DAYLIGHTING IN ATRIUM SPACES

by

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ABSTRACT

Among the different environmental functions atria perform, this research has focused only on daylighting. The thesis has been presented in two parts. The first part provides the background information, the extent of daylighting research in atria, objective and scope of the research. The environmental role of atria has also been discussed. The second part deals with the research procedure, the description of the scale model used for the study, the conditions under which the study have been conducted, and finally, the conclusions of the study.

The effects of changing the reflectivity of the wall and floor surfaces of the atria well on the illumination in the adjacent spaces to atria have been studied. The objective of the thesis was to establish the relative contributions of the changes in the surface reflectance of the wall and the effects of variations in the area of the openings in the wall facade on lighting in the adjacent occupied spaces. The importance of the floor reflectivity in lighting the spaces adjacent to the atria was also determined.

Quantitative analysis of daylighting in atria has been conducted using physical scale models under natural overcast skies using daylight factor and well index to normalize the results.

Although the thesis has concentrated on daylighting, in reality there are other functions, both social and environmental, that atria are required to perform, and where appropriate, these functions have been acknowledged.

It has been established by this research, that the atria well and the spaces adjacent to it are affected by changes in the area of openings in the form of windows in the wall facades of the well. Small variations in higher reflective surfaces on the wall facade
produce greater differences in the daylight factors as compared to similar differences in surfaces with lower reflectances.

Using high surface reflectance on the floor of the atria well will enhance illumination in the lower levels of the atria. As the area of the (high) reflective surfaces along the edges of the floor is increased, the illumination in the side spaces in the lower levels also increases. The area of floor reflectivity needed for increasing the illumination levels in the side spaces is dependent on the area of openings on the walls at the lower levels.
# TABLE OF CONTENTS

Abstract ii  
Table of contents iv  
List of Figures viii  
List of Graphs ix  
List of Plates x  
Acknowledgement xi  

Introduction 1  

**PART 1**  

Chapter One: Daylighting in atria 4  
1.0 Daylighting research 4  
  1.1 Physiological, psychological and aesthetic benefits of  
  of daylight 4  
  1.2 Daylighting research for energy savings 6  
  1.3 Daylighting strategies in atrium buildings 7  
  1.3.1 Traditional techniques 7  
  1.3.2 Reflective techniques 8  
2.0 Lighting in atria 10  
  2.1 Atrium well 10  
  2.2 The spaces adjacent to atrium 11  
3.0 Objective 11  
4.0 Scope 12
Chapter Two: Environmental role of atria

1.0 Non-energy related phenomena

  1.1 Fire protection

1.2 Acoustics

  1.2.1 Reflection

  1.2.2 Absorption

  1.2.3 Transmission

  1.2.4 Shape and volume

2.0 Energy related phenomena

  2.1 Heating and ventilating

  2.2 Lighting

    2.2.1 Sunlight

    2.2.2 Daylight

3.0 Light Wells

4.0 Design of atria

5.0 Physical characteristics of atria

  5.1 Proportions

6.0 Well Index

7.0 Bounding elements

  7.1 Roof

    7.1.1 Glazing materials, form and shape

  7.2 Walls

    7.2.1 Wall reflectivity

    7.2.2 Facade arrangements

  7.3 Atrium floor
PART 2

Chapter Three: Methodology 50

1.0 Model studies 50

1.1 Models for practice and daylighting research 51

1.1.1 Quantitative studies 52

1.1.2 Qualitative studies 53

1.2 Model used for the daylighting study 53

1.2.1 Model design and construction 53

1.2.2 Materials 56

1.2.2.1 Reflectivities 56

1.2.2.2 Light tight 57

1.2.3 Size and scale 58

1.2.4 Measurements 60

1.2.5 Measurement process 62

1.2.5.1 Walls 62

1.2.5.2 Floor 65

2.0 Daylight Factor 66

3.0 Sky condition 67

4.0 Location 70

Chapter Four: Results 71

1.0 Data analysis 71

1.1 Walls 71

1.2 Floor 77

1.2.1 Entire floor 79

1.2.2 Specific parts of floor 88
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Lighting in atria</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Smoke extraction via atrium space</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Sound in atria</td>
<td>19</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Natural lighting in atria</td>
<td>27</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Light well and atrium</td>
<td>30</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Atria design to support natural lighting</td>
<td>31</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Different techniques for admitting light into atria</td>
<td>33</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Generic forms of atria</td>
<td>34</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Atria proportions in plan and section</td>
<td>36</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Selection of roof glazing affects lighting in atria</td>
<td>39</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Different types of roof forms</td>
<td>40</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Roof orientation for thermal benefits</td>
<td>41</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Variable openings on atria facade to acknowledge the differences in daylight levels</td>
<td>45</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Facade arrangements to promote natural lighting</td>
<td>46</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Atrium floor</td>
<td>48</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Design of model atrium</td>
<td>54</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Different arrangements of photo cells</td>
<td>59</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Positions of photo cells in the model atria</td>
<td>61</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Measurements at lower well indexes</td>
<td>63</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Effects on light distribution by varying reflectivity of perimeter of floor</td>
<td>64</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Stable sky conditions for daylighting analysis</td>
<td>68</td>
</tr>
</tbody>
</table>
# LIST OF GRAPHS

<table>
<thead>
<tr>
<th>Graph 1</th>
<th>Variation in daylight factors for 25% opening</th>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graph 2</td>
<td>Variation in daylight factors for 50% opening</td>
<td>73</td>
</tr>
<tr>
<td>Graph 3</td>
<td>Variation in daylight factors for 75% opening</td>
<td>74</td>
</tr>
<tr>
<td>Graph 4</td>
<td>Daylight factor and wall reflectivity at 3.0m and at well index 1.95</td>
<td>78</td>
</tr>
<tr>
<td>Graph 5</td>
<td>Daylight factor and wall reflectivity at 3.0m and at well index 0.375</td>
<td>80</td>
</tr>
<tr>
<td>Graph 6</td>
<td>Daylight factor and wall reflectivity for 25% openings at 3.0m</td>
<td>82</td>
</tr>
<tr>
<td>Graph 7</td>
<td>Daylight factor and wall reflectivity for 50% openings at 3.0m</td>
<td>83</td>
</tr>
<tr>
<td>Graph 8</td>
<td>Daylight factor and wall reflectivity for 75% openings at 3.0m</td>
<td>84</td>
</tr>
<tr>
<td>Graph 9</td>
<td>For various openings using white floor at 3.0m</td>
<td>86</td>
</tr>
<tr>
<td>Graph 10</td>
<td>For various openings using black floor at 3.0m</td>
<td>87</td>
</tr>
<tr>
<td>Graph 11</td>
<td>Daylight factors for specific parts of the floor (along perimeter)</td>
<td>89</td>
</tr>
<tr>
<td>Graph 12</td>
<td>Daylight factor and well index at 3.0m</td>
<td>92</td>
</tr>
<tr>
<td>Graph 13</td>
<td>Variation in illumination using 90% floor reflectivity</td>
<td>95</td>
</tr>
<tr>
<td>Graph 14</td>
<td>Variation in illumination using 5% floor reflectivity</td>
<td>96</td>
</tr>
<tr>
<td>Graph 15</td>
<td>Variation in illumination at different levels for well index 1.95</td>
<td>98</td>
</tr>
<tr>
<td>Graph 16</td>
<td>Variation in illumination for changes in reflectivity along perimeter of floor</td>
<td>99</td>
</tr>
<tr>
<td>Graph 17</td>
<td>Illumination and well index at 3.0m</td>
<td>101</td>
</tr>
</tbody>
</table>


## LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate 1</td>
<td>Atrium spaces in shopping malls</td>
<td>72</td>
</tr>
<tr>
<td>Plate 2</td>
<td>Atrium spaces in office buildings</td>
<td>73</td>
</tr>
<tr>
<td>Plate 3</td>
<td>Atrium well in model</td>
<td>74</td>
</tr>
<tr>
<td>Plate 4</td>
<td>Office space in model atrium</td>
<td>78</td>
</tr>
<tr>
<td>Plate 5</td>
<td>Photo cells in model office room</td>
<td>80</td>
</tr>
<tr>
<td>Plate 6</td>
<td>Megatron light meter</td>
<td>80</td>
</tr>
<tr>
<td>Plate 7</td>
<td>Atria walls lined with 75% opening size</td>
<td>80</td>
</tr>
<tr>
<td>Plate 8</td>
<td>Measurements at well index 0.375</td>
<td>80</td>
</tr>
<tr>
<td>Plate 9</td>
<td>Location of model</td>
<td>80</td>
</tr>
</tbody>
</table>
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INTRODUCTION

A review of atrium buildings in the past decade suggest that the design of atria as an architectural feature was conceived mainly for their aesthetic and commercial values.

Atria have been used extensively in different types of new structures to offer user amenities and social interaction in a tempered environment. Not only do atria provide physical and visual cohesiveness to the entire structure, they also provide environmental benefits. The environmental potential of the atria is still to be consciously explored.

Atria originated in the Roman times as the physical and social center of the house, with the intention of providing light and ventilation to the spaces surrounding it. Contemporary atria are not necessarily in the geometric center of the structure, but as given by Bednar (1986), "a centroidal, interior, daylit space which organizes a building." Today, atrium designs are complex and their functions, varied.

From the environmental perspective, atrium spaces perform certain specific functions. By default, atria modify the environmental conditions within the atrium well and the spaces adjacent to it. For example, large expanses of glazed areas along the wall facade or the roof of an atrium space provides natural lighting. Because of the nature of sunlight, thermal benefits or heat gains are associated with it. Depending on the climatic location, the thermal benefits associated with natural lighting may be modified and exploited or may have to be controlled. In warm locations, heat gain is undesirable, and required strategies, either by solar control or increased ventilation may be adopted to keep it minimum. In cold climates, an atrium may be used as a buffer space. Passive heating may be achieved by direct heat gain in an atrium space and by storage of heat in the thermal mass consisting of atrium floor and the walls bounding the atria.
An atrium space cannot be designed in isolation for any one function, ignoring the existence of the others. The type of building, the climatic location and the economics involved are significant in designer descisions as to which factor should be given priority. Any design feature used to enhance one function should clearly not be detrimental to another.

To enhance the atrium space, art forms such as sculptures, murals, and paintings have been frequently used. Landscape features such as water and vegetation have also been used to provide a humanized scale and a soft visual atmosphere. Their presence may be essential for aesthetic reasons, but may conflict with the environmental performance of an atrium space, for example, lighting levels could be reduced when vegetation is present as it absorbs light. Regardless of the intent of the original design, any atrium space must conform with the basic non-energy environmental needs: it must be safe against fire and prevent unwanted sound transmission.

This thesis has concentrated only on daylighting due to its potential for energy savings. Regardless of its size, shape or form, atria, by default, serve to daylight the well and the spaces adjacent to it. However, it is essential to provide the appropriate amount of light for all tasks within the atrium space and the spaces adjacent to it, free from glare and of the right contrast. The lighting system in the work place should provide optimum performance, a pleasant working atmosphere and also keep both the operating and capital cost of the lighting system to a minimum. Since daylight is variable, it needs to be supplemented by artificial lighting.

The physical characteristics of the space affects its daylighting performance. The reflectivity of the walls and floor surfaces, the size, shape and volume, influence the light levels within the atria well and its adjacent spaces.

This thesis has been divided into two parts. The first part provides the overview for the thesis, and the second deals with the procedure and the results of the thesis.

The first part contains two chapters.
Chapter one: **Daylighting in Atria**, provides the background for the substance of the thesis - it covers the areas of *daylighting research* significant to the study, *lighting in atria, objective* and *scope* of the thesis.

Chapter two: **Environmental Role of Atria** deals with the *non-energy and energy related phenomena* in atrium spaces. *Fire protection* and *acoustics* have been addressed briefly in the non-energy related issues of atria. And, the basic energy needs of *heating* and *ventilation*, and *lighting* have also been been discussed. The importance of the study of *light wells* to understand daylighting in atria, *design of atria* to enhance its daylighting performance, and the *physical characteristics*, such as *form, shape, size and proportions*, which defines the concept of the *well index* for daylighting studies using physical scale models have been discussed in detail. The role of the *bounding elements* of the atria: *roof, wall* and *floor* to support daylighting have also been studied in detail.

The second part also contains two chapters.

Chapter three: **Methodology** discusses the advantages and disadvantages of *model studies* for daylighting analysis. The *model used for the daylighting study*: the *design and construction, materials, size and scale of the model, and the measurement process* followed during the course of the study has been dealt with in detail. This is followed by a section on the *daylight factor, sky conditions* and the *location* of the model for the study.

The concluding chapter, **Results**: deals with the *data analysis* and *design implications*. The last section of part two contains the **Conclusion**.
PART 1
CHAPTER ONE

DAYLIGHTING IN ATRIA

The use of daylight in an atrium building requires a detailed analysis of its effects in the space itself and in the spaces around it. This involves an understanding of both, the appropriate quantity and quality of light for the working atmosphere.

Presently, there is very little information available to fully understand the changes affecting illumination levels in the spaces adjacent to atria caused by slight modifications in different factors, such as reflectivity and area of openings on the wall facade that affect the illumination levels in the well. This chapter covers the areas of research that is of significance to the study, the objective and the scope of the thesis.

1.0 DAYLIGHTING RESEARCH


1.1 Physiological, psychological and aesthetic benefits of daylight

The physiological benefits of daylight include the importance of ultraviolet radiation to human health, the need of changing stimulus to the body and mind provided by the
constantly changing nature of daylight, and the visual contact with nature (Evans, 1987). Being visually separated from the exterior for long periods can be counter-productive (Evans, 1987, Vischer, 1987 and Robbins, 1986). The psychological benefits include the strong desire for direct sunshine in interiors, view to the exterior, and brightness gradient and 'color constancy' of daylight. The brightness gradient and 'color constancy' deal with daylight as the 'standard' or yardstick against which all things seen by the human eye are measured. The aesthetic functions of daylight deal with the sculptural quality of light, the play of light on surfaces and textures which may cast beautiful and interesting shadows.

Most qualitative analysis for daylighting has been done on windows, probably because, traditionally, windows have been the most simple means to provide daylight, view and visual connection with the outdoors. As stated by Vischer, (1987), definite conclusions regarding the trade-off between energy loss caused by the poor thermal qualities of windows and the pleasure and satisfaction windows bring to building users cannot be drawn from existing data.

In office environments, lack of windows in the work spaces seems to contribute to various psychological and physiological problems (Vischer, 1987, p. 110). In a study reported by Wotton and Barkow (1983), although there was no significant relationship between worker productivity and access to daylight and area of glazing, the sense of well-being and job satisfaction seems to be associated with the presence of windows in the work spaces. If windows are to be provided in atrium spaces, not only do they provide daylight; in addition, owing to the presence of windows, the atrium well serves as a space to look into for aesthetic and for psychological reasons. If the well is to serve functions other than daylighting, it is treated as any other "outdoor" space and qualities of the outdoor environment need to be incorporated within the space.

