OREGON SUNSPACE REDESIGN / BUILD: NEW PRIORITIES FOR THERMAL MASS

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ABSTRACT

Two similar sunspaces in Eugene, Oregon, both with massive floors, were monitored from January-June 2011 in a previous study (1). One sunspace was redesigned and rebuilt in light of results, adding thicker floor mass, fully insulating that mass from soil, and reducing infiltration. Monitoring of mass heat fluxes and temperatures of mass, air, and perimeter soil resumed from January-June, 2012.

Field data revealed markedly warmer mass surfaces, greater nighttime heat return, and warmer air in the redesigned sunspace than in its unchanged counterpart. However, 2012 was warmer than 2011; to extract redesign effects, sunspace EnergyPlus models were compared using 2012 weather data after validation with their respective (2011 and 2012) weather files.

Models showed that the redesigned floor lost much less heat to underlying soil than the original, particularly in the center. Moisture-wicking clay soils facilitated these losses, showing that in this climate, thermal mass must be isolated from moist soils by insulation, drainage, or internal positioning. Perimeter insulation is not sufficient.

Modeled addition of further mass, to reach levels recommended by prevailing design guides, diminished air and operative temperatures and heat retention; oversizing of thermal mass is therefore also to be avoided.

1. INTRODUCTION

Passive solar space-heating design in the Pacific Northwest, as in the rest of the U.S., has long been guided by the venerable work of Douglas Balcomb and colleagues with respect to orientation, glazing tilt, mass configuration, and predicted performance (2-5). Recent work has challenged these beliefs in cloudy climates (1), however, and investigated new possibilities for thermal mass responsiveness to program needs (6). The current study documents a thermal mass experiment in a well-characterized existing sunspace, evaluating “rules of thumb” regarding mass sizing, insulation, and position in the process.

Passive solar heating can be highly effective in northern climates because heating needs increase with latitude more rapidly than solar resources decline: MacGregor showed a useful solar contribution four times greater in Lerwick, Shetland Islands (60°N) than in Messina, Italy (38°N), for example (7). This result reflects, in part, the duration of the northerly coastal heating season well past the spring equinox, a pattern shared by Eugene, OR (44°N) and other cities of the Pacific Northwest: Portland, OR (45°N), Seattle, WA (47°N), and Vancouver, BC (49°N) (Fig. 1). Comparison of Eugene’s heating season with those of inland cities of equal annual heating need highlights the coastal influence in both moderating the depth of the heating season and extending its length (Fig.2).

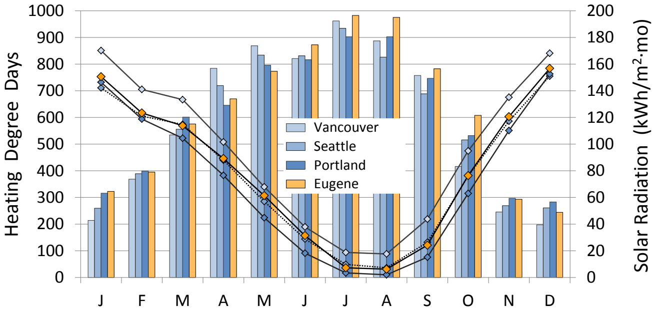


Fig. 1. Normal heating season intensity (HDD$_{65F}$, 1981-2010) compared to solar resources (incident solar radiation on a 45° surface), showing the extent of the heating season past the spring equinox into months with significant solar resources (8, 9) .

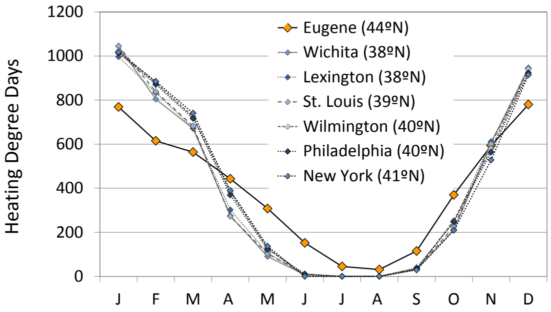


Fig. 2. Heating degree-days (base 65F) for Eugene and cities of the mid-western and eastern US with comparable annual heating degree-days (4800-5000), emphasizing the mild but long heating season of the Pacific Northwest (7).

