# A Case Study of the Thermal Performance of Two Glazed Atria and Their Open Lightwell Alternatives in an Office Building

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## ABSTRACT

This paper presents a case study approach to the investigation of the thermal performance of two glazed atria and their open lightwell alternatives in an office building in Finland.

The case study building has two storys of office space, which are daylighted through two central atria in the interior zone. Both of the atria are glazed in order to reduce the heat loss of the external envelope of the building and increase the occupancy potential of the central courtyards. The energy performance of the glazed atria, together with the effects of glazing on the energy use of the building, is evaluated by a thermal simulation model. In addition, the thermal behavior of the glazed atria as well as the energy performance of the building is evaluated by long-term measurements.

The study shows an advantage of heat loss savings of 15% and 17% for the glazed atria over the corresponding open lightwell envelopes during the heating season, when the glazed atria are heated up to 62.6°F (17°C) and the target temperature in the adjacent office space is 71.6°F (22°C). It also shows a disadvantage of heat gain increase of 5% and 7% for the glazed atria over the open lightwell envelopes during the cooling season, when the glazed atria are naturally ventilated and the target temperature in the adjacent office space is 77°F (25°C).


## INTRODUCTION

The code of building regulations in Finland sets requirements for daylighting of working spaces. Lightwells have been architectural solutions for daylighting of the interior of deep plan buildings. New building technologies and materials, together with concerns over energy efficiency of buildings, have developed the idea of glazing of the lightwells in order to reduce the heat loss of lightwell envelopes and increase the occupancy potential of courtyards.

The design trend of atrium building has been growing rapidly during 1980s in the Nordic countries. Many of existing lightwells and open courtyards are converted or are being considered for conversion into atria. The growing trend has activated many national and international research projects and case studies of atrium buildings.

The aim of this case study was to evaluate the thermal performance of two central atria (glazed lightwells) in an office building in Finland. The energy performance of the atria is evaluated and compared with the heat loss and heat gain effects of the corresponding open lightwell envelopes on the adjacent office space by a thermal simulation model. In addition, the thermal behavior of the atria as well as the energy performance of the whole building are evaluated by long-term measurements. The simulation results are validated and enhanced by measured data.

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## THE CASE STUDY BUILDING

### Site and Location

The building is located on a flat site in a tight commercial center of 3 to 7 level buildings of the city of Vantaa, which is about 9 miles (15 km) northwest of Helsinki. The location and monthly averages of global irradiation on horizontal and external temperature are shown in Figure 1.

### Building Form and Applications

It is a 3-story cubic building, 199.4 ft (60.8 m) long, 175.8 ft (53.6 m) wide, and 37.4 ft (11.4 m) high with a total gross volume of 1,381,625 $ft^3$ (39,100 $m^3$). Two atria of 3939.7 $ft^2$ (366 $m^2$) each are located symmetrically in two centers of the building. One of the atria is on the ground floor level with a height of 42.6 ft (13 m) and a volume ratio (atrium/total) of 0.12. This atrium has a south-facing skylight (SFA) and it functions as a transitory to the outside. The other atrium is on the first level with a height of 29.5 ft (9 m) and a volume ratio of 0.09. Its skylight is facing north (NFA) and it is used for internal circulation. Two storys of office space are wrapped around the atria. The atria are used as plant rooms and they provide daylight to the adjacent offices. The ground floor of the building is used for public and commercial services. The basement of the building is used for shelters, storage, hobby and social spaces, and technical rooms. The attic space on the third level between two atria is an executive space with a conference room, dining room, kitchen, services, and two saunas. The building form is shown in Figure 2.

### Construction

The building has a reinforced concrete frame with facing brick finish. The exterior walls in the perimeter zone of the building include 0.46 ft (140 mm) mineral wool and the windows are triple-glazed extract-air windows in offices. Elsewhere they are normal triple-glazed windows. The intermediate boundaries of atria are uninsulated brick walls with single-glazed windows. The skylights (glazed roof) of atria, 4305.7 $ft^2$ (400 $m^2$) each, are made of three-pane translucent polycarbonate panels, 0.20 ft x 0.29 ft (60 mm x 88 mm) of 19.7 ft (6 m) long with an average inclination of 17° from horizontal. The vertical parts of the external envelope on the top of the atria facing east and west are glazed by clear triple-glazed window elements, some of which function as automatic air gates for natural ventilation in summertime. Others are designed for fire safety and smoke management, which are controlled automatically by fire and smoke indicators. The floor slabs are hollow concrete and they are used for ducting of supply and extract air of the offices. The building construction is shown in Figure 3.

### Heating, Cooling, and Ventilating

The building is connected to a district heating network. The air-conditioning system of the offices has two zones. One serves the south and west facades and adjacent spaces to the atria and is equipped with both cooling and heating capabilities. The other zone, which serves the north and east facades, is equipped with heating capabilities only. In addition, there are split air-conditioning units in the computer suite, the text editing unit, and the copying unit. The attic space between the atria as well as the spaces for commercial services on the ground floor are equipped with separate air-conditioning units. The atria are heated by separate air-handling units and temperature in the atria is controlled by each one's thermostat. In the summertime the atria are naturally ventilated by openings which are controlled by the thermostat of each atrium. During this period, the air-handling units in the atria are stopped in order to enlarge the thermal stratification and optimize the efficiency of the natural ventilation. The temperature control strategy of the atria is shown in Figure 4. A liquid circulation system using an ethylene glycol and water mixture is used as an extract-air heat recovery unit. In addition the excess heat from the refrigeration systems of the commercial spaces as well as the condensing heat of the cooling units are used for space heating.

