DAYLIGHTING, PASSIVE HEATING AND COOLING IN SOUTHSIDE ELEMENTARY

Design exercises from consecutive courses in Passive Heating and Passive Cooling

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ABSTRACT

A series of design exercises investigate improving the suitability of classrooms in Southside Elementary for daylighting, passive heating and passive cooling with minimal changes to the plans, which are in Schematic Design. Quick design guidelines establish a direction and are followed by detailed calculations for passive heating and cooling. Discrepancies between the results predicted by guidelines and the detailed calculations lead to an examination of the assumptions behind the guidelines and a deeper understanding of key components of successful passive strategies.

Southside Elementary is currently being designed by Dull Olsen Weekes Architects for the 4J School District in Eugene, OR. The Willamette Valley is known for its mild climate year round and for its overcast skies from late fall through early summer. The average January ambient temperature is 39°F. Summer design temperature is 89°F, but school is not in session for the hottest months of July and August. Analysis of six classrooms (three upper and three lower) show that the west upper is the (slightly) worst-case scenario for passive heating and cooling. For simplicity, the results of that room are presented as representative of all classrooms. Schematic plans show approximately 130 ft^2 of glazing, half of which faces south.

1. PASSIVE DESIGN GUIDELINES

1.1 Daylighting

Effective daylighting has many variables, but a good place to start is with the daylight factor, which is defined as

$$DF = \frac{\text{indoor illumination from daylight}}{\text{outdoor illumination}} \times 100\%$$

A daylight factor of 2 or 3 is appropriate for most rooms. Slightly higher light levels are OK for a classroom, but over daylighting a space can contribute to significant overheating and glare problems. A quick rule of thumb for determining required window area as a percentage of floor area is given by the following formula.

$$DF = 0.2 \times (A_g/A_f) \times (V_t/90) \times 100.$$

A_g = area of glazing
A_f = area of floor
V_t = visible transmission of the glazing

