High-Performance Building at Extreme Climate Locations - Comparative Analysis of Exterior Wall Assemblies Coupled With Thermal Mass at Case Study Buildings in Greenland and in Arizona

Vidar Lerum

University of Illinois at Urbana-Champaign

Follow this and additional works at: http://docs.lib.purdue.edu/ihpbc

http://docs.lib.purdue.edu/ihpbc/53

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html
**High-Performance Building at Extreme Climate Locations - Comparative Analysis of Exterior Wall Assemblies Coupled With Thermal Mass at Case Study Buildings in Greenland and in Arizona**

Vidar LERUM

University of Illinois at Urbana Champaign, School of Architecture, Champaign, Illinois, USA

Phone 217-244-1799, Fax 217-244-2900, E-mail vidar@illinois.edu

**ABSTRACT**

Two buildings, located in Nuuk, Greenland and in Phoenix, Arizona, are under investigation. Typical cross sections of the two buildings show striking similarities in the configuration of the East and West facing facades and their relationship to thick concrete walls exposed to the interior. Within the paradigm of the conceptually similar exterior wall to interior thermal mass configuration, there are distinct differences in the exterior wall detailing that reflect the extreme, opposite climate conditions.

At the Greenland Nature Center, designed by KHR Architects, the exterior wall assembly is a thick, super insulated framed wall with a narrow band of operable windows. The spaces between the exterior wall and the thermal mass wall are for the most part used as individual offices and laboratories for the researchers. In this particular configuration, the mass wall contributes to maintain a radiant symmetry of interior surface temperatures and therefore assists in keeping the operative temperature steadily within the comfort zone.

At the Phoenix Public Library, designed by Will Bruder, the exterior wall assembly consists of a perforated, corrugated copper skin that effectively shades a thick uninsulated concrete wall. The spaces between the exterior skin and the thermal mass wall are for the most part used as unconditioned spaces for fire escape stairs, air handling units, and storage rooms. These spaces are what the architect calls the “saddle bags of service”.

**1. INTRODUCTION**

This paper presents findings from a comparative analysis of the coupling of exterior wall assemblies with high mass interior walls will be. The two case study buildings under investigation are:

- Greenland Nature Institute office and laboratory building located in Nuuk, Greenland
- Phoenix Public Library located in Phoenix, Arizona

Typical cross sections of the two buildings show striking similarities in the configuration of the East and West facing facades and their relationship to thick concrete walls exposed to the interior. Within the paradigm of the conceptually similar exterior wall to interior thermal mass configuration, there are distinct differences in the exterior wall detailing that reflect the extreme, opposite climate conditions.

The author conducted extensive research at the building sites (Lerum, 2008). At the Phoenix location, temperature data were collected over a twelve month period, using Hobo data loggers. At the Nuuk location, data were collected over a few days in April. Detailed accounts of building energy use for both buildings were provided by the building owners, as monthly values.
2. METHODS

The method of analysis presented here is similar to a method that the author developed for teaching high-performance building design in architectural design studios. The method, named “the 32 variations”, takes a generic cross section of a building and uses it to generate 32 iterations reflecting the climate conditions day and night, during four seasons, in four climate zones (2x4x4=32). This exercise is designed to heighten the awareness of how a high-performance building design can be adapted to the characteristics of the local climate in order to take advantage of “free energies” in the environment and to increase energy efficiency.

Figure 1: Typical sectional diagram

Figure 1 shows a generic cross section representing the actual cross sections of the two buildings under investigation. Two thick, structural and thermal mass concrete walls define a central space by protecting it’s east and west facing boundaries. The building then opens up to the south and the north. Conceptually, saddlebags are hung on the outside of the mass walls, creating two additional bands of usable space. Within the conceptual boundaries of this scheme, the actual programing, construction, and conditioning of the saddlebag space take on different characteristics in the two buildings - in response to place.

