Post-Occupancy Testing of Thermal Dynamics of Design-Build Residences in Tucson, Arizona

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A series of low-cost residences were designed and constructed by students and faculty in the University of Arizona’s design-build program to examine the questions of appropriate materials and technology in the hot arid desert today. Descriptions of three projects representative of the spectrum of materials and conservation strategies in the series include design intentions, research questions, and methodology for study. Thermal sensors placed inside the wall assemblies measured thermal transfer, and post-occupancy assessments revealed energy use in each dwelling as well as occasional mismatches between design assumptions and occupant behavior. These case study prototypes, which were purchased and occupied by families earning less than 80% of the area’s median income, aim to alter default housing design in the Southwest to better suit the climate and available resources.

The Climatological and Economic Context of Tucson, Arizona

Under optimum circumstances, buildings will have budgets that enable careful energy use simulations and load calculations, high-technology HVAC systems, and computer-operated building envelopes. Modest building types, however, often do not. In particular, affordable housing is often built for the lowest possible initial cost, with design expectations for energy conservation or building envelope maintenance eliminated in the design process as a cost-savings means to the developer without consideration of operational costs to end users. Vernacular building methods and materials have been touted for increasing the affordability of housing construction through the use of locally available materials and climate control methods. Despite the efficacy of vernacular practices refined over centuries, local conditions have changed in recent decades with increasing urban density and the development of an urban heat island effect. Additionally, the operative human comfort zone may have narrowed in response to more readily available mechanical heating and cooling systems, and the behavior of inhabitants seems to have adapted to changing expectations about thermal comfort and personal security.

With the goal of identifying affordable, effective building assemblies for maintaining thermal comfort in low-cost housing in hot arid climates, the Drachman Design-Build Coalition (DDBC), a 501c3, nonprofit, design-build firm housed within the School of Architecture at the University of Arizona, designed, constructed, and monitored seven prototypical low-cost dwellings between 2007 and 2017. All of these projects were the outcomes of design-build studios in the BArch program that were led by faculty members who were both registered architects and residential...
and has 2972 cooling degree days and 1624 heating degree days, from a base of 65°F. Cooling is the main concern for indoor comfort in Tucson, and historically this issue has been approached in various ways. Indigenous peoples devised methods of using earth as a form of thermal mass to regulate indoor comfort by digging dwellings down into the earth (pit houses), or by using earth as a building material for thick walls (adobe or rammed earth) that created mass capable of slowing down thermal transfer between outdoor and indoor spaces. Later, residents used fans and evaporative coolers to move and cool air through interior spaces. For many years, these forms of cooling were sufficient to control indoor temperatures at a comfortable level for all but the monsoon months. During those months, Tucsonans often slept in sheltered outdoor porches, taking advantage of the cooler nighttime temperatures. Since World War II, however, there has been a gradual lessening of the difference between daytime and nighttime temperatures in Tucson due to massive areas of road and parking lot paving that retain heat. Simultaneously, expectations for indoor comfort have changed to include year-round comfort without much fluctuation in temperature. In present day Tucson, evaporative cooling is on the wane, while central air conditioning (combined with a heat pump) is the most common HVAC system in conventional housing. Home heating in Tucson has similarly evolved: from wood-burning fireplaces to gas furnaces to heat pumps. Older homes in the metro area have gas furnaces, while combination AC/heat pumps are the systems most commonly installed in new construction.

Using the guidelines developed in the conservation technologies research, Drachman Design Build Coalition architects chose 12 SEER AC/heat pumps as the active HVAC systems for the prototype residences, due to their relative efficiency, low water use, and short payback period of two years. Other systems considered were higher-efficiency AC units and two-stage evaporative coolers with a heat exchange first-stage unit, but these were rejected due to higher equipment costs. In the case of these residences, higher front-end construction costs posed the danger of pricing the homes above the economic range for low-income buyers, so a balance between initial costs and long-term savings had to be projected and carefully determined.