Canadian office building research distinguishes between worker productivity and worker satisfaction. While windows contribute to satisfaction with the working atmosphere, they do not appear to contribute to the occupants ability to do their work.
(Vischer, 1987). Control of daylight at the user's level in the working environment is essential. Since people have control (by using adjustable drapes and shades on windows) over the level of light admitted into the space, this seems to be one of the potentially significant contributing factors to worker satisfaction.

1.2 Daylighting research for energy savings

Daylighting research for energy savings deals with the issue of admitting daylight into the interior of a space in such a way as to reduce artificial illumination and therefore reduce electrical energy consumption. In general, depending on the building type, energy savings for daylighting could amount to between 30% to 80% of total energy cost of operating, depending on peak loads and climatic location (Ian, 1985). There is no doubt that if properly provided, daylighting can be used to keep the cost of electrical lighting minimum. Daylighting and energy performance have been reviewed in a number of buildings which have projected potential energy savings, including schools (Gillet & White, 1985 and Arsenault & Kinney, 1985), office and commercial buildings (Troyer & Kuhari, 1985, Busch & Scheuch, 1983, Cook, 1982 and Place, Fontoynont, Kammerud, Bauman, Anderson & Howard, 1982) or even church buildings (Kroelinger, 1987).

The quantitative aspect of daylighting research has dealt with different computer programs and simulation techniques for recording and studying the effects of daylight on openings on the wall facades such as windows (Balcomb, 1987, Boyer & Degelman, 1986, Shaviv, 1985, Johnson, Connell, Selkowitz & Araster, 1985, Selkowitz, Kim, Navvab & Winkelman, 1982 and Bryan, 1982). Studies for developing procedures for the calculation of reflected daylight (Hraska & Rybar, 1987, Hunter & Robbins, 1985 and Robbins & Hunter, 1983) have also been undertaken.

Commercial and office building daylighting research/practice has focused on determining the level of illumination reaching the working plane and the impact of fenestration on the energy use and peak loads in daylit buildings (Ander & Hassan, 1985)
as well as the integration of electric light and daylight with the thermal and the electric operations of the building to provide energy efficient performances (Selkowitz, Choi, Johnson, & Sullivan, 1983, Emery, Heerwagen, Johnson, Keppenhan & Lakin, 1982, Place et al., 1982,).

Daylighting strategies in office buildings indicate that 38% - 40% annual lighting energy reduction can be achieved by conventional means (Misuriello & Deringer, 1982). In another report, the use of natural and task lighting in a commercial building projected 50% savings in auxiliary lighting costs (Architectural Record, 1983).

1.3 Daylighting strategies in atrium buildings

A daylighting strategy may be an integral part of an energy strategy of the structure as a whole or by default, atria may be used to perform daylighting function. The simplest means of providing daylight into the interior of the atria well and its adjacent spaces is to provide large areas of glass at the source of light, which may be the roof or the wall, or both. However, daylight is not strictly used only for providing ambience and working illuminance, but in most cases, for supporting plant life within atria. Examples of these are Atria North (Toronto), Deere West (Illinois) and Ford Foundation Head Quarters (New York) (Saxon, 1987 and Saxon, 1983). Some designs use atria as an integral energy saving device: for daylighting, summer shading, ventilation, and winter heating, e.g. Gregory Bateson building (Sacramento, California) (Saxon 1987, Bednar, 1985, and Saxon, 1983) and North and South Enerplex buildings (Plainsboro, New Jersey) (Bednar, 1985).

Different types of techniques have been used to project light into the interior of the space, which may be classified into:

1.3.1. Traditional techniques

Windows, skylights and clerestories are traditional techniques used to bring daylight into a building interior. They may be used in atria also. Windows may be used
on the walls of the atria well to admit light into the interior of the occupied spaces. Skylights have been used in the Philadelphia Stock Exchange (Philadelphia) (Bednar, 1985) where steel trusses support skylights to form a gable roof, also in the Old Post Office (Washington, D.C.) (Bednar, 1985) where the old skylight was replaced with a new gable skylight at a different level. In the East Building of the National Gallery of Art (Washington, D.C.) (Bednar, 1985) and in Enerplex (New Jersey), the skylights have been specially designed for solar control. A clerestory-like arrangement has been designed for Dallas City Hall (Dallas) (Bednar, 1985), in which only north light is admitted into the interior from vertical members of three half-vaulted monitors. Appendix A shows some atria buildings in Vancouver which have used different means to draw light into atrium spaces using different roof forms and orientation, and different materials that have been used on the walls and floor to distribute light within the space.

Research has concentrated mainly on sizes, proportions and locations of windows for effective lighting levels throughout the rooms, also avoiding glare, excessive solar gains and providing a view to the outside (Glover, 1982). Studies on skylights and clerestories have dealt with the issues of increasing interior light by using reflected light, reducing glare, and eliminating direct solar gain in the cooling season (Felts, 1985 and Vonier, 1984).

1.3.2. Reflective techniques

Studies have been done on developing exterior baffles and louvers for introducing uniform lighting in the interior and reducing the solar gains when not required (Kitchen, 1985), and using various methods for deep light penetration such as light plenums (Mirkovich, 1983), which are light shelves extended into the office space to ‘trap’ light within the plenum for further reflection, light shelves which are horizontal projections above the view window and below a clerestory used to distribute light in the interior and also serve as a shading device to minimize the penetration of direct sunlight on the
FIGURE 1
DAYLIGHTING IN ATRIA

LIGHTING IN AN ATRIUM WELL

LIGHTING IN SPACES ADJACENT TO AN ATRIUM WELL
working plane, and sloped ceilings (Windheim, Riegel, Davy, Shanus, & Daly, 1983) to achieve maximum light distribution within the interior spaces. Sloped ceilings were used in conjunction with light shelves in Lockheed Missiles and Space Co., Inc., (Sunnyvale, California) (Saxon, 1987, Bednar, 1985, Saxon, 1983 and Windheim et al., 1983).

Light scoops may also be used to project light into the side spaces (refer to section 7.2.2 of Chapter 2). The use of light scoops for beam lighting was proposed in the Tennessee Valley Authority Office Complex, (Chattanooga, Tennessee), (Saxon, 1987, Bednar, 1985 and Saxon, 1983).

Light shelves may be used in the facade facing the atria (interior light shelf) or in the facade facing outside (exterior light shelf). An interior light shelf was used in Ventura Coastal Corporation, (California) and Shell Woodcreek, (Houston) (Bednar, 1985), whereas exterior light shelf was used only on the south side in Lockheed Missiles and Space Co., Inc., for controlling glare. Light shelves can be used as a light reflector, for glare control and as a shading device.

2.0 LIGHTING IN ATRIA

Since the oil embargo in 1973 and the subsequent 'energy crises', daylighting has been linked with energy benefits. Although it is not possible to generalize the extent to which the use of daylighting will actually decrease the energy consumption in any building, if provided properly, it will rarely increase the lighting energy consumption. There are two major considerations in the use of the atrium for daylighting (refer Figure 1):

a. Lighting in the atrium well to provide adequate light for activities within the atrium only.

b. Using the atrium as a source of light to provide adequate lighting to the spaces adjacent to the atrium.
2.1. Atrium well

The atrium well has higher levels of illumination compared to the spaces adjacent to it. As in the case of the light well, the illumination levels are highest at the top of the well and gradually decrease towards the floor of the atria (Cartwright, 1985 and Oretskin, 1982). The center of the horizontal plane at any height receives higher levels of illumination than the sides. This is because the center of the well "sees" a greater portion of the sky than the sides. Within the well, the illumination levels will be minimum along the edges of the floor.

2.2. The spaces adjacent to atrium

While it is relatively easy to illuminate the atrium well, it is more difficult to illuminate the spaces around the atria by virtue of their position in relation to the light source. This is more so in the case of lighting the lower levels and its surrounding spaces in an atrium where the source of light is from the roof. The atrium well acts as a means to deliver light to the spaces adjacent to it.

Illumination decreases as the depth of atria increases, as light is drawn off at each level, into the spaces adjacent to the atria. Openings on the wall facade will influence the amount of light drawn into the side spaces and at various levels in the well itself.

Openings like windows on the walls of the atria act as light absorbers, reducing the light intensity in the well especially in the lower reaches of the atria. Therefore, larger openings will draw more light from the well. The reflectivity of the atria walls is a significant factor in enhancing illumination levels, as higher reflectivity of the walls will increase the amount of available light in the well.

Thus, reflection may be used as an effective strategy for enhancing illumination levels within and in the spaces adjacent to the atria.
3.0 OBJECTIVE

The objective of this thesis is to assess the relative contributions of changes in the reflectivity and opening sizes on the illumination levels in the side spaces for different well indexes in atria. The relative importance of the bounding elements of the atria, the wall or the floor, or both for enhancing illumination in the spaces adjacent to the atria, is to be determined.

Studies conducted by Cole (1988), Cartwright (1985) and Oretskin (1982) suggest that the reflectivity of the wall facade and the floor affect the illumination in the atria well, and thereby in the adjacent side spaces. Inter-reflection from the floor also seems to play a key role in increasing the available illumination in the spaces adjacent to the atria.

4.0 SCOPE

Atria perform many environmental functions. However, only the function of daylighting has been dealt with in detail.

There are a number of variables involved in the study. There are many different forms of atria - with different width and length of the well in plan, different sectional schemes, different roof forms, different surfaces and openings in the wall facades.

For this study, the physical form of the atria is kept constant: in this research a rectangular, top-lit atrium without any roof glazing has been used. No glazing is used on the wall openings also. Measurements are taken at different heights in the spaces adjacent to atria. Thus the variables involved in the study are:

- the surface treatment of the wall and floor
- different size of openings in the walls facing the atrium well.

The emphasis of this study is to understand how the changes in the illumination levels are affected in the spaces adjacent to the atria only. The purpose of the study is to
demonstrate the relative importance of the use of specific reflective surfaces and openings of the atria walls on the light distribution, and utilize the results as a guide for further detailed studies.

Fully overcast skies offer the least lighting levels in terms of absolute illumination values. It is very difficult to interpret measurements for varying light conditions occurring under the natural skies, and hence stable overcast sky conditions are preferred. Hence, the study is conducted under fully overcast skies.

Using simplified calculation techniques, only the quantitative study of light using photometric measurements have been studied. Qualitative studies deal with occupant responses to daylight within the space and significance of providing view to the outside in the occupied spaces, which involves a different area of research beyond the scope of this thesis.
CHAPTER TWO

ENVIRONMENTAL ROLE OF ATRIA

This chapter deals with the environmental role of atria. Two primary aspects have been considered: non-energy and energy related environmental phenomena. The non-energy related phenomena are fire protection and acoustics and energy related phenomena are heating, ventilating and lighting. Both, the non-energy and the energy related phenomena affect the physical form and shape of the atria.

1.0. NON-ENERGY RELATED PHENOMENA

For atria design to be safe and pleasant, non-energy related factors like fire protection and acoustics have to be taken into consideration. Satisfying these requirements will invariably impact on the daylighting function.

1.1 Fire Protection

The danger of fire hazard is more pronounced for atrium than for other building types as the atrium space is comparatively large and unenclosed. It is linked to all other interconnected spaces directly. Due to stack action, fire and smoke can easily spread vertically in this large unhindered space. Atria by themselves are not usually a source of fire hazard, and fire can quite easily be detected on account of high visibility within the space. Smoke control is an area of concern as the fire may originate in the adjacent occupied space and the smoke may spread easily into this large space. If no escape is
provided, smoke fill up the occupied zones also. Therefore, efficient smoke exhaust systems have to be provided.

There are three steps of control needed in the design strategy of the atrium spaces (Saxon, 1987):

a. means of escape
b. smoke control
c. fire control.

The means of escape deal with the circulation routes for evacuation in the event of a fire. Since the atria can be easily converted into a smoke reservoir, the exit stairs should be separated from the atria by cut-off lobbies. The entire evacuation process may be designed in three distinct stages (Saxon, 1987 and Bednar, 1985):

1. access to the means of escape through a corridor or room which may or may not be protected from fire
2. the means of escape itself, which is a usually a stair protected from fire by fire resistant walls and door
3. the route to the outside or a safe refuge area.

Smoke control is an essential part of the ventilation strategy of the structure as a whole. Smoke control means extracting smoke from the structure by venting. Smoke control is needed to prevent the atria well and the adjacent spaces from smoke-logging. Extraction of smoke depends on the volume of the atria and the type of atria, that is, totally enclosed or open-sided. If the atrium well is open on one or all the sides, extraction may be through the atrium well or through the surrounding structure. If the atrium space is totally enclosed and sealed from the surrounding spaces, the structure may be treated as any other and smoke control strategy need not involve the atrium well at all. The smoke control strategy for such a structure is independent of the atria well.

The fire-control and fire-fighting strategy deals with measures to limit the spread of fire within the structure and to the adjoining structures as well. The most important
requirement is the early detection of fire. Detection within the atrium space is difficult as
detectors placed on the top of the well cannot detect fires on the floor. Restricting flame
spread is dependent on whether the atria is totally enclosed or open on any side. While
fully enclosed atria are efficient for smoke control, they are not for flame spread, as floor
to floor spread is faster in this case than for the open sided atria. The final outcome of
any fire eventually lies in the hands of the fire department, for which quick and safe
access to the fire is required. Service access for the fire engine must be provided around
the building.

Building codes and regulations state the specifications for fire detection, fire
suppression, fire alarm, smoke control and emergency power, materials to be used, fire
ratings of the atrium enclosures, atrium exit and interior finish, atrium size and use which
varies depending on the height and number of stories of the atrium building. The
materials used and the size/shape of the atria designed specifically for fire protection may
adversely affect the performance for daylighting.

1. A smoke reservoir at the top of the atria well are recommended when smoke
exhausts through the atrium well is desired. If the occupied zones on spaces adjacent to
the atria are open to the well, the smoke will travel into the well, rising to the top and
filling the atrium space. If the smoke reservoir is not provided, the smoke which collects
at the top can spread to the other floors. A smoke reservoir collects the smoke away from
the occupied zones, which can be exhausted from vents on the sides. Alternatively, the
smoke can be exhausted by mechanical means. The height of the smoke reservoir varies,
but a minimum of 1.7m from the highest exposed floor to the centreline of the vent has
been recommended (Saxon, 1987, p.126). Using a smoke reservoir increases the overall
height of the atria well, which increases the distance for light to travel into the lower
reaches of the atria. The roof system chosen will have to be designed to incorporate the
vents of the smoke reservoir, placing restrictions on the type of roof of the atria well.
FIGURE 2
SMOKE EXTRACTION VIA ATRIUM SPACE

VENTS FOR SMOKE

SMOKE PLUME (15 DEG.)

EDGE SCREENS

SMOKE RESERVOIR

1.7 M

LIGHT SHELF (20 DEG.)

