

Mini-Split: Two-Story Houses and Stratification

BY BRIAN A. ROCK, PH.D., P.E., FELLOW ASHRAE

A common complaint from occupants of low or moderate cost two-story houses and apartments is that their “upstairs” floor is often uncomfortably warm in the summer, while their “main” floor is either comfortable or too cool.¹ The source of this problem can usually be traced to the exclusive use of single-zone² all-air HVAC systems, which are the most common type used in much of North America’s housing.³ This article describes one practical energy-saving solution to this cooling-mode stratification problem in such an existing multistory residence.

In each of these low-cost residential HVAC systems, its air-handling unit is the blower-containing furnace. Split system central air conditioning is via an evaporator coil mounted to the furnace, with a condensing unit installed outdoors. A refrigerant line set connects the two, and ductwork attached to the furnace conveys air to registers and from return grilles. Ventilation air is usually via infiltration and the use of operable windows and exhaust fans.

Typically, simple on/off cycling control of this air-conditioning system is used and is controlled by a thermostat mounted on an interior wall of a residence’s lower floor. The furnace’s blower, with typically a 0.25 hp to 0.5 hp (186 W to 373 W) electric motor, cycles on and off. When deactivated, buoyancy causes warm air to rise in the house, and cooler air to fall. Variable speed fans and compressors, while available in premium systems, are not yet commonly used in low and moderate cost residences, which number in the tens of millions in the United States. Simple, single-speed systems have lower initial cost and are perceived to be easier and less costly to maintain and replace. Retrofitting these systems to have multizone capabilities is usually not an economically feasible option.

Occupants can use several methods to combat uncomfortable stratification between floors in their houses when in cooling-mode, but none are optimal for comfort, productivity, or energy conservation. Occupants may adjust their clothing or activity levels, or more likely will lower their thermostats’ setpoints. Or they may choose to endure the warmth upstairs to save money.

Another adaptation is to switch the blower’s control from “AUTO” to “FAN,” which causes its motor to run continuously.⁴ This latter option mixes the indoor air, which reduces stratification between levels, but at the cost of much higher fan energy consumption as well as slightly reduced moisture removal due to evaporation of condensate already on the coil. Additionally, the thermostat will call for operation of the compressor more often due to the loads of the blower’s motor as well as the upstairs’ becoming more apparent to the thermostat.

Case Study

The cost- and energy-conscience author has lived in such two story apartments and houses since 1987 and experienced all of the above in each. “Necessity is the mother of invention,” or experimentation in this case,

Brian A. Rock, Ph.D., P.E., is an associate professor of civil, environmental and architectural engineering at the University of Kansas, Lawrence.

PHOTO 1 The original four ton (14 kW), SEER 10, R-22 condensing unit that had settled several inches, stressing its line set. Note the easy to inspect and clean fins it had.



and it was the timing of the inevitable failure of his current split system that has brought about not only a practical solution to the stratification problem, but also reduced energy consumption at a reasonable cost.

The current residence is a typical lightweight wood-framed, two-story single family house of 2,200 ft² (204 m²) near Lawrence, Kan. It was purchased in 1998 when it was three years old. The house also has an unfinished 1,000 ft² (93 m²) basement. The typical thicknesses of wall and ceiling insulation were installed during its construction, but the current owners, over the years, reduced energy use by sealing cracks in the house's envelope and exposed ductwork, improving the weatherstripping, adding storm windows and doors, and installing a setback thermostat and more energy-efficient appliances and lighting. However, the central air conditioner and furnace, installed with the original construction in 1995, had only SEER 10 and 80% efficiencies, respectively. *Photo 1* shows that system's condensing unit. With both the furnace and air conditioner being generally in good operating condition and serviced regularly, economics indicated they should not be replaced before failure.

