Ain Shams University
Faculty of Engineering
Department of Architecture

DAYLIGHTING
IN
UNDERGROUND BUILDINGS

Presented by

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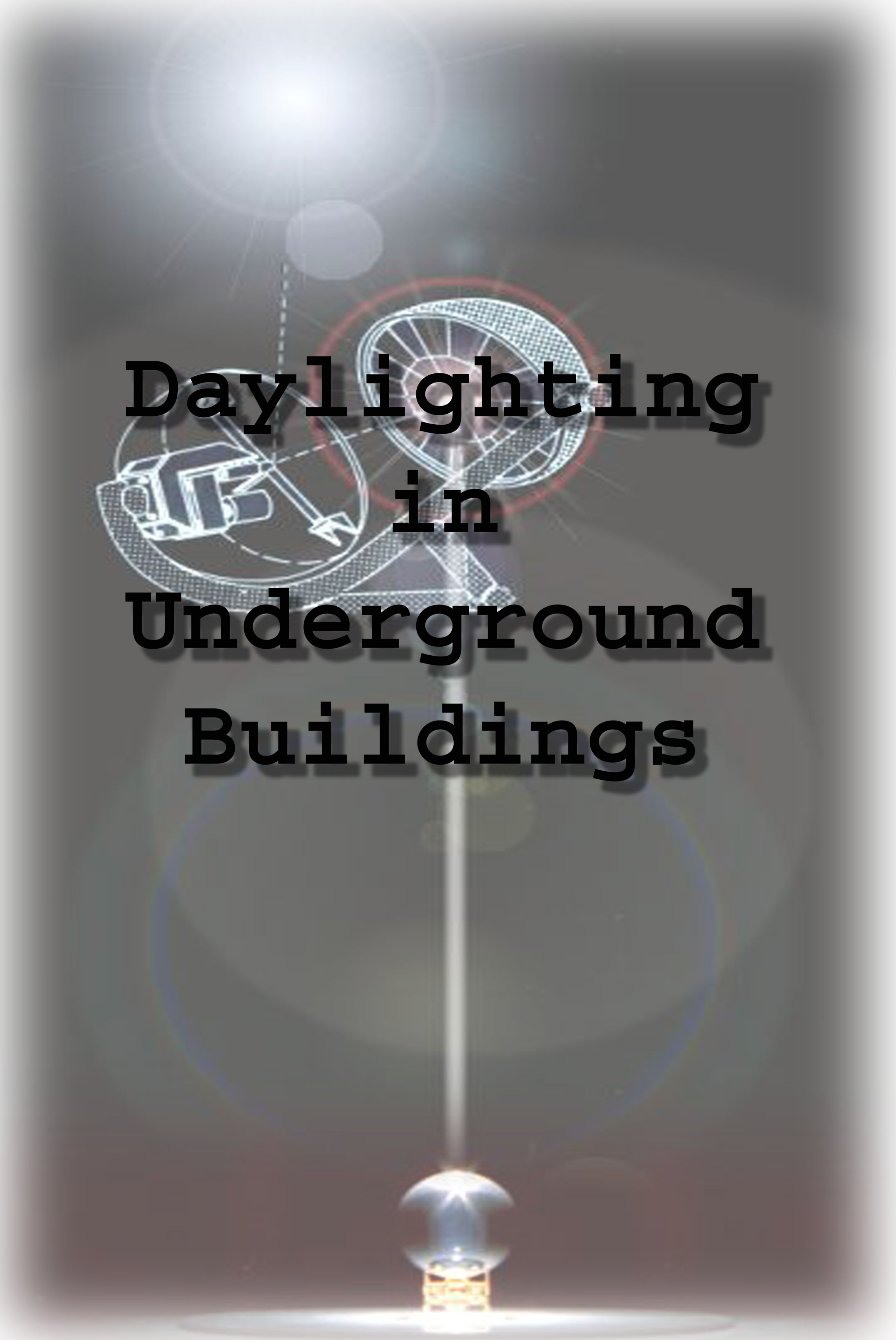

Daylighting in Underground Buildings

STATEMENT

This thesis is submitted to Ain Shams University for the degree of Master of Science in Architecture.

The work included in this thesis was accomplished by the author at the Department of Architecture, Faculty of Engineering, Ain Shams University, during the period from January 2002 to September 2005.

No part of this thesis has been submitted for a degree or a qualification at any other university or institute.

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TO MY FAMILY

TO MY FATHER, MY MOTHER, & MY SISTER

TO MY LOVING WIFE NASHWA &

MY LITTLE ANGEL ALI

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Ashraf Ali Ibrahim Nessim
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ABSTRACT

Underground spaces are currently used for various purposes. Unlike natural above ground spaces, underground spaces must be used with purpose and intelligence.

In the near future, underground spaces may be used to an unprecedented extent through the use of modern technology and design. It will be difficult to modify these spaces once they are built. Thus, developing and putting the new underground spaces to practical use will require considerable forethought.

Among the many constrains that prevent the wide spread of underground spaces is the use of daylighting in those spaces. Other constrains include natural ventilation, safety, construction techniques, and cost.

Daylighting is one of the most primary sources of light that has a great opportunity in the increasing the aesthetics of building and its spaces. Daylighting the underground spaces has many potentials. It provides simulation and connection with nature through the outside view and sunlight. It eliminates any sense of confinement underground. In addition to the energy conservation that daylight provides through the use of natural resources.

This thesis aims at integrating the use of daylight in the underground buildings through incorporating the basic concepts and techniques of both traditional and innovative daylighting systems in the underground building design.

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INTRODUCTION

Throughout history, underground buildings have been directly influenced by the technological advancements of the daylighting techniques and systems used. From prehistoric cave dwellers to our present day, the need for natural daylight in the occupied space influenced the way these spaces evolved.

At first, traditional daylighting concepts were used. Traditional concepts include courtyards which were used by primitive dwellers, for centuries, to provide daylight to the surrounding shallow underground spaces. Then, the courtyard evolved, after the industrial revolution, producing what is known today as the modern atrium. The modern atrium differs from the traditional courtyard in having a controlled thermal environment that is provided by the use of glazing materials. Also, the atrium can provide daylighting to underground spaces of moderate depth.

Technological advancements in the field of the used materials allowed the use of top-lighting methods to daylight the underground spaces. Top-lighting methods, which include vertical and horizontal top-lighting techniques, were used at first to enhance daylight penetration deep into the space. Recently, top-lighting methods were applied to single-storey underground spaces and they work efficiently as any other daylighting technique.

Nowadays, innovative daylighting systems are used to daylight both shallow and deep underground spaces. Innovative systems, which include Heliostats, Light Pipes, and Fiber Optics, allow the use of deep underground spaces to an extent that has never been reached before.

Problem Definition

The recent wide spread use of underground spaces worldwide made a clear demonstration that underground spaces have much more capabilities than being a mere energy conservation technique. They can provide a better and a more enhanced physical environment (by moving certain functions below grade and increasing the open areas above grade thus enriching the built environment).

By investigating previous research going through the potentials of the underground spaces, it was found that the daylighting of underground spaces has not been touched sufficiently in spite of the great role it plays in the enhancement of the underground environment and its evolution.

Therefore, it is of great importance that the idea of integrating the daylight in the underground spaces to be studied and investigated thoroughly.

Value of Research

By using daylight in the underground spaces many advantages can be clearly identified. Starting with the increase of underground space use, passing by the enhancement of the built environment - by increasing open areas above grade by moving certain undeceived functions below grade - and finally discovering different and new environments that have never been explored before.

Thus enabling the designers and the practitioners to be fully aware of the potentials of daylight in such spaces and how to use it efficiently as the spaces created will affect us and our children just as historic buildings and construction have affected our emotions, desires and ideas. In a sense, the creation of a new space will lead to the creation of a new culture.

Thesis Objective

Previous researches involved with underground spaces have merely discussed the daylighting issue. A few researches mentioned the traditional daylighting concepts and techniques used to deliver light to shallow underground spaces without detailed investigations. Innovative techniques were merely mentioned.

By the detailed study of the traditional and innovative daylighting techniques used, this leads to providing a new generation of underground environment.

Thus, the main goal involved in this thesis is:

"Identifying the architectural design parameters to integrate the daylight into the underground spaces in order to establish daylighting design guidelines for architects"

Thesis Methodology

Conducting this research involved using different methodologies to accomplish the thesis main objective.

The thesis consists of three main parts. The first part introduced the underground buildings in which the different types of data and literature concerning the underground structures were reviewed, analyzed and classified. It is considered to be an introductory part.

In the second part, which included the traditional and innovative systems for daylighting the underground buildings, the analytical and comparative analytical methods were applied in order to study this part.

In the third part, the deduction method was used to achieve the main objective of the thesis and to establish the daylighting design guidelines for the different concepts that are used to daylight underground buildings.

Thesis Structure

The main goal of this thesis is achieved throughout its five chapters.

Chapter One: *Overview of Underground Buildings*

This chapter presents a general overview of the underground buildings. It reviews the main principles and definitions of the underground structures, their historical background, their potentials, and their uses. Examples of the various uses are presented in this chapter. At the end of the chapter a classification of the underground spaces is established.

Chapter Two: ***Introducing Daylighting to Underground Buildings***

Chapter two reviews the daylighting definition and main components, its benefits and history in architecture. Then, concepts for daylighting the underground are pointed out. Those concepts include traditional and innovative daylighting techniques. Two of the traditional techniques are then discussed and compared in detail in this chapter: Courtyards and Atria. Their definition, potentials, orientation, shape, and geometry are reviewed. Finally, Examples of underground buildings using these concepts are presented and analyzed.

Chapter Three: ***Top-lighting Concepts for Daylighting Underground Buildings***

Chapter three reviews the top-lighting concepts used to daylight shallow underground spaces. Top-lighting concepts include horizontal and vertical top-lighting. Their definition, potential, shape, placement, and layout are reviewed. The light distribution patterns of these concepts are presented. Finally, Examples of underground buildings using these concepts are presented and analyzed.

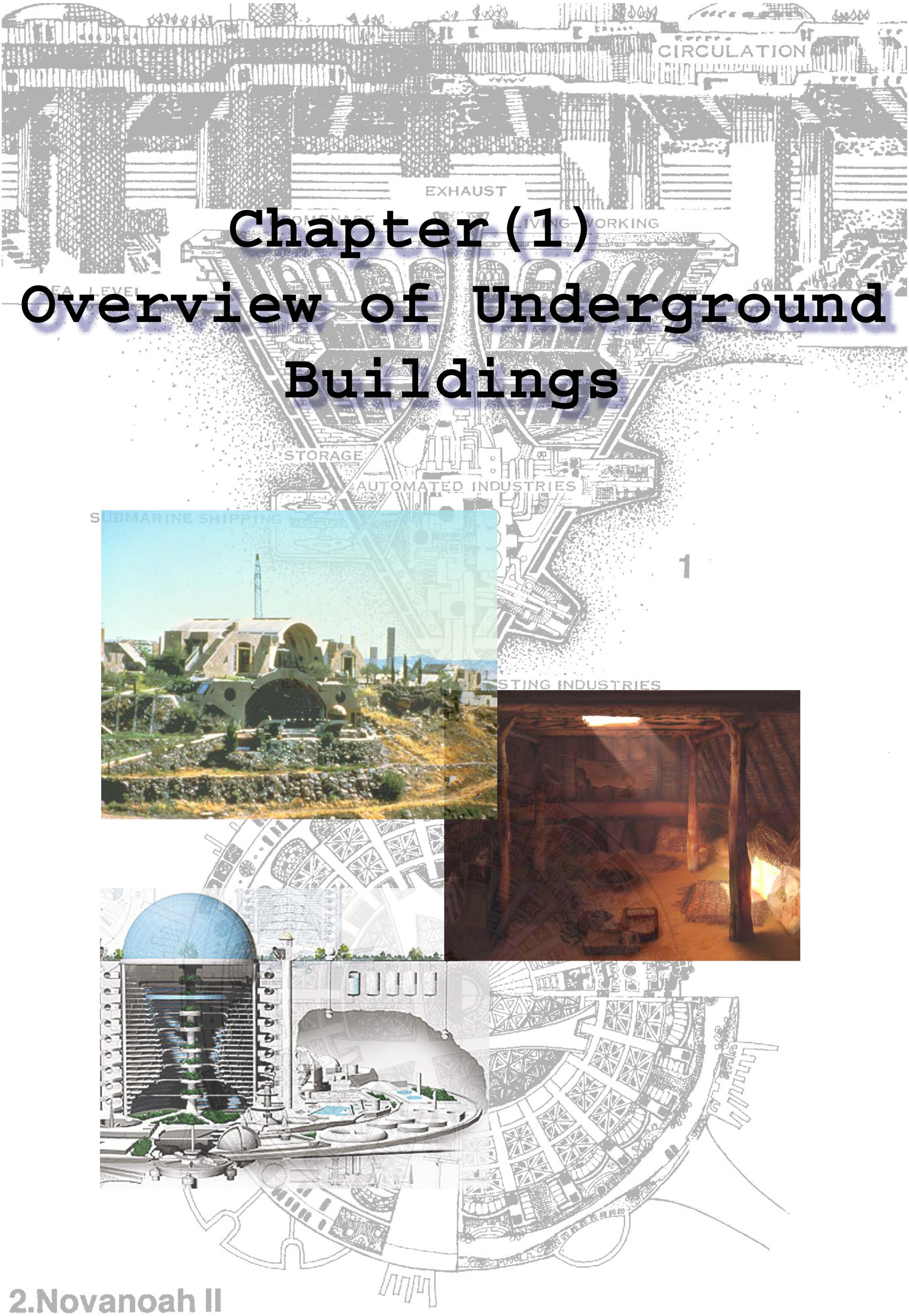
Chapter Four: ***Innovative Daylighting Systems for Underground Buildings***

Chapter four introduces the innovative daylighting systems for the underground buildings. At first, the general concept of those systems is discussed. Then a detailed study of each system is presented. Each system definition, potentials, and components is reviewed. Finally Examples of existing applications for each system is Presented and discussed.

Chapter Five: ***Daylighting Design Guidelines for Underground Buildings***

Chapter five introduces the results which are in the form of design guidelines, for each of the daylighting concepts discussed in the previous chapters, which the designer uses in order to choose the best daylighting method that harmonizes with the architectural design concept. This chapter also includes a computer simulation study that was applied to the courtyard concept and the results were used in designing the daylighting guidelines for this concept.

Chapter(1)
Overview of Underground Buildings



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Chapter (1)

Overview Of Underground Spaces

1-1 Introduction

A life of comfort and safety is the perpetual desire of humanity. To achieve this desire, suitable space is required for dwellings and workplaces as well as for various necessary functions such as storage, mobility, and many others. However, fulfilling this need for suitable space is becoming more and more difficult in many areas of the world due to a growing shortage of urban land. Also, concern has been rising over the social costs of above grade construction and the lack of the open space left for improving the social environment.

Spurred by these factors, interest in underground space utilization is increasing throughout the world. In fact, the use of underground spaces is not a new revelation. Since man first began to use caves for shelter, use of the underground has protected man and simultaneously enhanced the environment. Throughout time, society has looked to the underground any time there was a need for a safe haven, or whenever something needed to be protected against harm or for future use, or for disposal of undesirable wastes.

The use of underground spaces was limited before due to the lack of the proper tools used for construction and the shortage of researches in this filed. Nowadays, recent technological advancements have enabled builders to overcome prior restrictions that had largely precluded underground construction. Many underground projects have already been proposed and successfully carried out worldwide and extensive research and development plans have been implemented.

The objective of this chapter is to present a review of the underground buildings, their main principles and definitions, the historical background of such spaces, their potentials, and finally the classification of those spaces in order to make a clear image about the future use of the underground buildings.

1-2 Main Principles and Definitions

Many terms have been applied to the use of space below ground. Some indicate the level or depth of the space in relation to the surface; others refer to the type of soil in which the space is constructed. Terms such as earth-covered, subsurface, semi-subterranean, subterranean… etc. may be confusing due to similar meanings, but may involve different implications. Below are some brief definitions and interpretations of those terms(1) Fig. (1-1).

- *Below ground or Underground:* General terms associated with the use of space under the surface of the earth.
- *Earth-covered or Earth-sheltered:* A structure built primarily above ground but covered by a thick layer of soil (a minimum of 50 centimeters) that functions as insulation and minimizes the effect of the outdoor diurnal temperature on the indoor space Fig (1-1A).
- *Semi-subterranean:* A structure built partly below and partly above ground (like basements and cellars) Fig (1-1B).
- *Subsurface:* A structure located entirely below ground but covered by a very thin layer of soil, leveled with the surface of the ground. Good examples are the dwellings designed and constructed by the Romans in Bulla Regia, Tunisia. In this case the subsurface sections of the houses were used only in summer Fig (1-1C).
- *Subterranean:* Structures located deep within the ground. The depth may vary. The soil cover functions not only as an insulator but also and primarily as a heat retainer, and uses the benefits of the lag of seasonal temperature variations to receive heat gain and heat loss at the right time. The subterranean system is usually found in a hot/dry climate and is used for dwellings, food storage; schools, offices, restaurants, and shops Fig (1-1D)
- *Geotecture:* Relating to structures in or of earth (*geo*, earth; *tecton*, worker, builder). A general term that can apply to various types of space below ground at any depth and for any purpose.

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(1) Golany, G; "Earth-Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design"; P. 19

- *Terratecture:* Constructed space formed with earth materials (terra, earth).
- *Terraspatial:* Space formed within the earth.
- *Lithospatial:* Space formed within or with rocks (*litho*, rock).
- *Cave:* A natural hollow place or cavity within the earth created by erosion or tectonic movement or both. A cavern is a large cave.

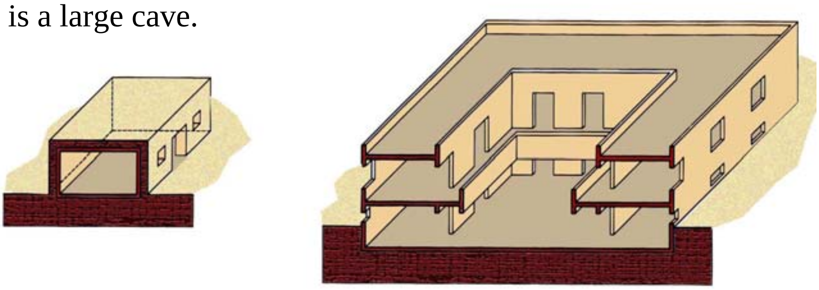

Fig (1-1A): Earth Sheltered / Earth-Covered structure.

Fig (1-1B): Semi-Subterranean.

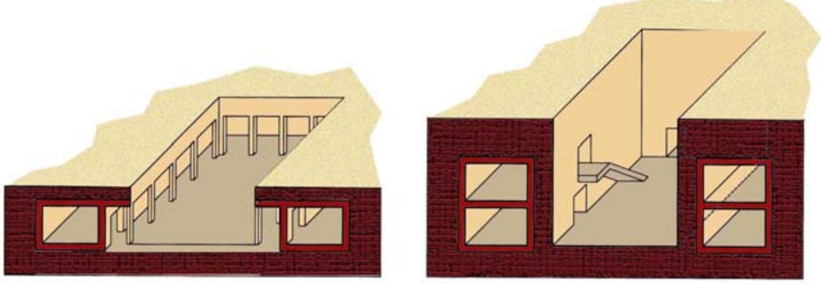

Fig (1-1C): Subsurface structure.

Fig (1-1D): Subterranean structure.

Fig (1-1): Cross-sections of various types of structures below ground(1).

1-3 Historical Background of Underground Buildings

From the prehistoric period to the present day, people all over the world have built and lived below the earth’s surface. Subterranean dwellings are among the oldest types of shelters used by human beings. People have occupied space below ground throughout history in different regions at different times for a variety of needs. Prehistoric cave dwellers, seeking warmth and protection from wild creatures and natural

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(1) ibid; P. 20

phenomena, chose an existing natural earth form, the cave, that provided those qualities⁽¹⁾. The use of caves as a dwelling place goes back to more than 50,000 years ago⁽¹⁾ Fig (1-2).

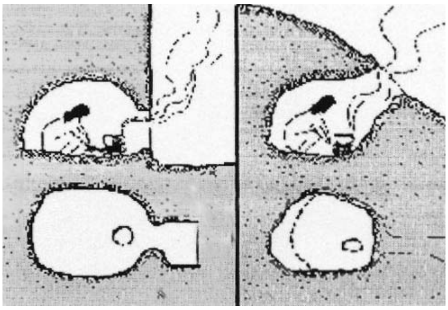

Fig (1-2): Prehistoric cave dwellings.

In some regions, where soil conditions or geological formation support the development of underground shelters, large communities were established thousands of years ago. Such developments are still scattered throughout the world Fig (1-3). In fact the form of houses that we use today evolved from what is called a “Pit House” Fig (1-4).

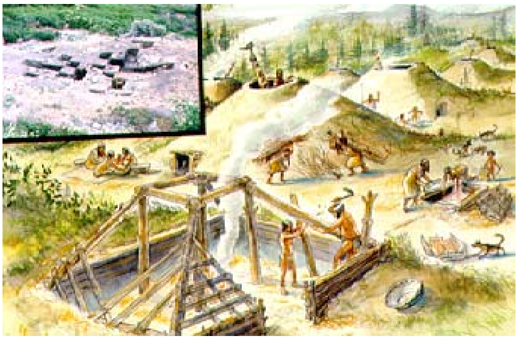

Fig (1-3): The development of large underground communities.

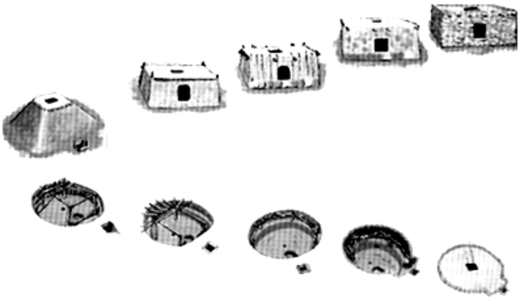

Fig (1-4): The modern house development stages.

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(1) Ahrens, D., Ellison, T. and Sterling, R.; “Earth-Sheltered Homes”, P. 15

One of the earliest records of constructed semi-underground shelters is at a site near Kostenki in Russia where remains of partly underground shelters built with a structure of large mammoth bones were discovered. This site was estimated to be 23,000 years old and was similar to more than a dozen of other sites discovered on the East European plain(2). Subterranean communities are now found in many regions. The principal causes for the underground use appear to be the harsh climate, the availability of conventional building materials and the availability of a suitable geology, topography, or landscape for construction.

1-3-1 Egypt

As a result of the nature of the "Ancient Egyptians' Civilization", which was an agricultural civilization in the first place, the moderate climate and its safe location most of its buildings were constructed above ground. However, the underground architecture existed in such great civilization in the form of its great tombs and some of its temples.

The Ancient Egyptians' sanctified the human body and made him a mean for the endless life so the use of the underground was suitable for serving the old pharaoh's beliefs. The ancient Egyptians religion, on its turn, affected the form and function of the underground tombs as never had been done by any other civilization. One of famous examples of such civilization is Abu-Simble temple Fig. (1-5)

Abu-Simble temple, which was classified as an underground construction with only one façade and uncovered Courtyards(3), is located on the western side of the River Nile in Aswan City with a total area of 2000m^2. The temple was carved inside the mountain hence an earth cover of 30m exists on its roof.