3. CLIMATE

3.1 Nuuk Climate
The town of Nuuk is located at 64 degrees Northern latitude on the West coast of Greenland. The coastal influence makes the temperatures less extreme as compared to inland locations, but Nuuk is still a very cold place with average outside air temperatures below freezing for six or seven months a year.

While the number of heating degree-days in a typical meteorological year is very high, the number of cooling degree-days is zero. Theoretically, there is a need for space heating all year, but this does not necessarily mean that a well-insulated building with a fair amount of windows will not overheat. It is still safe to conclude, however, that heat loss through conduction – and through ventilation – is a major concern. The need for protection against the cold is enforced by the generally high wind exposure at the site.

3.2 Phoenix Climate
Phoenix is located in the Valley of the Sun at the northern edge of the Sonoran desert. The climate is hot and dry with average summer day temperatures reaching 40-45 °C. The summer design day temperatures extracted from a typical meteorological year weather file are: dry bulb temperature 41.7 °C, with a wet bulb temperature of 21 °C. An average winter day sees dry bulb temperatures in the range of 7-18 °C, with wet bulb temperatures ranging from 4 to 9 °C.
An average early spring day in March sees dry bulb temperatures from 13 to 24 °C. This is a time of year when a high mass building can float comfortably without applying any energy for heating or cooling.

4. DESIGN CONCEPT

4.1 Nuuk Design Concept
Ove Neumann, the project architect at KHR, outlined five major concepts that drove the schematic design:

- energy-efficiency by introducing passive and active solar design principles
- selecting sustainable materials
- minimizing water usage
- a comprehensive approach to indoor air quality
- enter carefully into the sensitive arctic environment

These five principles of sustainable design were carried forward into the successive phases of the project. One exception was the idea to use active solar technologies (solar collectors and/or photovoltaic panels), an idea that was dropped from the menu as it met stiff competition from artificially low cost electricity produced in a recently completed hydro electric power plant. The facades of the building is still proportioned and detailed in a way that solar panels could be applied (on east and west facades) at a later stage.

![Figure 2: The Seal (left) and the Mesa (right) as conceptual design drivers](image)

4.2 Phoenix: Design Concept
According to the architect Will Bruder, the shape and form of the Phoenix Public Library is in essence a box with its long axis oriented North-South, which causes the east and west sides to be exposed to high solar gains: “As part of the energy diagram, we decided to take the box and move all the core functions of the box that would normally be around the elevators and the main stair; the restrooms, the mechanical support; the janitor’s closet; all those things you see in any building up and down the street - we pushed them outside the box. They live in the saddlebags of service.”

5. SECTIONAL ADAPTATION

5.1 Nuuk: Sectional Adaptation
Sitting on a high point, the Greenland Nature Center hugs the landscape and protects itself from the winds much like the streamlined form of a seal. The natural ventilation system is integrated with the architecture in a straightforward
way, expressed by the hoods of the ventilators projecting out through the building skin. High thermal mass, embedded in structural concrete walls, is acting as heat storage inside the building.

The exterior wall assembly is a thick, super insulated framed wall with a narrow band of operable windows. The spaces between the exterior wall and the thermal mass wall are for the most part used as individual offices and laboratories for the researchers (Figure 3). In this particular configuration, the mass wall contributes to maintain radiant symmetry of interior surface temperatures and therefore assists in keeping the operative temperature steadily within the comfort zone.

Two 300 mm thick concrete walls flank the central space (the “panoptic room”) while the exterior walls are highly insulated, light weight components. The panoptic room opens up to the landscape on the south side through a tall, six meters wide slanting glass wall.

![Figure 3: Sectional adaptation at Nuuk (left) and Phoenix (right)](image)

5.2 Phoenix: Sectional Adaptation
At the Phoenix Public Library, designed by Will Bruder, the exterior wall assembly consists of a perforated, corrugated copper skin that effectively shades a 300 mm thick uninsulated concrete wall. The spaces between the exterior skin and the thermal mass wall are for the most part unconditioned spaces used for fire escape stairs, air handling rooms, storage rooms, and the like (Figure 3). These spaces are what the architect call the “saddle bags of service”.