The energy conservation measures reduced the heat gains to the house, which meant the air conditioner didn't need to run as often or for as long; an unintended consequence was, therefore, increased time for buoyancy forces to act. To help reduce stratification during the day when the house was occupied, the thermostat's switch was often manually reset to "FAN" to operate the blower continuously, but returned to "AUTO" each night to save energy. Still, the many extra hours of blower-motor operation consumed considerable electricity and

TABLE 1 The occupants' negotiated temperature choices for the setback thermostat, to optimize thermal comfort vs. energy savings.

TIME	HEATING	COOLING
2 a.m.	60°F	73°F
5:30 a.m.	67°F	77°F ¹
8:20 p.m.	65°F	75°F
9:30 p.m.	60°F	74°F

¹Often reset manually to 76°F when occupied

added to the sensible heat load that the air conditioner needed to remove.

Setback Thermostat Combats Stratification

One of the more severe periods for the two-story stratification problem was late at night. On summer evenings the air conditioner ran a lot to pick up each day's peak loads, and this decreased stratification during those hours. Then, as the outdoor temperatures fell at night, the system cycled off, and largely stayed off, because the first floor—where the thermostat was mounted—remained cool. However, each night warm air eddies flowed by buoyancy to the upper level.

Most or all bedrooms are usually upstairs in these two-story residences. This buoyancy, internal loads including the occupants, and conduction and infiltration from outdoors, causes uncomfortable sleeping conditions in warm climates. Rather than keeping the setpoint very low at all hours, the occupants of this house combated nighttime stratification by having the setback thermostat lower the temperature by 1°F (0.6°C) to 73°F (23°C) at 2 a.m., as shown in *Table 1*. This caused the air-conditioner to activate at that hour on all but very cool nights.

In addition to decreasing the stratification discomfort, this approach also precooled the house for the next morning via off-peak electricity use. With the higher daytime setpoint of 77°F (25°C), as also shown in *Table 1*, the AC normally didn't activate until late morning on the very hottest days, or more typically mid- to late afternoon on average summer days. The high daytime setpoint was, and still is, then reduced in two steps each evening with the goal of moving most compressor operation to after sunset to reduce peak-hour electrical demand. There isn't yet time-of-use electricity pricing in this location, but with the recent installation of smart meters, their imposition can't be too far off; a voluntary test-program is underway by the region's power company.

System Failure

In early August 2014, during the traditionally hottest portion of the cooling season, the split system failed. Upon returning from work one day, the house's interior was warm, with an unusual odor. The compressor was running, audibly, at no load. Further inspections revealed that the evaporator had sprung a leak and dumped the refrigerant charge indoors.

Given the known difficulty, time, and cost of removing the evaporator and fixing the leak—and still having a 19-year-old R-22 system if the repair was successful—the decision was made to replace the whole system instead. Because it was near the end of cooling season, dealers' equipment selections were low and prices too high. But a hot house with no air conditioning for a couple of months was not feasible. One option available, via having not one, not two, but three very small 120V window air-conditioning units in storage, was to install them temporarily to delay the “big ticket” purchase until the more-economical off-season. This option would also allow deciding the fate of the furnace, which had been a consistent performer, after the heating season.

The strategy selected that late summer was to first install two window units, and then the third if needed. One unit, the newest and highest efficiency (SEER 10.7), was installed in the master bedroom window on the second floor, and the second (SEER 9.7) was installed in the living room near the kitchen. While the original split system was single-zone, using the two window units this way provided floor-by-floor zoning.

With both units installed and after operating continuously for a few days, it was very surprising how well the combined 1 ton (3.5 kW) capacity, one-quarter of the original, kept most of the house comfortable except in the evenings of the warmest days. Activity level reductions and clothing adjustments made these few hours just acceptable.

Placement of one unit in the bedroom gave very comfortable sleeping conditions compared to the prior swings in temperature due to stratification and the split system's cycling; an exception to comfort was the window unit's high noise level. However, this unit's placement also allowed its supply air to be projected from that room through the straight hallway, which helped provide comfort, somewhat, in the other rooms on that top floor, but the unit was undersized. Installing the third window unit in the opposite end of the top floor

was considered and would have provided better comfort there, but was not undertaken. Only a couple of months was left in that cooling season, with only the first month expected to be hot, and that side of the house is very visible to the homeowners' association (HOA) regulated neighborhood.