DIFFERENT FLOOR EDGE PROFILES TO PREVENT SMOKE ENTRY

FIRE
2. Enclosing the atrium from the adjacent spaces offers a very effective means of limiting fire and smoke spread. But this is not desirable for both lighting and aesthetic reasons. Also, for daylighting, the barriers between the well and the surrounding must not be opaque. Glazed surfaces may be provided, but they do not prevent heat radiation while opaque barriers do. If glazing is to be used, intumescent laminated glazing which turns opaque in fire, thus blocking radiation is preferred (Saxon, 1987, p. 99). The 1984 BOCA (Building Officials and Code Administrators International) Basic Building Code requires that the glass should not have any barriers such as curtains and drapes to keep the water from wetting the surface. Where barriers have to be provided for protection against glare, this may present a problem.

3. Balconies and terraces opening into the atrium well must also be protected by barriers, unless they are intermittently used or function as "break areas". The openings between the well and the overhang spaces should have barriers upto cill height at least, so that people can crawl past the barrier in the event of a fire. Barriers made of glazing which are suitable for daylighting may be used, but of the laminated type, for protection against heat radiation.

4. The design of the profile varies depending on the type of atria (height, width, mechanical ventilation system used), and the system adopted for smoke extraction. Where the extraction is through the atrium well, there are some general rules to be followed (refer Figure 2):

   a. Floors that are set back with every increase in level protect themselves. This type of arrangement of the floor is also advantageous for lighting as more area is exposed to the sky vault.

   b. A fire and smoke barrier along the perimeter and at least 0.45m from the ceiling of each floor and opening into the atrium well is used to keep the smoke from spreading to that floor along the ceiling. There is a similar projection from the floor called the 'floor
FIGURE 3
SOUND IN ATRIA

ATRIA WELL
ADJACENT SPACES
PREVENT SOUND
edge' used to prevent spread of fire from the lower floors. These edge screens must not be too big so as to allow sufficient entry for make-up air in the event of a fire.

c. To prevent smoke entry into side spaces (refer Figure 2), the edge screen from the ceiling should cut the 15 deg. angle (as the smoke plume expands at approximately 15 deg. to the vertical) from the floor edge and light shelves, if any, should not cut the 20 deg. angle (Saxon, 1987).

1.2 Acoustics

One of the main concerns in any kind of design is to avoid conflicts between other functions that the space may be required to perform. In office spaces, to ensure a quiet working environment, it is necessary to have acoustical separation between the office compartments and the circulation spaces, and also between noisy mechanical equipment and the working area. This may conflict with an atrium space that may be designed primarily for daylighting function. Although the basic properties of light and sound are analogous, the design requirements for the two are different.

In designing for light and sound in atria, one essentially deals with contained light and sound. Within the well, the sound can be 'moderate' to 'loud', measured on the atrium floor predominantly from speech or from office activities, ranging between 50 dB to 70 dB (Egan, 1988, p. 13). Most often, noise due to mechanical equipment is physically isolated from the main working areas. Since the atrium space is typically larger than the adjacent spaces, the sound waves can be easily enhanced by reflection if there are no absorptive surfaces. Therefore, prevention of sound transmission from the sound source is required (refer Figure 3).

Since an atrium space is comparatively large, the reverberation time for sound is increased, hence "time period" for decay of the sound is longer. This causes noise levels in the space to be intensified. Therefore, necessary strategies will have to be undertaken to reduce the reverberation time. The reverberation can be reduced by incorporating sound
absorbent surfaces. These may be in the form of porous plasters as wall finishes, decorative hangings and blinds even, the use of dense planting.

Noise is unwanted sound, and in office buildings, quiet working conditions are recommended. However, there should be some background or masking sound, not "pin-drop" silence. In large offices, the preferred range or noise criteria is between NC-35 to NC-40 and equivalent dBA levels of 42-47 (Egan, 1988, p. 233).

1.2.1 Reflection

Reflectivity is surface-dependent for sound. The inherent physical properties of the material determines its capacity to absorb or reflect sound.

Sound reflection is dependent on the "wave length" of sound wave from the source and the dimensions of the surface reflecting the sound waves. If the surface dimensions are equal to the "wave length" of the incident sound wave, the reflected waves are randomly distributed from the surface (diffusion). The reflected waves bend through an opening or around the object when the dimension of the surface is less than that of the incident sound wave (diffraction). If the dimensions of the surface is about four times the wavelength of the incident waves, then sound is reflected specularly from the surface.

Sound reflection is also dependent on the characteristics of the reflecting surface. This is a more significant aspect than the shape or dimensions of the reflecting surface. If the reflecting surface is made of rigid, non-porous materials such as glass, concrete and wood, the sound waves are reflected from the surface. Porous materials such as carpets, drapes, and upholstered furniture are very good sound absorbers. Reflecting glasses are often used for enhancing illumination, but they also enhance sound in the space, raising the noise level. There is also some importance regarding the thickness, density (porosity) and method of mounting, that is, with or without airspace behind the surface material.
1.2.2 Absorption

Sound absorption is the loss of sound energy through the interconnected pores of the material due to friction with consequent heat gain (not likely measurable). Materials that are good sound absorbers are not good sound insulators, as these materials allow sound energy to pass through the surface of the material. Smooth and hard surfaces reflect sound, so do rough surfaces, however, if the material within is fibrous, it is absorbed. The thickness and mounting of the hard surfaces, and the air space behind may still act as absorbers for low frequency sounds.

Usually, sound absorbers are mounted with a covering panel to protect their surface from possible mechanical/physical damage. However, if the surface is not likely to encounter mechanical/physical damage, as for most surfaces 8 feet from the floor level, covering panel is unnecessary.

Within the atria well, the materials used for shades and blinds for solar control may also serve as sound absorbers, if they have sufficient thickness and porosity. Decorative hangings may also be used as sound absorbers.

Vegetation are effective for glare control by absorbing light, but are not effective sound absorbers if the depth is less than 30m. If a thin layer of vegetation is to used, it should have a layer of absorptive surface backing to be an efficient sound absorber. The type of vegetation must also be considered; deciduous trees are very poor sound absorbers and dense, evergreen vegetation, slightly better.

1.2.3 Transmission

If the sides of the atria well are open, there would be 100% sound absorption into the occupied spaces, that is, complete transmission. If any form of barrier is used, sound is reflected, depending on the nature of the surface. The thickness of the surface and its density are important criteria for sound transmission.
Certain types of sounds such as those due to fountains or cascades are welcome sounds. In atria where the side walls are completely open they may be transferred to the occupied zones around as ambient or background levels, but the magnitude of this should not exceed the recommended NC levels for the office space.

1.2.4 Shape and volume

The shape of the surface affects the behavior of reflection of sound waves, not in the quantity of the sound energy but in the direction of the reflected waves. Concave surfaces are poor sound reflectors as they focus sound. On the other hand, convex or flat surfaces scatter the reflected sound waves diffusively. However, this may not be so significant in atrium spaces as they would be in "listening" rooms such as auditoriums.

Although the shape makes considerable difference to the distribution of sound in the space, the key problem is the reduction of sound energy, that is avoiding reflection via use of absorptive materials/surfaces in the space. This brings conflicts with the daylighting function of atria.

1. Different shapes of atria may be used to enhance lighting in atria which affect sound distribution in the space, but the most critical factor is the physical characteristics of the surface lining the walls and the floor of the space. Usually, smooth and hard surfaces are used to reflect light, but these also reflect sound. The color of the surface does not affect sound energy in the space, but it enhances illumination.

2. Certain elements used for aesthetic reasons or for solar control, such as blinds and shades, decorative hangings, and vegetation may also be used for acoustic control.

Water may be used to enhance illumination as well as provide a masking sound. Visually, it often serves as an aesthetic element in atrium spaces. But it may cause glare, in which case necessary precautions will have to be taken.

The function of all these elements in the atrium space has to be decided and their positions, materials/mounting techniques have to be designed accordingly.
3. The noise from the floor of the atria can be controlled by using balconies and overhangs facing the well. The sound waves striking the projections are diffracted. They form shadow zones on the side of the occupied spaces, isolating sound from the atria floor. If the sides of the projections are lined with sound absorbing materials, the noise levels can be further reduced (upto 10 dB).

Balconies, overhangs and such similar projections increase the surface area available for reflection, enhancing reflection, but they also form shadow zones in the spaces below.

2.0 ENERGY RELATED PHENOMENA

The atria that were built before the oil embargo in 1973 focused solely on the aesthetic quality and social function of the interior spaces (Lehrman, 1984, p.20, Saxon, 1983, p.5, Hawkes, 1983 and Collymore, 1980). Atrium spaces in hotels and shopping malls were designed for the public, to attract large numbers of people to increase their commercial value. They were huge spaces where people could meet and talk, and often had elaborate furnishings and eating areas incorporated within. These atria were designed mainly for their aesthetic value with lush planting, running or still water, sculptures, murals, paintings, etc.

Many atria built throughout the late 1970's and the 1980's also continued to be designed on aesthetic grounds, but there was an increasing awareness of the energy benefits, which in many examples (Enerplex in New Jersey, Childrens' Hospital in Philadelphia, The Atrium on the Bayshore in Florida (Bednar, 1985), to name a few) have incorporated energy conscious design.

Whatever energy savings an atrium can provide to a building or complex usually takes the form of daylighting spaces adjacent to an atrium. However, the very presence of the atria does not guarantee energy efficiency in the structure. The atrium design has to
be integrated with the passive techniques and mechanical systems of the structure. While there have been many examples that have shown energy savings (Architectural Record, 1982, Architectural Record, 1981 and Collymore, 1980) the presence of an atrium does not automatically reduce energy consumption (Baker, 1988, p.40).

The energy related functions an atrium involve are heating and ventilating, and lighting.

2.1 Heating and Ventilating

The heating and the ventilating strategies are often designed together. Depending on the climatic location, an atrium may perform primarily as (Saxon, 1983, pp. 84-91):

a. a warming atrium - an atrium to collect and transfer heat, or supply preheated air to the adjacent spaces, decreasing heat losses from adjacent spaces and in the well itself by trapping warm air from spaces around the atria (compared to the heat losses directly to the outside)

b. a cooling atrium - an atrium to serve as shade in summer and cross ventilating space or single sided ventilating space in summer or in warm latitudes

c. a convertible atrium - an atrium that does both: provides warmth in winter and provides shade or prevents overheating in summer.

In very hot climates, an atrium has to serve a cooling function for most part of the year. Over heating of the atrium is avoided through orientation and shading. Comfort may also be achieved by using the atria to induce cross ventilation. In cold locations, the emphasis should be to provide warmth during most months of the year. However, in certain type of structures, such as shopping malls, it is likely that heat surplus is generated by people and use of artificial lighting and machinery. In temperate climates, buildings are required to be heated in the winter and cooled in the summer, and for these atria, the thermal and ventilation functions are required to change over the year.
One important factor to be noted is whether the atrium is designed to act as a buffer space or is intended to be a zone where normal occupancy conditions are met. The buffer space provides only a tempered climate, and hence would require further refinement to its services to ensure comfort in the space.

In buffer spaces especially, warm air may be collected on the upper levels (the warm air having the tendency to rise), and hence fans will have to be used to redirect the heated air downward, so that the air may be used effectively. Blinds and other shading devices may be used for shading in the summer, and where the atria are required to be cooled, courtyard principle for cross ventilation is can be applied.

The ventilation air flow may be designed to move from the atrium well to the surrounding spaces, or conversely from the adjacent spaces to the atrium well, or it may recirculate between the two. The latter provides the maximum savings in thermal energy (Baker, 1988). This may be done by simply opening the windows between the atrium well and the occupied spaces. However, a certain amount of fresh air will have to be continuously supplied, to avoid the air becoming too stale, since it is constantly being circulated between the well and the occupied spaces. Vegetation, if provided, helps to retain freshness to a certain extent. If an atrium and its adjacent space are independent of each other, that is, each has its own separate heating and ventilating scheme, the energy consumption of the structure will increase (Baker, 1988).

2.2 Lighting

For the atria to function as a building element that reduces energy consumption, it must reduce the lighting, heating and air conditioning costs of the complex as a whole. For office buildings in North America, lighting represents the largest portion of the total energy load (Robbins, 1986, p. 7, Gardner, 1984, and Misuriello & Dringer, 1982). Hence, the need to focus on lighting as a major means of energy savings.
FIGURE 4
NATURAL LIGHTING IN ATRIA

SUNLIGHT

DAYLIGHT
A primary role of atria is to deliver useful levels of natural light to the atria and its adjacent spaces. Although energy savings is the main reason for favoring daylight, there are other reasons also (Selkowitz & Johnson, 1980, p.15,16).

1. In many utility service areas, commercial building owners are required to pay, in addition to payments for total electrical consumption, a demand charge which reflects the peak demand of the building for each month. Using natural lighting effectively will reduce the use of electric lighting, which in turn will decrease the peak energy consumption, required for both heating and cooling.

2. Using windows to provide natural light in the work space reduces dependency on electrical systems. Also, if these windows are operable, it allows the user to be independent of the mechanical ventilation systems in the event of a breakdown.

An atrium provides the designer with an opportunity to exploit daylight, and thereby reduce the costs of operating electrical lighting. The intensity and distribution of daylight can be controlled by orientation and by architectural devices such as fenestration. User control devices such as blinds and shades; even overhangs may also be used to control the distribution of light. Within the interiors, the factors affecting this are surface reflectances and furnishings. Some type of solar control is needed to reduce solar heat gain during the hot months of the year. The control systems may be dynamic wherein the system is capable of responding to the changes in the sky conditions. Such systems function as selective light transmitters, admitting only diffused light and not direct sunlight.

While considering natural lighting in atria, it is essential to distinguish between sunlight and daylight (refer Figure 4).

2.2.1 Sunlight

This is the direct light falling on the building during clear or partially clear sky conditions. Sunlight is highly dynamic and follows defined daily and seasonal paths
relative to the building. Sunlight penetrating through the openings can serve as a powerful and highly dynamic illuminant as well as a source of useful winter heat (Cole, 1989).

However, this can also create problems of glare and adverse overheating. Glare is excessive brightness that causes discomfort and reduces visual perception.

Overheating is a problem that has to be dealt with particularly in the hot months of the year. In winter, the heat produced due to direct sunlight can be used to heat not only the atria, but also the adjoining spaces. In summer, diffused instead of direct sunlight is preferred. This can be achieved by using solar shading techniques such as shades and blinds, movable louvers to intercept direct sunlight. It could also be achieved by appropriate design of roof and selection of glazing types. These issues have been addressed in detail in section 7.0 of this chapter.

2.2.2 Daylight

This is the diffuse light that comes from the complete sky vault that envelopes the building. During overcast sky conditions, buildings are bathed in daylight alone (Cole, 1989). Overcast conditions can also cause problems of glare. If this glare can be minimized, daylight can be used to provide working illuminance in the interiors.

In temperate climates, cloudy skies dominate for most part of the year. These skies have greater luminance at the zenith than at the horizon. Top lit atria are therefore preferred, with a clear unobstructed glazed roof for maximum transmission of light. This would provide the maximum use of diffuse light from all parts of the sky.

3.0 LIGHT WELLS

Atria and light wells are very similar in design. Both deal with the issues of admitting light to the lower levels, and ultimately, in the form of suitable and useful light
FIGURE 5
LIGHT WELL AND ATRIUM

LIGHT WELL

ATRIUM
FIGURE 6
ATRIA DESIGN TO SUPPORT
NATURAL LIGHTING

[Diagram showing the roof form, surface treatment of the wall, and surface treatment of the floor.]