### Lighting

The atria provide daylight in the adjacent spaces and windows provide daylight in the perimeter zone. In addition, an indirect lighting system which uses 150 W metal halide lamps was chosen for high color rendition, high efficiency, and long lifetime. Lights are controlled manually.

## EVALUATION METHODS

The aim of this study was to evaluate the thermal behavior of the atria and their energy-saving potential as well as the amenity values and building cost. Thermal behavior of the atria is evaluated by monitoring the building and long-term measurements.

A thermal simulation model is used for evaluation of the energy-use and energy-saving potential of the atria in comparison to the heat loss and heat gain of the corresponding open lightwell envelopes as the references. The construction of the envelopes of the alternative open lightwells is assumed to be the same as the exterior wall construction of the building with triple-glazed windows.

The amenity values are evaluated by interviewing the building users and owners. Building cost is evaluated due to the actual construction contracts.

### Monitoring of the Building

The monitoring of the building was planned in the early stages of the construction project in order to ensure the required instrumentation level. The aim of monitoring was to provide measured data for evaluation of the thermal performance of the atria and the energy performance of the whole building as well as the required data for evaluation and validation of the simulation model. Monitoring of the atria was planned for measurements of the following:

- thermal stratification in each atrium
- surface temperatures in each atrium
- supply air temperature in each atrium
- heating power demand of each atrium
- heating energy use of each atrium
- global solar radiation penetrating the skylight in each atrium
- global solar radiation outside (horizontal)
- outdoor temperature
- air change and infiltration rates in each atrium.

A data acquisition system (DAS) was used for the above-mentioned measurements with a record interval of 5 minutes. Thermoelements (T-type) were used for temperature measurements. The sensors were protected against radiation. Air change and infiltration rates were measured by rate of decay method with a record interval of 60 seconds. The accuracy of the temperature sensors was 0.2°F (0.1°C), the same as for the DAS. The accuracy of the instrument for measurement of the tracer gas concentration was 0.1 ppm. The measured data were transmmited to a microcomputer for further analysis. In addition the whole building was monitored for measurements of the following:

- supplied district heat to the building
- energy used for space heating (separately for different units)
- energy used for domestic hot water (separately for different spaces)
- supplied electricity to the building
- electricity used in different spaces
- electricity used for lighting (office space).

These data were registered from the instrument indicators manually with an interval of one week (in some cases one day) and analyzed by a microcomputer.

### Thermal Simulation of the Atria

The Model. Evaluation of the thermal performance of the atria was carried out by a thermal simulation model. The model was developed (Hejazi-Hashemi 1987) based on the transfer function method using precalculated weighting factors (PWF). It is a single-zone model (one-temperature zone) for hour-by-hour calculations. Heat flows of external envelope (walls and fenestration) are calculated by iteration. Optical properties of the fenestration and external sun shading are calculated due to the sun position at each hour. Infiltration rate is calculated due to the stack and wind effects based on ambient factors and construction looseness as well as the unbalancement of the mechanical ventilation. Air change rate between the enclosed space of the atrium and the adjacent space is given as input data (measured data). Load components are calculated separately using transfer function coefficients (PWF). Space temperature is calculated by iteration method.

The Cases. The objective of the thermal simulation is to evaluate the effects of glazing of open lightwells on the heat loss and heat gain of lightwell envelopes under the circumstances of the case study building. The simulated cases are:

-- two atria (glazed lightwells) of the case study building
— the same atria assumed to be uncovered (open lightwells).

The simulated atria are heated up to 62.6°F (17°C) during the heating season, when the target temperature in the adjacent spaces is 71.6°F (22°C). The extract heat from the adjacent spaces to the atria is calculated due to the transient heat flows and the air change rate (measured data) between the enclosed spaces of atria and the adjacent spaces. The air change rates between the spaces are estimated to be 0.1 changes per hour during the working hours and 0.2 changes per hour at the rest of the time. The extract heat of adjacent spaces together with the heating energy used by the heating coils (air-handling units) of the atria are considered as the heating energy use of the atria. The extract heat from the atria to the adjacent spaces during the heating periods when the atria function as heat sources (early spring and fall) is subtracted from the sum of the heating energy use of the atria.

During the cooling season the simulated atria are naturally ventilated by openings which are controlled by thermostats, but not cooled. During this period the heat gains of the adjacent spaces through the atria are considered as cooling energy loss of the atria. The target temperature in the adjacent spaces is assumed to be 77°F (25°C) during this period.

The corresponding open lightwells with standard insulated exterior walls and triple-glazed windows are simulated due to the same adjacent space conditions as the atria. The heat loss and gain of the lightwell envelopes are considered as the heating and cooling energy loss of the lightwell, which are comparable to the heating energy use and cooling energy loss of the atria (effects on the adjacent spaces).

## EVALUATION RESULTS

The most significant evaluation results are presented in this section. The evaluation results of two atria (SFA and NFA) are reduced to only one of them when they are indicating similar patterns.

### Monitoring Results

Atrium Temperature. Temperature measurement results show that the atria warm up mainly by the extract heat from the adjacent spaces and solar heat gains. The temperature difference between the unheated atria and outdoor varies between 20° and 25°F (11° and 14°C) during a long heating season. This is seen in Figure 5, which shows the temperatures in three different heights of the atrium with a south-facing skylight (SFA) together with outdoor and supply air temperatures in a typical day of this period. The supply air (recirculating and fresh air) temperature is slightly lower than atrium temperature because it consists of 9% unheated outdoor air. At the same time the atrium with a north-facing skylight (NFA) warms up even more (see Figure 6), as the supply air in this atrium consists much less fresh air rate (1%).