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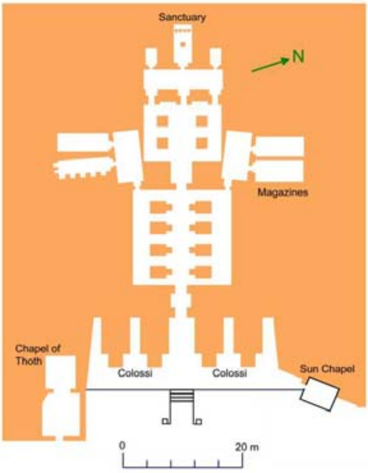
(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 71

(2) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 15

(3) Konswa, A.; "The Architecture of the Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt", P. 19

Above: Abu-Simble great temple exterior view
Below: Abu-Simble great and small temple exterior view



Abu-Simble great temple plan

Fig (1-5): Abu-Simble temple plan and exterior views showing the temple façade and the underground spaces.

Nowadays, In Egypt, there are subterranean dwellings at the Siwa Oasis in the western Desert, which is part of the Sahara. The inhabitants use underground space formerly used as burial grounds to escape the harsh climate of the desert(1).

1-3-2 Tunisia

For Centuries, residents of Matmata, Tunisia have craved into the soft rock to create atrium houses in which several excavated rooms 5 meters deep in the ground open onto a single sunken courtyard(2) Fig (1-6).Those houses are built primarily below ground to protect the inhabitants from the extreme daytime heat and nighttime cold typical of this desert region(3) Fig (1-7).

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(1) Golany, G.; “Earth -Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design ”, P. 21

(2) Golany, G.; “Earth -Sheltered Habitat: History, Architecture, and Urban Design ”,P. 5

(3) Ahrens, D., Ellison, T. and Sterling, R.; “Earth-Sheltered Homes”, P. 15

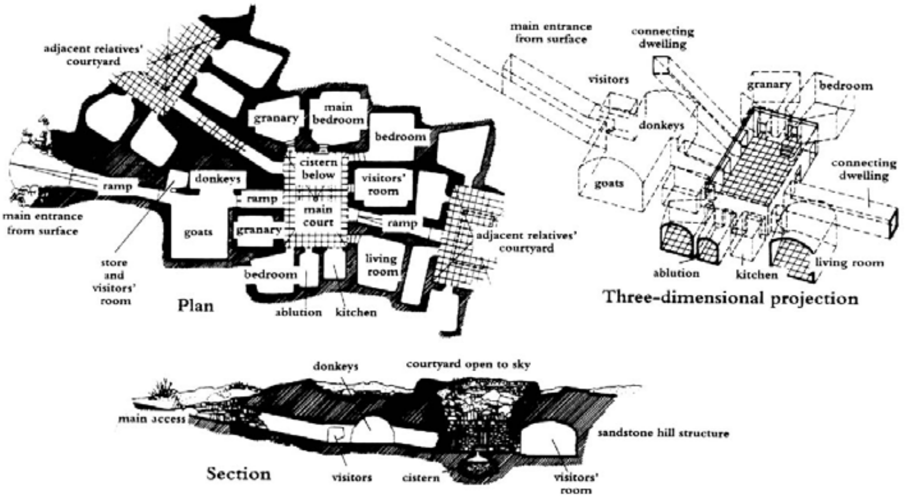

Fig (1-6): Typical plan, section, and isometric view of an underground dwelling in Matmata, Tunisia[1].

Fig (1-7): Birds eye view of a group of underground dwellings in Matmata, Tunisia.

Bulla Regia, which was a Roman settlement in Tunisia, is located in the present day in northern Tunisia. The Romans are only known to have constructed underground housing at their settlements in northern Africa. The hot climate, together with the example of existing underground dwellings constructed by the local Berber inhabitants in Matamata, is thought to have influenced the Roman settlers[2]. Their

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[1] Facey, W.; "Back to Earth: Adobe Buildings in Saudi Arabia", P. 65

[2] Golany, G.; "Earth-Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design", P.109

housing design retained the conventional atrium style built in other areas. They constructed rooms with high ceilings and covered them with 0.5 to 1 meter of earth cover on the roof of the structure. The combination of the central atrium and small perimeter openings provided daylighting and ventilation to all living spaces Fig (1-8).

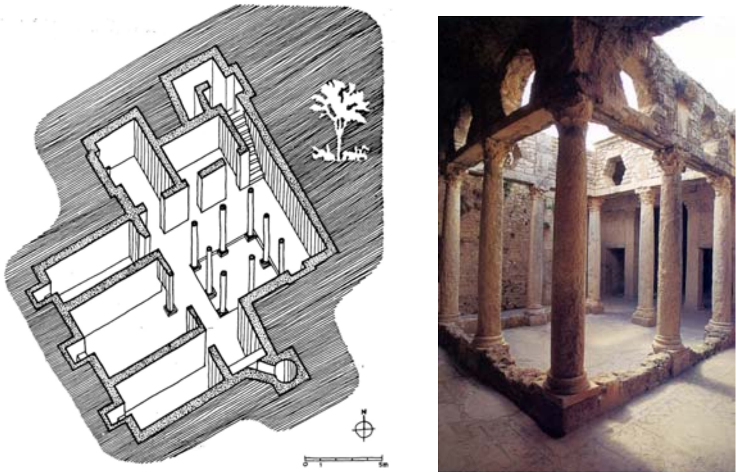

Fig (1-8): Isometric and interior view of a typical underground dwelling in Bulla Regia, Tunisia showing the dwelling organization(1).

1-3-3 Turkey

During the tenth and eleventh centuries of the Byzantine Period, the underground settlements in Cappadocia, Turkey reached its peak(2). They included rock-cut dwellings, churches, and towns Fig (1-9). Two of the best known examples of the underground towns are kaymakli and Derinkuyu in Central Anatolia. They reached depths of 8 to 10 floors below ground and comprised several kilometers of tunnels leading to rooms of varying sizes excavated into volcanic tuff(3). The excavations included ventilation shafts and wells to provide fresh water to the town. The towns were used as a refuge during Arab raids into the region,

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(1) Golany, G.; "Earth-Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design", P. 118, P125

(2) Golany, G.; "Earth -Sheltered Habitat: History, Architecture, and Urban Design ",P. 13

(3) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 36

although this may not have been the primary reason for their existence(1).

Fig (1-9): Different views of the cliff type cave dwellings, Cappadocia, Turkey.

1-3-4 China

In China, the 6,000 year old Bampo site near Xian discovered in 1953 records a village of semi-underground pit homes with floor levels up to 1 meter below ground level. The superstructures were either square or round and used branches and sod cover supported by posts set in rammed earth(2).

Extensive underground settlements have existed in China since the early historical records(3). The easily excavated loess soil that covers much of the central and north central regions of China can be excavated by hand to form underground chambers 2 to 3 meters wide. Chambers 5 to 10 meters long are either dug from a central courtyard excavated on flat sites or directly into the side of a hill. Dwellings, dug out around the sunken courtyard, were of total area 500m^2 and a depth of 8-10meters Fig (1-10). The land above the houses was for agricultural uses. The sunken courtyard was used to allow daylighting to enter the

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(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 72

(2) Konsowa, A.; "The Architecture of The Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt", P.4

(3) Parker, H.; "Underground Space: Good for sustainable Development, and vie versa" P. 6

adjacent rooms(1). The ability to provide shelter with minimum materials and the protection the underground location provides against the severe heat and cold of the region are the principle reasons why more than 30 million people are estimated to live in such structures in China today(2) Fig (1-11)(3).

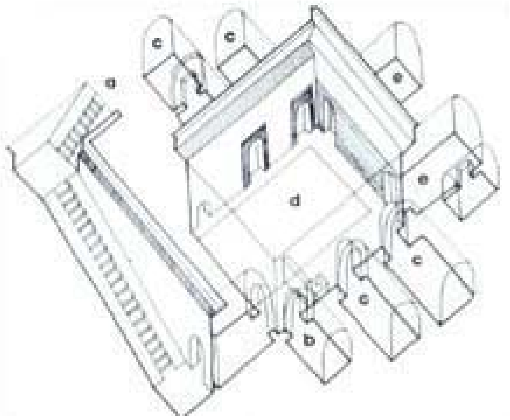

Fig (1-10): Isometric view of a typical Chinese underground courtyard dwelling.

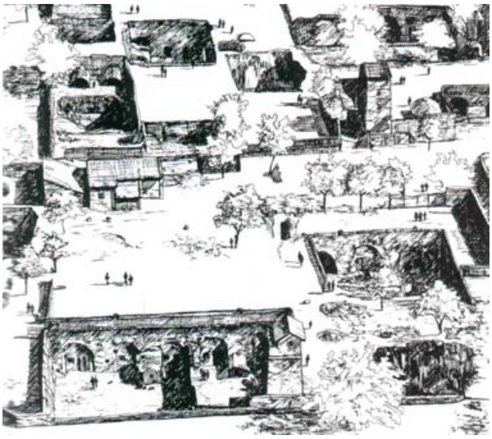

Fig (1-11): General view of underground courtyard houses in China mined out of loess soil

1-3-5 Other Regions in the World

In Spain, underground settlements still exist today in the southern Andalusia region. Early Iberian Civilizations inhibited caves and painted them up to 25,000 years ago. The caverns near Guadix in Granada province have been occupied since the sixteenth century, but

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(1) Vale, B., Vale, R.; "Green Architecture: Design for A Sustainable Future", P143

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 72

(3) ibid, P.71

most of the caves in use today have been occupied only in the last 100 years. The caves are constructed mostly out of soft rock, and many include natural ventilation towers and adjacent above ground structures. In Spain as a whole, it is estimated that approximately 80,000 people live in caves. A survey has indicated that while there are cases of severe poverty, many cave-dwellers are house-proud, contented, and prosperous(1).

In France, there are many sites of underground settlements. Some important sites were inhabited throughout prehistoric times, initially using overhanging rocks and natural caves but later incorporating excavated rooms in the sides of the cliffs. In the Middle Ages many underground chambers were used principally as defensive shelters near villages(2). In the seventeenth and eighteenth centuries, especially in the valley of the Loire, the use of the cave dwellings expanded and caves were used as a single–family houses Fig (1-12). At the peak of their use in the eighteenth century, hundreds of thousands of cave-dwellers lived in France. By the beginning of the twentieth century it was estimated that 20,000 French citizens still live in caves. In the last two decades, there has been a renewed interest in the cave dwellings both for use as a holiday cottages for Parisians and for their historical and cultural importance in France.

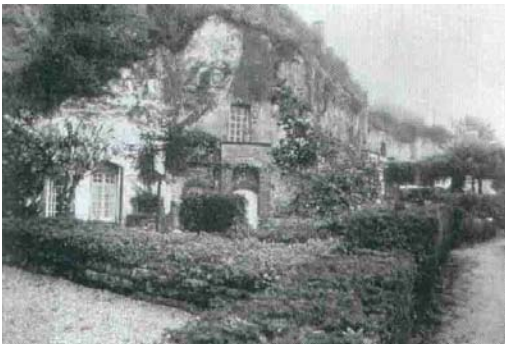

Fig (1-12): Façade of a house dug into the hillside in the Loire Valley, France(3).

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(1) Konswa, A.; "The Architecture of The Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt", P.7

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.73

(3) ibid, P.73

Other countries with an ancient tradition of underground dwellings include Italy (especially Sicily); Greece (especially Santorini); and Jordan⁽¹⁾.

Since the energy crisis of the seventies there has been an increasing interest in the use of underground space⁽²⁾. Many plans and construction projects have been initiated around the world using innovative design techniques and the application of new technology in order to solve a variety of problems such as daylighting, natural ventilation, safety, security, comfort, and climatic stress.

Contemporary use of below-ground space now includes many functions and purposes such as houses in the unites states, large shopping centers in Japan and Canada, industry and storage in Sweden and Norway, as well as military installations in Russia, Switzerland, and the united states. An ever growing number of underground structures are being used as libraries, especially in large universities, offices, restaurants, theatres, concert halls, churches, schools, and trade and conference centers⁽³⁾.

1-4 Benefits of Underground Buildings

In the field of studying the underground space use, it is important to discuss the benefits of the underground space itself because of the special characteristics of such spaces that differ from any other ordinary above-ground space. Studying the benefits of such spaces helps in the decision making of their use and clears the image about the debate of the use of underground spaces in different aspects of our daily life.

There are a large number of various benefits for choosing to build underground which have been verified worldwide and in different times through the actual experiences of using the underground space.

In this thesis, the direct benefits are separated from the indirect ones while the physical benefits are separated from those that can be expressed

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(1) ibid

(2) Ahrens, D., Ellison, T. and Sterling, R.; “Earth-Sheltered Homes”, P.16

(3) Golany, G.; “Earth-Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design”, P.15

in actual cost to a specific project. Although some physical benefits can be measured in terms of cost, others such as aesthetic issues must be balanced within a decision making framework(1).

1-4-1 Physical Benefits of Underground Buildings

1-4-1-1 Land Use and Location Reasons

In many cases, underground space use results from a lack of surface space. The use of underground space allows a facility to be built in a location where a surface facility is not possible either because of lack of space or because building a surface facility in that location is not acceptable to the community(2).

The underground solution also allows to build in close proximity to existing facilities or on otherwise unbuildable sites, thus offering services to the surrounding community(3).

Underground facilities play an important role in preserving historic areas. For example, the new addition of the Louvre museum, Paris, France. The new extension is a buried structure built in the courtyard of the historic Louvre Palace. The glass pyramids are the only signs above ground of the hall and new galleries, which provides an eye-catching entrance point and natural light to the space below. Locating the entrance hall below ground removed a large potential intrusion from the courtyard and allowed the designers freedom in choosing the best shape and layout for the hall(4) Fig (1-13).

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(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 27

(2) Golany, G.; "Earth-Sheltered Habitat: History, Architecture, and Urban Design", P.207

(3) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P.12

(4) Chow, F., Paul, T., Vähäaho, I., Sellberg, B. and Lemos, L.; "Hidden Aspects of Urban Planning: Utilization of Underground Space" P. 2

Cross sectional isometric view Interior view

Fig (1-13): The Louvre museum underground extension, Paris, France

Architect: I.M.Pei.

1-4-1-2 Isolation Considerations

The ground provides a variety of benefits in terms of isolation which in turn provides an important impetus for placing facilities underground.

I) Climate

The underground provides isolation from the surface climate. The temperature within the soil or rock offers a moderate and uniform thermal environment compared with the extremes of surface temperature. The slow response of the large thermal mass of the earth provides a wide range of energy conservation and energy storage advantages(1).

II) Natural Disasters

Underground structures are naturally protected from severe weather (hurricanes, tornadoes, thunderstorms, and other natural phenomena). Underground structures can also resist structural damage due to floodwaters. Moreover, underground structures have several intrinsic advantages in resisting earthquake motions. They tend to be less affected by

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(1) Parker, H., "Underground Space: Good for Sustainable Development and Vice Versa", P.4.

surface seismic waves than surface structures(1).

III) Protection

Underground structures offer advantages in terms of preservation of objects or products stored within the structure due to the moderate and constant underground conditions and the ability to maintain a sealed environment(2).

Small amounts of earth cover are very effective at protecting from the transmission of airborne noise(3) Fig. (1-14). Similarly, if the vibration sources are at or near the ground surface, levels of vibration will diminish rapidly with depth belowground and distance of the source. As with noise and vibration, the earth provides protection by absorbing the shock and vibration energy of an explosion. In case of radioactive fallout or industrial accidents, underground structures can be valuable emergency shelter facilities(4).

Fig (1-14): Seward town houses, Minneapolis, Minnesota.
Architect: Michael Dunn / Close Associates.
(The project was placed underground to reduce the airborne noise from the adjacent highway)

IV) Containment

Containment is the inverse function of protection. With containment, the goal is to prevent a damaging release from the facility to the surface ecosystem.

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(1) Chow, F., Paul, T., Vähäaho, I., Sellberg, B. and Lemos, L.; "Hidden Aspects of Urban Planning: Utilization of Underground Space", P. 2.

(2) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P. 35

(3) Golany, G.; "Earth-Sheltered Habitat: History, Architecture, and Urban Design", P.131

(4) Konsowa, A., "The Architecture of The Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt ", P.56

This is very important for protecting the surface from the dangers generated by some facility like hazardous material storage and hazardous processes(1).

V) Security and Safety Issues

The principal security advantage for underground facilities is that access points are generally limited and easily secured and controlled(2).

1-4-1-3 Environmental Preservation

The ground also provides a variety of benefits in terms of protection of the environment. These are notably important aspects in designing facilities with a low environmental impact.

I) Aesthetics

A fully or partially underground structure has less visual impact than an equivalent surface structure. This may be important to hide unattractive technical facilities in sensitive locations or when industrial facilities must be sited adjacent to residential areas. This is also important for the preservation of natural landscapes(3).

II) Ecology

In some cases, underground structures help preserve natural vegetation. Less damage is thus inflicted on the local and global ecological cycle. Plant life, animal habitat and passages, and plant transpiration and respiration are maintained to a greater extent than with surface construction(4) Fig (1-15)

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(1) Parker, H., "Underground Space: Good for Sustainable Development, and Vice Versa", P.4

(2) Chow, F., Paul, T., Vähäaho, I., Sellberg, B. and Lemos, L., "Hidden Aspect of Urban Planning: Utilization of Underground Space" P.2

(3) Michael, M., "Architecture of the Underground Structures: The Influence of Underground Subways", P. 83

(4) Godard, J., Sterling, R.; "Geoeengineering considerations in the optimum use of underground space", P.5

Fig (1-15): Burnsville house, Burnsville, Minnesota(1).
Architect: John Carmody, Tom Ellison.
(The project has a minimum impact on the surrounding environment and the ecological system)

1-4-1-4 Layout and Topographic Reasons

Underground space use offers many advantages with regard to the layout of facilities and infrastructures. These advantages derive essentially from the freedom (within geological, cost, and land ownership limitations) to plan a facility in three dimensions and from the removal of physical barriers on the land(2).

1-4-2 Life Cycle Cost Benefits

The economic benefits of an underground facility need to be calculated over the full life cycle of the facility and should be taken into account the various indirect benefits they offer notably with regard to the environment.

1-4-2-1 Initial Cost

I) Construction

Although underground structures typically cost more to construct than equivalent surface structures, some combinations of geological environment (use of natural caves), and scale of the facility and type of activity (storage activities) may provide direct savings in construction cost(3).

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(1) Ahrens, D., Ellison, T. and Sterling, R.; "Earth-Sheltered Homes", P.34

(2) Konsowa, A., "The Architecture of The Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt", P.59

(3) Carmody, J., Sterling, R.; "Underground Space Design; A Guide to Subsurface Utilization and Design for People in Underground Spaces" P.33

II) Sale of Excavated Material or Minerals

If the underground facility is excavated in a geologic material with an economic value, the sale of this material can be used to offset excavation cost(1) .

III) Savings in Specialized Design Features

The physical characteristics of underground facilities can provide direct cost benefits when compared with a surface facility. For example, the thermal isolation of the ground reduces peak load demands for a facility's air conditioning system, enabling a smaller and thus less expensive system to be installed(2). Savings can also be made in other areas such as a reduction in need for external building cladding. Cladding or external finishes typically account for about 15% of a building's cost(3).

1-4-2-1 Operating Cost

I) Maintenance Costs

The physical isolation of underground structures from the external environmental effects - impact of temperature fluctuations, ultraviolet determination, and freeze-thaw damage - that deteriorate the building components can result in low maintenance costs for underground structures(4).

II) Energy Costs

The thermal advantages of underground buildings are usually translated into reduced energy costs to operate them. Although Ventilation and lighting costs may increase, thermal benefits outweigh these in moderate to

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(1) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 88.

(2) Golany, G.; "Earth-Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design", P.16

(3) Chow, F., Paul, T., Vähäaho, I., Sellberg, B., Lemos, L.; "Hidden Aspects of Urban Planning: Utilization of Underground Space", P.2

(4) Godard, J., Sterling, R.; "Geoeengineering considerations in the optimum use of underground space", P.10

server climates(1).

III) Replacement Costs

Underground structures last significantly longer than their surface counterparts. Above ground structures are generally much more susceptible to damage and deterioration. Good examples of the longevity of underground structures include the numerous railroad tunnels worldwide that have been in service for over 100 years.

1-4-3 Indirect Societal Benefits

These benefits may be important for large scale underground space use or the long term use of such space even though they may have negligible impact on an individual user.

1-4-3-1 Land Use Efficiency

The ability to place service and support facilities below grade and preserve the land surface for uses requiring the surface environment is an important benefit. It is also possible to improve existing land use problems through underground construction by placing existing facilities below grade and reclaiming the surface for other uses(2).

1-4-3-2 Energy Conservation

Beyond the immediate financial impact to a building user or developer, energy conservation has implications for national security, economic development, and the balance of trade. Those implications have a direct impact on the society and the standard of living.

1-4-3-3 Reduced Surface Disruption

The construction of new underground systems or facilities can be organized to disrupt the existing area less than equivalent surface construction. This is particularly true for

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(1) Golany, G.; "Earth-Sheltered Habitat: History, Architecture, and Urban Design", P.208

(2) Parker, H.; "Underground Space: Good for Sustainable Development and Vice Versa", P.4

facilities that can be excavated with only limited surface access. For example tunneled subway system construction interferes less and may only be noticeable at station locations(1).

1-4-3-4 Environmental and Aesthetics Issues

Underground space has important role to play in the achievement of environmentally friendly development, whether it be in the reduction of pollution or noise nuisance, the efficient use of space, the preservation of the living environment, public health or safety(2).

1-5 Contemporary Uses and Examples of Underground Spaces

The underground space was used from the beginning of history till the present day to satisfy a variety of needs. At first, it was used for shelter and storage and it was developed until it became used almost in every field of our lives. The reason for this vast spread of the use of the underground spaces is the recent technological developments in the construction field and the new materials used(3).

1-5-1 Residential Uses

Residential uses probably represent the oldest use of underground space by human kind. From our early ancestors till the energy crisis of the seventies, the earth-sheltered houses used were somehow primitive with the traditional plan (a central sunken courtyard surrounded by rooms). Afterwards, a variety of modifications and developments were applied to the plans and sections in order to consume much more renewable energy resources and less non-renewable energy resources(4). Historical residential use of underground spaces was

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(1) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 90

(2) Godard, J., Sterling, R.; "Geoeengineering considerations in the optimum use of underground space", P.6

(3) For more information on the underground space utilization worldwide refer to Appendix (A): "Underground Space Utilization"

(4) Ahrens, D., Ellison, T., and sterling, R.; "Earth-Sheltered Homes", P.15

reviewed earlier in this chapter. Today, most of the residential earth-sheltered structures built in the past twenty or thirty years have been single-family dwellings(1). Fig (1-16)(2) shows different modern examples for earth-sheltered dwellings.

Left: Clark house, Portland, Oregon. (Architect: Norm Clark)
Right: Seward town houses, Minneapolis, Minnesota. (Architect: Michael Dunn/Close Associates)

Fig (1-16): Different examples of modern earth-sheltered houses.

1-5-2 Religious Uses

Throughout history many of the underground spaces had been used due to a strong religious connotations while in other civilizations it is not clear if the religious significance attached to many underground uses and sites implies a special relationship of underground space with the spiritual essence of the religious activities. The preservation afforded by the underground location of religious artifacts found in caves, underground temples, or catacombs may provide a distorted impression of the relative importance of such spaces in everyday religious life in prior civilizations. Infact, the underground location of many religious sites may be due to practical considerations as the mystery of the netherworld(3). Carved images and paintings were better preserved underground, and the use of burial for preservation and sanitary reasons has contributed to religious connotations. Religious history has also been marked by many persecutions that caused religious sects literally to go underground to survive.