Under the Department of Housing and Urban Development assisted home ownership program, low-income families are defined by gross income and family size. In 2017, for example, the median family income for all families in Pima County, Arizona, was $59,300. Low-income families can earn no more than 80% of the AMI in order to qualify for assistance: families of three could earn no more than $42,750; families of four could earn no more than $47,450; families of five no more than $51,250, and so on. HUD also defines income limits for very low-income households that fall into this income level. With such restricted incomes, higher front-end construction costs posed the danger of pricing the homes above the economic range for low-income families, but the demographic for DDBC residences is any family in the “low income” category. To qualify for a mortgage loan through the HUD program, the mortgage payment plus estimated monthly utilities payment must be no greater than 30% of the family’s gross monthly income. Therefore, in 2017, a family of four earning $47,450 could not qualify for a HUD mortgage unless the house payment plus utilities are less than $1,116. The average single family in Tucson uses 82 gallons of water per
To measure the efficacy of conservation strategies designed into each residence, sensors were embedded in wall and ceiling cavities or placed on interior and exterior surfaces to collect thermal, humidity, and air velocity data on thermal transfer and assess the performance of building envelopes. In each dwelling, the sensors and cables were placed during the construction process, and all that were located within walls or ceilings were abandoned after the data was harvested. Any sensors and cables placed on the interior or exterior wall and ceiling surfaces were recovered at the end of the data collection period and reused. All of the sensor cables plugged into a data logger (usually located in a central room of the residence), and so traveled through perimeter or partition walls and ceiling cavities to reach the data logger location. Additionally, there was one cable running from the data logger to an outdoor weather station, usually affixed to the roof of the dwelling or carport. The weather station recorded outdoor temperature, humidity, and wind velocity to provide context for the sensor readings from the building envelope. The data logger and weather station were left in place for one year from the date of closing on the sale of each home, a period of time determined by the necessity of retrieving the expensive equipment for use on the next design-build residence project. Temperature readings were taken from each sensor every 15 minutes via an onsite data logger. Information was relayed twice daily to a software supported website for readout and analysis.
Post-Occupancy Testing of Thermal Dynamics

DDBC Residence Research Goals

The energy saving strategies for the seven DDBC residences completed are divided into three main categories: insulative, thermal mass, and hybrids of those two. Additionally, tectonic strategies specific to Tucson’s hot arid climate (vented wall cavities, trombe walls, and the elimination of east- and west-facing apertures) were incorporated into some of the designs. The projects presented here are a representative sample.

DDBC Residence 2 is an insulated wall design that incorporates a ventilated wall cavity on the south façade. Because stick frame construction has been the dominant type of envelope for single-family dwellings in Tucson since the 1970s, a variant of that wall assembly was the simplest way to depart from the normative residential model and search for low-cost improvements to the thermal performance.

DDBC Residence 4 is a hybrid of thermal mass walls with an insulated steel framed circulation corridor. Its design privileges a thermal mass wall as both a tectonic strategy with performative benefits and is additionally used as an organizing element for the residence’s parti. The properties of this wall reflect those long celebrated for use in the desert Southwest.

DDBC Residence 5 is a hybrid of south-facing trombe walls with insulated north, east and west walls. This trombe wall strategy has been promoted in environmental control literature and textbooks as an appropriate design response to hot arid climates because of its responsiveness to the diurnal temperature swings that characterize the weather in the southwestern US.7

These tectonic strategies were employed, to the degree that budget allowed, to learn whether they are indeed appropriate technology for affordable single-family residential dwellings that temper the desert climate in Tucson, Arizona.
DDBC Residence 2
Research Questions: Does a south-facing ventilated cavity wall reduce the cooling needs in the house during the warm months of the year? Is a ventilated wall cavity an effective thermal strategy during all seasons of the year?

Description
Floor area: 1040 sq. ft.
Site orientation: Long axis E-W
Tectonic strategy: Frame construction with ventilated cavity wall
Thermal strategy: Insulative

Cavity walls (or rainscreen walls) are often used for weather protection, as the outer layer of wall structure deflects most of the precipitation and allows the structural wall behind it to serve as a drainage plane for any moisture that has penetrated that far. But in a hot arid climate, a rainscreen wall has potential to serve as a shading screen for the insulated wall behind it. Because the southern exposure receives the most direct sunlight, the DDBC2 was designed with a double wall incorporating an insulated wall plus ventilated wall cavity on the south façade. The wood-framed cavity wall was intended to shade the exterior of the insulated structural wall and also lessen the daytime heat absorption of the wall most exposed to direct sunlight by the use of thermal convection through the 3.5-inch cavity that is vented both near the bottom and top of the wall. Foil-backed rigid insulation was layered over the exterior of the structural 2 x 4 wall (thus facing south within the cavity) and the exterior of the 2 x 4 cavity wall was clad with fiber cement panels perforated near the bottom and top.