For the winter those two cooling-only window units were uninstalled and the original 80%-efficient natural gas furnace functioned well. Despite its fine operation and ease of maintenance, the decision was made to replace the furnace with a higher-efficiency model at the same time as the central AC. Their replacement occurred in the spring just as the heating season ended, but before the cooling season began; the region's variable spring and fall “swing seasons,” when natural ventilation and internal loads can be used to maintain comfort, are short, often only about one month each. The timing for the replacement proved fortunate for both thermal comfort and economics that year.

Equipment Sizing

The original furnace was rated 80,000 Btu/h (23.5 kW) output, and the air conditioner was 4.0 ton (14 kW). Due to weak building codes in effect at the time of construction of the house, the furnace and AC were likely sized with rules of thumb by the mechanical subcontractor; in other locations a *Manual J* calculation⁵ would have been the norm. For this 2,200 ft² (204 m²) house, not including its basement, the 1995 split system was selected at 550 ft²/ton (14.5 m²/kW), which is within the typical range of 500 ft²/ton (13.2 m²/kW) to 700 ft²/ton (18.5 m²/kW) for this region's single-family residences.

During its 19 years of operation, the original equipment seemed to have very sufficient heating and cooling capacity, with the furnace still cycling during the very coldest periods below 0°F (−18°C), and the air conditioner ran continuously, but maintained its setpoint during extreme conditions, e.g., 105°F (41°C) outside vs. the 96°F (36°C) 1% design.

Due to the weatherization and other energy conservation efforts, and by internal loads from the occupants and ever-increasing electrical devices, the furnace seemed very oversized. Hand calculations showed that the design heat loss rate was only about 35,000 Btu/h (10.3 kW), but natural gas furnaces are usually oversized, often greatly, to provide rapid warm-up and because of their low incremental price differences between sizes.

TECHNICAL FEATURE

Also, it was predicted that the air conditioner could be downsized somewhat with little effect beyond the hot-test hours.

Research by others⁶ advises to intentionally under-size such HVAC systems to encourage them to run longer to increase efficiency and reduce wear from excessive cycling, and to improve moisture removal in the summer. For this house the first plan was, therefore, to downsize the furnace to about 60,000 Btu/h (17.6 kW) and the central AC from four tons (14.1 kW) to three tons (10.6 kW), which would result in 733 ft²/ton (19.4 m²/kW). The co-occupant wanted to stay at four tons (14.1 kW). The compromise was 3.5 tons (12.3 kW), with the understanding that a solution would be sought if it were undersized.

The next choice was efficiency; a code-minimum SEER 13 unit was chosen due to excessive paybacks for higher SEERs. It was also decided to use a conventional AC unit instead of a heat pump, the latter of which would add “dual fuel” capabilities for heating; this decision was due to the dramatic plunge in the cost of natural gas in recent years and the projections that its supply should stay generous in the decades ahead. *Photo 2* shows the purchased condensing unit as installed on a much-improved base that corrected backfilled-soil settling, and with vibration-absorbing pads between the unit and the reused pad.

With a specific new split system AC identified, a furnace that could easily accept the evaporator coil's case was sought. A warning from a fellow member of the ASHRAE Kansas City Chapter was heeded about reliability, so simple, single firing stage, single-speed blower models were studied. When a suitable model was found, unlike for the higher efficiency ACs, the about \$400 price increase for their condensing furnace would pay back in a reasonable time in this climate compared to their base 81% annual fuel utilization efficiency (AFUE) unit. For only another \$30, a 95% AFUE unit was selected over the 92% version. With the much higher efficiency of the new furnace, its 84,000 Btu/h (24.6 kW) rated-input was much lower than the old furnace's 100,000 Btu/h (29.3 kW).

Its output was about the same; a lower-output version would have been preferred to reduce heating cycling, but this was the smallest that matched the new evaporator's very large case. The new upflow furnace was substantially shorter than the old, but the new evaporator

PHOTO 2 The new 3.5 ton (12.3 kW), SEER 13, R-410A condensing unit on a much-improved base and with a new, rerouted line set. To the right is the mini-split's outdoor unit. Both are on the thermally-optimal north-northeast side of the house, and are also near the electric panelboard and meter reducing their conductors' line-losses.

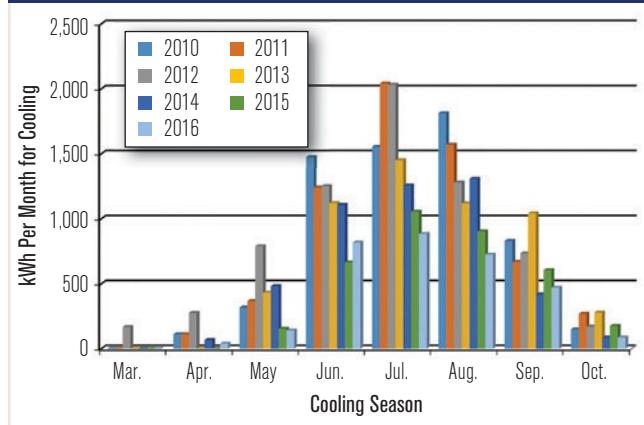


was much taller, necessitating customization of the discharge plenum; the plenum also still needed to accommodate the separate whole-house humidifier. A new refrigerant line set for the split system was required due to the change from R-22 to R-410A, as well as the poor condition of the old set due to settling of the condensing unit. The safety power disconnect box and wiring “whip” were replaced too because the old disconnect was partially melted, likely either from added corrosion resistance or a lightning strike. By selling the still-operable furnace and recycling the copper-bearing split system and old line set, about \$350 was recovered.

The new, smaller split system AC should have cycled less frequently, but it didn't solve the stratification problem. After experiencing how the \$99 window unit addressed the problem upstairs the summer before, it was decided to reinstall it for the summer of 2015. Again improved upstairs and nighttime comfort resulted. The window unit was also allowed to run continuously despite the new split system's sufficient capacity and higher efficiency.

An interesting side effect was that the main AC system didn't need to operate nearly as long each day. Also, the furnace's blower didn't need to be run continuously in the evenings to reduce stratification. The resulting electrical use for cooling in 2015 was noticeably lower. *Figure 1* shows the monthly consumption, and *Figure 2* shows the annual cooling seasons' totals, along with the average outside temperatures.⁷ The new split system was

FIGURE 1 Monthly air-conditioning energy consumption for seven years: four years before, two during, and one after the retrofits.



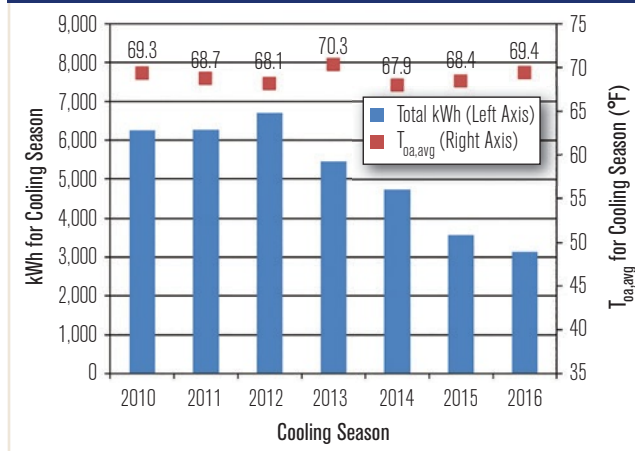
13 SEER vs. the old's 10 SEER, but that alone did not seem to account for the reduction; the severity of the cooling seasons was similar, so a cooler summer wasn't the cause.

With the almost half ton (1.8 kW) window unit reinstalled upstairs that summer of 2015, the total cooling capacity was again about the original four tons (14.1 kW), and the nighttime stratification problem was solved. However, the window unit was somewhat unsightly, blocked part of the window, the indoor noise level at night was too high, and installing it and uninstalling it each year was unappealing. A long-term solution was needed. A better window unit might have reduced the noise, but the appearance and need for annual installation and removal could not be overcome. Another option, one already in use for the house's attached workshop, was a through-the-wall unit that's similar to but smaller than a packaged terminal air-conditioning (PTAC) unit. Unfortunately, due to a low-hanging roof eave, as well as having little indoor wall space above or below the available window, various through-the-wall units wouldn't fit.

To Mini-Split, Too

The only practical option left—short of severing the riser and downcomer ducts from the basement to the second floor via the attic and installing a second split system's evaporator in the remaining attic ductwork—was a mini-split AC with which the author lacked in-person experience. A convincing argument was made by an energy auditor in Michigan through a video he posted online.⁸ He installed a mini-split in his own house due to an excessively warm summer. His single-story house,

FIGURE 2 Total seasonal kWh for air conditioning and the average outside air temperatures.⁷



with baseboard heat, had no ductwork because that traditionally cooler climate did not require air conditioning. He reports that one mini-split, installed to throw air down his central hallway, was enough to cool the entire house of nearly 1,600 ft² (147 m²) in that more-northerly climate.

Investigating appropriate mini-splits revealed several choices: ducted vs. ductless, cooling-only vs. heat pump, single speed vs. “inverter”-driven, capacity options, two voltages, and various manufacturers. All mini-splits investigated had similar appearances due to market forces—mini-splits have been in use for many years elsewhere, mainly as retrofits for high-rise “flats” that didn't have air conditioning previously. Their upright, suitcase-like outdoor units were designed to fit easily on small balconies or to be hung on exterior walls with brackets, and their nearby indoor units were to be mounted high-sidewall so as not to use valuable floor space in those apartments and condominiums.

Due to space limitations for this mini-split, a ducted or “cassette” indoor unit was decided against in favor of a ductless, high-sidewall version. Heat pump mini-splits were found to be of similar cost to AC-only, but if not for other choices, the cooling-only version would have been selected for simplicity and not needing the heating capacity.

Inverter units are now widely available and their part-load performance gives them greater SEERs. A capacity of only the half ton (1.8 kW) was sought, but the smallest units had 8,500 Btu/h (2.5 kW) to 9,000 Btu/h (2.6 kW) of cooling. Most mini-splits for sale in the U.S. market use single-phase 240V, and these units were observed

TECHNICAL FEATURE

to have the highest SEERs as compared to the few 120V versions. Mini-split installations in the U.S. must meet the National Electrical Code (NEC), which requires dedicated wiring circuits as well as safety disconnects. For this application, only one circuit breaker slot was easily available in the panelboard, so a 120V unit was needed. After much hunting, a major-manufacturer's system was identified that was a 120V, 9,000 Btu/h (2.6 kW) cooling, inverter-driven, ductless heat pump mini-split with SEER 17 for cooling. One was installed in the spring of 2016. A 20 amp circuit was needed with conventional components such as the disconnect box and whip shown as-installed in *Photo 3*. The already-short conductors were upsized to the lugs' rated maximum to reduce line losses further.