Despite the importance of these external pressures, there is

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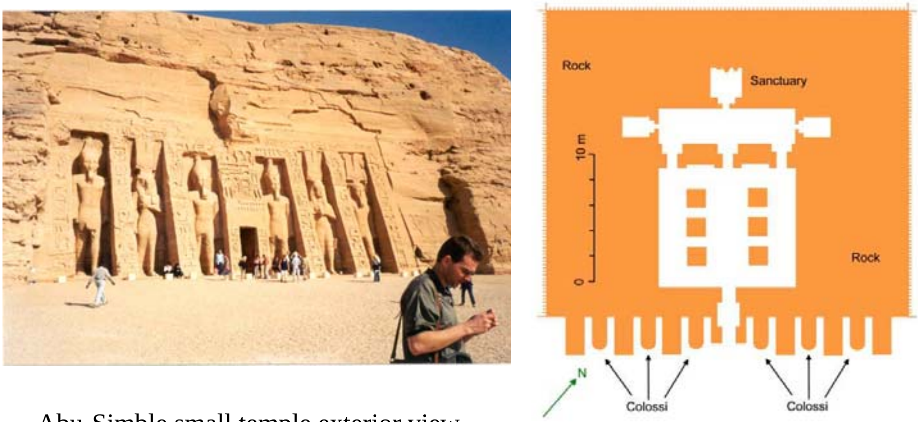
(1) Parker, H.; "Underground Space: Good for sustainable development, and vice versa", P. 9

(2) Ahrens, D., Ellison, T., and sterling, R.; "Earth-Sheltered Homes", P.38

(3) Konsowa, A.; "The Architecture of the Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt", P.16

still a special character of unadorned underground spaces - slient, dark, and somewhat forebiding - that provides a separation from the normal world and an opportunity for spiritual reflection.

Underground burial has been common in much of the ancient world. The Egyptian, Greek, Roman, and Chinese Civilizations all left behind important records of their civilizations attached to underground religious sites and tombs Fig (1-17). During the Roman empire, Roman gods were consulted at underground oracles, and persecuted christians hid underground and excavated the network of catacombs in Rome(1).



Abu-Simble small temple exterior view

Abu-Simble small temple plan

Fig (1-17): Abu-Simble small temple, Aswan, Egypt.

The rise of Buddhism in India and Southeast Asia led to the excavation and Carving of many rock-cut temples containing carved and painted Buddhist images. Some of the largest sites are the Thousand Buddha Caves in XinJiang Province in northwest China and the Ajanta and Ellora sites in India(2) Fig (1-18) (3).

Fig (1-18): Buddhist temples cut into the rock at Ellora, India.

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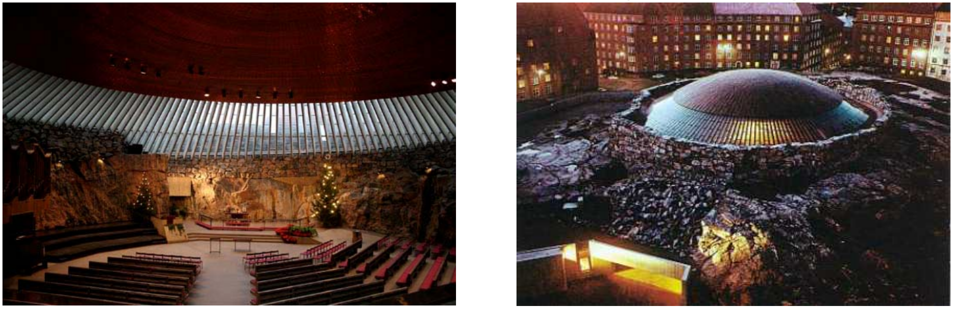
(1) Carmody, J., Sterling R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.76

(2) ibid

(3) ibid, P.76

Modern day underground churches do exist, but there are only a few examples. The Temppeliaukio church (also known as The Church in The Rock) in Helsinki, Finland, constructed in 1968–69, was built underground primarily for aesthetic reasons and to preserve the existing open space in Temppeliaukio Square near the city center(1) Fig (1-19).



Interior view Exterior view

Fig (1-19): The Temppeliauko church in the Rock, Helsinki, Finland.
(Architect: Timo and Tuomo Suomalainen)

1-5-3 Recreational Uses

1-5-3-1 Sports Facilities and Community Centers

Modern recreational facilities constructed in the underground principally include sports facilities and community centers. Many such facilities have been constructed in Scandinavia as dual–purpose facilities available for civil defense. The type of facilities in use includes: swimming pools, gymnasia, running tracks, ice hockey rings, and multipurpose facilities(2) Fig (1-20).

In china, another community use has been for amusement centers in cities and recreational areas. The city of Hanzhou, for example, has coffee shops, a dance hall, and many amusement rooms for children in various rock caverns. Auditoria and concert halls have also been built in rock caverns.

The inward focus of many sport courts and the enclosed nature of many sports facility buildings above ground make

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(1) http://www.ita-aites.org/cms/117.html # top

(2) Michael, M., "Architecture of the Underground Structures: The Influence of Underground Subways", P. 170

them a natural candidate for underground construction when surface space is limited. The principal limitations are related to the maximum clear spans possible in mined facilities in rock, and the cost of providing large clear spans in near-surface facilities in soil.

An increase in the number of recreational underground facilities is expected in crowded urban areas. This is especially so in developing cities, where the combination of increasing affluence and congestion creates demand for more sources of recreation.

Fig (1-20): Yates Field House entrance, George Washington University.
(Architect: Daniel F.Tully Associates)

1-5-3-2 Parks

Although at first a seeming oxymoron, cities with severe climates already have indoor spaces that function as public parks in inclement weather. In Edina, Minnesota, in the United States, a fully indoor city-operated public park is attached to senior citizen high-rise apartments to provide a snow-free, climate controlled park for wintertime use. Park facilities include an open playing area, an amphitheater, children’s playground, and a landscaped strolling area(1) .

1-5-4 Commercial and Institutional Uses

Commercial and institutional uses are relatively late developments in the history of underground space use. They are spurred most often by the constraints of high level prices, aesthetic considerations, or by an advantageous proximity to important existing facilities or large volumes of pedestrian traffic.

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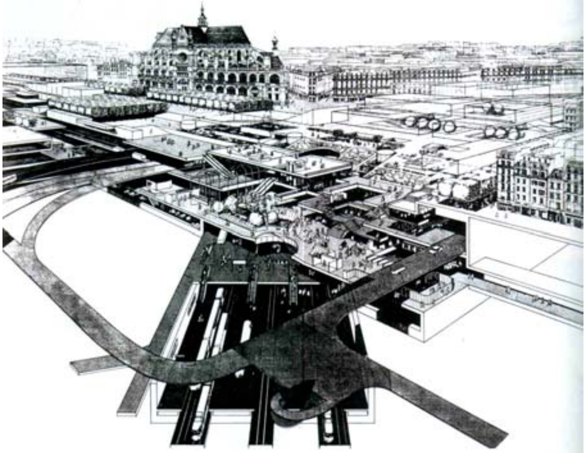
(1) Carmody, J., Sterling R.; “Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces”, P. 80

1-5-4-1 Integrated Urban Developments

Integrated underground commercial, institutional, and transportation centers have been proposed in several futuristic development concepts that will be reviewed later in this chapter.

One of the largest examples of an underground commercial and institutional complex connected to the urban transit system is the redevelopment of the "*Les Halles*" site in Paris Fig (1-21). This site was made available when the old "Halles" market was moved to Rungis. The complex covers 10,000 square meters while preserving most of the surface as a park surrounded by beautiful historic structures. Les Halles is notable for the density of systems and uses it contains. These include a major subway station, roadways, car parking facilities, a shopping arcade, and community recreational facilities including a swimming pool. This complex is an excellent model of enhancing the total human environment by utilizing underground space(1).



Above: Exterior view of "*Les Halles*" Complex, Paris, France.
Above Left: Interior view of "*Les Halles*" Complex, Paris, France
Left: Isometric section of the complex.

Fig (1-21): "*Les Halles*" Complex, Paris, France.
(Architect: Claude Vasconi and Georges Pencreac'h)

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(1) Konsowa, A.; "The Architecture of the Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt", P.135

1-5-4-2 Museums

Many of the old or historic museums were expanded by adding underground exhibition spaces to the existing buildings in order to sustain the increasing numbers of the visitors and monuments. New museums with exhibition spaces fully or partly below ground were constructed worldwide.

1-5-4-3 Libraries

Additions to existing above ground libraries may be placed underground to retain proximity to existing facilities to preserve the aesthetics of existing open spaces. Nowadays, new libraries are constructed totally or partly below ground. Examples of this type of buildings primarily include library additions on university campuses or urban sites(1). There are many examples of underground library facilities. Some notable examples are the Nathan Marsh Pusey Library built in the famous Harvard Yard at Harvard University in Cambridge, Massachusetts, the Radcliff Science Library at Oxford University, Oxford, U.K., and the New Alexandria, Alexandria, Egypt Fig (1-22).

Fig (1-22): The New Alexandria Library, Alexandria, Egypt showing the above and below ground sections
(Architect: Sonohita Group)

1-5-4-4 Office Buildings

Government buildings often must occupy a central position in a city and may be important symbols for the city or region.

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(1) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P.174

Additions to existing government buildings in historic settings are often placed largely underground to minimize their site impact (and sometimes for civil defense purposes)(1). The California State Office Building in Sacramento, California, USA, is an example of open space preservation on a central two-block site in the city as well as demonstration of energy conservation techniques.

1-5-4-5 Educational Institutions

Educational buildings are an important class of underground buildings. They are usually shallow cut-and-cover structures to facilitate fire exit requirements and in most cases they are designed to provide low energy consumption and retain play areas on the roof of the building(2). The Wildwood School in Aspen, Colorado, USA, was designed to provide an intriguing, naturalistic learning environment for elementary children Fig (1-23).

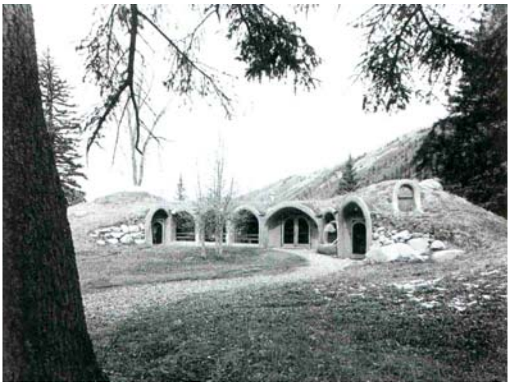

Fig (1-23): Wildwood Elementary School, Aspen, Colorado, U.S.A.
(Architect: David F. Gibson and William N. Gardner, Associated Architects)

The Civil and Mineral Engineering Building at the University of Minnesota, was built in response to the lack of open space on campus and the severe Minnesota climate, demonstrates the potential for mined space development(3). The 15,000 square meter building houses classrooms, offices, and research laboratories Fig (1-24).

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(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.85

(2) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P.178

(3) Jankowski, W.; "The Best of lighting Design", P.214

Fig (1-24): The Civil and Mineral Engineering Building, University of Minnesota.
(Architect: David J. Bennett)

1-5-4-6 Special Use Facilities

Some unusual special-purpose facilities constructed underground includes convention centers Fig (1-25), exhibition spaces, prisons, national research facilities, medical facilities, and emergency response facilities.

Fig (1-25): George R. Moscone Convention Center, San Francisco, California.
(Architect: Hellmuth, Obata, and Kassabaum)

1-5-4-7 Parking

Parking is a common use of underground facilities in major urban areas. The need to place parking adjacent to activity sites without spoiling the above ground environment often forces an underground solution even when the costs of underground parking are several times that of a surface parking.

1-5-5 Industrial Facilities

There are three principal reasons why industrial facilities may be placed underground: first protection, second special attributes of the underground environment, and third use of available or low-cost underground space(1) i.e the use of natural caves. During World War II many industrial facilities were moved underground either to escape aerial detection or to provide protection from bombing.

In addition to protection, there are other potential special attributes available underground that are favorable for certain kinds of development. These include a stable thermal environment, a typically lower vibration level than surface sites, close control of ventilation air and low infiltration levels, and the high security offered(2) Fig (1-26).

Above left: Use of underground factories and ware houses to improve land use in Kansas City, Missouri(3).

Above right: Holaday Circuits headquarters and factory, Hopkins, Minnesota. (Architect: David J. Bennett).

Fig (1-26): Different industrial uses of underground buildings.

Many uses of underground spaces for industrial purposes are most effective if the space has been designed specially to accommodate the nature of the industrial process. Reducing the aboveground height of the building by full or partial placement underground can significantly ease placement of facilities in sensitive locations.

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(1) Chow, F., Paul, T., Vähäaho, I., Sellberg, B., and Linos F.; "Hidden Aspects of Urban Planning: Utilization of Underground Space", P. 3

(2) Konsowa, A.; "The Architecture of the Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt" P. 118

(3) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.89

1-5-6 Military and Civil Defense Facilities

Security, defense, and military uses have always been associated with the use of the underground. Underground facilities can provide a secure refuge with limited points of entry and protection from bombing. The nuclear age brought new demands for defense protection and for the ability to provide a sure retaliation against an initial attack. Explosion and fallout shelters have been developed around the world to provide a measure of protection against this threat, but the nature and extent of the development has varied widely from country to country(1) Fig (1-27).

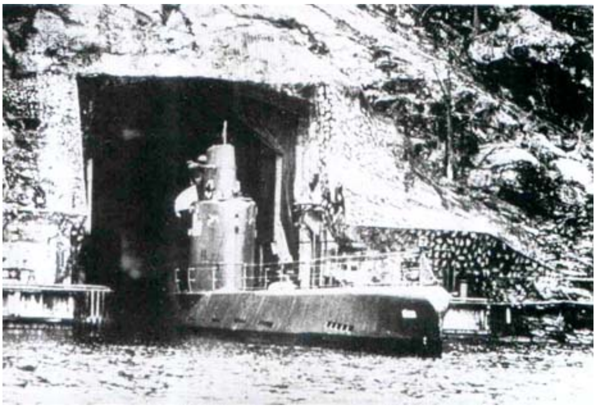

Fig (1-27): Swedish submarine base constructed in a rock cavern(2).

Civil defense uses include the creation of underground telecommunication centers, underground national archives, underground oil storage caverns, and public shelter facilities that have dual-purposes (security and defense and community purposes).

More specific military underground facilities include missile silos, underground submarine bases, ammunition stores, and a wide variety of specialized facilities. The protection afforded and the difficulty of detecting military hardware or facilities underground makes such facilities desirable.

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(1) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P.184

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.91

1-5-7 Storage

Underground cellars and bins of limited scale have been used for centuries to safely store food and other goods. This may be one of the best and least expensive ways to improve the quality of life in rural areas and in the least developed countries⁽¹⁾ Fig (1-28)⁽²⁾.

Fig (1-28): Unloading of "**Matmora**" a traditional grain storage pit in Morocco.

The problems of underground bulk storage have always been the difficulty in grain handling during emptying, and the prevention of groundwater infiltration that could damage the grain Fig. (1-29)⁽³⁾.

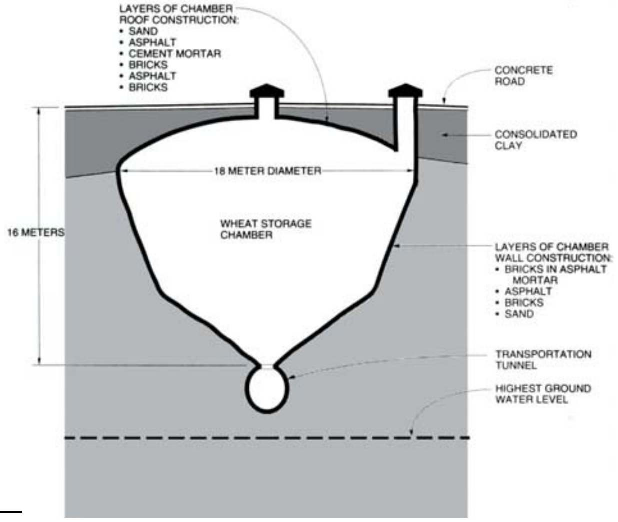

Fig (1-29): An underground wheat storage facility in China with a capacity of 1500 tons.

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(1) Parker, H.; "Underground Space: Good for Sustainable Development, and Vice Versa", P.8

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.93

(3) ibid, P.92

Underground spaces can be used to store oil and gas. Oil and gas are critical elements in the fuel supply of all industrialized countries, both economically and military. Many of the largest stores have been constructed underground in recent years due to a lower coast, higher security, and a reduced potential for environmental damage(1) Fig (1-30)(2).

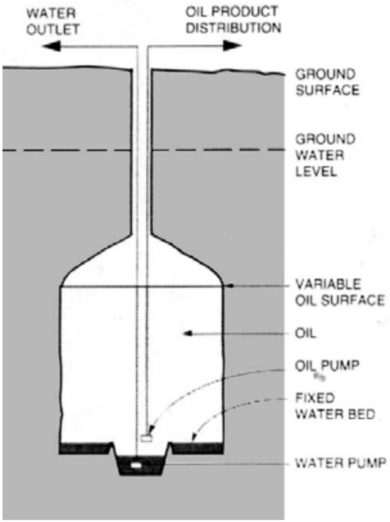

Fig (1-30): Section of oil storage cavern in the rock. The surrounding groundwater forms a barrier that prevents the oil from leaking out into the rock joints

Finally, many countries and large companies pay great attention to the secure storage of archival records and essential operating records for continued functioning in case of natural disaster or act of war.

1-5-8 Transportation

Underground space has long been important to the development and advancement of transportation systems. Transportation underground space uses are principally in the form of tunnels for canals, railways, subways, or roads. Tunnels provide convenient routes past natural and artificial obstacles for a variety of transportation and utility purposes. Other transportation components, such as transit stations, can also be placed underground(3) Fig (1-31).

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(1) Michael, M.; “Architecture of the Underground Structures: The Influence of Underground Subways”, P. 188

(2) Carmody, J., Sterling, R.; “Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces”, P.94

(3) Parker, H.; “Underground Space: Good for Sustainable Development, and Vice Versa”, P. 10

Fig (1-31): Bilbao metro line2 underground subway station
(Architect: Norman Foster)

The earliest evidence of tunneling dates from about 15,000 years ago. With development of gun powder in the 1600s, the speed of tunneling in rock increased greatly and permitted a wider range of uses. The rise of rail road systems in 1800s necessitated a large increase in tunneling activity to reduce route lengths. As cities have expanded, tunnels have been used for urban transportation systems such as subways, motor traffic tunnels, and utility tunnels(1). The first subway line opened in London in 1863. Not all transportation related uses are tunnels. Less visible underground transportation facilities may include facilities for ventilation, emergency rescue, equipment servicing, or system control.

1-5-9 Utility Services

The use of underground space for urban utility systems is by far the most extensive use of the underground. Although utility systems are a relatively recent development in the history of humankind, life in developed areas today would be unthinkable without them(2). The ancient Babylonians constructed water supply tunnels in about 2500 B.C. in the Indus Valley, and the Romans had a well developed water supply system and sewage disposal system. A long period of neglect followed in almost all parts of the world except for the provision of water supply. Until the 1800s sewer systems in urban areas consisted principally of open ditches,

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(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.97

(2) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 189

but since this time utility systems have developed rapidly in urban areas around the world. Some utility tunnels today combine several services, and are termed “Utilidors”(1).

Nowadays, underground utility services include: water supply and sewerage treatment, waste disposal, Energy product and storage, and Mining.

1-6 Underground Space Classification

In the study of underground space utilization, it is useful to develop a classification scheme that provides an organizational basis for description, analysis, and research. Classification allows the most important attributes of an object to be described in a manner that others can understand without detailed examination. It allows objects to be grouped into similar classes so that the characteristics of the subgroups can be studied. Finally, it allows new objects to be readily fit into the context of prior knowledge.

The difficulty in approaching this issue for underground space is that the uses are very broad and major categorization may be desired from several different aspects. For example, uses range from utilities to churches, projects range from microtones to vast mining operations, and spaces range in size from the pore spaces in soil to city wide tunnel systems. Also a wide variety of practitioners are also involved - architects, planners, and several engineering specialists each with different design parameters. For example, “deep” underground space to an architect may be any space more than 8 to 10 stories (~ 30 meters) below grade, where as deep underground space to a mining engineer may not be reaches until depths exceed 1000 meters.

Table (1-1) gives the major classification groupings chosen for underground space use: function, geometry, origin, site features, and project features. The major subcategories are listed under each category. These subcategories further organize the way underground uses are descried.

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(1) Parker, H.; “Underground Space: Good for Sustainable Development, and Vice Versa”, P.13

Major Grouping	Major subcategories
Function	Residential Non- Residential Infrastructure Military
Geometry	Fenestration / Relation to surface Depth Dimensions Scale of project
Origin	Natural Mined (Man Made)
Site Features	Geography Climate Land use Ground conditions Building relationship with other elements
Project features	Design Contraction Age

Table (1-1): Major classification groupings of underground space use

1-6-1 Classification by Function

One of the important categories when classifying the underground space is the function. This major category (function), according to the previously detailed mentioned uses, is further divided into two subcategories: people-oriented and product-oriented uses. The division of the subcategories helps in determining the design approach. Design for people-oriented spaces will not be successful unless human acceptance factors are considered. For product-oriented uses, such factors are less important than satisfying the proper functional requirements, but they may still have an impact on the efficiency and well being of any personnel operating or servicing the facility(1). The major functions together with the subcategories are illustrated in Table (1-2).

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(1) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 3

Major functions	**Subcategories of Use**	
	People-oriented uses	**Product-oriented uses**
Residential	Single-family Multifamily	
Non- Residential	Religious Recreational Institutional Commercial	Industrial Parking Storage Agriculture
Infrastructure	Transportation of people	Transportation of goods Utilities Energy Mines
Military	Civil defense	Military facilities

Table (1-2): Classification of underground space use by function

1-6-2 Classification by Geometry

The geometrical data is important in organizing underground space uses. It include the fenestrations of the underground space and its relation with the surface of the earth, depth, project size, and the building type and its geographical extent.

1-6-2-1 Fenestration Types

The classification of the underground space according to the fenestration type is very useful in determining the means of admitting daylighting and natural ventilation into the space. The fenestration arrangements include the chamber type, the courtyard type, the elevational type, and the penetrational type(1) Fig (1-32).

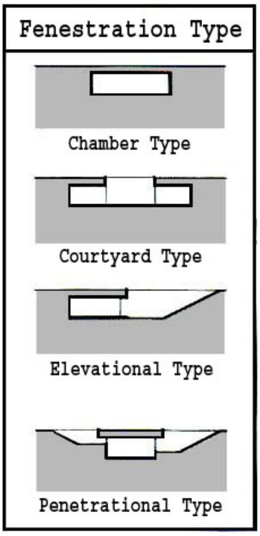

Fig (1-32): Classification by fenestration type

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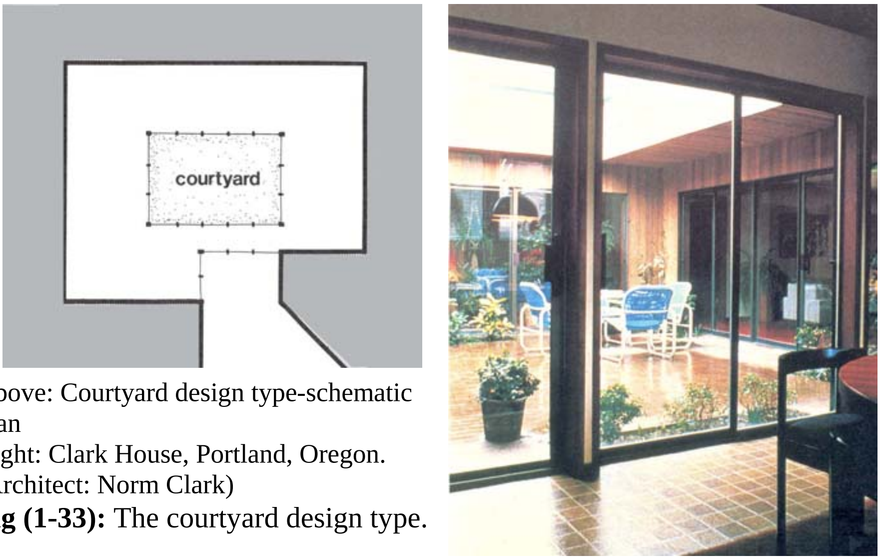
(1) Moore, F.; “Environment Control Systems: Heating, Cooling, and Lighting”, P.213

I) *The Chamber Type*

This type of buildings is completely sunken into the earth without any widows. The only access to the outside is the entrance point. It has good insulation properties and a very poor natural environment.