To obtain performance metrics regarding these design intentions, thermal sensors were placed in the following locations:

a. South face of framed wall at master bedroom (on exterior surface of fiber cement siding and on the surface of interior drywall)
b. Inside the vented wall cavity at the middle of wall and at the top of the wall
c. On the surface of drywall ceiling in living/dining area (main living space)
d. On the roof surface
e. On the weather station mounted on rainwater cistern adjacent to south wall of the residence (at a height of 6’ from the slab).

A sensor capable of recording air velocity was placed in the vented wall cavity. Two-day data samples taken approximately six months apart are illustrated here as summaries of hot and cold seasonal data. Many more fine-grained data sets can be compared to understand longer trends, effects of humidity, etc., but for the sake of brevity, data snapshots are presented here.

The August temperature data (Figure 8) graph gives an indication of the wall assembly performance (with air conditioning running) during summertime in Tucson. The highest recorded temperatures were (in descending order) on the exterior surface of the roof, on the exterior of the fiber cement panels on the south-facing master bedroom wall, air exiting the cavity, air within the vented wall cavity, and the outdoor air. These data reveal that the air within the cavity heated up because of the high surface temperature of the fiber.

\[ \text{Figure 8. DDBC2 Temperature Data; August 21-22, 2010.} \]
\[ \text{Figure 9. DDBC2 Cavity Air Velocity Data; August 21-22, 2010.} \]
\[ \text{Figure 10. DDBC2 Temperature Data; January 6-7, 2011.} \]
\[ \text{Figure 11. DDBC2 Cavity Air Velocity Data; January 6-7, 2011.} \]
cement, creating a convective stream that had a cooling effect on the air temperature within the cavity; otherwise the air temperature inside the cavity would have been the same as the exterior surface temperature. This cooling effect reduced the temperature of air touching the insulation in the structural wall, pre-cooling it to reduce heat transfer into the interior of the dwelling. The temperature on the surface of the drywall within the air-conditioned master bedroom remained stable over the two-day period and was the lowest of the recorded temperatures. The ambient temperature in the living room was slightly higher, perhaps due to the south façade at that location being mainly composed of sliding glass doors, which allow more heat transfer than does an insulated wall.

Figure 9 illustrates the timing of the air velocity within the cavity; as the wall surface received more direct sun, the air velocity increased, thereby increasing the pre-cooling effect of air convection flow.

January data show that lower air velocity within the cavity didn’t create the same convection effect. The air exiting the cavity was about the same temperature as the surface temperature of the exterior wall surface. The air lower in the cavity was still a higher temperature than the roof and weather station, however.

**Construction Costs:** Total = $88,764 (2008). Building envelope = $26,782.15 for 2,055 square feet of walls and 1,424 square feet of roof at a surface cost of $7.70 per square foot. This includes the framing, insulation, and sheathing (OSB, metal panels, and fiber cement exterior and drywall interior), but no windows or doors.

**Energy Use and Energy Cost Data**
The total electricity used for the year the house was monitored was 8,532 kWh, and its cost amounted to $965. This compares favorably to the Tucson average of 12,732 kWh/year and $1440 per year per household in 2009. (The average household occupancy in Tucson is 2.5 people, while this household numbered 4.)

The projected operational cost savings for the thirty-year period of the buyer’s mortgage payback amounts to $14,250 if electric rates stay the same. The addition of the vented cavity wall cost $80 in materials. The energy savings that could be attributed to the vented cavity wall for the year were $60.61. In less than two years, the savings paid back the cost of the design feature.

**Research Insights**
During the daytime in the hottest summer months, the cavity wall acted as a shading device for the structural wall (reducing the air temperature inside the cavity wall by up to 40%), and the convective air loop within the cavity brought air into the cavity that was an average of 12 degrees cooler than the exiting air. The cavity wall reduced the cooling needs during the hottest months. As built in this dwelling, the cavity wall was not a strong asset during winter months on bright and sunny days because the convection activity within the wall still occurred to some degree, and thus continued to pre-cool the air that touched the insulated surface. However, when the air velocity was low within the cavity, some extra heating benefits accrued as the air reached temperatures approximating the exterior wall surface temperatures. This suggests that stopping air flow in the cavity during the colder months might be a way to add heat to the envelope. Incorporation of an operable baffle within the cavity would be a way to manipulate this condition.