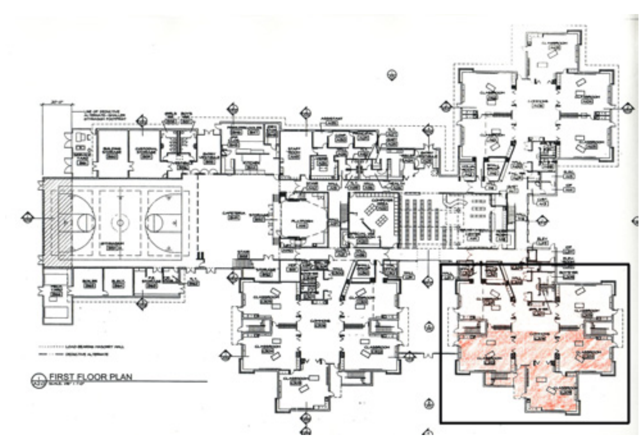

Fig. 1 Floor plan of Southside Elementary in Eugene, OR

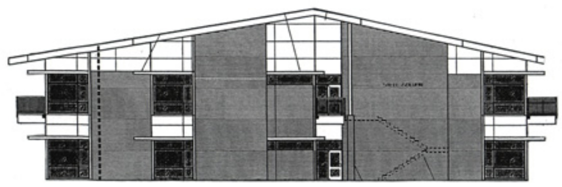

Fig. 2 – South elevation in Schematic Design

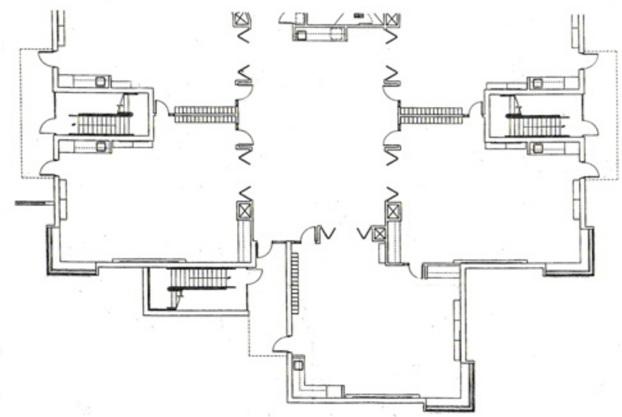

Fig. 3 – Three classrooms in Schematic Design

For Southside Elementary, a 1074 ft^2 classroom needs between 200 and 300 square feet of window (significantly more than the schematic plans) to provide a daylight factor of 3. Maintenance factors and shading devices influence this range. Prevalent overcast skies in the Willamette Valley mean that the orientation of this glazing is not important for daylighting (although it is very important for passive heating).

1.2 Passive Heating

Quick design guidelines for passive heating center around a value called the Solar Savings Fraction (SSF), which is defined as the extent to which a solar design reduces a building's auxiliary heat requirement relative to a "reference" building – one that has, instead of a solar wall, an energy-neutral wall (Stein and Reynolds, page 211). A high SSF means more of the energy needed to heat a space is provided directly by the sun. The vertical axis of the chart in Figure 4 shows the ratio of solar collector area (south facing glass) to floor area, and the horizontal axis shows the corresponding SSF for Portland, OR (closest available climate to Eugene). Southside Elementary uses the left bar indicating no night insulation or super insulating windows.

Schematic design shows insufficient solar collector area of 63ft^2, which would correspond to SSF of only 15. A more effective solar collector area would be about 400 ft^2, yielding SSF of over 40.

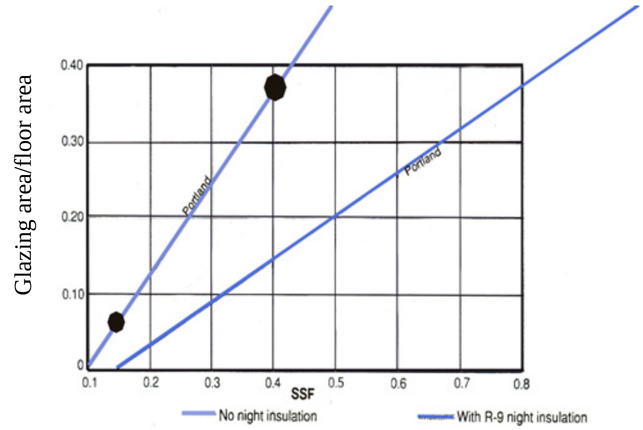

Fig. 4 – Solar Savings Fraction

1.3 Passive Cooling

Although heat gain characteristics in a space make passive cooling more complicated to calculate than passive heating, design guidelines can give early indications of whether a building is suitable for a particular cooling strategy. For instance, a certain amount of opening area is necessary for cross or stack ventilation and a certain amount of exposed mass is required for night ventilation of mass. A quick review of window sizing, location, mass characteristics, and diurnal outdoor temperature swings indicate that night ventilation of mass is the most promising passive cooling strategy for Southside Elementary.

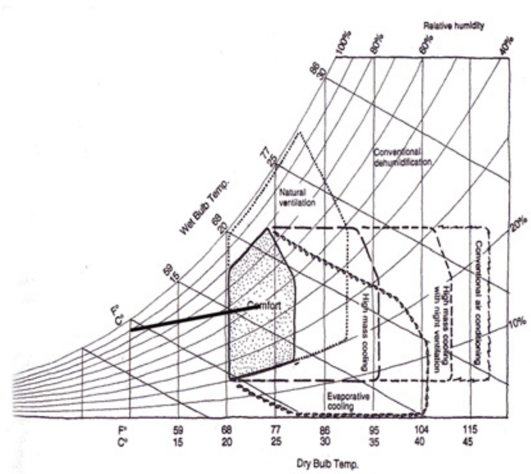

Fig. 5 – Psychrometric Chart

The heavy bar on the chart in Figure 5 represents the temperature and relative humidity range for the months of June and September in Eugene. Note that the right end of the bar does not extend out of the comfort zone, and the left end of the bar shows temperatures that are well below the comfort zone. These conditions are ideal for using cool night air to flush away heat that has accumulated in the building during the daytime.