II) *The Courtyard Type*

In this type, the building has a central courtyard or atrium. The court serves as the focus of the building and in some cases the entry into the structure. The windows and glass doors that are opened on the atrium provide daylighting, solar heat, outside views, and access via a stairway from the ground level[1] Fig.(1-33).



Above: Courtyard design type-schematic plan
Right: Clark House, Portland, Oregon. (Architect: Norm Clark)
Fig (1-33): The courtyard design type.

III) *The Elevational Type*

This type of buildings has a roof covered with earth and the building is surrounded by earth except for one of its walls. This wall has openings, probably to a view and with the preferable orientation for passive-solar purposes for which this type is ideal. This type is particularly appropriate for colder climates thus the exposed elevation preferably faces the south. In the plan distribution it is found

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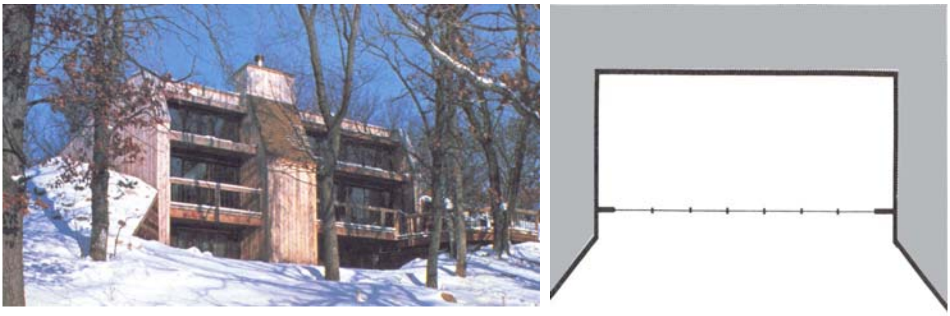
[1] The National Renewable energy laboratory(NREL), Department of Energy Efficiency and Renewable Energy "Earth Sheltered Houses",[www.eere.energy.gov.]

that the major living or working spaces are placed along the exposed elevation and secondary spaces not requiring windows are located to the rear of the building. Skylights or light monitors can be added to admit more light and allow natural ventilation of the back spaces(1) Fig (1-34).



Burnsville House, Burnsville, Minnesota (Architect: John Carmody and Tom Ellison)

The elevation design type (Schematic plan)

Fig (1-34): The elevational design type.

IV) The Penetrational Type

This type of buildings has openings to more than one elevation of the building. Of all the types of earth-covered buildings, this is the least energy-efficient type unless special provisions such as double-glazing to doors and windows, or shutters, are used to conserve thermal energy. However, if windows are used all around, the internal spaces would not need skylights and ventilation occurs naturally In fact, this is the closest type to conventional buildings(2).

1-6-2-2 Relation of the Underground Building to the Surface

The relation of the underground building with the surface depends on the special considerations of the building function and the site nature which can be divided into two kinds: Flat sites and Hillside sites. The relation of the building to surface can be in one of the following forms: Subgrade, Bermed with an earth cover, Bermed with no earth cover, and Hillside. Fig (1-35) illustrates a classification of the basic relationships of the building to the ground surface.

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(1) Ahrens, D., Ellison, T., and Sterling, R.; "Earth-Sheltered Homes", P. 12

(2) Michael, M.; "Architecture of the Underground Structures: The Influence of Underground Subways", P. 8

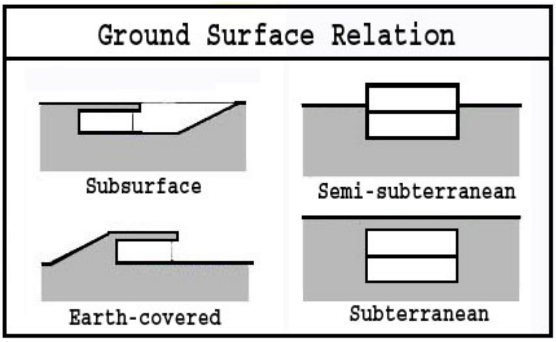

Fig (1-35): Classification according to ground-surface relationship

1-6-2-3 Depth

The differences in physical depth associated with the terms shallow and deep are based on the differences in perspectives of the practitioners in their respective design fields. Table (1-3) illustrates the different uses of terminology associated with the depth of underground facilities(1).

Term	**Typical Range of Depth Implied According to Use (Meters)**			
	Local Utilities	**Buildings**	**Regional Utilities Urban Transit**	**Mines**
Shallow/Near Surface	0-2	0-10	0-10	0-100
Moderate Depth	2-4	10-30	10-50	100-1000
Deep	more than 4	more than 30	more than 50	more than 1000

Table (1-3): Classification of underground space by depth.

1-6-2-4 Project Size

The size of the project may be important from two principal aspects. First, the size of the individual spaces in terms of access and clear spans is important in terms of structural / geological design and the construction systems used. The other aspect that may be important is the scale of the project in terms of overall size and complexity (i.e. small or large scale projects). Projects of a large scale

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(1) Carmody, J., Sterling, R., "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.50

require major public or private investments, may have considerable societal impacts, and present much more difficult administrative problems than small projects(1).

1-6-2-5 Building Type and the Geographical Extent

It is useful to classify underground uses by scale based on the area or volume of a building and its geographical extent. For example, a regional building type, such as cave dwellings in China, may be very small projects individually, but when large numbers exist in a region it may be useful to treat the use as a single entity to examine local or regional impacts(2). Table (1-4) classifies underground uses by both their general function and the description of scale.

General function	Description of scale
Residential	Single family Small multifamily Large multifamily Settlement Widespread regional building type
Non-Residential	Small Storage or working chamber Medium Sized building scale Large Building scale Block Scale District scale
Infrastructure (Utilities, Tunnels, and Mines)	Block scale District scale City scale Regional scale National scale

Table (1-4): Classification of underground space by scale of use.

1-6-3 Origin

Under origin, natural spaces are separated from spaces excavated for mining, military, or civil purposes. Mixed uses, adaptations, or reuses are also possible to identify.

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(1) Michael, M., "Architecture of the Underground Structures: The Influence of Underground Subways", P. 13

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.50

1-6-4 Site Features

Classification by site features allows the collection of data concerning a wide range of factors that may affect the design of an underground facility. From those factors are economic, cultural, topographic, or climatic setting; local land use issues; and the ground conditions present.

1-6-5 Project Features

The remaining grouping of project features allows the classification of underground space by project design features, construction features, or relationships to existing facilities. Such classification permits projects with similar features to be identified for comparison. For instance, in occupied underground buildings, special natural lighting concepts may be of interest. In tunnels, the interest may lie in the type of excavating equipment used. Classification by age separates modern uses from vernacular traditional uses and historically recorded uses(1).

1-7 The Future of Underground Space Development

Although existing underground facilities throughout the world provide some models for future development, they are limited in scale, in use, or in their lack of a comprehensive vision for the total city environment. As a complement to more detailed planning and research studies, it is useful to examine the visions of extensive underground complex, even entire cities that have been proposed by futuristic planners and designers.

1-7-1 Utopian Underground Proposals

Visionary underground networks of space have been proposed as a comprehensive solution to congestion and environmental problems in many urban areas. In Paris, a multilevel underground city containing many functions and systems beneath the Seine River was envisioned in the 1960s Fig (1-36). This concept was used to promote the eventual Les Halles development in Paris, France.

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(1) ibid, P.52

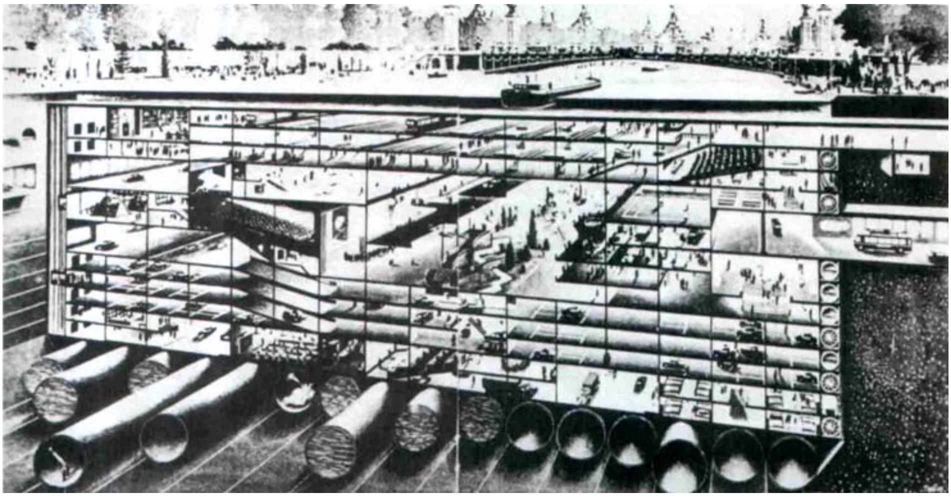

Fig (1-36): Concept for the development beneath the Seine River in Paris, France.

The unique geology in the Minneapolis–St.Paul area, in the United States, has led to several proposals since 1970 envisioning a complete layer of underground space beneath the existing city. Under the congested University of Minnesota underground space at a depth of 30 meters could contain parking, transit, library archives, laboratories, service delivery, district heating, and utilities[1] Fig. (1-37).

Fig (1-37): Concept for the underground development at the University of Minnesota. (Drawing John Carmody)

When completely new cities are envisioned for the future, the underground often is a major component, as illustrated by the work of the architect Paolo Soleri over the last 40 years. in his sketches, future cities often are depicted as self-contained, climate controlled, and units frequently located underground for protection from the elements and

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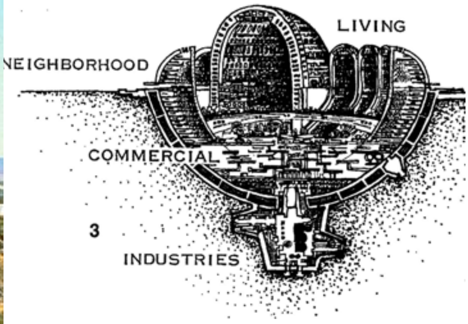
[1] ibid, P.21

possibly from a hazardous or polluted environment(1) Fig(1-38) - Fig(1-39)



The Arcosanti project, Phoenix
(Architect: Paolo Soleri)

Paolo Soleri's sketch for the residential and commercial zones in the NovanoahII imaginary city

Right: Paolo Soleri's sketch for the industrial and agricultural zones in NovanoahII imaginary city.

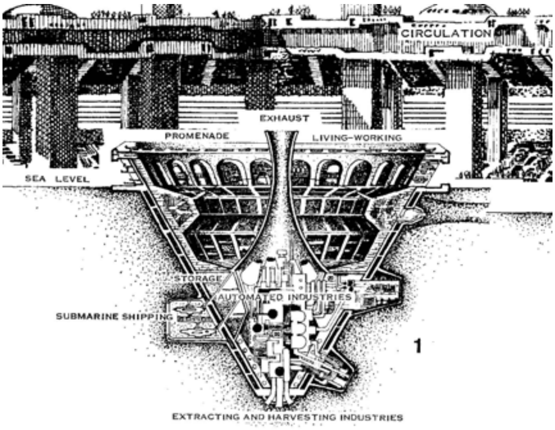
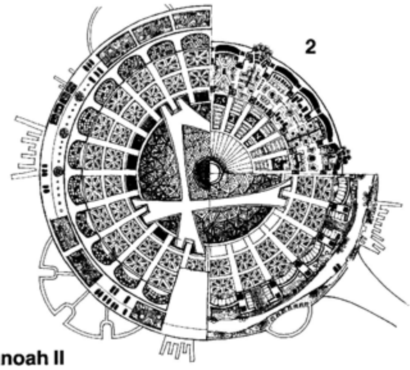


Fig (1-38): Paolo soleri's sketches and works.



2.Novanoah II

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(1) Soleri, P.; "The City in The Image of Man", P.37

Fig (1-39): Paolo Soleri’s “*Hyper Building*”
(In this proposal Soleri collected all the functions of the city in a single building and called it The Hyper Building).

1-7-2 The Fourth Wave of Underground Space Utilization

- In the human history, the development of the underground space utilization has passed through several waves. In the early human history, people lived in caves and caverns to avoid the harsh climate and the attacks of wild animals. This can be seen as the first tidal wave.
- During the industrial revolution in the 19th Century, along with the urbanization movement, local engineering facilities as drainage and water supply were buried under the ground, the metros were constructed (1863 in London), and in connection to the mines tunnels were built. This marked the coming of the second tidal wave in the development of underground space(1). The military protective engineering and the hydroelectric plants were also quickly developed in this wave.
- The sign of the third wave is the relocation of some

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(1) Konsowa, A.; “The Architecture of the Underground Buildings: An Analytical Study of Buildings in The Underground and Its Ability to be used in Egypt”, P. 234

human activities from the surface to the underground. Those activities include underground parking facilities, cultural and sports facilities such as exhibition halls, gymnasiums, swimming pools and ice rings halls.

- In the last ten years of the 20th century, the working out of the sustainable development strategy in the Untied Nations and all countries of the world and the continues awareness of environmental protection and resources conservation have lead to the appearance and the development of the fourth wave in the underground space utilization(1). The sign of the fourth wave is to protect the urban environment and natural ecological environment. The waves for construction and utilization of underground space have come forth one by one. Instead of replacing or excluding one another they developed and consummated one another more and more. The construction of underground public utilities and metro in the second wave still develop at a higher level in the third and fourth waves. The construction of underground car parks and various cultural and gymnastic facilities in the third wave still goes on in the fourth wave and in more and more cities worldwide. In the last 30 years, great progresses have been made in tunneling and excavating in hard rock and complicated geological conditions. The hardness of the rock has become a positive factor to the underground engineering instead of being a negative factor. It helps to increase the spans of underground structures and the rock mass can withstand higher speed tunneling and excavating.
- Since the 1990's the location and orientation technology represented by laser orientation and GPS location, the underground survey technique represented by remote sensing and geology radar and the auto control construction

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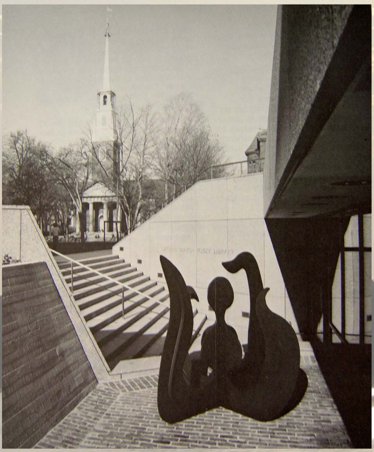
(1) Godard, J., Sterling, R.; "Geoengineering Considerations in the Optimum Use of Underground Space", P. 15

technique for underground tunneling and construction are all applied in the practical engineering to some extent. In addition to the previous, many modifications and developments have been applied to the design of the underground spaces -especially in the field of daylighting and ventilation. Nowadays, solar and fiber optics are used to deliver daylighting to the deep underground spaces. All this makes the fourth wave in development and utilization of the underground space move far and wide in a higher level.

1-8 Conclusions

Underground buildings have been used since the beginning of history. They can take many forms and can be divided into natural or man-made spaces. Throughout history, they were used in all regions of the world most notably in China, Tunisia, Turkey, Egypt, and many other regions. Underground spaces have much potential that can be classified as physical, societal, and economical. It is considered to be a worldwide solution for many above ground problems. Contemporary uses of such spaces include: residential, religious, recreational, commercial, educational, industrial, and many other uses. Classification of underground spaces can be handled from many different points of view. They can be classified according to their function, geometry, origin, site features, and project features. In this thesis, classification of the underground spaces according to their function and geometry is the main interest. Classification by function can be subdivided into people or product-oriented uses which gives an indication of how strong the daylight is related to the underground spaces. Classification by geometry has many subcategories and the ones influencing the main theme of this thesis are: the fenestration types (courtyard, chamber, elevation, and penetration), the relation of the underground space to the surface (semi-subterranean, subsurface, and subterranean), and finally the depth of the space from the surface (shallow, moderate, and deep). Understanding and using the previously mentioned classifications helps in determining which of the daylighting concepts, discussed later in the thesis, is to be used to daylight the underground spaces.

Chapter (2)
Introducing Daylighting Into Underground Buildings



Chapter (2)

Introducing Daylighting To Underground Spaces

2-1 Introduction

While daylighting is only one of many considerations in the interior design of a building, it takes on a fundamental and multifaceted importance in the design of underground spaces. Associations with darkness are frequent in underground imagery and lack of windows and natural light are among the most commonly cited drawbacks of below-grade facilities. If underground spaces are designed to be positive, healthy environment for people, then natural lighting will play a significant role. Light is the medium for all visual experience and thus is integral to creating perceptions of spaciousness, providing definition and character in spaces, as well as simply providing light to facilitate the performance of activities and tasks.

In the design of underground environments, providing natural light may fundamentally shape the entire building layout. Using certain methods for daylighting the underground spaces, such as creating naturally lighted sunken courtyards or atria, may be the major organizing principles of the facility. On the other hand, it simply may not be possible to provide natural light to deep isolated spaces by conventional means thus using innovative daylighting concepts is the only solution.

This chapter focuses on introducing daylighting to underground spaces by means of courtyards and atria. At first, daylighting is defined; its history in architecture, and its characteristics and benefits are reviewed. Then the courtyard and the atrium, traditional methods of admitting daylighting to underground spaces, are studied in detail and analyzed. This chapter highlights some key areas: the potentials of courtyards and atria, their shape and geometry, their orientation to the sun, the reflectance of their floor and walls, and the penetration of daylighting into adjoining spaces. Finally, world wide contemporary examples, using the courtyard and atria, are reviewed and analyzed in order to use such concepts with their full potentials in the near future.

2-2 Daylighting: Definition, Components, History and Benefits

2-2-1 Daylighting Definition

"Any light that the sun produces and strikes the earth directly, indirectly, or both is daylight"(1). This includes sunlight (direct from the solar disc), skylight (whether clear or partly cloudy).

The sun is the origin of all daylight Fig (2-1). Direct radiation comes from the sun which emits 63 million watt of power per square meter of its surface area (this is equivalent to approximately 6 thousand million lumens). It takes the light from the sun just over 8 minutes to reach the earth. Traveling in a vacuum at 3 x 10^8 m/s this equates to a distance of 150 million kilometers. This light either reflects off, absorbed by or refracts through the atmosphere(2). The fraction that refracts through the atmosphere reaches the ground directly as sunlight or is diffused by the atmosphere as skylight. The diffuse skylight is produced by light that is scattered by particulates in the atmosphere. Due to the Rayleigh scattering by air molecules, the red end of the visible spectrum with longer wavelengths is scattered more and blue is scattered less so the sky appears blue.

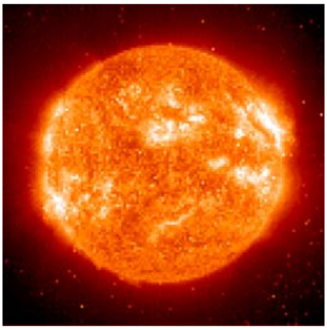


Fig (2-1): The sun
The only source of
all daylight

Visible light is a natural phenomenon that stimulates the sense of sight in the form of radiation from the sun, fire or artificial source. Humans need visible light to see. There is more, however, to the electromagnetic (EM) spectrum than just the visible light Fig (2-2). Three

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(1) Steffy, G.; "Architectural Lighting Design", P.99

(2) Ashely, J., "Modification of Atrium Design to Improve Thermal and Daylighting Performance", P. 40

sections make up what is known as the solar spectrum and are called Ultraviolet, Visible, and Infrared Table (2-1). Radiation from each section has different advantages including their effects upon humans.

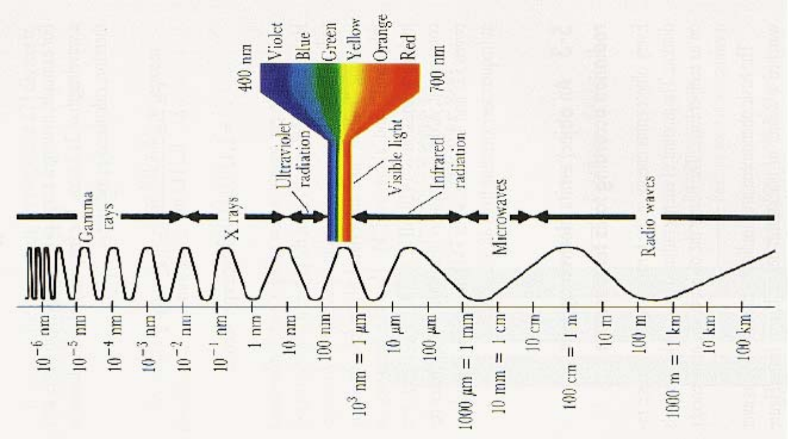

Fig (2-2): EM wave spectrum: Gamma rays, X-rays, Ultraviolet, Visible, Infrared, Micro, and Radio(1).

Optical radiation	100nm(2) to 1mm
Ultraviolet radiation (UV)	100nm to 400 nm
Short wave (UV-C)	100nm to 280 nm
Middle wave (UV-B)	280nm to 315 mm
Long wave (UV-A)	315nm to 400 nm
Visible radiation	400nm to 700 nm
Infrared Radiation (IR)	700nm to 1mm
Short wave (IR-A)	700nm to 1.4 µm(3)
Middle-wave (IR-B)	1.4 µm to 3 µm
Long-wave (IR-C)	3 µm to 1 mm

Table (2-1): Designation of wavelength bands(4).

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(1) ibid, P.37

(2) The nanometer is equivalent to 1x10^{-9} meter (i.e. one billionth of a meter).

(3) The micrometer is equivalent to 1x10^{-6} meter.

(4) Ruck, N.; "Building Design and Human Performance", P.44

The Ultraviolet (UV) spectrum can be divided into three areas known as UV-A, UV-B, and UV-C. Most of UV-C radiation is absorbed by the ozone layer of the atmosphere. UV-B radiation is harmful and causes skin cancer. UV-A radiation causes sun reddening(1).

The Visible spectrum can be divided into seven main color regions: Indigo, violet, blue, green, yellow, orange and red. The sensitivity of our sight peaks at 555 nm, which is in the middle of the visible spectrum.

The Infrared spectrum also has a number of divisions including the near, medium, and far infrared. This radiation spreads out over a large range of wavelengths. All objects reradiate heat energy in the infrared range of the spectrum. People need an adequate amount of light to perform any prescribed task. The more precise the task, the more light is needed.

2-2-2 Daylight Components

The daylight available on the interior of the building is dependent on several factors including:

- The amount of daylight available outside which is dependant on the site’s latitude, the sun’s azimuth angle and cloud cover percent.
- The size of the window opening.
- The orientation of the window.
- The reflectance of the materials inside the space, and
- The location and reflectance of any exterior obstructions

The daylight reaching any point inside the space consists of three main components: the sky component (SC), the external reflected component (ERC), and the internal reflected component (IRC) Fig (2-3).