Despite its climatic advantage, however, Pacific Northwest buildings rarely implement passive solar heating because persistently overcast skies and often-substantial tree shading are viewed as overwhelming obstacles. The goal of this investigation, as part of an ongoing series, is to separate actual, field-verified mechanisms of heat gain and loss in Pacific Northwest passive solar spaces from conventional passive solar design guidelines developed primarily in sunnier climates (2). Here, we consider the dramatic differences between conventional thermal mass design guidelines and results from an unusual redesign/build experiment.

2. METHODS

Sunspace field sites. Two sunspaces, each attached to an adjacent dwelling, were instrumented from January through June, 2011 as part of a previous study (1). The Gates sunspace was subsequently redesigned and rebuilt, and monitoring resumed for both it and the similarly-performing Shaw space from January-June 2012.

Both sunspaces share two insulated common walls with their dwellings, and both are used extensively for plant growing and afternoon / evening occupancy. As casual outdoor rooms, both originally had high infiltration resulting from open passageways for frogs, cats, and garden hoses. Differences between the two included a rainwater fish tank in the Gates space, providing additional mass; polycarbonate roof glazing in the Shaw space; a slightly shallower tilt angle in the Shaw roof; and a difference in orientation of approximately 45°, with the Gates space oriented southeast and the Shaw space oriented slightly west of south (Fig.3, Table 1).

Sunspace monitoring. Dry-bulb temperatures of each sunspace, its adjacent conditioned living space, and outside air were measured with factory-calibrated Hobo U12 or UA pendant dataloggers (Onset) at 10-min. intervals; sunspace measurements were made in triplicate. U12 loggers also recorded relative humidity. Soil temperatures were measured by TMC20-HD sensors (Onset), also

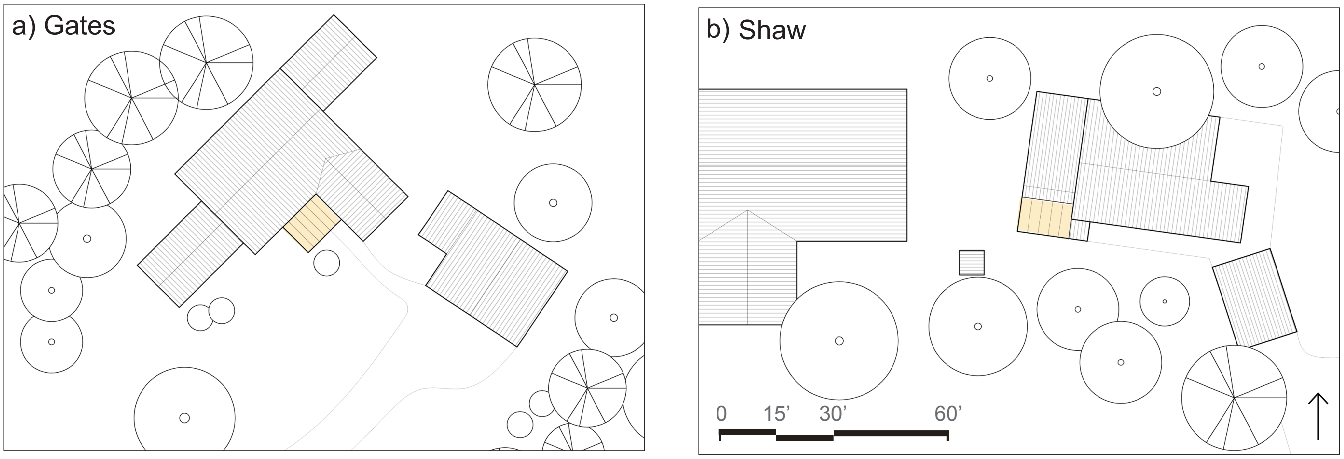


Fig. 3. Sunspaces within their contexts of buildings, evergreen trees (sectored), and deciduous trees (open). The Gates site is semi-rural, while the Shaw site is in a low-density urban area. Arrow shows solar north.

TABLE 1. SUNSPACE CHARACTERISTICS

	Gates Original	Gates Redesign	Shaw
Roof glazing	single clear	no change (n.c.)	polycarbonate
Skylight area	78 sf	n.c.	95 sf
Roof tilt	23°	n.c.	15°
Wall glazing	single clear	n.c.	single clear
Floor layers	2” pavers / soil + 4” concrete / soil	4” concrete / R-10 insul / gravel / soil	concrete / soil
Floor mass	115 sf	n.c.	52 sf
Additional mass	fish tank, pots, soil	n.c.	pots, soil
Infiltration	high	moderate	very high
Shading	low	n.c.	medium
Location	entry	n.c.	side
Orientation	SE	n.c.	S

connected to U12 loggers. Surface temperatures were obtained with SA1 T-type surface thermocouples (Omega) and U12 thermocouple loggers, and surface heat fluxes were measured with a HFS-4 thin film heat flux sensor (2 $\mu V/W \bullet m^{-2}$); Omega) connected to a Fluke 289 logging microvoltmeter. Incident solar radiation was estimated with S-LIB-M003 silicon pyranometers and H22-001 energy loggers (Onset). Because even the lower-infiltration spaces had cracks too large to permit blower-door tests, opening and crack areas were measured directly for infiltration estimation by EnergyPlus (below).