The temperature control in the atria during the heating period is based on a simple on/off system which starts heating of the atrium supply air (circulating hot water in the coil of the air-handling unit) as the temperature in the occupation zone drops below the thermostat setpoint. Correspondingly the heating is stopped (coil is not heated, but the fan runs) as the atrium temperature rises over the setpoint. This is shown in Figure 7, which illustrates the instability (saw-tooth) of atrium temperature.

Summertime temperature measurements show a high degree of thermal stratification, when the air-handling units are stopped and the atria are naturally ventilated (see Figure 8). The temperature gradient is very nonlinear and two zones of warm and extreme warm are separable.

Heating Power Demand. The measurements of hourly demand in heating power of the atria show the effect of solar heat gains on atria heating. The atrium with a south-facing skylight operates as a passive solar collector. Its hourly demand of heating power alternates strongly due to the solar heat gains. Instead, the hourly demand of heating power of the atrium with the north-facing skylight stays rather constant in lack of solar gains. Hourly averages of the heating power demand of both atria during a three-day period in February are shown in Figure 9.

Air Change Rate. The air change rate and ventilation efficiency of the atria were measured with both mechanical ventilation and natural ventilation (in the summertime). The measurements show an average of 0.6 changes per hour with mechanical ventilation for each atrium. This air change rate consist of (1) air change due to the mechanical ventilation, (2) infilteration, and (3) air change between the atrium enclosed space and the adjacent space.

The air change rate with natural ventilation was measured in both of the atria. The measurements showed an average of 0.9 changes per hour for NFA with two open air gates, 53.8 $ft^2$ (5 $m^2$) each, at its two top vertical glazings. The corresponding result for SFA was 0.7 changes per hour. The SFA also was measured with its main entrance doors (external doors) compeletely open, 43 $ft^2$ (4 $m^2$), and two open air gates, 53.8 $ft^2$ (5 $m^2$) each, at the top vertical glazings. The air change rate was measured to 6.9 changes per hour in the lower zone and 4.1 changes per hour in the upper zone (average of 5.5 changes per hour). The air change rate in SFA also was measured with closed entrance doors and closed air gates when the air change was limited to the infiltration and to the air change between the enclosed and adjacent spaces. The measurements showed an average of 0.3 changes per hour.

Energy Performance of the Building. The new building was occupied in late September 1985. The energy consumption measurements were started after the final adjustments of the HVAC systems in the begining of February 1986. The annual energy use of the building from February 1986 to February 1987 is shown in Table 1. The results are classified in two groups of excluding the commercial spaces and including them in order to approach more comparable figures with the energy use of the corresponding buildings. The energy use of the typical office building in Finland is about 114,000 Btu/$ft^2$ (361 kWh/$m^2$) and for the low-energy and best new office buildings it varies between 66,000 and 88,000 Btu/$ft^2$ (209 and 279 kWh/$m^2$). The measured energy use of the building excluding the commercial spaces was 832,400 Btu/$ft^2$ (243.9 kWh/$m^2$), which compares well with the energy use of the low-energy office buildings. Including the commercial spaces the energy use was 962,100 Btu/$ft^2$ (281.9 kWh/$m^2$).

## Simulation Results

The simulation results of the atria and corresponding open lightwells are shown in Figures 10 and 11. The simulation results show a heat-loss saving of 15% (NFA) and 17% (SFA) for the atria over the corresponding open lightwell (OLW) envelopes when the target temperature in the atria is 62.6°F (17°C) during the heating season. They also show a cooling energy use increase of 5% (NFA) and 7% (SFA) over the corresponding open lightwell envelopes during the cooling season, when the atria are naturally ventilated.

## The Amenity Values

The amenity values were evaluated by interviewing the building users and owners. The interviews showed a deep satisfaction on their part. The large spaces of the atria have offered lots of opportunities for social gatherings including exibitions, staff parties, client parties, and product demonstrations for clients. The main problems with the atria had been water leakages of the skylights and noise of the fans as well as overheating in the summertime. All the problems were solved easily, but overheating required some extra openings on the entrance level of the atria to improve the natural ventilation in the summertime.

Building Cost

The building cost was \$72 per $ft^2$ (\$780 per $m^2$) which compares well with the cost of typical office buildings in Finland, \$79 per $ft^2$ (\$851 per $m^2$). The glazing costs of the atria are covered by savings in floor area and volume of the office spaces by placing the supply and extract air ducts of the office space into the atria and using the hollow concrete slabs for ducting. Also, savings in the construction materials of the intermediate boundaries of atria are significant. These are uninsulated structures with single-glazed windows in comparison to the standard insulated external envelope structures with triple-glazed windows for open lightwells.

## DISCUSSIONS

The validity of the simulation model used in this study was examined by the measured data. The simulation results were in close agreement with the measurement results in the case study building. The average deviation was 8% from the measured values and the maximum deviation was 21%. The comparison of the measured and simulated global irradiation on horizontal as well as the heat gain of the atrium with a south-facing skylight (SFA) is shown in Figure 12. Measured data of the heating power demand of SFA are compared with the corresponding simulation result in Figure 13. The maximum deviations in this figure appear in the evening hours, when the pressure difference between the enclosed space of the atrium and adjacent space is changed as the air-conditioning systems in the adjacent space are stopped after work hours.

## CONCLUSIONS

Energy performance of the case study atria and their open lightwell alternatives are analyzed and compared. The case study shows a heat loss saving of 15% and 17% for the atria over the corresponding open lightwell envelopes when the target temperature is 62.6°F (17°C) during the heating season. It also shows a cooling energy increase of 5% and 7% over the open lightwell alternatives during the cooling season when the atria are naturally ventilated by two air gates at the top of each atrium and the target temperature for the adjacent spaces is 77°F (25°C).