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(1) ibid

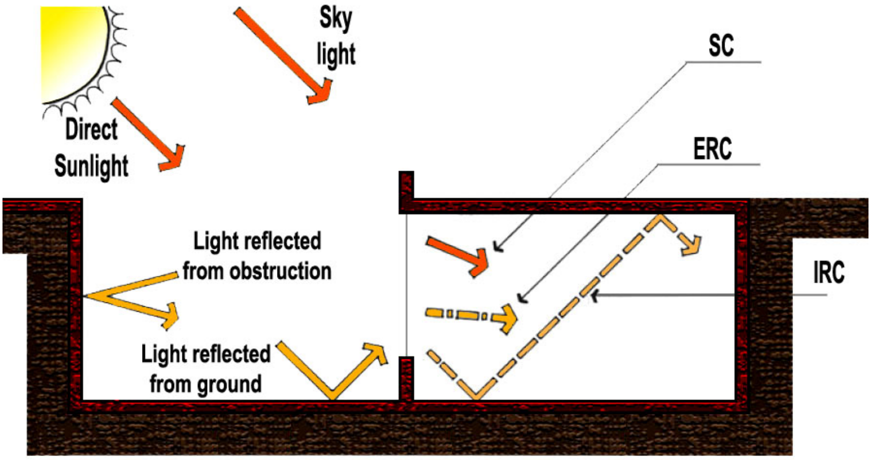

Fig (2-3): The daylight components showing the SC, ERC, and IRC.

The Sky Component (***SC***) is that portion of the total daylight at a point, which is received directly from the areas of the sky visible through the aperture. Total illumination is determined by latitude, sky condition and orientation.

The External Reflected Component (***ERC***) is that light reflected from exterior obstructions on the point under consideration. Size of the obstruction and its reflectance are factors in determining illumination from this source.

The Internal Reflected Component (***IRC***) is the light received at the point under consideration that has been reflected from interior surfaces. The interior reflected component is further subdivided into reflected skylight and reflected ground light.

2-2-3 Daylight History in Architecture

Light and architecture have been profoundly related since the beginning of time. This relationship, beginning with the light emanating from the hearth and the cave dwelling, has comprised a deeper and much more integral interdependence than is frequently understood. Light and its expression through the architecture of a particular time and place have represented the philosophy of a specific society, geographic location, as well as the deeper beliefs of a society as a whole(1).

Inspiring examples of this expressive treatment of light are plentiful, and span the history of the built environment. In Ancient Egypt, the worship of the sun and the power of its illumination inspired the design of the Egyptian temple as well as other building types(2). In their temple design the orientation, axial path, processional movement from dark to light and the location of the sanctuary all dealt with the movement and availability of sunlight Fig (2-4).

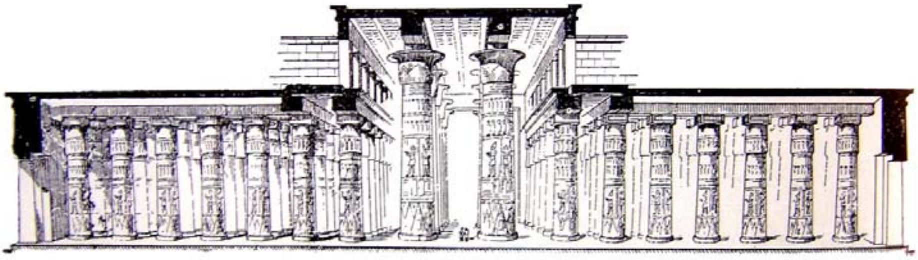

Fig (2-4): The temple of Amon at Karnak (1500 BC)
The use of daylight through monitors to define the temple axial path.

The Parthenon is an appropriate example to study the Greek treatment of light and architecture Fig (2-5). The temple is oriented towards the east, to relate directly to the first, rejuvenating light of day. The Parthenon’s sharp contours and details, mouldings, cornices and fluting were all designed to be read in the strong Mediterranean light, and to create emphatic shadows.

Fig (2-5): The Parthenon, Athens, Greece (438B.C.)
(Architects: Iktinos and Kallikrates)

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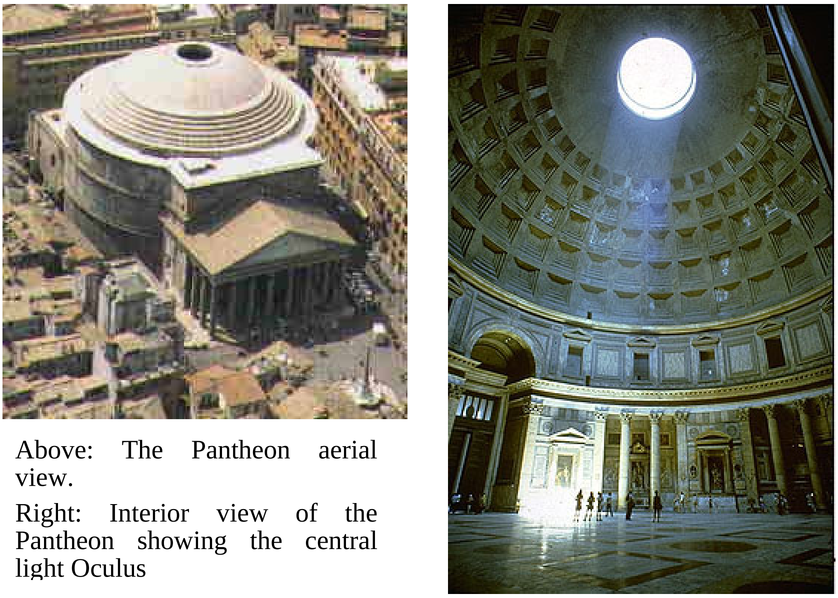
(1) Brogan, J.; “Light in Architecture”, P. 6
(2) ibid

The Roman Pantheon, with its central oculus, is a further example from the ancient world illustrating how the Romans used light to enhance and articulate space. They utilized light so that as sunlight moved through the space it would highlight the figures and statues presented along the Pantheon's drum(1) Fig (2-6).



Above: The Pantheon aerial view.

Right: Interior view of the Pantheon showing the central light Oculus

Fig (2-6): The Pantheon, Rome, Italy.
(Constructed 27 B.C. by Marcus Vipsanius Agrippa, rebuilt 118-128 by Hadrian)
(Architect: Unknown)

Gothic architecture is primarily a result of the quest for maximum window area. Only small windows were possible when a barrel vault rested on a bearing wall. The Roman groin vault supplanted the barrel vault partly because it allowed large windows in the vaulted spaces Fig (2-7). Gothic groin vaulting with flying buttresses provided a skeleton construction that allowed the use of very large windows(2) Fig (2-8).

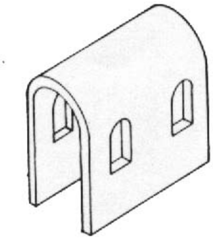


Fig (2-7): Romanesque barrel vault.

Few windows were possible in the massive bearing walls required to support the Romanesque barrel vault.

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(1) ibid

(2) Lechner, N.; "Heating, Cooling, lighting: Design Methods for Architects", P. 307

Fig (2-8): Notre Dame Cathedral, Paris, France. (1163-1250)
(Architect: Maurice de Sully)
Groin vaulting and Flying buttresses allowed Gothic cathedrals to have windows where there had been walls

Large numerous windows were a dominant characteristic of the Renaissance architecture. Windows dominated the facade, especially in regions with cloudy climates. Bay windows became very popular. Although the facades of such Renaissance palaces were designed to give the impression of great massive structures, their E-and H-shaped floor plans provided for their ventilation and daylight requirements. As a matter of fact, such shapes were typical of floor plans for most buildings until the twentieth century(1) Fig (2-9).

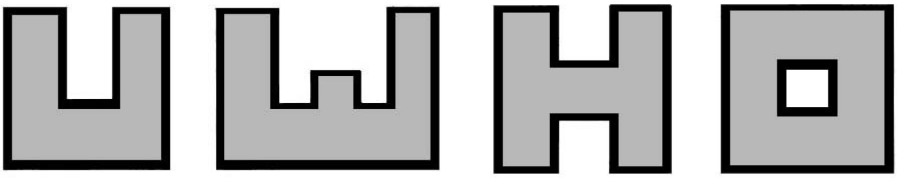

Fig (2-9): Common floor plans for larger buildings prior to the twentieth century (because of the need for natural light and ventilation).

During the nineteenth century, all glass buildings became possible because of the increased availability glass combined with the new ways of using iron for structures. The Crystal Palace by Paxton is the most famous example Fig (2-10). In England laws that tried to ensure access to daylight date back as far as the year 1189.

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(1) ibid

Fig (2-10): The Crystal Palace, London, England (1851)(1).
(Architect: Joseph Paxton)

As seen above, from the Ancient Egyptian architecture and passing by the Roman groin vault until reaching the Crystal Palace of the nineteenth century, all the major structural changes in buildings reflected the goals of increasing the amount of light that entered the buildings. Because artificial lighting had been both poor and expensive until then, thus buildings had been designed to make full use of daylight.

The industrial revolution brought with it cheap sources of electricity, as thought of it at that time, so the interest in using daylighting demolished and the use of artificial lighting gained interest(2). It wasn't until the energy crisis of the seventies when the world interest in the daylighting arouse once more. From that date researches were conducted to make sure of the full use of daylighting in architecture and other fields of our daily life.

2-2-4 Daylight Benefits

A well thought out building designed with daylighting in mind can have a number of significant benefits for building owners and occupants. These benefits can be summarized as follows:

2-2-4-1 Health

Daylight is one of many important environmental health factors. As a result, medical researches continue to explore the tangible and intangible effects of daylight on the human body and mind(3). Physiological conditions associated with insufficient daylight range from rickets, jaundice, and osteoporosis to more elusive conditions

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(1) http://www.uic.edu/

(2) Lechner, N.; "Heating, Cooling, lighting: Design Methods for Architects", P. 312

(3) Phillips, D.; "Lighting Modern Buildings", P.18

such as seasonal affective disorder (*SAD*). Other health issues directly or indirectly related to visual comfort and the qualities of light in the built environment include building-related illness (*BRI*) and sick building syndrome (*SBS*)(1).

2-2-4-2 Visual Comfort

Lighting quality refers to visual performance, visual comfort, and ease of seeing. Daylight provides the highest quality light source for visual tasks because it is a full spectrum source of visible light. It enhances the color and visual appearance of objects and helps users to see small detail better. Building occupants generally prefer a well daylit space, provided that attention is paid to problems of glare and overheating(2).

2-2-4-3 View

Daylight provides a connection to the natural world. Natural light, through the slow continuous motion of the sum and the periodic influence of clouds, provides relief from monotony and information about the weather and time of day(3). A sense of time and orientation often impacts the occupants of the space. The variety in the quality and quantity of daylight also helps in keeping occupants alert.

2-2-4-4 Sustainability and Energy

Daylighting is the primary source of light in the buildings during the working hours. The use of daylighting reduces energy consumption and participates in the building sustainability process. The synthesis of a properly daylit space and well-controlled artificial lighting system can produce a favorable environment for the occupants.

2-3 Daylighting the Underground Spaces

Daylighting differs from other environmental services in that it is a fundamental element of architecture, while electric lighting or

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(1) Guzowski, M.; "Daylighting for Sustainable Design", P.291

(2) Ruck, N.; "Building Design and Human Performance",P.47

(3) Guzowski, M.; "Day lighting for Sustainable Design", P. 5

mechanical heating and cooling systems are add-on services that architects can hand over to the building services engineer(1).

Many factors affect daylight penetration into an interior space. These include the depth of the room, the size and location of the fenestration, the glazing system and external obstructions. These factors usually depend on decisions made at the initial design stage of the building. A well daylight building can often provide sufficient natural illumination for general activities for the greater part of the day, and adequate working lighting for a substantial part of the year. It is also important to avoid problems such as glare and overheating, which may stem from excessive direct daylighting and appropriate shading devices should be provided.

2-3-1 Design Objectives Related to Daylighting the Underground Spaces

The key design problems related to lighting in underground buildings are(2):

1- Windowless spaces lack the stimulation and connection with nature provided by outside views and sunlight. Conventional uniform, overhead artificial lighting contributes further to a monotonous interior environment.

2- Because there are no windows, there can be a sense of confinement underground.

3- Underground space is often associated with darkness and coldness.

4- Most artificial lighting lacks the characteristics of sunlight, which raises physiological concerns in environments without any natural light.

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(1) ibid,P.4

(2) Carmody, J., sterling, R; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 261

From the above lighting design problems, the design objectives related to lighting the underground spaces can be concluded as follow(1):

1- Provide appropriate levels of illumination to enhance visual clarity and facilitate all activities. Spaces should be well lighted to offset associations with darkness underground.

2- Provide natural light whenever possible.

3- Design artificial lighting systems to supplement natural light and not to replace it.

4- Use lighting to enhance feelings of spaciousness.

5- Use lighting to create a stimulating, varied environment. Lighting patterns should help define and reinforce social spaces.

2-3-2 Methods for Daylighting the Underground Spaces

There are different methods used to admit daylighting into the underground spaces. These methods depend on the characteristics of the underground space. For example, the relation of the underground space to the surface whether it is semi-subterranean, subsurface, or subterranean space. Other characteristics include the size of the space, the scale of the project, and technical aspects regarding the construction of the space(2).

The methods for daylighting the underground space include traditional and innovative daylighting systems. Traditional methods include courtyards, atria, and top-lighting concepts(3) Fig (2-11). Innovative daylighting systems include active or passive heliostats, light pipes, and daylighting fiber optics systems.

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(1) ibid, P. 268

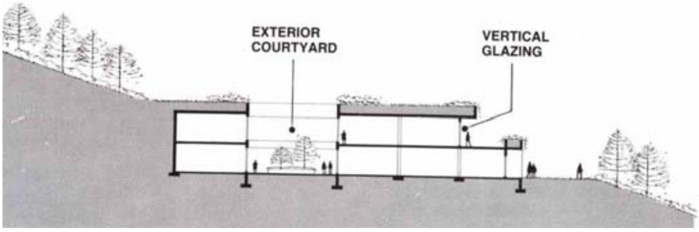
(2) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures",P.54

(3) ibid,P.54

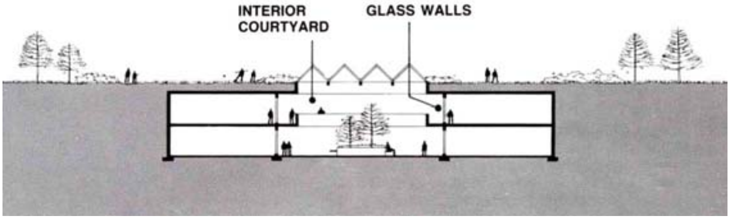
The underground spaces are divided into shallow and deep spaces. Shallow spaces include earth-covered or earth-sheltered, semi-subterranean, and subsurface. Deep spaces include subterranean spaces.

The courtyard and the top-lighting concepts are used to daylight shallow underground spaces while the atrium and innovative systems are used to daylight mainly deep spaces but they can also be used to daylight shallow spaces.

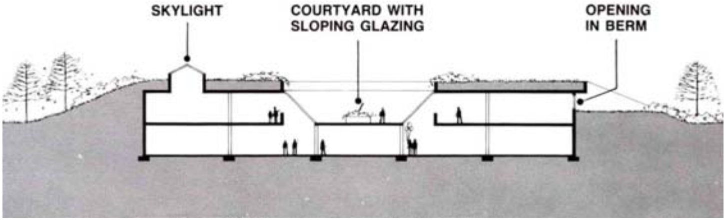
This chapter reviews the courtyard and the atrium as traditional methods for daylighting the shallow and deep underground spaces. The other methods and systems are discussed later in the following chapters.



The Courtyard concept



The Atrium concept



The Top-lighting concept

Fig (2-11): Traditional daylighting methods for different kinds of underground buildings(1).

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(1) ibid

2-4 Courtyards: A Traditional Concept for Daylighting Shallow Underground Spaces

2-4-1 Courtyard: Definition, History, and Evolution.

A courtyard is a space within a building or between buildings that is open to the sky. It is largely or wholly surrounded by the buildings(1).

Courtyards are special places that are outside yet almost inside, usually in contact with the earth, but surrounded by spaces. The courtyard is closely related to its surrounding spaces, serving them as both a conduit and a filter of daylight. A courtyard is often the most beautiful place in a building. As seen in the history of architecture, courtyards do not belong to a certain time or place and are not related to a specific culture or civilization. In other words, courtyards were born with the beginning of architecture.

There are courtyards in many parts of the world, in varying climates, in differing cultures(2). The courtyard is at least as old as the Ancient Civilizations (Egyptian, Greek, and Roman), and this building type was used for housing throughout the ancient Mideast. In China courtyard houses abound. In the colder north, courtyards are larger (to admit winter sun), in the warmer south, courtyards are smaller (to exclude summer sun). Pit dwellings utilize central courtyard to bring light and air to underground housing, with cultivated field above. There are buildings clustered around courtyards in rural Japan, Europe, Africa, and America. Contemporary architects incorporate courtyards when a semi-controlled outdoor space is appropriate(3).

2-4-2 Courtyard Potentials

Sunken exterior courtyards provide numerous benefits for people in near surface underground buildings. In terms of orientation

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(1) Aizlewood, M.; "The Daylighting of Atria: A Critical Review", P. 841

(2) Golany, G.; "Earth-Sheltered Dwellings in Tunisia: Ancient Lessons for Modern Design",P.117

(3) Golany, G.; "Earth-Sheltered Habitat: History, Architecture, and Urban Design", P.115

within an underground facility, courtyards provide a visual connection between surface and subsurface. If the dimensions of courtyard are sufficient, landmarks such as surface buildings may be seen from below. In addition, the courtyard itself is usually such an amenity and is so distinct from the other windowless areas of the building that it becomes a major landmark that aids in orientation(1). Their beauty, accessibility and social centrality within their buildings add enormously to their appeal. At their best, courtyards are exquisite landscapes, worthy centers of attention and activity within a building(2). At their worst courtyards are meager holes in buildings, concerned solely with the technical role of bringing light and air down to spaces below(3).

While courtyards bring nature within a building, they also moderate nature's extremes. They are rarely as hot at summer's mid-afternoon, or as cold just before dawn, as the temperatures in the countryside, or even in the street outside.

There is one last advantage inherent in the geometry of courtyards. While the opposite wall obstructs the sky dome, it also obstructs low angle direct sunlight, reducing glare problems(4).

2-4-3 Daylighting Analysis in Courtyards

Several characteristics are addressed in the daylighting analysis of the courtyard. These characteristics include: the courtyard orientation to the sun, the shape and geometrical proportion of the courtyard, the reflectivity of the floor and walls, and the daylight penetration in the adjoining spaces.

2-4-3-1 The Courtyard Orientation to the Sun

The sun is influential for both people and plants in courtyards; which side receives direct sun and at what time of day determines where and when maximum daylight and optimum thermal

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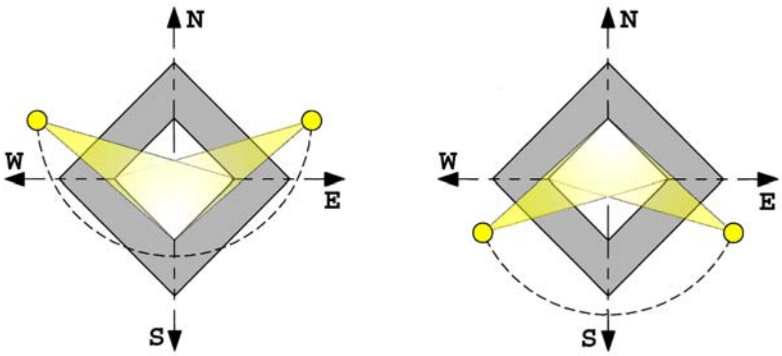
(1) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P. 54.

(2) Achi, A.; "Design Criteria for Courtyards in the Architecture of the Arab world", P. 120

(3) Reynolds, J.; "Courtyards: Aesthetic, Social, and Thermal Delight", P, IX

(4) Moore, F.; "Environmental control systems: Heating Cooling Lighting", P. 314

comfort is available. In older cities, with no grid pattern of streets, there is a huge variety of courtyard orientations. In newer grided cities, the streets - and thus courtyards - are usually either oriented to the cardinal points (north-south, east-west) or set at about 45 degree off the cardinal points. The result of 45 degree orientation is a democratic distribution of sunlight on the facades through the year. At summer solstice, morning sun fills the northeast–facing walls; evening sun fills the northwest–facing walls. At winter solstice, morning sun fills the southeast–facing walls; evening sun fills the southwest–facing(1) Fig (2-12).



Summer solstice Winter solstice

Fig (2-12): Summer and winter solstice

Courtyards oriented to the cardinal compass points, for the rectangular but non-square courtyard, those that are elongate east-west have their longer sides face north and south. At these orientations, direct sun in summer can be prevented from entering the longer sides with shallow overhangs. The shorter sides, however, get strong direct sun across the length of the courtyard in the morning or evening Fig (2-13). In winter, when strong sun is welcome, it is almost absent Fig (2-15).

When plans elongated north-south, the longer walls face east-west. There are difficulties with summer sun in morning or afternoon, but one long wall partially shades the other at the earliest and latest hours. Meanwhile the shorter side gets direct sun across the length

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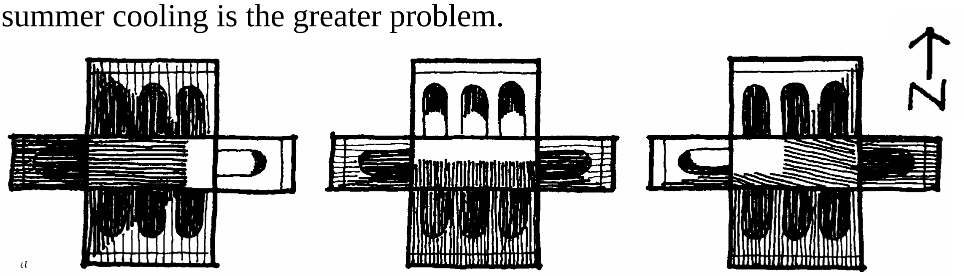
(1) Reynolds, J.; “Courtyards: Aesthetic, Social, and Thermal Delight”, P.11

of the courtyard around noon Fig (2-14). Again winter sun is welcome, and in the hours near noon, some walls receive its warmth[1] Fig (2-16).

Thus, the optimum orientation depends on which functions inhabit the long or short sides, and whether winter heating or summer cooling is the greater problem.

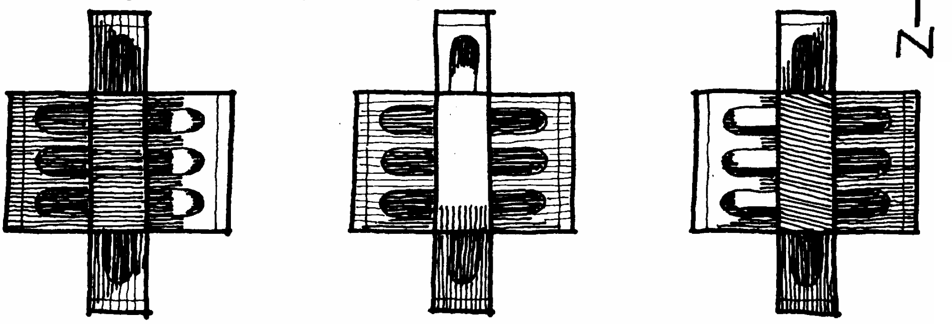


4PM: About 3/4 of the floor is in shadow. The sun, due west, just grazes the north and south faces, leaving their arcades in shadow. The sun fully illuminates the short east face and its arcade.

NOON: Half the courtyard floor is in sun, and the north face is fully illuminated. But the high sun angle leaves much of the north face's arcade in shadow. (The sun, due south, is just grazing the east and west faces).