Finite difference modeling. Mass surface temperature measurements, which reflected convective and radiative heat transfer to the space, were used to drive models of conductive heat transfer through the mass layer into a homogeneous underlying substrate representing the soil (11). The MATLAB suite of ordinary differential equation routines (12) was employed to solve equations describing the evolution of temperature through the layers, discretized to second order accuracy at equally spaced nodes. These extended to a depth comparable with the annual thermal diffusion distance, where the background temperature was assigned based on appropriately attenuated TMY3 soil temperatures (also used as initial conditions) from Eugene-Mahlon Sweet Field Airport (13). Heat capacities, densities, and thicknesses of slab materials were measured or estimated from standard tables (14). Slab thermal conductivities and soil thermal diffusivities were chosen to minimize RMS model misfits to measured nighttime heat flux data collected over five days in the Gates space (beginning 37 days after model initiation) and over six days in the Shaw space (beginning 42 days after model initiation).

EnergyPlus modeling. To distinguish and quantify heat flow pathways, the two sunspaces were modeled in EnergyPlus 7.2, a rigorous building energy simulation tool developed by the U.S. Department of Energy from BLAST and DOE2 (15).

Envelope geometry, site orientation, and shading surfaces were input using OpenStudio 1.0.6, an EnergyPlus plug-in for SketchUp 8 (16). Glazing assembly properties were calculated by WINDOW6 (17) and referenced by EnergyPlus; all other parameters (materials, constructions, operable openings, schedules, internal mass, soil characteristics from above models) were input directly using the EnergyPlus IDF Editor. Floor constructions included below-floor soil layers to a depth of 10 in. (25 cm), necessary for prediction of measured air and surface temperatures; floor sections covered by furniture or rugs were represented as carpeted. Infiltration was estimated from input of measured crack and opening areas, as well as site-appropriate wind and stack coefficients, into Zone Infiltration:EffectiveLeakageArea objects. Transmittance schedules for tree shading were developed from densitometry of tree photographs and regional deciduous tree leaf-out schedules (18).

Building solar distribution was simulated as “FullInteriorAndExteriorWithReflections”, in which beam solar radiation is projected through glazing to the correct surface, and absorbed / reflected accordingly, rather than assumed to fall on the floor. This was essential to simulating floor mass thermal activity but required convex zone geometry; the small projection of the Shaw space was therefore removed and incorporated into a single larger shape.

Weather. Spring 2011 and 2012 real weather files were created by replacing data in the Eugene TMY3 EPW file with data obtained at the Solar Radiation Monitoring Laboratory weather station at the University of Oregon (dry-bulb temperature, relative humidity, barometric pressure, global horizontal radiation, direct normal radiation, diffuse radiation; (19)) and from the Eugene-Mahlon Sweet Field Airport weather station KEUG (sky cover, wind speed, wind direction (8)). Dewpoint temperatures were calculated using the August-Roche-Magnus approximation (20). Other weather variables (e.g. global horizontal illuminance, zenith luminance, ceiling height, weather codes) not used in model calculations (21) were left unchanged.