1.4 Design Modifications per Guidelines

Based on early analysis, the original classroom plans for Southside Elementary were modified as shown in Figures 6 and 7. The common area in the center of the classrooms (not analyzed for daylighting or passive heating since it has no exterior walls) has been turned 90° so that the south-center classroom can nest between the other two without overlapping their southern walls. The stairwell has been turned so that its short wall faces south. South facing glazing is increased to provide daylight, view and direct gain (DG) solar collector area. Most of the remaining south wall area is a trombe wall (TW), further increasing the solar collector area and exposed mass in the room. A survey of the SSFs of different passive heating strategies indicates that water walls and trombe walls have superior performance in the Portland/Eugene climate (Balcomb).

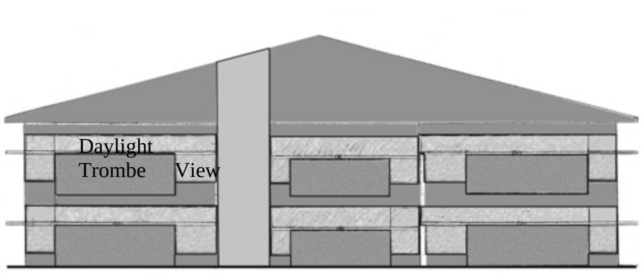

Fig. 6 – Elevation as modified

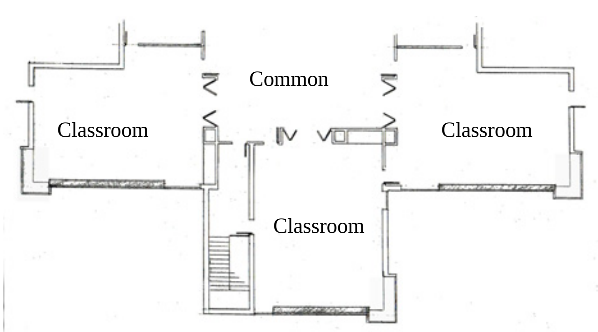

Fig. 7 – Plan as modified

2. DETAILED CALCULATIONS

Detailed calculations for both passive heating and cooling start with information about the building envelope. Details are provided in Figure 8.

Roof	R value
Air film	0.61
Roof system with metal trusses and R30 batts.	23.7
Air film	0.17
Total R	24.48
U value (1/R)	0.041
Wall	
Air film	.017
Brick veneer	0.88
Metal studs with R19 batts	7.1
5/8" gyp. Board	0.56
Air film	0.68
Total R	9.39
U value (1/R)	0.107
Assumption: No heat transfer between interior floors or walls since ΔT is zero.	
Slab: metal stud wall, uninsulated from edge to footer (interpolated value for 4852DD) 1.19 Btu/h °F ft.	
Other components	U value
Doors 45% glazed	0.56
Windows, double pane, no low e or argon	0.5
Trombe wall	0.22