9 AM: About 3/4 of the floor is in shadow. The sun just grazes the north face, leaving its arcade in shadow. But sun fully illuminates the short west face and its arcade.

Fig (2-13): Courtyard elongated east-west shadow in summer.



4PM: The floor is in shadow. The sun due west, just grazes the short north and south faces, leaving their arcades in shadow. The sun illuminates about half the long east façade and its arcade.

Noon: About 4/5 of the courtyard floor is in sun, and the short north face is fully illuminated. But the high sun angle leaves much of the north face's arcade in shadow. (The sun, due south, is just grazing the long east and west faces, leaving their arcades in shadow).

9AM: The floor is in shadow. The sun just grazes the short north face, leaving its arcade in shadow. But sun illuminates almost all the long west face and its arcade.

Fig (2-14): Courtyard elongated north-south shadow in summer.

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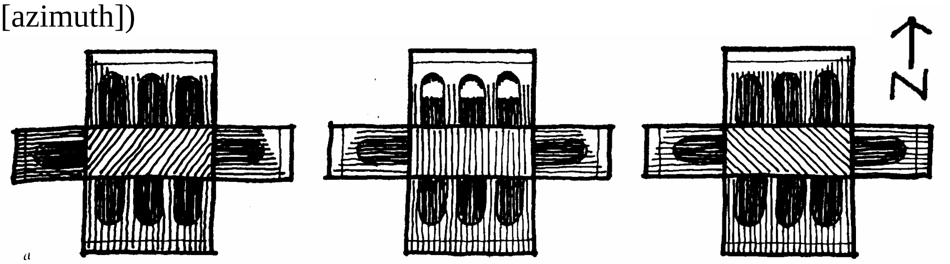
(1) ibid

In Fig (2-13) and Fig (2-14) courtyards orientation and shadow in summer are compared. On July 21, rectangular courtyards elongated east-west are compared to those elongated north-south at (sun time) 9 AM, Noon, and 4 PM (about an hour past the hottest time of day) at 36 degree north latitude. July is the time of the hottest temperatures, when sun is an enemy. (The shadow lines on the courtyard floor show the sun's direction [azimuth])

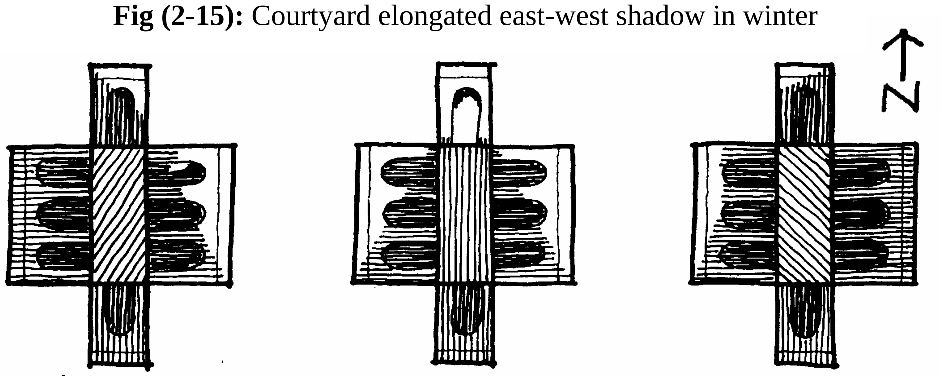


2PM: The sun hits just above the top of the arches of the long north face, and the upper corner of the short east face. All else is in shadow.

Noon: Most of the courtyard surfaces are in shadow. The sun only grazes the top of the short east and west faces. The long north face is about half illuminated, with some penetration into the arcade (at about eye level).

9AM: Almost all is in shadow. The sun only illuminates the top of the short west face and the long north face.

Fig (2-15): Courtyard elongated east-west shadow in winter



2PM: The sun penetrates more than halfway down the wall in the northeast corner of the courtyard, with a small patch of sun in that corner of both the arcades of the north and east faces. All else is in shadow.

Noon: The courtyard floor is in shadow, except for the very back of the short north arcade. The sun only grazes the top of the long east and west faces. The short north face is almost fully illuminated, with deep penetration into the arcade.

9AM: Almost all is in shadow. The sun only illuminates the top of the short north face and strikes the long west face just above the top of the arches.

Fig (2-16): Courtyard elongated north-south shadow in winter

In Fig (2-15) and Fig (2-16) courtyards orientation and shadow in winter are compared. On December 21, rectangular courtyards elongated east-west are compared to those elongated north-south at (sun time) 9 AM, NOON, and 2 PM (about an hour before the warmest time of day) at 36 degree north latitude. December is the time of the coldest temperatures, when sun is a friend. (Note: the shadow lines on the courtyard floor show the sun's direction).

2-4-3-2 Courtyard Shape and Geometry

The size, form, and depth of the court determine the amount of daylight available in the court(1).To determine an appropriate size for a courtyard, the designer must examine its intended functions. If the courtyard is intended to be the central amenity and image of the facility then maximizing its size is a priority. On the other hand, if the only purpose is visual relief by permitting the eyes to focus at infinity, then a minimum width of 5 meters is adequate. Finally, if the purpose of the courtyard is to bring sunlight into the building, then local sun angles must be calculated to determine the degree to which sunlight will actually penetrate the courtyard(2).

Courtyard types can be divided into:

1- Two-sided courtyards

In this case, the court is surrounded from two sides by the building while the other two sides can be defined by plants, fence, or any vertical elements Fig (2-17).

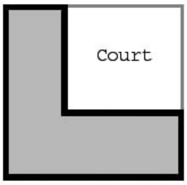


Fig (2-17): Two-sided court schematic plan.

2- Three-sided courtyards

In this case, the building surrounds the court from three directions while the fourth direction is defined by any vertical elements Fig (2-18).

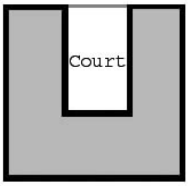


Fig (2-18): Three-sided court schematic plan.

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(1) Golany, G.; "Earth-Sheltered Habitat: History, Architecture, and Urban Design", P.116

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P 205

3- Four-sided courtyards

The court, in this case, is in the core of the project which means that it is surrounded from its four directions by the building Fig (2-19).

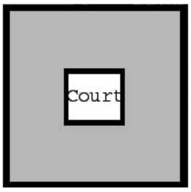


Fig (2-19): Four-sided court schematic plan.

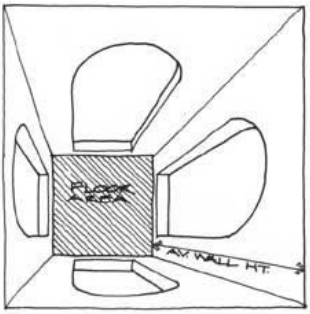
If the form of the courtyard can be entirely independent of the size and shape of the site, then the designer's first task is to determine its proportions: Length, Width, and Height. The choice of deeper or more shallow court is fundamental and affects the courtyard's social role (introverted or extroverted), technical performance (deeper means cooler and darker), and aesthetics (sunny or shady). In general, one large courtyard is better than two smaller ones. If sun penetration into the adjoining spaces is desirable then the court should be wide and not too deep. On the other hand, small, deep courts minimize daylight penetration(1). The design of the courtyard proportions leads to studying two important proportions: the courtyard aspect ratio and the solar shadow index (*SSI*)(2).

A- Courtyard Aspect Ratio

The aspect ratio, or degree of openness to the sky, is an important consideration when designing a courtyard for daylighting Fig (2-20).

$$\text{Aspect Ratio} = \frac{\text{Area of the courtyard floor}}{(\text{Average height of surrounding walls})^{2}}$$

Fig (2-20): Aspect ratio nomenclature sketch.



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(1) Golany, G.; "Earth-Sheltered Habitat: History, Architecture, and Urban Design", P.116

(2) Oikos, Green Building Source; "Courtyard Characteristics: Exposure", [http://oikos.com/]

The greater the aspect ratio, the more exposed is the courtyard to the sky⁽¹⁾. This exposure allows efficient daylighting to adjacent spaces, heating by the sun by day, cooling by radiation to the cold sky by night, and some entry to the wind. Table (2-2) illustrates the expected Daylight Factor in adjacent spaces and its relation with the courtyard aspect ratio (in case of light–colored courtyard walls).

Aspect Ratio	**DF Adjacent Space**
5	4.0 %
4	3.8 %
3	3.5 %
2	3.0 %
1	2.1 %

Table (2-2): Relation between the courtyard aspect ratio and the DF in adjacent spaces (for light–colored courtyard walls) (2)

B- Solar Shadow Index (SSI)

Although aspect ratio is an indicator of sun penetration, the SSI deals with winter sun exposure and compares north south floor width to the south wall's height(3) Fig (2-21)

$$\text{Solar shadow Index} = \frac{\text{South wall height}}{\text{North-south floor width}}$$

In general, the smaller the courtyard's floor area, the higher the solar shadow Index. The Greater the *SSI*, the deeper the well formed by the courtyard, and the less winter sun that reaches the floor, or even the north wall, of the courtyard(4).

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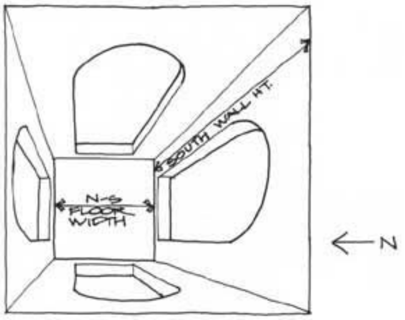
(1) Reynolds, J.; "Courtyards: Aesthetic, Social, and Thermal Delight", P.111

(2) ibid

(3) ibid, P.112

(4) Oikos, Green Building Source; "Courtyard Characteristics: Exposure", [http://oikos.com/]

Fig (2-21): Solar shadow index nomenclature sketch.



2-4-3-3 Courtyard Walls and Floor Surface Reflectance

The courtyard admits, absorbs, and reflects daylight according to its proportions and surface colors. When the courtyard floor is very light in color, a substantial amount of reflected light is cast onto the walls and ceilings of the adjoining spaces. Light-colored courtyard surfaces diffuse daylight in the court better(1). On the other hand white walls quickly become a glare source when direct sun strikes them because they are directly in one's field of vision.

Despite of their attractive appeal and aesthetics, any planting used in the courtyard reduce the amount of daylighting reaching the floor which in its turn decrease the daylighting factor in the adjacent spaces. Thus careful planning should be given to the use of plants in the courtyard.

2-4-3-4 Daylighting in Spaces Adjoining the Courtyard

The daylighting in the adjoining spaces consists of three components: the sky component, the external reflected component, and the internal reflected component. Thus special attention should be given to these three components.

Because daylight coincides with the sun's heat, rooms in colder climates benefit from higher daylight factors while rooms in hotter climates are often content with lower daylight factors.

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(1) Reynolds, J.; "Courtyards: Aesthetic, Social, and Thermal Delight", P. 181

Recommended daylight factor for specific tasks are shown in Table (2-3)(1).

Task	**DF**	
	Ample winter daylight (nearer equator)	**Scarce winter daylight (nearer pole)**
Ordinary seeing tasks, such as reading, filing, and easy office work.	1.5%	2.5%
Moderately difficult tasks, such as prolonged reading, stenographic work, normal machine tool work	2.5%	4.0%
Difficult, prolonged tasks, such as drafting, proofreading poor copy, fine machine work, and fine inspection.	4.0%	8.0%

Table (2-3): Recommended daylight factors

In Plan, a typical proportion for the spaces that adjoin the courtyard is three times as wide as the depth(2) Fig (2-22). In this arrangement, daylight from the courtyard can fill the space more evenly. Obviously, this limits the number of such ideal spaces that can face the courtyard.

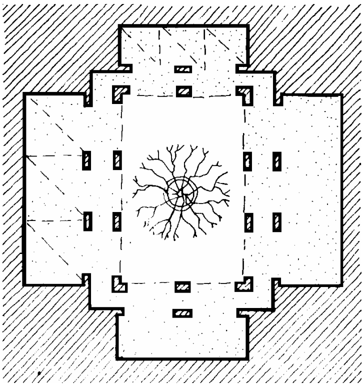

Fig (2-22): Typical adjoining spaces proportions (Schematic plan)

For even distribution of daylight, preferred proportions of a space adjacent to a courtyard are 3:1 (length along courtyard: depth to rear wall).

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(1) ibid, P. 179

(2) ibid, P. 178

In section the higher the top of the window above the floor the deeper the daylight penetration into the space, and the larger the window relative to the floor area the higher the daylight factor Fig (2-23). The diagram in Fig (2-23) is based on the assumption that, at a distance into a room that exceeds 2.5 times the height (H) of the daylight opening, there will be so little daylight relative to the daylight Just inside the opening that electric light will probably be routinely used. In courtyard building with arcades, this 2.5 H distance must be measured from the face of the arcade at the courtyard edge. Clearly, the arcade intercepts daylight that would other wise serve the room beyond(1).

For the floor area within the 2.5 H zone the DF are as follows:

$$DF_{av} = \frac{(0.2)\ \text{window area}}{\text{Floor area}}$$

$$DF_{min} = \frac{(0.1)\ \text{window area}}{\text{Floor area}}$$

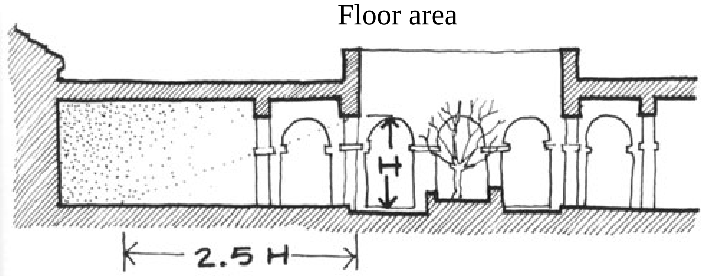

Fig (2-23): Daylight penetration from windows openings on courtyard.

2-5 Atria: A Traditional Concept for Daylighting Deep Underground Buildings.

2-5-1 Atrium: Definition, History, and Evolution.

Atria are central courts with glazed roof and are considered part of the building to which they are attached(2). They allow daylight penetration deep into the core of the building and provide pleasant spaces

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(1) Reynolds, J.; "Courtyards: Aesthetics, Social, and Thermal Delight", P. 179.

(2) Aizlewood, M.; "The Daylighting of Atria: A Critical Review", P. 841.

for users(1). Atria that are too small to be useful spaces are known as light wells. The amount of light available at the base of the atrium depends on a number of factors: the translucency of the atrium roof, the reflectance of the atrium walls, and the geometry of the atrium (depth versus width)(2).

Originally atriums were open central courts that allowed light into the interior of the ancient Roman and Greek houses(3). The buildings were of a defensive style with thick closed off outside walls, so the interior courtyard provided a private and open area.

In medieval ages, a second storey was added with a view down to the court floor. Protection from some of the weather was then added to the second storey with the use of overhangs.

The 19th century brought the industrial revolution with the great advances in iron and glass manufacturing techniques. Courtyards could then have glazing overhead, eliminating some of the weather elements from the space and giving birth to the modern atrium. The atrium style lost its popularity for two thirds of the 20th century due to the development of artificial lighting and the cheapness of the energy that powers this lighting(4). During 1973 energy crisis, fuel prices skyrocketed resulting in resurgence in energy efficient architecture and the popularity of atrium style buildings was recaptured.

Today, central atria are used in modern buildings including office buildings, shopping malls, hotels, and underground buildings Fig (2-24). These atria are built in the form of large spaces with glazed roof that allow occupants access to the positive aspects of the environment including the natural light, space and vegetation without the extremes of the external climatic conditions(5).

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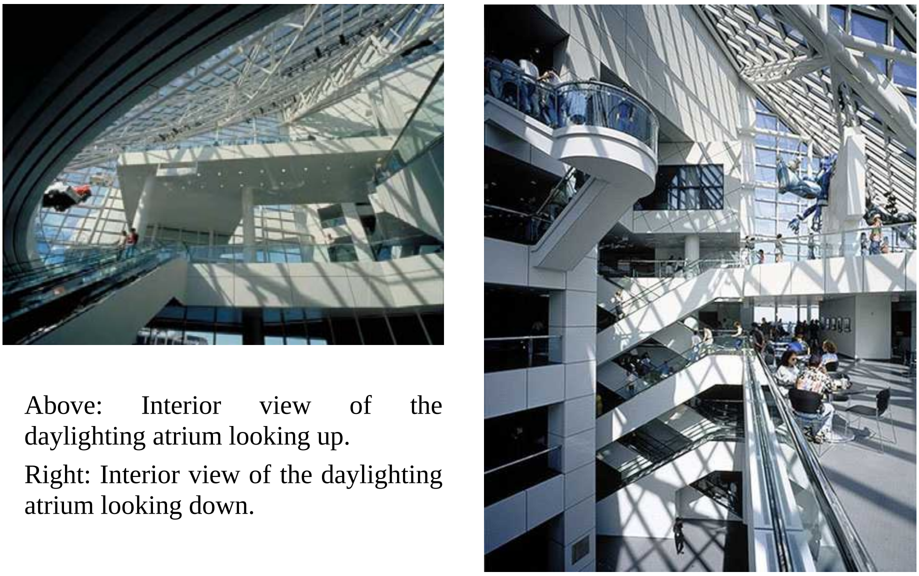
(1) CADDET; "Saving Energy with Daylighting Systems", P.8. [*http://www.caddet-ee.org*.]

(2) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.320

(3) Salem, D.; "The Study of Natural Lighting in the Atrium Buildings within the Local Environment Level to Reach the Optimum Performance by the Aid of Computer",P.3

(4) Saxon, R.; "Atrium Buildings: Development and Design", P.73

(5) Ashley, J.; "Modification of Atrium Design to Improve Thermal and Daylighting Performance", P.14



Above: Interior view of the daylighting atrium looking up.

Right: Interior view of the daylighting atrium looking down.

Fig (2-24): Rock and Roll Hall of Fame and Museum, Cleveland, Ohio.

(Architect: I M Pei)

(The Rock and Roll Hall of Fame and Museum consists of two parts: an above ground main hall and a semi-subterranean museum space. The site's change of grade was maximized to place the bulk of the museum underground and create a controlled environment for its highly interactive installations)

2-5-2 Atrium Potentials

The atrium has been a very popular style of buildings. It admits natural light, connects the adjoining spaces with the outside world, and creates a meeting point between people; in other words it becomes the focal point of trade and human activities; increasing the qualitative value of the indoor spaces. Moreover, the possibilities of having natural light enter the spaces are important assets(1).

An atrium not only provides quality daylight to spaces adjacent to it, but also acts as an environmental buffer zone between the exterior and interior(2). Covered atria have the same daylighting benefits

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(1) Calcagni, B., Paroncini, M.; "Daylighting Factor Prediction in Atria Building Designs", P.669

(2) Boubekri, M.; "The Energy Conservation Potential of Daylighting in a Four-Sided Atrium: A Simplified Calculation Procedure", P.165

as an open courtyard but greatly improved thermal qualities⁽¹⁾. In above ground buildings atria can be used to maximize the reduction of artificial lighting but careful planning is needed in the design to achieve this. While atria are designed for many reasons in aboveground buildings, this style of buildings, the atrium style, can be beneficial for energy efficiency and psychological reasons in underground buildings.

Atrium glazing allows the occupants to view the sky and therefore have a connection to the external environment. The difficulty in designing an atrium is to avoid excessive glare and still have enough natural light to illuminate adjacent spaces⁽²⁾.

In spite of using the bottom floor of the atrium as a functional part of the building, atria add substantially to the volume of their buildings without adding equally to the net usable floor area⁽³⁾.

2-5- 3 Daylighting Analysis in Atrium

The daylight performance of an atrium is complex⁽⁴⁾. An atrium design involves the analysis of several characteristics: the atrium orientation to the sun, the shape of the atrium and its geometrical proportions, the transmittance of the atrium roof, the reflectivity of the atrium surfaces and the penetration of daylight into adjoining spaces⁽⁵⁾.

Atrium wells are typically social gathering areas so the light levels are not as critical as in the adjoining spaces where people often work and need task level lighting⁽⁶⁾.

2-5-3-1 The Atrium Orientation to the Sun (Clear Sky).

The orientation of the atrium and the openings within its walls are very important factors that plays a major role in the

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(1) Moore, F.; "Environmental Control Systems: Heating Cooling Lighting", P.314

(2) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.272

(3) Saxon, R.; "Atrium Buildings: Development and Design", P.6

(4) The European Commission Directorate-General for Energy (DGXVII); "Daylighting in Buildings", P.8.[*erg.ucd.ie/mb_daylighting_in_buildings.pdf*]

(5) Calcagni, B., Paroncici, M.; "Daylighting Factor Prediction in Atria Building Design", P.669

(6) Ashley, J.; "Modification of Atrium Design to Improve Thermal and Daylighting Performance", P.24

penetration of daylight into the atrium and adjoinig spaces. The linear atrium orientation is far more important than the orientation of a square atrium. A north-south alignment may allow sunlight penetration to the base of the atrium but not to the spaces adjoining it. An east-west alignment will allow sunlight penetration to the upper floors of the south facing interior façade but not to the base of the atrium(1) Fig (2-25).

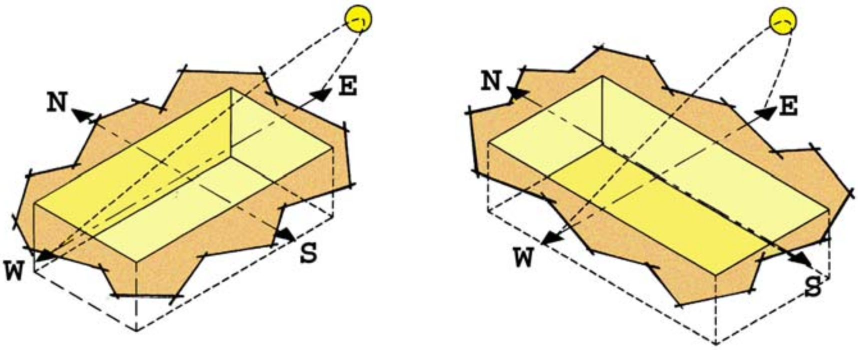

Fig (2-25): Atrium elongated east-west versus atrium elongated north-south.

In general, the best orientation of the atrium openings is the north orientation in which the intensity of light is almost stable and the light quality is the best. The second orientation choice is the northeast or northwest as the openings can be easily shaded by the use of simple small overhangs. The south orientation follows, where the sun's angle is high and can be overcomed by the use of moderate overhangs. The southeast and southwest orientations are considered the worst as the sun's angle is low and the intensity of the ligth is variable and the ligth quality is poor which may cause visual problems. In addition large complicated overhangs are needed to overcome the direct sunligt penetrating the openings(2).

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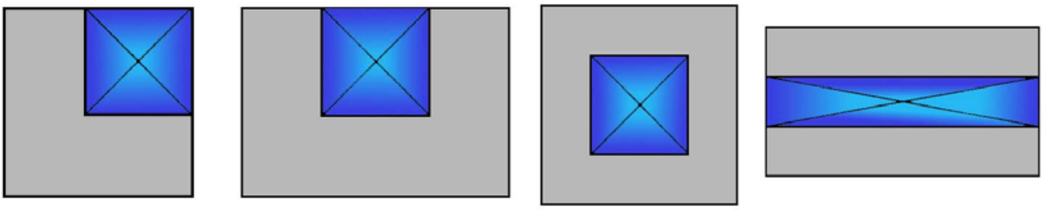
(1) Aizlewood, M.; "The Daylighting of Atria: A Critical Review", P.849

(2) Salem, D.; "The Study of Natural Lighting in the Atrium Buildings within the Local Environment Level to Reach the Optimum Performance by the Aid of Computer",P.105

2-5-3-2 Atrium Shape and Geometry

One of the important architectural parameters that differentiate one atrium from another is its shape(1). Among all the atrium spaces, which are dominated by the cubical, cylindrical, or pyramidal forms, the most common form is the cubical form. Within this latter, a classification has been developed to identify the atrium type according to the location of the glass portion within the atrium envelope and the location of the atrium itself in relation to the rest of the building. Typical simple atria types that can be identified are: four-sided, three-sided, and two-sided or linear atria(2) as shown in Fig (2-26).