**Description**
**Floor area:** 1200 sq. ft.
**Site orientation:** Long axis E-W
**Tectonic strategy:** Hybrid Integra Block and frame construction
**Thermal strategy:** Thermal mass

Thermal mass walls have long been a strategy for control of thermal comfort in hot arid regions of the world; the earthen materials are readily available, and the diurnal temperature swing activates the temperature “flywheel” that keeps interior spaces cool during the day and allows accumulated heat to radiate back out to the cool sky at night. Building with adobe blocks and rammed earth, however, has changed from being standard practice a hundred years ago to a high-end market choice today due to labor costs for these labor-intensive building methods. In Arizona, there is a contemporary alternative: a proprietary CMU product (Integra Block), designed as a post-tensioned loadbearing masonry system that features large cavities to reduce thermal bridging and allow for insulating with polyurethane foam fill. Its manufacturers claim an effective R-value of 25 with this system, allowing the block to remain exposed on both exterior and interior faces and making furring out for insulation unnecessary. This residence is a hybrid design that combines thermal mass with light gauge steel frame plus insulation. The exposure of 1.63” of thermal mass on both the exterior and interior of the building affords opportunities for “charging” the interior mass through window openings during periods of cooler temperatures for passive heating of the dwelling, and using carefully sized roof overhangs prevents charging of the exterior mass during summer months but allows direct sun exposure to heat the mass during winter months. The insulation in the block cavities retards the thermal transfer from the exterior of the house to the interior during all seasons; the summer shading is essential to slowing down heat transfer while the direct sun in winter speeds it up. The cavity insulation thus works to separate the two thermal mass layers, allowing the exterior one to gain and lose heat in concert with the diurnal temperature swing while allowing the interior mass to be charged by sunlight during the colder months and hold onto its heat, eventually reaching a fairly stable interior temperature.

To keep the cost of building materials and labor within the established budget, Integra Block was used selectively on three sides of each main volume. The remaining side of each volume (the circulation spine) was framed with 2” x 6” light gauge steel, insulated with either fiberglass batts (walls) or closed-cell foam (ceiling)
and clad with steel panels. The circulation spine is higher than the other volumes, allowing for clerestory lighting along its entire length, as well as providing a conditioned interior space for HVAC ducts. The window and door openings are located to take advantage of winter sun angles and bring direct solar gain to the interior surface of the exposed concrete masonry units and concrete floor slab. In order to collect data about the design intentions for this residence, thermal sensors were placed in the following locations:

a. South exterior face of block wall and corresponding interior block face at same location (at windowsill height)
b. South face of framed wall (on surface of metal cladding) and directly inside that face on the surface of the drywall (at windowsill height)
c. On surface of drywall ceiling in living/dining area (main living space)
d. On exterior and interior surfaces of circulation spine
e. Exterior face of courtyard wall (at a height of 6’ from slab)
f. On weather station mounted on rainwater cistern adjacent to north wall of the residence (at a height of 6’ from slab)

Data was collected for a year after the home was sold and inhabited by a family of six. Two-day data samples taken approximately three months apart are illustrated here as summaries of typical seasonal data.

Figure 16 gives an indication of the insulated block wall performance during the month with the highest average temperature in Tucson. The south exterior wall temperatures fluctuated predictably with the diurnal temperature swing of the desert sky, varying as much as 42°F in an 8-hour period from early morning to midday. The exterior surfaces of the two types of exterior wall heated and cooled at roughly the same rates; the block wall reached its peak high and low temperatures one hour later than the frame wall. The lag times for thermal transfer to the interior wall surface vary by two hours, with a 4-hour lag for the frame wall and a 6-hour lag for the block wall. The ambient temperature within the main living space fluctuated from a low of 75°F to a high of 83°F. The actual temperatures recorded on the exterior walls were lower at this time of year than the temperatures recorded in March and September of the same year, in spite of the high outdoor temperatures. This is because the south roof overhang of 30” at the window locations and 48” at the sliding glass door locations effectively shaded the southern walls during the summer months and reduced direct thermal gain. There was a greater difference in temperature between the exterior and interior wall surfaces of the frame wall versus the block wall, illustrating the different behaviors of an insulative wall versus a thermal mass wall. The temperature data graph reveals that the interior surface temperatures of the block wall were higher than those of the frame wall, and that the delta between the two was smaller, because the thermal mass tends to stabilize the interior temperature over time. At this hottest time of the year, the thermal mass wall was actually contributing slightly to the cooling load (compared to the frame wall). The courtyard temperature was the highest of all temperatures due to the direct solar gain it received early in the morning and late in the afternoon with no overhead shading.