The experimental study of the atria shows that a buffer atrium (unheated) warms up 20° to 25°F (11° to 14°C) over the ambient temperature by extract heat of the adjacent spaces and solar heat gains. This shortens the heating period of the atrium and reduces the heat loss of the exterior envelope of the building. This also shows the importance of the manner in which the atrium enclosed space is conditioned and its effects on conditioning of the adjacent spaces. The integration of the conditioning of the atrium enclose space and adjacent spaces (supply or exhaust air atrium) can have a significant impact on energy-saving potential. However, these strategies are very much restricted by fire safety and smoke management regulations.

Summertime heat gains and overheating of the atrium enclosed space can be reduced by openings at top and down part of the atria. Measurement results show the great influence of the location of the openings on ventilation efficiency. Overheating can also be reduced by shading devices, which may be operable or fixed. The orientation and slope of the glazing is the key factor in the amount of solar gain the atrium receives. Solar gains of a south-facing inclined glazing can reduce the heating power demand in the heating period, but it may require shading in the summertime.

Glazing of a courtyard has a significant impact on occupancy potential of the courtyard. Enclosed space of an atrium can offer opportunities for different social gatherings which are not possible in the corresponding open courtyard to the same extension. Glazing cost can be covered by savings in the construction materials of the intermediate boundaries of the atria. Use of the atrium enclosed space for supply and extract air ducting of the adjacent space has a great saving potential in the building cost.

The overall performance of the case study building has deeply satisfied the part of the building users as well as the owners.

## REFERENCES

Hejazi-Hashemi, M.G. 1987. "Atria in office buildings." KTM, D:130. Helsinki: Government Printing Center.

## ACKNOWLEDGMENTS

This study was financed by the Energy Department of the Ministry of Trade and Industry of Finland. I would like to acknowledge my colleagues in PI-Consulting Ltd., who assisted me in preparing this paper.

TABLE 1
Annual Energy Use of the Building (measured)

| Fuel Type | Function | Delivered Fuel Total Btu (Million) | Delivered Fuel Total MWh | Per Unit Area (appropriate) $Btu/ft^2$ (Thousands) | Per Unit Area (appropriate) $kWh/m^2$ |
|---|---|---|---|---|---|
| Excluding Commercial Spaces | | | | | |
| District Heat | Space Heating, 71.6°F (22°C) | 2226.9 | 652.6 | 314.7 | 92.2 |
| District Heat | Atrium Heating. 62.6°F (17°C) | 217.7 | 63.8 | 297.3 | 87.1 |
| District Heat | Domestic Hot Water | 137.5 | 40.3 | 19.4 | 5.7 |
| District Heat | All | 2582.1 | 756.7 | 330.7 | 96.9 |
| Electricity | Lighting (office space) | 597.1 | 175.0 | 84.3 | 24.7 |
| Electricity | Other (incl. cooling) | 3320.9 | 973.2 | 425.2 | 124.6 |
| Electricity | All | 3918.0 | 1148.2 | 501.7 | 147.0 |
| District Heat & Electricity (Total) | | 6500.1 | 1904.9 | 832.4 | 243.9 |
| Including Commercial Spaces | | | | | |
| District Heat | Space Heating | 3694.5 | 1082.7 | 362.8 | 106.3 |
| District Heat | Domestic Hot Water | 244.3 | 71.6 | 23.9 | 7.0 |
| District Heat | All | 3938.8 | 1154.3 | 386.7 | 113.3 |
| Electricity | All | 5856.2 | 1716.2 | 575.4 | 168.6 |
| District Heat & Electricity (Total) | | 9795.1 | 2870.5 | 962.1 | 281.9 |