HEIGHT

WIDTH

ROOF FORM

SURFACE TREATMENT OF WALL

SURFACE TREATMENT OF FLOOR
into the spaces that are adjacent to it (refer Figure 5). Since the light well has no physical barrier at the light-source, there is no solar control. Solar control can be achieved only at the next level, at the openings in the walls facing the well.

The study of the light wells may form the basis of daylighting study in atrium spaces (Giovani, Kroner & Leslie, 1986). Studies by Cartwright (1985) and Oretskin (1982) concentrate on the changes in the illumination levels between the top and the bottom of the light well, and the effects of their sizes on illumination levels in the well and in the adjacent spaces. Cartwright's study indicates a simple relationship between the size of the light well, and the daylight level in the adjacent spaces. Bigger the size of the well, higher are the light levels in the well and the spaces adjacent to it. The study by Oretskin shows that for similar volumes and areas of the well, those with elongated plans have lower illumination levels when measured at similar points. Windows in the center of the well receive more light than those at the corners.

4.0 DESIGN OF ATRIA

The design of an atrium to provide natural lighting depends on (refer Figure 6):

\textit{a.} fenestration system of the roof

\textit{b.} orientation, of the roof in top-lit atria and of the walls in side-lit atria

\textit{c.} the relative proportions of the length, width and height of the atria.

\textit{d.} atrium wall surface treatments

\textit{e.} the treatment of the atrium floor, i.e., presence of plants and water

The means by which natural lighting is effectively used, which may be divided into three distinct areas:

\textit{1.} How light is brought into an atrium. In top-lit atria, this is dependent on the fenestration system of the roof. In side-lit atria, fenestration and orientation are the determinants.
FIGURE 7
DIFFERENT TECHNIQUES FOR ADMITTING LIGHT INTO ATRIA

TOP LIGHTING

SIDE LIGHTING

LATERAL LIGHTING
FIGURE 8
GENERIC FORMS OF ATRIA

TOP LIT ATRIUM
SIDE LIT ATRIUM
TOP LIT ATRIUM
LATERAL ATRIUM
2. How the light is distributed into an atrium. This is dependent on the relative width, length and height of the atria, and the surface treatments of the atria wall and floor.

3. How the light is collected and delivered effectively to the working plane of the occupied spaces and within the atrium itself. This is dependent on the atrium wall surface treatments, the sectional scheme (such as projecting terraces and balconies, light scoops, etc.).

Inter-reflection seems to be the most important factor responsible for providing working illuminance within the atria well and in the occupied spaces adjacent to it (Bednar, 1985 and Navvab & Selkowitz, 1984).

5.0 PHYSICAL CHARACTERISTICS OF ATRIA

The quantity of light admitted into an atrium is dependent on the form of the atrium. Similar spatial forms may use different strategies for admitting light into an atrium. Generally, light is admitted into the atrium using the following strategies (refer Figure 7 and Appendix A):

a. Top lighting: where light is admitted from the top of the atrium only.

b. Side and lateral lighting: where light is admitted from the sides of the atrium.

Often atria designs incorporate not just one of these methods in isolation, but a combination of top and side (lateral) lighting methods.

It is difficult to classify atria into any specific category such as linear, closed, open-sided, lateral, multiple lateral or partial atria. This is because many variations of any one category exist, leading to hybrid arrangements. However, some generic forms exist, which are shown in Figure 8.

The atria space that is created between the occupied spaces around the atria well is dependent on the proportions of the space, shape and volume and the overall design of the
FIGURE 9
ATRIA PROPORTIONS IN PLAN AND SECTION

PLAN

\[ \text{PAR} = \frac{\text{WIDTH}}{\text{LENGTH}} \]

SECTION

\[ \text{SAR} = \frac{\text{HEIGHT}}{\text{WIDTH}} \]
roof, walls and floor of the atria well. However, the factors influencing this are site restrictions, building program and the energy strategy.

5.1 Proportions

In the use of atria for daylighting, the proportions in plan and section have to be considered (refer Figure 9) (Bednar, 1986, p. 66).

The proportions of the atria, called the aspect ratios by Bednar determine the amount of light in the atria. The plan aspect ratio (PAR) is the ratio of the width to the length of the atria floor. The section aspect ratio (SAR) is the ratio of the height to the width of the atria well. Therefore, for rectangular atria, the PAR is between 0.40 - 0.90 and for square atria, it is 1.00. If the PAR is less than 0.40, the atria is called linear. A linear plan generates the largest perimeter for the least enclosed volume followed by triangular, square, and the least by circular plan (Bednar, 1985). SAR of less than 1.00 has a very shallow atrium and SAR of 2.00 has a very tall and narrow atrium. For effective daylight penetration, SAR between 1.00 - 2.00 is sufficient.

The SAR plays a major role in determining the amount of natural light reaching the floor and the spaces around the atria. Atria that have high SAR values, that is, atria having wells which are very tall and narrow will not be very effective for daylight penetration to the bottom of the well. On the other hand with very small SAR, light penetration to the bottom of the well and to its occupied spaces is relatively easier. For daylight to reach the bottom of very tall atria, the reflectivity of the walls becomes an important factor in the distribution of light in the well and the adjacent spaces.

For lighting, one large well of a given area is more effective than several small wells, totaling the same area (Oreitskin, 1982). For a given area in plan, illumination measured at the atrium floor will be greater for the one in which the depth of the well is smaller. If wells of equal area, but different shapes are compared, wells of circular plan
receive more light at a given level followed by square and rectangular plans (Oretskin, 1982).

6.0 WELL INDEX

For the purpose of daylighting studies, it is not possible to examine atria of so many different forms, shapes/volumes since there has to be some standard of measurement.

Traditionally, the concept of well index has been the single most effective means to analyze natural lighting efficiency in light wells and atria. For daylighting studies using physical scale models, well indexes have been used to standardize the various configurations of atria/light well.

The illumination within an atrium is related to the dimensions of the atria well. The behavior of light in the adjacent spaces is also expressed as a relationship to light levels in atria well, since light levels in the adjacent spaces are dependent on the physical dimensions of atrium. It is expressed by the well index, given as,

\[
\text{well index} = \frac{H \times (W + L)}{2 \times W \times L}
\]

where, W is the width, L is the length of atrium well in plan and H, the height of atrium well.

The formula for the well index is applicable only to top-lit atria.

7.0 BOUNDING ELEMENTS

The architectural elements defining an atrium space are the roof, the walls and floor of an atrium. These, collectively, may be used to modify the lighting conditions in
FIGURE 10
SELECTION OF ROOF GLAZING
AFFECTS LIGHTING IN ATRIA

CLEAR GLAZING ADMITS DIRECT SUNLIGHT ALSO
REFLECTIVE GLAZING ALLOWS ONLY DIFFUSE LIGHT
FIGURE 11
DIFFERENT TYPES OF ROOF FORMS
FIGURE 12
ROOF ORIENTATION FOR THERMAL BENEFITS

NORTH FACING ROOF:
DIFFUSE LIGHT

SOUTH FACING ROOF:
THERMAL GAINS
the well and in the adjacent occupied spaces. The level of illumination finally reaching the working plane is due to the performance of the size/shape/materials of these elements.

7.1 Roof

The design of the roof is essential to ensure that the appropriate amount, direction and the right combination of sunlight and daylight is provided in the space (Kim & Boyer, 1986). The design of the roof includes its form and shape, and the type of glazing material used. Similar roof designs will have different lighting levels in the interior for different orientations, and when placed in different locations.

7.1.1. Glazing materials, form and shape

Under cloudy sky conditions, clear-glazed, horizontal skylights will bring in the most daylight, since the sky dome is the brightest at the zenith. In sunny conditions, however, solar control will be needed. In winter in cold climates, direct sunlight is desirable for passive heat gain, whereas in summer, solar control will be needed to prevent the atria from overheating. The type of glazing used on the roof in combination with its form and shape, will affect the quantity, quality and distribution of light within the atrium. This will have a direct impact on the availability of light, to meet the working requirements (refer Figure 10). Shading in the roof itself may greatly reduce the transmission of diffuse light under overcast conditions, unless a dynamic system is adopted to respond to the changing sky conditions.

Various types of roof configurations are shown in Figure 11. Saw-tooth skylights with vertical glazing facing the north or south are most effective under clear sky conditions (refer Figure 12). If the vertical glazing faces the south, sunlight admitted will be very intense and dynamic. In summer, owing to the relatively higher position of sun in the sky, direct light in the interior will be very little through the vertical glazing. Vertical glazing on the north provides even and diffused light throughout the year.
Side glazing, as in lateral atria does not provide the most effective means of lighting the atria well. Under sunny conditions, the availability of daylight may be decreased due to neighboring obstructions. Reflective glazing may be used to control glare under sunny conditions, but this also restricts the amount of available light. Lantern lighting, which means using clerestories for distributing light in the atria may be used in hot climates where direct sunlight has to be excluded for most parts of the year and, only diffused light admitted. The clerestories are used to collect light from the sides and diffusing glass on the inner surface of the roof are used to transmit the light through the well.

7.2. Walls

The reflectivity of the walls and the facade arrangements of atria influence the light distribution in the well, and in the occupied spaces around the well.

7.2.1 Wall reflectivity

Light incident on an opaque object is reflected or absorbed. Reflection for light, like sound, is dependent on the inherent physical properties of the material: color and surface texture of the material.

Light colored surfaces (high reflective capacity) reflect light more than dark colored objects. White paint has a reflectivity between 70% to 90%, and white porcelain enamel between 60% to 83%, whereas red brick on an unpainted wall has a reflectivity between 10% to 20% (Egan, 1983, p. 27). Therefore, using light colored paints on the material of the atria wall facade, white color or similar surfaces will provide diffuse light for ambient lighting conditions in atria. Significant increases in the illumination levels in the well will provide subsequent increases in the adjacent spaces also. There may be changes in the reflectivity of the surface depending on shade of the colour, for example, ‘diamond blue’ has a reflectance of 86.5% and ‘delft blue’ of 7.8%.
Matte, rough or heavily textured surfaces reflect light diffusively, scattering light evenly in all directions. The surface texture of material also dictates its reflective capacity. For example, for Crescent board materials, depending on whether the surface is smooth and glossy or matte, white colour may have a reflectivity anywhere between 96% to 90% (Robbins, 1986, p. 751). Smooth white plaster has a reflectance of about 80%, while rough or stippled has a reflectance of 40% (Robbins, 1986, p. 750).

Reflective glazing or mirrors on the atria facade will also increase illumination levels in the well. Reflective glasses have a reflectance between 20% to 30%, and clear or tinted glazing of 5% to 10%. If transparent glazing is used in the lower levels maximum light will be projected in the interior. Although reflective glasses have been used as strategies to reflect light, they are not considered as an effective strategy of transporting light down from the top of the well (Saxon, 1983). This is because the light is reflected specularly, i.e., reflected in one direction only, and can be a source of glare within the well.

There are thus, considerable differences in the lighting levels in the atria depending on the reflective materials and surfaces used. While the upper levels of the atria can avail direct light, the lower levels are dependent on light reflected from the upper levels. Windows and similar openings on the atria facade act as light absorbers. Light transmitted is used for lighting the spaces beyond these openings by further reflection of the walls, floor and ceiling in these spaces. Openings on the wall facade decrease the surface area available for reflection.

Ideally, if there are complete wall facades around the atria, with no openings, no light will be ‘lost’ to the adjacent spaces, and supported by highly reflective walls, there would be maximum light within the lower reaches of the well. Actually, at each level, light is drawn off into different levels and its intensity decreases, until it attains minimum values at the lowest level. The relative sizes of the openings is thus, important and the design of the facade should acknowledge the difference in the daylight levels in the top and the bottom of the atria (refer Figure 13).
FIGURE 13

VARIABLE OPENINGS ON ATRIUM FACADE TO ACKNOWLEDGE THE DIFFERENCES IN DAYLIGHT LEVELS
FIGURE 14

FACADE ARRANGEMENTS TO PROMOTE NATURAL LIGHTING

STEPPED SECTIONS

LIGHT SCOOPS

PROJECTIONS
7.2.2. Facade arrangements

While a stepped section can be a useful design device for receiving direct light when the section below projects from the one above it, it also makes the floors successively deeper, hence daylight penetration into the spaces beyond becomes more difficult. A reversed stepped section on the other hand shades the one below it, which is advantageous when direct sunlight has to be controlled. Balconies and terraces projecting from the facade may be used as surfaces for reflecting light. Strategically placed niches in the wall facade may be used as light pockets for providing light to the lower levels of the atria, and also in the spaces adjacent to it. But the spaces below the projections act as shadow zones. Light scoops may be used on the projecting facade to enhance reflectivity in the well, and therefore in the spaces around it as was proposed in the Tennessee Valley Authority Complex (refer Figure 14). Light is projected back to the ceiling using the light scoops to enable uniform distribution throughout the space. Vegetation may be used as light absorbers to control glare. But, if not used properly, it may absorb useful light, leaving very little for further reflection.

7.3 Atrium Floor

The floor of an atrium plays an important role in lighting spaces adjacent to the atria at the lower levels (refer Figure 15). Light reaching the ground is dependent on the reflective quality of the upper surfaces. Light reaching the working plane within the adjacent spaces on the lower floor depends on the reflective quality of the ground. It is also crucial to understand what parts of the floor area are essential for increasing the illumination levels. It may be quite possible that only a small part of the floor provides majority of the reflected light.

a. The colour of the floor can significantly raise the illuminance in the adjacent spaces at the lower levels (Cole & Hui, 1988). Light colored finishes are generally used on the atrium floor to increase reflection into the side spaces.
FIGURE 15
ATRIUM FLOOR

VEGETATION FOR GLARE CONTROL

REFLECTING PORTION OF FLOOR
b. Water reflects as much as 70 percent of light if the surface is smooth; and if the surface is rough, about 30 percent of light is reflected (Robbins, 1986, p.750). Although pools of still water are also found, water used in atria is usually dynamic, in the form of fountains or cascades. Although it is used mainly for traditional reasons, for actual or symbolic refreshment, water may also be used to provide a visual sparkle, pleasant acoustical atmosphere in the case of moving water and add to the scale and depth of the space by being a surface to mirror the surrounding spaces.

The presence of water itself affects the lighting quality. If the surface is calm, as in a pool of still water, more light would be reflected into the well and therefore, into the adjacent spaces, as compared to a fountain where the water is not still. This may be used as a reflecting surface to enhance lighting levels in the well and in the occupied spaces. On the other hand, the reflecting surface of water may also be a source of glare, especially if direct sunlight falls on it.

c. Vegetation in the form of trees and plants are very commonly seen in atria. Trees and plants on the floor of the atria are used to provide shade, a sense of scale, and a soft visual atmosphere. Plants are used on terraces and along balconies. While, to ensure their proper growth, there are the problems of providing adequate light, steady interior temperatures, right soil, watering and maintenance of plants; the very presence of plants itself affects the lighting quality.