In this study, the scope of the research is the four-sided atria in underground buildings, which is considered the atrium worst case as the area through which the light enters the atrium is minimum and light is coming exclusively from the top.



Two-sided atrium Three-sided atrium Four-sided atrium Linear atrium

Fig (2-26): Typical simple atria types.

The atrium geometry was found to be one of the most important factors that affect the daylight penetration(3). The depth and the cross sectional area of the well affect the solid angle of the sky component and, thus, determine the amount of direct daylight reaching the floor of the atrium(4).

The critical proportional relationship in designing an atrium is the ratio of the width of the atrium (*W*) to the height of the

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(1) Boubekri, M., “The Energy Conservation Potential of Daylighting in a Four-Sided Atrium: A Simplified Calculation Procedure”, P.2

(2) Saxon, R.; “Atrium Buildings: Development and Design”, P.76

(3) Amer, N.; “Atrium Buildings’ Design in Urban Context”, P.135

(4) Moore, F.; “Environmental Control Systems: Heating Cooling Lighting”, P.314

building (*H*). This ratio is expressed by *H/W*(1). Fig (2-27) illustrates the atrium nomenclature. The three geometric proportions of the atrium space were related to the distribution of the daylight(2). The geometric proportions of an atrium are best described by the combination of two parameters, the Plan Aspect Ratio **(*PAR*)**, which is the ratio of the atrium width to its length, and the Section Aspect Ratio **(*SAR*)** which is the ratio of the atrium height to its width.

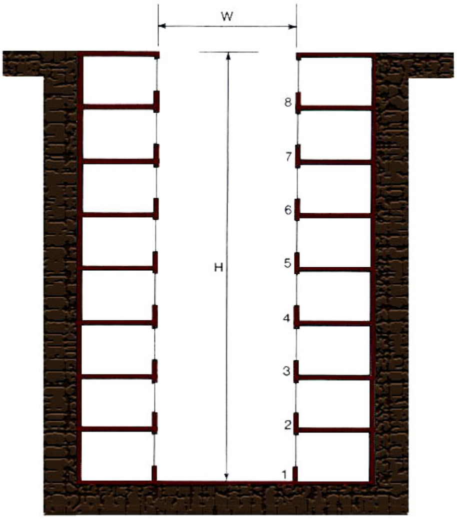

Fig (2-27): Building section illustrating the atrium nomenclature

For an atrium of given length **(*L*)**, width **(*W*)**, and height **(*H*)**, these ratios are:

$$\text{PAR} = \frac{\text{well width}}{\text{well length}} = \frac{W}{L} \qquad \text{SAR} = \frac{\text{well height}}{\text{Well width}} = \frac{H}{W}$$

The PAR can be used to define the following terms(3):

Square atrium	PAR between 0.9 and 1.0.
Rectangular atrium	PAR between 0.4 and 0.9.
Linear atrium	PAR less than 0.4.

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(1) Robbins, C., "Daylighting: Design and Analysis", P.115

(2) Boubekri, M.; " The Energy Conservation Potential of Daylighting in a Four-Sided Atrium: A Simplified Calculation Procedure", P.2

(3) Aizlewood, M., "The Daylighting of Atria: A Critical Review", P.846

Some proportions were chosen for each type of atria⁽¹⁾.

The proportions chosen for the four-sided atrium is: SAR=1.5, PAR=0.4. The proportions chosen for the three-sided atrium is: SAR=2.1, PAR= 0.75. The proportions chosen for the linear atrium is: SAR=2.5, PAR=0.2

Another parameter often used to describe the geometric properties of the atrium is the Well Index **(*WI*)**, which is defined as⁽²⁾:

$$WI = \frac{H \times (L+W)}{2\ L \times W} = \frac{SAR \times (1+PAR)}{2}$$

This expression shows that the *WI* depends on two independent variables *PAR* and *SAR* and that atria with different proportions may have the same *WI*, so, the *WI* alone is not sufficient to describe the geometric proportions. The *WI* represents the relationship between the light admitting area and the surface area of the atrium. Two atria with the same *WI* can have different light admitting areas. In some cases the *WI* is used to derive the daylight factor (*DF*). Table (2-4) shows that atria having same width and length may have different WI depending on their height.

Width (m)	Length (m)	Height (m)	WI
20	20	4.2	0.21
20	20	7.8	0.39
20	20	11.4	0.57
20	20	22.2	0.78
20	40	22.2	0.83

Table (2-4): The atrium geometric characteristics in terms of the well index.

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(1) Amer, N.; "Atrium Buildings' Design in Urban Context", P.149

(2) Boubekri, M.; "The Energy Conservation Potential of Daylighting in a Four-Sided Atrium: A Simplified calculation Procedure", P.166

For atria which have different shapes (square, rectangular, triangular, and circular) but have the same plan area and same height, both of the SC and the IRC are dependent on the atrium shape but the IRC is more critical. The internally reflected component is greatest for the shape which has the least surface area for a given volume and hence the least absorption at the atrium surface. For the above-mentioned shapes, the circular shape has the least surface area-to-volume ratio and performs best(1). (Considering the plan area of the atrium, for a given atrium area of 1 unit^2, the perimeter of the atrium will be 3.54 units for the circle, 4 units for the square, 4.01 units for the equilateral triangle, and 4.24 units for a rectangle with a PAR of 2:1).

Naturally lighted atria are not limited to shallow depths of two or three stories - just as they are used to provide space and light within very tall above grade buildings, designers have suggested extending naturally lighted atria to deep and large underground complexes(2).

Daylight penetration in atria depends on many factors as the light that reaches any point in the atrium can be divided into two parts: the direct (or sky) component and the indirect (or internally reflected) component.

The most important relationships in daylight penetration involve the dimensional aspect ratios of the atrium(3). The other important variable that affects daylight penetration was found to be the atrium surface reflectivity. Light-colored walls aided in daylight penetration deeper into the atrium well.

As the width of the atrium is increased relatively to its height the daylight penetration in the atrium is improved. As the width of the atrium is decreased relatively to its height, the penetration becomes lower.

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(1) Aizlewood, M., "The Daylighting of Atria: A Critical Review", P.846.

(2) Carmody, J., sterling, R; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 271

(3) Ashley, J., "Modification of Atrium Design to Improve Thermal and Daylighting Performance", P.22

In general, the shallower and wider the atrium space the better the penetration of the direct daylight. Atria that are higher than their width generally result in poor daylight levels for all lower floor levels, and thus require atrium walls with high reflectance. Atrium walls with low reflectance are only suitable for daylighting when the space is wider than its height(1).

The shape of the floor plan is also important. If the atrium is shallow and wide, then the shape of the floor plan is less critical. From the daylighting point of view, wide shallow square atria perform better than deep narrow rectangular ones(2).

Tall, narrow atria have less View of the sky than short, wide atria. Since less daylight is available at higher latitudes than at lower latitudes, atria at high latitudes must be larger to provide the same level of daylight indoors. Taller buildings with more floors require larger atria than shorter buildings. At low height to width ratios (H:W = 1:1) atrium plan is not significant. At higher ratios (H:W = 2:1), square atria provide 7-10% more daylight to the atrium floor than rectangular atria(3) (with a W:L = 1:2 plan sides ratio).

In atrium buildings, side lighting can be usable to a depth of (2–2.5) times the head height (H) of the atrium wall windows(4), thus the thickness of the rooms between two atria is limited to about (5H) for full daylight penetration. A thickness dimension between two atria of (6H) can be used to achieve 90-100% daylight area, and (7H) to achieve 80-90% daylight area. This principle holds true for all latitudes and atrium sizes(5) as shown in Fig (2-28).

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(1) Iyer-Rangia, U.; "Daylighting in Atrium Spaces", P.195

(2) The European Commission Directorate-General for Energy (DGXVII), "Daylighting in Buildings", P.8. [*erg.ucd.ie/mb_daylighting_in_buildings.pdf*]

(3) Brown, G., Dekay, M.; "Sun, Wind, and Light: Architectural Design Strategies", P.198

(4) ibid, P197

(5) ibid, P198

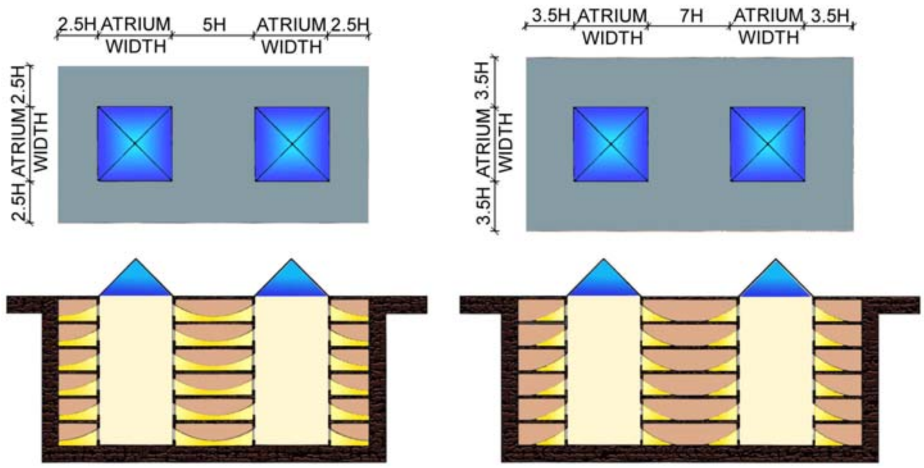

Fig (2-28): Decrease in daylight penetration when decreasing the width of the atrium.

As for the atrium walls shape, most atria tend to be built with straight or near straight sides. Splaying the atrium walls inward or outward has its drawbacks in spite of having many advantages.

Daylight penetration is improved by splaying the atrium walls so that the atrium is wider at the top. This could be noticed from the increase of the portion of the sky light component and the increase of the internally reflected component⁽¹⁾ Fig (2-29).

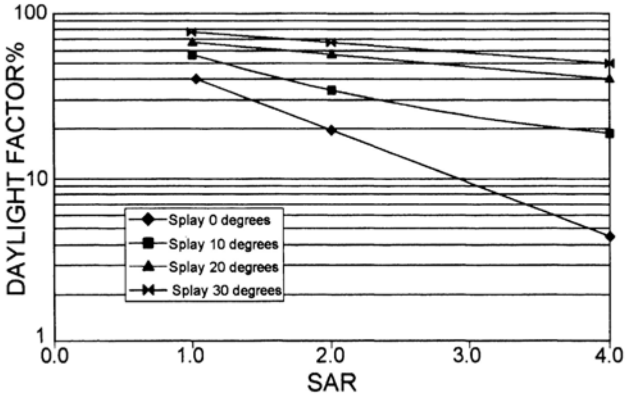

Fig (2-29): Internally reflected component at the center of the atrium floor.

(The reflected component changes slowly with increasing the well depth.)

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(1) Aizlewood, M., "<u>The Daylighting of Atria: A Critical Review</u>", P.849.

On the other hand splaying the walls reduces the rentable floor area of the upper stories. If the size of the atrium base remains constant, then an extra floor may be required to compensate for the lost floor area Fig (2-30). In general, there is an improvement in the daylight factor at the base of the atrium of about 25% to 30% increase at 10-degree to 30-degree splays from the vertical⁽¹⁾.

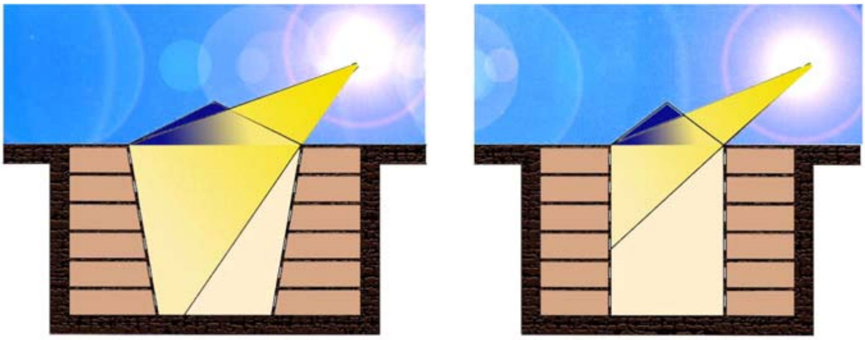

Fig (2-30): Splayed versus straight atrium walls.

2-5-3-3 The Atrium Roof

One of the factors that can vary the daylight penetration and performance in the atrium dramatically is the glazing system of the atrium roof (shape, type, and position of the glazing).

Careful design of the roof fenestration system limits glare, reduces passive solar effects, supplies adequate daylighting, and minimum sun lighting. The structural system supporting the glazing and fenestration, shading and any external obstructions also affect the amount and direction of the daylight in the atrium⁽²⁾.

I) The Atrium Glazing System and Its Transmittance.

The amount of light admitted through a window or any fenestration is naturally dependent on the transmission factor of the glazing material used. For example, aconventional single-glazed clear float glass will transmit approximately 85% of the light that falls upon it.

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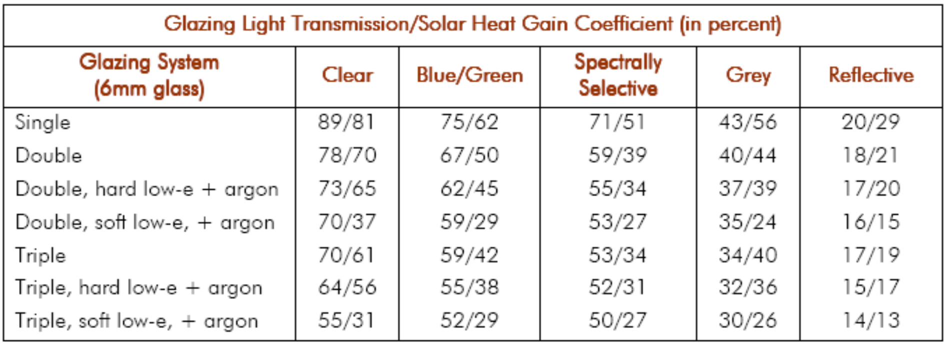
(1) ibid

(2) Ashley, J.; "Modification of Atrium Design to Improve Thermal and Daylighting Performance", P.21

Double or triple glazing will reduce light transmission to 70% and 60% respectively[(1)].

Early in the design process, the design team will have to consider the light and thermal transmittance characteristics of various glazing materials[(2)]. In many designs, the choice of the glazing material is largely based on the solar heat gain coefficient (*SHGC*) of the material, that is, on the ability of the glazing material to reduce the solar gains to the space[(3)] Table (2-5).



Glazing Light Transmission/Solar Heat Gain Coefficient (in percent)					
Glazing System (6mm glass)	Clear	Blue/Green	Spectrally Selective	Grey	Reflective
Single	89/81	75/62	71/51	43/56	20/29
Double	78/70	67/50	59/39	40/44	18/21
Double, hard low-e + argon	73/65	62/45	55/34	37/39	17/20
Double, soft low-e, + argon	70/37	59/29	53/27	35/24	16/15
Triple	70/61	59/42	53/34	34/40	17/19
Triple, hard low-e + argon	64/56	55/38	52/31	32/36	15/17
Triple, soft low-e, + argon	55/31	52/29	50/27	30/26	14/13

Table (2-5): Typical light transmission and *SHGC* for glazing systems[(4)].

The optical properties of the glazing material influence the daylighting quality and the potential for energy savings due to reduced artificial lighting. The two major types of glazing are: Transparent and Translucent (either colorless, tinted, or reflective).

Transparent colorless glazing transmits the most daylight, and provides the most natural view of the sky. Translucent glazing materials, which diffuse and distribute sunlight, do not allow a direct view of the sky[(5)].

To provide a uniform light quality under direct sunshine, the glazing material has to be highly diffusing. However,

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[(1)] The European Commission Directorate General for Energy (DGXII); "Daylighting in Buildings", P.9. [*erg.ucd.ie/mb_daylighting_in_buildings.pdf*]

[(2)] Robbins, C., "Daylighting: Design and Analysis", P115

[(3)] Iyer-Rangia, U.; "Daylighting in Atrium Spaces", P.196

[(4)] 1997 ASHRAE Fundamentals, Table 11, P. 29.25

[(5)] Salem, D.; "The Study of Natural Lighting in the Atrium Buildings within the Local Environment Level to Reach the Optimum Performance by the Aid of Computer",P.104

highly diffusing materials tend to have lower light transmittance that reduces the light levels under overcast sky conditions. On the other hand, diffuse materials have better thermal characteristics than transparent glazing(1).

In some cases, the acceptance of some direct sunlight can be desirable to give an edge and sharpness to the atrium design. Overheating, however, has to be avoided to maintain occupants' comfort.

II) *The Structural System for The Atrium Glazing and Fenestration.*

The amount of daylighting entering the atrium is affected by the structural system for the glazing. The size of the structural system determines the net glazed area. When designing for climates with mainly overcast sky conditions, the dimension and the type of roof construction must be carefully evaluated. The aim is to minimize any obstructions within the light-collecting area, thus maximizing the contribution of daylight. However, even the most minimal roofing construction would reduce the light-admitting area by at least 8-10%(2). Using a single-plane glazing material would cause a further 10% reduction. Thus covering an open court with any kind of glazing system would reduce the daylight level in the atrium by at least 20%(3) and sometimes it may reach 50% or more(4).

It should be noted that about one third of the fenestration losses will come from the transmittance of the glass itself, one third from the major structural elements, and one third from the minor structural elements(5). It must be taken in consideration that the

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(1) Aizlewood, M., "The Daylighting of Atria: A Critical Review", P.845

(2) Calcagni, B., Paroncini, M.; "Daylight Factor Prediction in Atria Building Designs", P. 674

(3) Iyer-Rangia, U.; "Daylighting in Atrium Spaces", P. 200

(4) The European Commission Directorate-General for Energy (DGXVII), "Daylighting in Buildings", P. 9 [*erg.ucd.ie/mb_daylighting_in_buildings.pdf*]

(5) Aizlewood, M.; "The Daylighting of Atria: A Critical Review", P.844

atrium roof glazing may be physically difficult to access, and special thought must be given to its maintenance(1).

2-5-3-4 Surface Reflectance of the Atrium Walls and Floor

The design of the atrium walls significantly affects the light distribution once it has entered the atrium. The quantity of the reflected light is the product of the average reflectance of the walls and the floor.

Daylight advantages are achieved by increasing the reflectance of the walls. Diffuse reflecting materials reduce the quantity of daylight reaching the lower part of the atrium walls and floor. Specular reflecting materials perform better but tend to increase glare for occupants' especially when sunlight strikes the atrium facades(2). Dark finishes reduce the internal reflectance, thus the deeper the atrium the more important the surface reflectance of the walls becomes.

The upper walls are critical in reflecting the light down into the atrium, so it is best to limit windows in this area. Spaces at the upper levels tend to receive plenty of light but need protection from glare, while those at the base need to maximize the amount of light they receive(3).

For increasing the IRC all the opening sizes, in the atrium wall, must be progressively increased from top to bottom. Fig (2-31) illustrates the increasing size of glazing used in atria.

The floor reflectance of the atrium influences the amount of light reaching the atrium walls but it is limited to the lower part of the atrium walls(4). A glossy floor material, such as marble, would provide the greatest benefit. However, plants and greenery tend to reduce

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(1) Saxon, R.; "Atrium Buildings: Development and Design", P.82
(2) Iyer-Rangia, U.; "Daylighting in Atrium Spaces", P. 199
(3) Saxon, R.; "Atrium Buildings: Development and Design", P.80
(4) Aizlewood, M., "Daylighting of Atria: A critical Review", P.850

the reflection of the floor(1). To maximize the contribution of light reflected from the floor of the atrium, plants should be positioned in the center of the atrium with a band of highly reflective floor near the walls. This results in higher daylight factors in the side spaces especially in the lower storeys. The size and location of the opening in the walls determine the area of the floor perimeter needed to enhance the illumination.

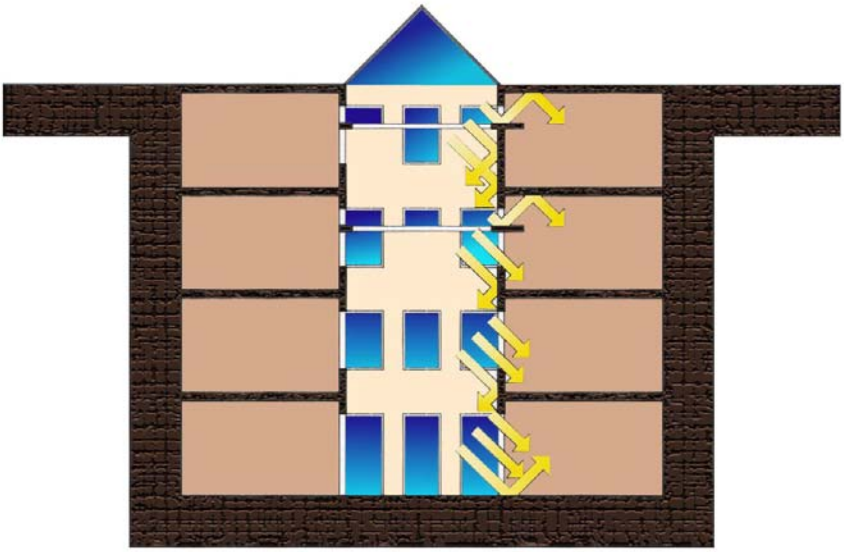

Fig (2-31): Glazing size in atrium walls as a function of the atrium height(2).

2-5-3-5 Daylighting in Adjoining Spaces

The spaces adjoining the atria can be used for shops, offices, classrooms or any other function. In those spaces specific tasks are often performed which require a stable and high quality light conditions.

Daylighting levels in those spaces are affected by the atrium height and width, the amount of daylight available from the sky in the buildings climate, the reflectivity of the atrium interior facades

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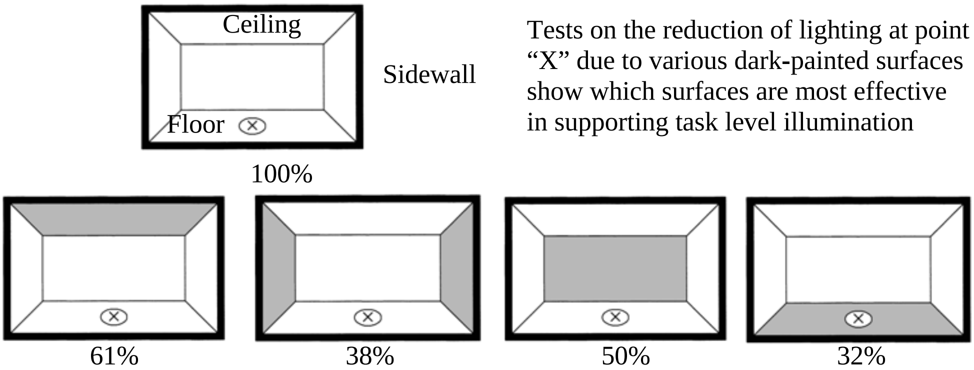
(1) Salem, D.; "The Study of Natural Lighting in the Atrium Buildings within the Local Environment Level to Reach the Optimum Performance by the Aid of Computer",P.115

(2) http://www.oikos.com

and floor, the size and position of the windows in the atrium facades, the roof design, the glazing system transmittance, and the reflection strategies at the interior windows wall(1).