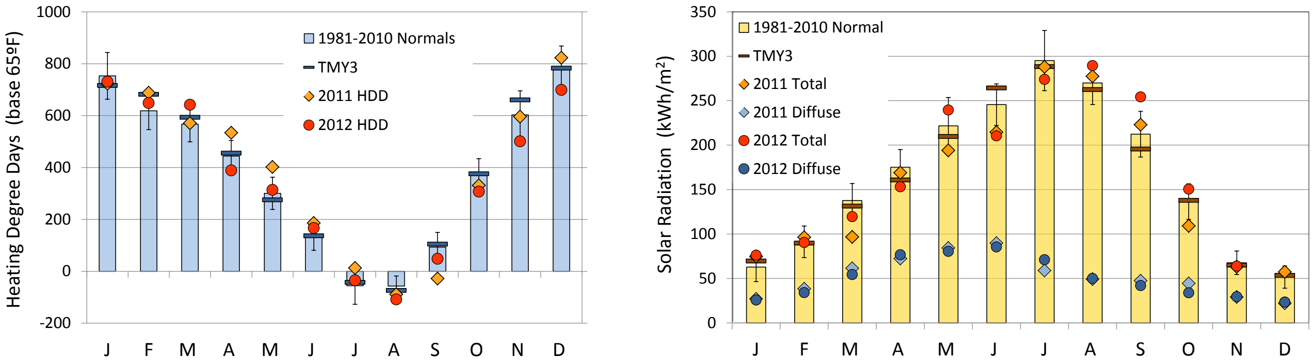


Fig. 4. Heating degree-days (left) and direct + diffuse solar radiation (right) for 2011 and 2012 compared to "normal" levels, represented by NOAA thirty-year climate normals ± 1 standard deviation (8, and "typical" levels, represented by the Eugene TMY3 weather file (13). Notably, March 2011 was unusually cloudy, April and May 2011 were unusually cool, and June months of both years were unusually cloudy; overall, 2012 weather most closely approximated normal and typical conditions.

January and February 2011 experienced weather fairly consistent with reported 30-year normals (8) and with typical conditions catalogued in the Eugene Mahlon-Sweet Field Airport TMY3 file (13). March 2011, however, was unusually cloudy; April and May 2011 were unusually cool, and June was again unusually cloudy (Fig. 4). 2012, in contrast, experienced a warmer-than-typical April and a sunnier-than-typical May, with a June comparable to that of 2011. Overall, 2012 weather more closely resembled typical weather patterns.

4. REDESIGN / BUILD

The original Gates and Shaw sunspaces, monitored in 2011, transmitted and retained comparable quantities of solar radiation. Their similar achievements, despite their orientation differences, testified to the relatively minor role that orientation plays in cloudy winter climates (1). Both, however, lost substantial heat through floors exposed to moist, fine-grained soils with high thermal diffusivities and to infiltration (1).

To improve the performance of the Gates space, during the summer of 2011, a redesign was undertaken. Thermal mass was increased by replacing the original floor (part 2-in. concrete pavers over soil, part 4-in. concrete slab over soil) with a 3.5-in. thick concrete slab over the entire area, covered with black ceramic tile and fully insulated underneath with R-10 rigid foam over several inches of coarse gravel for drainage. Infiltration was also diminished by removing the frogway, a 2-in. high opening at the ground edge of the wall glazing, and replacing it with a tiled concrete ridge or screens with manually removable insulation.

To accomplish this, the entire sunspace was disassembled, the floor was excavated and rebuilt, and the framing was re-assembled over the new floor. All original single-pane glass was therefore retained. In addition, the original rainwater-catching and koi-supporting ceramic pots were replaced with a larger single fish tank, framed in wood but open to the sunspace air.

The Shaw sunspace was not changed structurally during the spring of 2012, allowing it to serve as a benchmark for evaluation of the Gates sunspace redesign.

Air temperatures. From March through June, 2011, Gates median sunspace dry-bulb temperatures remained within 1-2°F of those of the Shaw sunspace. Dissimilarities were greater during January and February, resulting in part from greater infiltration in the Shaw space (1); in every month, both sunspaces remained 7-10°F warmer than outside air (Fig. 5). In 2012, however, median air temperatures in the Gates space remained approx. 5°F warmer than those in the Shaw space, suggesting that the mass and infiltration changes had indeed led to greater heat retention.

Mass temperatures. Floor mass surface temperatures, in turn, offered insight into a contributing mechanism. Again, median Gates and Shaw mass surface temperatures remained close to each other throughout 2011, with the Gates temperatures slightly higher (Fig. 6). In February 2012, however, the two diverged, and median Gates mass temperatures remained approx. 7°F warmer from March through May. The most straightforward explanation for the warmer mass temperatures is that less mass-intercepted heat was lost to the soil. Whether this resulted primarily from insulation at the perimeter, however, as held by design guides (2, 3, 14, 22-24), or whether central under-slab insulation also played an important role, is a question that required models to answer.

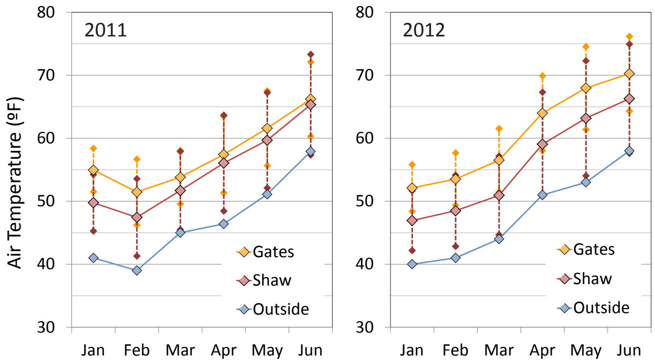


Fig. 5. Median air temperatures of the Gates and Shaw sunspaces ± ½ interquartile range in spring 2011 and 2012. Both sunspaces experienced approx. 7-10°F warmer air compared to outdoor dry-bulb temperatures in 2011, increasing to approximately 12-15°F for the redesigned Gates space in 2012.

5. NEW MODEL VALIDATION

EnergyPlus models of the original Gates and Shaw spaces predicted approx. 90% of the sunspace air temperature variability and >85% of the mass surface temperature variability (1). To create the redesign model, the original Gates model was modified to represent the thicker insulated floor, the reduced infiltration, and increased fish tank volume; it was then re-tested against field measurements using 2012 real weather data.

Modeled redesign air temperatures closely approximated measured temperatures (R^2>85%), as expected given the simplicity of the model changes, and modeled mass surface heat fluxes closely approximated the nighttime (heat return) fluxes (R^2>80%) (Fig. 7). The new models therefore appeared to capture the major heat flow pathways faithfully, allowing them to be used to generate further insights.

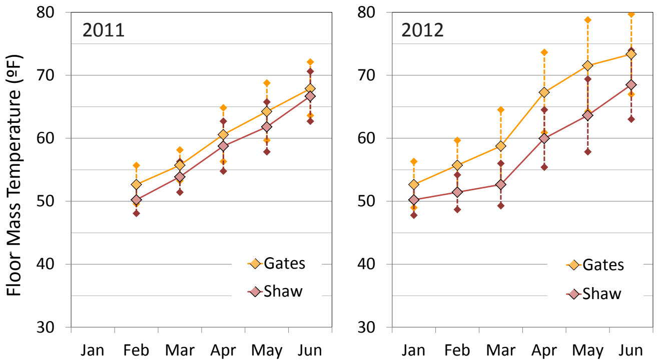


Fig. 6. Median floor mass surface temperatures ± ½ interquartile range of the Gates and Shaw sunspaces in spring 2011 and 2012. The original Gates mass surface showed approx. 1-3°F warmer temperatures than that of the Shaw mass in 2011, increasing to approx. 5-8°F warmer in 2012.

6. HEAT FLOW PATHWAYS

The central questions posed to the Gates models were: "How much more heat did the redesign retain?", and, more usefully, "By what means?". To answer these, both models were simulated with 2012 real weather data, which best approximated typical conditions.

Solar interception by the original and redesigned models was identical, as expected, because glazing and external shading had not been altered (Fig. 8). In the original, floor heat loss was low in January, when the mass was cool, but increased progressively through the spring as the floor warmed. Window heat loss was, as expected, the second-greatest sink, followed by infiltration and, distantly, opaque walls. Heat not lost by one of those pathways was quantified as "retained" in materials or air, and that "returned" by mass through radiation or conduction is shown as well (Fig. 8).

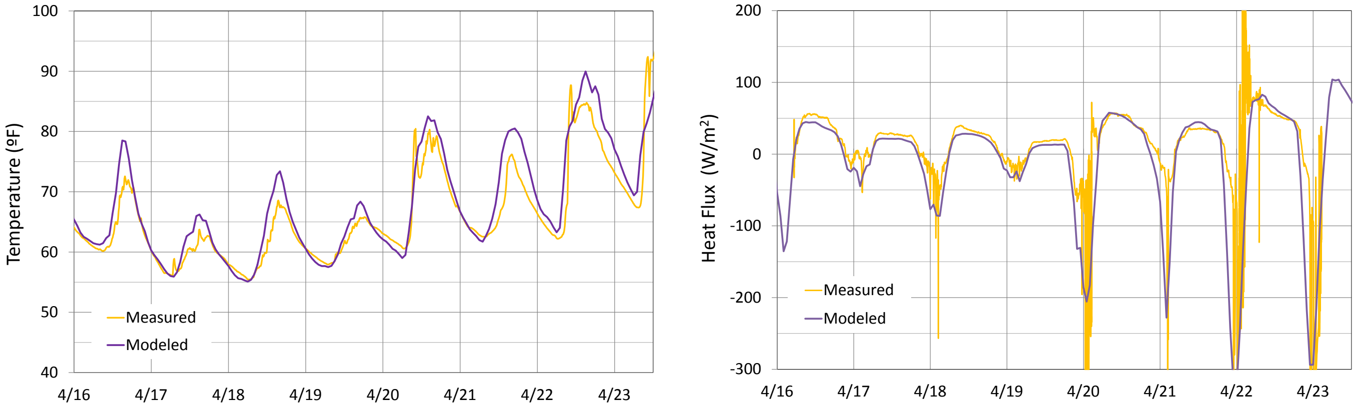


Fig. 7. Modeled sunspace air temperatures (left) and slab surface heat fluxes (right), compared to measured values, for one week in mid-April, confirming that the redesign model captured the thermal behavior of the redesigned space.

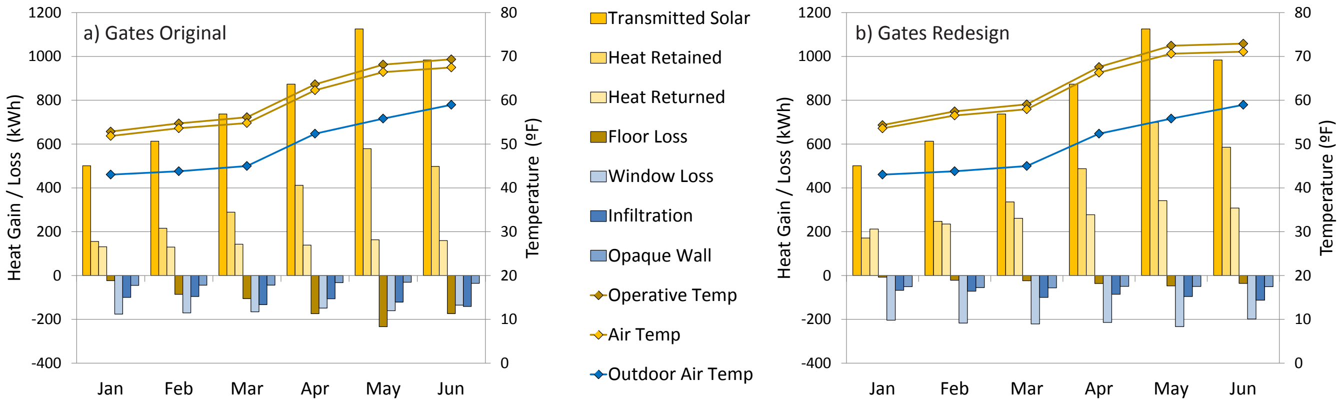


Fig. 8. Heat gain and loss pathways, and resulting sunspace air and operative temperatures, in the Gates original sunspace (a) and redesigned sunspace (b), illustrating the effect of the redesign in reducing mass floor and infiltration heat losses. Heat "retained" quantifies heat retained in sunspace materials or air, and heat "returned" quantifies heat returned to the space from floor and internal mass via radiation and convection.

In the redesign, seasonal floor heat loss dropped to approx. 20% of its former level, and infiltration loss was approximately halved, as expected. Windows, however, became by far the greatest avenue of heat loss as indoor air and operative temperatures rose (Fig. 8). Despite this, however, seasonal heat retention increased from approx. 1500 kWh in the original to 2000 kWh in the redesign, and average indoor air and operative temperatures increased by 3-4°F (Fig. 8), particularly during late afternoons and evenings (not shown).

7. HEAT LOSS TO WET SOIL

The previous sunspace study, which included the Gates and Shaw spaces, strongly suggested that heat losses through their massive floors were not simply perimeter phenomena, as losses through central regions were substantial (1). This resulted from warm afternoon slab temperatures combined with the cool soil temperatures typical under small unconditioned spaces.