September and March data are very similar, except that the thermal lag times for the two types of wall assemblies were shorter (about 2 hours for the frame wall and 3 hours for the block wall), and the exterior wall temperatures reached higher values because the south roof overhangs did not offer complete shade during the hottest hours of the day at this time of year. The data reveals that the block wall contributed about the same to the interior heat gain (+ 2 to 3 degrees F) at these times of year as it did during the summer months. The courtyard space was still too warm for comfort during most of the daytime in September, but was fairly comfortable in March.

December data showed that the block wall made a similar contribution to the interior heat gain at that time of year, although winter is arguably the only time in Tucson that this is a desirable outcome. The thermal lag time for the block wall was longer than the lag time for the framed wall by about one hour. The lag times were shorter during winter days because the south walls were receiving direct sunlight for a long period each day. The winter courtyard temperatures were finally a daytime asset to this outdoor living space.

Construction Costs: Total = $88,800 (2010). Building envelope = $36,373.24 for 2,340 square feet of walls and 1,400 square feet of roof. This includes the masonry, framing, insulation, and sheathing (OSB exterior and drywall interior), but no windows or doors. The cost per square foot of steel-clad insulated frame walls and roof was $12.50. The Integra Block walls cost $6.39 per square foot of wall. While student labor was free (wall and roof framing, sheathing and cladding), there were labor costs in the insulation, drywall, and masonry components.

Energy Use and Energy Cost Data
The total energy used for this household was 14,201 kWh for the first year and 14,088 kWh for the second. This exceeds the amount used by the average Tucson household (12,732 kWh per year). The annual electricity expenditures were $1,766.54 and $1,825.59, respectively (compared to the $1,440 average for Tucson). However, this is a family of six, which exceeds the average family size by 143%. Without a more detailed energy audit, it is not possible to determine whether it is family size and use habits or building performance that affects the amount of electricity use for this home.
Post-Occupancy Testing of Thermal Dynamics

Research Insights
Both types of wall assemblies transfer heat from exterior to interior, but the insulated frame wall transfers less heat than the Integra Block wall during all seasons. The block wall does not reach exterior surface temperatures as high as the metal clad frame wall, but the interior of the block wall is always closer to the temperature of its exterior as compared to the frame wall. This is a detriment to interior thermal comfort during the warmer months of the year, but an asset during cooler months. Summer nighttime ventilation was recommended to flush out higher temperatures of the thermal mass wall and slab, but this practice was not followed by the homeowners due to security concerns. Hypothetically, this would have allowed the interior temperature of the thermal mass to more closely resemble the exterior temperature on summer nights, but this was not verified. Southern roof overhangs affected the surface temperature of south walls in the summertime, thus reducing their surface temperature and internal heat gain. Other months recorded higher peak surface temperatures for the south walls. The southern roof overhangs allowed direct sun onto the south walls during the winter months, which shortened the time lag for thermal transfer to the interior of the dwelling by approximately three hours. The use of insulated block as the building envelope for southern exposures is more effective as a thermal strategy for passive heating than the use of metal-clad insulated frame walls. However, the use of insulated block as the building envelope for southern exposures is less effective as a thermal strategy for passive cooling than the use of metal-clad insulated frame walls. These results illustrate the need for other design parameters to work in concert with thermal goals (designing a secure aperture for nighttime ventilation, for example), as well as the importance of homeowner education. The thermal time lags varied with the seasons. In the summertime, the time lag was longer for the block wall than for the frame wall by about two hours. This facilitates the removal of heat via nighttime ventilation. During the shoulder seasons and the winter, the thermal lag in the block wall had a lag time of about one hour longer. Overall, the shortest lag times were in the winter due to full direct sun exposure.
Figure 16. DDBC4 Temperature Data; June 15-16, 2011.