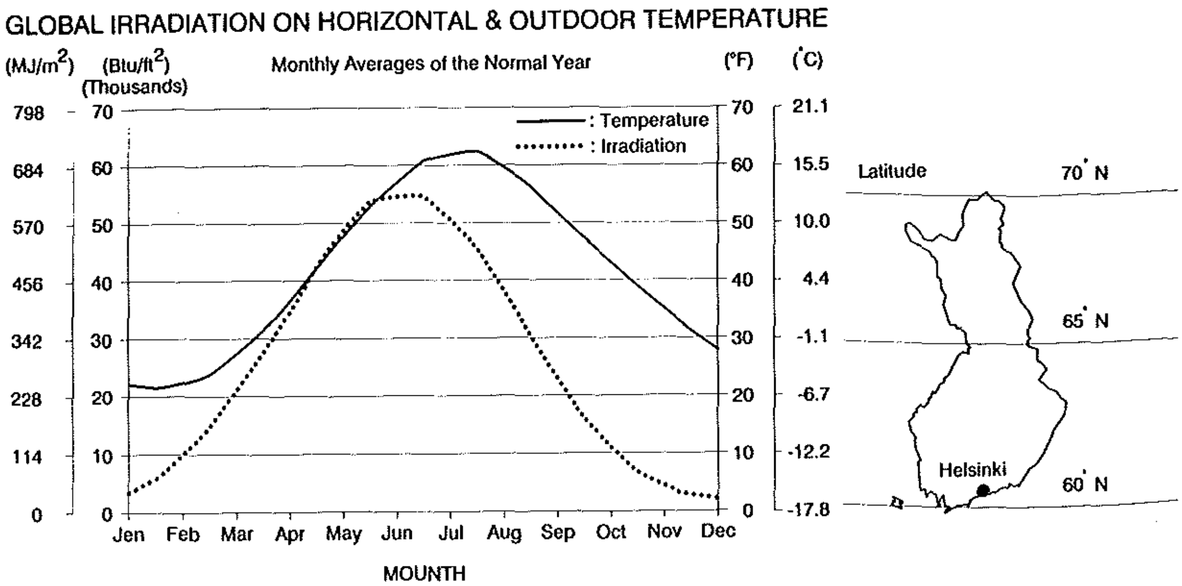


*Figure 1. Site location and climate data*

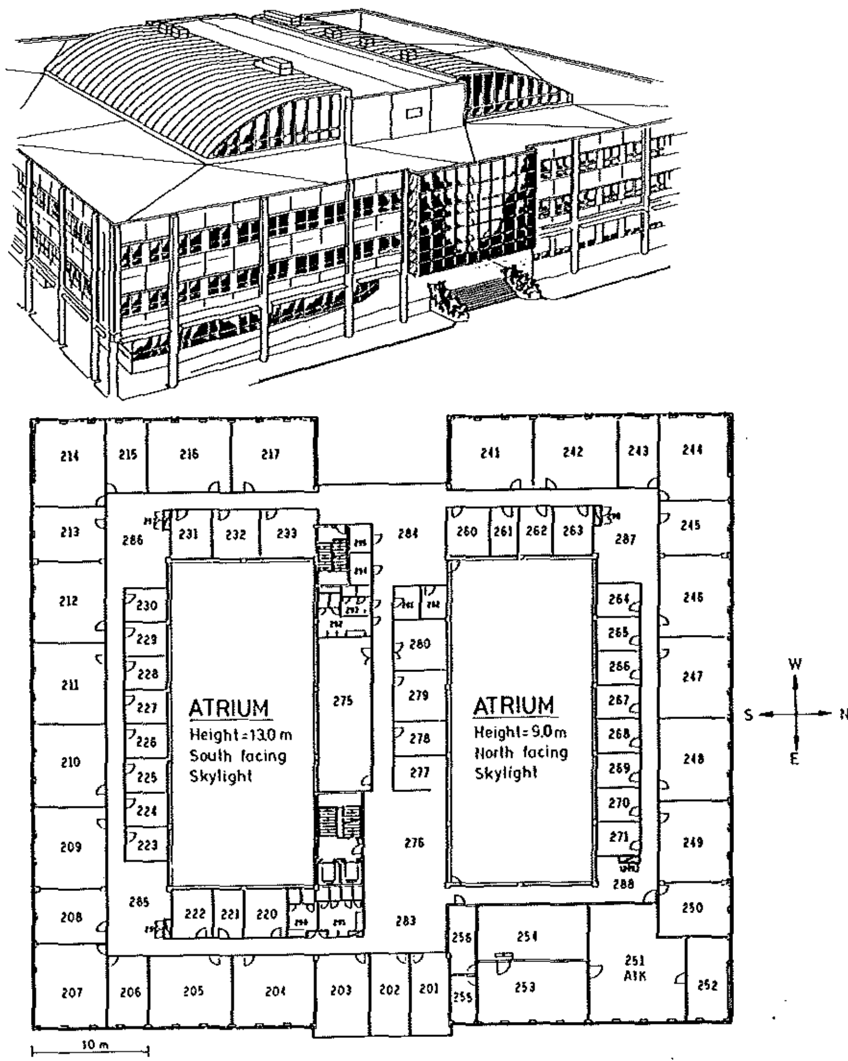


*Figure 2. Building exterior and floor plan of the office space*

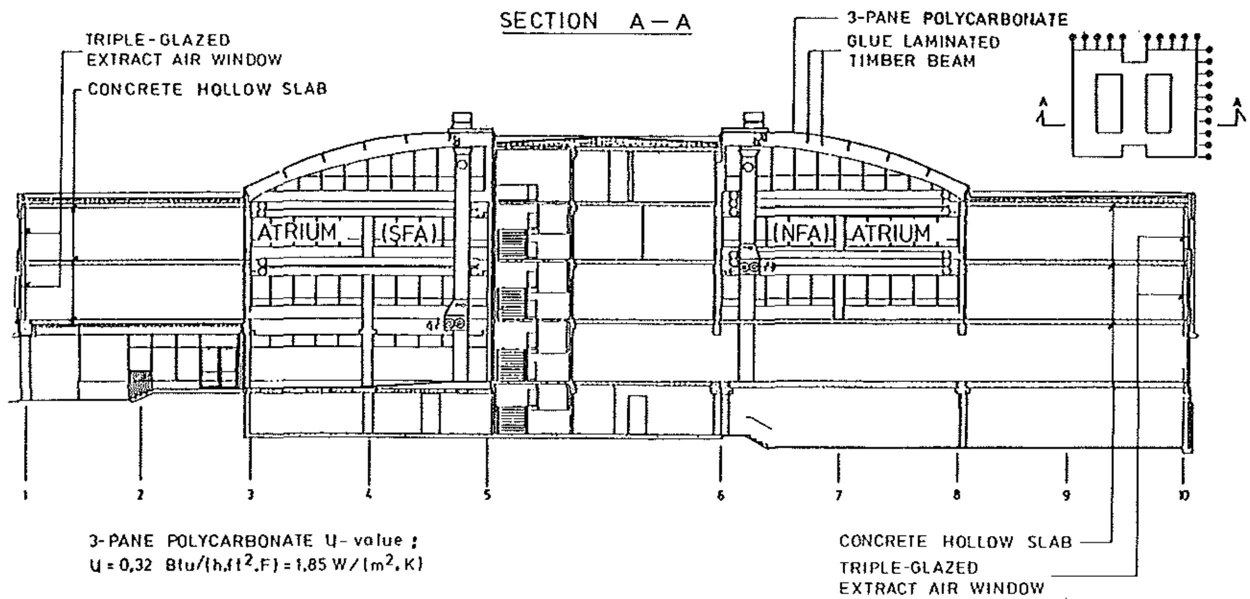


***Figure 3. Construction materials and section of the building***

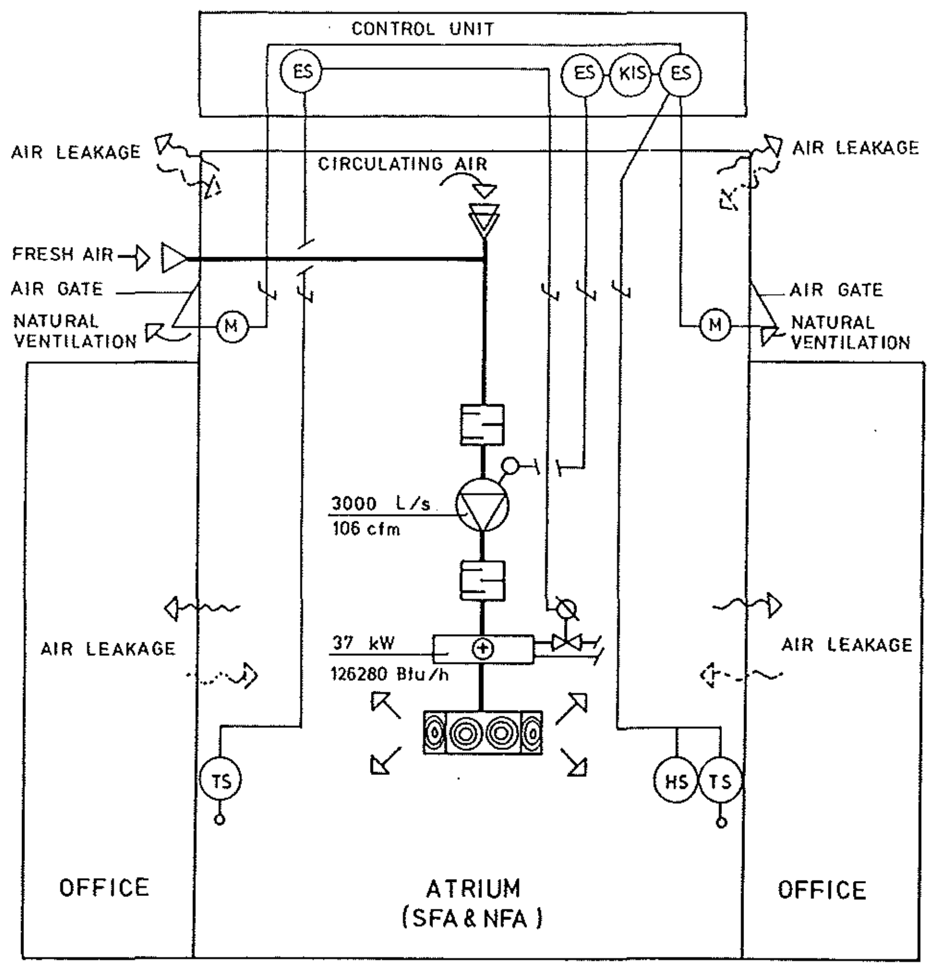


