

## **A Thermal Balance Report**

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## **The Carpenter Center for Visual Arts**

Architect: Le Corbusier, 1960-1963

24 Quincy Street

Cambridge, MA 02138

## I. Qi: Internal heat gain/loss

The Carpenter Center is used duly as Harvard's Graduate School of Design as well as a screening area for films. As such, there are several secondary heat sources from a myriad appliances with high heat gain such as kilns and glass blowing apparatuses, as well as the human traffic of about 200 people during the day for classes and bit less during the night for film screenings and continuing education classes.

For primary heating and cooling, there are noticeable air ducts and intake vents in the basement as well as general heating and cooling appliances.

Therefore, we estimate there to be 200 people during the day at 70W each, and 150 people at night, about 200 lamps running at 85W each, and tools in the machine shop running at about 25kWh/day, presumably not in the evening. And finally computers which run at about 1-2 kW for about 8 hours a day, most likely in the morning to afternoon period. In sum, we get that there is 647000W during the day and 27500W during the evening.

## II. Qc: Conduction heat gain/loss

The building is made entirely of flat or curved reinforced concrete and glass,<sup>1</sup> and there is no visible insulation. Moreover, "the facades are of concrete poured into standard steel forms and for the largest surfaces, eventually, or Isorel or of plywood or wooden strips for the curved surfaces."<sup>2</sup>

We estimate there to be a fairly constant temperature inside the building at about 20°C. For purposes of this analysis, morning is defined as 7am to 10am, midday as 11am to 2pm, afternoon as 3pm to 5pm, and evening as after 6pm to 10pm. The temperature outside building for 14 March is approximately:

Interval	Temperature (°C)	$\Delta T = T_o - T_i$ (°C)
Morning	0	20
Midday	4.44	15.66
Afternoon	5.55	14.45
Evening	2.77	17.23

Using the equation

$$Q_c = UA\Delta T$$

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<sup>1</sup> Found both by inspection and a study of Corbusier's basic theories for modern architecture.

<sup>2</sup> Sekler, Eduard and William Curtis. *Le Corbusier at Work*. Harvard University Press: Cambridge, Massachusetts, 1978.

with a U-conductivity value for concrete to be  $3.31 \text{ W/m}^2 \cdot \text{K}$  and  $2.44 \text{ W/m}^2 \cdot \text{K}$  for double pane glass,<sup>3</sup> we can calculate  $Q_c$ . The surface area is found roughly by looking at elevations of all the facades of the building<sup>4</sup>, and is calculated to be about  $1665 \text{ m}^2$  of glass and  $8135 \text{ m}^2$  of concrete. Therefore, we calculate  $Q_c$  to be:

<b>Interval</b>	<b>Qc Concrete (W)</b>	<b>Qc Glass (W)</b>	<b>Qc Total (W)</b>
<b>Morning</b>	538537	81252	619789
<b>Midday</b>	421674	63620	485294
<b>Afternoon</b>	389093	58704	447797
<b>Evening</b>	463950	69999	533949

Keep in mind that these values are all negative.

### III. Qs: Solar heat gain

We begin calculating the solar exposure by dividing the building facade into five surfaces based on the building plan and orientation: south, southwest, northwest, northeast, and southeast. For convenience, we will treat the curved part of the 'south' facade separately, as it's glazing is actually oriented due south. The exterior wall faces southwest, and the other three walls are taken to point northwest, northeast, and southeast. We make the approximation that nearby buildings block all direct sunlight to the lower three floors, while the upper two have full exposure. We also neglect solar gain through the opaque wall sections. Dimensions of glazed surfaces are taken from section drawings as follows:

<b>Area (m<sup>2</sup>)</b>	<b>exposed</b>	<b>shaded</b>
<b>S</b>	175	
<b>SW</b>	0	55
<b>NW</b>	385	150
<b>NE</b>	0	205
<b>SE</b>	380	315

Diffuse radiation is calculated to comprise .65 times total solar radiation.<sup>5</sup> Shaded windows are taken to see the sky between 45 degrees and 90 degrees altitude. We assume that on a clear day that they receive .32 times the radiation reaching a horizontal surface. The azimuth is thus irrelevant, so the important number is the total

<sup>3</sup> These numbers were calculated from the  $\text{W/m}^2 \cdot \text{K}$  values from Szokolay multiplied by the thickness of the concrete (20cm) and glass (1cm)

<sup>4</sup> Sekler.