Figure 17. DDBC4 Temperature Data June 15-16, 2011; Temperature Delta Between Wall Assemblies.

Figure 18. DDBC4 Temperature Data; September 21-22, 2011.

Figure 19. DDBC4 Temperature Data; March 15-16, 2011.

Figure 20. DDBC4 Temperature Data; December 20-21, 2010.

**DDBC Residence 5**

Research Questions: Does a south-facing trombe wall reduce the cooling/heating needs in the house over the course of one year? Is a trombe an effective thermal strategy during all seasons of the year? Is there any difference in the thermal behavior of a “classic” trombe wall compared to that of a “modified” trombe wall?

**Description**

**Floor area:** 1200 sq. ft.

**Site orientation:** Long axis E-W

**Tectonic strategy:** Trombe wall

**Thermal strategy:** Thermal mass

Trombe walls emerged as a passive solar design strategy in the United States during the 1970s, and many examples were constructed in the arid Southwest. To construct this type of heat storage wall, a glass wall is placed several inches in front of a thermal mass wall (composed of solid masonry or containers of water), and as the air cavity between the two walls heats up, vents are manipulated to allow warm air to flow to the interior or back outside. A roof overhang is used to shade the glass during warm weather but allows direct sunlight on it during colder weather. Because the design element costs little to implement (the glass wall may add some expense), it was one that could be incorporated by DDBC without challenging the limited construction budget. This residence included a masonry and glass wall design on the south façade and walls of insulated concrete forms (ICFs) for the other three exposures. The ICF walls were a proprietary system produced in Tucson, AZ. The 12-inch by 48-inch expanded poly styrene foam blocks have 2 ¾-inch sides with a 5-inch cavity that holds rebar and is filled with concrete. The R-value claimed by the manufacturer for this system is 28. The ICF walls were clad with Tyvek and corrugated steel panels with a zinc finish on the exterior and drywall on the interior.

DDBC Residence 5 featured two types of trombe wall designs. The “classic” trombe wall was a CMU wall, grouted solid and faced with glass, with a 4-inch air cavity between the glass and the CMU. There were operable air vents in the CMU wall that allow heated air into the interior of the house on winter days and close it off on warm days. There were operable vents at the top of the air cavity to allow heated air to escape to the exterior of the home on warm days. The other type of trombe wall was modified with a glass wall and a 36” hallway between the glass and the solid grouted CMU wall. This modified type of trombe wall relied upon winter heat gain to the concrete slab floor as well as the CMU wall; it was ventilated by the movement of air through the hallway (driven by the mechanical system within the house or by the ceiling fans). The two trombe walls sat side by side, facing south, with a roof overhang that controlled direct solar exposure. The classic
Post-Occupancy Testing of Thermal Dynamics

Data was collected for one year after the home was sold and inhabited by a family of two. Two-day data samples taken approximately three months apart are illustrated here as summaries of typical seasonal data.

The mid-June data graph gives an indication of the wall assembly performance during the hottest time of the year in Tucson. This data sample was taken before the home was occupied, so the temperatures were unmitigated by HVAC because the air conditioning was not yet running. The outdoor temperatures fluctuated predictably with the diurnal temperature swing of the desert sky, varying as much as 39 degrees F in a 7-hour period from early morning to midday. The temperature of the classic trombe wall was climbing and dropping in parallel with the outdoor temperatures.

The modified trombe wall required the homeowners to operate it by opening and closing vents, while the modified trombe wall did not.

To obtain metrics comparing the performance of the two trombe wall types, thermal sensors were placed in the following locations:

a. In the ceiling of the hallway, immediately behind the “classic” trombe wall
b. In the ceiling of the middle bedroom, immediately behind the “modified” trombe wall
c. In the ceiling of the master bedroom, with no trombe wall (immediately behind furred-out, insulated masonry wall)
d. In the exterior weather station atop the rainwater cistern on the north side of the dwelling

Data was collected for one year after the home was sold and inhabited by a family of two. Two-day data samples taken approximately three months apart are illustrated here as summaries of typical seasonal data.