In order to maintain high quality illumination in the adjoining spaces, the internal reflectance in the side spaces should be as high as possible Fig (2-32). For example, a falt matt ceiling will reflect light if white and clean while a textured ceiling losses its efficiency. In addition, the structure of the adjoining spaces should be given special attention.Unless a flat-slab structure is used, beams should be arranged to run perpendicular to the windows, to provide adequate reflecting surfaces to channel the light deeper into the space(2).



Tests on the reduction of lighting at point “X” due to various dark-painted surfaces show which surfaces are most effective in supporting task level illumination

Fig (2-32): Daylight reduction due to changing floor, wall, and ceiling surface reflectance(3).

The proportion of glazing between the atrium and its adjoining spaces affects the light penetration further in the well and the spaces. Penetration of light is best at the top floors of a building, which have a less limited view of the sky(4). Because the upper floors of the building have no ground plane, none of the light typically reflected off the ground is reflected into the upper-floor spaces. The lower floors, on the other hand, have little or no view of the sky. The ground plane and

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(1) Brown, G., Dekay, M., “Sun, Wind and Light: Architectural Design Strategies” P. 198

(2) Saxon, R.; “Atrium Buildings: Development and Design”, P.83

(3) Evans, B.; “Daylight in Architecture”, P. 75

(4) Robbins, C.; “Daylighting: Design and Analysis”, P. 115

the opposing walls of the atrium are critical reflective surfaces for daylighting the spaces adjoining the atrium. Daylight penetration in adjoining spaces is maximum at the top floors of the atrium

A scale-model approach (Szerman 1992) was used to develop a nomograph for the average daylight factor in adjoining spaces. Fig (2-33) illustrates the nomograph that takes into account the shape of the atrium, the floor level of the adjoining space, the reflectance of the opaque atrium wall elements, the reflectance of the atrium floor, and the glazing types of the outside-to-atrium and atrium-to-office boundaries. The actual daylight factors calculated are specific to the fixed values of the room's size, shape, and reflectance(1).

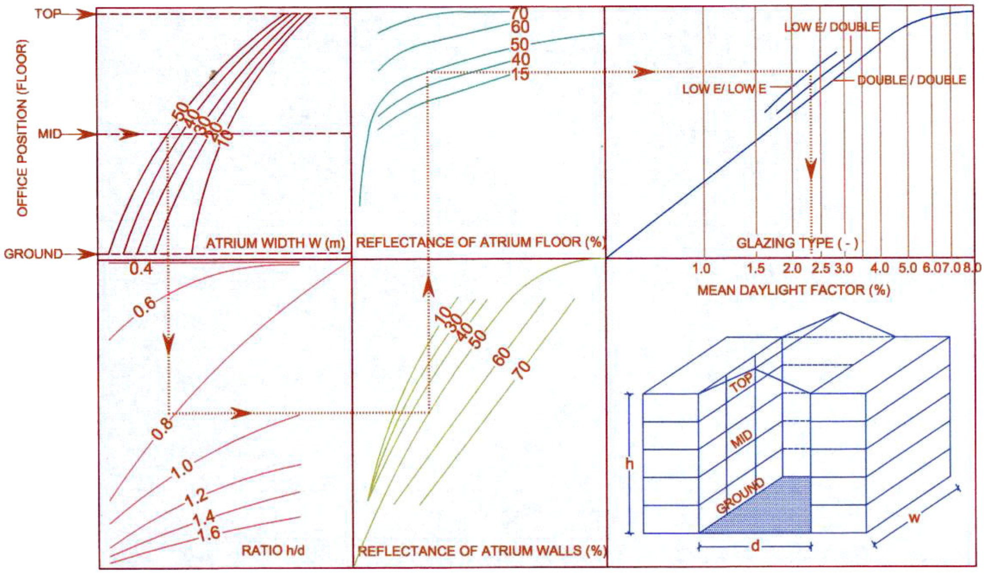

Fig (2-33): Szerman's nomograph for deriving mean daylight factors of rooms' adjoining atria(2).

Graph assumptions: (Graph solved example)

1- Office at the mid level of the atrium.
2- Atrium depth 15m.
3- Atrium width 50m.
4- Atrium height 12m.

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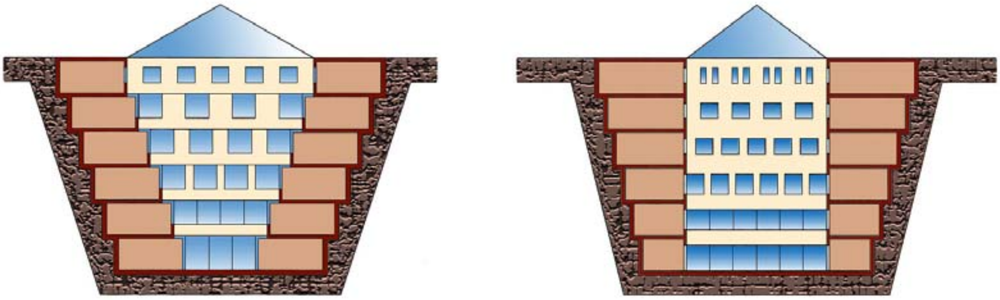
(1) Aizlewood, M.; "The Daylighting of Atria: A Critical Review", P.200

(2) Brown, G., Dekay, M.; "Sun, Wind, and Light: Architectural Design Strategies", P.200

5- Reflectivity of opaque atrium wall 50%.
6- Reflectivity of atrium floor 50%.
7- Glazing type:
    Office-Atrium, Double.
    Atrium-Outside, Low-E.

Resulting mean daylight factor 2.4%

Other design strategies for increasing the daylight penetration in the adjoining spaces include making spaces near the base shallower, increasing their floor-to-ceiling height or stepping back the upper floors in successive steps so that all the spaces have some view of the sky. For example, raising the floor-to-ceiling heights from 2.7meters to 3.6meters can allow good daylight up to 9meters into the adjoining spaces(1). These solutions are shown in Fig (2-34). The closer the space is to the bottom of the atrium the greater its dependence on the light reflected from atrium walls and floor(2).



Stepping back the spaces allows each space to have a direct sun view.

Shallower spaces at the base of the atrium improve their daylight conditions.

Fig (2-34): Various design strategies for improving the light conditions at the lower floors of atria.

Reflectors may be fixed at the windows of lower rooms to redirect more of the zenithal light onto their ceilings, but this is generally cost effective only when other considerations determine that

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(1) Saxon, R.; "Atrium Buildings: Development and Design", P.73.

(2) The European Commission Directorate General for Energy (DGXII), "Daylighting in Buildings", P. 9. [*erg.ucd.ie/mb_daylighting_in_buildings.pdf*]

the reflectance's of the atrium walls and floor must be low(1). While rooms further from the atrium roof may have lower light levels, they may have better light quality in terms of uniform distribution and absence of glare.

Estimating the amount of light likely to be available in the adjoining spaces is a difficult task because it is affected by both the characteristics of the atrium and the characteristics of the room itself. A two-stage process to determine first the vertical illuminance on the window wall and then how that light is distributed in the adjoining space appears to offer the clearest understanding of this complex interaction(2).

The design of atrium buildings often leads to creation of hard-to-daylight(3) spaces adjacent to the atrium corners, as shown in Fig (2-35). These spaces can be used for a wide variety of functions that do not call for a great deal of light or are not occupied on a continuous basis.

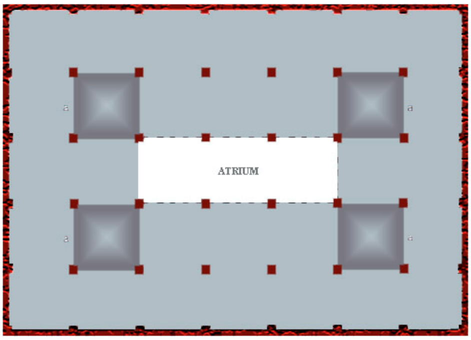

Fig (2-35): Underground building plan illustrating the hard-to-daylight spaces adjacent to the atrium corners.

2-5-4 Thermal Performance of Atria.

The main problem with the atrium thermal environment is the glazing used in the roof. The large amount of glazing in the atria

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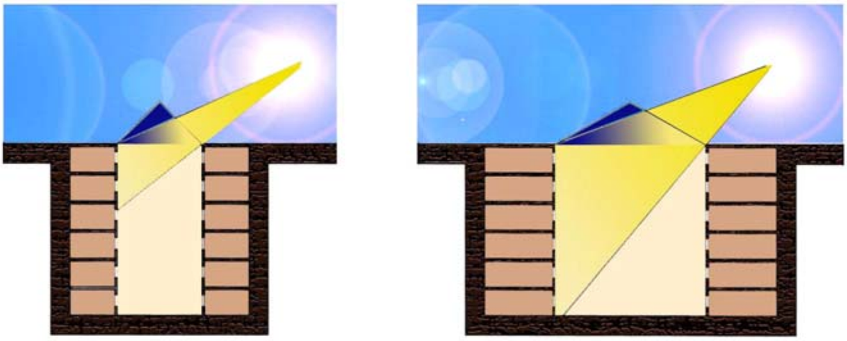
(1) Salem, D.; "The Study of Natural Lighting in the Atrium Buildings within the Local Environment Level to Reach the Optimum Performance by the Aid of Computer",P.118

(1) Aizlewood, M., "The Daylighting of Atria: A Critical Review", P.854

(3) Robbins, C., "Daylighting: Design and Analysis ", P.118

results in an overheating green house effect. With clear single glazing and the sun at high solar latitude, there is great heat penetration. Short-wave solar energy is transmitted through the glazing and absorbed by the solid elements of the building. These elements then re-emit long wave radiation that is prevented from re-transmitting back through the glazing. Fig (2-36) shows the solar penetration and heat gain into the atrium.

The human thermal comfort zone is between 21º and 27º Celsius so the temperature within atrium buildings should be kept within this temperature range. The large amount of glazing in the roof results in excessive heat gain via direct radiation, which produces a thermal stratification stack effect within the atrium well. This results in a much higher temperature towards the top of the atrium. The temperature differences between the lowest and highest points could be as much as 7º Celsius(1).



More focused direct solar impact thus more stratification

More spreaded direct solar impact area thus less stratification

Fig (2-36): Solar penetration and heat gain into atrium.

Tall and narrow atria have a more focused direct solar impact area, less air mixing and less emitted radiation and therefore more stratification compared to shorter and wider atria as shown in Fig (2-37).

In tropical areas, diffusing glazing or shading under skylights and atrium roofs are often used to deflect or reject the direct

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(1) Ashley, J., "Modification of Atrium Design to Improve Thermal and Daylighting Performance", P.27

solar radiation. This makes these glazing systems more comfortable but also has the effect of reducing the daylight penetration and the light level.

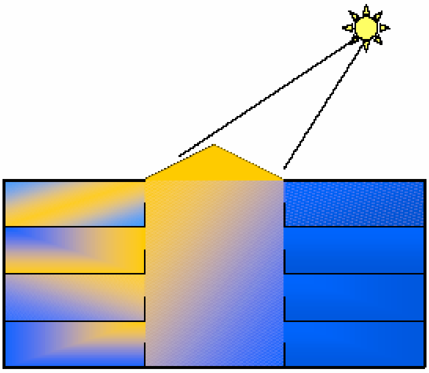

Fig (2-37): Solar impact in tall and narrow atria.

In order to reduce the stratification within the atria, specially treated glass can be used to control heat losses or gains(1). The early tinted glasses reduced solar heat gain to some degree but also cut down daylight transmission and distorted the color of the landscape outside. Heat absorbing glasses do not reduce daylight transmission to quite the same degree, but reduce heat gain by only 10% because a large percentage of the heat absorbed is reradiated into the interior. Reflective glass blocks solar radiation effectively (reflectances up to 50% are available) but, like tinted glass, it blocks light as well as heat, and it continues to do so in winter when heat gain and daylight may be beneficial. Selective 'low-e' double glazing, with a heat loss equivalent to that of triple glazing, has a light transmission factor of approximately 80%.

Current developments include the Electrochromic glass which changes its optical absorption properties and becomes dark or cloudy in response to an externally applied electric field. The opacity disappears when the field is reversed. It can be readily integrated into a

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(1) The European Commission Directorate General for Energy (DGXII); "Daylighting in Buildings", P.9 [*erg.ucd.ie/mb_daylighting_in_buildings.pdf*]

responsive building climate control system, but the cost of the glass is very high and, at present, the life of a unit is too short for practical use in the building industry. Thermochromic glass switches between a heat-transmitting and a heat-reflecting state at selected temperature thresholds. Photochromic glass darkens and lightens in response to changes in light intensity. Material costs of both are high and durability at this time is uncertain(1).

The action of all of these coated glasses is selective blocking of radiation. Glass to which a holographic film has been applied does not block radiation but diffracts it. Windows with holographic film can be designed to direct incoming sunlight on to a reflective surface such as the ceiling, or deep into a room. A film can also be designed to reflect sunlight coming from well defined angles – high-angle sun on south facades or low-angle sun on east and west facades, for example. Up to four images containing different ‘instructions’ can be combined in one layer. A view out through the window is retained but from some viewing angles there is a rainbow effect. Its performance for diffused light is poor, but research is continuing. Costs are not high but at the moment holographic film is not available in the sizes needed for the building industry(2).

Prismatic glass (or plastic) controls transmitted light by refraction and can be used to redirect or to exclude sunlight. The direction of incoming daylight is changed as it passes through an array of triangular wedges whose geometry can be designed for particular conditions and orientations. Prismatic glass is translucent rather than transparent, so cannot be used where a view outdoors is required. In several recent applications it has been used to reduce glare. Normally a prismatic refracting panel consists of two sheets with their prismatic faces facing each other to protect them from dust accumulation. Prismatic sheets can also be used within double-glazed units. Prismatic assemblies,

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(1) ibid
(2) ibid

including sophisticated systems incorporating silvered wedge-faces and several panel types, are increasingly available.

Table (2-6) illustrates the main differences between the courtyard and atrium concepts used for daylighting underground spaces.

	Courtyard	**Atrium**
Orientation	- The optimum orientation depends on which functions inhabit the long or short sides of the court, and whether winter heating or summer cooling is the greater problem.	- Linear atrium orientation is more important than square atrium. - In north-south alignment sunlight penetrates to the base of the atrium. - In east-west alignment sunlight penetrates to the upper floors of south facing interior façade.
Shape and Geometry	• ***Shape*** - Can take any shape (square - rectangle - triangle - circle...etc). - Types: 2-sided, 3-sided, or 4-sided. • ***Geometrical Proportions*** 1- Aspect Ratio(AR): $AR = \frac{\text{Area of court}}{(\text{Av. height of court walls})^2}$ - The aspect Ratio describes the courtyard exposure. 2- Solar Shadow Index (SSI): $SSI = \frac{\text{South wall height}}{\text{North-south floor width}}$	• ***Shape*** - Can take any shape (square - rectangle - triangle - circle….etc.) - Types: 2-sided (linear), 3-sided, or 4-sided. • ***Geometrical Proportions*** 1-Plan Aspect Ratio (PAR): $PAR = \frac{\text{Well Width}}{\text{Well Length}}$ 2-Section Aspect Ratio (SAR): $SAR = \frac{\text{Well Height}}{\text{Well Width}}$ - The chosen proportions: Four-sided atrium PAR=1.5, SAR= 0.4 Three-sided atrium PAR=0.75, SAR= 2.1 Linear (two-sided) atrium

	Courtyard	**Atrium**
	• ***Depth*** - One to three stories is the normal and economic range. - Three stories or more the unusable area increases so it becomes less economic.	PAR= 0.2, SAR= 2.5 3-Well Index (WI) $WI = \frac{SAR \times (1 + PAR)}{2}$ - The WI represents the relationship between the light admitting area and the surface area of the atrium. - When the width of the atrium increases relative to its height, the daylight penetration into the atrium increases and vice versa. - Splaying the atrium walls improves daylight penetration significantly. • ***Depth*** - One storey atrium is more like a skylight. - In two to three stories the roof cost is a major component of the total cost of the atrium. - In four to ten stories, the roof cost is less significant to the total cost. - More than ten stories, the unusable space increases leading to the decrease of the rentable area.
Roof Glazing	- No roof glazing is available (open interior space).	- The roof of the atrium consists of two components: the atrium glazing and its structure system.

	Courtyard	Atrium
		• ***Atrium Glazing and Its Transmittance*** - For single float glass a minimum 10-15% daylight loss occurs. - For double or triple glazing a minimum of 30-35% daylight losses occurs. • ***The Structure System for the Atrium Glazing*** - Minimum roofing construction reduces light admitting area by at least 10%. • ***Fenestration Losses*** - 1/3 of the daylight losses are due to the glass transmittance. - 1/3 of the losses are due to major structural elements. - 1/3 of the losses are due to minor structural elements.
Floor & Walls Surface Reflectance	- Floor and walls surface reflectance are not very critical in case of courtyards. - In general, light-colored surfaces diffuse daylight in courts better. - White walls can become a glare source. - Excessive planting reduces daylighting reflected component into the adjoining spaces.	- Floor and walls surface reflectance significantly affects the daylight penetration and distribution in the atrium well. - The deeper the atrium the more important the surface reflectance of the walls. • ***Wall Finishes*** 1-The upper walls are the most critical in reflecting the light down in the atrium. 2-Diffuse materials decrease the quantity of light reaching

	Courtyard	**Atrium**
		the base. 3-Specular materials perform better but become a glare source. 4-Dark finishes reduce the internal reflectance within the atrium well significantly. • ***Glazing / Fenestration*** 1-All the glazing within the atrium well diminishes the internal reflected component. - 50% glazing reduces the IRC to 1/2. - 100% glazing in Atrium walls reduces the IRC to 1/3. 2-Increase the openings size from top (minimum) to bottom (maximum) to increase the IRC reaching the base. • ***Floor*** 1-Floor reflectance is limited to the lower part of the atrium, glossy floor material increase daylight penetration in the lower adjoining spaces. 2-Planting reduces floor reflectance thus decreasing the quantity of daylight reaching the lower adjoining spaces.
Adjoining Spaces	- In plan, typical adjoining spaces proportion is L = 3W L: Length of adjoining space. W: width of adjoining space.	- Daylighting in adjoining spaces is affected by: the atrium geometry, roof and glazing, atrium surface reflectance, and fenestration

	Courtyard	**Atrium**
	- In section, daylight penetrates to 2.5H where H is the opening height. For floor area within the 2.5H zone the DF are as follows: $DF_{av.}= \frac{0.2 \text{ window area}}{\text{Floor area}}$ $DF_{min.}= \frac{0.1 \text{ window area}}{\text{Floor area}}$	size and position. - The Internal reflectance within the adjoining spaces should be as high as possible. - Daylight penetration in adjoining spaces is best at the upper floors due to the direct penetration from the sky view. - Lower floors have less or no direct view of the sky thus the internal reflected component (IRC) within the atrium is very important to those floors. - Estimating natural light in adjoining spaces is done by a two stage process: First, the vertical illuminance on the window wall is determined then the light penetrating from the window is estimated.
Thermal Performance	- Not significant due to the absence of any glazing. - Simple or complex shades could be used to provide suitable shading to the openings.	- The main problem with the atrium thermal environment is the glazing used which produces a greenhouse effect. - Air stratification occurs within the atrium well due to the rise of hot air to the top and colder air remains at the bottom. - Tall narrow atria have more stratification compared with shorter and wider atria. • ***Thermal solutions*** 1-Use of diffuse glazing or

	Courtyard	Atrium
		shades under the atrium roof (this solution reduces the light levels). 2-Specially treated glass or innovative glazing performs better but is very expensive. For example, selective “low-e” double glazing has a light transmission factor of approximately 80%.

Table (2-6): Differences between courtyards and atria.

2-6 Examples of Underground Buildings using Courtyards as a Daylighting Concept

2-6-1 Clark House

***Location*:** Portland, Oregon.

***Architect*:** Norman Clark

***Construction Date*:** June 1977

***Project Size*:** 215 m^2

Underground Classification:

1- *Function*: Residential
2- *Fenestration Type*: Courtyard and Elevation type.
3- *Relation to Surface*: Subsurface building
4- *Depth*: Shallow (4meters)
5- *Project Scale*: Medium sized single family Building.

Earth Cover: 80% on roof at 61cm, 88% on walls.

Reason for going Underground(1)**:**

The main reason for locating the building below grade is its energy conservation potentials. In addition to the energy

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(1) Ahrens, D., Ellison, T., Sterling, R.; “Earth Sheltered Homes: Plans and Design”, P.62

conservation, the building was placed below grade due to the site constraints (sloping site as well as having less environmental impact in a rather dense suburban neighborhood) Fig (2-38).

Fig (2-38): Exterior view of the Clark House.

Project Description(1)**:**

The courtyard building type was used as the main theme of this subsurface building Fig (2-39). As with most such designs, the main living spaces - bedrooms, living, and dining rooms are arranged around a central courtyard that provides them with sunlight Fig (2-40).

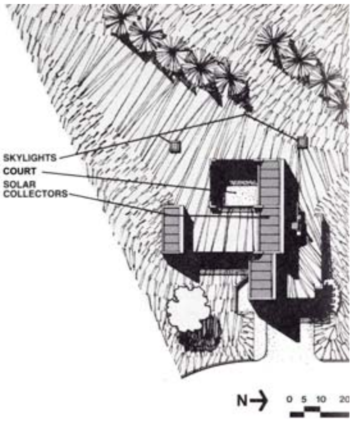

Fig (2-39): Clark House site plan showing the central courtyard.

Fig (2-40): Clark House plan showing rooms arrangements.

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(1) ibid

The interior of the courtyard, adorned with numerous plants and shrubs, is an inviting family gathering place; in winter, it is converted to a green house by stretching a poly ethylene cover across the top of the space. Secondary spaces and corridors requiring less natural light are located at the back of the primary spaces. The projections that appear on the roof of the building are utility spaces in addition of being passive solar collectors that provide solar heat gain in winter Fig (2-41).

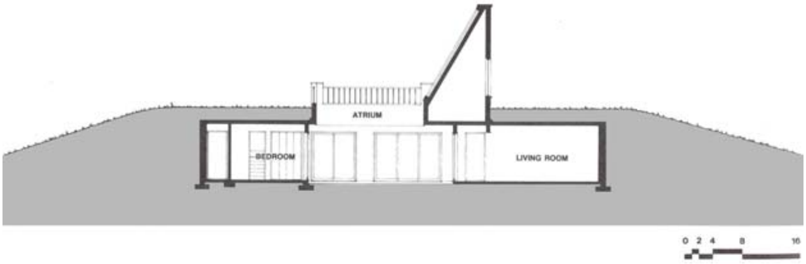

Fig (2-41): Clark House section showing the central courtyard and solar collectors.

Daylighting Concept and Analysis:

1- *Daylighting Method*: Central sunken courtyard (5.75x5.75ms).

2- *Orientation*: The courtyard is oriented to the Cardinal points (north-south, east-west). The glazing in the living room faces south, the kitchen and the dining room glazing faces west, a secondary bedroom faces north, and the master bedroom and another secondary bedroom faces east.

3- *Shape and Geometry*: The courtyard is square shaped with rooms surrounding it from all directions (4-sided). The court is 1 storey deep.

4- *Floor and Walls Surface Reflectance*: The walls of the court are finished with light-colored paints and the court floor is also light-colored reflective ceramic tiles to maximize the reflected daylight to the adjoining spaces.

5- *Adjoining Spaces*: Walls facing the courtyard are fully glazed to maximize daylight penetration into the adjacent spaces.

2-6-2 California State Office Building

Location: Sacramento, California.

Architect: The Benham Group, Oklahoma City, Oklahoma.

Construction Date: 1982.

Project Size: 24,525m^2 includes 7000m^2 in below grade office space and auditorium.

Underground Classification:

1- *Function*: Non-residential / Institutional / