THE UNIVERSITY OF CALGARY

Computer Simulation of Thermal Behavior of Atriums

by

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ABSTRACT

The thermal environment in atriums is more strongly affected by solar radiation, temperature stratification and stack effect than in most interior spaces. Prediction of temperature stratification and airflows in atriums is important at the initial stage of design. It helps in designing to reduce energy consumption and in adopting appropriate measures to provide comfort conditions. In this study, computer modeling of the thermal behavior of atrium spaces was carried out using an existing energy simulation program called ESP-r (Environmental Systems Performance-research) version 9.0. Predicted temperatures and airflows were compared with measured data in order to determine the capacity of ESP-r to model the thermal environment in atrium spaces. The results show a reasonable agreement between predicted and measured data.

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NOMENCLATURE

ACRONYMS AND TERMS:

ASHRAE	American Society of Heating, Ventilating, and Air-conditioning Engineers
ACH	Air Change per Hour
DOE-2.1D	Building Energy Simulation Program sponsored by Department of Energy, USA
EECS	Electrical Engineering and Computer Science
ESP-r	Building Energy Simulation Program called Energy Systems Performance-research developed by the University of Strathclyde, Scotland, UK.
HVAC	Heating, Ventilating, and Air-conditioning
Dead band	The range of temperature within which neither heating nor cooling is called for
Night set-up	increase of temperature setting at night in order to save energy that would otherwise be used to cool unoccupied spaces

Night set-back	decrease of temperature setting at night in order to save energy that would otherwise be used to heat unoccupied spaces

CHAPTER 1
INTRODUCTION

1.1 Overview

Energy use per capita in Canada is quite high compared with other developed countries [1]. It is widely accepted that the greenhouse effect is caused by extensive use of nonrenewable energy. For instance, Canada has adopted a National Action Plan for Climate Change. Seventeen percent of the electricity produced in Canada is generated by combustion of coal, while in Alberta it is dramatically higher (89 percent) [2]. It is crucial to design buildings that are less dependent on nonrenewable energy, because heating, ventilation and air-conditioning (HVAC) systems and artificial illumination in buildings account for about 25 to 30 percent of national energy use in the USA and Canada [3,4]. Therefore, it is essential to reduce energy use in buildings. It is very important to have an understanding of the thermal behavior of buildings to provide the required comfort conditions and to improve the energy performance of the built environment. As electrical utilities charge for peak demand as well as for energy consumption, consideration should be given to reducing peak electric energy demand as well as decreasing energy consumption.

Atrium buildings offer great potential for energy conservation by providing passive cooling in summer and passive heating in winter. The large volume of air in atriums can also be exploited to reduce nonrenewable energy use.

Recognition of the significance of the energy-conserving potential of atriums has been increasing in recent years. The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (BCS) program recognized the need for guidance in the design of large spaces in buildings and launched a project called Energy-Efficient Ventilation of Large Enclosures (IEA Solar Heating and Cooling Task XI and IEA Annex 26) [5,6].

The prediction of temperature distribution and airflow patterns in atriums is very important in order to design atrium buildings to effectively control indoor climate [7,8]. This will not only reduce energy consumption, but will ultimately help in adopting appropriate design measures for maintaining comfort conditions. There are basically two approaches to the determination of temperature stratification and airflow - experimental and analytical. Experimental approaches are expensive and time-consuming. Computer simulation, if suitable tools are available, could be very expedient for the building designer.

Uneven temperature distributions, rapid changes in temperature, and airflows strongly affected by buoyancy make it difficult to predict the thermal behavior of atriums.

Some researchers used Computational Fluid Dynamic (CFD) numerical methods to model temperature stratification and air flow in atrium buildings, including Togari et al., Kato et al., and Schild et al. [8,9,10]. The accuracy of solution and speed are highly dependent on the number of grid elements [11]. As atriums are very large, reasonably accurate solutions require long computation times.

Simulation of atrium buildings with multi-zone modeling and airflow has not been extensively reported in the literature, insofar as could determined through a review. Among existing energy simulation programs, FRES is the only multi-zone program that accounts for temperature stratification [5]. Modeling of thermal and airflow conditions in atriums was the subject of this thesis.

1.2 Atrium buildings

1.2.1 Definition

The courtyard has been used successfully for thousands of years to bring fresh outdoor air and daylight into buildings. During the ancient Roman period, the word atrium was used for an open courtyard within a building. The development of strong glass made it possible to cover courtyards and still enjoy many advantages of open courtyards (i.e., daylighting and a view to outdoors) [12,13]. The atrium performs as a buffer zone between indoor and outdoor environments. The dictionary meaning of the term atrium is a) a rectangular-shaped open courtyard surrounded by a building and b) a multi-storied courtyard in a modern building, usually with a skylight. There has been confusion regarding this terminology for some time. However, the recent commonly accepted meaning for the term atrium refers to a covered, centroidal, interior space with skylights and/or one or more glazed facades around which a building is organized [12]. The glazed interior spaces that can be found in train stations and greenhouses cannot be considered atriums, because the former are not enclosed, while the latter are not attached to a building. To be considered an atrium, a space should fulfill at least three conditions. First of all, it should be attached to a building. It need not be in the geometric center as long as a large number of spaces relate to it. Second, the space must be covered for protection from the weather. Third, it must also have some sort of provision for daylighting (i.e., a skylight, and/or one or more glazed facades).

1.2.2 Classification

Atrium buildings could be of unlimited shapes and configurations. According to Hastings [5] there are five basic types of atriums based on configuration (see Figure 1.1).

1. core
2. integrated
3. linear
4. attached, and
5. envelope

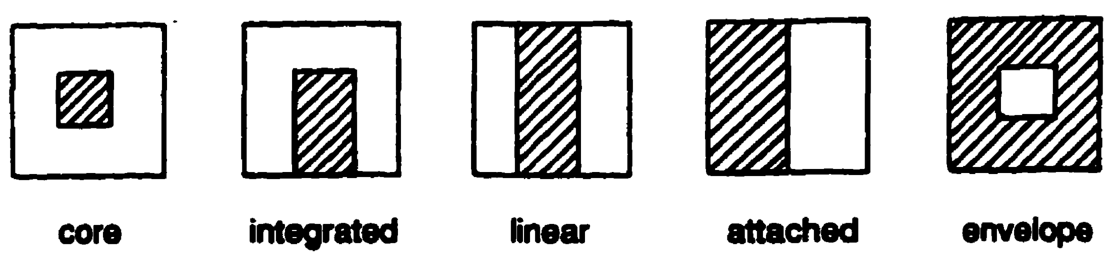


Figure 1.1 Atrium topologies (adapted from [5])

An other classification stated by Yoshino et al. [14] is as follows (see Figure 1.2):

1. tower type with high ceiling,
2. large volume with wide floor area,
3. small volume with low ceiling, and
4. greenhouse type with extensive glazed area.

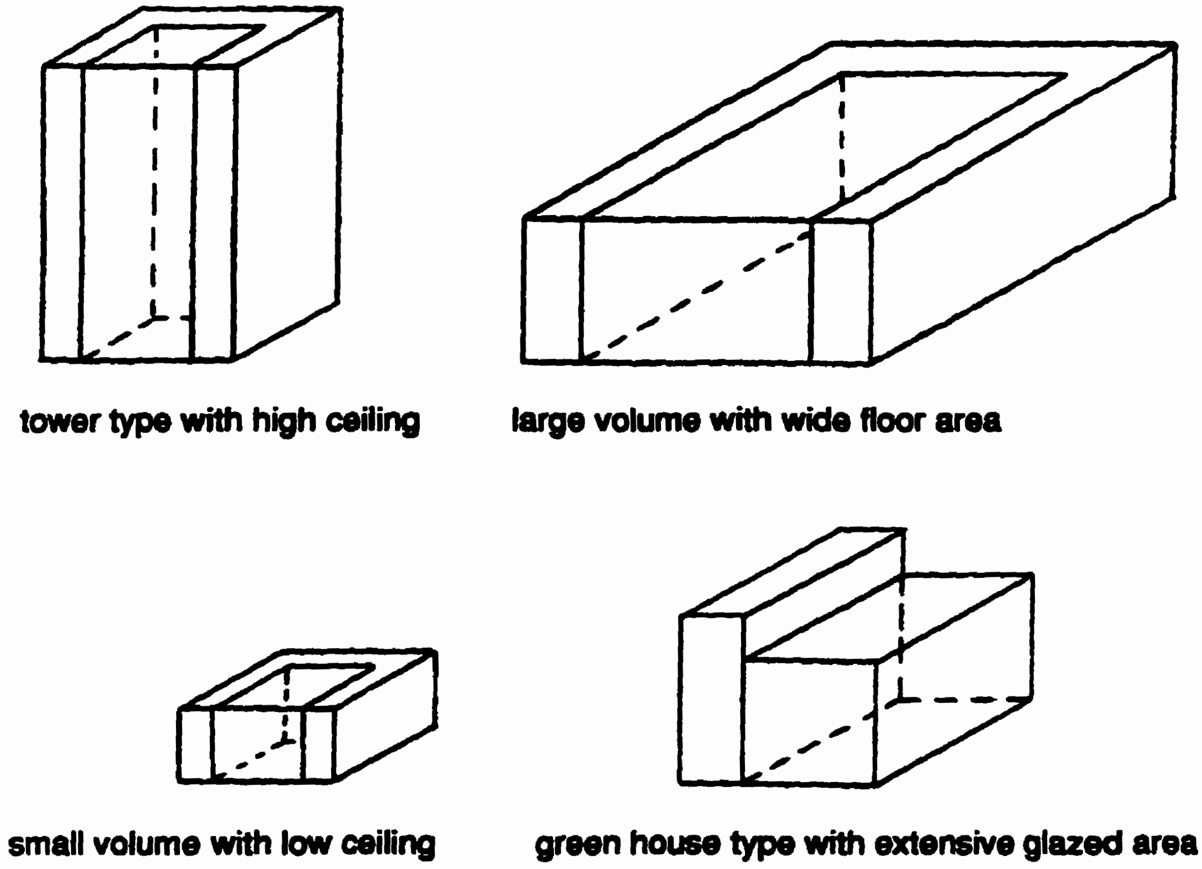


Figure 1.2 Configuration of atriums (adapted from [14])

They also categorized atrium buildings based on spatial connections to adjacent buildings, which are as follows (see Figure 1.3):

1. totally separated,
2. open to only lower floors,
3. open to corridors, and
4. totally open.

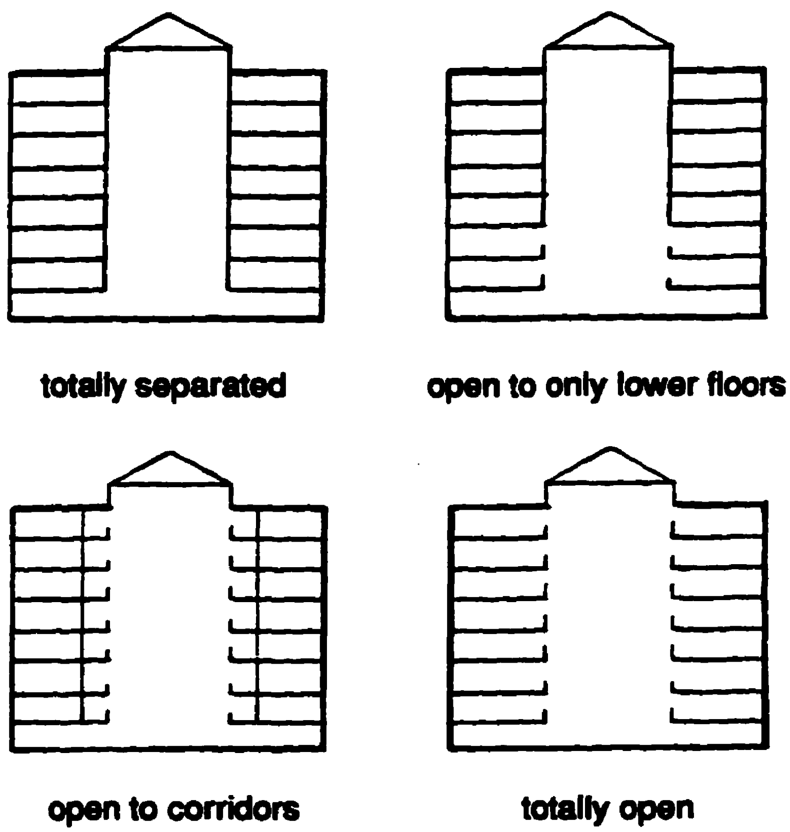


Figure 1.3 Types of atriums based on spatial connections to adjacent buildings (adapted from [14])

The most important geometrical parameters of atrium spaces are the relationships between length, width, and height. Therefore, it might be beneficial to quantify these geometrical parameters in a single number. Bednar [12] used section aspect ratio and plan aspect ratio, while Baker et al. [15] used well index, room index, and aspect ratio in order to characterize the geometry of atriums. These are defined as follows:

1. Sectional aspect ratio (SAR) = Height/Width,
2. Plan aspect ration (PAR) = Width/Length
3. Well index (WI) = Height (Width + Length) / (2 · Length · Width)

4. Room index (RI) = (Length · Width) / Height (Length + Width)

5. Aspect ratio (AR) = Length · Width/Height^2

Based on SAR and PAR atrium spaces could be categorized as follows:

1. linear, if PAR < 0.4,
2. rectangular, if 0.4 <PAR <0.9, and
3. square, if 0.9 < PAR = 1,

and,

1. shallow if SAR < 1, and
2. tall and/or if SAR > 2,

The AR is used to compare atriums with daylight admitting areas of the same size, but different heights.

1.2.3 Basic reasons for incorporation of atriums in building

Basic reasons for incorporation of atriums in building are as follows:

1. **An architectural role**: This has been one of the most dominant factors from the inception of modern atrium buildings. The atrium is used by architects and planners as a versatile urban design element [16,17]. It allows the use of complex and unusual sites and permits efficient land use. Saxon gave a good example of the ability of atriums to handle the odd sites created by radial avenues (Pennsylvania Avenue) crossing gridded streets (Fourth Street) (see Figure 1.4). Furthermore, Professor Sir Leslie Martin and Lionel March in their book - "Land Use and Built Form" proved that the same floor area could be

delivered in relatively low buildings by arranging them around the perimeter of a site using a Fresnel square as shown in figure 1.5.

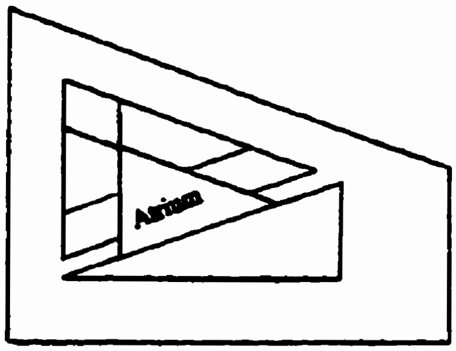


Figure 1.4 Site plan of atrium building at Washington DC (adapted from [16])

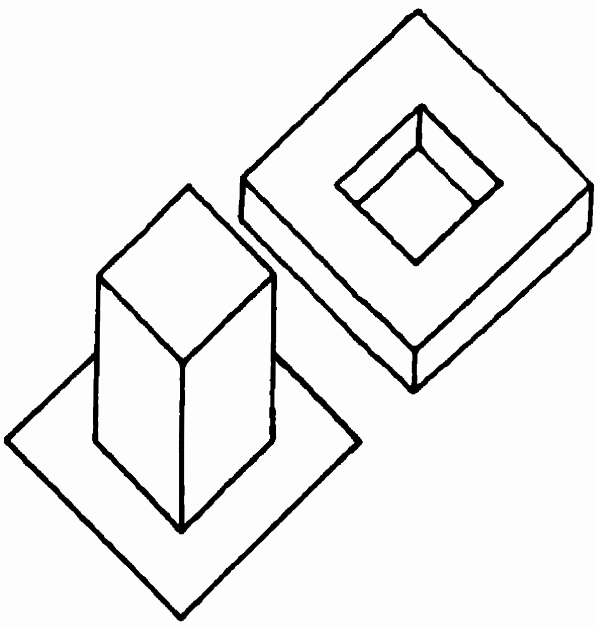


Figure 1.5 Illustration of efficient land use (adapted from [16])

The Fresnel square is a square divided into concentric rings of decreasing width, but of equal area. Furthermore, the area of each ring equals the area of square at centre as shown in figure 1.6.

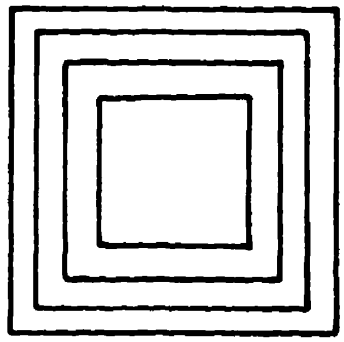


Figure 1.6 Fresnel square (adapted from [16])

2. **Provide an outdoor view**: Atriums with glazed facades provide a view to outdoors, while landscaped atriums without glazed facades provide a sense of connection to the outside world. Atriums with plants and water falls and fountains are very popular in hotels. Studies have shown that most people prefer workplaces with views compared to workplaces without windows [18].

3. **Profitability**: Market studies show that buildings with atriums are very attractive and have higher occupancy rates, increased sales and are capable of generating higher rental rates [19,20].

4. **Energy conservation**: Atriums offer great potential for energy conservation through daylighting, passive heating and passive cooling.

1.3 Hypothesis of the research

The hypothesis of this investigation was that the computer simulation program called ESP-r (Environmental Systems Performance-research) version 9.0 can be used to model temperature stratification in atrium buildings with acceptable accuracy i.e. error will be less than ± 2°C between predicted and measured temperatures. This is equal to about 10 percent of the temperature at comfort conditions.

If the error in prediction is within an acceptable range, ESP-r may be a suitable tool for design of atrium buildings.

The thermal comfort zone ranges from 20 °C to 26 °C. In terms of human comfort, it is very important that the accuracy of ESP-r should be sufficient that the predicted temperatures fall inside the range of comfort conditions. Where atriums are use as transient spaces, the comfort range might be relaxed a bit.

1.4 Objective of the research

The objective of this investigation was to model the dynamic thermal behavior of atriums including temperature stratification.

In order to test the hypothesis, the following research was carried out:

1. selection of data from published experimental research on atriums,
2. computer simulation of temperature distributions, and
3. comparison of the calculated and measured results.

1.5 Arrangement of the thesis

The remainder of this thesis is divided into four distinct chapters. Chapter 2 contains the literature review and discussion of major issues. Chapter 3 presents the methodology and procedures adopted in this research. It also describes the test sites and energy simulation computer program ESP-r version 9.0. Chapter 4 discusses the data analysis and results, while Chapter 5 contains the conclusions, summary of work completed, and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The architectural role of atrium spaces has been a major driving force for incorporating them into buildings, while the least priority has been given to their energy conservation potential [12,13,16]. As a result, most atrium buildings are not as energy efficient as they could be. Many are energy guzzlers. For amenity and convenience, glazed areas have been increased. Buildings were oriented to capture view without consideration of energy implications. Furthermore, most atrium spaces are fully conditioned so that they can be used all year. In such cases, the energy use can be quite high. After the energy crisis in 1970s, people became more conscious of energy conservation and environmental issues. Atrium buildings gained a bad reputation and were labeled as "energy wasters".

Many researchers argue that incorporation of atriums in buildings could improve the energy efficiency of buildings [5,12,19,21,22]. The specific energy use (kWh/m^2) is used to evaluate the energy efficiency of buildings. The basis for comparison of performance is discussed later (see 2.2.1). Furthermore, if designed properly, atrium buildings could not only be architecturally attractive and energy conserving, but also be built with a lower initial cost [17]. The basic rule, according to these authors is that atriums should be incorporated into buildings as an energy conserving strategy, not only for amenity. There are many examples of both energy intensive and energy conserving atrium buildings [5,19,20,22]. Although atriums provide opportunities for energy conservation, they also pose many challenges [12]. On the one hand, atriums provide possibilities for daylighting, passive heating, and passive cooling. On the other hand, they present difficulties in terms of glare control, overheating, problems with indoor air quality, fire and smoke control, condensation on surfaces, housekeeping, and acoustics. This literature review will focus mainly on thermal behavior and energy performance of atrium buildings. It did not reveal any articles on thermal behavior and the energy performance of atrium buildings in Canada.

2.2 Major Issues

The major issues arising nowadays regarding the thermal behavior and energy performance of atrium buildings are as follows:

1. energy use,
2. temperature stratification and stack effect,
3. heat transfer through envelopes, and
4. space conditioning.

Another issue is the investigation of atrium performance. Although experimental methods could be employed, they are time-consuming as well as expensive. Furthermore, experimental methods are more appropriate for investigation of thermal behavior of existing atrium buildings and are not generally suitable as design tools. Computer modeling would be more convenient at the design stage, if sufficiently accurate.

2.2.1 Energy use

Previous investigations of the energy performance of atrium buildings have been carried out using both field measurements and computer simulation.

2.2.1.1 Experimental studies on energy performance of atrium buildings

Two case studies suggest that atriums can contribute to improved energy efficiency in cold climates.

The case study for climatic conditions closest to those in Canada was reported by Hejazi-Hashemi. The author conducted an experimental case study of a three-story office building with two atriums (PI-Group Headquarters) in Vantaa, Finland located at 60° north latitude. The mean annual temperature in Vantaa is 5.5 °C compared with 5.5 °C in Ottawa, 6.5 °C in Montreal, 8.3 °C in Toronto, and 3.9 °C in Calgary. The results showed that the specific annual energy consumption of this building (282 kWh/m^2) is quite a bit lower than that of typical Finnish office buildings (360 kWh/m^2) and is comparable to low energy buildings (210-280 kWh/m^2) in Finland [23,24,25]. The specific annual energy use of this building is also comparable to the specific energy use (about 320 kWh/m^2) that would be used by a building meeting ASHRAE Standard 90 [26]. The annual energy saving of the atrium option is 16 percent (564 MWh) compared with a reference design without an atrium. Furthermore, the author claimed that the cost of the building was only FIM 3400/m^2 (US $ 800/m^2), which is almost 10 percent less than the cost of typical office buildings in Finland i.e., FIM 3700/m^2 (US $ 870/m^2). The cost saving was mainly from reductions in the following:

1. construction materials of the intermediate envelopes, due to reduced insulation and single-glazed windows.
2. floor area and volume of the office spaces by placing the supply and return ducts in the atriums.

Additional cost savings were achieved by using hollow concrete slabs for ducting.

The energy performance of another atrium building (ELA-atrium) at the Norwegian Institute of Technology, Trondheim, Norway, located at 64° north latitude, was monitored for 18 months [27,28,29]. The mean annual temperature in Trondheim is 4.9 °C. An investigation of the impact of the atrium on energy use showed that the measured specific annual energy consumption of this atrium building was only 127 kWh/m^2 compared with 270 kWh/m^2 for other Norwegian university buildings. The specific annual energy use of this building is comparable to the standard set by the C 2000 programme (the Advanced Building Technology Demonstration Program of National Resources Canada) (about 160 kWh/m^2). The C 2000 programme aims to double the efficiency of buildings meeting the present ASHRAE Standard 90.1 [30]. The authors also claimed that incorporation of the atrium reduced the annual energy costs and the total construction costs by 20 and 3 percent respectively.

The climatic conditions in Trondheim, Norway are similar to those in Vantaa, Finland (the average annual temperature in Trondheim is 4.9 °C, while the average annual temperature in Vantaa is 5.5 °C). However, the reported specific energy use of the Norwegian Institute of Technology atrium building is 55 percent less than that of the PI-Group Headquarters. One of the causes of the large differences in energy use may be differences in atrium temperatures. The temperatures inside the atrium at the Norwegian Institute of Technology (15 °C) were 2 °C lower than that of the PI-Group Headquarters (17 °C) in winter. The atrium space was not initially intended for regular use but became a study area. Thus, the temperature inside the atrium at the Norwegian Institute of Technology was gradually increased to 18 °C as desired by occupants. The other causes may be different occupancies and mechanical systems, wall constructions and glazed materials, different proportions of glazed area to intermediate envelopes and different configurations and orientations of the atriums. However, the reasons for the difference were not addressed by the authors.

Both case studies were part of the IEA Project mentioned above, but no comparative studies were carried out. Hastings argued that, as energy use by HVAC systems is significantly influenced by building configuration, operating hours, temperature set point, equipment efficiency, and other factors, comparison of building performance is inappropriate [5]. However, comparison of energy use of buildings of the same category can be useful to assess the energy efficiency of buildings as well as to determine the ways to improve it. The degree-day concept can be used to compare the energy performance of buildings in different climates. Standards for building energy efficiency vary from country to country [10].

2.2.1.2 Computer simulation studied on energy performance of atrium buildings

One of the most extensive investigations of energy conserving features of atrium buildings was carried out by Landsberg et al. [22]. They conducted case studies of four atrium buildings with different occupancy and atrium configurations in different climates. They also analyzed the impact of a wide range of design strategies on thermal performance. They field-monitored the buildings for three years, and modeled them using the energy simulation program called DOE-2.1B. These simulation studies focused on two major aspects of the energy performance of atrium buildings. The first aspect is the most efficient design strategies for energy efficient atrium design, while the second aspect is the energy liabilities of the atrium concept. In order to obtain more reliable results, the models were calibrated using measured energy use data for each case. A series of energy optimization runs were performed after achieving reasonable calibration. They concluded that incorporation of selected design strategies in atrium buildings could dramatically reduce the total energy consumption, whereas incorporation of atriums into buildings might be energy consuming if poorly designed. The range of design strategies simulated for the atrium buildings included envelope enhancements, destratification, and modification of mechanical systems. Incorporation of these strategies would produce reductions of:

1. 24 percent of overall building energy use in a small office atrium building in Albany, New York,
2. 19 and 36 percent in the atrium heating and cooling loads respectively, equivalent to 1 percent of overall building energy use in a large office atrium building in Washington, D.C.,

3. 6 percent of overall building energy use in a large hotel atrium building in San Antonio, Texas, with reductions of 9 and 25 percent in building heating/cooling and HVAC auxiliary energy use respectively, and
4. 6 percent of overall building energy use in a multifamily high-rise atrium building in Chicago, Illinois, with reductions of 4 percent and 53 percent in building heating/cooling and HVAC auxiliary energy use respectively.

The reduction in overall building energy use could be considerably higher, if all potential design strategies were incorporated. For instance, in the case of the small office atrium building in Albany, New York, incorporation of three more design strategies - namely 6°C (10°F) dead band, heating night set-back/cooling night set-up, and double-glazing instead of triple-glazing could increase savings about 13 percent. For the large office atrium building in Washington, D.C., the large hotel atrium building in San Antonio, Texas, and the multi-family high-rise atrium building in Chicago, Illinois, the additional reductions could be about 10 percent, 11 percent, and 2 percent respectively. In this case, all four atrium buildings would be more energy efficient than the same buildings without atriums. The authors analyzed the energy conserving potential of all these individual design strategies. However, it is surprising that they did not include these potential design strategies when analyzing overall energy use. Most of these strategies were quite simple, such as increases in dead band, night set-up and night set-back (see nomenclature), changes in orientation, and reductions in glazed area.

Landsberg et al. also simulated all four buildings without atriums and found that removal of atriums would decrease total building energy use by only 1 percent for the San Antonio, Texas and Washington, D.C buildings. The reductions for the Albany, New York and Chicago, Illinois buildings were 12 percent and 8 percent respectively. The primary reasons for the low energy impact for San Antonio, Texas and Washington, D.C. were that these buildings have significant process loads and because of the particular design of the atriums. The reason for the high energy impact for Albany, New York was a reduction of glazed areas with an unfavorable orientation. The simulation showed that all four existing atrium buildings were not as energy efficient as they could be without atriums.

These findings suggest that atriums can make a positive contribution to building energy efficiency in a wide range of climates and that incorporation of atriums in buildings does not necessarily lead to intensive energy consumption. However, this study also indicates that energy requirements are highly dependent on design decisions. The energy simulation program DOE 2.1B used by Landsberg et al. is not capable of modeling airflow and radiant energy exchange between zones nor temperature stratification, which are the most prominent thermal features of atrium buildings. The DOE program was validated for predicting energy use in conventional buildings. If the energy simulation program used is incapable of modeling the thermal behavior of the atrium building, it is uncertain whether the energy use predicted by the program is reliable. The authors used several strategies for modeling stratification, atrium daylight borrowing, atrium solar plenum etc., and the models were calibrated using measured energy use data for each case. Thus for these case studies the result obtained by simulation might not be too far from the actual one.

2.2.1.3 Summary

From previous research, it appears that an atrium building could be energy efficient, if it is only partially conditioned or is fully conditioned and incorporates certain design strategies [5,19,22]. However, full conditioning of an atrium building will often be energy intensive [21,28,31]. Nevertheless, in such cases the values of additional work place and amenity value (e.g., the atrium could be used for different social functions, as well as recreation, for small retail shops, and circulation) as well as greater marketability and higher rental rates should not overlooked. These factors might help to offset the energy expenditures as well as the requirement for a larger site.

Earlier studies improved our understanding of the thermal behavior of atrium buildings in some respects. However, the results of these case studies varied widely. It seems clear that the energy performance of atrium buildings depends upon geographic location and orientation, ratio of atrium size to adjacent building size, type and function of the atrium, thermal nature of adjacent spaces, adaptation of passive cooling and heating strategies, envelope constructions and operation hours, temperature set point and equipment efficiency. However, guidance for energy efficient atrium building design is still inadequate[21]. Therefore, further investigation is required to evaluate the performance of atrium buildings in the Canadian climate.

2.2.2 Temperature stratification and stack effect

Temperature stratification is a temperature difference between the temperature at any two levels (usually highest and lowest) in an enclosed space. The height and solar gain through glazing of most atriums contributes to more extreme temperature stratification compared to typical commercial and institutional spaces, which will affect environmental control requirements.

The difference in densities between cold and hot air creates a vertical pressure difference and results in air movement from the bottom to the top (known as stack effect) provided there are openings at the bottom and the top. Outdoor climate influences stack effect in atrium buildings. It is more pronounced in cold climates, because of greater temperature differences between indoors and outdoors[32].

2.2.2.1 Experimental studies on temperature stratification and stack effect

One atrium of the PI Group building is 13 m high, with one entrance from the outside and one from the office corridors. The other atrium is 9 m high, with no entrances from outside, but two entrances from office corridors [23,24,25]. Hejazi-Hashemi reported that the maximum temperature stratification between 3 m and 13 m in the atriums of the PI Group building reached 10 °C with outdoor temperatures ranging from 15 °C to 30 °C in summer, when the air circulating units were stopped and the enclosed spaces of the atriums were naturally ventilated as shown in Figure 2.1. However, during winter, when the air circulating units were running, the thermal stratification was only 2 °C as shown in Figure 2.2). The target temperature for both atriums was 17 °C.

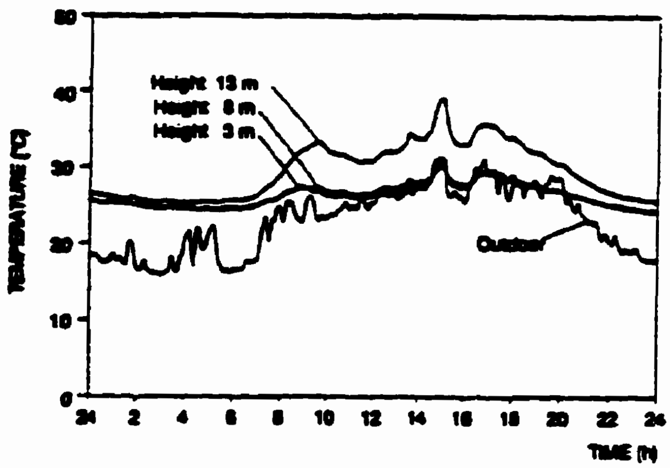


Figure 2.1 Thermal stratification in a naturally ventilated atrium for July 21, 1988 (adapted from [23])

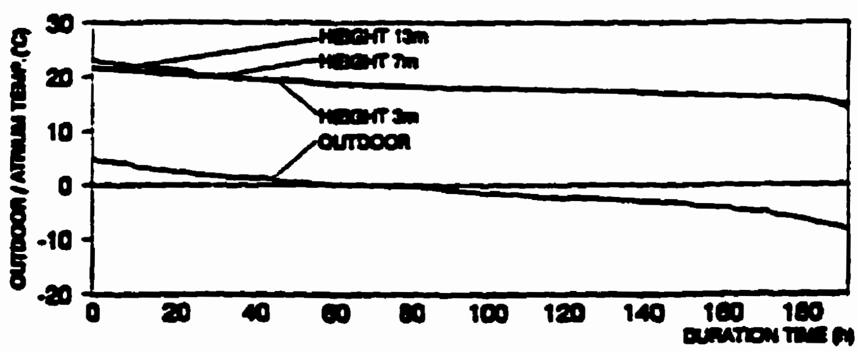


Figure 2.2 Thermal stratification in a mechanically ventilated atrium for October 27, 1988 (adapted from [24])

With vents open at the top and bottom levels of the atriums, natural ventilation driven by stack effect caused 5.5 air changes per hour (ACH) compared with only 0.7 ACH with vents open only at the top level in summer (see Figure 2.3). However, the sizes of openings were not provided. The authors also failed to report the temperatures in the atrium spaces at different heights when airflow measurements were carried out nor did they mention when they carried out airflow measurements and whether 5.5 ACH was adequate to maintain comfort conditions in the atriums.

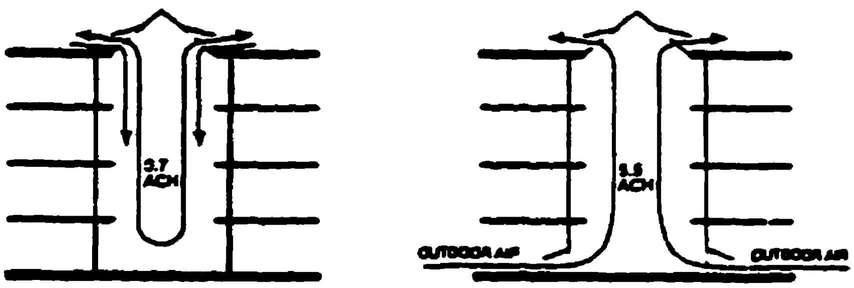
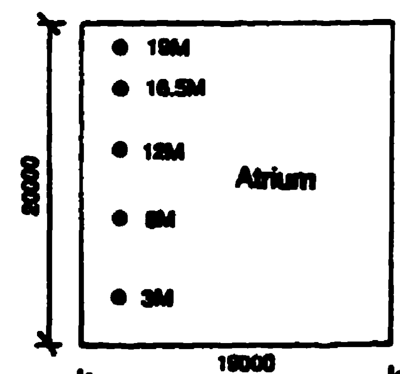


Figure 2.3 Air change rates in a naturally ventilated atrium (adapted from [25])

Temperature measurements were carried out in the ELA-atrium building at the Norwegian Institute of Technology in order to quantify the temperature stratification and the potential of natural ventilation [27,28,29]. The atrium was 17 m high. The measurements were carried out on July 18, 1988 with roof hatches closed. The maximum temperature stratification was 16 °C. The temperature ranged from 24 °C to 30 °C at 1.7 m and 24 °C to 44 °C at 13 m above floor level. The authors also measured ventilation rates with a step-down tracer gas method and mixing fans and found that air change rates ranged from 0.45 to 0.50 ACH and 3 to 4 ACH when hatches were closed and open respectively. However, the authors also mentioned that the results obtained for air change rates might be inaccurate because of inadequate capacity of the mixing fans used during testing. Unfortunately the sizes of openings were not mentioned.

2.2.2.2 Experimental and computer simulation study on temperature stratification and stack effect

One of the most extensive investigations of temperature stratification and natural ventilation driven by stack effect in atrium buildings was conducted at a hospital complex (AZG) with atriums in Groningen, the Netherlands [33,34]. An investigation was carried out for the second of the nine atriums to be added. It was 20 m high (see Figure 2.4) and 10 percent of the roof was openable for ventilation. During 1987 and 1989, several measurements were carried out to characterize the performance of the atrium in different seasons (i.e., spring, warm summer, hot summer and winter). During spring and summer, natural ventilation driven by thermal buoyancy ranged from 4 ACH to 6 ACH, which was satisfactory for maintaining comfort conditions. The occupied zones in the atrium are the main floor, and balconies on the first, second, and third levels. The balcony on the third level is 12 m above the ground floor.



section A-A (see Figure 3.5)

Figure 2.4 Section of AZG atrium showing temperature measurement height (adapted from [33])
(second atrium at a hospital complex at Groningen)

The results showed that, on a spring day (May 6, 1989), the maximum temperature stratification in the atrium reached about 5 °C (24 °C at 3 m and 29 °C at 19 m from floor level), when the roof vents were closed (see Figure 2.5).

The diurnal outdoor temperature ranged from 8 °C to 11 °C. The temperature in the atrium ranged from 22 °C to 24 °C at 3 m and 21 °C to 29 °C at 19 m above floor level. However, the occupied zones (main level and balconies at first, second, and third levels) were within comfort conditions.

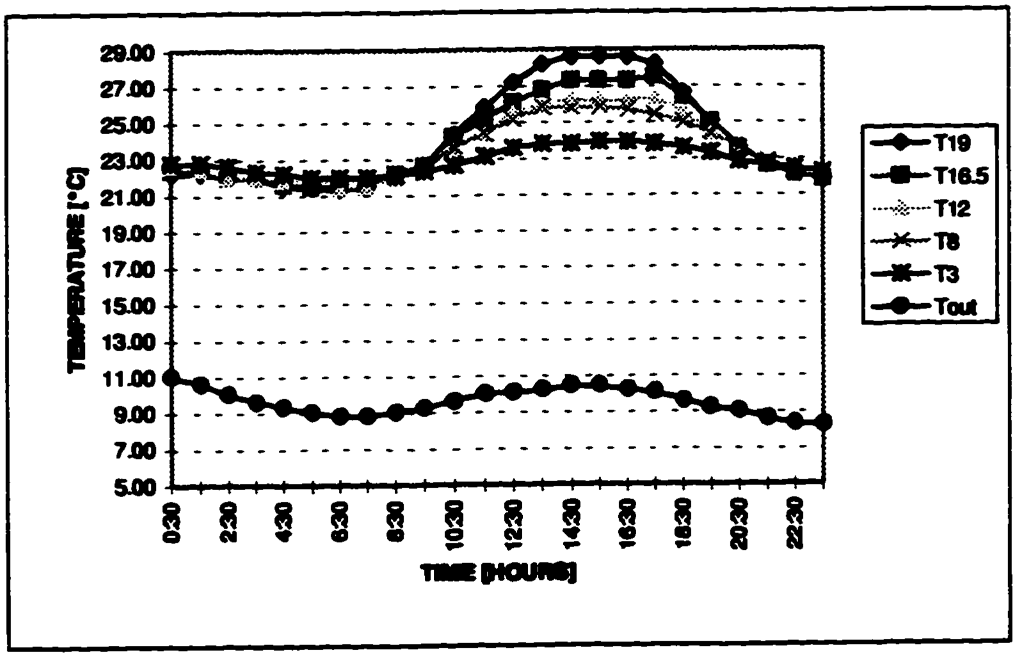


Figure 2.5 Temperature profiles in the AZG atrium for May 6, 1989 (adapted from [34]), where the number after T indicates the height above the floor level.

During a warm summer day (June 12, 1989), when roof vents were opened, the maximum temperature stratification in the atrium reached about 4 °C (26 °C at 3 m and 30 °C at 19 m from floor level) (see Figure 2.6).

The diurnal outdoor temperature ranged from 14 °C to 24 °C. The temperature in the atrium ranged from 23 °C to 26 °C at 3 m and 21 °C to 30 °C at 19 m above floor level. The conditions in some occupied zones (the balcony at the third level) were slightly outside comfort conditions from 1700 to 1900. As the maximum temperature at that zone reached 27 °C to 28 °C for only 2 hours, such conditions were acceptable for occupants. Thus no complaints were received. Balconies at lower levels were within comfort conditions.

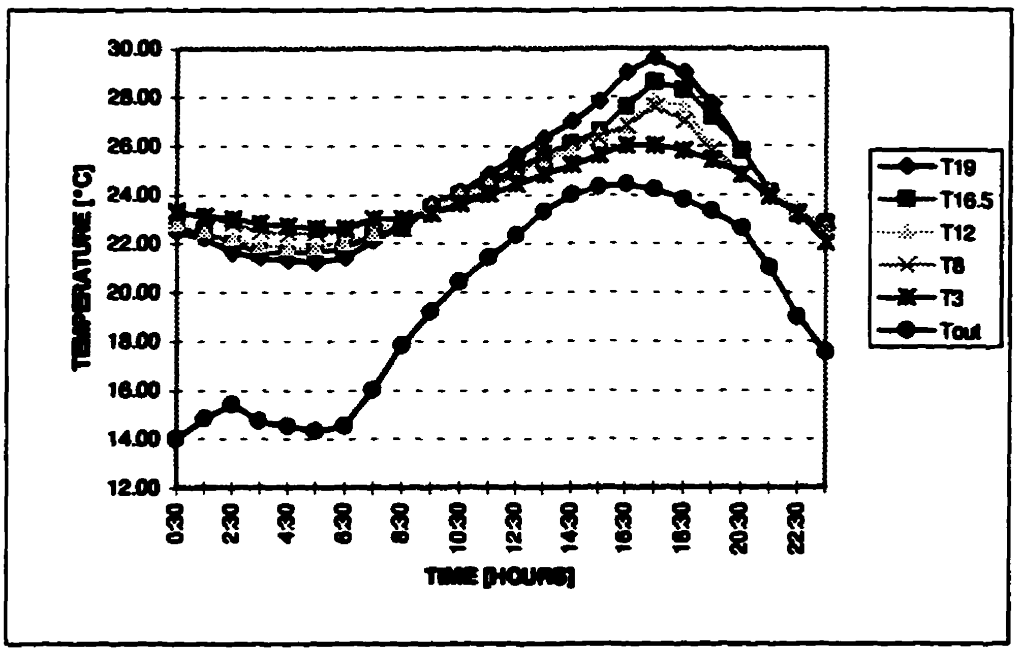


Figure 2.6 Temperature profiles in the AZG atrium for June 12, 1989 (adapted from [34])

During a hot summer day (July 7, 1989), when roof vents were opened, the maximum temperature stratification in the atrium reached about 4 °C (29 °C at 3 m and 33 °C at 19 m from floor level) (see Figure 2.7). The diurnal outdoor temperature ranged from 18 °C to 31 °C. The temperature in the atrium ranged from 23 °C to 29 °C at 3 m and 23 °C to 33 °C at 19 m above floor level. The conditions in some occupied zones (balconies on first, second, and third levels) from 1100 to 2100 were hotter than comfort conditions.

The maximum temperature reached in occupied zones was around 30 °C at 12m above ground level. However, the author mentioned that no complaints were received. The occupied zones at the main levels were within comfort conditions.

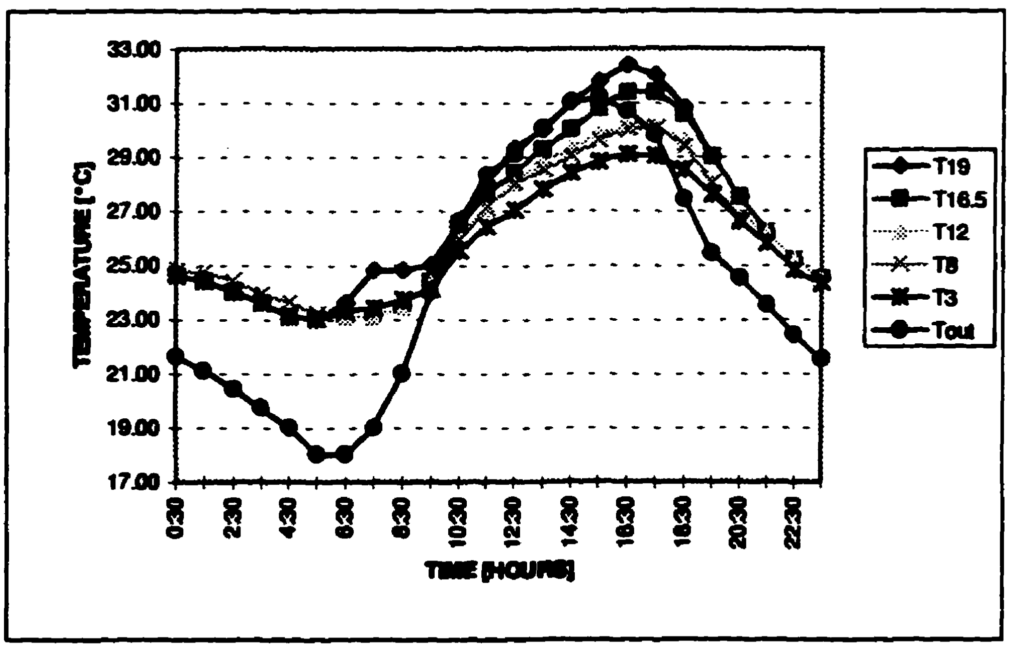


Figure 2.7 Temperature profiles in the AZG atrium for July 7, 1989 (adapted from [34])

During another warm summer day (August 20, 1989), when roof openings were closed, the maximum temperature stratification in the atrium reached about 10 °

C (29 °C at 3 m and 39 °C at 19 m from floor level). The diurnal outdoor temperature difference ranged from 17 °C to 30 °C. The temperature in the atrium ranged from 24 °C to 29 °C at 3 m and 24 °C to 39 °C at 19 m above floor level. (see Figure 2.8) The conditions in the occupied zones (balconies at all levels) from 1100 to 2100 were hotter than comfort conditions. Complaints were received very quickly during that period. The temperature in the atrium space dropped quickly after the roof vents were opened.

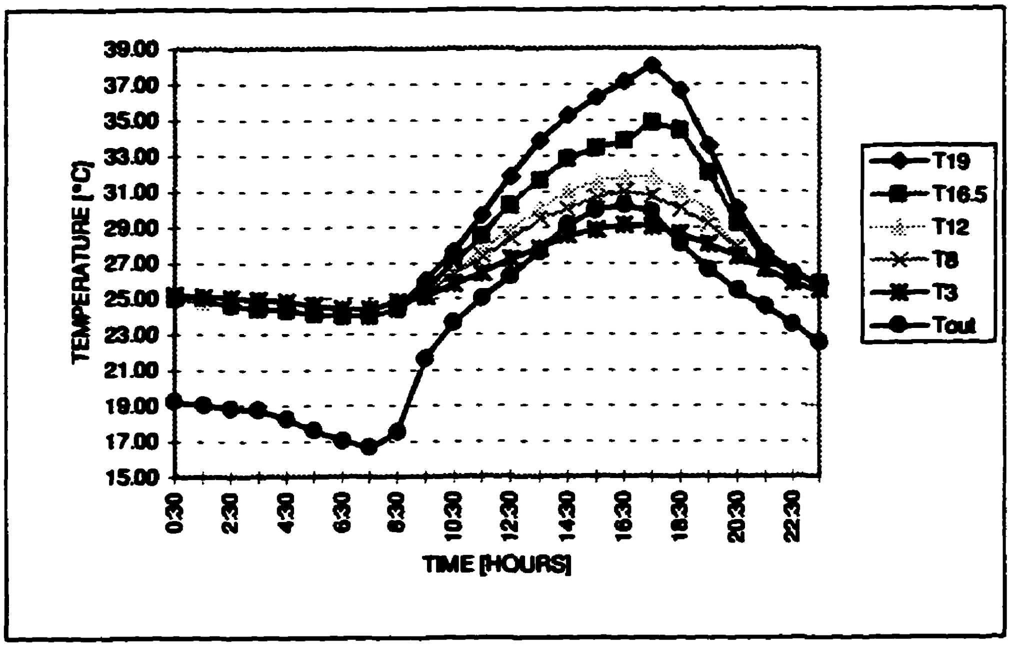


Figure 2.8 Temperature profiles in the AZG atrium for August 20, 1989 (adapted from [34])

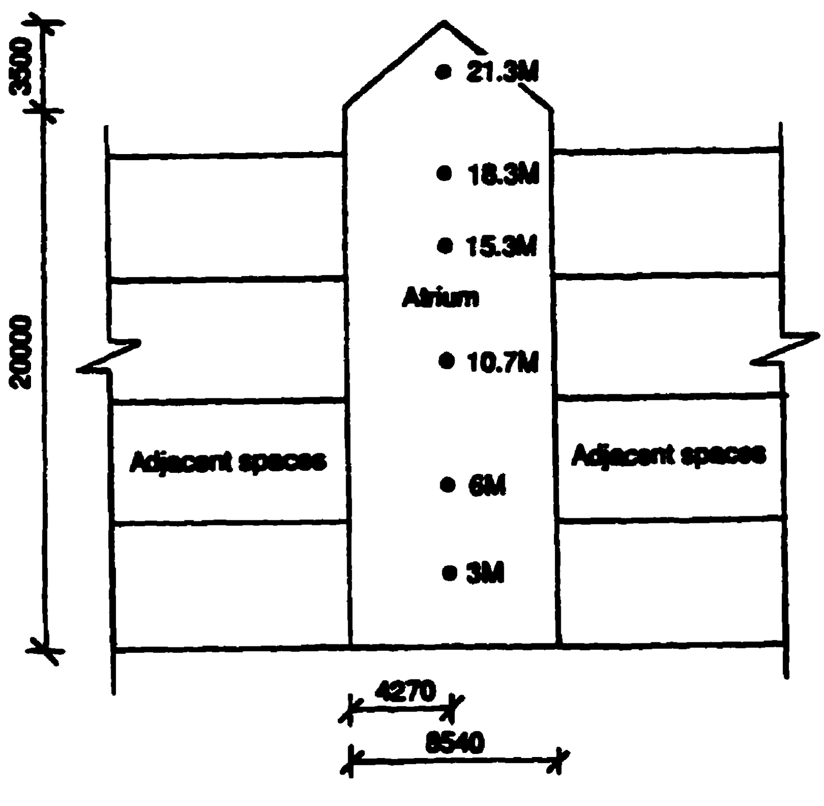
The maximum temperature stratification in the atrium was 5 °C, 4 °C, 4 °C, and 10°C in May, June, July, and August, while the outdoor diurnal temperature fluctuated from 8 °C to 11 °C, from 14 °C to 24 °C, from 18 °C to 30 °C, and from 17 °C to 30 °C, respectively. The roof vents were opened in June and July, while, in May and August, roof vents were closed. This resulted in higher temperature stratification in May and August.

The author also carried out computer simulation of thermal environment and ventilation of the atrium space. The ROOM program developed by ARUP Research and Development, London, England, was used to model the thermal behavior of the atrium space. The VENT program was used to model air flow between the atrium and adjacent spaces. The ROOM program accounts for temperature stratification and buoyancy driven air flow as well as effect of humidity. The VENT program is capable of modeling natural ventilation and patterns of air movement within a building. The author claimed that the temperatures predicted by the ROOM program correlated very well with the measured data. The median temperature differences between simulated and measured temperatures were 2.3 °C and 0.3 °C in June and July respectively, while maximum absolute temperature differences were about 5 °C in both cases, which seems high. The temperature measurements were carried out at five different heights for 4 days in different seasons. However, comparisons of simulated data with measured data were presented only for the temperature at one level (3 m above ground) for June12 and July 8. Furthermore, Simmonds did not indicate whether the error at other levels and for other periods were similar. Note that ground level temperatures exhibit the least variation.

On August 20 with vents closed, the temperature at 3 m above floor level rose to 29 °C with the outside air at 31 °C.

2.2.2.3 Experimental and analytical study on temperature stratification in atrium building

Another study conducted by Jones and Luther of two atrium buildings at the University of Michigan found that temperature stratification reached 15 ° C in the Electrical Engineering and Computing Science (EECS) atrium building on July 8, 1989, while the HVAC system was off [35,36] (see Figure 2.11). The atrium in the EECS building was 23.5 high and there were bridges on each floor to connect the two sides of building (see Figure 2.9).



section A-A (see Figure 3.7)

Figure 2.9 Section of EECS atrium building

The temperature ranged from 22.5 °C to 23.9 °C at 3m and 23 °C to 40 °C at 21.3 m above floor level. The conditions in the atrium at the main level, and the bridges at the second and third levels were within comfort conditions. The bridge at the fourth level (maximum temperature of 28 °C) was close to comfort conditions, while the bridge at the fifth (top) level (maximum temperature of 34°C was too hot. The authors reported only outdoor temperatures for March 11. Prof. Dennis Baker at the Department of Atmospheric Sciences at the University of Michigan provided additional weather data for March 10 - 11 and July 7 - 8, including temperature, solar radiation (direct normal, global, and diffuse), relative humidity, wind speed and wind directions.

The overall vertical temperature stratification pattern in the EECS atrium building in winter (March 11, 1989) was same as in summer (See Figure 2.10).

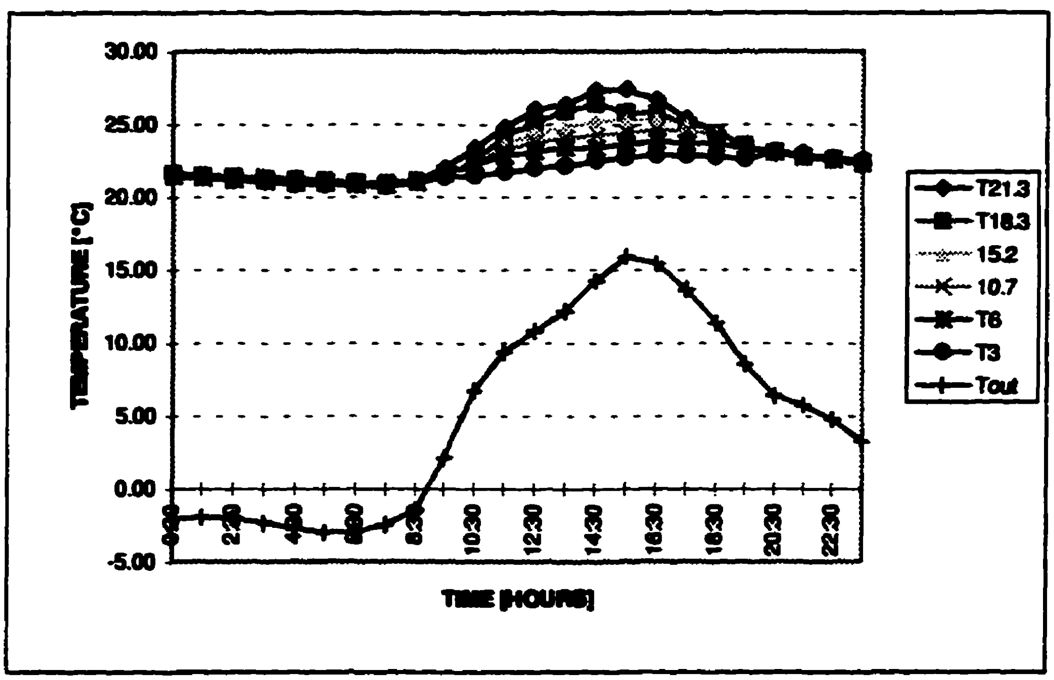


Figure 2.10 Temperature profiles in the EECS atrium for March 11, 1989 (adapted from [35])

However, indoor temperatures as well as temperature stratification were much lower in winter. The temperature stratification was only about 5 °C, and the temperatures at 3 m and 21.3 m ranged from about 21 °C to 23 °C and 21 °C to 28 °C, while mechanical ventilation was turned off in the atrium.

On July 8, temperatures at 3 m above ground level remained around 23 °C during day and night even though the outdoor air rose to 28 °C compared with the August 20 ground level temperature at the AZG atrium, which rose to 29 °C under similar conditions. This suggests that the atrium was being cooled by adjacent spaces, either through air leakage, conductive heat transfer, or both.

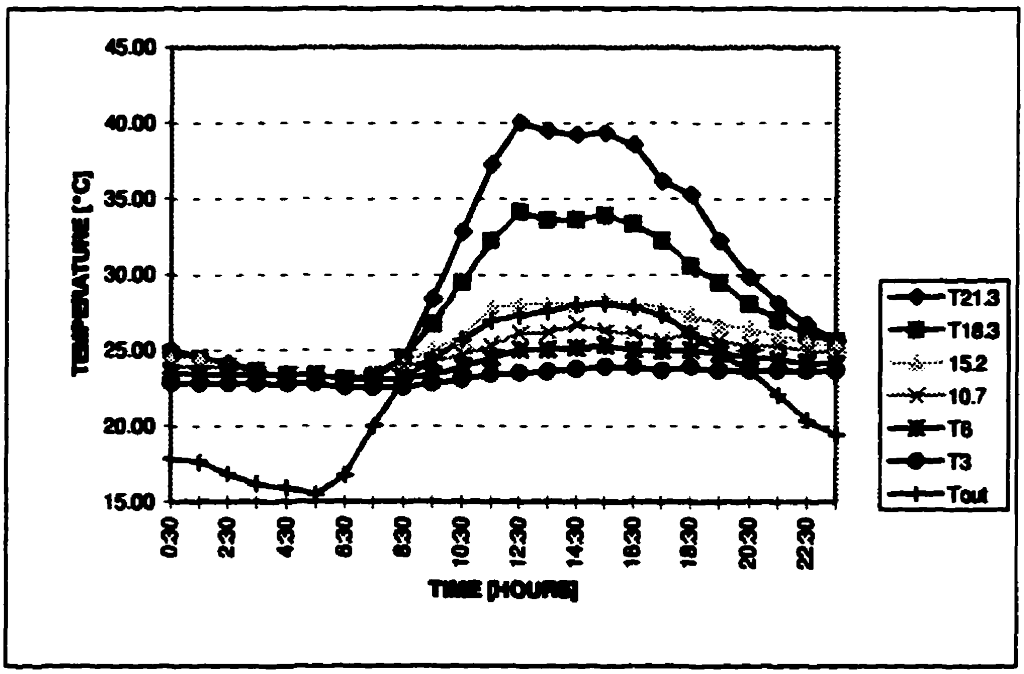


Figure 2.11 Temperature profiles in the EECS atrium for July 8, 1989 (adapted from [35])

The ventilation systems for the adjacent buildings were operating during measurements, because they were occupied. Only the ventilation system for the atrium space was turned off. Because spaces are normally pressurized by the

HVAC systems, this could produce an imbalance of air pressure between the atrium and adjacent spaces.

The authors also derived empirical equations that represent the thermal conditions inside the atriums. The equations showed that the most significant variables affecting stratification are outdoor air temperature, sun position, and global radiation, while wind speed is less significant compared with the other variables. The temperature stratification increases as outdoor air temperature, height and solar radiation increase. However, for similar outdoor conditions, it is greater in the atriums with higher SAR. The coefficients used in the equations were empirically determined for these particular atriums, so the equations can not be utilized for other atriums. Further studies covering a broad range of atrium buildings in different climatic conditions would be required to determine the coefficients that could be used for a broad range of atrium buildings.

2.2.2.4 Computer simulation study of temperature stratification

In a recent study, Kato et al. analyzed the temperature and airflow patterns in a partially conditioned, 130 m high atrium in Japan, with computational fluid dynamics (CFD) and radiation simulation [9]. As there are no partitions between the occupied spaces and the atrium spaces at any level, air flows between them. This is an east-west linear atrium with office areas on both sides and floors connected by bridges. The atrium was partially conditioned, whereas the office spaces were fully conditioned. The authors found that temperature stratification reached 8 °C (25 °C at lowest level, 33 °C at highest level) and 4 °C (26 °C at lowest level, 30 °C at highest level) without and with mechanical exhaust from the roof level respectively during summer. The authors reported that the impact of roof top ventilation on temperature distribution in the atrium was noticed only above 105 m. However, they did not mention the reasons. Furthermore, the authors failed to report the accuracy of the simulation tool.

2.2.2.5 Summary

Research has shown that temperature stratification in atriums due to thermal buoyancy may be quite high. It has also shown that the temperatures at upper levels are more dynamic, while at lower levels the temperatures are more uniform over time. Temperature stratification is a function of height, sectional aspect ratio, and outdoor temperature as well as solar radiation. There were no parametric studies that determined the general significance of each of these variables in terms of temperature stratification in atriums, although Jones and Luther did some parametric studies for two atriums.

These studies showed that temperature stratification may play a positive role in the creation of comfort conditions during mild weather, if cooler air is required only in the lower part of the atrium i.e., the floor level is the only occupied area. However, there are some limitations in using natural ventilation such as acceptable quality of outdoor air and outdoor noise levels. Passive ventilation may also create problems in terms of thermal comfort, if there are occupied zones at upper levels. Furthermore, in the case of single volume multi-story atriums and atriums with multiple occupied levels, temperature stratification may also increase cooling loads in adjacent spaces at the top due to higher temperature gradients and higher U-values of intermediate envelopes. Temperature stratification may play a negative role in winter during occupied periods, with warmer air collecting at the top and cooler air at the bottom. On the one hand, cold air at the bottom contributes to uncomfortable conditions, and on the other hand, because of greater temperature gradients, hot air at the top increases heat loss through the roof. Therefore, during winter, it is advisable to recirculate the hot air collected at the top to the bottom with the help of fans.

2.2.3 Heat transfer through atrium envelopes

The proportion of exterior glazed envelope to intermediate envelopes of atrium spaces depends upon the configuration and type of atriums.

Typically, a high proportion of the exterior envelopes of atriums is glazed and the height is considerable compared to conventional built spaces. Therefore, it is difficult to meet criteria for U-values of exterior walls and roof specified (recommended) by ASHRAE Standard 90.1. Thus overall heat loss and gain will be higher in atriums compared with conventional building envelopes. The magnitude and direction of the conductive/convective heat transfer through glazed areas are highly dependent upon the temperature and pressure gradient (due to stack effect and wind) between indoors and outdoors. Apart from conductive/convective heat transfer, extensive glazed areas will also allow large amounts of radiative heat transfer.

Glazed materials usually have higher U-values than nonglazed wall constructions. Therefore, because of extensive glazed areas, atrium spaces are affected more by outdoor climate conditions i.e., extremely high temperatures during the day and rapid heat loss during the night, and may have several problems such as over-heating in summer and mild winter, and cold drafts and condensation on glass in winter.

As a rule, intermediate walls of atriums also have higher U-values compared with conventional exterior walls, because intermediate walls are constructed with reduced insulation or no insulation at all. Furthermore, intermediate walls may be constructed without air barriers and with single-glazed openable windows. However, because of lower temperature gradients between atrium spaces and adjacent spaces, heat transfer through intermediate envelopes will still be less than through exterior envelopes, provided atrium spaces are used as buffer zones. Moreover, atriums allow an increase in the surface of glazed areas on intermediate envelopes to compensate for the reduced daylight availability in adjacent spaces because of the glazed roof and reduced sky exposure.

A glazed roof (skylight) is also a significantly different feature of atrium buildings, because of the extensive areas exposed to direct solar radiation. A large glazed roof will admit solar radiation during the day and allow radiative heat loss during the night. On the one hand, solar radiation in winter will help to reduce heating loads and, on the other hand, it will increase cooling loads in summer. Radiation heat loss at night may be utilized as a cooling strategy in summer, whereas it will increase heating loads in winter [12]. The solar incident angle is high in summer and low in winter. The intensity of solar transmission received at a surface is a function of the angle of incidence. Solar transmission will be a maximum, when the angle of incidence is 90°. Therefore, when designing the roofs of atriums, the solar angle and the orientation should be considered in order to take best advantage of solar radiation i.e., designed to capture less solar radiation in summer and more solar radiation in winter. The latter could be done by designing the slope and orientation of roofs such that the glazed surface is close to 90° with the solar incident angle. The skylight can be shaped and oriented to exclude or admit direct sunlight [16]. Furthermore, steeper roofs minimize the collection of snow, thus allowing a lighter roof construction.

Whether the atrium loses or gains heat to/from adjacent spaces depends upon the temperature gradient between them.

2.2.3.1 Summary

Previous studies have shown that atrium spaces are affected more by outdoor climate conditions than other types of spaces, because of large glazed surfaces having high U-values. Attached and envelope atriums are more sensitive to outdoor conditions than core and integrated atriums of the same size for similar conditions.

As atrium spaces act as buffer zones, heat loss and gain from adjacent spaces to atriums through intermediate envelopes can be less in winter and summer respectively. Therefore, intermediate envelopes can have higher U-values than exterior envelopes without excessive energy loss and gain compared to buildings without atriums.

2.2.4 Space conditioning

The outdoor climate is a major factor that suggests the appropriate thermal strategy for atrium buildings, followed by the thermal nature of the building i.e., whether it is heat deficit or heat surplus. According to Saxon, based on the thermal strategy, there are basically three types of atrium buildings [16], which are as follows:

1. warming atriums,
2. cooling atriums, and
3. convertible atriums

Warming atriums will be designed to maximize the capture of solar radiation through a low SAR, which will help to maintain higher temperatures compared with outdoors. A cooling atrium will be designed to admit less solar radiation through a high SAR that helps to create buoyancy-driven ventilation. Skylights should be constructed to exclude direct solar radiation in cooling atriums. Convertible atriums should be capable of working as warming atriums in winter, and as cooling atriums in summer. External shading devices that admit low-angle sun in winter and exclude high angle sun in summer help in this regard.

Warming atriums are suitable for cold climates with heat-deficit buildings, whereas cooling atriums are best for warm/hot climates with heat surplus buildings. In countries with cold winters and hot summers, convertible atriums will be most desirable.

Atriums vary widely in terms of thermal (space) conditioning, ranging from unconditioned to partially conditioned and fully conditioned [5]. The use of an atrium affects the approach to its thermal climate (see Table 2.1).

Table 2.1 Use of atrium and its thermal requirement adapted from [5])

Use	Description	Minimum temperature °C (°F)
Communication	The users do not stay in the atrium, but use it to move from one place to another or to get fresh air	10 - 14 (50 - 57)
Active use	Functions where the users move around like in a lobby, sports hall or an exhibition centre.	12 -18 (54 -64)
Relaxing, sedentary	The users are sitting down for long periods.	20 (68)
Plant growing	Greenhouse or park, minimum temperature depends on the plants	5 (41)

The arrangement of space use in atriums will affect the parts of the space that will need to be maintained at comfort conditions. From this perspective, atriums can be classified as follows:

1. small volume low-rise atriums with occupancy only at main level,
2. large volume high-rise atriums with occupancy only at main level, and
3. large volume multi-story atriums with occupancy at many levels (e.g., multi-level atriums for circulation in multi-story office buildings or multi-level atriums for circulation and small retail shops in multi-story multi-purpose buildings).

Depending upon the type of atrium (see above), the environmental control requirements will differ. Temperature stratification will be minimal in the first category of atrium, while it may be high in the second and third categories. Furthermore, temperature stratification will be a major issue in the creation of thermal comfort in the second and third categories.

As stated by Schild et al. [10], the environmental control system in an atrium should satisfy the same design criteria as conventional built space:

- satisfactory thermal comfort of the occupants,
- satisfactory indoor air quality for the occupants,
- must be energy-efficient, and
- adequate acoustic, lighting, aesthetic, and fire safty performances.

One of the most significant problems regarding the conditioning of atriums is their relatively large volumes compared with traditional commercial and institutional spaces. This may lead to high energy consumption, if atriums are fully conditioned. Most case studies [5,19] show that incorporation of atriums in buildings will only contribute to increased energy efficiency if atriums are used as buffer zones, providing passive heating during heating seasons and natural ventilation during cooling seasons. However, the case studies conducted by Landsberg et al. showed that full conditioning of atriums can also be energy efficient, if effective design strategies are implemented [22].

Jones and Luther [36] proposed some solutions for efficient conditioning of atrium spaces for both cooling and heating modes.

They suggested that two situations be considered during the cooling seasons.

- First, if the indoor temperature is not within comfort conditions and the outdoor air temperature is quite high for maintaining comfort conditions without mechanical cooling, the upper zone should be treated separately from the lower zone i.e., the atrium should be treated as two zones. When thermal stratification is highest, roof vents should be opened to allow for natural ventilation. If this is not sufficient or possible, hot air at the top level should be exhausted with the help of fans. In the lower (occupied) zone, cool air should be supplied from the bottom and return air collected at the highest level of the lower zone. However this contradicts the air distribution system for stratified cooling proposed by Gorton and Sassi. They proposed to supply cool air a few meters above the floor and collect return air at floor level. Warm air at the top of the unconditioned upper zone would be exhausted with help of fans. According to Gorton and Sassi, in such system the boundary between two thermal zones is coincident with the level at which supply air is introduced into a space.

- Second, if outdoor air temperatures are between 13 °C and 22 °C, the atrium should be treated as a single zone and naturally ventilated. If natural ventilation is not possible for some reason, free cooling (economizer operation) could be used. Under these conditions, the return air dampers should be fully closed and hot air should be exhausted from the roof vents.

Treatment of atriums as two zones will be possible if only the lower zone is occupied. However, in multi-story atriums with multiple occupied levels it might not be effective, if the occupied zones extend to a considerable height.

Jones and Luther also suggested that at least three situations be considered during the heating periods.

- First, it is possible that, at some times, indoor temperatures at the lowest level in atriums will be comfortable without mechanical heating. In such conditions, the HVAC system could be shut off and the space temperature allowed to float.

- Second, during clear winter days with moderate outdoor temperatures, the HVAC system should extract the warm air collected at the top of atriums and recirculate it to the lower zone to reduce the energy use.

- Third, during overcast winter days and nights, when the air temperature in the upper level is less than in the lower zone, the upper zone and lower zone should be conditioned separately in order to reduce energy use. The upper zone should be conditioned to prevent condensation on the glass surface, while the lower zone should be conditioned to maintain comfort conditions.

However, the first and third option work if only the lower level of the atrium is occupied. In the case of multi-story atriums with multiple occupied levels, if the space temperature is allowed to float, the temperature at the top level might be uncomfortable when conditions at floor level are within comfort levels. One of the solutions for maintaining comfort conditions in occupied zones at higher levels might be spot ventilation (conditioning) as discussed by Kato et al. [9], or enclosing bridges at higher levels and conditioning them separately. Furthermore, during overcast days, when the air temperature in the upper level is less than in the lower zone, both the upper and lower zone might need conditioning. However, during winter nights, the upper zone and lower zone could be conditioned just to prevent condensation on the glass surfaces. One of the better ways to reduce energy consumption during winter evenings and nights is to utilize heat extracted during the day. Instead of exhausting the hot air at the top to the outdoors, it could be stored in some sort of thermal storage system and used when required.

Yoshino et al. conducted an extensive survey of the trends in the design of thermal environments in atrium buildings in Japan [14]. They found that most atrium spaces were partially or fully conditioned, while unconditioned atrium spaces were very rare. The conditioning of occupied zones had been achieved by one or more options mentioned below:

1. conditioned air diffused downward from the walls or ceilings of the lower floor,
2. floor heating or cooling,
3. spot control with stand alone air conditioner,
4. air curtain systems for thermal separation between atriums and adjacent buildings,
5. air curtains to prevent upward airflow,
6. diffusing warm air on the glazed surfaces, and
7. horizontal wired glass sheets to avoid temperature stratification.

Treatment of hot air in the area under roof was provided through:

1. natural ventilation,
2. mechanical ventilation, or

3. cooling with fan coil units.

In order to control direct solar radiation in atrium spaces, the following methods were adopted:

1. blinds inside glazed roof, and
2. suspension of cloths under roof.

If the atrium space is wide, horizontal air curtains may not be effective, while installation of horizontal wired glass could be troublesome, because of difficulties in installing structures required for support.

Bender and Mills [12,19] proposed the use of atriums as supply or return air plenums integrated into building HVAC systems for energy conservation. Such a strategy is only applicable if atriums are fully conditioned. However, as noted by Hejazi-Hashemi such strategies are restricted by fire safety and smoke management regulations [23]. Use of atriums as supply air plenums will be more energy intensive than as return air plenum, because it will be necessary to maintain lower atrium temperatures during the cooling season and higher atrium temperatures during the heating season (compared with adjacent spaces) in order to maintain comfort conditions in adjacent spaces, which are the most important in terms of comfort conditions. Use of atriums as supply and return air plenums is also not advisable if there are any food outlets in the atriums, or if smoking is allowed in order to avoid spreading of air pollutants. Furthermore, the thermal loads and requirements in atriums and adjacent buildings can be quite different. It is quite possible that passive heating, natural ventilation or economizer cycle (free cooling) alone is capable of maintaining comfort conditions in atrium spaces, whereas, the adjacent spaces might require energy input for the conditioning of supply air (heating/cooling). Full conditioning of atriums will be energy intensive due to the huge volume of air. However, the authors did not mention the solutions to these difficulties.

Most people perceive atriums as indoor environments, not as outdoor or intermediate environments and therefore demand high comfort levels i.e., moderation of temperatures during winter and summer. It is often very difficult to achieve high thermal comfort and low energy consumption at the same time. A 1°C decrease in indoor temperature in winter, will decrease energy consumption by 5 percent [31]. If people are aware of such relationships, it might lead them to accept atriums with lower temperatures in winter and higher temperatures in summer (unconditioned, buffer zone) and wear appropriate clothing while in atrium spaces, thus achieving considerable savings in energy use.

2.3 Energy conservation design measures

There are many potential energy conservation measures for energy efficient atrium buildings. The most important are as follows:

1. buffer zones,
2. stratified cooling,
3. more efficient operation and design of mechanical systems,
4. passive heating,
5. optimum orientation and configuration of the atrium building,
6. passive cooling, and
7. daylighting.

2.3.1 Energy conservation by creating buffer zones

Use of an atrium as a buffer space, which is a transition space between the indoor and outdoor environments, could provide energy savings. Heat transfer through walls is a function of the temperature gradient between the two sides of the wall. Therefore, the heat transfer through intermediate walls of spaces facing an atrium may be considerably reduced compared with exterior walls, even with the high U-values of intermediate walls. This could be achieved by maintaining the temperature of the atrium slightly higher in summer and lower in winter than that in the adjacent occupied building and keeping the ratio of exposed surface to interior surface at its lowest. In a core type atrium with cubic shape, one exposed surface shields four interior surfaces of equal area. The buffering effect of atriums is beneficial whether the occupied spaces are being heated or cooled, because it reduces heat gain and heat loss during summer and winter respectively. Atriums also protect walls of buildings facing them from direct solar radiation, rain and infiltration caused by wind [12]. This can be used for conservation of historical buildings.

2.3.2 Energy conservation by stratified cooling

In conventional total volume cooling systems, the temperature of air throughout an entire space will be maintained close to the same level. In air mixing cooling systems (as opposed to displacement ventilation systems), cool supply air will usually be distributed from the top level and return air will be collected either at the bottom or top level. If the occupied zone is only at floor level, then it seems wise to maintain comfort conditions only up to a few meters above floor level, not throughout the entire volume. In such cases, a stratified cooling system could be used successfully.

Gorton and Sassi conducted model studies on stratified cooling, which is a technique of cooling only the lower, occupied zone of a high-ceiling space [37,38]. The objective of their model study was to determine the impact of various factors on the thermal behavior of high ceiling spaces with stratified cooling. They also developed a computer simulation program in order to predict temperature stratification in such spaces and found very good correlation with the measured data. Thermal loads in a thermally stratified air-conditioning system are quite different from thermal loads in conventional total volume cooling system. The authors mentioned that thermal loads such as conductive heat gain from the roof, upper zone and artificial lighting will not be part of the cooling load, while radiative heat gain through the roof and from artificial lighting will be the part of the cooling load. The thermally stratified air-conditioning system may be especially helpful in reducing some potential thermal loads by isolating them in the upper zone, thus reducing the initial and operating costs of the equipment compared with a conventional total volume cooling system for the same space. They proposed to supply cool air a few meters above the floor and collect return air at floor level. Warm air at the top of the unconditioned upper zone would be exhausted with help of fans.

It has been found that, in stratified cooling systems, the boundary between the cool zone and the stratified upper zone is coincident with the level at which supply air is introduced into a space. The cool air is supplied from a mechanical HVAC system. If the floor area is wide, it creates difficulties for the installation of the network of overhead ducts. In such cases, floor cooling systems or free standing air-conditioning units as mentioned by Yoshino et al. [14] could be used. However, the literature review did not reveal any articles on how well floor cooling systems and free standing air-conditioning units perform stratified cooling. Yoshino et al. also reported that horizontal air curtains and horizontal wired glass might help to reduce temperature stratification.

Gorton and Sassi conducted model studies and developed a computer program to determine the temperature profile and thermal loads in a thermally stratified air conditioning system and found very good agreement between measured data and computer stimulated data. However, their model study was conducted to simulate industrial environments, the thermal behavior of which is very different from the thermal behavior of atrium buildings. A large proportion of glazed surfaces is one of the most important components to be considered in atrium buildings, because of solar radiation during day and radiative and conductive heat losses during overcast winter days and nights. There were no glazed surfaces in the model study. For these reasons, this tool cannot yet be used for atrium buildings. Furthermore, it has some other limitations:

1. it does not account for the effect of the non-uniform air distribution,
2. it does not account for the effect of concentrated heat sources and their associated thermal plumes, and
3. the experiments were carried out at scale model and still need to be extended to full-scale i.e., the validation of the computer program is still incomplete.

The authors mentioned that testing of stratified cooling in full-scale spaces is planned.

2.3.3 Energy conservation by more efficient operation and design of mechanical systems

As stated earlier, use of atriums as buffer zones with passive cooling and heating is the most energy conserving strategy. However, if partial or full conditioning is required, it is still possible to build energy efficient atrium buildings through more efficient operation and design of mechanical systems.

The computer simulation case study conducted by Landsberg et al. showed that implementing efficient operation techniques such as thermostatic control (heating night set-back, cooling night set-up, increase in dead band) and destratification help to reduce energy consumption in atrium buildings. Furthermore, efficient design of mechanical systems such as use of variable air volume (VAV) systems instead of constant air volume (CAV) systems and closed loop hydronic heat pumps instead of air-to-air heat pumps reduces energy consumption. Replacement of the constant air volume (CAV) system with a variable air volume (VAV) system with variable speed fan would have reduced total energy use by 0.11 GBTU/YR (2 %) in the multifamily atrium building, Chicago, Illinois [22].

Incorporation of thermal storage techniques is another viable option for energy conservation, which might help to reduce peak demand. However, detailed economic analysis should be carried out to justify the cost-effectiveness for individual cases.

Central heat-cool, local air distribution system make energy recovery more feasible. Single duct variable air volume (VAV) systems not only reduce ducting costs, but also reduce space required for duct installation.

As in other commercial and institutional buildings, further savings may be achieved by introducing more intelligent technology (building automation) in conjunction with thermal storage techniques for improved energy efficiency of HVAC systems. Building automation helps to provide a productive, cost-effective and comfortable environment by optimizing the interrelationship among the building's structure, service and management [3]. However, detailed economic analysis should be carried out to justify the cost-effectiveness for individual cases.

2.3.4 Energy conservation by passive heating

In most commercial, industrial and office buildings, perimeter heating is not as significant a concern as lighting and cooling, because environmental control in these buildings is usually dominated by internal heat gains and ventilation requirements. Heating may be required in residential buildings, hotels or museums [10]. Many internal load dominated buildings sometimes require core-cooling and perimeter-heating.

In winter, large glazed areas help to warm an atrium by admitting large amounts of solar radiation, and massive concrete walls and floors can store the solar heat. As it is a property of glazed materials to admit solar radiation with short wavelengths and trap radiation with long wavelengths, it is possible to store large amounts of heat inside atriums. Furthermore, if that heat is stored in some kind of thermal mass, it could be recirculated into atriums in order to avoid condensation during cold nights or directed to other spaces requiring heat during the day. The problems associated with passive heating are over-heating, radiation heat loss, and down drafts. Temperatures inside atriums may rise far above comfort levels during sunny days. During overcast days and clear nights, atriums in cold regions may experience radiative heat loss as well as down drafts. However, overheating could be used for other purposes requiring heat such as drying or water heating etc.

The problem of downdrafts can be reduced either by active measures or by passive measures [39]. Active measures include increasing surface temperatures of glazed surfaces with convectors or radiation heating, while passive measures include use of glazed materials with lower U-values and protrusions (structure frame) along the glazings. The experimental studies conducted by Heiselberg et al. have shown that it is possible to improve comfort conditions in the occupied zone by using the structural system as an obstacle in the boundary-layer flow in glazed facades. They also found that depth of the structural frame should be greater than the critical depth, in order to separate the boundary layer flow.

The potential for utilization of direct solar radiation depends upon the proximity to taller buildings and orientation of the building, which determines the availability of direct solar radiation.

2.3.5 Energy conservation by orientation and configuration

Orientation of glazed surfaces is one of the most important design considerations for energy conservation in atrium spaces. The impact, however, is far more important for linear atriums than for square atriums [13]. Furthermore, sensitivity to orientation and slope decreases as U-value and visible transmission decrease [31]. As it is difficult to control low-angle solar radiation, it is better to avoid east- or west- oriented glazed walls; north- or south-oriented atrium are preferable [this may be less effective in the Canadian climate, because of lower sun angles]. In an internal load dominated building in a warm climate, a glazed wall facing north (polar) is useful to avoid solar gain, while preserving a glare-free view. For instance, at One West Loop Plaza in Houston, Texas, a tinted glass skylight and north wall preserves views while minimizing solar gain. In cool climates, a south (equator)-oriented atrium wall is the most useful, particularly if it is designed to keep out high-angled summer solar radiation while admitting low-angled winter solar radiation for passive solar heating. The Children's Hospital of Philadelphia adopts this strategy, utilizing open play decks as summer shading devices [40].

Configuration of atriums is another important design factor for energy conservation, whether unconditioned, partially conditioned or fully conditioned. For attached and linear atrium buildings with equal area, the former will be more energy-conserving, if the atrium is unconditioned, while the latter will be more energy-conserving if the atrium is partially or fully conditioned [31], because of the large proportion of exterior glazed surfaces exposed to outdoors in attached atriums. Likewise, core-type atriums will be more appropriate if full conditioning is required, because less glazed surface is exposed to outdoors than in the envelope type. Furthermore, the temperature swing is likely to be more profound in attached atriums than in linear atriums with the same area, because of the increased ratio of glazed to intermediate surfaces. Atriums with high SAR are subjected to greater temperature stratification causing high stack effect, while low SAR and high PAR are more appropriate for daylighting, passive heating, and radiative cooling.

2.3.6 Energy conservation by passive cooling

As atrium buildings have extensive glazing and are usually used during daytime, they may require cooling for the majority of annual operating hours even in cold climates. Passive cooling techniques proposed by Bednar [12] are as follows:

1. control of solar heat gain (shading),
2. use of thermal mass,
3. radiative cooling, and
4. convective cooling

In summer, solar shading devices may reduce solar heat gain. Vertical exterior shading devices are most effective on the east and west for lower sun angles, horizontal on the south for higher sun angles. For example, a system of metal baffles is mounted above the skylights to modify the incoming daylight at the Yale Center for British Art, New Haven, Connecticut [41]. However, fixed shading devices may reduce solar heat gain during winter and have a negative effect overall. For example, as mentioned by Landsberg et al. [22], increases in heating loads due to fixed shading are three times greater than the decrease in cooling load in case studies conducted in Albany. Variable external shading is the best in terms of efficiency, but the cost is comparatively high [31].

The thermal mass of the building can help to reduce the temperature of the building at night, and ultimately absorb the heat generated in buildings during the daytime. This concept works well in climates where night temperatures drop below 20 °C and the diurnal temperature swing is 8 to 11 °C. At night, the cold air from outside can be used to flush the heat absorbed in an atrium during daytime and to cool the rock bed. During the daytime cool air from rock beds may be supplied from the bottom of the atrium. "The Gregory Bateson Building at Sacramento, California was designed to actively utilize such a cooling strategy" [42]. However, as reported by Landsberg et al., the effect of thermal mass variations on heating and cooling load of atriums will be minimal as diurnal outdoor temperature swing decreases. The case studies conducted in Albany, showed that a 100 % increase in atrium mass reduces peak system load and building energy use by only 1.2 % and 0.2 % respectively.

The cold night sky and the polar sky during mild summer days can serve as a heat sink for the radiative cooling of a building. Heat will transfer most effectively by means of radiation from a warm atrium to the cooler area of the sky, if the sky is clear. The potential for radiative cooling decreases as the sky becomes cloudy or humid. However, night insulation might be required to prevent radiative cooling during cold winter nights, but it is not a very popular option [31].

Convective cooling (natural ventilation) is mainly based upon the stack effect, which increases as SAR increases and PAR and AR decrease. Natural ventilation driven by stack effect might be capable of maintaining comfort conditions in regions with mild summers. Furthermore, convective cooling might also be driven by wind, if openings are placed at correct locations. However, this strategy is limited to buildings with internal loads of less than 50 w/m^2 [19] and acceptable outdoor air quality and noise levels. One of the most important conditions for natural ventilation is that the temperature of outdoor air should be less than the temperature of indoor air.

Even though the above-mentioned passive cooling techniques are not suitable for cooling large atrium buildings, they could be very helpful in the reduction of cooling loads and will reduce the initial and operating cost of HVAC systems to some extent.

Another possible passive cooling technique in hot and dry climates is incorporation of evaporative cooling into natural ventilation provided there are large exposed water surfaces such as water fountains, water falls or ponds. Large atrium spaces provide excellent opportunities to utilize such strategies, which are not only visually stimulating but also energy-conserving. However, condensation on glazed surfaces should be avoided.

2.3.7 . Energy conservation by daylighting

Energy consumption by artificial lighting in Europe is about 50 percent of total electrical energy consumed in commercial, institutional and office buildings [43]. In North American countries, it accounts for only about 20 percent [44]. Therefore, it is a potential area to reduce building energy use as well as peak energy demand. The daylighting potential of atriums depends upon their ability to admit daylight to adjacent spaces [13].

According to Hastings, an atrium reduces daylighting by 20% compared to an open courtyard [5]. However, this can be offset by increasing glazed surfaces in the intermediate envelope without increasing thermal loads to the adjacent spaces, because of lower temperature gradients between the atrium and adjacent spaces.

There is a wide range of glazing materials available to control solar transmission, light transmission, and U-values. One disadvantage is that it affects the whole year. Dark colors might give a continuous dull impression [45].

Glazed materials with high U-value (2.7 W/m^{2}K) are preferable for skylights to ensure melting of snow in cold regions. Glazed materials with U-values of 2.0 W/m^{2}K are preferable for facades. Transparent insulation with U-values of 0.3 W/m^{2}K is also available. However, glazing with U-values less than 1 W/m^{2}K is very costly, thus not economically viable at this time [31].

Larger glazed areas in atriums will help to admit more daylight into the centre of a building and allow reductions in the use of artificial lighting. Artificial lighting not only consumes electrical energy and also produces a large amount of heat, which eventually increases cooling loads in hot weather, but may decrease heating loads in cold weather. However, orientation, high solar radiation, and extensive glazed surfaces may have an adverse effect on the thermal performance of buildings. According to Landsberg et al. [22], one should be very careful when increasing glazed areas to increase natural lighting, because increases in cooling loads due to extensive glazed surface may be greater than the combined reductions in lighting and heating loads. Furthermore, in the Canadian context, where the cost of electricity is quite high compared with the cost of natural gas, decreasing heating loads by heat dissipation of artificial lighting during cold seasons is not economically rational. Thus, increasing daylighting may reduce not only the cost of electricity for artificial light, but also the initial and operating cost of HVAC systems [12,46]. For each case, it is necessary to determine the optimal balance between daylighting, cooling and heating loads in a way that ultimately reduces total annual energy use.

One of the most critical characteristics of daylighting is its variability. The availability of daylighting at any place depends not only upon the season and geographical location but also on weather conditions (specially sky conditions), and proximity to tall buildings and local terrain (obstruction, reflection) [3]. Thus, artificial lighting is necessary for overcast days and night-time use.

2.4 Design criteria and recommendations for energy efficient atrium buildings

Several studies were conducted to increase our understanding of the thermal behavior of atrium buildings. However, we still lack definitive guidance for energy efficient atrium building design [21].

Luther et al. gave some recommendations for design and operation of HVAC system, which are as follows [36]:

1. HVAC systems for atriums should be capable of handling atriums as two zones and as a single zone depending on indoor and outdoor conditions.

2. Due to higher return air temperatures, the economizer changeover temperature should be "carefully reset or an enthalpy controller should be used". However, no explanation of the meaning of "careful" or of the enthalpy control strategy was given.

3. Sometimes outdoor conditions allow the provision of economizer operation to maintain comfort conditions in atriums. These conditions should be identified and incorporated into energy management strategies. Openable louvers should be provided near the roof to allow for natural ventilation and avoid overheating.

However, they did not provide information such as determination of thermal loads, size of openings required, maximum temperature in the atrium space, maximum temperature stratification etc. and the ways temperature stratification will affect annual energy use.

Kainlauri et al. conducted field studies on five atrium buildings at Iowa State University for several years [7,47,48]. Although the authors claimed that they offered design criteria for energy efficient atrium buildings with different orientations and interfacing of environmental system, the guidance was vague. The options were not supported by quantitative information, nor were methods provided for application of the criteria. For example, they did not mention the significance of orientation, ratio of glazed to intermediate envelope, the best way to minimize temperature stratification in multi-story atriums, and how to determine the volume of loft (below roof) area etc. Furthermore, the authors carried out snap measurements with handheld measuring equipment only at the main level and fifth levels, 3 times/day, 1 time/week (on the same day) throughout the season, not with a dynamic data recorder for continuous measurement. Therefore, the results obtained are neither sufficient nor very reliable.

2.5 Prior research done in Canada

As mentioned earlier, no articles on the thermal behavior and energy performance of atrium buildings were found.

2.6 New approaches for modeling temperature stratification

One of the major current problems regarding the modeling of thermal behavior of atriums is that most building energy simulation programs do not offer air flow modeling and assume homogeneity of air temperatures within a thermal zone (e.g., DOE-2, tsbi3, TRNSYS). ESP-r [5] also assumes homogeneity of air temperatures within a thermal zone. However, this program is capable of simulating buoyancy driven air flow and radiant energy transfer between zones. Hensen [49] used a customized version of ESP-r to model thermal stratification in an office by dividing the space to be treated into several sub-zones separated by fictitious floors. Each sub-zone was represented as a node in a mass flow network. The nodes were linked by connections which could be modeled as window cracks, doors, openings, or ducts. The mass flow network approach is based on the assumption that there is a simple nonlinear relationship between the flow through a connection and the pressure difference across it. Conservation of mass for the flows to and from each node leads to a set of simultaneous nonlinear equations that must be solved. Hensen mentioned that modeling of mass flow by network approach requires:

1. translation of the real world problem into nodes and connections,
2. determination of boundary conditions,
3. mathematical and numerical characterization of fluid flows and pressure difference relationships, and
4. solution of the resulting set of simultaneous (non-linear) equations.

The first two tasks are to be accomplished by the user, while the latter two are performed by a mass flow modeling module called mfs.

2.7 Conclusions drawn from the literature review

The reported research was of two distinct types. It focused on energy use of atrium buildings, to be more specific, on the energy effects of the integration of atrium into buildings or on the thermal behavior of atrium spaces i.e., temperature stratification and stack effect.

The methods used in the investigations included both field measurements and computer simulations. Energy use was investigated by both field measurements and computer simulations, while temperature stratification and stack effect were investigated mainly by field measurements.

A principal difficulty existing at the present in modeling temperature stratification and stack effect is that most existing energy simulation programs are incapable of modeling thermal buoyancy and the transfer of solar radiation transmission into adjacent zones.

Most of the simulation tools used in the research were of the following type:

- capable of simulating annual energy use but incapable of simulating mass flow and predicting temperature stratification (DOE 2.1B, TARP),
- capable of predicting temperature stratification with mass flow but incapable of simulating annual energy use (VENT and ROOM), and
- capable of predicting annual energy use and natural ventilation but not temperature stratification (PI-Group).

Furthermore, some of the energy simulation programs claimed to be capable of modeling multiple zones are proprietary programs (FRES, ROOM & VENT, ROYAL DEBAC), the algorithms of which may not be open to public scrutiny. Among them, only FRES is capable of taking account of temperature stratification in atriums.

Some researchers used CFD numerical simulation, which is capable of predicting temperature stratification and air flow. This approach is based on the solution of conservation equations for mass, momentum and thermal energy on all grid points inside or around the object under investigation [48]. However, this approach is still in its initial stage of development and is restricted to snap modeling. Otherwise, it will consume excessive central processing unit (CPU) time. It is only suitable for use at the final stage of design. Other major drawback is that the user must have an extensive knowledge of HVAC and fluid dynamics, numerical methods, and building engineering [10].

Therefore, it is desirable to use a simulation tool that could simulate annual energy use and predict temperature stratification with mass flow. ESP-r offers this possibility. ESP-r is capable of simulating temperature stratification and buoyancy driven air flow in atrium spaces as well as plant systems and energy use.

In order to simulate energy use of atrium buildings with reasonable accuracy, it should be capable of modeling the thermal behavior of atrium spaces reasonably accurately i.e., take account of temperature stratification, transmission of solar radiation to adjacent zones, stack effect due to thermal buoyancy, etc.

CHAPTER 3
METHODOLOGY AND PROCEDURES

3.1 Scope of the research

Investigation of computer simulation of the thermal behavior of atriums was the major task of this research. It was done with an existing energy simulation program called ESP-r (Environmental Systems Performances-research) version 9.0. The major purpose of this research was to assess the ability of ESP-r to model the thermal behavior of atrium spaces. In order to broaden the investigation, computer simulations were carried out for two atrium buildings in different geographical locations under a wide range of climatic conditions. Data were obtained for an atrium at a hospital complex at Groningen, the Netherlands (see 2.2.2.2) and the EECS (Electrical Engineering and Computer Science) Building at the University of Michigan, Ann Arbor (see 2.2.2.3).

The investigation was carried out to identify the temperature distribution field (temperature stratification) in atriums, while ventilation systems were off i.e., dynamic natural temperature stratification. The temperature stratification induced by thermal buoyancy is one of the major characteristics of atrium buildings that can play a crucial role in maintaining comfort conditions.

3.2 Computer simulation

Hand calculations are not only tedious, they also fail to give accurate results. As mentioned by Moser et al. "The heat balance of a real building is never in perfect equilibrium. Transient heating up or cooling down of walls and other thermal mass calls for time-dependent simulation"[6]. The need for dynamic computer simulation programs has long been realized. A variety of building energy simulation programs has been developed. These programs vary in many ways - for instance, method of determining thermal loads, the number of thermal zones and systems allowed, types of equipment that can be modeled, and time step used in simulation.

Public domain energy simulation programs such as DOE-2, BLAST, TRNSYS, tsbi3, and MBDSA have been used for simulating the thermal behavior and performance of buildings for a long time. However, these computer tools are not suitable for predicting the thermal behavior of atriums, because they do not account for temperature stratification, mass flow or radiative heat transfer between zones.

3.2.1 Description of ESP-r version 9.0

3.2.1.1 Overview

One of the main reasons for choosing ESP-r is its capability of modeling air flow and transfer of radiant energy between thermal zones. Furthermore, it is available for research purposes for a nominal fee and widely used in Europe.

In order to evaluate the energy use of atrium buildings and the impact of temperature stratification on energy use (e.g., for passive ventilation), it is desirable to evaluate the capacity of ESP-r to simulate temperature stratification.

The earliest version of ESP-r was developed by Prof. Joe Clarke at the University of Strathclyde, UK in 1977 as a part of his doctoral research. In 1987, the Energy Simulation Research Unit (ESRU) was formed, in order to address the problems facing environmental simulation. Since then, many researchers have participated in developing ESP-r and have improved it in several ways. Hensen incorporated fluid flow and plant simulation during his doctoral research [50].

ESP-r is a dynamic thermal (energy) simulation system, which is capable of modeling a diverse set of features such as building envelope, mass flow, and plant systems. It consists of interrelating major program modules such as project manager (prj), simulation (bsp), result recovery and display (res), database management (db) and report writing (rw).

Each of the major program modules is comprised of several sub-modules. For example, project manager handles geometry, constructions, operations control, shading/insolation, view factors, site obstructions, system configuration, system control, and the mass flow network. Geometry, construction, operation, system configuration, and transparent constructions (if there are glazed surfaces) files are required. Shading/insolation, view factors, site obstructions, system control, mass flow network, utility, and casual gains control are optional files that are supplied in order increase the detail of the simulation.

Project manager deals with defining a building and/or plant system configuration. One or more zones within a building can be defined. The description of a building is comprised of the geometry of spaces as well as construction details. User-defined operation schedules can specify internal loads such as lighting, occupancy, and equipment. A control file may be used to define control algorithms and project-specific control conditions. If no control law is specified, simulation will be done for free-floating conditions. To simulate air flows (both wind-and buoyancy-driven) among zones and to/from outdoors, a mass flow network must be defined. The insolation module predicts time-series insolation of internal surfaces due to solar penetration through glazed areas, while the shading prediction sub-module predicts the time-series shading of facades by site obstructions.

All ESP-r modules are invoked from the project manager.

The building simulation program (bps) uses the system configuration file to model heat and mass transfer for user-defined periods with a user-defined time step. This can provide information on thermal behavior and energy use of the specified building and produces simulation results. It requires hourly weather data. Weather data must be provided for the period of simulation. The simulator can handle problems related to building, heat flow, mass flow, and plant systems separately and/or combined.

The results analyser (res) gives access to the results files generated by the simulator. Output options available include perspective visualizations, results interrogation, statistical analysis, graphical display, tabulations, frequency binning, and 3D plotting. Graphical display includes time:variable graphs, variable:variable graphs, pie charts 3-D surface plots of a variable over time, temperature profiles within constructions and histograms, while tabular facilities consists of casual heat balance and zones and surfaces, time step listings for most temperatures and fluxes within a problem, interrogation of maximum and minimum values and comfort analysis.

The database management module may employ pre-existing or user-defined databases such as primitive elements (e.g., glazing, type of concrete), composite constructions, optical properties, event profiles, temporal definitions, climate, pressure distributions and plant components. Primitive and composite construction databases contain thermophysical and optical properties of construction materials. Event profiles consist of a number of project-specific time-dependent variations in zone occupancy, lighting, plant control, and equipment (e.g., specific predefined operation schedules), while the plant database consists of standard plant components. The climate database contains hourly climatic data for diffuse horizontal solar intensity, dry bulb temperature, direct normal solar radiation, wind speed, wind direction, and relative humidity. It also contains the latitude, longitude difference, altitude and name of the city. The default climate database contains climatic data for several European cities. The temporal definition database includes facilities to describe schedules or events and time-dependent data required for combined heat and mass transfer simulation.

Most of these databases are in binary format for random access and data security. However, ESP-r also provides an option to have these data in ASCII format for editing and transmission.

The calculation of buoyancy driven airflow in mfn is similar to the approach proposed by Walton [51]. In this method, homogeneity of air temperature and pressure within a single volume is assumed. A volume of air is represented by a node and connected by some fluid flow components as shown in figure 3.1.

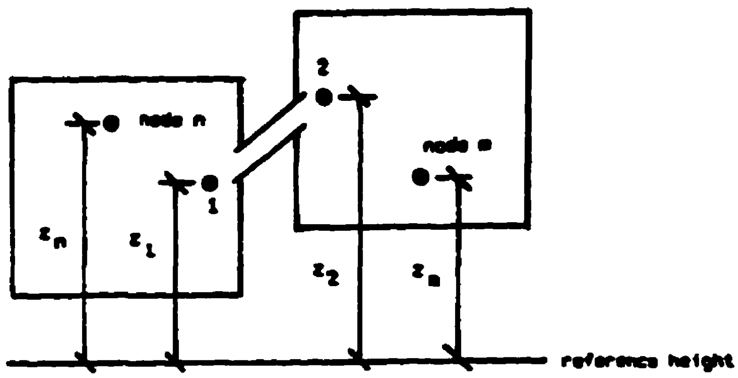


Figure 3.1 Schematic two-volume configuration (adapted from [50])

Analysis of fluid flow through a connecting component i is based on Bernoulli's equation for one-dimensional steady flow of an incompressible Newtonian fluid as mentioned below.

$$\Delta P_i = (p_1 + \sigma v_1^2/2) - (p_2 + \sigma v_2^2/2) + \sigma g\,(z_1 - z_2) \qquad [Pa]$$

The density of fluid is always density of fluid at inlet. Therefore, depending on the direction of flow, it might be σ_n or σ_m.

The stack pressure can be calculated using following equations.

If flow is in the positive direction:

$$Ps_i = \sigma_n g(z_n - z_m) + h_2 g\,(\sigma_m - \sigma_n) \qquad [Pa]$$

If the flow is in negative direction:

$$Ps_i = \sigma_m g(z_n - z_m) + h_1 g\,(\sigma_m - \sigma_n) \qquad [Pa]$$

Where,

ΔP_i	⇒ sum of all frictional and dynamic losses	[Pa]
Ps_i	⇒ stack pressure	[Pa]
p_1, p_2	⇒ static pressures at inlet and outlet	[Pa]
v_1, v_2	⇒ velocity of fluid at inlet and outlet	[m/s]
z_1, z_2	⇒ inlet and outlet elevation from reference height	[m]
z_n, z_m	⇒ elevation of nodes n and m from reference height	[m]
σ	⇒ density of the fluid flowing through the connecting component	[kg/m³]
g	⇒ acceleration of gravity	[m/s²]
$h_1 = z_1 - z_n$		[m]
$h_2 = z_2 - z_m$		[m]

ESP-r version 9 runs on UNIX workstations. In principal, ESP-r can be ported to any machine. However, a SUN Sparcstation with X-windows is the preferred environment. It also requires at least 8 MB of RAM and 100+ MB of hard disk, X windows version 11 revision 5, FORTRAN 77 and C compilers. A laser printer is required for hard copy of graphical outputs.

One of the strengths as well as weakness of ESP-r is its ability to offer multiple ways to represent and analyze problems in order to emphasize particular design aspects and deal with parameter uncertainty. The other characteristic of ESP-r is that it assumes that the problem has meaning in a thermophysical sense -i.e., it has no internal capability to check semantics. While an expert will benefit from this, a beginner often will feel discouraged.

Readers interested in the theoretical basis of ESP-r are advised to consult the following references:

Clarke J.A., Energy Simulation in Building Design, Adm Hilger Ltd, Bristol and Boston, 1985.

Hensen J.L.M., On the Thermal Interaction of Building Structure and Heating and Ventilation System (sic), Doctoral Dissertation, University of Eindhoven, 1991.

3.3 Description of test sites

3.3.1 AZG atrium

3.3.1.1 Building orientation and location

The AZG hospital complex at Groningen, the Netherlands, is located at 52° north latitude. The thermal behavior of atrium building in a hospital complex at Groningen was reported in the literature review (see 2.2.2.2).

3.3.1.2 Building geometry

This is a large building complex with 9 atriums. The atrium where temperatures measurements were made has a floor area of 560 m^2 and is 20 m high as shown in Figures 2.4 and 3.2. For purposes of simulation, the atrium geometry was simplified to a rectangular plan having the same floor area as the actual atrium as shown in figure 3.3. The atrium is a linear type and used for circulation. It is open to corridors (balconies) from adjacent spaces in terms of spatial connections to them. There are several balconies at each level on either side of theatrium. Therefore, the main level and balconies are the occupied zone. The atrium is bounded to its full height by the ward to the north and the main hospital to the south. The atrium is bounded by circulation spaces at the first level only on the east and west sides. The upper east and west walls are exposed to exterior conditions.

The flat roof of the atrium was made of double-skinned PVC with 80% transmittance. The aspect ratio of the atrium is 1.4, while the sectional aspect ratio is 1.1 and the plan aspect ratio is 0.66.

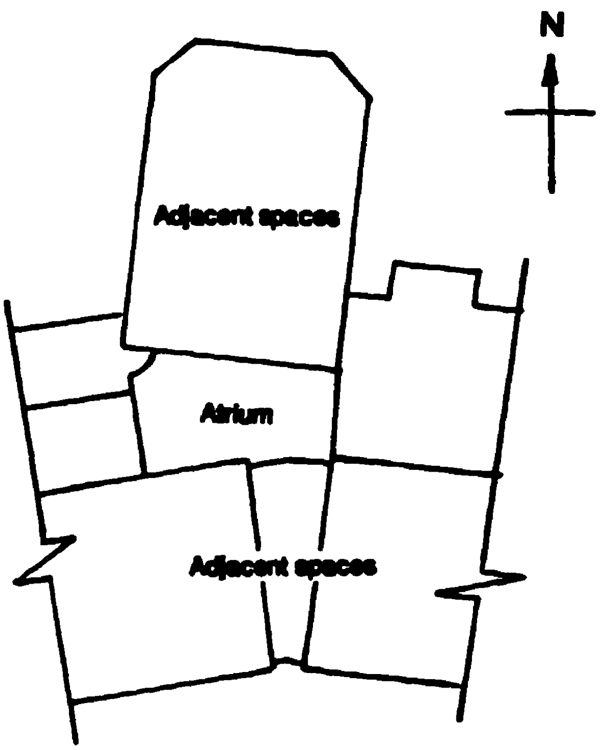


Figure 3.2 Plan of AZG atrium building
(second atrium at a hospital complex at Groningen)
(adapted from [33])

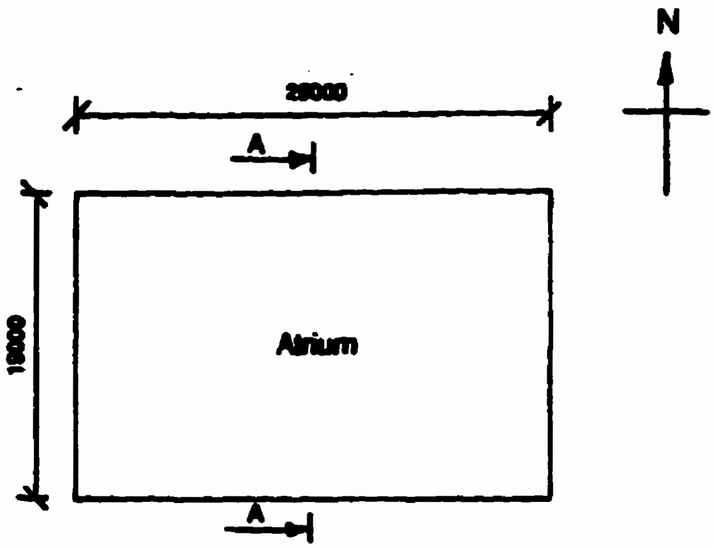


Figure 3.3 Simplified plan of AZG atrium

3.3.2 EECS Atrium

3.3.2.1 Building orientation and location

The EECS atrium building at the University of Michigan, Ann Arbor, is located at 42° north latitude. Its thermal behavior was reported in the literature review (see 2.2.2.3).

3.3.2.2 Building geometry

The EECS building is a four-storey building 105 m long, 85 m wide and 19 m high. The atrium is 91 m long, 9 m wide, and 23.5 m height, and is located along the center of the building as shown in figures 2.9 and 3.4.

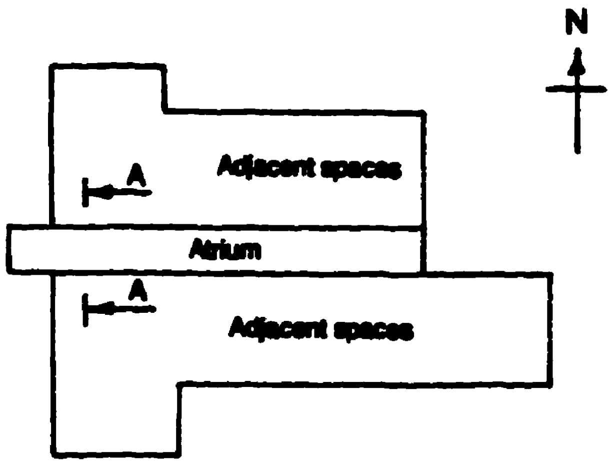


Figure 3.4 Plan of EECS atrium building, the University of Michigan, Ann Arbor (adapted from [33])

The atrium is of the linear type and separated from adjacent spaces in terms of spatial connections to them. It used solely for circulation. Several bridges cross the atrium. Therefore, the main level is the only occupied zone except the bridges on each level.

The roof of the atrium has a double-glazed skylight with a 40° slope. The aspect ratio of the atrium is 1.9, while the sectional aspect ratio is 2.3, and the plan aspect ratio is 0.1.

3.4 Thermal zoning of atrium buildings

3.4.1 AZG atrium

3.4.1.1 Identification of key parameters of the AZG atrium

Basic calculations were made to determine the relative significance of various heat transfers on the thermal behavior of the AZG atrium.

Conduction heat transfer through the exterior and interior envelopes could be calculated using equation (1). The radiation incident on the skylight could be approximated by equation (2). The ventilation load could be estimated using equation (3).

$q_{cond} = U\,A\,\Delta t$	[W]	(1)
$q_{rad} = G_{global}\,A$	[W]	(2)
$q_{vent} = 1200\,v\,\Delta t$	[W]	(3)

where,

q_{cond}	⇒	conductive heat transfer	[W]
q_{rad}	⇒	radiative conductive heat transfer	[W]
q_{vent}	⇒	ventilation load	[W]
U	⇒	overall heat transfer coefficient	[W/m^2°C]
A	⇒	area	[m^2]
Δt	⇒	temperature gradient	[°C]
G_{global}	⇒	global radiation	[W/m^2]
v	⇒	airflow rate	[m^3/s]

The peak conductive heat transfer through the exterior end walls will be about

$$q_{cond} = U\,A\,\Delta t$$

$$= 0.4 \times 380 \times 2 \times (25 - 9.5)$$

$= 4712$ W

$\approx$ 5 kW

The peak conductive heat transfer through the interior walls will be about

$q_{cond} = U\ A\ \Delta t$

$= 1.7 x\ 580 \times 2 \times (27.5 - 22)$

$= 10846$ W

≈ 11 kW

The peak conductive heat transfer through the skylight will be about

$q_{cond} = U\ A\ \Delta t$

$= 2.8 \times 560 \times (25 - 9.5)$

$= 23870$ W

≈ 24 kW

The peak radiative energy incident on the skylight will be about

$q_{rad} = G_{global}\ A$

$= 700 \times 560$

$= 392000$ W

≈ 392 kW

The peak heat loss through ventilation for 1 ACH will be about

$q_{vent} = 1200\ v\ \Delta t$

$=1200 \times 3 \times (20 -(-3))$

$= 55800$ W

≈ 56 kW

The peak heat loss through ventilation for 6 ACH (maximum ventilation rate) will be about

$q_{vent} = 56 \times 6$

$= 336$ kW

Based on the calculations, it is obvious that the influence of the radiative heat gain is the most significant followed by the ventilation load. The influence of the conductive heat transfer through perimeter walls is minimal. However, the influence of the conductive heat transfer through the skylight on the temperature of the top zone is significant.

3.4.1.2 Observations on temperature stratification at the AZG atrium

During all 4 days for which data were published (see 2.2.2.2), the night time atrium temperature remained at 21 °C or higher when the outdoor temperature was as low as 9 °C. Therefore, the air passing through the atrium due to stack effect must be heated air drawn from the adjacent spaces. This is consistent with Simmonds' observations.

The mass flow model had to show this effect of warmed air being drawn from the adjacent spaces.

3.4.1.3 Computer modeling of the AZG Atrium

It was decided to model the AZG atrium space as a simple single zone in order to show that single zone modeling is not capable of representing the dynamic thermal behavior of atriums at different heights (see figure 3.5). The thermal zones of atrium spaces are quite different from geometrical zones. The atrium itself is a single zone in terms of geometry, while there are several thermal zones in terms of thermal conditions. The next step was to model the atrium as multiple zones. The atrium space was divided into different thermal zones stacked over each other as shown in figure 3.6, in order to consider thermal stratification as suggested by Hensen [49]. The zoning of the atrium is based on the measurement locations.

In order to model mass flow in the atrium, each thermal zone was represented by a node. The nodes are connected by airflow components. In order to allow mass flow between zones, the mass flow network included a large orifice (40 m^2) between each set of adjacent atrium zones. The skylight of the atrium is defined as double-glazed, exterior surface having direct normal transmittance of 0.611 (the default value in ESP-r). For June 12 and July 7 simulations, when the roof vents were open, the mass flow network included an orifice of 40 m^2, equal to the area of the roof vents. For May 6 and August 20 simulations, when the roof vents were closed, the mass flow network included an orifice of 2 m^2 at the roof. It was chosen to provide an airflow of about 1 ACH, based on Hejazi-Hashemi's observation regarding air change for an atrium with roof vents closed and openings at lower level opened.

The walls facing east and west were modeled as opaque exterior walls, while walls facing north and south are modeled as partitions. The environment on the other side of these partition walls is specified as constant temperature of 22 - 23 °C. The boundaries between atrium zones are specified as transparent "fake" walls with very high U-values (2.7 W/m^2K). The construction details and thermophysical and optical properties of all envelopes may be found in the relevant construction files in Appendix 2.

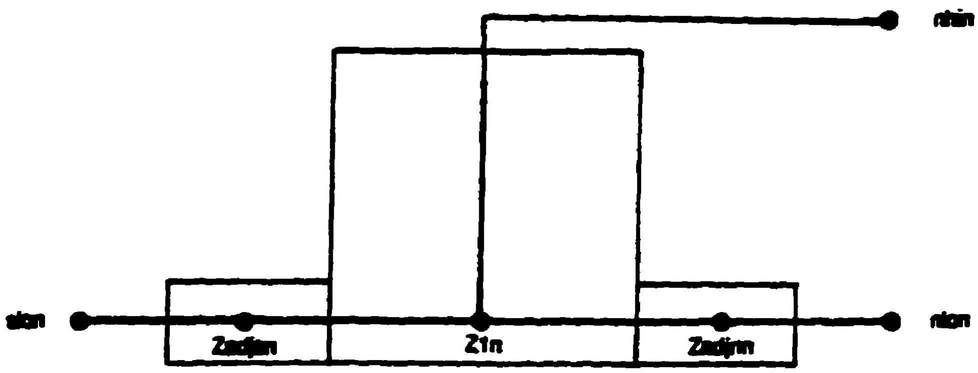


Figure 3.5 Mass flow network for single zone AZG model

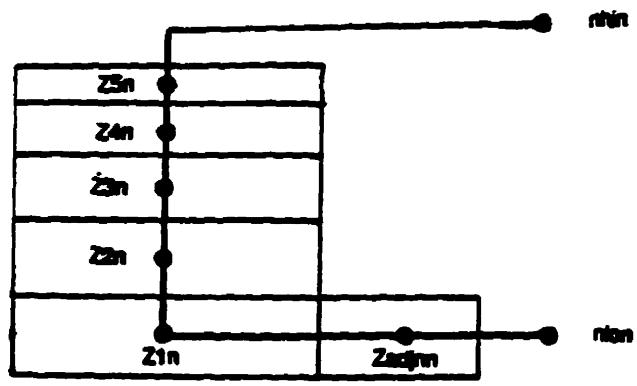


Figure 3.6 Mass flow network for 5-zone AZG model

3.4.1.4 Simulation conditions

As we were modeling natural temperature stratification in atrium spaces, the control algorithm was specified as free floating. Simmonds mentioned that the roof is made of double-skinned PVC with 80% transmittance. He also said that the roof system was designed to exclude direct sunlight and admit diffuse skylight. However, he did not give some optical properties of the roof, such as solar transmittance. Therefore, simulations were run with default direct normal solar transmittance value of 0.611. Simulation with direct normal transmittance of 0.8 resulted similar temperature profiles, but higher airflows. Casual gains for occupancy and lighting were set at zero in the operation schedules. The operation schedules specified are attached in Appendix 2.

3.4.2 EECS atrium

3.4.2.1 Identification of key parameters of the EECS atrium

Basic calculations were also made to determine the relative significance of various heat transfers on the thermal behavior of the EECS atrium.

The peak conductive heat transfer through the exterior end walls (double-glazed) will be about

$$q_{cond} = U\,A\,\Delta t$$
$$= 2.8 \times 189 \times 2 \times (20 - (-3))$$
$$= 24343\ W$$
$$\approx 24\ kW$$

The peak conductive heat transfer through the interior walls will be about

$$q_{cond} = U\,A\,\Delta t$$
$$= 1.7 \times 1730 \times 2 \times (30 - 22)$$
$$= 47056\ W$$
$$\approx 47\ kW$$

The peak conductive heat transfer through the skylight will be about

$q_{cond} = U\ A\ \Delta t$

$= 2.8 \times 635 \times (20 - (-3))$

$= 40894$ W

≈ 41 kW

The peak radiative energy incident on the skylight will be about

$q_{rad} = G_{global}\ A$

$= 700 \times 635$

$= 444500$ W

≈ 445 kW

The peak heat loss through ventilation for 1 ACH will be about

$q_{vent} = 1200\ v\ \Delta t$

$= 1200 \times 4.8 \times (20 - 9\text{-}3))$

$= 132480$ W

≈ 132 kW

The peak heat loss through ventilation for 6 ACH (maximum ventilation rate) will be about

$q_{vent} = 132 \times 6$

$= 792$ kW

Based on the calculations, it is obvious that the influence of the radiative heat gain is the most significant followed by the ventilation load. The influence of the conductive heat transfer through exterior walls and interior walls is minimal, while conductive heat transfer through the skylight is of significant magnitude for the top sub-zone of the atrium.

3.4.2.2 Observations on temperature stratification at EECS atrium

The temperature in the top zone did not drop below 20 °C during a cold night (March 11, 1989), when the outdoor temperature was below -3 °C. This suggests that the air in the atrium was heated by some kind of heating system. Further inquiry revealed that there was a heating system in the atrium and the thermostat was set at about 20 °C.

The temperature at lower levels remained around 23 °C during day and night even though the outdoor temperature rose to 28 °C. This suggests that the atrium was being cooled by adjacent spaces.

The atrium temperatures at lower zones during day remained close to the temperature at night, whereas the temperature at upper levels fluctuates from day to night. The reason for this behavior is the geometry of this atrium i.e., because of high SAR solar radiation did not penetrate to the lower zones. The maximum temperature stratification was only about 5 °C in March, while it was about 15 °C in July.

3.4.2.3 Computer modeling of the EECS atrium

Because single-zone modeling has already shown to be inadequate, EECS atrium was only modeled as a modified 6-zone system. As the SAR of this atrium is as high as 2.3, the solar radiation could not penetrate to the lowest zones. The thermal zoning and mass flow network are shown in figure 3.7.

The nodes are connected by airflow components. In order to allow mass flow between zones, the mass flow network included a large orifice (40 m^2) between each set of adjacent atrium zones. The skylight of the atrium is defined as double-glazed, exterior surface having direct normal solar transmittance of 0.611 (the default value in ESP-r). There were no roof vents in the EECS atrium. However, a small orifice was provided, in order to simulate airflow through roof cracks.

The walls facing east and west were modeled as double-glazed exterior walls, while walls facing north and south are modeled as partitions. The environment on the other side of these partition walls is specified as constant temperature of 22°C. The boundaries between atrium zones are specified as transparent "fake" walls with very high U-values (2.7 W/m^2K). The construction details and thermo-physical and optical properties of all envelopes may be found in the relevant construction files in Appendix 3.

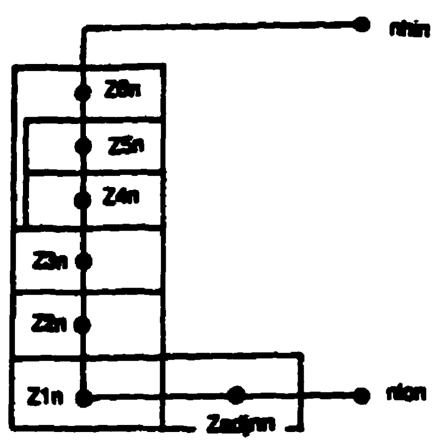


Figure 3.7 Mass flow network for 6-zone EECS model

3.4.2.4 Simulation conditions

In order to model natural temperature stratification in atrium spaces, the control algorithm was specified as free floating. Casual gains for occupancy and lighting were set at zero in the operation schedules. The operation schedules specified are attached in Appendix 3.

CHAPTER 4
RESULTS AND DATA ANALYSIS

4.1 Overview

The results presented in this chapter were obtained by computer simulation of the thermal behavior of atriums using the energy simulation program called ESP-r. Simulated data were compared with measured data and the possible causes of discrepancies were analyzed.

4.2 AZG Atrium

It was decided that the AZG atrium simulation model would be calibrated first for two reasons:

1. the measured atrium temperatures were available for four days under different climate conditions and roof vent positions, which provided a range of validation conditions, and
2. no heating or ventilation systems were installed in the atrium at the time the measurements were conducted, which reduced the number of variables to be addressed.

4.2.1 Weather data for AZG atrium simulations

Simmonds presented only outdoor temperatures for the days during which measurements were conducted. Additional weather data required for computer simulation were obtained from the Royal Netherlands Meteorological Institute (KNMI). The global solar radiation values obtained were hourly, while wind speed and wind directions data were 6 hour averages. ESP - r requires diffuse and direct normal solar radiation for simulation. Therefore, diffuse solar radiation was estimated based on data measured in Calgary for days with similar levels of global radiation. Direct normal solar radiation was calculated by the following relationship.

$$G_{Global} = G_{Diffuse} + G_{Direct} \sin\alpha \qquad [W/m^2]$$

where,

G_{Global} ⇒ global solar radiation $[W/m^2]$

$G_{Diffuse}$ ⇒ diffuse solar radiation $[W/m^2]$

G_{Direct} ⇒ direct solar radiation $[W/m^2]$

α ⇒ solar altitude [degrees]

4.2.2 Basic features of the AZG simulation model

The details provided by Simmonds are summarized in Appendix 1.

4.2.3 Temperature profiles for single-zone(volume) AZG simulation model

The results obtained from computer simulation of the AZG atrium as a single zone are shown in figures 4.1 and 4.2. Simulations were carried out with and without modeling of mass flow. As single-zone modeling predicts only one temperature profile for the whole atrium, it is obvious that it would not be capable of characterizing the thermal behavior of the atrium at different heights.

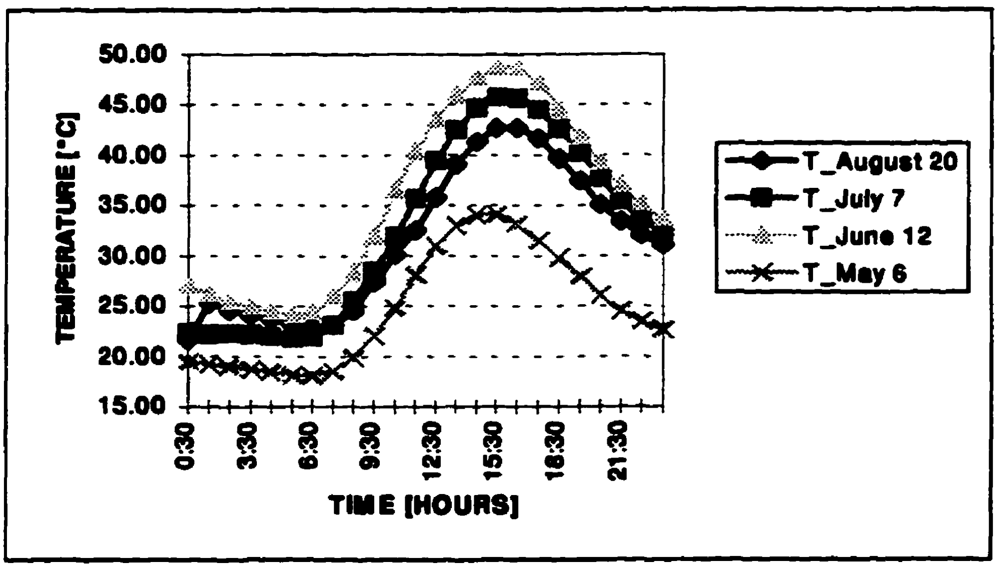


Figure 4.1 Modeled temperature profiles in the single-zone AZG atrium (without airflow model)

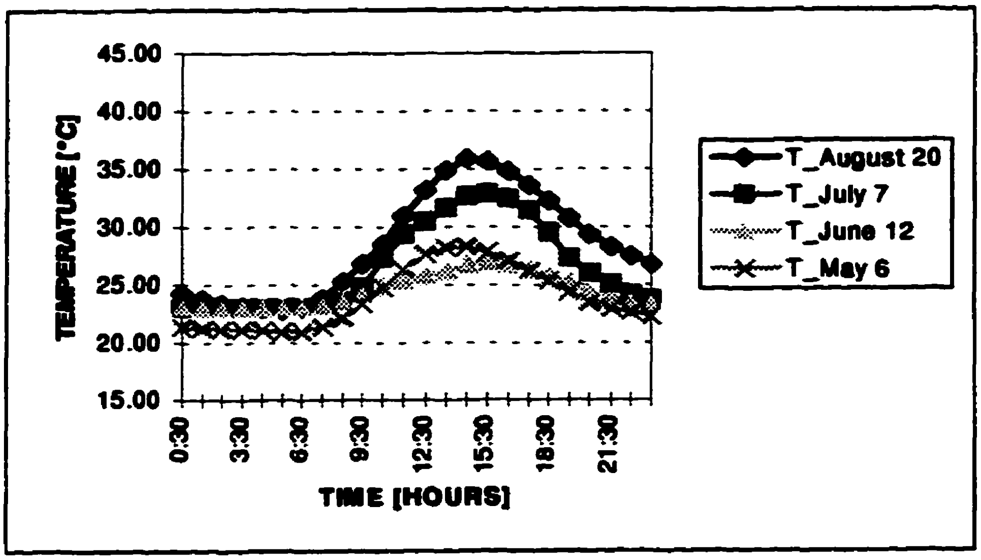


Figure 4.2 Modeled temperature profiles in the single-zone AZG atrium (with airflow model)

4.2.4 Comparison of modeled and measured data for the AZG atrium

The results obtained by computer simulation and measurement were compared, in order to evaluate the capacity of ESP-r version 9.0 to predict the temperature in atriums.

4.2.4.1 Modeled versus measured temperature profiles for single-zone AZG atrium

Several studies [4,25] have shown that single-zone models of atrium spaces were incapable of representing their thermal behavior. These studies showed that the temperatures predicted by single-zone models are closer to the temperature at the higher level rather than the temperature at the lower level. The results obtained by us also demonstrated the same fact.

The comparison of modeled and measured temperature profiles for the single-zone AZG model without and with mass flow are presented in figures 4.3 and 4.4 respectively (note that the number after T in the legends show the height in meter above the atrium floor).

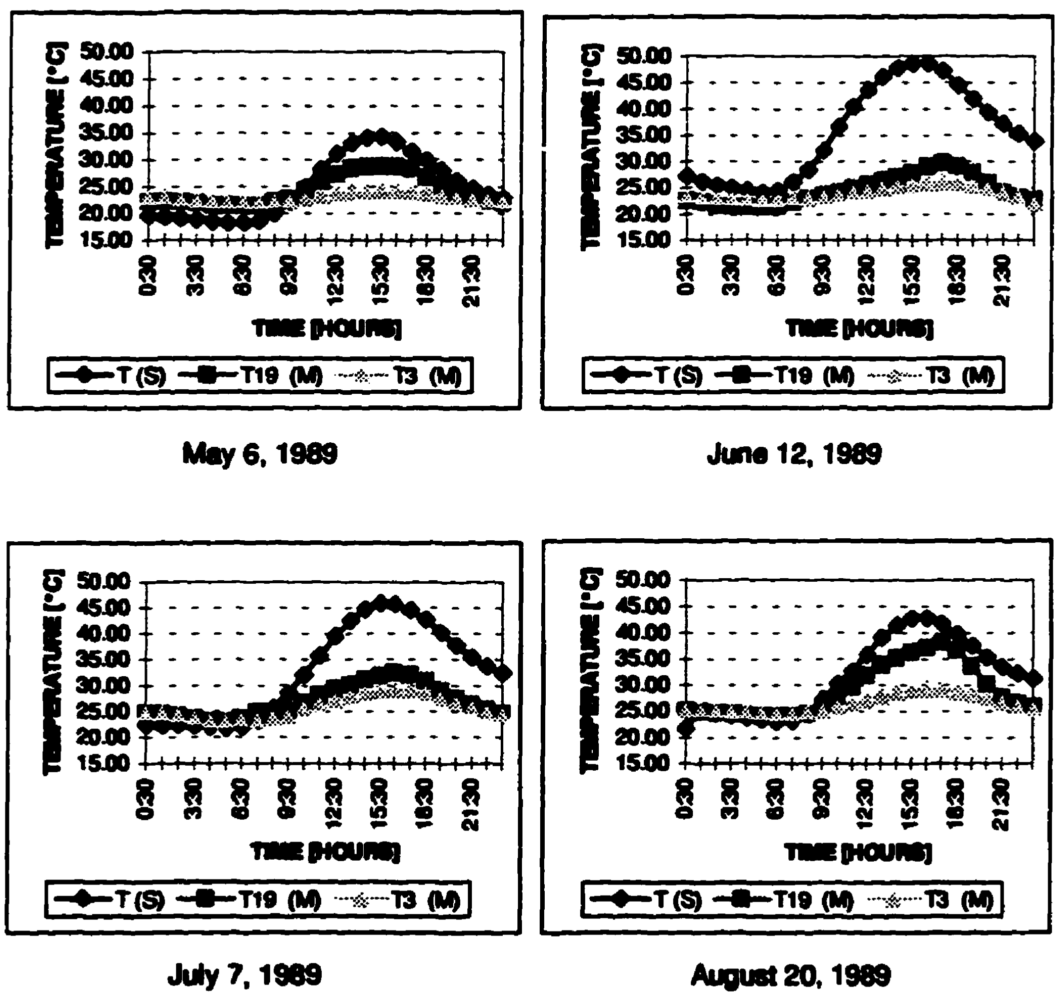


Figure 4.3 Modeled versus measured temperature profiles for the single-zone AZG atrium (without mass flow model)

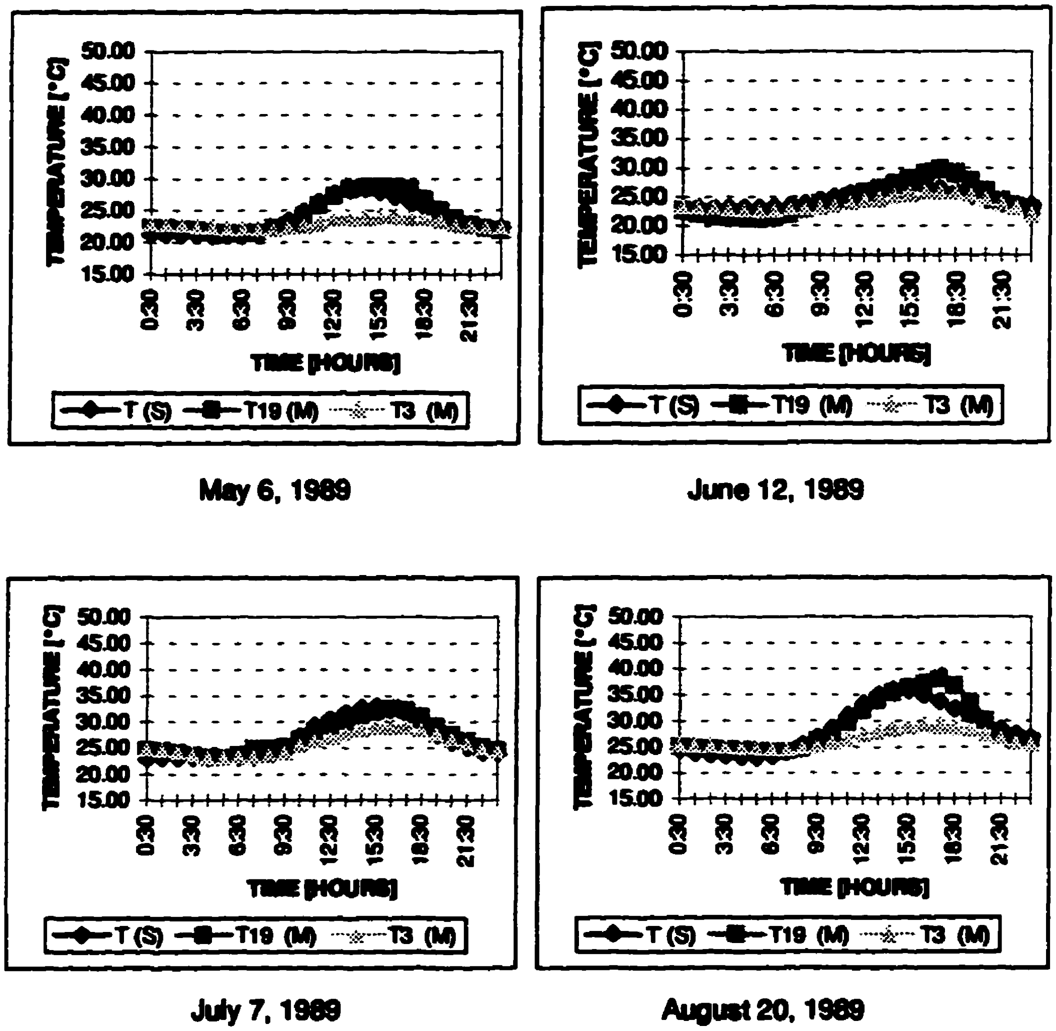


Figure 4.4 Modeled versus measured temperature profiles for the single-zone AZG atrium (with mass flow model)

Note: (S) indicates the temperature is simulated

(M) indicates the temperature is measured

4.2.4.2 Result analysis for single-zone AZG atrium mode without mass flow

The temperatures predicted by the single-zone model without mass flow for the periods of May 6 and August 20 were closer to the measured temperature at the highest level. However they were significantly higher than the measured temperature at the highest level for the periods of June 12 and July 8. The major reason for this discrepancy is that the model without mass flow was incapable of modeling the open position of roof vents and airflows through the atrium i.e., incapable of accurately modeling convective heat transfer in the atrium.

4.2.4.3 Result analysis for single-zone AZG atrium model with mass flow

The temperatures predicted by the single-zone model with mass flow for all 4 days were closer to the measured temperature at the highest level. This is consistent with findings of other researchers.

4.2.5 Temperature profiles for 5 zone AZG simulation model

The results obtained from computer simulation of the AZG atrium as a 5 zone model are shown in figures 4.5 - 4.8. The simulations were run with airflow modeled for all four periods (note that the number after T in the legends shows the height in meters above the atrium floor).

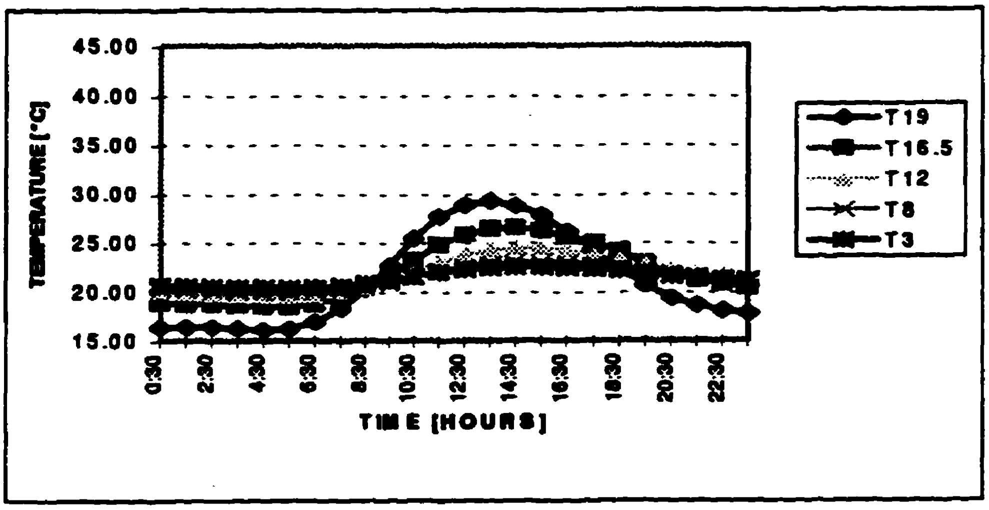


Figure 4.5 Modeled temperature profiles in the 5 zone AZG atrium for May 6, 1989

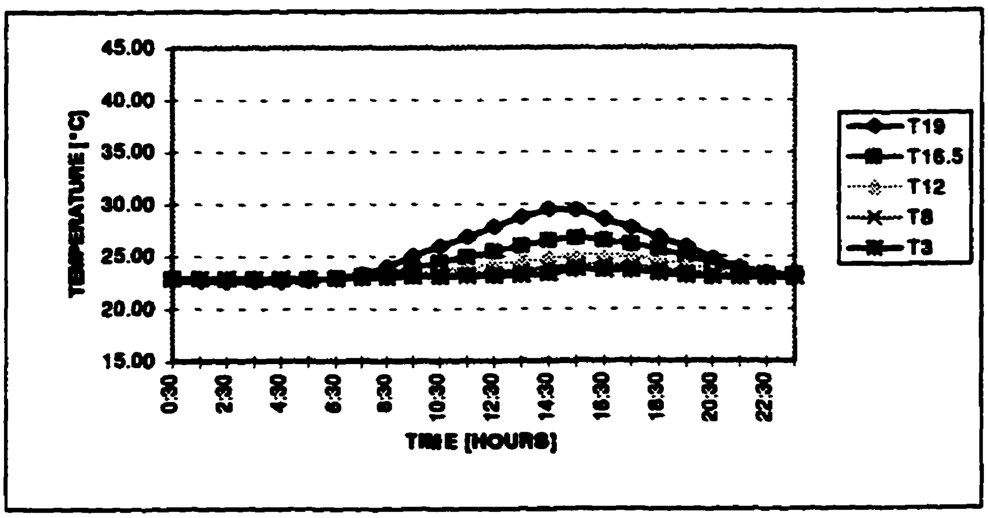


Figure 4.6 Modeled temperature profiles in the 5 zone AZG atrium for June 12, 1989

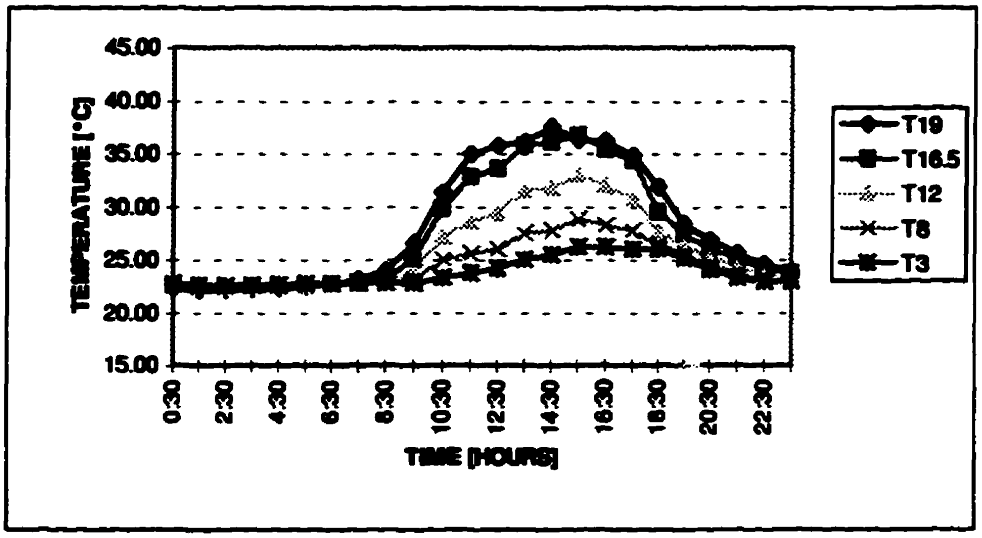


Figure 4.7 Modeled temperature profiles in the 5 zone AZG atrium for July 7, 1989

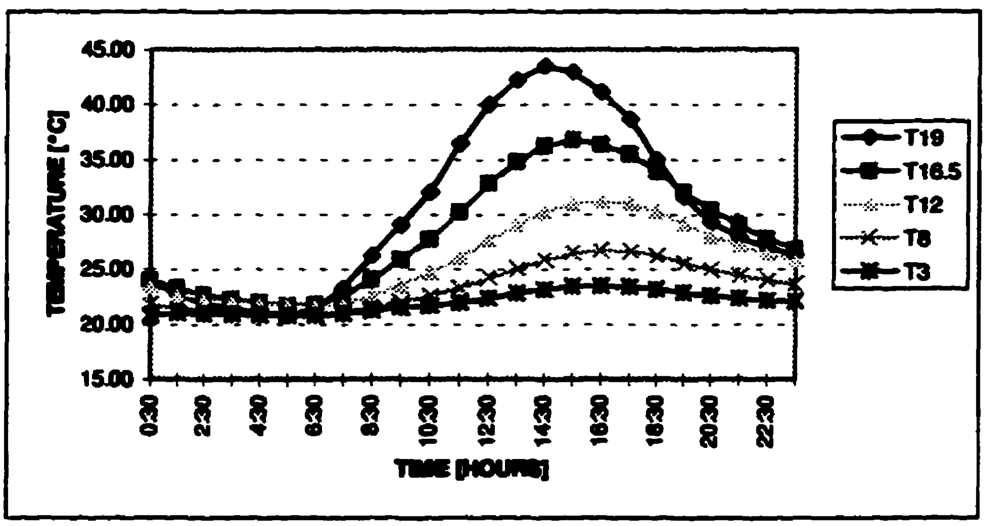
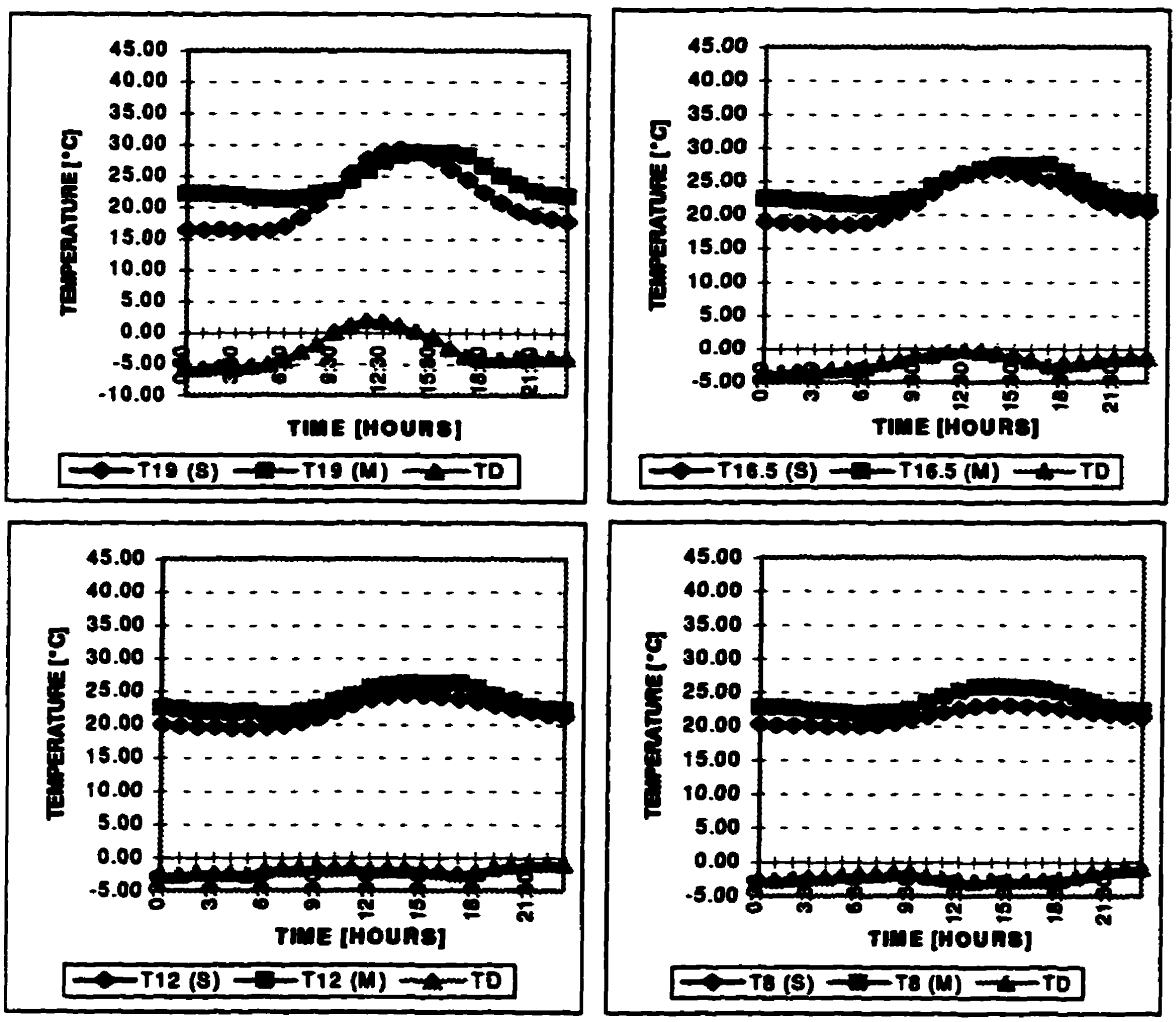


Figure 4.8 Modeled temperature profiles in the 5 zone AZG atrium for August 20, 1989

4.2.6 Comparison of modeled and measured data for the 5 zone AZG atrium

4.2.6.1 Modeled versus measured temperature profiles for 5 zone AZG atrium

The temperatures predicted by the 5 zone model for the AZG atrium are presented in figures 4.9 - 4.12.