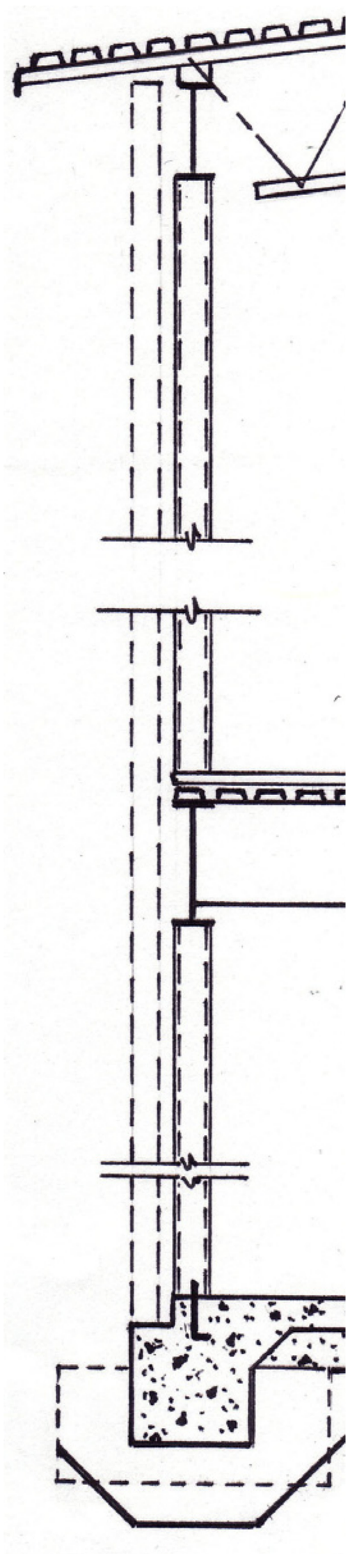

Fig. 8 – Building envelope details

2.1 Passive Heating

Load Collector Ratio is a method for calculating SSF with detailed information about envelope heat loss, building mass, solar collector area and floor area. The following table summarizes the areas and values for this calculation.

Floor area (ft^2)	1074
Direct gain thermal mass (ft^2)	1074
South facing glazing A_p (ft^2) includes DG and TW	436
DG glazing A (ft^2)	219
TW glazing A (ft^2)	217
UA_{ns} including opaque south wall (ft^2). Total UA excluding DG and TW areas.	591
UA opaque south wall	41
UA for the rest of the building	550
BLC=24xUA_{ns} (Btu/DD)	14182
LCR=BLC/A_p	33
SSF from MEEB 9th Table C.3	27
HLC – Heat loss criteria Btu/DDF ft^2	13.2
Note: recommended HLC for passively solar heated buildings in this climate region is 5.6	

Passive solar heating strategies rely on exposed mass to moderate temperatures in a space. In general, direct gain systems need a 3:1 ratio of mass area to glazing area. For the Southside classrooms, exposed concrete floor area to DG collector area is about 5:1, indicating that overheating should not be a problem. The trombe wall has its own associated mass.

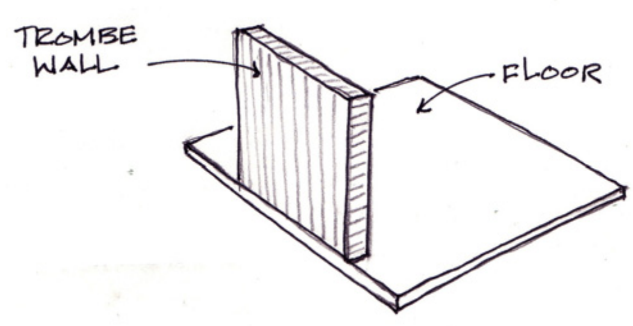

Fig. 9 – Mass for passive heating

2.2 Passive Cooling

Successful passive cooling with night ventilation of mass has two significant tests: the ability of the mass to absorb heat gains during the daytime, and the ability of the night flush to cool the mass sufficiently in preparation for the next day's heat.

Sources of heat gain	Btu/h ft^2
People and equipment	7.6
Electric lighting	1.6
Ventilation	5.6
South windows	5.3
West windows	1.7
Envelope	2.6

Heat gains vary during the day. For instance, the gain from people and equipment, electric lights and ventilation occur only during occupied hours. Gain from the west windows does not start until the afternoon. The 24 hour heat gain is calculated to be 194,717 Btu.

Even though all design guidelines indicated that the amount of exposed mass required for passive heating would also be adequate for passive cooling, detailed (hourly) calculations indicated that it was not. In fact, an extra 500 ft^2 of exposed mass, half the floor area, is required for successful cooling using night ventilation of mass.