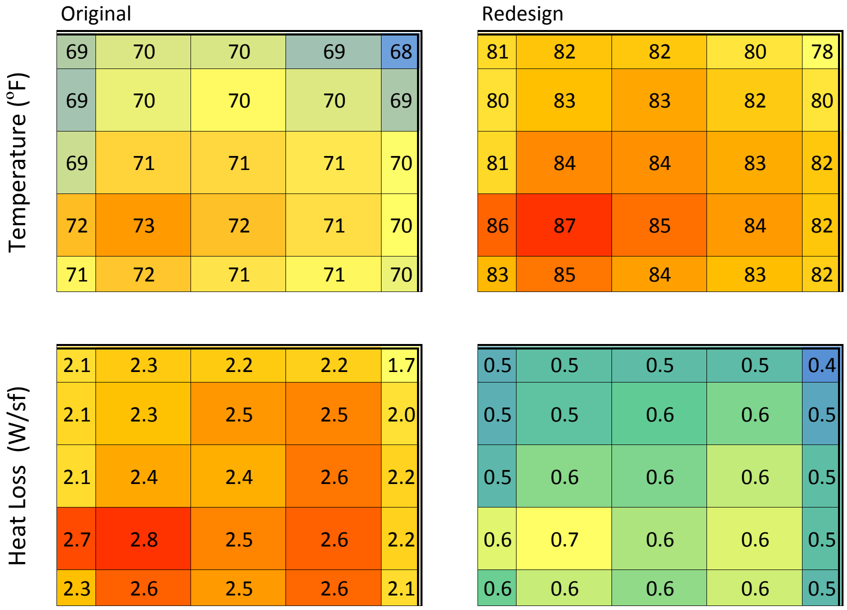
Moreover, high soil moisture, routine in Pacific Northwest winters, increased soil thermal diffusivity to such an extent (25, 26) that only small temperature differences existed between perimeter and central soils of these sunspaces (27).

As a result, the greatest temperature gradients (and greatest potential for heat loss to soil) occurred during high-solar-gain afternoons, in regions with greatest solar exposure - usually central rather than perimeter regions. Nevertheless, the belief in perimeter-only insulation for massive floors in passive solar spaces, except in very cold climates, is widespread (2, 3, 22-24) and deserves further examination.

Subdivision of the Gates original and redesigned floor surfaces into a grid of 1 ft. wide perimeter regions and remaining core regions, and reporting of the EnergyPlus variable *"Surface Inside Face Temperature"*, shows the effectiveness of the redesign in raising mass surface temperatures (Fig. 9). Note that both original and redesigned floors show greatest warmth in central rather than perimeter regions, indicating greater solar gain relative to total heat loss.

The heat flux of each sector from its underside to the soil below, however, is the best indicator of loss through that pathway. EnergyPlus cannot simulate two-dimensional slab-to-ground heat transfer, but it instead approximates that process using the SLAB pre-processor mentioned above to estimate monthly ground temperatures at perimeter and central locations. This procedure incorporates sunspace size, floor construction, and average indoor air temperature to determine the space's effect on the soil below (27). These distinct core and perimeter soil temperatures, the latter of which agreed closely with measured slab-edge soil temperatures (above), were then subject to the standard one-dimensional heat transfer simulation. Model-reported heat fluxes showed that, despite cooler perimeter soil temperatures, heat losses from the massive floor were greater, and accounted for far greater total heat loss, than losses from perimeter sectors. Core losses still exceeded perimeter losses in the insulated slab floor, and total heat losses were reduced to approx. 20% of their original value (Fig. 9).

While this simulation is inexact, it is consistent with a growing body of literature concerning soil moisture-accelerated heat loss, and loss from central regions, of



Original – Temperature (°F)

69	70	70	69	68
69	70	70	70	69
69	71	71	71	70
72	73	72	71	70
71	72	71	71	70

Redesign – Temperature (°F)

81	82	82	80	78
80	83	83	82	80
81	84	84	83	82
86	87	85	84	82
83	85	84	83	82

Original – Heat Loss (W/sf)

2.1	2.3	2.2	2.2	1.7
2.1	2.3	2.5	2.5	2.0
2.1	2.4	2.4	2.6	2.2
2.7	2.8	2.5	2.6	2.2
2.3	2.6	2.5	2.6	2.1

Redesign – Heat Loss (W/sf)

0.5	0.5	0.5	0.5	0.4
0.5	0.5	0.6	0.6	0.5
0.5	0.6	0.6	0.6	0.5
0.6	0.7	0.6	0.6	0.5
0.6	0.6	0.6	0.6	0.5

Fig. 9. Average mass floor surface temperatures and heat losses to underlying soil found in the Gates original and redesigned sunspaces for the month of May; data were generated by EnergyPlus models previously validated with field measurements. Models were simulated with 2012 real weather data in both cases.

While average mass surface temperatures increased by 10°F or more, heat losses diminished to 25% or less of their original levels, illustrating the behavior of the newly-insulated mass floor.

Heavy lines indicate common walls shared with the adjacent dwelling; glazed walls face southeast and southwest (see Fig. 3 for orientation).

slabs-on-grade (28-30). Under-slab drainage, and/or full under-slab insulation, therefore appear essential to thermal mass deployment over moist soils.