The mid-June data graph gives an indication of the wall assembly performance during the hottest time of the year in Tucson. This data sample was taken before the home was occupied, so the temperatures were unmitigated by HVAC because the air conditioning was not yet running. The outdoor temperatures fluctuated predictably with the diurnal temperature swing of the desert sky, varying as much as 39 degrees F in a 7-hour period from early morning to midday. The temperature of the classic trombe wall was climbing and dropping in parallel with the outdoor temperatures.
temperature, with a time lag of about 3 hours, indicating that the thermal mass of the grouted masonry wall was releasing heat into the interior space. The temperature was slightly lower than the outdoor temperatures, because the vents were open to channel any heated air back outside of the cavity rather than allow excess heat to build up. During summer months, the classic trombe wall was in full shade, and did not receive direct sun through the trombe glass. The temperature recorded on the ceiling of the middle bedroom (behind the modified trombe wall) was the lowest at all times. The interior thermal mass of the modified trombe wall appeared to keep the temperature fairly stable. By contrast, the temperatures in the master bedroom (behind an insulated masonry wall) fluctuated more than those in the middle bedroom, and showed a 3-hour time lag behind the outdoor temperatures.

For the remaining three data sets, the outdoor temperatures were retrieved from public weather records for those dates due to a failed sensor on the weather station. September, December, and February data were taken while the home was occupied and the HVAC systems were active. There were several gaps in data due to failed sensors in this project, so the data presented here is from time periods closest to the solstices and equinoxes. September data show that the temperatures immediately inside of the classic trombe wall parallel outdoor temperatures closely, with peak temperatures being ahead of the exterior temperature highs during the day (about an hour ahead) and low temperatures being behind the exterior lows at night (by about 3 hours). This suggests that the vents in the trombe wall were set to the winter heating position, because the direct sun was charging the air cavity rather quickly in the daytime and heating the air to a slightly higher temperature than the exterior air, and that the thermal mass of the wall was holding onto heat during the night. Daytime temperatures of the trombe wall were almost identical to exterior air temperatures, while the trombe wall temperatures were about 6 degrees warmer at night. The sensors in the middle bedroom and master bedroom showed similar patterns to what occurred in June: the modified trombe wall kept temperatures almost completely steady, while the insulated block wall showed a clear lag time.

December and February data showed that the temperatures just inside the classic trombe wall were parallel to exterior temperatures, but always higher. Again, this was the function of the vents open to the interior, allowing warm air from the cavity to enter the dwelling. While this strategy brought desirable heat into the home during December, by February it was adding too much. In Tucson, the mechanically operated vents should be set to the exterior venting position even during the shoulder seasons. The vents within the glass wall, which allow air to escape the cavity toward the exterior, are operable from the exterior of the residence and are positioned at a height of 2’ above the porch floor. The vents within the masonry wall, which allow heated air to enter the residence, are operable from the living room and are positioned at 2’ and 5’ above the floor.

Construction Costs: Total = $85,754 (2014). Building envelope = $39,059 for 2,428 square feet of walls and 1,400 square feet of roof. This includes the masonry, ICF, framing, insulation, and sheathing (OSB roof and drywall interior), but no windows or doors. The cost per square foot of the masonry walls was $13.06.
The glass panels and frames for the trombe walls were donated at no cost. The ICF walls cost $9.85 per square foot of wall (including external metal cladding and interior drywall). While student labor was free (ICF walls and roof framing, sheathing, and cladding), there were labor costs in the insulation, drywall, and masonry components.

Energy Use and Energy Cost Data

During the year this house was monitored, the energy use was 10,305 kWh and the cost was $1,376.00. The Arizona Energy Fact Sheet for that year shows an average household energy use of 13,550 kWh at a cost of $1,831.00. This household of two people reports never having to turn on the heat during the winter to date.

Research Insights

Passive solar strategies for this residence included grouping all apertures on the north and south façades, where they do not receive direct sunlight (on the south due to roof overhangs), planting deciduous trees to shade all southern outdoor spaces during the warmer months, providing ceiling fans for each room, locating ductwork within the insulated building envelope, placing closets and storage spaces on west walls for an additional thermal buffer, and providing aperture locations for natural ventilation across all spaces. The modified trombe wall was not affected much by direct solar gain, as only the lower 18” of it ever received direct sun. It did not contribute significantly to active heating or cooling, except by passively stabilizing the atmospheric temperature in conjunction with other design strategies for conditioning interior space. This wall served as an internal temperature stabilizer, keeping comfortable temperatures year-round. The two types of trombe wall performed quite differently. The classic trombe wall allowed for superheating of the air cavity and quick additions of heated air to the interior spaces adjacent to it. The classic trombe wall reduced heating needs during the cooler months. However, the nighttime ventilation necessary to flush out heat gain from the thermal mass walls in DDBC4 was negated by the homeowner’s fear of opening windows at night due to neighborhood crime. Consequently, heat buildup during the warmer months was an environmental liability. An alternative solution for subsequent designs that include thermal mass walls may be to incorporate a whole house attic or ceiling fan to vent the heat gain during the daytime hours out at night without the necessity of opening windows. This could be an automated fan or a manually operated fan. An alternative would be the design of security covers for windows. The homeowners of DDBC5 didn’t change the position of the exterior vent louver as often as would have been beneficial to the interior comfort because a step ladder was needed to reach the control lever on each vent. A revised design of the trombe wall might include longer handles for the exterior vent levers, and/or an insulated sliding screen to cover the glass during the warmer months. All of these revisions would increase the chances that homeowners would participate in the seasonal adjustments to their environmental control systems.

It is critical that the suppositions made during the design phase of housing projects be tested and verified (or debunked) during occupancy by the intended users because the consequences are so important for this particular demographic. It is important, as well, for architecture students to learn that design decisions have real-world consequences, and that research performed as part of design projects can be a valuable contribution to the body of architectural knowledge.

Research plans for design-build projects in academia are difficult to develop, due to the challenges of managing all of the moving pieces of such endeavors—semester schedules, fund-raising, permits and plan review processes, loan or grant applications and award periods, land acquisition, neighborhood association approvals, inspections and construction draws, to name a few. Knitting in a research plan that informs the project design, implementing a methodology for measuring the research results, and following through in the post-occupancy period adds another layer of complexity to the planning and necessitates a bird’s eye view at a higher altitude than the design-build project logistics. The groundwork for the sort of research included in these projects was established over a decade ago, with the incorporation of DDBC as a business entity and nonprofit organization. This allowed DDBC to be designated by NCARB as a community design center, to hold a contractor’s license, open a business bank account, apply for grants and loans, and partner with other nonprofits such as city and tribal governments and universities. In this
context, DDBC could accommodate long-term visions for projects that would allow a series of investigations under an umbrella such as energy conservation. The research design preceded any of the design-build projects and became the basis for the grant application mentioned in the introduction. The program for each residence, then, included parameters such as materials choices and conservation strategies in addition to functional spaces and budget outlines. As with any research plan, strategies for dissemination of the findings were integral to the efforts. Continuity of personnel also contributed to an understanding of the overarching goals so that research intentions were not lost along the way.

Finally, the recognitions and awards for the seven DDBC projects have been instrumental in the dissemination of research findings. Most of the projects have received regional AIA Awards or national ACSA awards for design, as well as recognitions by other organizations that support design-build delivery, service-learning education, and student engagement in the community. This type of public attention has ensured the continued availability of funding and in-kind donations as well as appreciation in local news publications and social media. The recognition of design quality in modest housing projects has contributed to higher expectations for work done in this arena, as evidenced by invitations for consultation and partnership from organizations such as Habitat for Humanity and Chicanos Por La Causa. Replication of these designs in the affordable housing market is possible; the model permit sets have been deeded to the City of Tucson for use by other nonprofit home builders. Widespread use of the energy and water conservation strategies employed in these projects has the potential for scaled savings if adopted by the mainstream housing market. Additionally, the availability of a designed aesthetic different than that of production housing in Tucson has the potential to change expectations for design of low-income housing.

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Drawings, diagrams, and graphs produced by Rachael Varin.

Notes

8. Onset 12-bit temperature cable smart sensors, capable of recording temperatures from -40 to 212 degrees F.
13. Water conservation strategies for all of the residences included the collection of rainwater from the roofs using gutters and above-ground storage cisterns, reuse of grey water from the washing machines, and the formation of micro-basins in the landscaping of the lot to collect on-site rainwater. The amount of potable water (provided by the City of Tucson) used by each household was measured by readings from the main water meter, and the amount used for outdoor purposes was separated from the total by the use of a sub-meter attached to each outdoor hose bib.

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