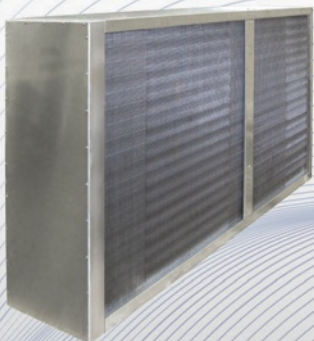
A noticeable challenge with mini-splits, compared to familiar split systems, is that power is delivered to the indoor "head" unit, and control signals to the outdoor unit, via a properly rated four-conductor cable run between them. Also, a condensate drain line is needed; gravity drainage is much preferred over pump-assisted,

PHOTO 3 The new 0.75 ton (2.6 kW), SEER 17, R-410A heat pump mini-split's outdoor unit. The stand-off mount keeps the unit well above potential snow drifts and allows air to enter its coil from all four directions. In the U.S., an electrical safety disconnect (right) is required even for this 120V unit, but in many other countries mini-splits are directly wired.



for reliability. Mini-splits' pre-insulated refrigerant line sets of small diameter soft copper ACR tubing are most often sold separately from the mini-splits. Line set kits may also include both the needed electrical cable and

heat pipes for heat recovery from Colmac Coil



- Ideal for pre-heating or pre-cooling supply air
- Recovers up to 80% of the energy lost in exhaust air
- Operating temperatures from -40° to +575°F (-40° to 350°C)
- HFC-free working fluids available
- Wide range of materials and operating temperatures
- Web-based selection software
- Standard, wrap-around and tilt configurations



PO Box 571 | Colville, WA 99114 | USA | +1.800.845.6778 | www.colmaccoil.com

www.info.hotims.com/65135-10

drain line. The line sets' separate sale is due to the choice of length; the lines should be kept as short as possible. Putting loops in the refrigerant lines to take up excess length is not recommended.

The line set/wire/drain bundle is then typically run on the exterior of an existing building and can be very unsightly; various covers are available, including at least one that mimics a rain downspout. For this application, however, a custom covering made of the same painted wood trim found on the exterior of this house was used, some of which can be seen in *Photos 2* and *3*. The latter also shows that this heat pump's outdoor unit needed to be hung from the exterior, rather than mounted on a pad, to lift it above the level of potential snow drifts.

Due to wall-space limitations, another non-standard feature of this mini-split's installation, as shown in *Photo 4*, is that the indoor unit had to be mounted low-sidewall. High-sidewall is strongly recommended so the warmest air is treated when in cooling mode and the discharge from the nozzle on the bottom can better mix air into the room. However, due to the roof eave

PHOTO 4 The indoor unit of the mini-split system was installed, by necessity, low-sidewall rather than high. Its discharge, at the bottom, was set to throw air down the hallway just opposite this window. In cooling mode a thin, very cold but dehumidified layer of air is produced; no moisture condensation occurs on the thicker-type carpet and pad.



High-Efficient Air Mover for HVAC Systems

Powered by Electronically Commutated (EC) Technology



AC source input

AC power directly connects to brushless DC motors



Wide operating voltage range

Single-phase and three-phase for both 200-277Vac and 380-480Vac



Energy efficiency and safe protection

ErP2015 compliant, UL, IP54, over current, over voltage, over temperature, and lock protections



Speed control

DC Voltage, PWM, or optional build-in communication interface (Modbus, I2C, RS232, RS485)



Reliability testing

IP, shock, dust, temperature, life testing, and more

Contact us today for more product information or sample requests.
thermal@delta-corp.com | www.delta-fan.com



www.info.hotims.com/65135-13

that comes close to the top of this tall window, there wasn't sufficient space to mount and connect the indoor unit. The choice to mount low-sidewall, made in the design phase before purchasing the system, was risky. Interestingly, if ultimately used for its heating capabilities, too, the low-sidewall position should prove to be more effective during that mode.