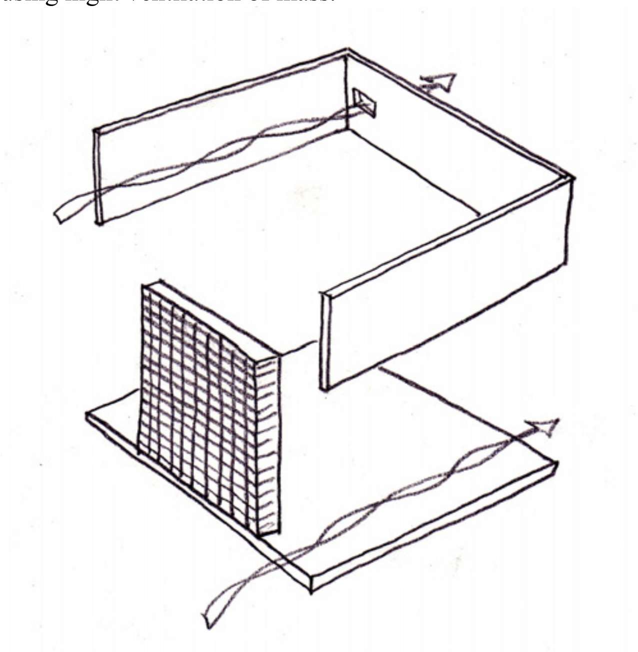

Fig. 10 – Mass for passive cooling

The recommended location for this extra mass is high on the interior walls. Lower wall area is obstructed with storage cubbies, display boards and marker boards. Space on the south wall available for mass is already a trombe wall. It is important for inlet and outlet areas to be positioned so that the cool night air flows across the mass. Fan assist for the 20 air changes per hour required to cool the mass in these classrooms at night is readily available from the variable air volume system that cools other parts of the building.

Also noteworthy in the cooling calculations is that actual temperatures for a statistically typical day in June and September were used instead of average temperatures for July and August when school is not in session. To cope with July and August temperatures, the ceiling would also have to be exposed mass. While this is structurally feasible, it adds to the first cost and is unnecessary for the foreseeable school calendar.

3. EXAMINING GUIDELINE ASSUMPTIONS

Comparing the design guidelines for passive heating with the detail calculations based on LCR shows a discrepancy in the SSF, 44 and 27 respectively. The question is why? The design guidelines assume an energy conserving Heat Loss Criteria (HLC) of 5.6. The actual for Southside Elementary classrooms turned out to be 13.2 in the LCR calculation. The windows are double pane, but they have no low e coating or argon between the glass layers. The walls and roof have metal framing members which significantly de-rate the R19 and R30 insulation (to R7.1 and R23.7). The concrete slab has no perimeter insulation. But the biggest culprit is ventilation air, which accounts for almost 70% of the heat loss. The space is densely populated with 25 students in each classroom, and the original LCR calculations were based on ventilating for a full population 24 hours a day, 365 days a year. One could easily argue that the building only needs to be ventilated when it is occupied. Changing the ventilation time to 7 hours a day for 180 school days reduces the ventilation load to 14% of the originally calculated requirement and improves the passive solar heating characteristics of the building as shown on the table below

	Ventilation 24x365	Ventilation 7x180
UA_{ns} (non-south envelope heat transfer times area)	591	244
BLC (building load coefficient)	14182	5860
HLC (heat loss criteria)	13.2	5.5
LCR (load collector ratio)	33	13
SSF (solar savings fraction)	27	40

An interesting 'back-of-the-napkin' calculation shows that turning the ventilation system off for 5.5 hours out of 24 over 365 days will save as much heat as doubling the insulation levels of the entire building envelope (minus the south glazing). This implies that recovering heat from the ventilation system should get high priority in any internal load dominated building (as compared to a low occupant-density, skin load dominated building).

In the winter, even though cold outside ventilation air has to be heated when it is brought into the building, body heat assists the process. In the summer, however, hot outside air has to be cooled, and body heat makes the cooling problem even more difficult. In fact, body heat and ventilation air account for two-thirds of the cooling load during occupied hours.