<sup>5</sup> Steven V. Szokolay. *Introduction to Architectural Science: The Basis of Sustainable Design*. Amsterdam: Architectural Press, 2004.

shaded window area, 725 m<sup>2</sup>. The solar radiation values for February 21<sup>6</sup>, summed over the four intervals of the day are as follows:

<b>21 Feb:</b>	<b>morning</b>	<b>midday</b>	<b>afternoon</b>
<b>S</b>	1475	2857	835
<b>SW</b>	214	1306	94
<b>NW</b>	156	287	91
<b>NE</b>	366	289	299
<b>SE</b>	2328	2693	1551
<b>horiz</b>	649	2093	199

Both the glass blocks on the west facade and the heavy panes of sheet glass are taken to be ASHRAE's 6.4mm double pane glazing. The SHGC is taken to be 0.7 for exposed glass, 0.6 for glazing only exposed to diffuse light. Multiplying out these data gives the solar gains for each period of time. After 5pm there is negligible sunlight, and so no solar gain.

Thus, Q<sub>s</sub> is calculated to be:

<b>Interval</b>	<b>(Wh)</b>	<b>Q<sub>s</sub> Average (W)</b>
<b>Morning</b>	1151000	287750
<b>Midday</b>	1539000	384750
<b>Afternoon</b>	700000	233333

#### **IV. Q<sub>v</sub>: Ventilation heat gain/loss**

The windows in the Carpenter Center are fixed glass “sealed in concrete,”<sup>7</sup> therefore they do not open and there is no heat loss due to airflow. There are *aérateurs* at each window for ventilation in the summer, but in mid-March, one can assume all of them are closed. In this case, almost all airflow is through the two main entrances on the first floor.

The volume of the first floor space is approximately 11,530 cubic meters, and the basement is about the same size. We don't need to consider the other four floors because doors seal the stairway and block free airflow above the first floor.

Assuming average incidental air renewal is between .5 and 3, we can estimate the air renewal as a result of people opening doors from the morning to afternoon to be about

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<sup>6</sup> taken from ASHRAE

<sup>7</sup> Sekler.

2 per hour, dropping to .5 per hour during the evening. Using the given equations, and the aforementioned table on temperature,

$$qv = 1200(\text{J}/\text{m}^3 \cdot \text{K}) * N \quad (1)$$

$$Q = qv * \Delta T \quad (2)$$

we obtain the following values for Qv:

<b>Interval</b>	<b>qv (1)</b>	<b>Q<sub>v</sub> (W) (2)</b>
<b>Morning</b>	15,373	307460
<b>Midday</b>	15,373	240741
<b>Afternoon</b>	15,373	222140
<b>Evening</b>	3843	66215

#### V. Q<sub>e</sub>: Evaporative heat loss

This is assumed to be zero.

#### VI. Thermal equilibrium

We are assuming that the building is at a level of thermal balance, where sum of total heat flow into and out of building is zero. To verify this by calculation,

$$\Delta Q_{\text{total}} = Q_i + (-) Q_c + Q_s + (-) Q_v + Q_e = 0 \text{ at thermal equilibrium}$$

Using the previously calculated values:

$$\text{Morning: } \Delta Q_{\text{total}} = 647000\text{W} - 619789\text{W} + 287750\text{W} - 307460\text{W} + 0 = 7501\text{W}$$

$$\text{Midday: } \Delta Q_{\text{total}} = 647000\text{W} - 485294\text{W} + 384750\text{W} - 240741\text{W} + 0 = 305715\text{W}$$

$$\text{Afternoon: } \Delta Q_{\text{total}} = 647000\text{W} - 447707\text{W} + 233333\text{W} - 222140\text{W} + 0 = 210486\text{W}$$

$$\text{Evening: } \Delta Q_{\text{total}} = 647000\text{W} - 533949\text{W} + 0\text{kW} - 66215\text{W} + 0 = 46836\text{W}$$

Keep in mind that all these values are very small, especially since most of the heating and cooling apparatuses were not taken into account into Q<sub>i</sub>.

Most of the data has been very roughly estimated, though the general investigation process was very well thought out. The most inaccurate values are most likely for Q<sub>i</sub> since there is no accurate way to approximate the primary and secondary heat gains/losses without the use of more in depth information that was not available to us. However, taking into account the several factors of thermal balance, we feel as though we have introduced a fair overview of the thermal conditions of the Carpenter Center.

## Works Cited

The Carpenter Center for the Visual Arts, on the Web at  
<http://www.archlab.tuwien.ac.at/~carpent/carpenter/carpenter.html> as of March 2006.

Sekler, Eduard F. and William Curtis. *Le Corbusier at work: the genesis of the Carpenter Center for the Visual Arts*. Cambridge: Harvard University Press, 1978.

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