(Figure 4.9 continued on page 93)

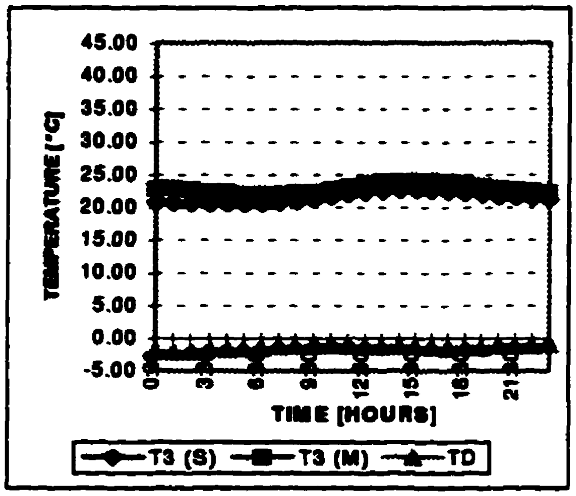
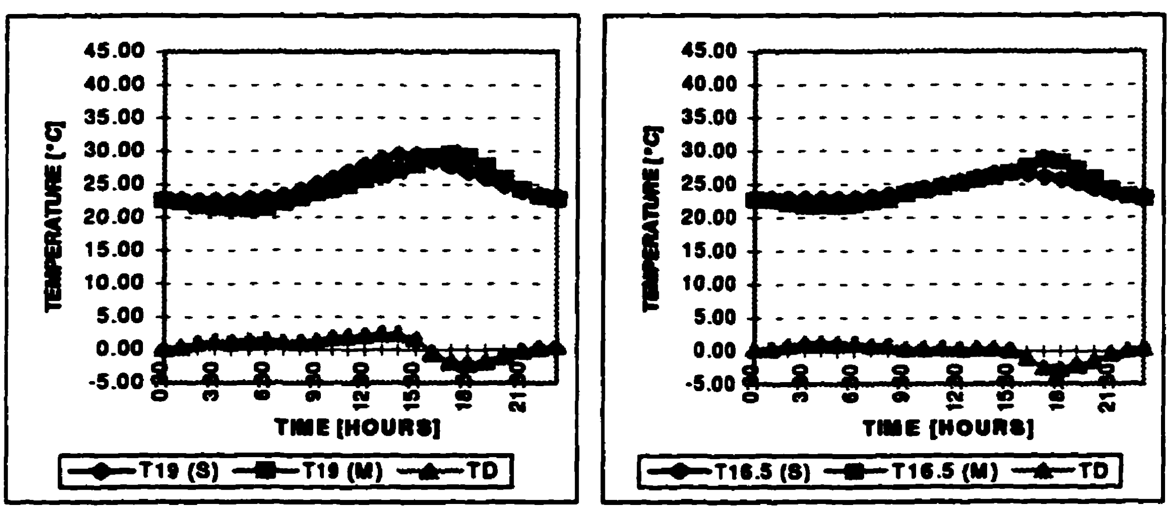


Figure 4.9 Modeled versus measured temperature profiles for 5 zone AZG atrium for May 6, 1989



(Figure 4.10 continued on page 94)

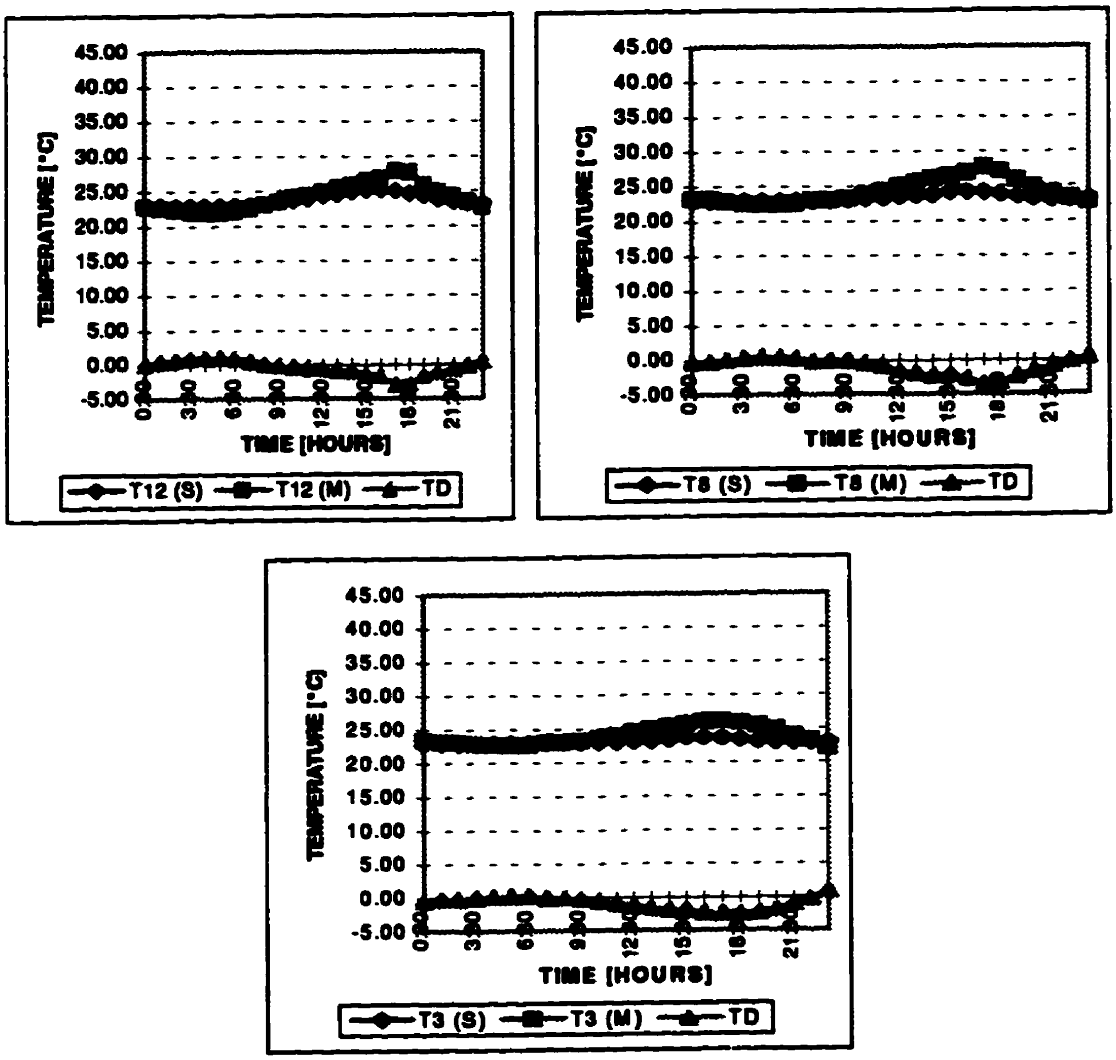


Figure 4.10 Modeled versus measured temperature profiles for 5 zone AZG atrium for June 12, 1989

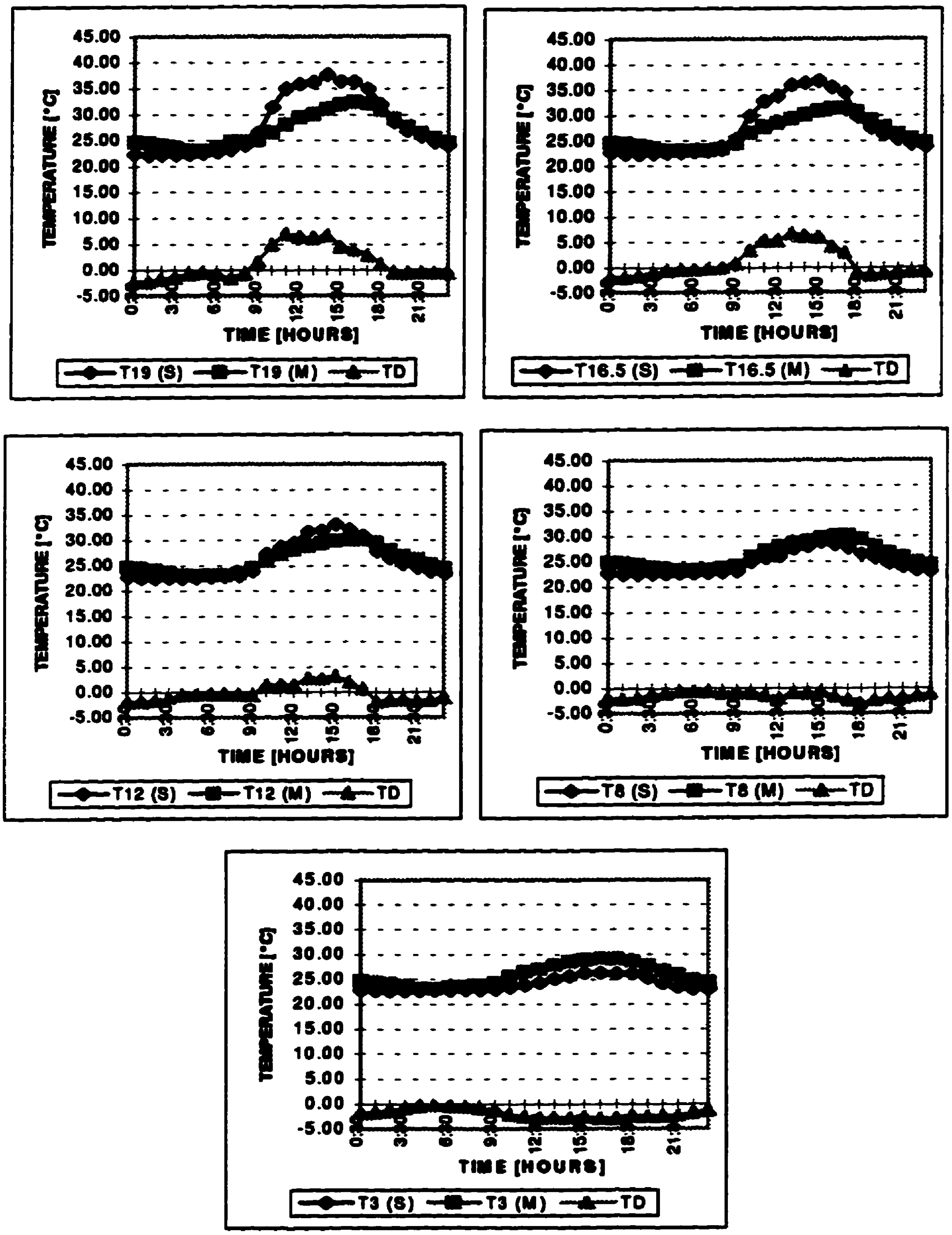


Figure 4.11 Modeled versus measured temperature profiles for 5 zone AZG atrium for July 7, 1989

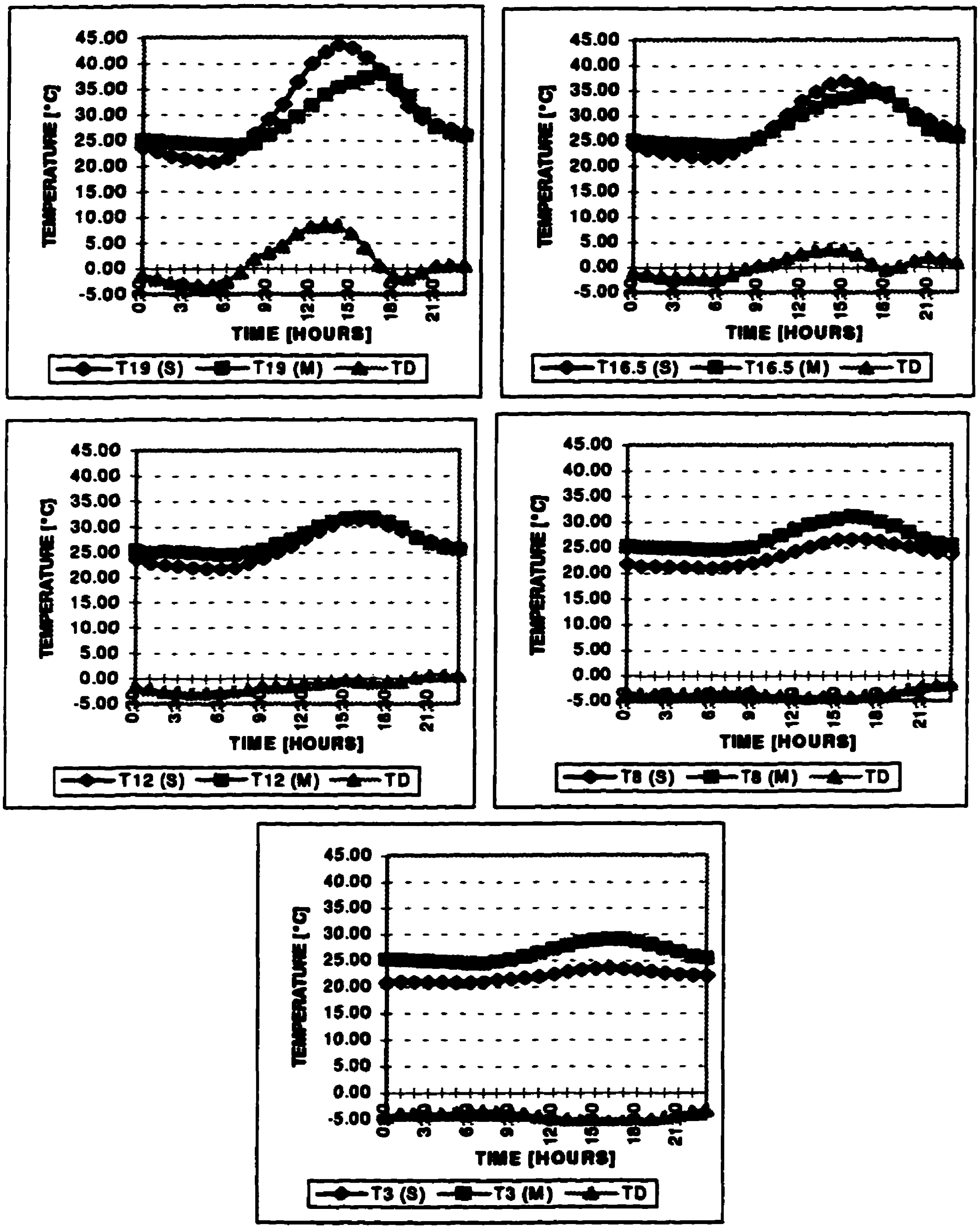


Figure 4.12 Modeled versus measured temperature profiles for 5 zone AZG atrium for August 20, 1989

The median and absolute temperature differences between predicted and measured temperatures are presented in Tables 4.1 and 4.2 (note that the number after T in the legends show the height in meter above the atrium floor).

Table 4.1

Median temperature difference between modeled and measured temperatures in 5 zone AZG atrium

	Median TD [°C]			
	6-May-89	12-Jun-89	7-Jul-89	20-Aug-89
T19	-4.0	1.1	-0.6	0.4
T16.5	-1.8	0.3	-0.5	0.5
T12	-1.8	-0.4	-0.5	-1.4
T8	-2.3	-0.5	-1.4	-3.7
T3	-1.4	-0.5	-2.0	-4.2

Table 4.2

Maximum absolute temperature difference between modeled and measured temperatures in 5 zone AZG atrium

	Maximum absolute TD [°C]			
	6-May-89	12-Jun-89	7-Jul-89	20-Aug-89
T19	-5.9	2.4	6.9	8.4
T16.5	-3.7	-2.7	6.6	3.4
T12	-2.7	-3.0	3.2	-4.4
T8	-2.8	-3.6	-3.0	-4.4
T3	-2.3	-2.5	-3.0	-5.6

Note: negative sign before the value means under estimation by ESP-r, positive sign means over estimation

4.2.6.2 Result analysis for the 5 zone AZG atrium model

The predicted temperature profiles of atriums with the 5-zone model were closer to the measured temperature profiles than those obtained with the single zone model. This model was capable of representing the dynamic thermal behavior of atrium at different heights. However, the maximum median and absolute temperature differences between predicted and measured temperature were about - 4.0 °C and 7 °C, which is comparable to Simmonds' simulation studies. Considering Simmonds' measured data and the geometry of the atrium, the reason for the discrepancy appears to be poor distribution of solar radiation below the top levels of the atrium in this model. ESP-r can only pass incident radiation to adjacent zones. Further investigations were carried out in order to more closely model the real radiative heat exchange between zones. In order to transfer heat gain due to radiative energy to the lower zones of the atrium, the stacked sub-zone model was modified. This was done by extending a small portion of the top zone to the lower zones as shown in figure 4.13. Solar energy was evenly distributed to zone 2 and 3.

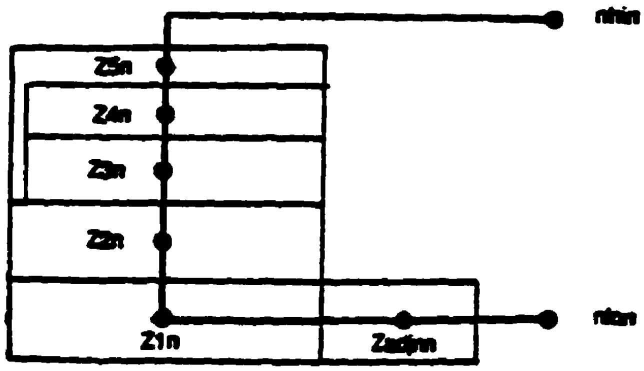


Figure 4.13 Mass flow network for the modified 5 zone AZG atrium model

4.2.7 Temperature profiles for the modified 5 zone AZG simulation model

The results obtained from computer simulation of the AZG atrium as a modified 5 zone model are shown in figures 4.14 - 4.17 (note that the number after T in the legends show the height in meter above the atrium floor).

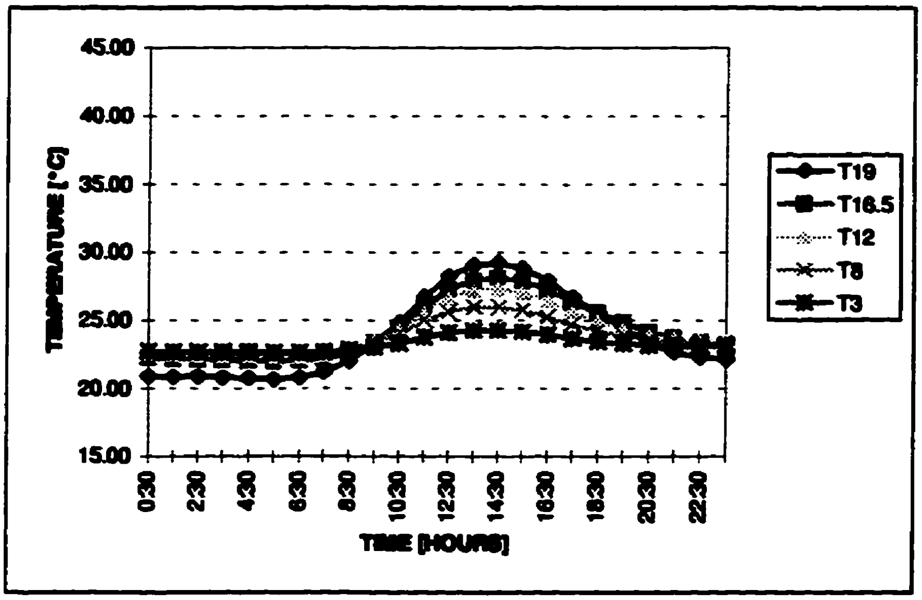


Figure 4.14 Modeled temperature profiles in the modified 5 zone AZG model for May 6, 1989

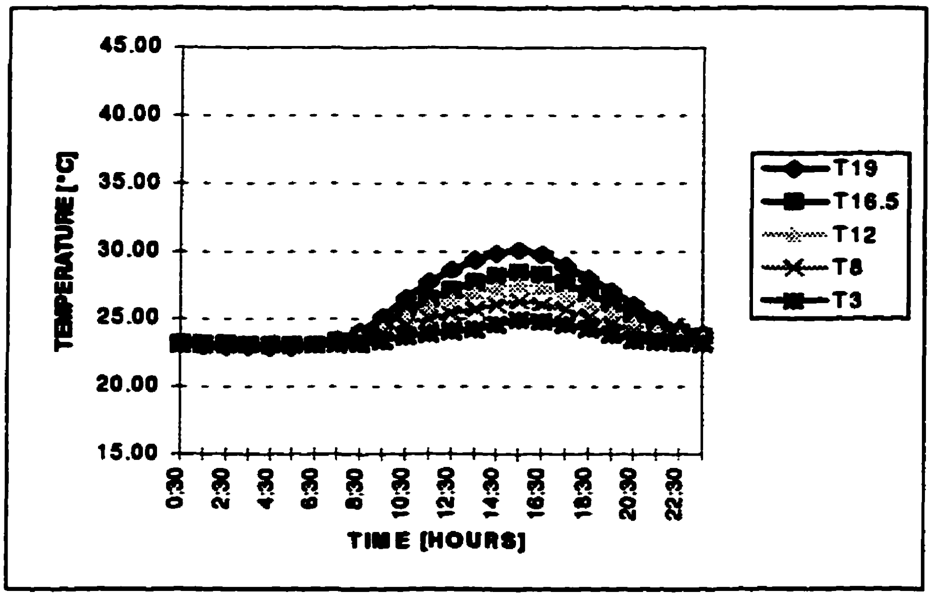


Figure 4.15 Modeled temperature profiles in the modified 5 zone AZG model for June 12, 1989

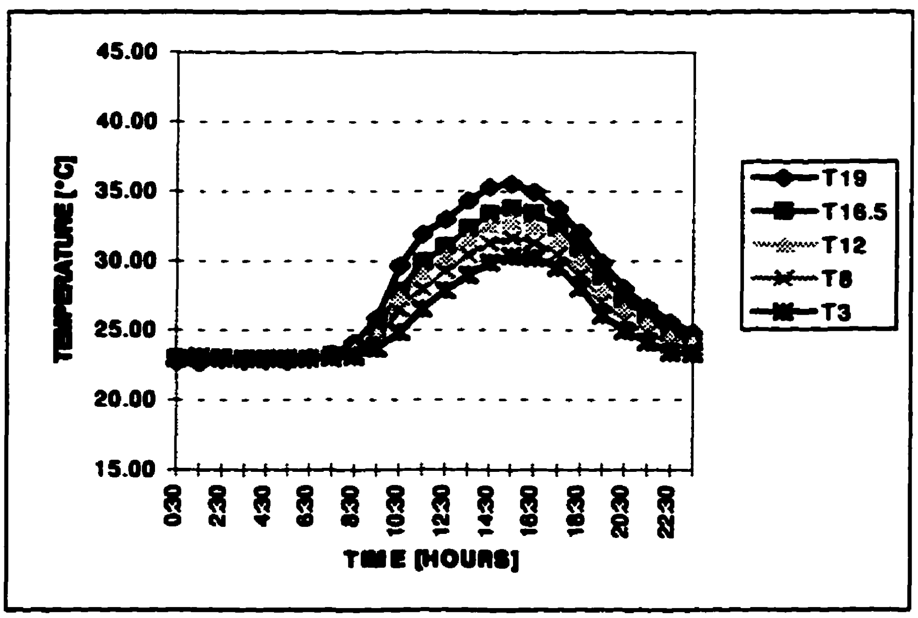


Figure 4.16 Modeled temperature profiles in the modified 5 zone AZG model for July 7, 1989

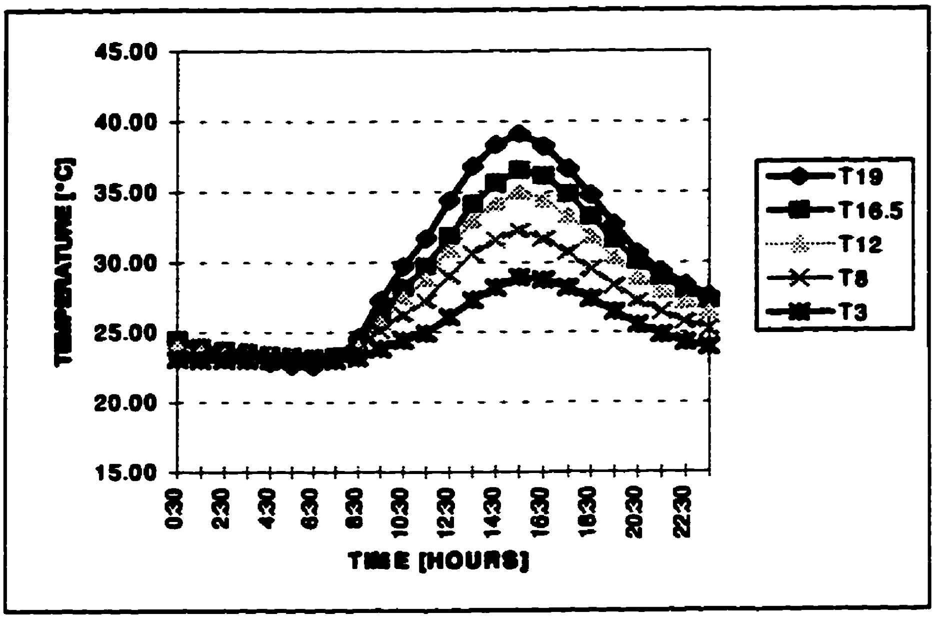


Figure 4.17 Modeled temperature profiles in the modified 5 zone AZG model for August 20, 1989

4.2.8 Comparison of modeled and measured data for the modified 5 zone AZG atrium

4.2.8.1 Modeled versus measured temperature profiles for modified 5 zone AZG model

The modeled versus measured temperature profiles for the modified 5-zone AZG model are presented in figures 4.18 - 4.21. The median and the absolute temperature difference between predicted and measured temperatures are presented in Tables 4.3 and 4.4.

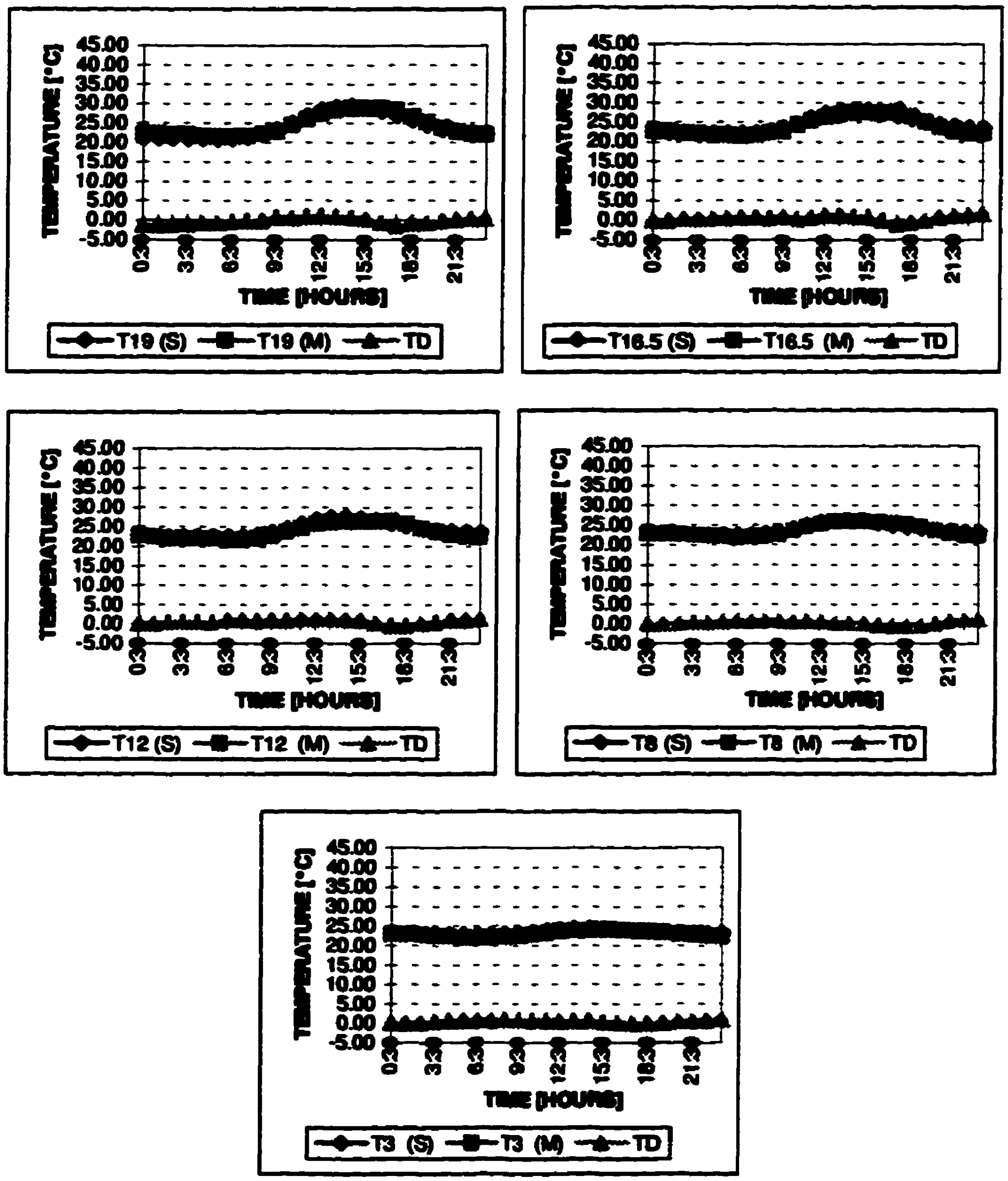


Figure 4.18 Modeled versus measured temperature profiles for modified 5 zone AZG model for May 6, 1989

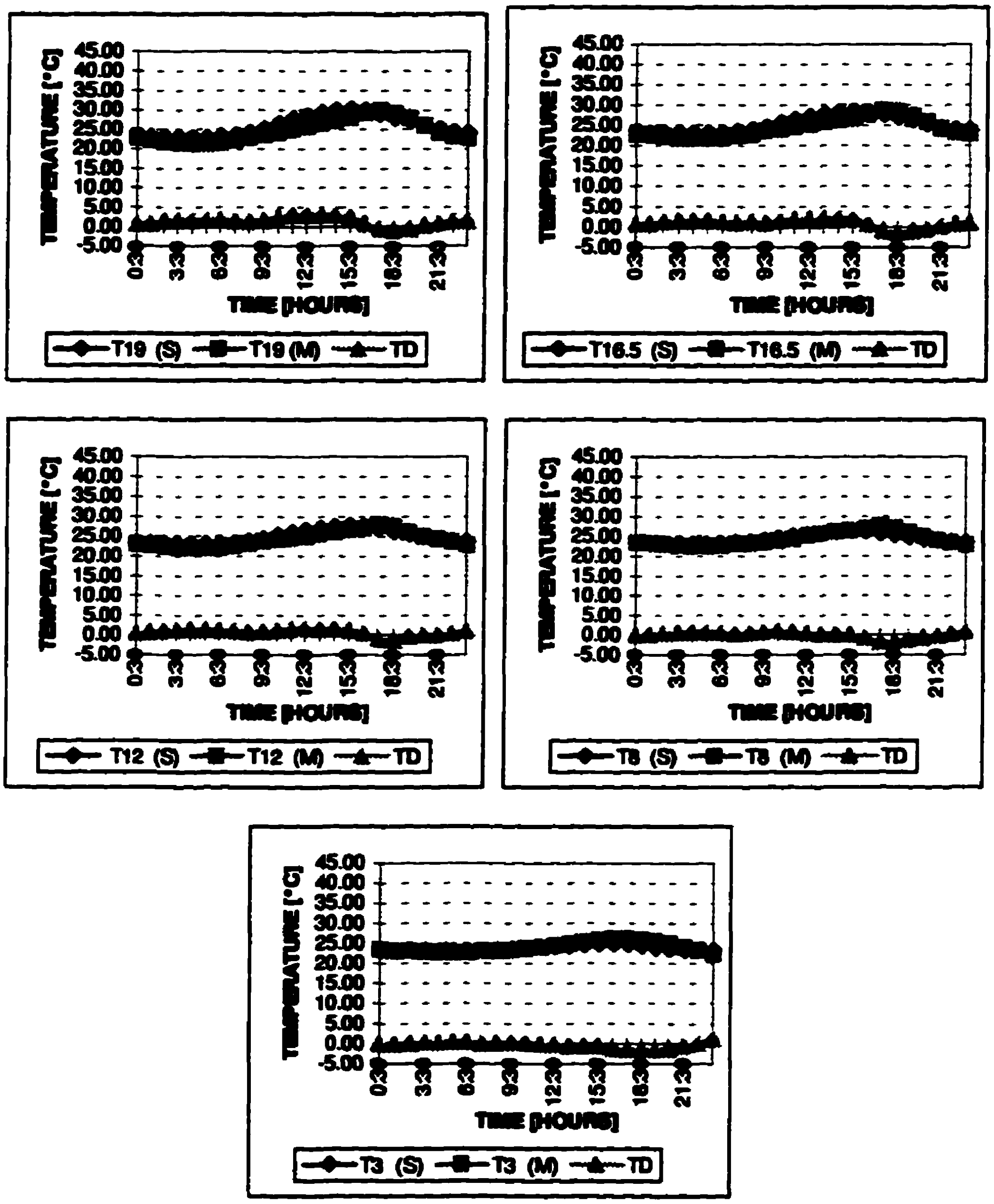


Figure 4.19 Modeled versus measured temperature profiles for modified 5 zone AZG model for June 12, 1989

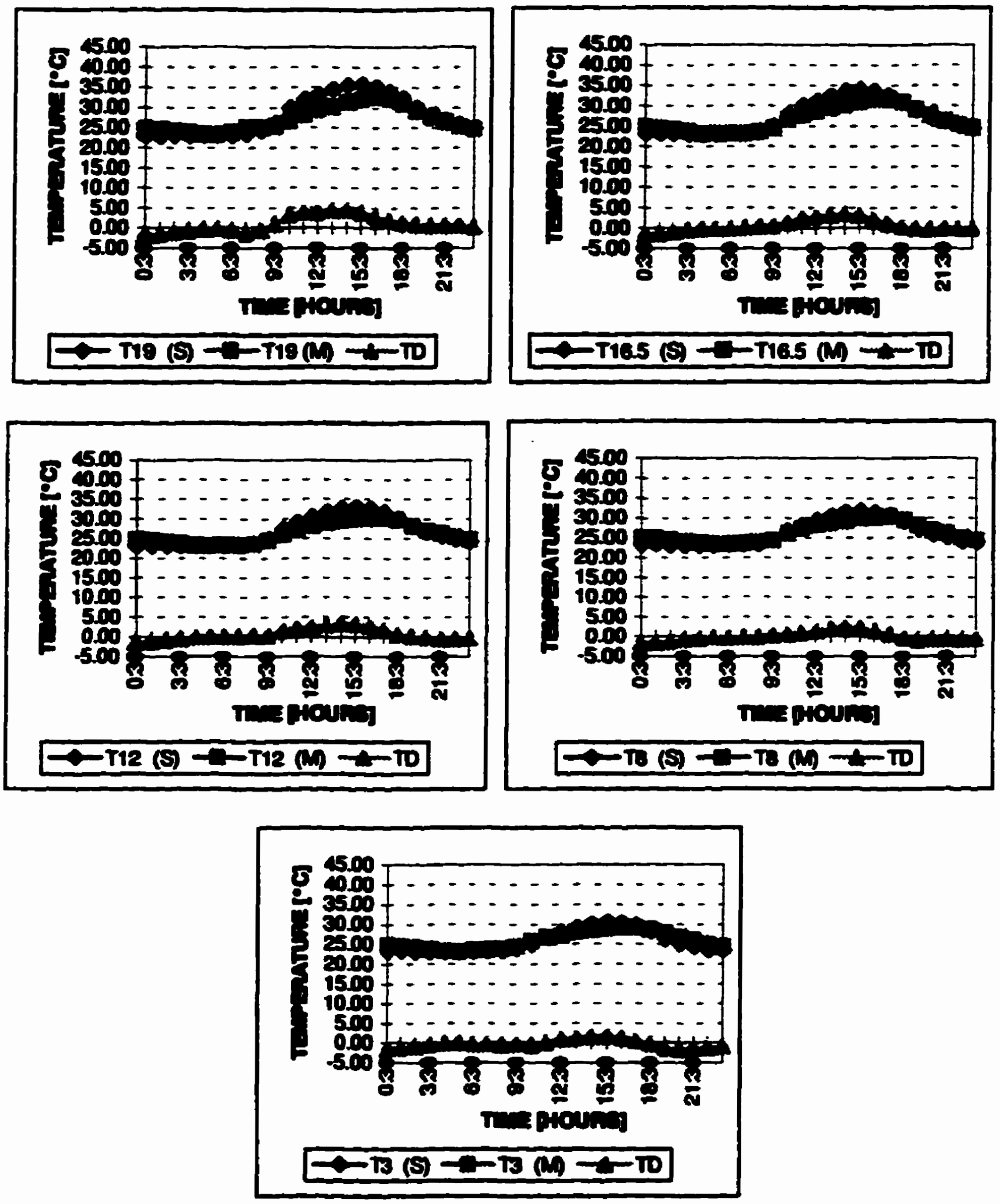


Figure 4.20 Modeled versus measured temperature profiles for modified 5 zone AZG model for July 7, 1989

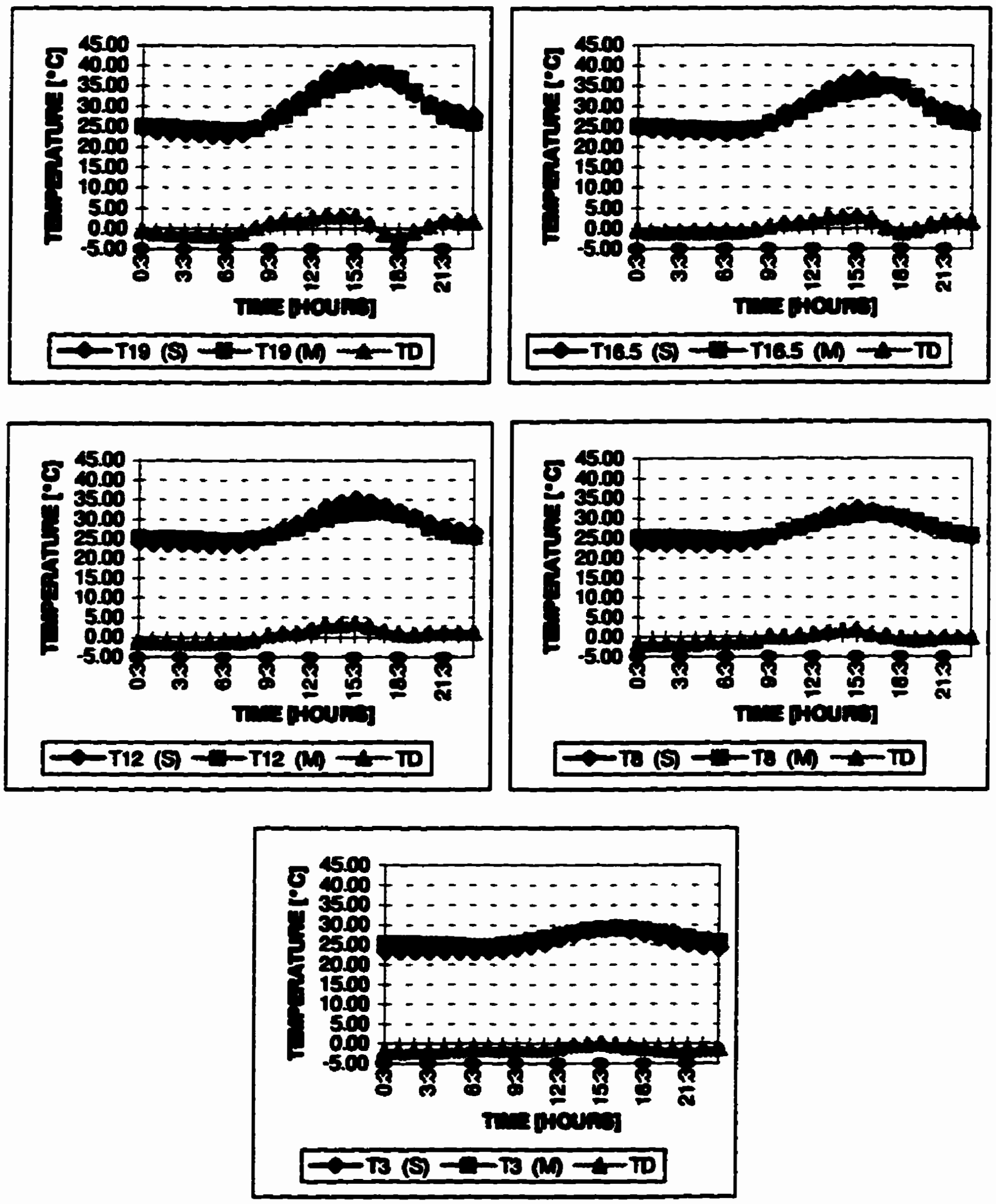


Figure 4.21 Modeled versus measured temperature profiles for modified 5 zone AZG model for August 20, 1989

Table 4.3

Median temperature difference between modeled and measured temperatures in modified 5 zone AZG atrium model

	Median TD [°C]			
	6-May-89	12-Jun-89	7-Jul-89	20-Aug-89
T19	-0.3	1.3	0.4	0.4
T16.5	0.5	1.0	-0.1	0.2
T12	0.7	0.9	-0.0	-0.8
T8	0.3	0.2	-0.4	-0.4
T3	0.4	-0.1	-0.5	-1.5

Table 4.4

Maximum absolute temperature difference between modeled and measured temperatures in modified 5-zone AZG atrium model

	Maximum TD [°C]			
	6-May-89	12-Jun-89	7-Jul-89	20-Aug-89
T19	-1.6	3.0	4.3	3.1
T16.5	1.4	2.0	3.3	3.1
T12	1.1	1.6	3.2	3.5
T8	1.0	-2.0	2.3	-1.9
T3	0.8	-1.6	-1.7	-2.2

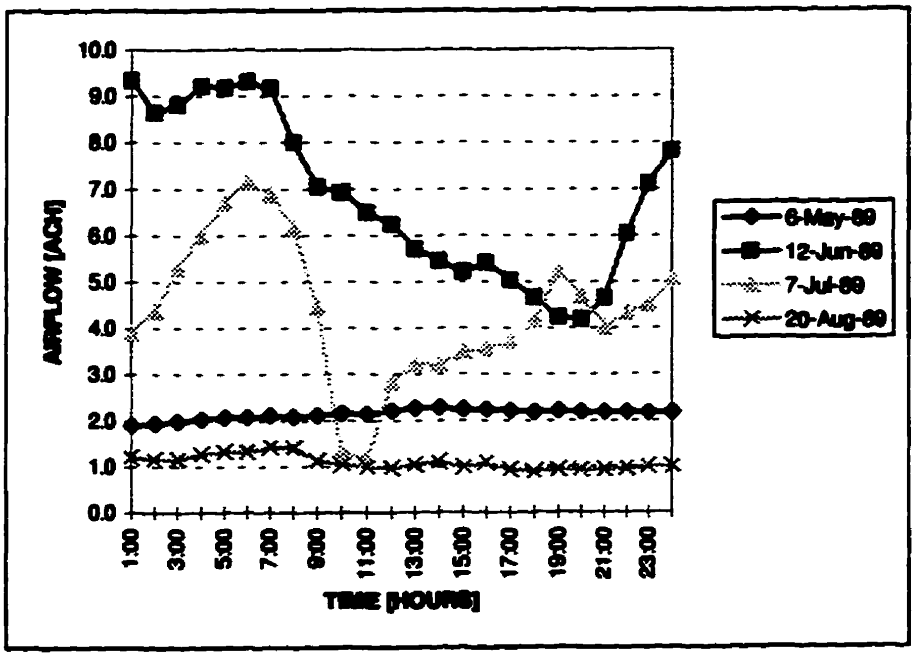


Figure 4.22 Modeled airflow profiles in the modified 5 zone AZG model

4.2.8.2 Result analysis for the modified 5 zone AZG model

The result obtained with the modified 5 zone model were closer to the actual temperature profiles in the atrium. It is shown in figures 4.18 and 4.21. The maximum median and maximum absolute temperature difference between modeled and measured temperatures in the atrium for all 4 days modeled were -1.5 and 4.3 respectively as shown in Tables 4.3 and 4.4. The modeled temperatures were fairly close to measured data for most of the time. The maximum absolute temperature differences mentioned in Table 4.4 occur at only a few moments.

In his article, Simmonds did not provide the detailed information on measured airflow. However he did mention that measured airflow was between 4 and 6 ACH on June 12 and July 7. Therefore, detailed comparison was not possible. However, predicted airflows were close to the measured data for majority of periods.

4.3 EECS Atrium

4.3.1 Temperature profiles for modified 6 zone EECS atrium simulation model

The results obtained from computer simulation of the EECS atrium as a modified 6 zone model are shown in figures 4.23 and 4.24 (note that the number after T in the legends shows the height in meters above the atrium floor).

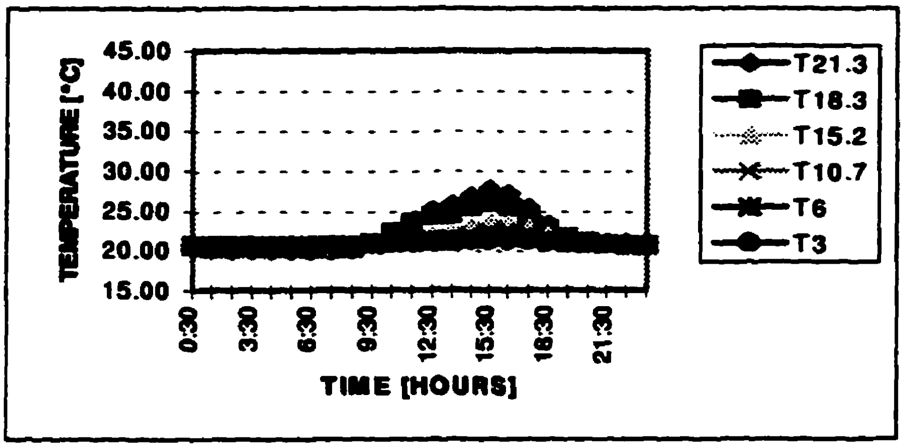


Figure 4.23 Modeled temperature profiles in the modified 6-zone EECS model for March 11, 1989

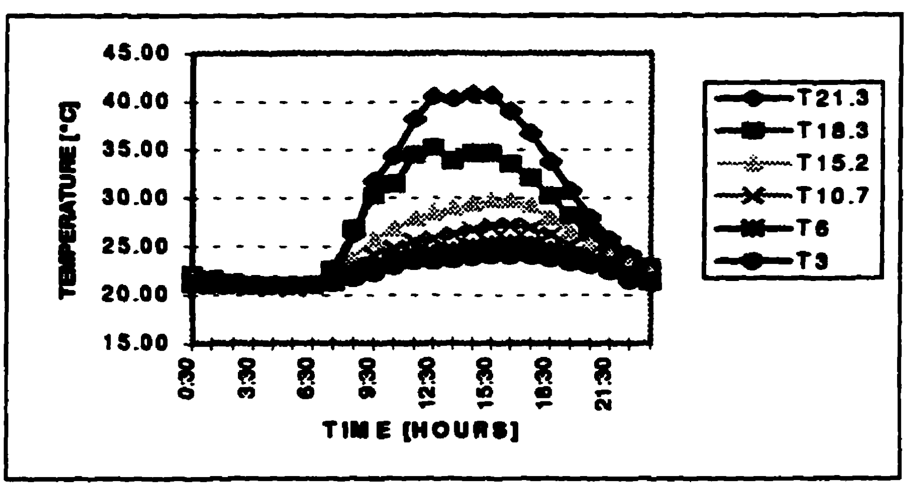
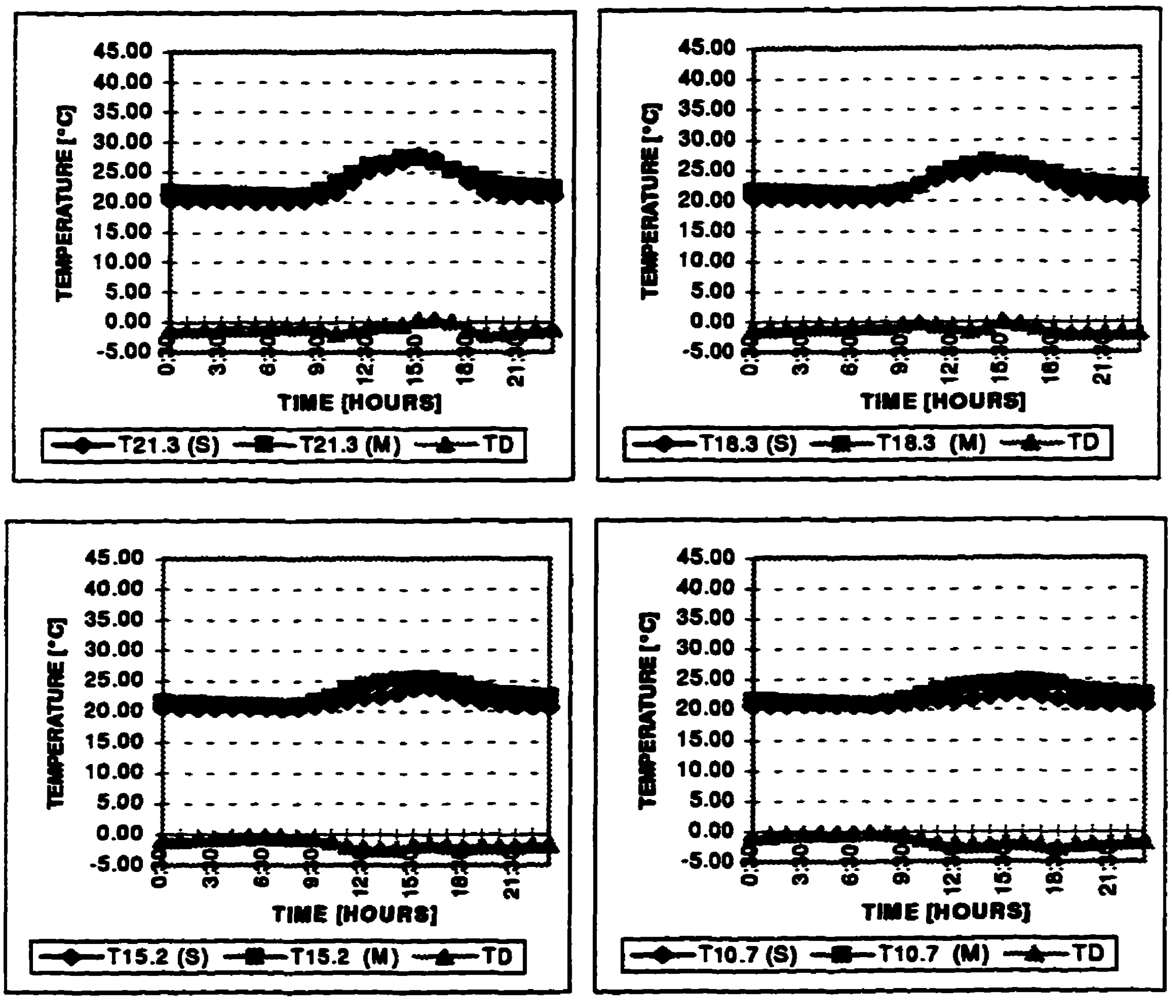


Figure 4.24 Modeled temperature profiles in the modified 6-zone EECS model for July 8, 1989

4.3.2 Comparison of modeled and measured data for the EECS atrium

4.3.2.1 Modeled versus measured temperature profiles for modified 6-zone EECS model

Modeled versus measured temperature profiles for modified 6 zone EECS model are presented in figures 4.25 and 4.26. The median and the maximum absolute temperature difference between predicted and measured temperatures are shown in Tables 4.5 and 4.6 respectively.



(Figure 4.25 continued on page 111)

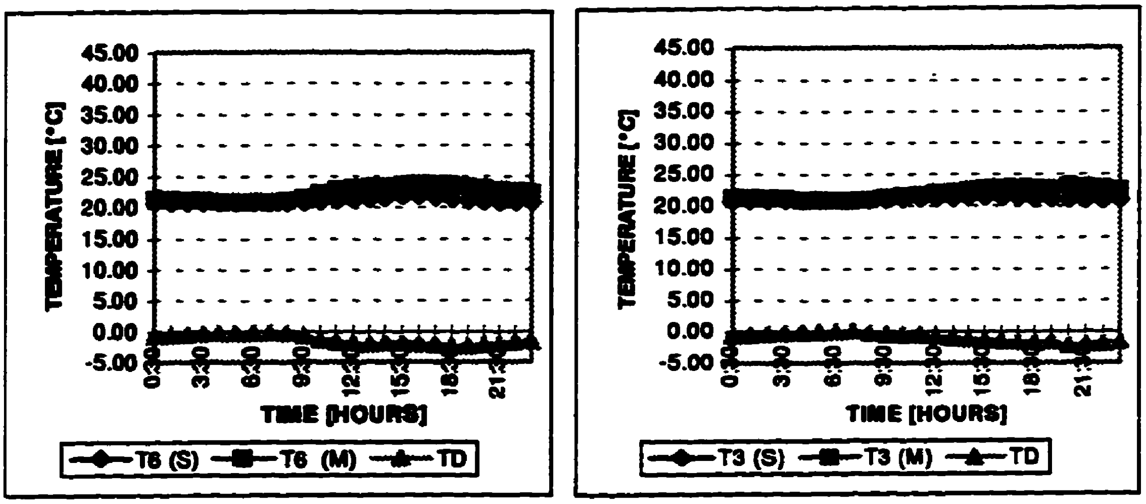
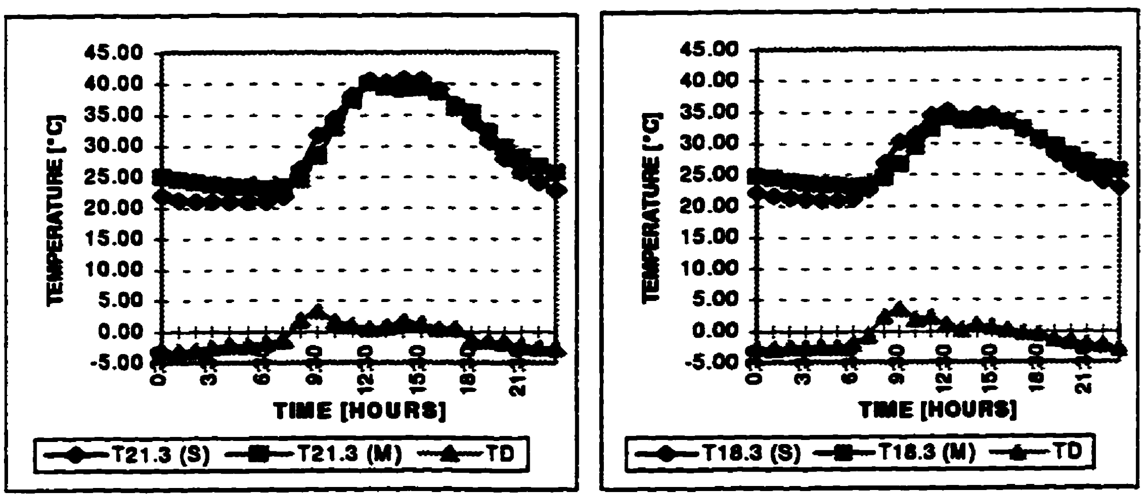


Figure 4.25 Modeled versus measured temperature profiles in the modified 6 zone EECS model for March 11, 1989



(Figure 4.26 continued on page 112)

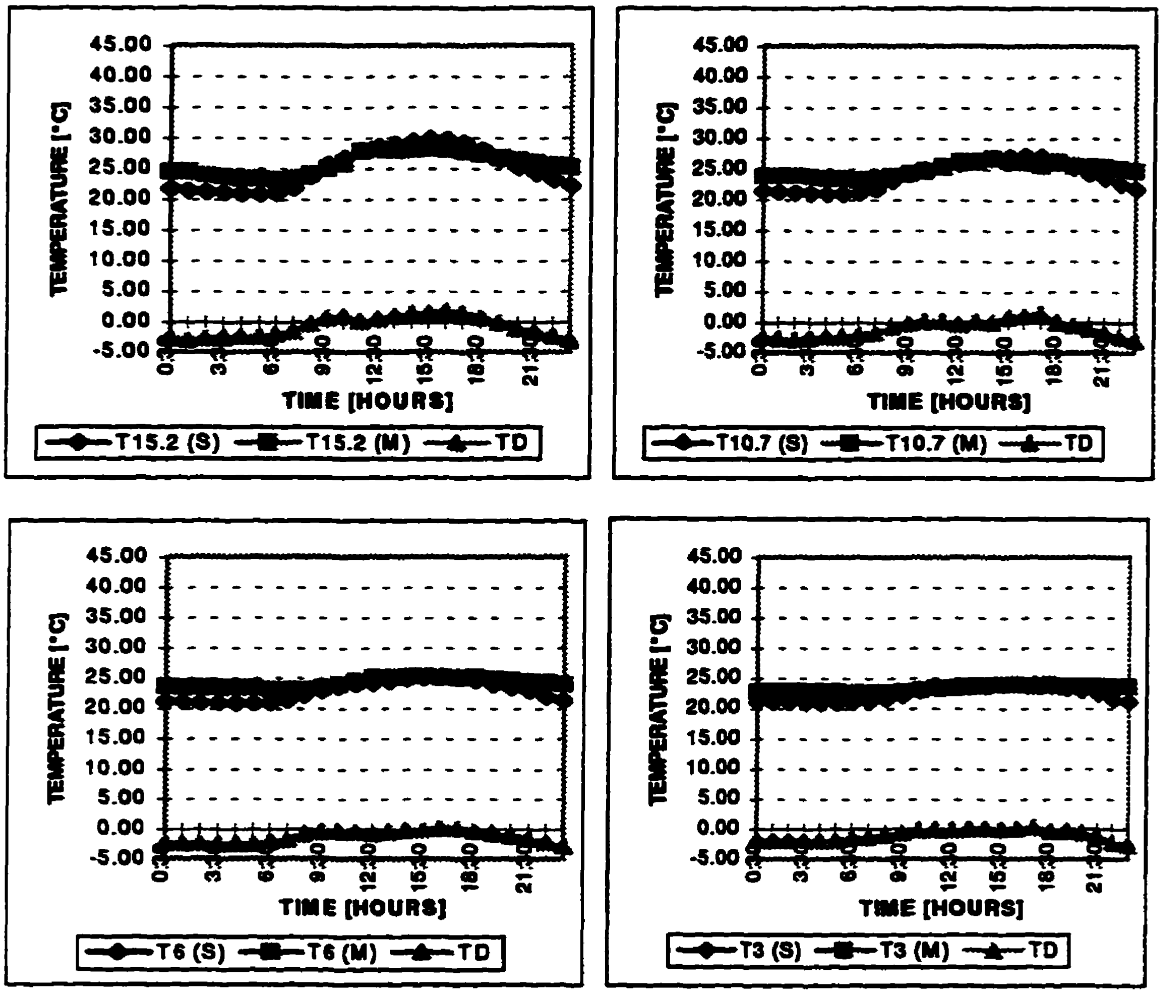


Figure 4.26 Modeled versus measured temperature profiles in the modified 6 zone EECS model for July 8, 1989

Table 4.5

Median temperature difference between modeled and measured temperatures in the modified 6 zone EECS atrium model

	Median TD [°C]	
	11-Mar-89	8-Jul-89
T21.3	-1.1	-1.6
T18.3	-1.0	-1.1
T15.2	-1.7	-0.8
T10.7	-1.8	-1.0
T6	-1.7	-1.0
T3	0.8	-1.0

Table 4.6

Maximum absolute temperature difference between modeled and measured temperatures in the modified 6 zone EECS atrium model

	Maximum TD [°C]	
	11-Mar-89	8-Jul-89
T21.3	-2.1	3.3
T18.3	-1.9	-2.9
T15.2	-2.4	-3.1
T10.7	-2.4	-3.0
T6	-2.4	-2.8
T3	-2.3	-2.6

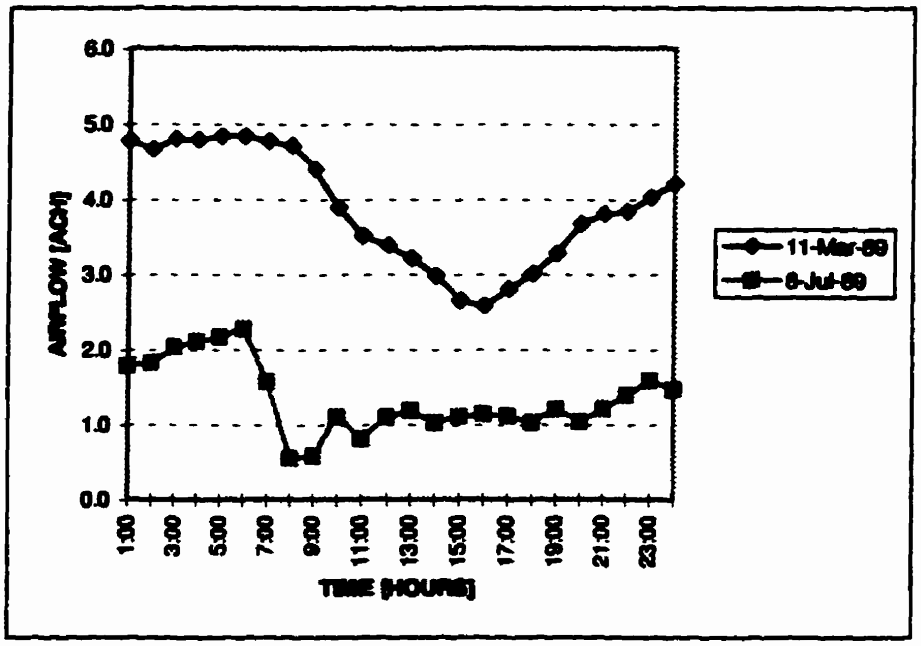


Figure 4.27 Modeled airflow profiles in the modified 6 zone EECS model

4.3.2.2 Result analysis of the modified 6 zone EECS atrium model

The results obtained with the 6 zone model were fairly close to the measured temperature profiles for most heights and days. The maximum median and absolute temperature differences between modeled and measured temperatures for both March and July were -1.8 and 3.3. The results obtained were best, when solar radiation was distributed from zone 6 to only zone 5.

It was not possible to compare predicted air flow because of the lack of measured data.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of work completed

The hypothesis of this investigation was that the computer simulation program called ESP-r (Environmental System Performances-research) version 9.0 could be used to model temperature stratification in atrium buildings with acceptable accuracy. The temperature difference between predicted and measured temperatures should be less than ± 2 °C. In order to evaluate the accuracy of ESP-r, maximum deviation and median deviation between measured and calculated temperatures were used.

Means are only valid averages for normal distributions. Median deviation gives a better indication of central tendency (most frequently occurring values) if the distribution of values follow a non-normal distribution. The median deviation was used as the first criterion, while maximum deviation was used as a supplemental criterion in order to evaluate the capability of ESP-r to model thermal behavior of atriums more rigorously (e.g., to identify extreme mismatches between measured and calculated values).

A detailed literature review on the thermal behavior of atriums and effects on building energy use was also conducted in order to determine the problems that exist in this field.

In order to test the hypothesis, the following work was carried out:

1. computer simulation of temperature profiles in the AZG atrium for 4 days in different seasons,
2. computer simulation of temperature profiles in the EECS atrium for 2 days in different seasons, and
3. comparison of predicted and measured temperatures for both AZG and EECS atriums and validation of the computer simulation program ESP-r as a reasonably accurate tool for prediction of the temperature stratification in atrium buildings.

5.2 Summary of results

As single-zone models only predict one temperature for a whole atrium, they are incapable of representing the dynamic thermal behavior of atriums at different heights. The need for multi-zone modeling of atriums has been demonstrated. Modeling of atriums using vertically stacked sub-zones was capable of representing the thermal behavior of atriums at different heights. However, the accuracy for the AZG atrium was not as good as the target in the hypothesis. This was due to the poor distribution of solar radiation below the top levels of the atrium in that model. ESP-r can only pass incident solar radiation to zones adjacent to this receiving zone. Therefore, further investigations were conducted in order to more closely model real radiative heat distribution for different levels of the atrium. The SAR (sectional aspect ratio) plays a vital role in the distribution of solar radiation at various levels. For instance, when modifying the vertically stacked sub-zone model of the AZG atrium, a portion of the top (fifth) zone was extended to the second zone in the AZG model. This allowed transfer of heat gain from solar radiation to the lower zones (zone 2 and 3). The results obtained were better. Because of the high SAR of the EECS atrium, modification of the vertically stacked sub-zones did not improve the accuracy of the model. Better results were obtained when heat gain from solar radiation was passed to only zone 5. The maximum median and absolute temperature difference between modeled and measured temperatures in the modified vertically stack sub-zones model of AZG atrium and the EECS atrium were -1.5 °C, 4.3 °C and -1.8 °C, 3.3 °C respectively. Although the maximum absolute temperature differences were greater than the ± 2 °C in both AZG and EECS atrium, they occurred at only a few points in time. For long periods the absolute temperature difference was within ± 2 °C.

5.3 General conclusions and restrictions

Several conclusions can be drawn from this investigation.

- the temperature predicted by a single-zone model with simulation of airflow, using ESP-r, is closer to the measured temperature at the highest level rather than the average atrium temperature,
- a single-zone model is not capable of representing the varying vertical temperature distribution in an atrium,
- vertically stacked sub-zone models, using ESP-r, are better than single-zone models, although the accuracy might not be as high as it could be,
- modification of vertically stacked sub-zone models could increase the accuracy of ESP-r when modeling atriums with low SAR,
- Airflows predicted by ESP-r are close to the measured data, and

- a variety of climatic conditions (several days in different seasons) are needed to calibrate a model (modeling for one day in one season is not enough).

The results presented in this investigation are specific to two atriums located in different climatic regions and for limited days. These results are an indication of the validity of ESP-r as a reasonably accurate thermal behavior prediction tool appropriate for atriums. More investigations should be carried out for individual atriums at different geographical locations. In this study, median and absolute temperature differences between simulated and measured data were used for validation of ESP-r. The median deviation was used rather than the mean deviation in order to fairly represent the majority of temperature differences for the 24 hour periods (mean is an appropriate average only for normal distributions).

Data that are of significant value for analyzing thermal behavior were not provided in published articles. These included solar radiation, ACH (infiltration from adjacent spaces and outdoors), optical properties of glazed materials, presence of heating or cooling sources in atriums, etc. Use of the simulation model highlights significant information that should be recorded during experimental research.

5.4 Recommendations for future work

It is obvious that this type of investigation depends upon the available of energy performance and thermal behavior analysis tools. It is ongoing research. The accuracy achieved will grow with the development of more effective prediction

- parametric studies could be done for both AZG and EECS atriums, in order to determine the significance of the impact of various parameters on temperature profiles in the atriums.
- simulation also could be done to assess the significance of the impact of various parameters on energy consumption of the atriums.
- investigations could be conducted for partially conditioned and fully conditioned atriums with various heating/cooling systems.
- investigations could be conducted to determine the temperature profiles in the atriums for places with different climatic conditions.
- more experimental investigations could be carried out for atriums in a range of climatic conditions with various configurations in order to identify the appropriate range of applications and limits of ESP-r as an accurate design tool for atriums.
- more research could be carried out for developing correlation between sectional aspect ratio and modification of vertically stacked zoning (extension of portion of upper zone to the lower zones).

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APPENDIX 1

Descriptive information on the AZG atrium

Plan	: See figures 3.2 and 3.3
Section	: See figure 2.4
Area	: 560 m^2
Height	: 20 m
Exterior wall constructions	: Aluminum plate, air cavity, and concrete
Intermediate wall constructions	: Aluminum plate, air cavity, and concrete
Roof constructions	: Double skinned polyvinylchloride (PVC) with 80% daylight transmittance
Roof vent area	: 40 m^2
Roof area	: 560 m^2

Descriptive information on the EECS atrium

Plan	: See figure 3.4
Section	: See figure 2.9
Area	: 810 m^2
Height	: 20 m
Intermediate wall constructions	: partition wall
Roof constructions	: Clear double glazed
Roof vent area	: 0 m^2
Roof area	: 910 m^2

APPENDIX 2

Input files of ESP-r modified 5-zone computer simulation model for AZG atrium

Configuration file

```
* CONFIGURATION
# ESRU system configuration defined by file
# gron.cfg
      1          # Building only
 52.000    0.000   # Latitude & Longitude
      1   0.200   # Site exposure & ground refl
* DATABASES
*prm  constr.dbl
*mlc  multicon.dbl
*opt  optics.dbl
*prs  /usr/esru/esp-r/databases/pressc.dbl
*evn  /usr/esru/esp-r/databases/profiles.dbl
*clm  ../../../../gronnw2
*pdb  /usr/esru/esp-r/databases/plantc.dbl
*ctl  atctl
* PROJ LOG
job.notes
* Building
AZG atrium
      6  # no of zones
      1   # reference for z1
z1.opr    # schedules
z1.geo    # geometry
z1.con    # constructions
      1
z1.utl
      2   # reference for z2
z2.opr    # schedules
z2.geo    # geometry
z2.con    # constructions
      1
z2.utl
      3   # reference for z3
z3.opr    # schedules
z3.geo    # geometry
z3.con    # constructions
      1
z3.utl
      4   # reference for z4
z4.opr    # schedules
z4.geo    # geometry
z4.con    # constructions
      1
z4.utl
```

```
      5   # reference for z5
z5.opr    # schedules
z5.geo    # geometry
z5.con    # constructions
      1
z5.utl
      6   # reference for zadjs
zadjs.opr    # schedules
zadjs.geo    # geometry
zadjs.con    # constructions
      0
     40   # number of connections
   1   1   2  23   0  #   1  Surf-1 in z1 >|< Constant @ 23 dC &   0 W
rad
   1   2   0   0   0  #   2  Surf-2 in z1 is External
   1   3   2  23   0  #   3  Surf-3 in z1 >|< Constant @ 23 dC &   0 W
rad
   1   4   0   0   0  #   4  Surf-4 in z1 is External
   1   5   3   2   6  #   5  Surf-5 in z1 >|< Surf-6 in z2
   1   6   4   1   0  #   6  Surf-6 in z1 >|< ground profile 1
   2   1   2  23   0  #   7  Surf-1 in z2 >|< Constant @ 23 dC &   0 W
rad
   2   2   0   0   0  #   8  Surf-2 in z2 is External
   2   3   2  23   0  #   9  Surf-3 in z2 >|< Constant @ 23 dC &   0 W
rad
   2   4   0   0   0  #  10  Surf-4 in z2 is External
   2   5   3   3   6  #  11  Surf-5 in z2 >|< Surf-6 in z3
   2   6   3   1   5  #  12  Surf-6 in z2 >|< Surf-5 in z1
   2   7   3   5   8  #  13  Surf5a in z2 >|< Surf6b in z5
   3   1   2  23   0  #  14  Surf-1 in z3 >|< Constant @ 23 dC &   0 W
rad
   3   2   0   0   0  #  15  Surf-2 in z3 is External
   3   3   3   5   9  #  16  Surf-3 in z3 >|< Surf-6al in z5
   3   4   0   0   0  #  17  Surf-4 in z3 is External
   3   5   3   4   6  #  18  Surf-5 in z3 >|< Surf-6 in z4
   3   6   3   2   5  #  19  Surf-6 in z3 >|< Surf-5 in z2
   4   1   2  23   0  #  20  Surf-1 in z4 >|< Constant @ 23 dC &   0 W
rad
   4   2   0   0   0  #  21  Surf-2 in z4 is External
   4   3   2  23   0  #  22  Surf-3 in z4 >|< Constant @ 23 dC &   0 W
rad
   4   4   0   0   0  #  23  Surf-4 in z4 is External
   4   5   3   5   6  #  24  Surf-5 in z4 >|< Surf-6 in z5
   4   6   3   3   5  #  25  Surf-6 in z4 >|< Surf-5 in z3
   5   1   2  23   0  #  26  Surf-1 in z5 >|< Constant @ 23 dC &   0 W
rad
   5   2   0   0   0  #  27  Surf-2 in z5 is External
   5   3   5   0   0  #  28  Surf-3 in z5 is adiabatic
   5   4   0   0   0  #  29  Surf-4 in z5 is External
   5   5   0   0   0  #  30  Surf-5 in z5 is External
   5   6   3   4   5  #  31  Surf-6 in z5 >|< Surf-5 in z4
   5   7   5   0   0  #  32  Surf6a in z5 is adiabatic
   5   8   3   2   7  #  33  Surf6b in z5 >|< Surf5a in z2
   5   9   3   3   3  #  34  Surf-6al in z5 >|< Surf-3 in z3
   6   1   5   0   0  #  35  Surf-1 in zadjs is adiabatic
   6   2   0   0   0  #  36  Surf-2 in zadjs is External
   6   3   5   0   0  #  37  Surf-3 in zadjs is adiabatic
   6   4   3   1   2  #  38  Surf-4 in zadjs >|< Surf-2 in z1
   6   5   5   0   0  #  39  Surf-5 in zadjs is adiabatic
   6   6   4   1   0  #  40  Surf-6 in zadjs >|< ground profile 1
```

```
      1    # mass flow analysis info follows:
at.mfn     # leakage description
  1  2  3  4  5  6
```

Control file

```
proj cntrl
* Building
no descrip
   2
* Control function
    0    0    0    0
    0    0    0
     0
    1  365
     1
    0    2   0.000
     0.0
    1  365
     1
    0    2   0.000
     0.0
    1  365
     1
    0    2   0.000
     0.0
* Control function
    0    0    0    0
    0    0    0
     0
    1  365
     1
    0    1   0.000
     6.0
     999998.  0.  0.  0.    23.0000   100.0000
    1  365
     1
    0    1   0.000
     6.0
     990000.  0.  0.  0.    23.0000   100.0000
    1  365
     1
    0    1   0.000
     6.0
     990000.  0.  0.  0.    23.0000   100.0000
   1  1  1  1  1  2
```

Geometry file for Zone 1

```
# geometry of z1 defined in: z1.geo
GEN  z1                          # type   zone name
       8       6   0.000    # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000     0.00000  # vert  1
     29.00000     0.00000     0.00000  # vert  2
     29.00000    19.00000     0.00000  # vert  3
      0.00000    19.00000     0.00000  # vert  4
      0.00000     0.00000     5.50000  # vert  5
     29.00000     0.00000     5.50000  # vert  6
     29.00000    19.00000     5.50000  # vert  7
      0.00000    19.00000     5.50000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface      geom  loc/  mlc db        environment
# no  name         type  posn  name          other side
  1, Surf-1        OPAQ  VERT  partition     CONSTANT
  2, Surf-2        OPAQ  VERT  ext_wall      EXTERIOR
  3, Surf-3        OPAQ  VERT  partition     CONSTANT
  4, Surf-4        OPAQ  VERT  ext_wall      EXTERIOR
  5, Surf-5        TRAN  CEIL  Fake_sep      z2
  6, Surf-6        OPAQ  FLOR  grnd_floor    GROUND
```

Geometry file for Zone 2

```
# geometry of z2 defined in: z2.geo
GEN  z2                          # type   zone name
      10       7   0.000    # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000     5.50000  # vert  1
     29.00000     0.00000     5.50000  # vert  2
     29.00000    19.00000     5.50000  # vert  3
      0.00000    19.00000     5.50000  # vert  4
      0.00000     0.00000    10.00000  # vert  5
     29.00000     0.00000    10.00000  # vert  6
     29.00000    19.00000    10.00000  # vert  7
      0.00000    19.00000    10.00000  # vert  8
     29.00000    18.00000    10.00000  # vert  9
      0.00000    18.00000    10.00000  # vert 10
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   5,  2,  3,  7,  9,  6,
```

```
   4,  3,  4,  8,  7,
   5,  4,  1,  5, 10,  8,
   4,  5,  6,  9, 10,
   4,  1,  4,  3,  2,
   4, 10,  9,  7,  8,
# number of default windows within each surface
   0  0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000 0.000
    1   3   0   3    # default insolation distribution
# surface attributes follow:
# id  surface        geom  loc/  mlc db        environment
# no  name           type  posn  name          other side
  1, Surf-1          OPAQ  VERT  partition     CONSTANT
  2, Surf-2          OPAQ  VERT  ext_wall      EXTERIOR
  3, Surf-3          OPAQ  VERT  partition     CONSTANT
  4, Surf-4          OPAQ  VERT  ext_wall      EXTERIOR
  5, Surf-5          TRAN  CEIL  Fake_sep      z3
  6, Surf-6          TRAN  FLOR  Fake_sep      z1
  7, Surf5a          TRAN  CEIL  Fake_sep      z5
```

Geometry file for Zone 3

```
# geometry of z3 defined in: z3.geo
GEN  z3                          # type   zone name
       8       6   0.000    # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000    10.00000  # vert  1
     29.00000     0.00000    10.00000  # vert  2
     29.00000    18.00000    10.00000  # vert  3
      0.00000    18.00000    10.00000  # vert  4
      0.00000     0.00000    14.50000  # vert  5
     29.00000     0.00000    14.50000  # vert  6
     29.00000    18.00000    14.50000  # vert  7
      0.00000    18.00000    14.50000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface        geom  loc/  mlc db        environment
# no  name           type  posn  name          other side
  1, Surf-1          OPAQ  VERT  partition     CONSTANT
  2, Surf-2          OPAQ  VERT  ext_wall      EXTERIOR
  3, Surf-3          TRAN  VERT  Fake_sep      z5
  4, Surf-4          OPAQ  VERT  ext_wall      EXTERIOR
```

```
  5, Surf-5         TRAN  CEIL  Fake_sep      z4
  6, Surf-6         TRAN  FLOR  Fake_sep      z2
```

Geometry file for Zone 4

```
# geometry of z4 defined in: z4.geo
GEN  z4                      # type   zone name
      8       6   0.000      # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000    14.50000  # vert  1
     29.00000     0.00000    14.50000  # vert  2
     29.00000    18.00000    14.50000  # vert  3
      0.00000    18.00000    14.50000  # vert  4
      0.00000     0.00000    17.50000  # vert  5
     29.00000     0.00000    17.50000  # vert  6
     29.00000    18.00000    17.50000  # vert  7
      0.00000    18.00000    17.50000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    1   3   0   0    # default insolation distribution
# surface attributes follow:
# id  surface       geom  loc/  mlc db       environment
# no  name          type  posn  name         other side
  1, Surf-1         OPAQ  VERT  partition    CONSTANT
  2, Surf-2         OPAQ  VERT  ext_wall     EXTERIOR
  3, Surf-3         TRAN  VERT  Fake_sep     CONSTANT
  4, Surf-4         OPAQ  VERT  ext_wall     EXTERIOR
  5, Surf-5         TRAN  CEIL  Fake_sep     z5
  6, Surf-6         TRAN  FLOR  Fake_sep     z3
```

Geometry file for Zone 5

```
# geometry of z5 defined in: z5.geo
GEN  z5                      # type   zone name
     14       9   0.000      # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000    17.50000  # vert  1
     29.00000     0.00000    17.50000  # vert  2
     29.00000    19.00000    10.00000  # vert  3
      0.00000    19.00000    10.00000  # vert  4
      0.00000     0.00000    20.00000  # vert  5
     29.00000     0.00000    20.00000  # vert  6
```

```
     29.00000    19.00000    20.00000  # vert  7
      0.00000    19.00000    20.00000  # vert  8
     29.00000    18.00000    10.00000  # vert  9
      0.00000    18.00000    10.00000  # vert 10
     29.00000    18.00000    17.50000  # vert 11
      0.00000    18.00000    17.50000  # vert 12
     29.00000    18.00000    14.50000  # vert 13
      0.00000    18.00000    14.50000  # vert 14
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   7,  2, 11, 13,  9,  3,  7,  6,
   4,  3,  4,  8,  7,
   7,  4, 10, 14, 12,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1, 12, 11,  2,
   4, 12, 14, 13, 11,
   4, 10,  4,  3,  9,
   4, 14, 10,  9, 13,
# number of default windows within each surface
   0  0  0  0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
    2   8   9  -1    # default insolation distribution
# surface attributes follow:
# id  surface      geom  loc/  mlc db      environment
# no  name         type  posn  name        other side
  1, Surf-1        OPAQ  VERT  partition   CONSTANT
  2, Surf-2        OPAQ  VERT  ext_wall    EXTERIOR
  3, Surf-3        OPAQ  VERT  partition   ADIABATIC
  4, Surf-4        OPAQ  VERT  ext_wall    EXTERIOR
  5, Surf-5        TRAN  CEIL  dbl_glz     EXTERIOR
  6, Surf-6        TRAN  FLOR  Fake_sep    z4
  7, Surf6a        TRAN  VERT  Fake_sep    ADIABATIC
  8, Surf6b        TRAN  FLOR  Fake_sep    z2
  9, Surf-6al      TRAN  VERT  Fake_sep    z3
```

Geometry file for adjacent Zone

```
# geometry of zadjs defined in: zadjs.geo
GEN  zadj                    # type   zone name
       8       6   0.000     # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
     29.00000     0.00000     0.00000  # vert  1
     58.00000     0.00000     0.00000  # vert  2
     58.00000    19.00000     0.00000  # vert  3
     29.00000    19.00000     0.00000  # vert  4
     29.00000     0.00000     5.50000  # vert  5
     58.00000     0.00000     5.50000  # vert  6
     58.00000    19.00000     5.50000  # vert  7
     29.00000    19.00000     5.50000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
```

```
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface        geom  loc/  mlc db        environment
# no  name           type  posn  name          other side
  1, Surf-1          OPAQ  VERT  ext_wall      ADIABATIC
  2, Surf-2          OPAQ  VERT  ext_wall      EXTERIOR
  3, Surf-3          OPAQ  VERT  ext_wall      ADIABATIC
  4, Surf-4          OPAQ  VERT  ext_wall      z1
  5, Surf-5          OPAQ  CEIL  roof          ADIABATIC
  6, Surf-6          OPAQ  FLOR  grnd_floor    GROUND
```

Construction file for Zone 1

```
# thermophysical properties of z1 defined in z1.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    3,     1  #  1 Surf-1        partition
    4,     1  #  2 Surf-2        ext_wall
    3,     1  #  3 Surf-3        partition
    4,     1  #  4 Surf-4        ext_wall
    1,     0  #  5 Surf-5        Fake_sep
    6,     1  #  6 Surf-6        grnd_floor
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# air gap position & resistance for surface  6
  4,   0.170,

# conduc-   |  density | specific | thick- |dpnd|  ref. |  temp.  |moisture| surf|lyr
# tivity    |          | heat     | ness(m)|type|  temp | factor  | factor |     |
     0.5100,    1400.0,    1000.0,  0.1000,   0,   0.00, 0.00000, 0.00000  #  1  1
     0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
   210.0000,    2700.0,     880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #  2  1
     0.0000,       0.0,       0.0,  0.0250,   0,   0.00, 0.00000, 0.00000  #     2
     0.0400,      12.0,     840.0,  0.0800,   0,   0.00, 0.00000, 0.00000  #     3
     0.5100,    1400.0,    1000.0,  0.2000,   0,   0.00, 0.00000, 0.00000  #     4
     0.5100,    1400.0,    1000.0,  0.1000,   0,   0.00, 0.00000, 0.00000  #  3  1
     0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
   210.0000,    2700.0,     880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #  4  1
     0.0000,       0.0,       0.0,  0.0250,   0,   0.00, 0.00000, 0.00000  #     2
     0.0400,      12.0,     840.0,  0.0800,   0,   0.00, 0.00000, 0.00000  #     3
     0.5100,    1400.0,    1000.0,  0.2000,   0,   0.00, 0.00000, 0.00000  #     4
     0.7600,    2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  5  1
     1.2800,    1460.0,     879.0,  0.2500,   0,   0.00, 0.00000, 0.00000  #  6  1
     0.5200,    2050.0,     184.0,  0.1500,   0,   0.00, 0.00000, 0.00000  #     2
     1.4000,    2100.0,     653.0,  0.1500,   0,   0.00, 0.00000, 0.00000  #     3
     0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     4
     0.1500,     800.0,    2093.0,  0.0190,   0,   0.00, 0.00000, 0.00000  #     5
     0.0600,     186.0,    1360.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     6
# for each surface: inside face emissivity
  0.91 0.90 0.91 0.90 0.83 0.90
```

```
# for each surface: outside face emissivity
  0.90 0.22 0.90 0.22 0.83 0.90
# for each surface: inside face solar absorptivity
  0.50 0.65 0.50 0.65 0.05 0.60
# for each surface: outside face solar absorptivity
  0.65 0.20 0.65 0.20 0.05 0.85
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for Zone 2

```
# thermophysical properties of z2 defined in z2.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
     3,      1  #  1 Surf-1       partition
     4,      1  #  2 Surf-2       ext_wall
     3,      1  #  3 Surf-3       partition
     4,      1  #  4 Surf-4       ext_wall
     1,      0  #  5 Surf-5       Fake_sep
     1,      0  #  6 Surf-6       Fake_sep
     1,      0  #  7 Surf5a       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# conduc-   |   density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity    |           | heat     | ness(m)|type|  temp |  factor |  factor |     |
     0.5100,    1400.0,    1000.0,  0.1000,    0,    0.00, 0.00000, 0.00000  #  1  1
     0.0000,       0.0,       0.0,  0.0500,    0,    0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #     3
   210.0000,    2700.0,     880.0,  0.0030,    0,    0.00, 0.00000, 0.00000  #  2  1
     0.0000,       0.0,       0.0,  0.0250,    0,    0.00, 0.00000, 0.00000  #     2
     0.0400,      12.0,     840.0,  0.0800,    0,    0.00, 0.00000, 0.00000  #     3
     0.5100,    1400.0,    1000.0,  0.2000,    0,    0.00, 0.00000, 0.00000  #     4
     0.5100,    1400.0,    1000.0,  0.1000,    0,    0.00, 0.00000, 0.00000  #  3  1
     0.0000,       0.0,       0.0,  0.0500,    0,    0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #     3
   210.0000,    2700.0,     880.0,  0.0030,    0,    0.00, 0.00000, 0.00000  #  4  1
     0.0000,       0.0,       0.0,  0.0250,    0,    0.00, 0.00000, 0.00000  #     2
     0.0400,      12.0,     840.0,  0.0800,    0,    0.00, 0.00000, 0.00000  #     3
     0.5100,    1400.0,    1000.0,  0.2000,    0,    0.00, 0.00000, 0.00000  #     4
     0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  5  1
     0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  6  1
     0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  7  1
# for each surface: inside face emissivity
  0.91 0.90 0.91 0.90 0.83 0.83 0.83
# for each surface: outside face emissivity
  0.90 0.22 0.90 0.22 0.83 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.65 0.50 0.65 0.05 0.05 0.05
# for each surface: outside face solar absorptivity
  0.65 0.20 0.65 0.20 0.05 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for Zone 3

```
# thermophysical properties of z3 defined in z3.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    3,     1  #  1 Surf-1       partition
    4,     1  #  2 Surf-2       ext_wall
    1,     0  #  3 Surf-3       Fake_sep
    4,     1  #  4 Surf-4       ext_wall
    1,     0  #  5 Surf-5       Fake_sep
    1,     0  #  6 Surf-6       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# conduc-   |  density | specific | thick-  |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity    |          | heat     | ness(m) |type|  temp |  factor |  factor |     |
    0.5100,    1400.0,    1000.0,  0.1000,    0,   0.00, 0.00000, 0.00000  #  1  1
    0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     2
    0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #     3
  210.0000,    2700.0,     880.0,  0.0030,    0,   0.00, 0.00000, 0.00000  #  2  1
    0.0000,       0.0,       0.0,  0.0250,    0,   0.00, 0.00000, 0.00000  #     2
    0.0400,      12.0,     840.0,  0.0800,    0,   0.00, 0.00000, 0.00000  #     3
    0.5100,    1400.0,    1000.0,  0.2000,    0,   0.00, 0.00000, 0.00000  #     4
    0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  3  1
  210.0000,    2700.0,     880.0,  0.0030,    0,   0.00, 0.00000, 0.00000  #  4  1
    0.0000,       0.0,       0.0,  0.0250,    0,   0.00, 0.00000, 0.00000  #     2
    0.0400,      12.0,     840.0,  0.0800,    0,   0.00, 0.00000, 0.00000  #     3
    0.5100,    1400.0,    1000.0,  0.2000,    0,   0.00, 0.00000, 0.00000  #     4
    0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  5  1
    0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  6  1
# for each surface: inside face emissivity
  0.91 0.90 0.83 0.90 0.83 0.83
# for each surface: outside face emissivity
  0.90 0.22 0.83 0.22 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.65 0.05 0.65 0.05 0.05
# for each surface: outside face solar absorptivity
  0.65 0.20 0.05 0.20 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for Zone 4

```
# thermophysical properties of z4 defined in z4.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    3,     1  #  1 Surf-1       partition
    4,     1  #  2 Surf-2       ext_wall
    1,     0  #  3 Surf-3       Fake_sep
    4,     1  #  4 Surf-4       ext_wall
    1,     0  #  5 Surf-5       Fake_sep
    1,     0  #  6 Surf-6       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# conduc-   |  density | specific | thick-  |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity    |          | heat     | ness(m) |type|  temp |  factor |  factor |     |
    0.5100,    1400.0,    1000.0,  0.1000,    0,   0.00, 0.00000, 0.00000  #  1  1
    0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     2
```

```
      0.4200,     1200.0,      837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #     3
    210.0000,     2700.0,      880.0,  0.0030,    0,    0.00, 0.00000, 0.00000  #  2  1
      0.0000,        0.0,        0.0,  0.0250,    0,    0.00, 0.00000, 0.00000  #     2
      0.0400,       12.0,      840.0,  0.0800,    0,    0.00, 0.00000, 0.00000  #     3
      0.5100,     1400.0,     1000.0,  0.2000,    0,    0.00, 0.00000, 0.00000  #     4
      0.7600,     2710.0,      837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  3  1
    210.0000,     2700.0,      880.0,  0.0030,    0,    0.00, 0.00000, 0.00000  #  4  1
      0.0000,        0.0,        0.0,  0.0250,    0,    0.00, 0.00000, 0.00000  #     2
      0.0400,       12.0,      840.0,  0.0800,    0,    0.00, 0.00000, 0.00000  #     3
      0.5100,     1400.0,     1000.0,  0.2000,    0,    0.00, 0.00000, 0.00000  #     4
      0.7600,     2710.0,      837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  5  1
      0.7600,     2710.0,      837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  6  1
# for each surface: inside face emissivity
   0.91 0.90 0.83 0.90 0.83 0.83
# for each surface: outside face emissivity
   0.90 0.22 0.83 0.22 0.83 0.83
# for each surface: inside face solar absorptivity
   0.50 0.65 0.05 0.65 0.05 0.05
# for each surface: outside face solar absorptivity
   0.65 0.20 0.05 0.20 0.05 0.05
# inside and exterior glazing maintenance factors
    0.00   0.00
```

Construction file for Zone 5

```
# thermophysical properties of z5 defined in z5.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
     3,     1  #  1 Surf-1       partition
     4,     1  #  2 Surf-2       ext_wall
     3,     1  #  3 Surf-3       partition
     4,     1  #  4 Surf-4       ext_wall
     3,     1  #  5 Surf-5       dbl_glz
     1,     0  #  6 Surf-6       Fake_sep
     1,     0  #  7 Surf6a       Fake_sep
     1,     0  #  8 Surf6b       Fake_sep
     1,     0  #  9 Surf-6al     Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# air gap position & resistance for surface  5
  2,   0.170,
# conduc-   |   density | specific | thick-  |dpnd|  ref. |  temp.  |moisture| surf|lyr
# tivity    |           | heat     | ness(m) |type|  temp | factor  | factor |     |
      0.5100,     1400.0,     1000.0,  0.1000,    0,    0.00, 0.00000, 0.00000  #  1  1
      0.0000,        0.0,        0.0,  0.0500,    0,    0.00, 0.00000, 0.00000  #     2
      0.4200,     1200.0,      837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #     3
    210.0000,     2700.0,      880.0,  0.0030,    0,    0.00, 0.00000, 0.00000  #  2  1
      0.0000,        0.0,        0.0,  0.0250,    0,    0.00, 0.00000, 0.00000  #     2
      0.0400,       12.0,      840.0,  0.0800,    0,    0.00, 0.00000, 0.00000  #     3
      0.5100,     1400.0,     1000.0,  0.2000,    0,    0.00, 0.00000, 0.00000  #     4
      0.5100,     1400.0,     1000.0,  0.1000,    0,    0.00, 0.00000, 0.00000  #  3  1
      0.0000,        0.0,        0.0,  0.0500,    0,    0.00, 0.00000, 0.00000  #     2
      0.4200,     1200.0,      837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #     3
    210.0000,     2700.0,      880.0,  0.0030,    0,    0.00, 0.00000, 0.00000  #  4  1
      0.0000,        0.0,        0.0,  0.0250,    0,    0.00, 0.00000, 0.00000  #     2
      0.0400,       12.0,      840.0,  0.0800,    0,    0.00, 0.00000, 0.00000  #     3
      0.5100,     1400.0,     1000.0,  0.2000,    0,    0.00, 0.00000, 0.00000  #     4
      0.7600,     2710.0,      837.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #  5  1
      0.0000,        0.0,        0.0,  0.0120,    0,    0.00, 0.00000, 0.00000  #     2
      0.7600,     2710.0,      837.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #     3
```

```
    0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  6  1
    0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  7  1
    0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  8  1
    0.7600,    2710.0,     837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  9  1
# for each surface: inside face emissivity
  0.91 0.90 0.91 0.90 0.83 0.83 0.83 0.83 0.83
# for each surface: outside face emissivity
  0.90 0.22 0.90 0.22 0.83 0.83 0.83 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.65 0.50 0.65 0.05 0.05 0.05 0.05 0.05
# for each surface: outside face solar absorptivity
  0.65 0.20 0.65 0.20 0.05 0.05 0.05 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for adjacent Zone

```
# thermophysical properties of zadj defined in zadj.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    4,      1  #  1 Surf-1       ext_wall
    4,      1  #  2 Surf-2       ext_wall
    4,      1  #  3 Surf-3       ext_wall
    4,      1  #  4 Surf-4       ext_wall
    4,      1  #  5 Surf-5       roof
    6,      1  #  6 Surf-6       grnd_floor
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# air gap position & resistance for surface  5
  2,   0.170,
# air gap position & resistance for surface  6
  4,   0.170,
# conduc-  |  density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity   |          | heat     | ness(m)|type|  temp |  factor |  factor |     |
  210.0000,   2700.0,     880.0,  0.0030,   0,    0.00, 0.00000, 0.00000  #  1  1
    0.0000,      0.0,       0.0,  0.0250,   0,    0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,     840.0,  0.0800,   0,    0.00, 0.00000, 0.00000  #     3
    0.5100,   1400.0,    1000.0,  0.2000,   0,    0.00, 0.00000, 0.00000  #     4
  210.0000,   2700.0,     880.0,  0.0030,   0,    0.00, 0.00000, 0.00000  #  2  1
    0.0000,      0.0,       0.0,  0.0250,   0,    0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,     840.0,  0.0800,   0,    0.00, 0.00000, 0.00000  #     3
    0.5100,   1400.0,    1000.0,  0.2000,   0,    0.00, 0.00000, 0.00000  #     4
  210.0000,   2700.0,     880.0,  0.0030,   0,    0.00, 0.00000, 0.00000  #  3  1
    0.0000,      0.0,       0.0,  0.0250,   0,    0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,     840.0,  0.0800,   0,    0.00, 0.00000, 0.00000  #     3
    0.5100,   1400.0,    1000.0,  0.2000,   0,    0.00, 0.00000, 0.00000  #     4
  210.0000,   2700.0,     880.0,  0.0030,   0,    0.00, 0.00000, 0.00000  #  4  1
    0.0000,      0.0,       0.0,  0.0250,   0,    0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,     840.0,  0.0800,   0,    0.00, 0.00000, 0.00000  #     3
    0.5100,   1400.0,    1000.0,  0.2000,   0,    0.00, 0.00000, 0.00000  #     4
  210.0000,   2700.0,     880.0,  0.0030,   0,    0.00, 0.00000, 0.00000  #  5  1
    0.0000,      0.0,       0.0,  0.0250,   0,    0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,     840.0,  0.0800,   0,    0.00, 0.00000, 0.00000  #     3
  210.0000,   2700.0,     880.0,  0.0030,   0,    0.00, 0.00000, 0.00000  #     4
    1.2800,   1460.0,     879.0,  0.2500,   0,    0.00, 0.00000, 0.00000  #  6  1
    0.5200,   2050.0,     184.0,  0.1500,   0,    0.00, 0.00000, 0.00000  #     2
    1.4000,   2100.0,     653.0,  0.1500,   0,    0.00, 0.00000, 0.00000  #     3
    0.0000,      0.0,       0.0,  0.0500,   0,    0.00, 0.00000, 0.00000  #     4
    0.1500,    800.0,    2093.0,  0.0190,   0,    0.00, 0.00000, 0.00000  #     5
    0.0600,    186.0,    1360.0,  0.0060,   0,    0.00, 0.00000, 0.00000  #     6
```

```
# for each surface: inside face emissivity
  0.90 0.90 0.90 0.90 0.22 0.90
# for each surface: outside face emissivity
  0.22 0.22 0.22 0.22 0.22 0.90
# for each surface: inside face solar absorptivity
  0.65 0.65 0.65 0.65 0.20 0.60
# for each surface: outside face solar absorptivity
  0.20 0.20 0.20 0.20 0.20 0.85
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Operation file for Zone 1

```
# operations of z1 defined in:
# z1.opr
nil_operations    # operation name
# control(no flow control          ), low & high setpoints
   0     0.000     0.000
     0   # no Weekday flow periods
     0   # no Saturday flow periods
     0   # no Sunday flow periods
     0   # no Weekday casual gains
     0   # no Saturday casual gains
     0   # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 2

```
# operations of z2 defined in:
# z2.opr
nil_operations    # operation name
# control(no flow control          ), low & high setpoints
   0     0.000     0.000
     0   # no Weekday flow periods
     0   # no Saturday flow periods
     0   # no Sunday flow periods
     0   # no Weekday casual gains
     0   # no Saturday casual gains
     0   # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 3

```
# operations of z3 defined in:
# z3.opr
nil_operations    # operation name
# control(no flow control          ), low & high setpoints
   0     0.000     0.000
     0   # no Weekday flow periods
     0   # no Saturday flow periods
     0   # no Sunday flow periods
     0   # no Weekday casual gains
```

```
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 4

```
# operations of z4 defined in:
# z4.opr
nil_operations    # operation name
# control(no flow control         ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 5

```
# operations of z5 defined in:
# z5.opr
nil_operations    # operation name
# control(no flow control         ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for adjacent Zone

```
# operations of zadj defined in:
# zadj.opr
nil_operations    # operation name
# control(no flow control         ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Transparent material construction file for Zone 1

```
# transparent properties of z1 defined in z1.tmc
   6    # surfaces
# tmc index for each surface
   0  0  0  0  1  0
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent material construction file for Zone 2

```
# transparent properties of z2 defined in z2.tmc
   7    # surfaces
# tmc index for each surface
   0  0  0  0  1  1  1
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent material construction file for Zone 3

```
# transparent properties of z3 defined in z3.tmc
   6    # surfaces
# tmc index for each surface
   0  0  1  0  1  1
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent material construction file for Zone 4

```
# transparent properties of z4 defined in z4.tmc
   6    # surfaces
# tmc index for each surface
   0  0  1  0  1  1
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
```

```
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent material construction file for Zone 5

```
# transparent properties of z5 defined in z5.tmc
   9   # surfaces
# tmc index for each surface
   0  0  0  0  1  2  2  2  2
   3  # layers
# Transmission @ 5 angles & visible tr.
   0.611   0.583   0.534   0.384   0.170   0.760
# For each layer absorption @ 5 angles
   0.157   0.172   0.185   0.201   0.202
   0.001   0.002   0.003   0.004   0.005
   0.117   0.124   0.127   0.112   0.077
   0  # blind/shutter control flag
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Utility file for Zone 1

```
# Optional zone files for z1              instanced in file
# z1.utl
   0    # time-step air flow
   0    # time-step casual gains
   0    # view factors
   0    # shading/ insolation
   0    # convective heat transfer coefficients
   0    # blind/ shutter control
   1    # transparent construction data
z1.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
   0    # moisture data
```

Utility file for Zone 2

```
# Optional zone files for z2              instanced in file
# z2.utl
   0     # time-step air flow
   0     # time-step casual gains
   0     # view factors
   0     # shading/ insolation
   0     # convective heat transfer coefficients
   0     # blind/ shutter control
   1     # transparent construction data
z2.tmc
   0     # casual gain control
   0     # obstructions
   0     # control volumes
   0     # connections
   0     # nodes coordinates
   0     # nodes temperature
   0     # domain flow data
   0     # moisture data
```

Utility file for Zone 3

```
# Optional zone files for z3              instanced in file
# z3.utl
   0     # time-step air flow
   0     # time-step casual gains
   0     # view factors
   0     # shading/ insolation
   0     # convective heat transfer coefficients
   0     # blind/ shutter control
   1     # transparent construction data
z3.tmc
   0     # casual gain control
   0     # obstructions
   0     # control volumes
   0     # connections
   0     # nodes coordinates
   0     # nodes temperature
   0     # domain flow data
   0     # moisture data
```

Utility file for Zone 4

```
# Optional zone files for z4              instanced in file
# z4.utl
   0     # time-step air flow
   0     # time-step casual gains
   0     # view factors
   0     # shading/ insolation
   0     # convective heat transfer coefficients
```

```
 orlo2     40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     20.0000    0.630000
 skyor     40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     2.00000    0.630000
 ator      40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     40.0000    0.630000
```

+Node	dHght	-Node	dHght	Comp	Snod1	Snod2
z1n	4.500	z2n	-2.500	ator		
z2n	2.000	z3n	-2.000	ator		
z3n	2.500	z4n	-2.00	ator		
z4n	1.000	z5n	-1.500	ator		
z5n	1.000	nhin	-2.000	skyor		
nlon	0.000	zadjn	0.000	orlo1		
zadjn	0.000	z1n	0.000	orlo2		

Mass flow network for June 12 and July 7 with roof vent opened

```
   8    4    7    1.000    (nodes, components, connections, wind
reduction)
```

Node	Fld.	Type	Height	Temperature	Data_1	Data_2
z1n	1	0	1.0000	20.000	0.	3100.0
z2n	1	0	8.0000	20.000	0.	2500.0
z3n	1	0	12.000	20.000	0.	2500.0
z4n	1	0	16.500	20.000	0.	1700.0
z5n	1	0	19.000	20.000	0.	1400.0
zadjn	1	0	1.0000	20.000	0.	3000.0
nlon	1	3	1.0000	0.	1.0000	0.
nhin	1	3	22.000	0.	1.0000	0.

```
 Comp     Type C+ L+ Description
 orlo1     40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     20.0000    0.630000
 orlo2     40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     20.0000    0.630000
 skyor     40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     40.0000    0.630000
 ator      40  3  0 Common orifice vol. flow rate comp. m =
rho.f(Cd,A,rho,dP)
     1.00000     40.0000    0.630000
```

+Node	dHght	-Node	dHght	Comp	Snod1	Snod2
z1n	4.500	z2n	-2.500	ator		
z2n	2.000	z3n	-2.000	ator		
z3n	2.500	z4n	-2.000	ator		
z4n	1.000	z5n	-1.500	ator		
z5n	1.000	nhin	-2.000	skyor		
nlon	0.000	zadjn	0.000	orlo1		
zadjn	0.000	z1n	0.000	orlo2		

Weather file for AZG atrium

```
# ascii climate file from /usr/esru/esp-r/climate/clm67 binary db,
# defined in: aaclim.asc
* day 10 month  3

*CLIMATE
# ascii climate file from /usr/esru/esp-r/climate/clm67 binary db,
# defined in: gronnwl-asc
# col 1: Diffuse solar on the horizontal (W/m**2)
# col 2: External dry bulb temperature   (Tenths DEG.C)
# col 3: Direct normal solar intensity   (W/m**2)
# col 4: Prevailing wind speed           (Tenths m/s)
# col 5: Wind direction     (clockwise deg from north)
# col 6: Relative humidity               (Percent)
Groningen climate                 # site name
  1989   52.00    0.00   0       # year, latitude, long diff, rad flag
     1   365                     # period (julian days)
* day 11 month  6
       0    140      0      0     30     57
       0    155      0      0     15     64
       0    152      0      0     10     69
       0    145      0      0     10     71
      75    145    144      0      5     75
      91    143    505      0      0     73
     123    146    369      0      5     72
     122    168    733      0     15     66
     131    186    786      0     20     63
     146    195    747      0     15     64
     156    208    715      0     25     57
     154    217    751      0     35     46
     152    228    752      0     30     40
     148    235    735      0     35     46
     140    242    712      0     35     45
     141    241    422      0     25     38
     124    242    357      0     35     35
     100    240    261      0     70     45
      67    238    177      0     85     49
       0    232      0      0     85     48
       0    221      0      0     95     54
       0    201      0      0    100     56
       0    184      0      0     80     65
       0    160      0      0     45     62
* day 12 month  6
       0    140      0      0     30     57
       0    155      0      0     15     64
       0    152      0      0     10     69
       0    145      0      0     10     71
       0    145      0      0      5     75
      75    143    144      0      0     73
      91    146    505      0      5     72
     123    168    369      0     15     66
     122    186    733      0     20     63
     131    195    786      0     15     64
     146    208    747      0     25     57
     156    217    715      0     35     46
     154    228    751      0     30     40
```

152	235	752	0	35	46
148	242	735	0	35	45
140	241	712	0	25	38
141	242	422	0	35	35
124	240	357	0	70	45
100	238	261	0	85	49
67	232	177	0	85	48
0	221	0	0	95	54
0	201	0	0	100	56
0	184	0	0	80	65
0	170	0	0	45	62
* day 6 month 7					
0	138	0	0	0	91
0	127	0	0	0	96
0	122	0	0	0	96
0	122	0	0	0	97
50	122	0	0	0	93
95	133	179	0	0	95
148	155	0	0	0	87
138	166	429	0	0	84
255	183	0	0	0	74
160	200	386	0	0	62
166	188	400	0	90	63
168	194	407	0	190	63
167	205	405	0	205	59
163	205	509	0	205	51
154	205	374	0	185	51
140	205	289	0	180	51
118	200	176	0	215	50
97	194	145	0	240	53
41	183	0	0	250	53
0	172	0	0	310	66
0	155	0	0	0	74
0	144	0	0	0	60
0	150	0	0	0	76
0	138	0	0	275	82
* day 7 month 7					
0	213	0	0	195	84
0	210	0	0	280	85
0	200	0	0	0	89
0	192	0	0	0	93
0	183	0	0	0	92
50	177	0	0	0	93
90	181	420	0	0	88
148	193	430	0	0	80
138	217	470	0	0	74
132	250	600	0	295	67
150	277	640	0	220	56
162	283	710	0	210	53
160	293	720	0	205	47
159	305	730	0	205	44
152	311	700	0	205	44
147	311	500	0	200	43
142	306	410	0	205	40
125	290	400	0	205	46
100	262	350	0	205	55

63	248	0	0	215	55
0	242	0	0	215	58
0	230	0	0	205	62
0	220	0	0	195	68
0	212	0	0	190	74
* day 19	month	8			
0	190	0	0	30	87
0	190	0	0	35	87
0	190	0	0	10	89
0	180	0	0	335	90
0	175	0	0	345	95
64	175	126	0	0	94
93	165	502	0	0	92
107	170	673	0	20	84
139	200	427	0	40	78
151	225	458	0	40	68
142	240	727	0	35	62
145	255	727	0	40	57
142	270	737	0	10	55
130	280	786	0	355	56
142	300	446	0	10	49
126	300	392	0	320	47
105	300	280	0	315	47
69	290	240	0	0	50
0	275	0	0	15	51
0	260	0	0	10	56
0	250	0	0	65	74
0	240	0	0	110	75
0	230	0	0	95	79
0	225	0	0	50	88
* day 20	month	8			
0	190	0	0	30	87
0	190	0	0	35	87
0	190	0	0	10	89
0	180	0	0	335	90
0	175	0	0	345	95
0	175	0	0	0	94
64	165	126	0	0	92
93	170	502	0	20	84
107	200	673	0	40	78
139	225	427	0	40	68
151	240	458	0	35	62
142	255	727	0	40	57
145	270	727	0	10	55
142	280	737	0	355	56
130	300	786	0	10	49
142	300	446	0	320	47
126	300	392	0	315	47
105	290	280	0	0	50
69	275	240	0	15	51
0	260	0	0	10	56
0	250	0	0	65	74
0	240	0	0	110	75
0	230	0	0	95	79
0	225	0	0	50	88

APPENDIX 3

Input files of ESP-r modified 6-zone computer simulation model for EECS atrium

Configuration file

```
* CONFIGURATION
# ESRU system configuration defined by file
# six.cfg
      1           # Building only
 42.000    0.000    # Latitude & Longitude
      1   0.200   # Site exposure & ground refl
* DATABASES
*prm  constr.db1
*mlc  multicon.db1
*opt  optics.db1
*prs  /usr/esru/esp-r/databases/pressc.db1
*evn  /usr/esru/esp-r/databases/profiles.db1
*clm  ../../detclm_bin4
*pdb  /usr/esru/esp-r/databases/plantc.db1
*ctl  atctl
* PROJ LOG
job.notes
* Building
six zone model -solar penetration
      7  # no of zones
      1   # reference for z1
z1.opr    # schedules
z1.geo    # geometry
z1.con    # constructions
      1
z1.utl
      2   # reference for z2
z2.opr    # schedules
z2.geo    # geometry
z2.con    # constructions
      1
z2.utl
      3   # reference for z3
z3.opr    # schedules
z3.geo    # geometry
z3.con    # constructions
      1
z3.utl
      4   # reference for z4
z4.opr    # schedules
z4.geo    # geometry
z4.con    # constructions
      1
z4.utl


       5   # reference for z5
z5.opr    # schedules
z5.geo    # geometry
```

```
z5.con    # constructions
      1
z5.utl
      6   # reference for z6
z6.opr    # schedules
z6.geo    # geometry
z6.con    # constructions
      1
z6.utl
      7   # reference for zadj
zadj.opr    # schedules
zadj.geo    # geometry
zadj.con    # constructions
      0
     46   # number of connections
   1   1   3   7   3   #   1   Surf-1 in z1 >|< Surf-3 in zadj
   1   2   0   0   0   #   2   Surf-2 in z1 is External
   1   3   2  23   0   #   3   Surf-3 in z1 >|< Constant @ 23 dC &   0 W
rad
   1   4   0   0   0   #   4   Surf-4 in z1 is External
   1   5   3   2   6   #   5   Surf-5 in z1 >|< Surf-6 in z2
   1   6   4   1   0   #   6   Surf-6 in z1 >|< ground profile 1
   2   1   2  23   0   #   7   Surf-1 in z2 >|< Constant @ 23 dC &   0 W
rad
   2   2   0   0   0   #   8   Surf-2 in z2 is External
   2   3   2  23   0   #   9   Surf-3 in z2 >|< Constant @ 23 dC &   0 W
rad
   2   4   0   0   0   #  10   Surf-4 in z2 is External
   2   5   3   3   6   #  11   Surf-5 in z2 >|< Surf-6 in z3
   2   6   3   1   5   #  12   Surf-6 in z2 >|< Surf-5 in z1
   3   1   2  23   0   #  13   Surf-1 in z3 >|< Constant @ 23 dC &   0 W
rad
   3   2   0   0   0   #  14   Surf-2 in z3 is External
   3   3   2  23   0   #  15   Surf-3 in z3 >|< Constant @ 23 dC &   0 W
rad
   3   4   0   0   0   #  16   Surf-4 in z3 is External
   3   5   3   4   6   #  17   Surf-5 in z3 >|< Surf-6 in z4
   3   6   3   2   5   #  18   Surf-6 in z3 >|< Surf-5 in z2
   3   7   5   0   0   #  19   Surf5a in z3 is adiabatic
   4   1   2  23   0   #  20   Surf-1 in z4 >|< Constant @ 23 dC &   0 W
rad
   4   2   0   0   0   #  21   Surf-2 in z4 is External
   4   3   2  23   0   #  22   Surf-3 in z4 >|< Constant @ 23 dC &   0 W
rad
   4   4   0   0   0   #  23   Surf-4 in z4 is External
   4   5   3   5   6   #  24   Surf-5 in z4 >|< Surf-6 in z5
   4   6   3   3   5   #  25   Surf-6 in z4 >|< Surf-5 in z3
   5   1   2  23   0   #  26   Surf-1 in z5 >|< Constant @ 23 dC &   0 W
rad
   5   2   0   0   0   #  27   Surf-2 in z5 is External
   5   3   2  23   0   #  28   Surf-3 in z5 >|< Constant @ 23 dC &   0 W
rad
   5   4   0   0   0   #  29   Surf-4 in z5 is External
   5   5   3   6   6   #  30   Surf-5 in z5 >|< Surf-6 in z6
   5   6   3   4   5   #  31   Surf-6 in z5 >|< Surf-5 in z4
   6   1   0   0   0   #  32   Surf-1 in z6 is External
   6   2   0   0   0   #  33   Surf-2 in z6 is External
   6   3   5   0   0   #  34   Surf-3 in z6 is adiabatic
   6   4   0   0   0   #  35   Surf-4 in z6 is External
   6   5   0   0   0   #  36   Surf-5 in z6 is External
```

```
   6   6   3   5   5  #  37  Surf-6 in z6 >|< Surf-5 in z5
   6   7   5   0   0  #  38  Surf6a in z6 is adiabatic
   6   8   5   0   0  #  39  Surf6b in z6 is adiabatic
   6   9   5   0   0  #  40  Surf-6al in z6 is adiabatic
   7   1   0   0   0  #  41  Surf-1 in zadj is External
   7   2   2  23   0  #  42  Surf-2 in zadj >|< Constant @ 23 dC &   0 W
rad
   7   3   3   1   1  #  43  Surf-3 in zadj >|< Surf-1 in z1
   7   4   2  23   0  #  44  Surf-4 in zadj >|< Constant @ 23 dC &   0 W
rad
   7   5   5   0   0  #  45  Surf-5 in zadj is adiabatic
   7   6   5   0   0  #  46  Surf-6 in zadj is adiabatic
      1    # mass flow analysis info follows:
at.mfn     # leakage description
  1  2  3  4  5  6  7
```

Control file

```
proj cntrl
*Building
no descrip
   3
*Control function
    0     0     0     0
    0     0     0
     0
    1  365
     1
    0     2    0.000
     0.0
    1  365
     1
    0     2    0.000
     0.0
    1  365
     1
    0     2    0.000
     0.0
* Control function
    0     0     0     0
    0     0     0
     0
    1  365
     1
    0     1    0.000
     6.0
     900000.  0.    900000.  0.    21.0000    23.0000
    1  365
     1
    0     1    0.000
     6.0
     900000.  0.    900000.  0.    21.0000    23.0000
    1  365
     1
    0     1    0.000
```

```
     6.0
     900000.  0.    900000.  0.    21.0000    23.0000
* Control function
    0    0    0    0
    0    0    0
     0
    1  365
     1
    0    1   0.000
     6.0
     40000.0  0.  0.  0.    21.0000   100.0000
    1  365
     1
    0    1   0.000
     6.0
     40000.0  0.  0.  0.    21.0000   100.0000
    1  365
     1
    0    1   0.000
     6.0
     40000.0  0.  0.  0.    21.0000   100.0000
   1  1  1  1  1  3  2
```