6. ORIENTATION

6.1 Nuuk: Orientation
The first major design move was to place the building as an elongated form along the prevailing wind directions. The building was aligned with the north-south axis and rotated 23 degrees to the east of north. The building form was then tapered both in plan and in section to resemble the streamlined, fluid dynamic shape of a seal, the symbolic sea mammal of the arctic (Figure 4).

With constant average wind speeds of twelve meters or more over sustained periods of time, the wind will frequently create shifting negative and positive pressure on the roof and the sides of the building. The streamlined form does not prevent the building from needing to be totally closed up in windy weather.
6.2 Phoenix: Orientation
The Burton Barr Central Library is located on Grand Avenue in Phoenix at 33 degrees North and 112 degrees west. The five-story building is aligned with the North-South axis (Figure 4). In an interview with the author, the architect Will Bruder elaborated on how the design responds to location and climate:

“When we started doing this building, we wanted to design a building that literally would not fit anywhere else, a building that was site specific to this latitude and this set of conditions and climate that you could not take it away. If you see a slide of this building somewhere and it doesn’t have the name Phoenix underneath it, if you have knowledge of what a good green building would be, there would be all kinds of clues that would tell you at least the latitude, and maybe the climate and why it was the way it was. As a detective, you could play Sherlock Holmes and you could nail the building.”

7. MATERIALS

7.1 Nuuk: Materials
The three major construction materials introduced in addition to glass were the concrete walls and floors in the interior, the solid hardwood floors in the offices, and the Canadian cedar cladding on the exterior (Figure 5). Extruded aluminum profiles are used in the window frames, which require no paint. These choices were made in order to minimize embedded energy from transport of building components (concrete made from aggregates and water found locally) and to avoid toxic gasses (untreated wood) and static electricity (waxed wood floors).
7.2 Phoenix: Materials
As for the Nuuk building, the choice of materials for the Phoenix Public Library also responds to location, climate, and culture. As expressed by the architect Will Bruder:

“We looked at primitive cultures that built in stone and we looked at the more primitive, but recent cultures of wonderful old adobes off the main street of Phoenix and we remembered going to a dinner party in the middle of summer and how the thermal swing was working with it. As we looked at this building, and started to understand the code implications of this building, the cost implications, the construct-ability implications, we came across the idea that it was going to really want to be made out of concrete (Figure 5). The skin is copper. It is the grain elevator silo. That wall is 90% solid copper, 10% open. We have the perforated skin so you can see through the transparency at night. It’s very dramatic.”

8. VITAL SIGNS

8.1 Nuuk: Vital Signs
A wind meter had been installed on the roof of the building from the very start. This device would prevent the clerestory windows from opening during strong winds. In fair weather, the windows would open automatically to allow for the air inside the central space to escape through natural ventilation. As the wind wore down the ball bearings, the wind meter malfunctioned and was not repaired or replaced. The windows are now operated manually, which means that they are generally closed during night time hours and opened only during fair weather when there seems to be a demand for more fresh air inside.

![Figure 6: Air movement and stagnation during smoke test at Nuuk](image)

A smoke test involved an office on the main floor, on the west side of the tall central space. A flow of cold air could be felt falling down from the open clerestory windows. These windows near the roof did not only let the hot air out, but also introduced fresh, cold air into the central space. Since the air temperature in the office now was higher than the air in the central space, the air exchange through the open door followed a pattern where warmer air from the office now escaped through the upper half of the door opening, while colder fresh air from the central space seemed to be replenishing the office through the lower part of the opening (Figure 6).