***Figure 4. Temperature control in the atria***

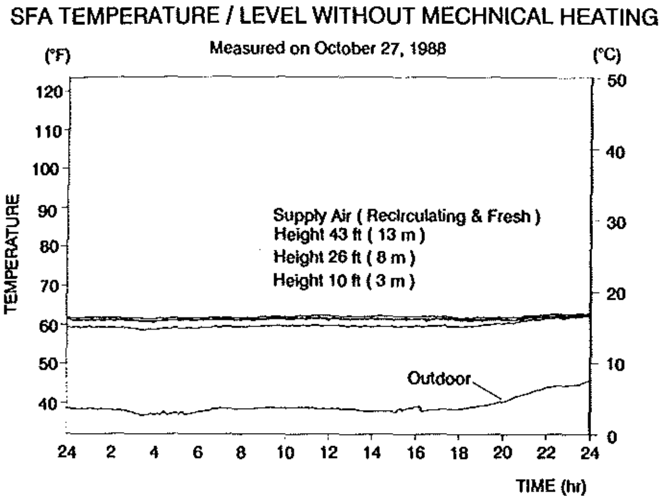


*Figure 5. Temperature in the unheated SFA*

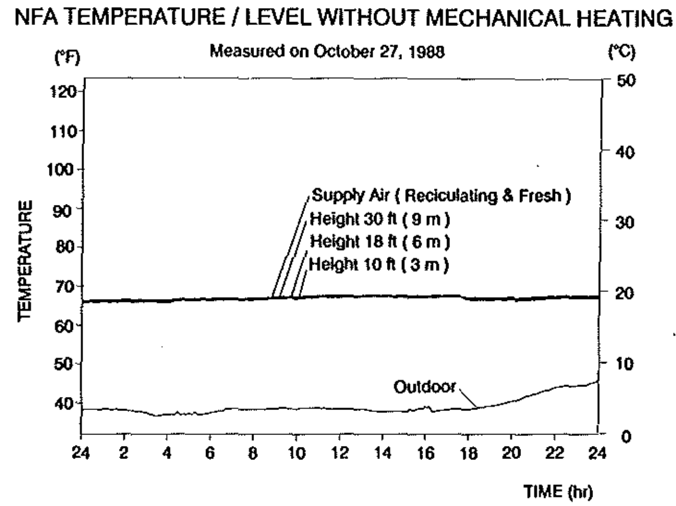


*Figure 6. Temperature in the unheated NFA*

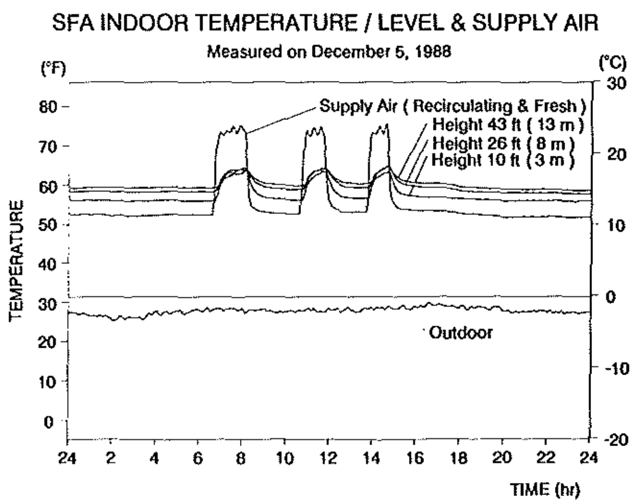


*Figure 7. The Instability of atrium temperature in the heating period*

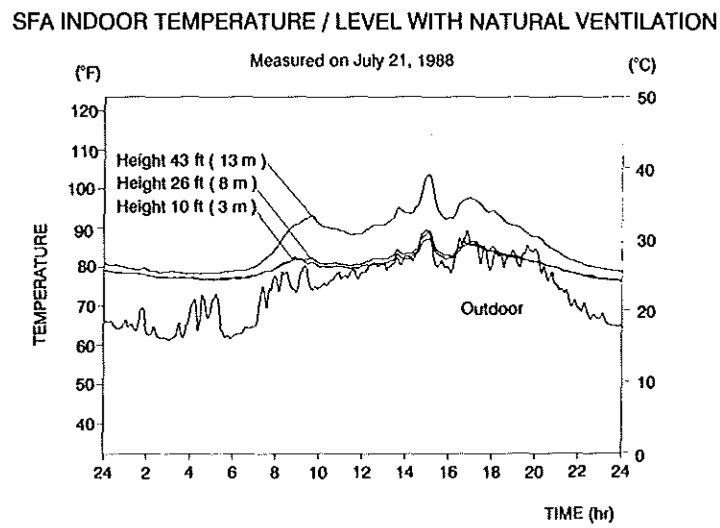


*Figure 8. Thermal stratification in the naturally ventilated atrium*

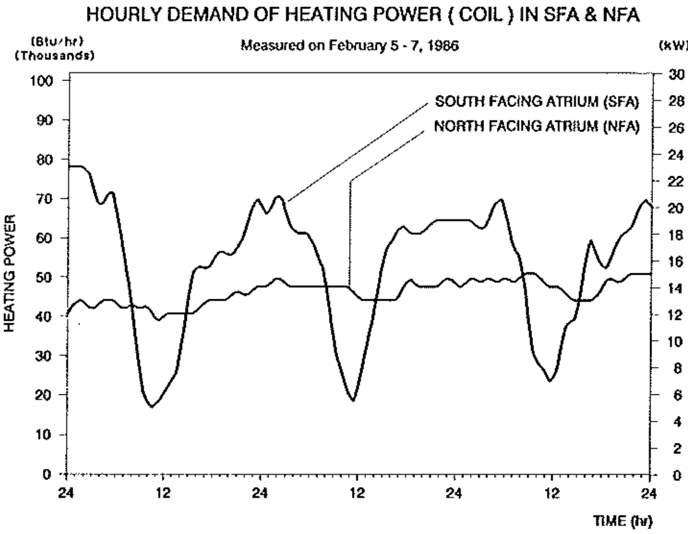


*Figure 9. The effect of the skylight orientation on the heating power demand*

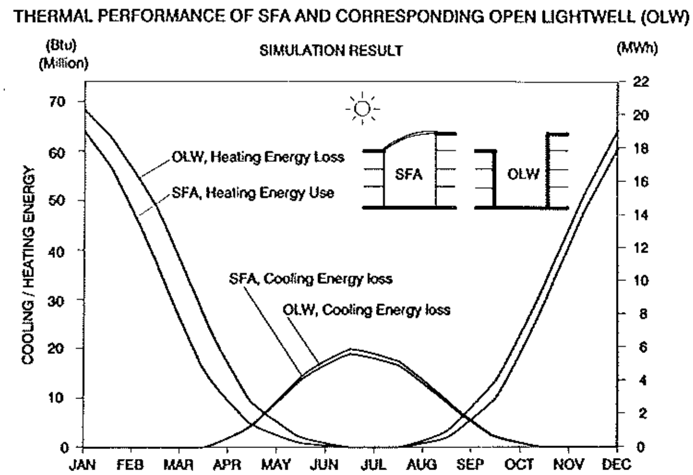


*Figure 10. Energy performance of SFA and the corresponding open lightwell*