Vegetation can absorb as much as 75 percent of light falling on it, grass and earth can absorb upto 93 percent (Robbins, 1986, p.750). If the walls of the atria are lined with plants, there will be less light reaching the lower levels, as there will be maximum absorption at every stage. If the floor of the atria has vegetation, there will be further absorption, and the occupied spaces around the atria at the lower levels will be most affected. Again, if used properly, vegetation can be used to reduce glare, since vegetation absorbs light.
PART 2

CHAPTER THREE

METHODOLOGY

This chapter describes the measurement program and quantitative analysis of the performance characteristics of different reflective surfaces and openings for daylighting in atria. Scale models have been used for quantitative analysis. The procedure for obtaining the raw data for analysis under naturally overcast sky conditions and at the location of the study has been presented.

1.0 MODEL STUDIES

Three types of design tools have been used by daylighting researchers to predict interior daylight calculations: computational methods, graphic techniques and physical scale models (Bryan, 1982).

Physical scale models serve as a powerful design method for daylighting analysis. "Lighting scales exactly, and, with attention paid to geometry, size, and surface reflectance, measurements made with a scale-model building will accurately predict the expected daylight levels in a full sized building" (Selkowitz & Johnson, 1980). Thus, a daylight model that reproduces the original structure in a smaller scale, if tested under similar sky conditions, will show similar results. Millet & Loveland (1985), identify computational methods and graphic techniques to be 'an abstraction of reality', which is not so for the physical scale models. Physical scale models are preferable because they 'provide the opportunity for true qualitative assessment of daylight in space and for
precise measurement of its photometric characteristics'. This may be done by visual observation (during the course of study) or by means of video recordings or photography. The physical scale models also offer other advantages (Bryan, 1982):

1. .... even very crude models can provide accurate quantitative information especially when single element design comparisons are to be made.
2. Physical scale model building is a common practice among many design offices and, with slight modifications, can result in a sensitive design tool for daylighting analysis while continuing to be an effective device for gathering spatial and volumetric information.

However, the time involved in studies using physical models is typically longer than the time used for computational and graphic techniques.

a. The time taken for the construction of the physical scale models.

b. When the study has to be conducted under natural sky conditions, the 'perfect sky' conditions have to be awaited.

On the other hand, the time taken to get acquainted with computational and graphic techniques, and mathematical calculations may be just as time consuming, but once acquired, permit rapid expansion and use. If such is the case, building a physical scale model and taking photometric measurements will provide equally accurate and detailed information.

1.1 Models for practice and daylighting research

Models that are typically used in architects' offices are quite different from the ones that are used for daylighting research. The set of parameters to be studied for such models and for those designed for daylighting research are different. In practice, models are typically constructed to understand the scale and massing of the design scheme. The models used here are small scale reproductions of the original design. They are used as a means of simulating the actual structure and the visual role is given importance. Other features around the main structure such as trees, pavements, roads etc. are represented so as to appear as realistic as possible. Typically, the aesthetic value is given importance, whereas for daylighting studies the model is required to be functional. Depending on the
what is being evaluated in the daylighting research, the models may need to be designed for quantitative or qualitative studies.

Physical models for lighting studies have to be versatile to allow manipulation of single-element design comparisons. A properly planned model may be used to evaluate a wide variety of design options. A 'modular-type' construction has been suggested by Bryan (1982), wherein the model becomes a support structure into which various wall, ceiling and floor reflectances, window and door configurations can be inserted for testing. In the case of an atrium, for example, a square atrium may be converted into a rectangular one by inserting a cardboard along the center if it is required to model the openings or the spaces adjacent to the well. If there are no walls along the sides of the atria well in the original model, different types of facade conditions in the form of variable sizes and shape of openings on the walls could be used.

1.1.1 Quantitative studies

For quantitative studies, models for research are used to assess the performance characteristics of certain specific elements in the model. The models must be constructed to duplicate the geometry of the building as well as the reflective and transmissive characteristics of the building materials and the surrounding areas. The elements which are of significance to model, differ depending on the project. If only the shadow patterns of the building mass are to be studied, it is sufficient to model only the geometry and mass of the buildings. But, if the actual reflective ability of the reflecting facades of the buildings are to be studied, the texture and reflectivity of the model should be the same as that of the actual building facades. Hence, it is essential to first establish what aspects of the building are critical for the study so that they can be modeled accurately and those which are not so that it can be ignored.
1.1.2 Qualitative studies

Models for qualitative studies require a considerable amount of detailing and realism as compared to quantitative studies. The color of the surface, the relative locations of the objects in the interior, the patterns due to direct light and the possibilities of glare are some of the factors that have to be considered. A mirror placed along the central axis of a symmetrical structure may be used to duplicate the entire space, saving time and money. For quantitative studies under overcast skies, the measurements in the reflected part of the model will be the same as that in the part that has been measured. However, this is not so for sunlit conditions where the inter-reflection creates considerable distortion.

1.2 Model used for the daylighting study

The model designed to study the effect of specific reflectivities and the area of openings on the facade of the atrium well, on the daylight distribution in the adjacent spaces of the atria had to be constructed and tested in such a manner as to provide accurate data for analysis. The design of the model, the materials used, the location of the model, the procedure followed for the study, and the sky conditions under which the study is conducted are factors in the daylighting study. The following section describes the scale model in terms of the model design and construction, materials, size and scale, and measurement process.

1.2.1 Model design and construction

A five storey atrium representing an office building was used, to elaborate upon a previous study by Cole and Hui (1988).

To allow sufficient flexibility for incorporating different surface reflectances and opening sizes on the wall facade of the atria, the base model had to be designed in such a manner as to allow for changes to these different elements.
FIGURE 16
DESIGN OF MODEL ATRIUM

NOTE: \( W_I = \text{WELL INDEX} \)
The structure of the model had to be such that these elements could be attached, removed and reused easily.

Since the model was symmetrical, measurements were taken on only one side. Therefore, only the side where the measurements were to be taken was built to accommodate the adjacent space with photo cells used for recording the illumination levels. The measurements were to be taken a level at a time.

Since the material of the model had to be opaque and reasonably lightweight, it was made of wood. The exterior walls were made of 12 mm ply and the floors of 6mm ply. The base model did not have any fenestration on the sides facing the atria well. Plywood was used to separate the space into levels of the required heights. This resulted in five compartments representing the adjacent office spaces on one side which did not have any reflective surface on the walls, floor and ceiling, and which were completely open on the side facing the well (refer Figure 16 and Plate 3 in Appendix B). A door, hinged on one side opening to the outside was used on the exterior face of the model so that there would be no light leaks into the model from the outside. Now, the adjacent space could be accessed from two sides at each level which was convenient for laying the photo cells at the predetermined locations. The bottom of the door on the non-hinged side had a small niche through which wires of the photo cells could be passed through when the door is shut, to avoid damaging the wires (refer Plate 4 in Appendix B).

The openings on the wall facade of the atria represented windows. The size of the openings were different for the three sets of experiments. The openings did not have any glazing material. The roof over the atrium well was considered to be a simple skylight with maximum glazing. But no glazing was used on the openings of the walls or the roof. This was because, since the study was only quantitative, the penetration data could just as easily be multiplied by the transmission coefficient of any glazing types selected. The glazing materials for the openings of the wall in the model were considered have a coefficient of 1.0.
Adjacent space

The 'office room' of the adjacent space was essentially a rectangular box open on the side facing the atria, to fit into each level in the adjacent space. The box was made of card and the sides representing the walls, floor and ceiling were made of the specified reflectivities conforming to the IES standards, which were 85% reflectivity for the ceiling, 50% for the wall and 25% for the floor. Photo cells were to be laid on the floor of this room at specified points and this could slide into any level in the adjacent spaces (refer Plate 5 in Appendix B).

1.2.2 Materials

As the objective of the study was to establish the effects of different wall surfaces on the penetration and distribution of light in the spaces adjacent to the atria, the exact reflectivity of the walls and the floor for the model atrium had to be obtained. The model also had to be light-tight to avoid any light leaks, which may cause errors in the measurement.

1.2.2.1 Reflectivities

It was anticipated that lighting levels would change drastically in the higher reflectance range for small decreases in the reflectivity than in the lower reflectances (Cole & Hui, 1988, Cartwright, 1985, Oretskin, 1982). Therefore, a range of the reflectances was chosen with small intervals in the high reflectances and large intervals in the low reflectances.

There were two possibilities for obtaining surfaces of known reflectivities on the wall facade: either the surface had to be coated with the known reflectance, or the facades had to be modeled from materials of known reflectance. Paint manufacturers offered only approximate reflectance values and not the exact reflective capacity of their products. For the daylighting study, this information was not precise, although in reality, the exact
reflectivities of the materials lining the walls and the floor of existing atria may or may not be known. Therefore, it was essential to find a material whose reflectance values were known, and which could also be used for the model atrium.

The only model-making material that offers accurate reflectivity is by manufacturers under the trade name, Crescent Board (Robbins, 1986, p.750-751). They offered a wide range of cards of different colors and reflectivities. The cards also fulfilled other criteria for obtaining reliable information on the daylighting study. The cards can be easily cut with a utility knife.

A range of reflectivities were selected to satisfy the conditions for the reflectances explained earlier, and their reflectances were rounded off for convenience. They are:

Arctic White (No. 3297): 91.4% reflectance, rounded to 90%
Antique Buff (No. 1095): 85.5% reflectance, rounded to 85%
Mist (No. 1088): 76.3% reflectance, rounded to 75%
Extra Light Gray (No. 928): 49% reflectance, rounded to 50%
Light Gray (No. 923): 27% reflectance, rounded to 25%
and for the study of the floor,

Raven Black (No. 989): 6.7% reflectance, rounded to 5%.

1.2.2.2 Light-tight

One of the important criteria to be met with, in choosing the material for the atria facade was to ensure that it is opaque. If the material is transparent or translucent, unwanted light penetrates into the model. In quantitative studies, light leaks may not be easily discernible to the eye, however, if present, they distort the measurements. The illumination measured at a point in the adjacent space should be only 'wanted' light, i.e., light transmitted into the space only through the aperture in the wall facade. Materials such as foamboard and most paper products are translucent. Chipboard, illustration board, heavy paper and plywood are materials that are opaque.
The other criteria that had to be satisfied was that the material should be lightweight and therefore easy enough to be handled. The materials used for the wall facade of the atria were expected to be inserted and removed a number of times during the course of the experimental study. Therefore, they also had to be sturdy.

1.2.3 Size and scale

The size and the scale of the model had to be appropriately chosen so that the photo cells could be moved easily. Also, as the location of the model for the measurement procedure was different from its location during construction, the size of the model had to be such that it could be moved with relative ease.

The size of the atrium selected in plan and section had to accommodate a range of well indexes. The size of the atrium at the selected scale had to be of a convenient size, so that it could be moved relatively easily without any difficulties. Since the adjacent space had to be moved from level to level, and with it the photo cells, a convenient working size was required to be established. The actual dimensions of the atrium well in plan were 12m by 6m. The total height of the atrium was 15m. Each storey was 3m high. The adjacent spaces represented an office room, 12m wide and 9m deep. This had to constructed to a convenient working scale.

Generally, the level of data required for the study determines the scale of the model. The governing criteria for quantitative scale model analysis is to ensure that the the photo cells can be placed and moved with relative ease in the model. The scale of the model also had to conform with the size of the photo cells. If the scale of the model was too small, the photo cells would be out of scale to measure light incident on a work surface.

The model was constructed to a scale of 1:30 (3/8" = 1'-0"). The photo cells were placed in the model at the height of the work plane (desk top height). If the size of the cell was very large, it could affect the daylight distribution inside the model. The diameter and the height of the cell were the same, 0.018m. This, in the scale of the model was 0.6m
FIGURE 17
DIFFERENT ARRANGEMENTS OF
PHOTO CELLS

GRID PATTERN

LINE PATTERN
from the floor level. Thus, the illumination levels recorded in the adjacent spaces were on the working plane.

**1.2.4 Measurements**

Photometric evaluation of the model involves measuring illumination levels in the space. A number of photo cells are needed to measure illumination within the adjacent space and outside. Both interior and exterior illumination measured simultaneously are required to calculate daylight factors.

Either different light meters, or one light meter having different photo cells could have been used. Since the study was conducted under overcast conditions, illumination levels were expected to be lower than under direct sunlight. Therefore, a light meter range of 0-10,000 lux was expected to be sufficient. A Megatron architectural model light meter was used to take the measurements. It had twelve photo cells (refer Plate 6 in Appendix B).

The light meter was calibrated to establish differences in the sensitivity of any two cells. By calibrating, the correction factors of the cells could be determined, and cells could be appropriately selected for placement in the model. The correction factors were used to calculate the exact correct interior and exterior illumination before calculating the daylight factors.

The measurements can be taken, using a single photo cell at a time, at a specific point in the adjacent space. This is not a very convenient method, as the cells have to be constantly moved to different points to take the readings. If however, a number of cells are used, the readings can be taken easily taken after arranging them only once. If different cells are used, they can be arranged either in a grid pattern or in a line pattern (Robbins, 1985) (refer Figure 17). Line measurements were taken, using a series of photo cells in a single row in the center of the adjacent space. A line of photo cells were placed perpendicular to the aperture, as the fall of light levels from points near the atria to the
FIGURE 18

POSITION OF PHOTO CELLS IN THE MODEL ATRIA

DISTANCES FROM THE ATRIUM WELL FOR

A = 0.6 m
B = 1.8 m
C = 3.0 m
D = 5.4 m
E = 7.8 m
back of the room was to be recorded. The position of the cells was also important. The cells were placed at short intervals near the atrium space, and further apart at the back of the room. This was because, light was expected to change significantly at points near the opening.

The decrease in the daylight factor between subsequent points near the opening was very important. Here, cells were placed at 0.6m and 1.2 m apart. At the back of the room, the cells were placed 2.4m apart, at larger distances as the light levels were expected to fall gradually, and the differences in the light levels between these points was not expected to be significant. They were placed at 0.6m, 1.8m, 3.0m, 5.4m and 7.8m from the atrium wall (refer Figure 18).

To measure the exterior illumination, a photo cell was placed at the top of the model.

1.2.5 Measurement Process

Cards of the predetermined reflectivities were cut to the exact dimensions of the walls and the floor of the atrium well.

1.2.5.1 Walls

The measurement procedure was carried out in three sets. In each set, measurements for the walls and the floor of the atria were recorded. The first set of readings consisted of openings of 25% in the wall facade of the atria. In the second set, the size of the openings was 50% of the wall area and in the third set it was 75%. In each set, readings were taken for all the five different surface reflectivities, viz., 90%, 85%, 75%, 50% and 25% (refer Plate 7 in Appendix B). Each set of readings was repeated twice, and the average of these readings was calculated.

The measurement program was conducted systematically, starting with the highest reflectivity, and using the others in a descending order. The office room containing the
FIGURE 19

MEASUREMENTS AT LOWER WELL INDEXES

NOTE: $WI = WELL\ INDEX$
FIGURE 20

EFFECTS ON LIGHT DISTRIBUTION
BY VARYING REFLECTIVITY ALONG PERIMETER
OF FLOOR

BLACK
0

25%

50%

75%

100%

WHITE
photo cells at the specific points was placed on level five and readings were taken for this level, that is, well index 0.375 (level five in the model) (refer Plate 8 in Appendix B).

The exterior illumination was recorded simultaneously. A set of readings was made for both, black and white atria floor.

The same procedure was repeated for well index 1.17 and 1.95, i.e. at levels 3 and 1. The office room was moved according to the level that was to be measured.

The reflectivity of the walls was then changed, and the entire procedure was repeated, in the manner described above for all the well indexes. This was done until the entire set of reflectivities for the 25% opening on the wall was completed. Another set of readings was taken for this set before the cards were used for 50% openings. The procedure for this set was the same as that for the 25% area of openings, except for some additional readings using the 90% reflectivity on the walls at level one.

1.2.5.2 Floor

The effects of light distribution using white over black floor was done for all well indexes and all conditions of the walls. In addition, to establish the changes in lighting in the side spaces by varying the reflective surface of different parts of the floor, combination of white and black floors were used.

Measurements were to be taken at well indexes, 0.375 (level five), 1.17 (level three) and 1.95 (level one), so the floor had to be raised to these levels. Measurements at the ground floor did not present a problem. Two struts had to be made to raise the floor, one each for well index 0.375 and 1.17 (refer Figure 19).

First readings were taken using a complete black floor. For the 50% openings on the wall, additional readings at well index 1.95 were taken as follows: starting with a black floor, the reflectivity along the perimeter was increased incremently by 25%, till the floor was completely white (refer Figure 20). This was done for well index 1.95 only.
The set of readings for the 75% opening on the wall followed the same procedure as that for the set of readings with 25% opening, which involved using only the white and the black floors.

2.0 DAYLIGHT FACTOR

Daylight factor is defined as the ratio of interior illuminance on a horizontal surface to the exterior illuminance on a horizontal surface simultaneously available outdoors from an overcast sky. It can also be applied to clear skies, but has to take into account the variations in luminance values on the horizontal surface for altitude and azimuth. Direct sunlight is excluded for interior and exterior values of illumination.

This is expressed (as a percentage) as:

\[
\text{Daylight Factor} = \frac{\text{interior illuminance}}{\text{exterior illuminance}} \times 100
\]

It is, therefore, only a relative measure of the illuminance and not the absolute measure.

Daylight factor can be divided into three main components:

\( a. \) Sky component.

\( b. \) External reflected component.

\( c. \) Internal reflected component.

The sky component is the relative illuminance striking a given point received directly from the sky. In top-lit atria, the illumination from the sky will depend on the sky vault covered by the roof. In the case of side-lit atria, the angle of the sky vault seen from a given point in the atrium well/side space is obtuse. The illumination from the sky component is greater for the top-lit atria under overcast conditions, as, the sky luminance is greater at the zenith than at the horizon.
The external reflected component is the relative illuminance striking a given point received from external reflecting surfaces, such as the facades of adjacent buildings. The internal reflected component is the relative illuminance striking a given point received from the daylight inter-reflected around the room.

For the overcast sky, the external reflected component is rarely more than a very small fraction of the total daylight factor. However, this could play a major role if the given point in an atrium space has no direct view of the sky. The internal reflected component is the illumination at a given point due to inter-reflection from the walls, floor and ceiling.

"In dry tropical regions, where the sky luminance distribution is predictable, where the average sky luminance remains fairly constant throughout the day, and where reflected sunlight from the ground and from other buildings makes a fairly constant contribution to the interior illumination the daylight in an interior can very usefully be specified in terms of absolute values of illumination. In cloudy and humid climates, the outdoor illumination varies with the cloud cover" (Hopkinson et. al, 1966. p. 59). Therefore, in such regions daylight is variable and daylight factor gives a more meaningful expression to the interior lighting.

3.0 SKY CONDITIONS

Models for daylighting studies may be used under natural or artificial skies. In most cases, testing outdoors under the real sky is easier and economical. But, it is not possible to reproduce the same measurements for every study conducted under natural sky conditions, as natural light is everchanging. By contrast, readings taken under artificial skies can be reproduced any number of times under the same set of conditions.
FIGURE 21

STABLE SKY CONDITIONS FOR DAYLIGHTING ANALYSIS

CLEAR SKY

OVERCAST SKY
Although studies under artificial skies may be preferred, they do not represent the true sky conditions. Therefore, results for studies under artificial sky laboratories have to be interpreted back into reality.

Under natural skies, it is difficult to interpret results for daylighting studies in varying light conditions, hence, they are conducted only in stable light conditions. Also, in reality, since the building will be subjected to changes in weather, it is more meaningful to evaluate for the extreme conditions, to ascertain the building's full scope and range of performance.

The clear and the overcast skies are the two extreme stable sky conditions for daylight design and the partly cloudy sky, as a condition between the two (refer Figure 21).

Fully overcast conditions obscure the sun completely (Hopkinson et. al, 1966, p. 46). Therefore, the illumination levels for the fully overcast sky is always lower than any other sky condition. In all regions where cloudy skies are predominant on account of high latitude, climate and industrial haze, this represents the worst case and hence studies on daylighting use this type of sky condition. The luminance between any two points of the sky vault of the overcast sky is not the same, although it is not as variable as that of the clear sky. The distribution of luminance is symmetrical about the zenith, and, the sky is brighter at zenith than at azimuth. This is taken into consideration for the CIE (Commission Internationale de l'Eclairage) standard overcast sky. The luminance gradually decreases away from the zenith, till it reaches only a third of the zenith value at the horizon.

The daylight factor for a particular point in the interior for the overcast sky is constant throughout the day, and only the absolute illumination varies for different overcast days. Thus the time of the day is not a very crucial factor, as, while the absolute illumination at a particular point varies from moment to moment in the day, the daylight factor remains constant. For the study, the natural overcast sky was used. The problem,
however, was to actually wait for the right sky condition to carry out the study. Since the proportion of the interior and exterior illumination remains the same for the overcast sky, the measurements taken for different overcast days would be valid.

4.0 LOCATION

The experimental study was conducted at the University of British Columbia, in Vancouver.

The testing had to be carried out on a relatively unobstructed site. If there were obstructions such as buildings or trees around the test model, they would affect light penetration into the model which would have to be accounted for, while calculating the daylight factors. To avoid this, an open space was essential.

The model was placed on the roof of a building. The location was a four level car park, and the model was placed on the roof. There were no obstructions, either from pedestrian traffic or from any buildings or trees (refer Plate 9 in Appendix B).
CHAPTER FOUR

RESULTS

This chapter of the thesis presents the results of the daylighting study and attendant discussion regarding the implications of surface reflectances and the size of openings on atria walls, with respect to daylight in the adjacent spaces.

1.0 DATA ANALYSIS

The methodology for the daylight measurements taken for the specific reflective surfaces and opening sizes on the wall facades have already been explained in section 1.2 of Chapter 3.

The surface reflectances of the wall used are 90%, 85%, 75%, 50% and 25%, and the floor, 90% and 5% reflectivities. The facade conditions for which they have been used are 25%, 50% and 75% area of openings on the wall.

1.1 Walls

Graph 1 shows the decrease in the daylight factors in the adjacent space with distance from the atrium space.

The daylight factor distribution in the adjacent space has been plotted for different surface reflectances of the walls by using a log scale. The floor was white (90% reflectance). Graphs 2 and 3 show the results for 50% and 75% openings of the wall facade respectively.
GRAPH 1
VARIATION IN DAYLIGHT FACTORS
FOR 25% OPENING

DAYLIGHT FACTOR

DISTANCE FROM ATRIUM (m)

90% REF.  85% REF.  75% REF.
50% REF.  25% REF.

AT WELL INDEX 1.95
GRAPH 2
VARIATION IN DAYLIGHT FACTORS
FOR 50% OPENING

AT WELL INDEX 1.95
GRAPH 3
VARIATION IN DAYLIGHT FACTORS
FOR 75% OPENING

AT WELL INDEX 1.95
The following observations can be stated:

a. *Higher the wall surface reflectance, higher is the daylight factor.*

All graphs exhibit a similar curve: the higher the reflectance of the atrium wall, the greater is the daylight factor in the adjacent space. If the surface reflectivity of the walls is high, available light in the well due to inter-reflection also increases. This provides higher daylight factors in the spaces adjacent to atria. The daylight factors at locations at the back of the room (at 5.4m and 7.8m), for the three different wall facade conditions are less dependent on the surface reflectivities of the wall. The daylight factors lie between 0.56 and 0.1.

b. *Daylight factor decreases significantly between two consecutive points at small distances from the well.*

This is especially the case with lower well index of atria. As distance from the atria well increases, the differences in the daylight factors between these points become less significant.

At points near the atrium well, the difference in the daylight factor between two points for a given reflectance successively decreases with increase in the area of opening. But daylight factors for specific points in atria of higher well index are not significantly enhanced using a higher surface reflectance on the wall as in 25% opening on the wall facade. Using different surface reflectances on the wall facade to enhance reflection at the lower levels makes significant differences only when small openings on the wall facade are used (below 25% opening). As the surface area available for reflection increases, the daylight factors also increase.

At points near the opening, the daylight factors are higher due to light being projected directly from the sky vault and part due to inter-reflection from the walls of the atria. At lower levels of atria with high well indexes, the contribution from the sky component is minimal, and most of it is due to inter-reflection from the walls and the floor of the atria. With subsequent inter-reflections, part of the light is reflected, and part
absorbed. Thus, light projected at a point due to multiple reflections has lower illumination levels. As a result, daylight factors are higher in the adjacent spaces at lower well index and near the atrium well, than at similar points in atria of higher well index, and for locations at the back of spaces adjacent to atria.

c. The differences in daylight factor between any two points in the adjacent space (near the atrium well) is greater when the wall reflectivity is higher.

Generally, the decrease in the daylight factors between any two points for higher surface reflectances (90%, 85%, 75% reflectance) is greater as compared to the decrease in the daylight factors in the lower surface reflectances (50%, 25% reflectance) between the same two points. The difference in the daylight factor between, say, 0.6m and 1.8m for 90% wall reflectance is more than the difference between the same two points for 85%, which is, in turn, more than that of the same points for 25% reflectance.

Higher reflectance of the wall facade gives greater daylight factors as it has been explained in 1.1 (a). As lighting due to inter-reflections increases towards the back of the adjacent space, lighting becomes more uniform.

With regard to opening sizes on the wall, for a given reflectivity, larger the area of openings (75% and 50% openings), lesser is the surface area available for inter-reflections. At a given point the daylight factor is mainly due to direct rather than inter-reflected light, giving therefore, higher daylight factors in the adjacent spaces, than when the openings on the wall facades are smaller (as in 25% openings). Therefore, differences in daylight factors for points near the atrium well for large openings on the wall facade are significant than for small openings.

d. The difference in the daylight factor between two reflectivities in the higher reflectances at any point in the side space is greater than in the lower reflectances.

At points close to the atrium well, (0.6m, 1.8m) the difference in the daylight factors in the higher reflective range, (90% - 85%, 85% - 75% and 75% - 50%) is comparatively greater than the difference in the daylight factor between these points in
the lower reflectances (50% - 25%). For points at the back of the adjacent space, these differences are very small, and insignificant.

The size of the openings affect the surface area available for reflection. But, for any given area of openings on the wall, the available light will be low if the surface reflectance of the walls itself are low. As the surface reflectance decreases, the daylight factors, and hence the available light decreases.

e. The differences in daylight factors between two reflectances are greater if the openings on the wall facade are smaller.

The difference in the daylight factor between two surface reflectances of the wall decreases as the openings on the wall facade increases. These differences are lower for large openings as compared to smaller openings, where they are significant.

This is because the wall surface available for inter-reflecting light down the atria well is greater when the openings in the wall are smaller. For the largest area of openings, in this case, 75%, the wall areas have been considerably reduced, hence the difference in the daylight factors are not as significant as they are for the 50% or 25% openings of the wall facade.

1.2 Floor

The readings of the illumination levels for the floor have been divided into two parts. In the first set of readings, the reflectance of the entire floor was changed from 90% to 5% reflectance. In the other set, to determine the parts of the floor which are essential for increasing the daylight factors in the adjacent spaces, the perimeter area of the floor was increased incrementally by 25% (of the floor area) from 0-100%, that is, from a black floor to a completely white floor.
GRAPH 4
DAYLIGHT FACTOR AND WALL REFLECTIVITY
AT 3.0 M AND WELL INDEX 1.95

For white (W - 90% reflectance) and black (B - 5% reflectance) floors for 25%, 50% and 75% openings of wall.
1.2.1 Entire floor

To understand the influence of the floor reflectivity on the illumination levels of the adjacent spaces, white (90% reflectance) and black (5% reflectance) floors, were used for the three different facade conditions.

The daylight factor at a point 3.0m from the atrium well was plotted against the wall reflectance for each condition. Graph 4 shows the relationship between the daylight factors and the surface reflectivity of the wall for well index 1.95, for the three conditions using the white and the black floor.

The following points can be observed:

a. Using a floor of 90% reflectance in the atrium well increases daylight factors.

The difference in the daylight factors using the black and the white floor at well index 1.95 shows that the daylight factor in the adjacent space is significantly higher when the floor reflectivity is also high (refer Graph 4) for any size of openings on the wall facade. The daylight factors could be increased upto five times the original values (using black floor).

With regard to the reflectivity of the wall facade, the difference between the daylight factors for the white and the black floors at well index 1.95 is least for higher reflectance (90%), and increases gradually upto 25% wall reflectance. The increases for 90% wall reflectance are about 2.5 times the values (using the black floor), gradually increasing to about 4.5 times for 25% wall reflectance.

This shows that when lower reflectances are used on the walls, using a higher reflectance on the floor will enhance illumination in the spaces adjacent to the atria. Direct reflection off the floor projects light into the adjacent side spaces, creating higher daylight levels. Also, since the floor reflectivity is high, there is maximum inter-reflection between the wall and the floor, thereby increasing the daylight factors.
GRAPH 5
DAYLIGHT FACTOR AND WALL REFLECTIVITY
AT 3.0 M AND WELL INDEX 0.375

For white (W - 90% reflectance) and black (B - 5% reflectance) floors for 25%, 50% and 75% openings of wall.
b. There are no significant changes in the daylight factors in the side spaces for openings beyond 50% openings on the wall facade.

At well index 1.95 there is very little difference in the daylight factors between the 50% and 75% openings on the wall facade, for either the white or the black floor (refer Graph 4).

Graph 5 shows the relationship between daylight factor and surface reflectance of the wall for well index 0.375.

At well index 0.375 the difference in the daylight factor for both, white and black floors is not very significant with increase in the openings on the wall facade. The daylight factors using smaller openings (25%) on the walls with a white floor can be compared to larger openings (50% and 75%) with black floor. The daylight factors lie between 3.0 and 5.0.