8.2 Phoenix: Vital Signs
March 16 was the coldest day in March 2005 and therefore can be seen as a typical early spring day in Phoenix. While the average outside temperatures (on the saddle bag side) are below the indoor temperatures, the maximum outside air temperature is equal to the indoor air temperature (on the corridor side) at the peak around 1800 hours. The minimum outside air temperature is about 12 °C at 0700 hours. The core temperature of the concrete wall is fairly stable and fluctuates between 19 and 21 °C. The greatest temperature difference between the core and the inside air is approximately 4 °K (Figure 7).
July 15 was the warmest day in July 2005 and can therefore be seen as a typical summer day in Phoenix. While the average outside temperatures (on the saddle bag side) are well above the indoor temperatures, the minimum outside air temperature approaches the indoor air temperature (on the corridor side) at around 0700 hours. The maximum outside air temperature (inside the air handler room) reaches 37.7 °C at 1800 hours. The core temperature of the concrete wall is fairly stable and fluctuates between 28.5 and 29 °C. The greatest temperature difference between the core and the inside air is approximately 2.2 °K (Figure 7).

9. ENERGY PERFORMANCE

9.1 Nuuk: Energy Performance

Records of the monthly energy use were made available for four years of operation since year 2001. The records show that the building checks in at a total specific energy use of 152 - 198 kWh/m2-Y for the years 2001 - 2004, which compares nicely to a proposed standard of 160 kWh/m2-Y for energy-efficient office buildings in arctic regions. The annual heating energy use for 2001-2004, by month, is compared to the monthly heating degree day data in a typical meteorological year. The energy use graphs for these four years are quite consistent (Figure 8). The energy graphs show a greater difference from winter (January) to summer (July) than the HDD graph, which indicate that the building does make use of solar radiation for space heating in the summer.

The energy use for space heating, including fans for the mechanical portion of the ventilation system and motors for the heat recovery system (mechanical ventilation only), represents the largest portion of the total energy use. Energy used for lights and plug loads are quite low. There is reason to conclude that the natural ventilation system makes a significant contribution to the energy-efficiency of the building. Simply because it functions quite poorly when it comes to flushing fresh air through the offices, the resulting low levels of outside air means that less energy is used to heat that air. A study by the author (Lerum, 1996) shows that limiting the outside airflow rate is the primary energy-efficiency measure in office buildings at high latitudes.
9.2 Phoenix: Energy Performance

Historical data on annual energy use was provided by the City of Phoenix. The graph shows monthly values in kWh/m² for the total energy used, with breakdowns into electricity and natural gas. Natural gas is mainly used for cooling, since the building is equipped with gas fired absorption chillers. Gas is also used for the boilers that deliver hot water for lavatories and for heating. The graph is based on actual energy use data for 2004 and the numbers were converted into SI units for comparison (Figure 8). The total specific energy use average 225 kWh/m²-Y, based on data for 2004 (232 kWh/m²-Y) and 2005 (221 kWh/m²-Y). This is quite good for a building that is more than ten years old, considering the extended hours of operation for a central library and the severe desert climate. The number corresponds to the actual annual energy use for education buildings in the USA, which one can assume have a different load profile and significantly fewer hours of operation than the Phoenix Public Library.

The relative significance of air conditioning as a major end use is visualized by the graph. While the use of electricity (lights, plug loads, fans, elevators) is relative constant throughout the entire year, the use of natural gas follows a curve that is comparable to the monthly distribution of cooling degree-days.

10. CONCLUSION

The findings presented in this paper support the notion that high performance building designs need to specifically address the environmental conditions at their location. While one shoe does not fit all high performance buildings, there is still room for a design approach that originates from a generic cross section. This might be true for the building plan as well, although that hypothesis is not tested here. The conclusion from this investigation is that there is great creative opportunity in testing and tweaking cross sections for various climate locations in an iterative process of developing high performance building designs.

REFERENCES


ACKNOWLEDGEMENT

The on site research that forms the base for this paper could not have been conducted without the help and encouragement from Architects Ove Neumann and Peter Barfoed at Nuuk, Greenland, Klaus H. Nygaard, Director of the Geenland Nature Institute, Architect Will Bruder in Phoenix, Arizona, and Rosemary Nelson, former Head Librarian at the Phoenix Public Library.