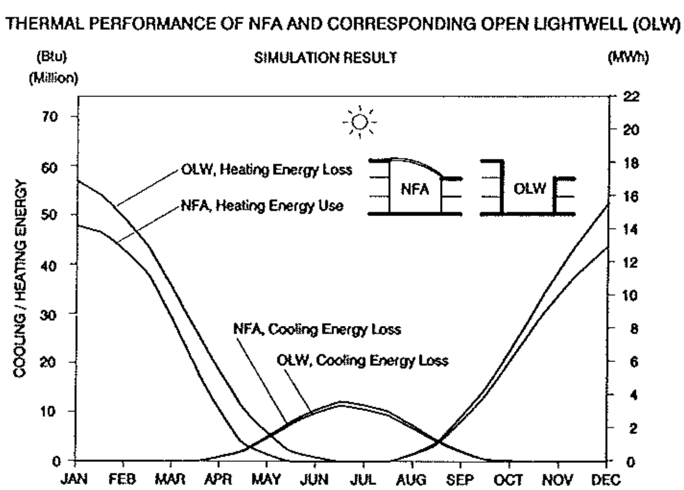


*Figure 11. Energy Performance of NFA and the corresponding open lightwell*

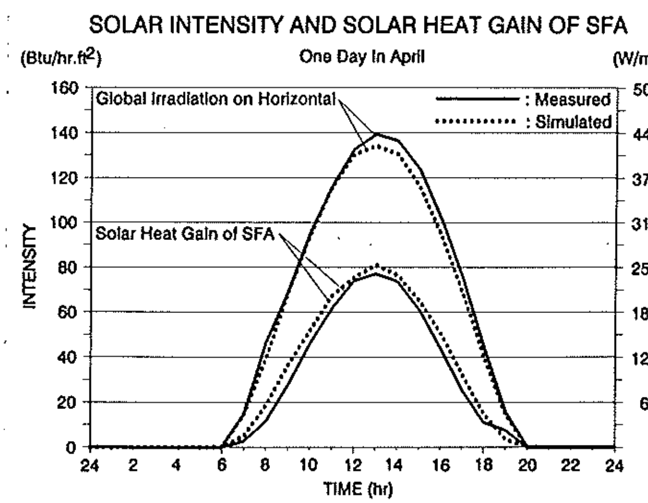


*Figure 12. Global solar intensity and solar heat gain of SFA by measurement and simulation*

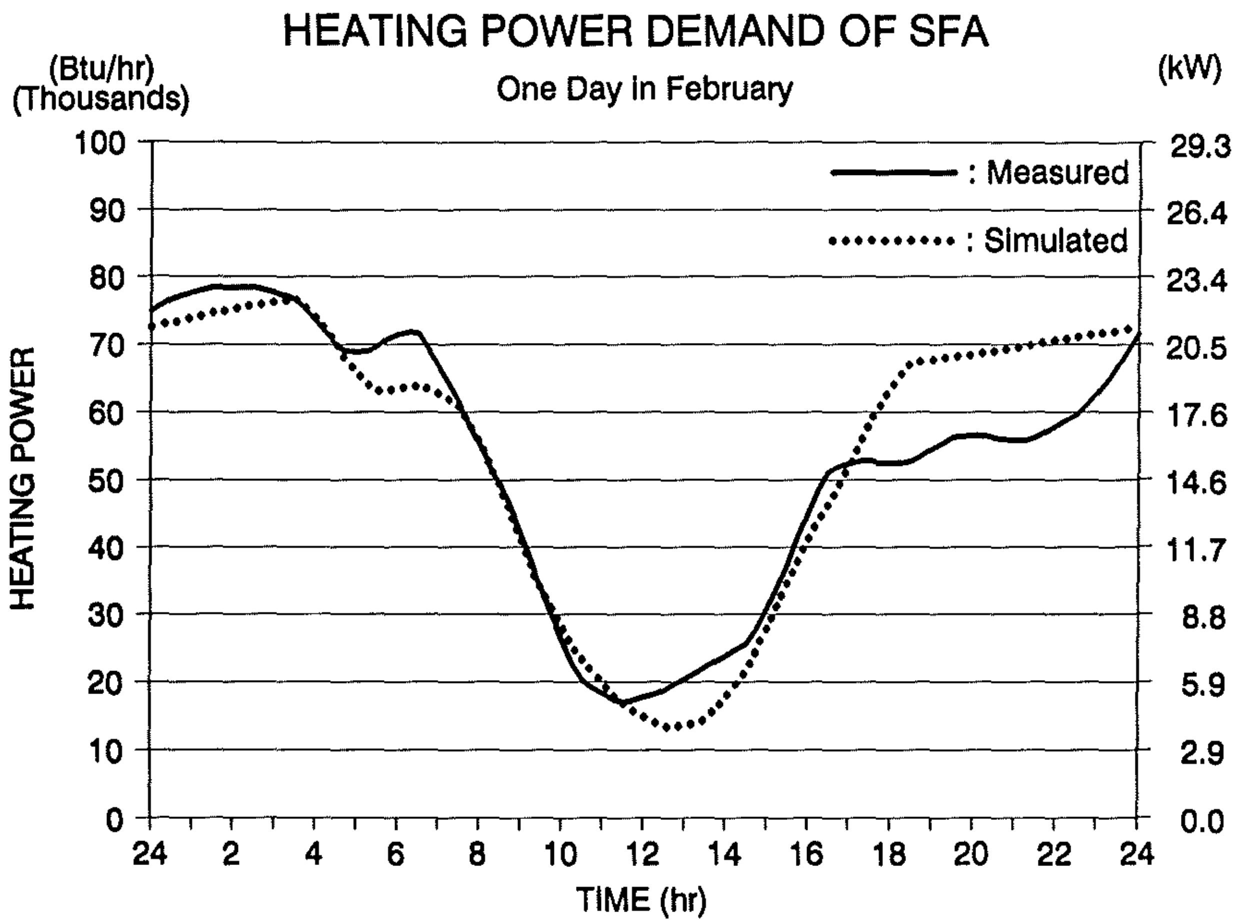


*Figure 13. Heating demand of SFA by measurement and simulation*