8. THERMAL MASS SIZING for WET WINTERS

By the standards of sunspace design guides, the redesigned Gates floor was substantially under-massed (2-4, 22, 24). Yet it performed far better than the original. Could it have retained even more heat, and become even warmer, if it had followed conventional wisdom?

To address this question, the Gates redesign model was tested with the two most widely-recommended mass alternatives: (1) a thick masonry common wall, and (2) an R-20 insulated common wall with substantial internal water mass. The mass in each case was sized according to design-guide recommendations: (1) 1 ft^2 of 12-in. thick concrete for each 1 ft^2 of projected glazing area, and (2) 1 ft^3 of water, in a tank of solar absorptance=0.9, for each 1 ft^2 of projected glazing area (2-4, 22, 24). Both alternatives also added floor mass to a total of 6 in., as recommended, and given R-10 perimeter insulation as well (2-4, 22, 24).

Peak air temperatures in the "high mass" and "high water"sunspaces decreased (not shown), and night minimum temperatures were warmest in the "high water" space, as expected (6). However, total retained heat, including heat delivered to living spaces by the massive common wall, and average air temperatures were lower in the two alternatives (Fig. 10).

While somewhat surprising, this result is consistent with reports from other cool, cloudy climates (7, 31). Should sunspaces in such climates be highly massed, nevertheless, to mitigate summer overheating? In the Pacific Northwest, the cooling season is mild and brief (Figs. 1, 2, 4), and natural ventilation has proven highly effective for cooling in the region (32). The heating season, in contrast, is extensive. These features argue for the judicious use of mass in regional sunspaces, placing it strategically and limiting it to the amount that can be effective in heating.

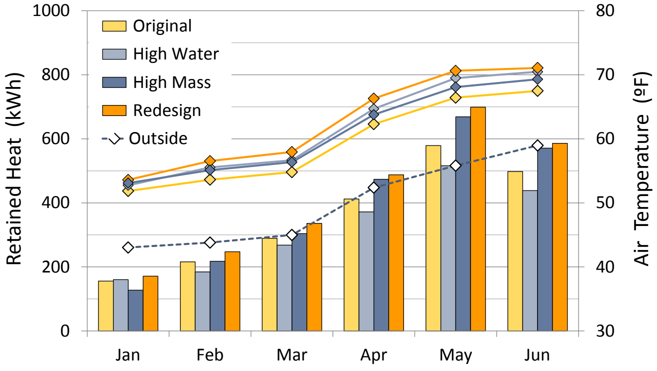


Fig. 10. Total heat retained (bars), and average air temperatures (lines), of the Gates sunspace under four design scenarios: (1) original, with a floor of uninsulated 4" thick concrete and 2" thick pavers; (2) "high water", adding 1 cubic foot of water for each square foot of projected glazing area (2, 3); (3) "high mass", replacing the insulated common wall with a 12-in concrete wall (2-4); and (4) the redesign, fully insulating the concrete slab. All designs except the original assumed the lower infiltration level of the redesign.

9. CONCLUSIONS

Every building is an experiment: even familiar designs inhabit unique environments, and understanding design-environment interactions is central to the creation of architecturally and thermally delightful buildings. Few building-experiments are asked to yield their data, however, and those that vary selected parameters are rare, providing robust tests of prior hypotheses.

The Pacific Northwest climate is promising for passive solar design (7), but it defies typical rules for glazing angle and orientation (1). Here, we show that it also requires adjustment to rules for thermal mass design: in particular, mass in floors must be fully isolated from wet soils through insulation, drainage, or position.

Recommended sizing of thermal mass is also problematic; while it reduced peak daily air temperatures in the models tested, it paradoxically increased heat loss through glazing by keeping nighttime temperatures warmer (highlighting the value of nighttime insulation). Since overheating of small spaces in the Pacific Northwest is readily addressed by natural ventilation (32), however, mass for that purpose is not required.

Instead, designers should consider choosing materials and sizing mass to respond to the programmatic needs of the space (6). These may not be limited to heating a “master” space: in this study, occupants prioritized the experience of daylight and early-evening warmth, plant protection, and thermal buffering of the house over heat for living spaces. Intriguingly, two priorities call for evening heat return, while the others call for heat return during the coldest hours of the night. The distribution of mass between water and solids, then, and between floor and walls, requires optimization.

Finally, sizing of thermal mass need no longer be confined to look-up tables and “rules of thumb”. EnergyPlus is a public, mathematically rigorous, flexible, and approachable building simulation engine uniquely suited to passive solar spaces (15, Fig. 7); designers and engineers should welcome it into their toolkits.

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