In general, the differences in the daylight factors between 50% openings and 75% openings on the wall facade can be neglected when compared with 25% opening on the wall facade. If the area of the openings on the wall facade were to lie anywhere between 50% and 75% or more, the increase in the daylight factors beyond the present values of 50% and 75% openings of the wall facade would almost be negligible. However, if the openings on the wall facade were to decrease lower than 50%, upto 25% or even less, the daylight factors of these new openings on the wall facade will correspond with the present values of 50% and 25% areas of the wall openings which is appreciable. When the openings in the walls are reduced below 25%, the daylight factors will be even lower. The differences in the daylight factors using smaller openings in the walls, when decreased below 25% opening on the wall facade is significant.

Alternatively, if the increase in the area of openings in the wall is from 0-50%, the increase in the daylight factors with increase in the area of opening at every step would be substantial. If the openings on the walls are larger, beyond 50% of its area, the increase
GRAPH 6
DAYLIGHT FACTOR AND WALL REFLECTIVITY
FOR 25% OPENINGS AT 3.0 M

AT WELL INDEX 0.375 AND 1.95
FOR WHITE (W-90% REFLECTANCE) AND
BLACK (B-5% REFLECTANCE) FLOORS
GRAPH 7
DAYLIGHT FACTOR AND WALL REFLECTIVITY
FOR 50% OPENINGS AT 3.0 M

AT WELL INDEX 0.375 AND 1.95
FOR WHITE (W - 90% REFLECTANCE) AND
BLACK (B - 5% REFLECTANCE) FLOORS
GRAPH 8
DAYLIGHT FACTOR AND WALL REFLECTIVITY
AT 3.0 M FOR 75% OPENINGS

DIALIGHT FACTOR

WALL REFLECTIVITY

0.375W  0.375B  1.95W  1.95B

AT WELL INDEX 0.375 AND 1.95
FOR WHITE (W- 90% REFLECTANCE) AND
BLACK (B- 5% REFLECTANCE) FLOORS
in the daylight factors for any surface reflectance of the wall is not significant. This is because with larger openings on the walls, the area for reflection is reduced. This is more so in well index 1.95 than in well index 0.375, as, at well index 1.95 lighting is mainly dependent on inter-reflection as compared to the shallow well in well index 0.375.

\textit{c. Difference in the daylight factor between 90\% reflectance and 5\% reflectance of the floor for any area of opening of the wall is higher in well index 0.375.}

Graphs 6, 7 and 8 show the relationship between the daylight factor and the reflectivity for the well indexes 1.95 and 0.375, using the white and the black floors for 25\%, 50\% and 75\% openings of the wall facade.

The differences in the daylight factors between white and black floors for different wall reflectances is higher in well index 0.375, than in well index 1.95. This is for any opening sizes of the wall facade.

The differences are higher for the low well index because the points in the adjacent spaces are less dependent on the facade condition or surface reflectance of the wall facade than for similar points in lower levels at higher well index. The high daylight factors are for the most part directly from the sky vault.

The increase in the daylight factor between well index 1.95 and 0.375 for any condition in the openings of the wall using either the white or the black floor is more for the 25\% wall reflectance than for the 90\% wall reflectance. This is because at the upper levels a major part of the daylight factor is due to the contribution from the direct sky component and very little due to inter-reflections. The illumination levels decrease rapidly for the 25\% wall reflectance towards the lower levels on account of lower reflectivity of the wall. Using black floors, the reflectivity is further reduced, hence the daylight factor in the upper levels has a significant increase for the 25\% reflectance of the wall surface.

\textit{d. The difference in daylight factor between well index 1.95 and 0.375 is significant for larger openings of the wall facade.}
GRAPH 9
FOR VARIOUS OPENINGS USING WHITE FLOOR
AT 3.0 M

AT WELL INDEX 0.375 AND 1.95
FOR 25%, 50% AND 75% OPENINGS OF WALL
GRAPH 10
FOR VARIOUS OPENINGS USING BLACK FLOOR
AT 3.0M

AT WELL INDEX 0.375 AND 1.95
25%, 50% AND 75% OPENINGS OF WALL
Graphs 9 and 10 are plotted at 3.0 m from the opening for the white and black floor. The curves have been drawn for different openings of the wall facade at well indexes 1.95 and 0.375.

The increase in the daylight factor for the white floor from well index 1.95 to well index 0.375 for different surface reflectances at points 3.0m from the atrium well in the adjacent space is greater when the openings on the wall facades are larger (refer Graph 9). For the 25% openings, the increase in the daylight factor was from 2 times the values at well index 1.95 for 90% reflectance up to 5 times increase in the values for 25% reflectance. The daylight factors using white floor at well index 0.375 was enhanced as the surface reflectance of the wall decreased.

For large openings (50% and 75%) on the wall facade, the increase was from 3 times for 90% reflectance in well index 1.95 to 6.5 times for 25% of the wall reflectance.

For the black floors, (refer Graph 10), the same pattern followed. For the 50% and 75% openings on the wall facade, the increases were up to 9 times the values at well index 1.95 for the 90% wall reflectivity, while the values increased by as much as 25 times for 25% wall reflectivity. For the 25% openings, the increase was 4 times for 90% wall reflectivity and 12 times for the 25% wall reflectivity.

Owing to the comparatively large area of surface reflectance for the 25% openings on the wall facade, the distribution of light down the well and in the side spaces is uniform. But, for the 50% and 75% openings on the wall facade the differences between the well indexes are critical.

1.2.2 Specific parts of the floor

To establish which part of the floor area enhances reflection, the reflectance along the perimeter of the floor was increased. It was hypothesized that the area along the edge of the floor plays a key role in the lighting of the spaces adjacent to it. Direct reflection into the adjacent spaces, and further inter-reflection into locations remote from the atria
GRAPH 11
DAYLIGHT FACTORS FOR SPECIFIC PARTS
OF THE FLOOR (ALONG PERIMETER)

AT WELL INDEX 1.95
FOR 50% OPENINGS OF WALL
well projects light into the side spaces. If the reflectance of this area of the floor is increased, the daylight factors were expected to increase significantly.

For only 50% openings of the wall facade, starting with a black floor, the area of reflectance along the perimeter of the floor was increased in increments of 25%, till the floor was completely white.

Graph 11 is plotted for well index 1.95, using daylight factor against area of the floor surfaces available for reflection. The graph has three lines, one showing the increase in the daylight factor at 0.6m from the opening, another at 3.0m from the opening and the third at 7.8m from the opening. The following observations can be stated:

a. *Increasing the floor reflectance increases the daylight factors.*

When the surface reflectance along the edge of the floor is increased, the daylight factor in the adjacent space increases. The daylight factors are higher at distances close to the opening on the wall facade than at points at the back of the adjacent space.

Light reflected off the floor edges is projected into the side spaces, directly or for further reflection, unlike the core where light may be reflected partly into the atrium well and partly into the side spaces. Hence, increasing the reflectivity along the edges of the floor increases the daylight factors in the lower levels.

b. *For 50% openings on the wall facades of the atria, the daylight levels were enhanced only if the area of the perimeter reflectance is greater than 25% of the floor area.*

As shown in graph 11, the increase in the daylight levels between 0-25% in the reflecting strip along the perimeter of the floor is not proportional to the increase in the light levels beyond 25% of the area of the reflecting strip.

Since the openings are 50% of the wall area (and placed along the center of the wall), part of the wall below the opening acts as an obstruction to the light reflected off the perimeter of the floor. Part of the light projected off the perimeter enters the adjacent space through the opening and part of it is bounced back into the atrium space. However, for increments beyond 25% of the floor along the perimeter, light reflected off this zone is
projected into the side spaces. This is because light projected off the area of the reflecting strip is larger, compared to the light reflected back into the atrium well due to the obstructing wall below the opening. Locations along the back of the atrium space are not affected by changes in the reflectivity of the perimeter of the floor, as lighting at these points is more or less uniform.

It is quite possible that the area of the perimeter of high reflectance of the floor may be equivalent or greater than the area of the wall below the opening on the wall surface. Therefore, for the 50% area of openings on the wall, the area of reflection of the perimeter of the floor is less than that of the 25% openings. And, for the 75% openings of the wall, the perimeter area would be even less than that of the 50% openings. This is because the obstructing wall below the opening is smaller for the 50% and 75% openings of the walls. Thus, location of the opening and its size determines the part of the floor perimeter that is needed to enhance the illumination in the adjacent spaces. It is also possible that the area of the reflecting strip is proportional to the height of the wall below the opening.

c. The increase in the daylight factors with increments along the perimeter of the floor is not consistent at specific points in the spaces adjacent to atria.

The differences in the daylight factors between 0.6m-3.0m, and 3.0m-7.8m become significant as the area of reflectivity along the edge of the floor increases. It is the least when the floor is black and highest when the floor is white. Although, the daylight factors generally increased with increase in the floor reflectivity, the percentage increase at these points in the adjacent space were not the same. The values were 3.13 to 4.7 for 0.6m from the opening, 0.41 to 1.45 at 3.0m from the opening, and 0.1 to 0.27 at 7.8m from the opening.

The reason for the inconsistency in the increase may be due to very low values in the daylight factor at the back of the rooms. Hence, the increases in the daylight levels at locations at the back of the rooms become insignificant.
GRAPH 12
DAYLIGHT FACTORS AND WELL INDEX
AT 3.0 M

FOR 90% (W) AND 25% (G) WALL REFLECTIVITY
FOR 25%, 50% AND 75% OPENINGS OF WALL
1.3 Well Index

Graph 12 presents the relationship between daylight factors and well index using 90% and 25% surface reflectance and 90% floor reflectance, for conditions 25%, 50% and 75% of the openings of the wall.

Irrespective of the surface reflectance, the daylight factors measured at specific points, decrease as the well index increase. For all curves, the differences between the well indexes were greater between well index 0.375 and 1.17 as compared to the difference between well index 1.17 and 1.95. The differences in the daylight factors between 90% and 25% surface reflectance of the wall at well index 0.375 was greater than at 1.95, for 50% and 75% openings of the wall facade. However, for 25% openings on the wall facade, the graph shows a different relationship. Here, the differences in the daylight factors between the surface reflectances at the two well indexes were comparable.

The reason for a more uniform distribution of light for the 90% reflectance curve for 25% openings on the wall facade derives from the increased inter-reflectance of light down the well, and hence into the side spaces. As the area of openings are smaller here than for the other two conditions of the wall facade, there is maximum inter-reflection of light. In addition, most of the light is inter-reflected and very little is absorbed, owing to the high reflectance of the wall facade. Therefore, the light projected into the adjacent spaces at the lower levels is mainly inter-reflected light. For either surface reflectance of the wall, the distribution of light in the spaces adjacent to the well is more uniform for the 25% opening than for any other area of opening of the wall facade.

2.0 DESIGN IMPLICATIONS

Section 1.0 discussed the results using daylight factors as a means of expressing the illumination levels at given points in the spaces adjacent to the atria. In this section, the illumination levels are expressed in terms of lux. Using the daylight factors already
calculated from the raw data, and the exterior illumination of an overcast sky to be an average of 7,500 lux (normal overcast sky varies from 5,000-10,000 lux), the interior illumination values were calculated. These are therefore the estimated values, and not the actual values, for the atrium based under the following assumptions (already given in chapter 3):

1. The roof covering the atrium well is a simple skylight with maximum glass area. The light levels in an atrium well are dependent on the transmission characteristics of the glazing material of the roof. In this case, the glazing coefficient of the roof was considered to be 1.0, so no light is reflected or absorbed by the roof glazing. All the light is transmitted down the well, so this atrium functions as a light well.

2. Similarly, the glazing material on the opening of the wall facades was considered to have a transmission coefficient of 1.0, so light transmitted through these openings are projected directly into the side spaces, without any part being reflected or absorbed.

3. The different opening sizes of the wall facade are located in the center of the wall at each storey.

4. The illumination levels given are at the working plane in the side spaces of the atrium, i.e. at 0.6m from the floor and, at points 0.6m, 1.8m, 3.0m, 5.4m and 7.8m from the atrium well.

5. The reflectivity of the walls, floor and ceiling of the office space has been derived from IES Standards: 50% reflectivity of wall, 85% for the ceiling and 25% for the floor.

6. The spaces around the atria well derive light only from the atrium and not through the external walls. The contribution from the external walls will depend on factors such as orientation, size and location of the openings on these walls.

7. The proportions of the atrium remains unchanged in plan. The height of the atrium well varies, giving different well indexes.
GRAPH 13
VARIATION IN ILLUMINATION USING 90% FLOOR REFLECTIVITY

ILLUMINATION (lux)

DISTANCE FROM ATRIUM WELL (m)

AT WELL INDEX 1.95 FOR 75% OPENINGS
GRAPH 14
VARIATION IN ILLUMINATION USING 5% FLOOR REFLECTIVITY

ILLUMINATION (lux)

DISTANCE FROM ATRIUM WELL (m)

REFLECTIVITY

AT WELL INDEX 1.95 FOR 75% OPENING OF WALL
While graphs 1-12 give a general understanding of the range of daylight factors, graphs 13-17 deal with actual illumination values in terms of lux that may be achieved under the given set of conditions. Since lighting levels are more critical in atria of higher well index, graphs have been plotted at well index 1.95, unless otherwise specified.

Usually, the barrier between the adjacent spaces and the atrium well is glazed. This is preferred for lighting as well as aesthetic reasons. In comparison to the total wall area, windows and such similar openings on the atrium wall facade equal 75% or more, being a more realistic value than 25% opening size.

1. Graph 13 has been plotted for 75% openings on the wall facade. The floor reflectance is 90%, which will represent the maximum values of illumination under the given circumstances. The distribution of light in the adjacent office space has been shown for different reflective surfaces of the wall (refer Graph 13). A maximum of approximately 350 lux may be achieved at a point 0.6m from the atrium well for 90% wall reflectivity and 270 lux for 25% wall reflectivity. At 7.8m from the atrium well, these values lie between 12 lux and 24 lux. Clearly, these points will have to have supplementary lighting.

2. Graph 14 is similar to graph 13, but here the floor reflectivity is only 5%. This graph contains a range of illumination values when there is maximum absorption of light by the floor: hence this represents the worst case (refer Graph 14). The illumination at 0.6m from the atrium well may range between 190 lux and 50 lux, and at 7.8m from the openings on the wall 6 lux to 2 lux. Therefore, here also supplementary lighting will have to be provided.

3. Realistically, the wall reflectivity is usually not more than 75%: very few facade walls around atrium spaces are smooth and colored white. Similarly, it is highly uncommon to see atria floor of high surface reflectance, as they usually have furniture, plantations, etc which will reduce the overall floor reflectance. Typically, a maximum floor reflectivity of 75% is to be expected.
GRAPH 15
VARIATION IN ILLUMINATION
AT DIFFERENT LEVELS FOR WELL INDEX 1.95

ILLUMINATION (lux)

DISTANCE FROM ATRIUM WELL (m)

FOR 75% OPENINGS OF WALL
LEVEL 1 WITH 75% REF. FLOOR,
LEVELS 3 & 5 WITH 5% REF. FLOOR
GRAPH 16
VARIATION IN ILLUMINATION FOR CHANGES IN REFLECTIVITY ALONG PERIMETER OF FLOOR

ILLUMINATION (lux)

DISTANCE FROM ATRIUM WELL (m)

AT WELL INDEX 1.95
FOR 50% OPENINGS OF WALL
This, therefore projects a more practical situation, with the opening sizes on the walls as 75% of the wall area, the floor and the walls with a maximum reflectivity of 75%. The illumination in Graph 15 presents an estimate of the actual values at different levels in side spaces of an atrium of well index 1.95.

In Graph 15, the variations in the illumination values have been shown at different levels for a well index 1.95. Surface reflectivity of the wall is 75%. The surface reflectance of the floor at the lowest level is 75%. For levels 5 and 3, the lux was calculated using 5% reflectance of the floor for well indexes 0.375 and 1.17. This is the same as taking readings at these levels in well index 1.95, as light penetrating into levels lower than five and three respectively are in fact 'absorbed' into the lower levels.

There are large variations in the illumination at specific points in the adjacent spaces at different levels (refer Graph 15). At level 5, the illumination at 0.6m is 2400 lux, a very high value as light at this point is mainly due to the sky component. At the same point in level 3, the illumination is 910 lux, which although lower than at level 5, is still greater than at the same point in level 1, as it still sees a part of the sky vault. At the same point at level 1, the illumination was 310 lux. The illumination is greatly reduced at 7.8m from the atrium well, it is 43 lux at level 5, 18 lux at level 3 and 14 lux at level 1. A comparatively uniform distribution of illumination at level 1 in the adjacent spaces is due to additional inter-reflection off the floor.

4. Graph 16 shows the changes in the illumination values for variations in the area of reflectivity along the perimeter of the floor (refer Graph 16). The opening sizes on the walls are 50%. The changes in the lux at 0.6m from the atrium well varies from 230 lux (for the black floor) to 350 lux (for the white floor) and at 7.8m from the opening, it ranges between 7 lux and 19 lux. Increasing the reflectivity of the floor to enhance illumination in the side spaces does not cause any significant increases in the values at the back of the adjacent spaces. The changes are significant only at very small distances from the atrium well.
GRAPH 17
ILLUMINATION AND WELL INDEX
AT 3.0 M

ILLUMINATION (lux)

WELL INDEX

FOR 90\%(W) AND 25\%(G) WALL REFLECTIVITY
FOR 25\%, 50\% AND 75\% OPENINGS OF WALL
The variations between subsequent increases of the floor reflectivity along the perimeter is dependent on the location and size of opening on the adjacent walls. In this case, the increase in the illumination between the uniform black (0) and 25% area of the floor reflectivity was only 15 lux. Subsequent increases ranged over 30 lux. The differences are, again significant only at small distances from the well.

5. Graph 17 deals with the well index and the illumination levels for specific reflectivities of the wall facades. For each opening size, namely, 25%, 50% and 75%, illumination values at 3.0 m from the atrium well for different well indexes have been shown for the maximum - 90% reflectance and minimum - 25% reflectance of the wall facades (refer Graph 17). This graph gives a range of values, however, based on earlier discussions (in 3 above), using 75% opening size on the walls, lighting levels may lie anywhere between 480 and 590 lux at well index 0.375, between 220 and 136 lux at well index 1.17 and between 110 and 60 lux at well index 1.95.

If the opening size of the walls are smaller; for the 50% openings, the illumination will lie between 450 and 480 lux at well index 0.375, between 120 and 210 lux at well index 1.17 and between 60 and 110 lux at 1.95.

If the opening size of the walls are 25%, the illumination will lie between 210 and 300 lux at well index 0.375, between 75 and 180 lux at well index 1.17 and between 30 and 90 lux at 1.95.

2.1 Discussion

A range of maximum, minimum and optimum values that would typically arise out of the given dimensions in plan and well index of the atria have been presented. These values are based on certain assumptions that have already been stated, and are to be merely used as guidelines in determining the suitability of specific reflectivities on the walls and floor surfaces of the atria and for specific opening sizes on the walls of the atria. For atria with 75% openings, a maximum of 350 lux can be obtained at a well index of
1.95. But this is for a point close to the atrium well, when the surface reflectivity of the wall and the floor is 90%. For similar conditions, using 5% reflectivity of floor, the maximum illumination is only 190 lux. Assuming the reflectivity of atria floor to be 75% in reality, the estimated illumination values at this point will be approximately 310 lux, which is less than 350 lux, the required illumination value at the working plane. As the distance from the atrium well increases, the illumination values in the office space decrease considerably, well below the required levels. And so, supplementary lighting is required to be provided. Daylight may be projected into the space through windows on the external walls or by using artificial lighting. Providing windows on the external walls will enhance the illumination values at distances remote from the atrium well, giving further reductions in the cost of lighting energy. However, problems of glare cannot be ruled out.

Generally, increasing the area of reflectivity along the perimeter of the floor increases the illumination at points close to the well but the increases at the back of the space are insignificant. For 50% opening on the walls, the maximum attainable illumination was 350 lux. If an area of 50% along the perimeter was lined with a surface of high reflectance, the illumination levels at 0.6m were 290 lux, at 3.0m 52 lux and at 7.8m, only 14 lux. This is below the required ambient lighting conditions. It would therefore, be advisable to keep the edges of the floor free from vegetation and furniture which will act as light absorbers, and use this area along the edges for circulation. Since water can be used for reflecting light, pools may be designed around a circulation core. Here again, glare due to high reflective surfaces is a problem to be dealt with.

Irrespective of the surface reflectances of the wall, large openings on the wall facade give a wider range of illumination values. For smaller openings of the wall facade, the differences in the illumination between two well indexes are not very significant. Also, in reality, it is very uncommon to find atria with 25% openings on the wall facade. Typically, the openings in the walls are at least 75%, which covers a range of 480-590 lux.
at well index 0.375, 120-200 lux at well index 1.17 and 60-100 lux at 1.95, all measured at 3.0m from the atrium well at the adjacent office space.

However, the wall reflectivity is rarely 90% and the well index 0.375, which ultimately gives projected illumination levels between 85-135 lux which is less than the required levels of 350 lux. Therefore, at these points supplementary lighting will have to be provided.

Large openings provide greater illumination and smaller openings provide a uniform distribution of light. At levels close to the source of light in top-lit atria, small openings in the wall facade will provide sufficient illumination at the working plane, as light projected at points in spaces adjacent to the atria is directly from the sky vault. Towards the lower levels, larger openings on the wall facade will provide higher illumination values. Hence, it is preferrable to have small openings at the upper levels increasing in size till 100% openings are provided at the lower levels. This will also provide sufficient area for inter-reflecting light to the adjacent spaces in the lower levels of atria.

To control glare, blinds and such similar devices may be used in atria. They may perform a dual role of controlling noise levels in atria also if the materials of which they are made are good for sound absorption.

Similarly hanging elements in atria wells may be used for sound absorption and reflection. This may be so provided the materials they are of which they are made are light colored so that it reflects light. Other elements such as murals, sculptures, etc may also function as light/sound/glare controllers, if their design, materials of construction and location are predetermined.
CONCLUSION

This research set out to establish the changes in the illumination levels in the spaces adjacent to atria resulting from changes in the wall and the floor and variations in the area of the opening sizes in the wall facade of an atria well. Based on research conducted earlier by Oretskin (1982), Cartwright (1985) and Cole (1988), it was hypothesized that changes in the reflectivity can dramatically affect the daylight in adjacent spaces. Also, the changes would be significant in the occupied adjacent spaces at the lower levels of atria.

A general conclusion is that lower the well index, greater is the illumination at that level, within the well or in the space adjacent to it. This was reported by Oretskin (1982), Cartwright (1985) and Cole (1988). At a particular well index, higher reflectances on the wall facade increases the illumination levels appreciably within the well. The same applies to spaces adjacent to the atria. However, the amount by which the daylight factors increase depends on the surface reflectance of the wall, the distance of the point from the opening in the adjacent space and the area of openings on the wall facade.

For atria of same well index, there are considerable differences in the amount of available light depending on the surface reflectance of the walls and the floor. Since lighting in the spaces adjacent are dependent on the amount of illumination in the well, it is critical that the surface reflectance of the wall and the floor be chosen with care. While the upper levels of the atria are relatively insensitive to the surface reflectances, the lower levels are, and therefore it is necessary to ensure that the surface reflectances are chosen in such a manner as to ensure that the working areas in the adjacent spaces will have a reasonable minimum daylight factor.
In practice, the maximum that may be achieved is 75% reflectance for the wall and the floor. For a well index of 1.95 (under a predetermined set of conditions), the illumination will range from 310 lux at points close to the atria to 14 lux for points at the back of the adjacent office space.

The well and the spaces adjacent to it are also affected by the changes in the area of openings such as windows in the walls. The size of the openings affect the available surface area, which also determines the amount of light reaching the lower levels. For larger openings, the daylight factors are higher (greater illumination), whereas for smaller openings they are not. The differences in the light levels between the top and the lower reaches of the atria are significant.

However, for smaller openings, the distribution of light is more uniform at different well indexes of the atria. Similarly, light projected into the occupied spaces also has a comparatively uniform distribution. For 75% opening of the wall and 25% reflectivity of the wall surface, illumination levels ranged between 60-485 lux: from well index 1.95 to 0.0375. For the same wall reflectivity, with 25% openings, the illumination ranged between 30-200 lux.

For openings beyond 50% of the wall areas, the daylight factors do not increase as much with small changes in the size of the opening as they do when the increase is for openings between between 0 - 50% of the wall areas. When the surface reflectance of the walls are low, the differences in the daylight factors in the adjacent space, especially at the lower levels, for different opening sizes of the walls are insignificant.

For a given reflectance there are considerable differences in the illumination levels between the top and the ground levels of the spaces surrounding the atria. Small differences in the higher reflectivities produce large differences in the daylight factors (and illumination values) as compared to similar differences in the lower surface reflectance range. This is especially so when the area of the wall surface available for reflection is comparatively high as in 25% opening of the wall facade. For 75% openings of the wall
facade, the illumination values at 0.6m from the atrium well ranged over 310 lux at level 1 and 2400 lux at level 5. Very high illumination values at the upper levels are quite unnecessary, as in top lit atria, the points in the adjacent office space are closest to the source of light. In fact, there may be problems of glare at these locations.

At locations at the back of the spaces adjacent to atria, however, the differences in the daylight factors are not significant for any change in the reflectance or the opening on the wall surface. The daylight factors are higher for points near the opening of the adjacent space, and fall rapidly as the distances from the atria well increases. In all cases, the illumination values seldom increased over 350 lux for points at/beyond 5.4m from the atrium well. In higher well indexes, this was a primary concern, especially when there is no contribution by the floor surfaces to enhance illumination within the side spaces. Supplementary lighting is therefore necessary. A simple means to achieve this would be drawing daylight into the space by using windows and similar openings along the exterior facade of the office space. Where this is not possible or insufficient, artificial lighting will have to be used.

It has been established by this study that floor reflectivity plays a key role in the availability of daylight, especially in the lower levels. To increase the available light in the ground floor, increasing the floor reflectance will enhance the levels of illumination.

Lining the edge of the floor with a high reflective surface increases the daylight factors in the space adjacent to it. But the increase at locations close to the atria well is dependent on the nature of openings on the wall facade: its size and its location within the wall. If the openings are small and placed in the center of the wall facade, increasing a large area of the perimeter reflectivity of the floor will increase daylight levels in the adjacent spaces. If the openings are large, a comparatively smaller area of high reflectivity along the perimeter of the atria floor will suffice. Whether the reflectivity of the entire floor is changed or increased intermittently, supplementary illumination in spaces adjacent to the atria in the lower levels are required to be provided.
Since lighting is additive, at a given point, the illumination level is the sum of values from different directions and light sources. In most cases, the external wall of the office space can be successfully used to balance the interior illuminance. Thus, the atrium space can be successfully used to draw light into the interior and provide an even distribution of light in spaces adjacent to the atria.

This research set out to demonstrate that atria may be used effectively to serve environmental benefits. Within the scope of daylighting itself, continuing studies on various aspects of this research may be explored. Confining the study to top-lit atria, and with no projections on the wall facades, further study may be done using the same well indexes, but for different proportions of the atria well. Increasing the area of the openings gradually, from the top to the bottom of the well with subsequent increases in the reflective areas from the edge to the core may provide higher daylight factors in the lower reaches of the atria. Further study may also be done changing the reflectivity of specific parts of the floor for different areas of openings on the walls to understand how lighting in the adjacent spaces in the lower reaches of the atria are affected.

Simulating vegetation and water on the atria floor to establish its effects on daylight in the lower levels is another important dimension to be explored. Very often, atria floors are lined with landscape features such as vegetation and water, sometimes with furniture and sculptures also. If they are to be used in an atria serving daylighting function, their location must be carefully chosen. Water can act as a reflective agent, but vegetation acts as an absorptive agent.

Certain guidelines can thus be drawn from this study which may be summarized as follows:

1. The most challenging factor in designing atria for daylighting is the compromise that will have to be made between the area of openings on the wall facade and the surfaces available for reflection. In the study conducted by Cole and Hui (1988), it was suggested that the size of the openings be changed as the well index increases, that is,
smaller openings on the upper levels gradually increasing to larger openings at the lower levels. This will provide sufficient area for reflecting light to the lower reaches of the atria.

2. If the size of the opening is to remain constant, the daylight factors in the adjacent spaces can be increased by increasing the surface reflectivity of the walls.

3. At the back of the adjacent space, the daylight factors do not increase appreciably, either with increase in the area of the surfaces available for reflection or the reflective surfaces of the walls. Instead, distribution of light in the side spaces can be obtained by increasing the floor reflectivity.

4. Illumination levels in the well and in the occupied spaces vary greatly with increase in distance from the light source in top-lit atria. If the distribution of light is to be uniform, very small or no openings on the wall should be provided.

5. The daylight factors in spaces adjacent to atria are higher at points close to the atrium well, and ease off at the back of the rooms. If the distribution of light in the lower levels is to be uniform, the reflectivity of the floor must be high.

6. Lining the edges of the floor with high reflective surfaces provides higher daylight factors in the side spaces. However, the size and the location of the opening determines what area of the floor perimeter is needed to enhance illumination.
REFERENCES


APPENDIX A

Plate 1: Atrium spaces in shopping malls

a. Pacific Center Mall
   *Top lighting,*
   *glass blocks used for*
   *filtering light down atria*

b. Oakridge Center Mall
   *Top lighting,*
   *fountain on the floor,*
   *walls sprinkled with vegetation*
Plate 2: Atrium spaces in office buildings

c. Hongkong Bank of Canada
   Top and side lighting

b. Law Courts
   Lateral lighting,
   stepped sectional facade to
draw light into the interiors,
vegetation on walls and floor
Plate 3: Atrium well in model

Plate 4: Office space in model atrium
Plate 5: Photo cells in model office room

Plate 6: Megatron light meter
Plate 7: Atria walls lined with 75% opening size

Plate 8: Measurements at well index 0.375
Plate 9: Location of model