In winter and summer, however, it is exposed mass that is the great moderator of temperature. For heating, the mass of the exposed concrete floor plus the trombe wall was sufficient to keeping temperatures in a comfortable range. For cooling however, mass had to be added to the upper interior walls to soak up heat during the day and be flushed with cool outside air at night.

In winter, the calculated temperature swing inside is between 75°F and 85°F. " Because the Pacific Northwest is largely overcast in winter, this daily range typically will be less wide, but the ΔT solar will also be smaller. Thus, the average January day temperature indoors will be lower." (Stein and Reynolds, p. 276)

On summer days, the mass temperature range is expected to fluctuate between 54°F and 66.3°F while indoor air temperature should be between 57°F (8am) and 78.2°F (2pm). Calculated hourly temperatures for a summer day and night in June or September are shown in a table at the end of this paper.

4. LESSONS LEARNED

Determine whether the building in question is skin-load-dominated or internal-load-dominated. If it is skin-dominated, look carefully at the building envelope to minimize heat loss. If the building is internal-load dominated, look at the ventilation requirements and consider matching active ventilation to the occupied hours and think about a heat exchanger.

Consider low e, argon filled windows for winter gain, and be aware that the windows will have to be shaded to prevent overheating in summer.

Metal studs significantly de-rate any amount of insulation that you put in a wall.

The hybrid system of direct gain and unvented Trombe wall is a good combination where the morning sun can warm a space, and the Trombe wall heat is needed later.

Look out for self shading and for nearby buildings or trees that obstruct solar access in winter. Be grateful for any of these in summer.

Design guidelines are only as good as the assumptions (e.g., mass ratios and heat loss criteria). For passive cooling, it is still necessary to do detailed calculations.

Mass is your friend in winter, and it is your *best* friend in summer. For the purposes of maintaining stable temperatures in a room, it is hard to have too much mass.

Calculated 24 hour temperatures for classroom June/Sept				
Mass surface 1790 ft^2		Mass heat capacity 13803 Btu/°F		
Total volume 13425 ft^3				
Hour	Outside Air Temp °F	Indoor Temp °F	Warming Btu/h	Mass Temp °F
8a	57	57.0	24380	54.0
9a	61	69.4	24380	55.8
10a	64	71.2	24380	57.5
11a	68	72.9	24380	59.3
12p	69	74.7	24380	61.1
1p	72	76.5	24380	62.8
2p	74	78.2	24380	64.6
3p	74	67.5	4618	64.9
4p	74	67.8	4618	65.3
5p	73	68.2	4618	65.6
6p	70	68.5	4618	65.9
7p	65	67.7	2792	66.1
8p	62	67.9	2792	66.3

Night flush requires 20 air changes per hour.			
Daily cooling load 194,717 Btu (24 hr. heat gain)			
Hour	Outside Air Temp °F	Cooling Btu/h	Mass Temp °F
8p	62	Open bldg.	66.3
9p	60	22554	64.7
10p	58	23864	62.9
11p	57	21255	61.4
12a	55	22902	59.7
1a	54	20542	58.2
2a	53	18794	56.9
3a	53	13920	55.9
4a	51	17469	54.6
5a	51	12938	53.7
6a	50	13163	54.0
7a	53	3580	54.0
8a	57	Close bldg.	54.0

5. ACKNOWLEDGMENTS

Many thanks to Prof. John Reynolds for his valuable insights into the nature of passive systems and for teaching these classes.

6. REFERENCES

(1) ***Mechanical and Electrical Equipment for Buildings, 9th Edition***, Benjamin Stein and John S. Reynolds, John Wiley & Sons, Inc., 2000

(2) ***Passive Solar Heating Analysis***, J. Douglas Balcomb, Robert W. Jones, Robert Dl McFarland and William Ol Wray, Los Alamos National Laboratory, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1984.