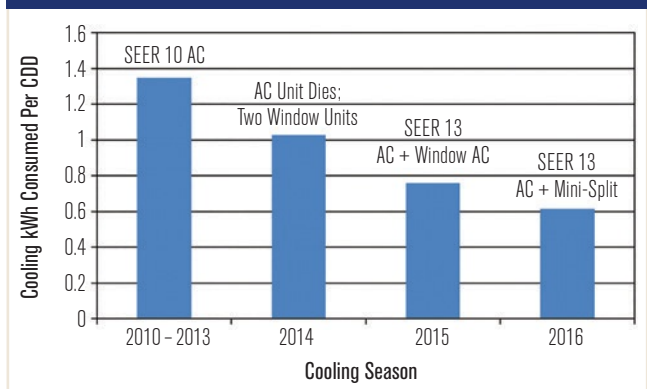
Existing ceiling fans in all the rooms of the second floor already reduce in-room stratifications, and when used in cooling mode in unison with this mini-split, less than a 0.5°F (0.3°C) stratification in the bedroom was measured outside the supply jet. With the ceiling fan turned off for two hours, this in-room stratification increased to only 1.6°F (0.9°C), which was smaller than anticipated. The mini-split's airflow is high velocity, which causes significant mixing and "room rolling." If mounted high-sidewall as recommended, the mixing would be even better and the cold layer of air on the floor near the indoor unit, while not objectionable to these occupants, would be less apparent.

Conclusions

This hybrid approach of using a reduced-sized central air conditioner, along with one or more small units added to the upstairs of an existing multistory residence, can significantly increase occupant satisfaction and reduce energy consumption, and at a cost lower than replacing one large central system with two smaller, zoned split systems. *Figure 3* shows that, for this application, the electrical energy consumption per cooling degree day (CDD) fell noticeably with each change implemented. This included operation of the small units at night during cooler hours. When the main air conditioner failed in 2014, the much lower capacity window units dramatically reduced energy use in the last two months of that cooling season, but at the cost of reduced comfort during peak hours. With the installation of the new, more efficient, slightly smaller central AC system for 2015 and with one window unit reinstalled upstairs to reduce blower-use for the stratification problem, the season-averaged energy consumption was decreased even further.

In 2016, with a more efficient, inverter-driven mini-split replacing the window unit, the energy consumption fell even more, and the occupants are satisfied with the final results. However, the cost of the mini-split, per unit of cooling capacity, was much higher than that for a window unit. It is recommended that others

FIGURE 3 Cooling-season average kWh per cooling degree day.



also experiment with using a window air conditioner upstairs before committing to a not-easily reversed, somewhat expensive mini-split installation. Part of the cost can be displaced by installing a smaller central AC system, but with care not to make it too small—when selling a residence, its appraiser and inspector will normally check for sufficient system capacity. They may not be familiar with, or sympathetic to, the use of a small, extra system for picking up part of the cooling load.

Acknowledgments

This work was supported by Rock Consulting Engineers and The University of Kansas School of Engineering, both near or in Lawrence, Kan., respectively.

References

- Baborska-Narozny, M., F. Stevenson, P. Chatterton. 2015. "Temperature in housing: stratification and contextual factors." *Proceedings of the Institution of Civil Engineers—Engineering Sustainability*.
- Friedman, G. 2004. "Too hot, too cold: diagnosing occupant complaints." *ASHRAE Journal* 46(1):157–163.
- EIA. 2011. "Air Conditioning in Nearly 100 Million U.S. Homes." Residential Energy Consumption Survey. U.S. Energy Information Administration.
- Rittelmann, W.D. 2008. "Thermal comfort performance: field investigation of a residential forced-air heating and cooling system with high sidewall supply air outlets." *BESTI Conference: Building for Energy Efficiency and Durability at the Crossroads* Paper E11-6. <http://tinyurl.com/jkf3xht>.
- ACCA. 2011. *Manual J Residential Load Calculations, Eighth Edition*. Arlington, Va.:Air Conditioning Contractors of America Association, Inc.
- EPA/DOE. 2005. "Right-Sized Air Conditioners." Energy Star Fact Sheets. U.S. Environmental Protection Agency and the U.S. Department of Energy.
- Weather Underground. 2016. "Weather Data for Lawrence, Kan., 2010 to 2016." <http://tinyurl.com/jhktz8>.
- Matt Knows Best. 2013. "Ductless Mini Split Advantages." YouTube.com. https://www.youtube.com/watch?v=nsem0_09YKc. ■

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.