heat into the domestic hot water system via a refrigerant cycle heat pump is actually more energy efficient overall than simply rejecting the heat into the atmosphere/soil. Separating the dehumidification and cooling aspects of the typical air-conditioning process allows an energy effective means of temperature control through the use of radiant cooling. Direct geothermal tempering and humidity control via fresh air supply is a cutting-edge design that borders on experimental in nature but has huge potential in the residential and low occupant density construction market.

Developing and demonstrating an energy storage and delivery system that allows very low temperature differentials while using cooler heating media and warmer cooling media has far-reaching potential in improving energy efficiency. Thermal mass storage at the point of energy use combined with hydronic radiant distribution is an innovative combination of technologies that is rarely seen in residential applications, but seems to be a perfect fit. This combination provides outstanding environmental temperature stability, nearly

Lessons Learned

The airflow pattern in the home was originally intended to be displacement ventilation. Cool ventilation air was to be supplied at the radiant floor level and exhaust taken at the bathroom ceiling level. Ceiling fans were provided in the great room and the main bedroom simply based on the preference of the owner. It was discovered in early occupancy that to improve occupant perceived comfort, it is very desirable to operate the ceiling fan on low speed during the heating mode of the home. Unless the ceiling fan is causing some air circulation, the thermostats, and to a lesser extent the humidity and CO_2 sensors, become very erratic and nonsensical. In cooling mode the fans are shut off and the room temperatures are simply controlled by holding a constant floor temperature. During the peak of hot days, the room temperature will rise 1.5°F (0.83°C) above the floor temperature. By holding a constant floor temperature rather than letting the thermostat drive the cooling cycles, overcooling of the home in the evening is prevented.

A CO_2 demand control sequence was originally used in an attempt to accurately control indoor CO_2 levels. This sequence either caused massive short-cycling of the fresh air system or excessive extended runtimes with large setpoint overshoots. A timer-based control logic was then developed of 40 minute (adjustable) runtime (five times a day, with manual override). This logic provides superior CO_2 stability with considerably less operation time. It was also discovered that the fresh air supply and exhaust points need to be separated both horizontally as well as vertically to minimize stagnant zones.

Originally, there was a concern that the geothermal tempering would be inadequate to handle the humidity control and additional moisture control such as a small water to air heat pump would need to be added in the saturated fresh air stream. Operational data eventually showed this additional equipment was unnecessary.

When reviewing performance logs it was noted that there was a 50% to 75% increase in average energy used to heat domestic hot water from summer to winter operations. This disparity existed even though all the domestic water makeup to the water heater was tempered to the same temperature regardless of season and the difference in geothermal temperatures on heat pump efficiency would only predict a 30% change. It was subsequently realized that a major portion of the hot water usage in the home went to showering and bathing. In the cooling season, the "cold" water used to bathe was being tempered for home cooling up to approximately 72°F (22°C). In heating mode the cold water for bathing was supplied directly from the utility at less than 40°F (4°C). In the winter, it takes considerably more hot water to mix with the colder "cold" water to achieve the same mixed water temperature desired for bathing. Since it takes much less input energy to temper the water through the floor mass, the cold water for bathing should also be tempered year-round to improve overall system efficiency.

Although the annual thermal load of the geothermal well system is significantly skewed toward heat removal from the wells, observation of any significant indication of well performance degradation has not been noted to date. The first proposed reason for this observation is that the well system capacity was initially "oversized" to minimize temperature change throughout the seasons. Secondly, the system experiences a 45- to 60-day rest period when the radiant system is shifted from heating to cooling in the early summer and the well system is not needed. This period seems to allow the wells' thermal gradients to equalize, somewhat resetting the differences between cooling and heating loads on the system.

There was a concern that by tempering the rather cold domestic cold water through the radiant floor mass, it would be possible to cause condensation on the floor near the water entrance point. It was found that after a couple of weeks with no radiant circulation and lots of domestic water use, condensation can occur. Reprogramming the control system to recirculate the radiant floor system a couple of times a week for a few minutes evenly spreads the thermal energy and totally eliminates this issue.

eliminating peak loads, which significantly reduces equipment sizing while increasing load factors.

According to the U.S. Energy Information Administration, the residential market consumes 22% of the energy in the U.S. This project has demonstrated a safe, cost effective design that has reduced energy consumption by more than 65% and is capable of similar impacts on an enormous portion of that energy market. This design is not dependent on a quirk of nature or ideal weather or geographical location, but can be fundamentally applied to many diverse climate zones and geographic diverse areas.

The critical design features of this project; separation of dehumidification and cooling functions, low resistance radiant heat transfer, large mass thermal storage, fresh air geothermal tempering, geothermal domestic hot water heating, low leakage thermal envelopes, etc., are not limited to the example demonstrated here, but can be accomplished in many diverse, high efficiency fashions to achieve similar results. ■