Geometry file for Zone 1

```
# geometry of z1 defined in: z1.geo
GEN  z1                        # type   zone name
       8      6  0.000    # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000     0.00000  # vert  1
     91.40000     0.00000     0.00000  # vert  2
     91.40000     9.00000     0.00000  # vert  3
      0.00000     9.00000     0.00000  # vert  4
      0.00000     0.00000     4.50000  # vert  5
     91.40000     0.00000     4.50000  # vert  6
     91.40000     9.00000     4.50000  # vert  7
      0.00000     9.00000     4.50000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface       geom  loc/  mlc db        environment
# no  name          type  posn  name          other side
  1, Surf-1         OPAQ  VERT  partition     zadj
  2, Surf-2         TRAN  VERT  dbl_glz       EXTERIOR
```

```
  3, Surf-3        OPAQ  VERT  partition    CONSTANT
  4, Surf-4        TRAN  VERT  dbl_glz      EXTERIOR
  5, Surf-5        TRAN  CEIL  Fake_sep     z2
  6, Surf-6        OPAQ  FLOR  grnd_floor   GROUND
```

Geometry file for Zone 2

```
# geometry of z2 defined in: z2.geo
GEN  z2                         # type   zone name
       8       6   0.000        # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
     0.00000     0.00000     4.50000  # vert  1
    91.40000     0.00000     4.50000  # vert  2
    91.40000     9.00000     4.50000  # vert  3
     0.00000     9.00000     4.50000  # vert  4
     0.00000     0.00000     9.00000  # vert  5
    91.40000     0.00000     9.00000  # vert  6
    91.40000     9.00000     9.00000  # vert  7
     0.00000     9.00000     9.00000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0     # default insolation distribution
# surface attributes follow:
# id  surface      geom  loc/  mlc db       environment
# no  name         type  posn  name         other side
  1, Surf-1        OPAQ  VERT  partition    CONSTANT
  2, Surf-2        TRAN  VERT  dbl_glz      EXTERIOR
  3, Surf-3        TRAN  VERT  Fake_sep     CONSTANT
  4, Surf-4        TRAN  VERT  dbl_glz      EXTERIOR
  5, Surf-5        TRAN  CEIL  Fake_sep     z3
  6, Surf-6        TRAN  FLOR  Fake_sep     z1
```

Geometry file for Zone 3

```
# geometry of z3 defined in: z3.geo
GEN  z3                         # type   zone name
      10       7   0.000        # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
     0.00000     0.00000     9.00000  # vert  1
    91.40000     0.00000     9.00000  # vert  2
    91.40000     9.00000     9.00000  # vert  3
     0.00000     9.00000     9.00000  # vert  4
     0.00000     0.00000    12.90000  # vert  5
```

```
     91.40000     0.00000    12.90000  # vert  6
     91.40000     9.00000    12.90000  # vert  7
      0.00000     9.00000    12.90000  # vert  8
     91.40000     8.90000    12.90000  # vert  9
      0.00000     8.90000    12.90000  # vert 10
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   5,  2,  3,  7,  9,  6,
   4,  3,  4,  8,  7,
   5,  4,  1,  5, 10,  8,
   4,  5,  6,  9, 10,
   4,  1,  4,  3,  2,
   4, 10,  9,  7,  8,
# number of default windows within each surface
   0  0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000 0.000
    1   3   0   3    # default insolation distribution
# surface attributes follow:
# id  surface       geom  loc/  mlc db       environment
# no  name          type  posn  name         other side
  1, Surf-1         OPAQ  VERT  partition    CONSTANT
  2, Surf-2         TRAN  VERT  dbl_glz      EXTERIOR
  3, Surf-3         OPAQ  VERT  partition    CONSTANT
  4, Surf-4         TRAN  VERT  dbl_glz      EXTERIOR
  5, Surf-5         TRAN  CEIL  Fake_sep     z4
  6, Surf-6         TRAN  FLOR  Fake_sep     z2
  7, Surf5a         TRAN  CEIL  Fake_sep     ADIABATIC
```

Geometry file for Zone 4

```
# geometry of z4 defined in: z4.geo
GEN  z4                        # type   zone name
       8       6   0.000       # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000    12.90000  # vert  1
     91.40000     0.00000    12.90000  # vert  2
     91.40000     8.90000    12.90000  # vert  3
      0.00000     8.90000    12.90000  # vert  4
      0.00000     0.00000    16.70000  # vert  5
     91.40000     0.00000    16.70000  # vert  6
     91.40000     8.90000    16.70000  # vert  7
      0.00000     8.90000    16.70000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
```

```
   3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface       geom  loc/  mlc db        environment
# no  name          type  posn  name          other side
  1, Surf-1         OPAQ  VERT  partition     CONSTANT
  2, Surf-2         TRAN  VERT  dbl_glz       EXTERIOR
  3, Surf-3         OPAQ  VERT  partition     CONSTANT
  4, Surf-4         TRAN  VERT  dbl_glz       EXTERIOR
  5, Surf-5         TRAN  CEIL  Fake_sep      z5
  6, Surf-6         TRAN  FLOR  Fake_sep      z3
```

Geometry file for Zone 5

```
# geometry of z5 defined in: z5.geo
GEN  z5                          # type   zone name
      8       6   0.000     # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
      0.00000     0.00000    16.70000  # vert  1
     91.40000     0.00000    16.70000  # vert  2
     91.40000     8.90000    16.70000  # vert  3
      0.00000     8.90000    16.70000  # vert  4
      0.00000     0.00000    19.70000  # vert  5
     91.40000     0.00000    19.70000  # vert  6
     91.40000     8.90000    19.70000  # vert  7
      0.00000     8.90000    19.70000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
   1   3   0   0    # default insolation distribution
# surface attributes follow:
# id  surface       geom  loc/  mlc db        environment
# no  name          type  posn  name          other side
  1, Surf-1         OPAQ  VERT  partition     CONSTANT
  2, Surf-2         TRAN  VERT  dbl_glz       EXTERIOR
  3, Surf-3         OPAQ  VERT  partition     CONSTANT
  4, Surf-4         OPAQ  VERT  ext_wall      EXTERIOR
  5, Surf-5         TRAN  CEIL  Fake_sep      z6
  6, Surf-6         TRAN  FLOR  Fake_sep      z4
```

Geometry file for Zone 6

```
# geometry of z6 defined in: z6.geo
GEN  z6                          # type   zone name
     14       9   0.000     # vertices, surfaces, rotation angle
```

```
#  X co-ord, Y co-ord, Z co-ord
    0.00000     0.00000    19.70000  # vert  1
   91.40000     0.00000    19.70000  # vert  2
   91.40000     9.00000    12.90000  # vert  3
    0.00000     9.00000    12.90000  # vert  4
    0.00000     4.50000    23.50000  # vert  5
   91.40000     4.50000    23.50000  # vert  6
   91.40000     9.00000    23.50000  # vert  7
    0.00000     9.00000    23.50000  # vert  8
   91.40000     8.90000    12.90000  # vert  9
    0.00000     8.90000    12.90000  # vert 10
   91.40000     8.90000    19.70000  # vert 11
    0.00000     8.90000    19.70000  # vert 12
   91.40000     8.90000    16.70000  # vert 13
    0.00000     8.90000    16.70000  # vert 14
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   7,  2, 11, 13,  9,  3,  7,  6,
   4,  3,  4,  8,  7,
   7,  4, 10, 14, 12,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1, 12, 11,  2,
   4, 12, 14, 13, 11,
   4, 10,  4,  3,  9,
   4, 14, 10,  9, 13,
# number of default windows within each surface
   0  0  0  0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
    1   6   0   6    # default insolation distribution
# surface attributes follow:
# id  surface      geom  loc/  mlc db       environment
# no  name         type  posn  name         other side
  1,  Surf-1       TRAN  VERT  dbl_glz      EXTERIOR
  2,  Surf-2       TRAN  VERT  dbl_glz      EXTERIOR
  3,  Surf-3       OPAQ  VERT  partition    ADIABATIC
  4,  Surf-4       TRAN  VERT  dbl_glz      EXTERIOR
  5,  Surf-5       TRAN  CEIL  dbl_glz      EXTERIOR
  6,  Surf-6       TRAN  FLOR  Fake_sep     z5
  7,  Surf6a       TRAN  VERT  Fake_sep     ADIABATIC
  8,  Surf6b       TRAN  FLOR  Fake_sep     ADIABATIC
  9,  Surf-6al     TRAN  VERT  Fake_sep     ADIABATIC
```

Geometry file for adjacent Zone

```
# geometry of zadj defined in: zadj.geo
GEN  zadj                     # type   zone name
       8      6   0.000       # vertices, surfaces, rotation angle
#  X co-ord, Y co-ord, Z co-ord
    0.00000   -20.00000     0.00000  # vert  1
   91.40000   -20.00000     0.00000  # vert  2
   91.40000     0.00000     0.00000  # vert  3
    0.00000     0.00000     0.00000  # vert  4
    0.00000   -20.00000     4.50000  # vert  5
```

```
     91.40000   -20.00000     4.50000  # vert  6
     91.40000     0.00000     4.50000  # vert  7
      0.00000     0.00000     4.50000  # vert  8
# no of vertices followed by list of associated vert
   4,  1,  2,  6,  5,
   4,  2,  3,  7,  6,
   4,  3,  4,  8,  7,
   4,  4,  1,  5,  8,
   4,  5,  6,  7,  8,
   4,  1,  4,  3,  2,
# number of default windows within each surface
   0  0  0  0  0  0
# surfaces indentation (m)
 0.000 0.000 0.000 0.000 0.000 0.000
    3   0   0   0    # default insolation distribution
# surface attributes follow:
# id  surface        geom  loc/  mlc db       environment
# no  name           type  posn  name         other side
  1, Surf-1          OPAQ  VERT  ext_wall     EXTERIOR
  2, Surf-2          OPAQ  VERT  ext_wall     CONSTANT
  3, Surf-3          OPAQ  VERT  partition    z1
  4, Surf-4          OPAQ  VERT  ext_wall     CONSTANT
  5, Surf-5          OPAQ  CEIL  roof         ADIABATIC
  6, Surf-6          OPAQ  FLOR  grnd_floor   ADIABATIC
```

Construction file for zone 1

```
# thermophysical properties of z1 defined in z1.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    3,     1  #  1 Surf-1        partition
    3,     1  #  2 Surf-2        dbl_glz
    3,     1  #  3 Surf-3        partition
    3,     1  #  4 Surf-4        dbl_glz
    1,     0  #  5 Surf-5        Fake_sep
    6,     1  #  6 Surf-6        grnd_floor
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# air gap position & resistance for surface  6
  4,   0.170,
# conduc-  |  density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity   |          | heat     | ness(m)|type|  temp |  factor |  factor |     |
    0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #  1  1
    0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
    0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
    0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  2  1
    0.0000,       0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
    0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
    0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #  3  1
    0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
    0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
    0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  4  1
    0.0000,       0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
    0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
    0.7600,    2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  5  1
```

```
    1.2800,     1456.0,      879.0,  0.2500,    0,    0.00, 0.00000, 0.00000  #  6  1
    0.5200,     2050.0,      184.0,  0.1500,    0,    0.00, 0.00000, 0.00000  #     2
    1.4000,     2100.0,      653.0,  0.1500,    0,    0.00, 0.00000, 0.00000  #     3
    0.0000,        0.0,        0.0,  0.0500,    0,    0.00, 0.00000, 0.00000  #     4
    0.1500,      800.0,     2093.0,  0.0190,    0,    0.00, 0.00000, 0.00000  #     5
    0.0600,      186.0,     1360.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #     6
# for each surface: inside face emissivity
  0.91 0.83 0.91 0.83 0.83 0.90
# for each surface: outside face emissivity
  0.91 0.83 0.91 0.83 0.83 0.90
# for each surface: inside face solar absorptivity
  0.50 0.05 0.50 0.05 0.05 0.60
# for each surface: outside face solar absorptivity
  0.50 0.05 0.50 0.05 0.05 0.85
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for zone 2

```
# thermophysical properties of z2 defined in z2.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    3,     1  #  1 Surf-1        partition
    3,     1  #  2 Surf-2        dbl_glz
    1,     0  #  3 Surf-3        Fake_sep
    3,     1  #  4 Surf-4        dbl_glz
    1,     0  #  5 Surf-5        Fake_sep
    1,     0  #  6 Surf-6        Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# conduc-  |  density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity   |          | heat     | ness(m)|type|  temp |  factor | factor |     |
    0.4200,     1200.0,      837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #  1  1
    0.0000,        0.0,        0.0,  0.0500,    0,    0.00, 0.00000, 0.00000  #     2
    0.4200,     1200.0,      837.0,  0.0130,    0,    0.00, 0.00000, 0.00000  #     3
    0.7600,     2710.0,      837.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #  2  1
    0.0000,        0.0,        0.0,  0.0120,    0,    0.00, 0.00000, 0.00000  #     2
    0.7600,     2710.0,      837.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #     3
    0.7600,     2710.0,      837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  3  1
    0.7600,     2710.0,      837.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #  4  1
    0.0000,        0.0,        0.0,  0.0120,    0,    0.00, 0.00000, 0.00000  #     2
    0.7600,     2710.0,      837.0,  0.0060,    0,    0.00, 0.00000, 0.00000  #     3
    0.7600,     2710.0,      837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  5  1
    0.7600,     2710.0,      837.0,  0.0010,    0,    0.00, 0.00000, 0.00000  #  6  1
# for each surface: inside face emissivity
  0.91 0.83 0.83 0.83 0.83 0.83
# for each surface: outside face emissivity
  0.91 0.83 0.83 0.83 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.05 0.05 0.05 0.05 0.05
# for each surface: outside face solar absorptivity
  0.50 0.05 0.05 0.05 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for zone 3

```
# thermophysical properties of z3 defined in z3.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
     3,      1  #  1 Surf-1       partition
     3,      1  #  2 Surf-2       dbl_glz
     3,      1  #  3 Surf-3       partition
     3,      1  #  4 Surf-4       dbl_glz
     1,      0  #  5 Surf-5       Fake_sep
     1,      0  #  6 Surf-6       Fake_sep
     1,      0  #  7 Surf5a       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# conduc-  |  density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity   |          | heat     | ness(m)|type|  temp |  factor | factor |     |
     0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #  1  1
     0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  2  1
     0.0000,       0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
     0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
     0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #  3  1
     0.0000,       0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  4  1
     0.0000,       0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
     0.7600,    2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  5  1
     0.7600,    2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  6  1
     0.7600,    2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  7  1
# for each surface: inside face emissivity
  0.91 0.83 0.91 0.83 0.83 0.83 0.83
# for each surface: outside face emissivity
  0.91 0.83 0.91 0.83 0.83 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.05 0.50 0.05 0.05 0.05 0.05
# for each surface: outside face solar absorptivity
  0.50 0.05 0.50 0.05 0.05 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00    0.00
```

Construction file for zone 4

```
# thermophysical properties of z4 defined in z4.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
     3,      1  #  1 Surf-1       partition
     3,      1  #  2 Surf-2       dbl_glz
     3,      1  #  3 Surf-3       partition
     3,      1  #  4 Surf-4       dbl_glz
     1,      0  #  5 Surf-5       Fake_sep
     1,      0  #  6 Surf-6       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
```

```
# air gap position & resistance for surface  4
  2,   0.170,
# conduc-   |  density | specific | thick-  |dpnd|  ref. |  temp.  |moisture| surf|lyr
# tivity    |          | heat     | ness(m) |type|  temp |  factor |  factor |     |
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #  1  1
     0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0060,    0,   0.00, 0.00000, 0.00000  #  2  1
     0.0000,       0.0,       0.0,  0.0120,    0,   0.00, 0.00000, 0.00000  #     2
     0.7600,    2710.0,     837.0,  0.0060,    0,   0.00, 0.00000, 0.00000  #     3
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #  3  1
     0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0060,    0,   0.00, 0.00000, 0.00000  #  4  1
     0.0000,       0.0,       0.0,  0.0120,    0,   0.00, 0.00000, 0.00000  #     2
     0.7600,    2710.0,     837.0,  0.0060,    0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  5  1
     0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  6  1
# for each surface: inside face emissivity
  0.91 0.83 0.91 0.83 0.83 0.83
# for each surface: outside face emissivity
  0.91 0.83 0.91 0.83 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.05 0.50 0.05 0.05 0.05
# for each surface: outside face solar absorptivity
  0.50 0.05 0.50 0.05 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00    0.00
```

Construction file for zone 5

```
# thermophysical properties of z5 defined in z5.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
     3,     1  #  1 Surf-1       partition
     3,     1  #  2 Surf-2       dbl_glz
     3,     1  #  3 Surf-3       partition
     6,     2  #  4 Surf-4       ext_wall
     1,     0  #  5 Surf-5       Fake_sep
     1,     0  #  6 Surf-6       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170, 5,   0.170,
# conduc-   |  density | specific | thick-  |dpnd|  ref. |  temp.  |moisture| surf|lyr
# tivity    |          | heat     | ness(m) |type|  temp |  factor |  factor |     |
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #  1  1
     0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #     3
     0.7600,    2710.0,     837.0,  0.0060,    0,   0.00, 0.00000, 0.00000  #  2  1
     0.0000,       0.0,       0.0,  0.0120,    0,   0.00, 0.00000, 0.00000  #     2
     0.7600,    2710.0,     837.0,  0.0060,    0,   0.00, 0.00000, 0.00000  #     3
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #  3  1
     0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     2
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #     3
   210.0000,    2700.0,     880.0,  0.0030,    0,   0.00, 0.00000, 0.00000  #  4  1
     0.0000,       0.0,       0.0,  0.0250,    0,   0.00, 0.00000, 0.00000  #     2
     0.0400,      12.0,     840.0,  0.0800,    0,   0.00, 0.00000, 0.00000  #     3
   210.0000,    2700.0,     880.0,  0.0030,    0,   0.00, 0.00000, 0.00000  #     4
     0.0000,       0.0,       0.0,  0.0500,    0,   0.00, 0.00000, 0.00000  #     5
     0.4200,    1200.0,     837.0,  0.0130,    0,   0.00, 0.00000, 0.00000  #     6
     0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  5  1
     0.7600,    2710.0,     837.0,  0.0010,    0,   0.00, 0.00000, 0.00000  #  6  1
```

```
# for each surface: inside face emissivity
  0.91 0.83 0.91 0.91 0.83 0.83
# for each surface: outside face emissivity
  0.91 0.83 0.91 0.22 0.83 0.83
# for each surface: inside face solar absorptivity
  0.50 0.05 0.50 0.50 0.05 0.05
# for each surface: outside face solar absorptivity
  0.50 0.05 0.50 0.20 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for zone 6

```
# thermophysical properties of z6 defined in z6.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    3,     1  #  1 Surf-1         dbl_glz
    3,     1  #  2 Surf-2         dbl_glz
    3,     1  #  3 Surf-3         partition
    3,     1  #  4 Surf-4         dbl_glz
    3,     1  #  5 Surf-5         dbl_glz
    1,     0  #  6 Surf-6         Fake_sep
    1,     0  #  7 Surf6a         Fake_sep
    1,     0  #  8 Surf6b         Fake_sep
    1,     0  #  9 Surf-6a1       Fake_sep
# air gap position & resistance for surface  1
  2,   0.170,
# air gap position & resistance for surface  2
  2,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170,
# air gap position & resistance for surface  5
  2,   0.170,
# conduc-   |  density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity    |          | heat     | ness(m)|type|  temp |  factor | factor |     |
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  1  1
     0.0000,        0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  2  1
     0.0000,        0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
     0.4200,     1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #  3  1
     0.0000,        0.0,       0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
     0.4200,     1200.0,     837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  4  1
     0.0000,        0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #  5  1
     0.0000,        0.0,       0.0,  0.0120,   0,   0.00, 0.00000, 0.00000  #     2
     0.7600,     2710.0,     837.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     3
     0.7600,     2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  6  1
     0.7600,     2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  7  1
     0.7600,     2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  8  1
     0.7600,     2710.0,     837.0,  0.0010,   0,   0.00, 0.00000, 0.00000  #  9  1
# for each surface: inside face emissivity
  0.83 0.83 0.91 0.83 0.83 0.83 0.83 0.83 0.83
# for each surface: outside face emissivity
  0.83 0.83 0.91 0.83 0.83 0.83 0.83 0.83 0.83
# for each surface: inside face solar absorptivity
  0.05 0.05 0.50 0.05 0.05 0.05 0.05 0.05 0.05
# for each surface: outside face solar absorptivity
  0.05 0.05 0.50 0.05 0.05 0.05 0.05 0.05 0.05
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Construction file for adjacent zone

```
# thermophysical properties of zadj defined in zadj.con
# no of |air |surface(from geo)| multilayer construction
# layers|gaps|  no.  name      | database name
    6,     2  #  1 Surf-1       ext_wall
    6,     2  #  2 Surf-2       ext_wall
    3,     1  #  3 Surf-3       partition
    6,     2  #  4 Surf-4       ext_wall
    4,     1  #  5 Surf-5       roof
    6,     1  #  6 Surf-6       grnd_floor
# air gap position & resistance for surface  1
  2,   0.170, 5,   0.170,
# air gap position & resistance for surface  2
  2,   0.170, 5,   0.170,
# air gap position & resistance for surface  3
  2,   0.170,
# air gap position & resistance for surface  4
  2,   0.170, 5,   0.170,
# air gap position & resistance for surface  5
  2,   0.170,
# air gap position & resistance for surface  6
  4,   0.170,
# conduc-  |  density | specific | thick- |dpnd|  ref. |  temp. |moisture| surf|lyr
# tivity   |          | heat     | ness(m)|type|  temp |  factor | factor |     |
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #  1  1
    0.0000,      0.0,      0.0,  0.0250,   0,   0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,    840.0,  0.0800,   0,   0.00, 0.00000, 0.00000  #     3
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #     4
    0.0000,      0.0,      0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     5
    0.4200,   1200.0,    837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     6
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #  2  1
    0.0000,      0.0,      0.0,  0.0250,   0,   0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,    840.0,  0.0800,   0,   0.00, 0.00000, 0.00000  #     3
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #     4
    0.0000,      0.0,      0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     5
    0.4200,   1200.0,    837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     6
    0.4200,   1200.0,    837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #  3  1
    0.0000,      0.0,      0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     2
    0.4200,   1200.0,    837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     3
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #  4  1
    0.0000,      0.0,      0.0,  0.0250,   0,   0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,    840.0,  0.0800,   0,   0.00, 0.00000, 0.00000  #     3
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #     4
    0.0000,      0.0,      0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     5
    0.4200,   1200.0,    837.0,  0.0130,   0,   0.00, 0.00000, 0.00000  #     6
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #  5  1
    0.0000,      0.0,      0.0,  0.0250,   0,   0.00, 0.00000, 0.00000  #     2
    0.0400,     12.0,    840.0,  0.0800,   0,   0.00, 0.00000, 0.00000  #     3
  210.0000,   2700.0,    880.0,  0.0030,   0,   0.00, 0.00000, 0.00000  #     4
    1.2800,   1456.0,    879.0,  0.2500,   0,   0.00, 0.00000, 0.00000  #  6  1
    0.5200,   2050.0,    184.0,  0.1500,   0,   0.00, 0.00000, 0.00000  #     2
    1.4000,   2100.0,    653.0,  0.1500,   0,   0.00, 0.00000, 0.00000  #     3
    0.0000,      0.0,      0.0,  0.0500,   0,   0.00, 0.00000, 0.00000  #     4
    0.1500,    800.0,   2093.0,  0.0190,   0,   0.00, 0.00000, 0.00000  #     5
    0.0600,    186.0,   1360.0,  0.0060,   0,   0.00, 0.00000, 0.00000  #     6
# for each surface: inside face emissivity
  0.91 0.91 0.91 0.91 0.22 0.90
# for each surface: outside face emissivity
  0.22 0.22 0.91 0.22 0.22 0.90
# for each surface: inside face solar absorptivity
  0.50 0.50 0.50 0.50 0.20 0.60
# for each surface: outside face solar absorptivity
  0.20 0.20 0.50 0.20 0.20 0.85
# inside and exterior glazing maintenance factors
   0.00   0.00
```

Operation file for Zone 1

```
# operations of z1 defined in:
# z1.opr
nil_operations     # operation name
# control(no control of air flow  ), low & high setpoints
   0      0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 2

```
# operations of z2 defined in:
# z2.opr
nil_operations     # operation name
# control(no control of air flow  ), low & high setpoints
   0      0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 3

```
# operations of z3 defined in:
# z3.opr
nil_operations     # operation name
# control(no control of air flow  ), low & high setpoints
   0      0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 4

```
# operations of z4 defined in:
# z4.opr
nil_operations    # operation name
# control(no control of air flow  ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 5

```
# operations of z5 defined in:
# z5.opr
nil_operations    # operation name
# control(no control of air flow  ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Operation file for Zone 6

```
# operations of z6 defined in:
# z6.opr
nil_operations    # operation name
# control(no control of air flow  ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

operation file for adjacent Zone

```
# operations of zadj defined in:
# zadj.opr
nil_operations    # operation name
# control(no control of air flow  ), low & high setpoints
   0     0.000     0.000
     0    # no Weekday flow periods
     0    # no Saturday flow periods
     0    # no Sunday flow periods
     0    # no Weekday casual gains
     0    # no Saturday casual gains
     0    # no Sunday casual gains
# Labels for gain types
 Occupt Lights Equipt
```

Transparent Material construction file for Zone 1

```
# transparent properties of z1 defined in z1.tmc
   6    # surfaces
# tmc index for each surface
   0  1  0  1  2  0
   3  # layers
# Transmission @ 5 angles & visible tr.
   0.361    0.333    0.284    0.144    0.130    0.760
# For each layer absorption @ 5 angles
   0.157    0.172    0.185    0.201    0.202
   0.001    0.002    0.003    0.004    0.005
   0.117    0.124    0.127    0.112    0.077
   0  # blind/shutter control flag
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985    0.985    0.985    0.985    0.985    0.990
# For each layer absorption @ 5 angles
   0.001    0.001    0.001    0.001    0.001
   0  # blind/shutter control flag
```

Transparent Material construction file for Zone 2

```
# transparent properties of z2 defined in z2.tmc
   6    # surfaces
# tmc index for each surface
   0  1  2  1  2  2
   3  # layers
# Transmission @ 5 angles & visible tr.
   0.361    0.333    0.284    0.144    0.130    0.760
# For each layer absorption @ 5 angles
   0.157    0.172    0.185    0.201    0.202
   0.001    0.002    0.003    0.004    0.005
   0.117    0.124    0.127    0.112    0.077
   0  # blind/shutter control flag
```

```
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent Material construction file for Zone 3

```
# transparent properties of z3 defined in z3.tmc
   7   # surfaces
# tmc index for each surface
   0  1  0  1  2  2  2
   3  # layers
# Transmission @ 5 angles & visible tr.
   0.361   0.333   0.284   0.144   0.130   0.760
# For each layer absorption @ 5 angles
   0.157   0.172   0.185   0.201   0.202
   0.001   0.002   0.003   0.004   0.005
   0.117   0.124   0.127   0.112   0.077
   0  # blind/shutter control flag
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent Material construction file for Zone 4

```
# transparent properties of z4 defined in z4.tmc
   6   # surfaces
# tmc index for each surface
   0  1  0  1  2  2
   3  # layers
# Transmission @ 5 angles & visible tr.
   0.361   0.333   0.284   0.144   0.130   0.760
# For each layer absorption @ 5 angles
   0.157   0.172   0.185   0.201   0.202
   0.001   0.002   0.003   0.004   0.005
   0.117   0.124   0.127   0.112   0.077
   0  # blind/shutter control flag
   1  # layers
# Transmission @ 5 angles & visible tr.
   0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
   0.001   0.001   0.001   0.001   0.001
   0  # blind/shutter control flag
```

Transparent Material construction file for Zone 5

```
# transparent properties of z5 defined in z5.tmc
  6   # surfaces
# tmc index for each surface
  0  1  0  0  2  2
  3  # layers
# Transmission @ 5 angles & visible tr.
  0.361   0.333   0.284   0.144   0.130   0.760
# For each layer absorption @ 5 angles
  0.157   0.172   0.185   0.201   0.202
  0.001   0.002   0.003   0.004   0.005
  0.117   0.124   0.127   0.112   0.077
  0  # blind/shutter control flag
  1  # layers
# Transmission @ 5 angles & visible tr.
  0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
  0.001   0.001   0.001   0.001   0.001
  0  # blind/shutter control flag
```

Transparent Material construction file for Zone 6

```
# transparent properties of z6 defined in z6.tmc
  9   # surfaces
# tmc index for each surface
  1  1  0  1  1  2  2  2  2
  3  # layers
# Transmission @ 5 angles & visible tr.
  0.361   0.333   0.284   0.144   0.130   0.760
# For each layer absorption @ 5 angles
  0.157   0.172   0.185   0.201   0.202
  0.001   0.002   0.003   0.004   0.005
  0.117   0.124   0.127   0.112   0.077
  0  # blind/shutter control flag
  1  # layers
# Transmission @ 5 angles & visible tr.
  0.985   0.985   0.985   0.985   0.985   0.990
# For each layer absorption @ 5 angles
  0.001   0.001   0.001   0.001   0.001
  0  # blind/shutter control flag
```

Utility file for Zone 1

```
# Optional zone files for z1               instanced in file
# z1.utl
  0    # time-step air flow
  0    # time-step casual gains
  0    # view factors
  0    # shading/ insolation
  0    # convective heat transfer coefficients
```

```
   0    # blind/ shutter control
   1    # transparent construction data
z1.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
   0    # moisture data
```

Utility file for Zone 2

```
# Optional zone files for z2            instanced in file
# z2.utl
   0    # time-step air flow
   0    # time-step casual gains
   0    # view factors
   0    # shading/ insolation
   0    # convective heat transfer coefficients
   0    # blind/ shutter control
   1    # transparent construction data
z2.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
   0    # moisture data
```

Utility file for Zone 3

```
# Optional zone files for z3            instanced in file
# z3.utl
   0    # time-step air flow
   0    # time-step casual gains
   0    # view factors
   0    # shading/ insolation
   0    # convective heat transfer coefficients
   0    # blind/ shutter control
   1    # transparent construction data
z3.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
```

```
   0    # moisture data
```

Utility file for Zone 4

```
# Optional zone files for z4              instanced in file
# z4.utl
   0    # time-step air flow
   0    # time-step casual gains
   0    # view factors
   0    # shading/ insolation
   0    # convective heat transfer coefficients
   0    # blind/ shutter control
   1    # transparent construction data
z4.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
   0    # moisture data
```

Utility file for Zone 5

```
# Optional zone files for z5              instanced in file
# z5.utl
   0    # time-step air flow
   0    # time-step casual gains
   0    # view factors
   0    # shading/ insolation
   0    # convective heat transfer coefficients
   0    # blind/ shutter control
   1    # transparent construction data
z5.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
   0    # moisture data
```

Utility file for Zone 6

```
# Optional zone files for z6              instanced in file
# z6.utl
   0    # time-step air flow
```

```
   0    # time-step casual gains
   0    # view factors
   0    # shading/ insolation
   0    # convective heat transfer coefficients
   0    # blind/ shutter control
   1    # transparent construction data
z6.tmc
   0    # casual gain control
   0    # obstructions
   0    # control volumes
   0    # connections
   0    # nodes coordinates
   0    # nodes temperature
   0    # domain flow data
   0    # moisture data
```

Mass flow network for March 11 and July 8

```
9    4    8    1.000    (nodes, components, connections, wind reduction)
 Node    Fld. Type    Height     Temperature    Data_1       Data_2
 z1n       1    0    1.0000        20.000          0.         3800.0
 z2n       1    0    6.5000        20.000          0.         3800.0
 z3n       1    0    11.000        20.000          0.         3200.0
 z4n       1    0    16.000        20.000          0.         3200.0
 z5n       1    0    18.000        20.000          0.         2400.0
 z6n       1    0    21.000        20.000          0.         1500.0
 zadjn     1    0    1.0000        20.000          0.         8000.0
 nlon      1    3    1.0000            0.       1.0000            0.
 nhin      1    3    25.000            0.       1.0000            0
 Comp   Type C+ L+ Description
  orlo1       40    3    0  Common  orifice  vol.  flow  rate  comp.  m  =
rho.f(Cd,A,rho,dP)
     1.00000     9.00000    0.630000
  orlo2       40    3    0  Common  orifice  vol.  flow  rate  comp.  m  =
rho.f(Cd,A,rho,dP)
     1.00000     9.00000    0.630000
  skyor       40    3    0  Common  orifice  vol.  flow  rate  comp.  m  =
rho.f(Cd,A,rho,dP)
     1.00000     9.00000    0.630000
  ator         40    3    0  Common  orifice  vol.  flow  rate  comp.  m  =
rho.f(Cd,A,rho,dP)
     1.00000    40.0000    0.630000
 +Node    dHght    -Node    dHght    Comp       Snod1   Snod2
 nlon     0.000    zadjn    0.000    orlo1
 zadjn    0.000    z1n      0.000    orlo2
 z1n      3.500    z2n     -2.000    ator
 z2n      2.500    z3n     -2.000    ator
 z3n      1.900    z4n     -3.100    ator
 z4n      0.700    z5n     -1.500    ator
 z5n      1.500    z6n     -1.500    ator
 z6n      1.000    nhin    -2.000    skyor
```

Weather file for EECS atrium

```
*CLIMATE
# ascii climate file from /usr/esru/esp-r/climate/clm67 binary db,
# defined in: aaclim.asc
# col 1: Diffuse solar on the horizontal (W/m**2)
# col 2: External dry bulb temperature   (Tenths DEG.C)
# col 3: Direct normal solar intensity   (W/m**2)
# col 4: Prevailing wind speed           (Tenths m/s)
# col 5: Wind direction     (clockwise deg from north)
# col 6: Relative humidity               (Percent)
AnnArbor climate                   # site name
  1989   42.00    0.00   0         # year, latitude, long diff, rad flag
     1   365                       # period (julian days)
* day 10 month  3
     0    -23       0       0    125      50
     0    -27       0       0     82      50
     0    -24       0       0     83      50
     0    -28       0       0    103      50
     0    -34       0       0    116      50
     0    -35       0       0    120      50
     0    -38       0       0    117      50
    80    -33     170       0    127      50
   130    -12      19       0    127      50
   220     12      82       0    137      50
   300     26     375       0    127      50
   300     35     142       0    134      50
   300     43     129       0    138      50
   350     49     178       0    128      50
   180     64     776       0    131      50
   160     73     729       0    135      50
   120     72     486       0    142      50
    50     55      23       0    150      50
     0     41       0       0    132      50
     0     25       0       0    121      50
     0     12       0       0    129      50
     0      0       0       0    125      50
     0    -12       0       0    123      50
     0    -18       0       0    120      50
* day 11 month  3
     0    -21       0       0    130      90
     0    -18       0       0    127      90
     0    -22       0       0    108      90
     0    -25       0       0    107      90
     0    -30       0       0     99      90
     0    -30       0       0    112      90
     0    -28       0       0    115      90
    36    -21      14       0    115      90
    16      8     399       0    151      90
    20     51     652       0    183      90
    32     83     730       0    191      90
   138    103     702       0    198      90
   256    113     383       0    195      90
   106    130     752       0    215      90
   151    155     706       0    227      90
```

184	162	584	0	263	90
184	146	195	0	278	90
103	126	89	0	292	90
0	101	0	0	300	90
0	69	0	0	317	90
0	58	0	0	322	90
0	56	0	0	336	90
0	39	0	0	331	90
0	25	0	0	329	90
* day 7	month	7			
0	221	0	0	269	50
0	214	0	0	269	50
0	210	0	0	270	50
0	201	0	0	269	50
0	199	0	0	265	50
18	196	38	0	264	50
74	212	268	0	265	50
138	239	352	0	267	50
171	265	509	0	253	50
312	274	449	0	272	50
344	283	450	0	277	50
280	291	603	0	305	50
322	296	609	0	301	50
327	297	659	0	303	50
183	297	763	0	323	50
112	299	785	0	326	50
79	293	783	0	323	50
75	290	642	0	323	50
57	278	453	0	335	50
22	256	14	0	348	50
0	223	0	0	21	50
0	206	0	0	36	50
0	198	0	0	76	50
0	187	0	0	93	50
* day 8	month	7			
0	178	0	0	95	50
0	174	0	0	218	50
0	162	0	0	191	50
0	161	0	0	161	50
0	157	0	0	162	50
14	152	175	0	136	50
39	183	542	0	174	50
56	217	691	0	178	44
147	242	693	0	256	42
269	247	299	0	260	42
222	266	651	0	272	35
266	272	621	0	271	35
478	273	120	0	259	35
404	278	380	0	262	35
341	281	386	0	270	35
320	280	267	0	275	35
283	276	155	0	264	35
214	270	62	0	263	35
68	252	0	0	267	40
26	244	0	0	268	40
0	228	0	0	272	42

0	212	0	0	295	44
0	195	0	0	210	50
0	193	0	0	190	50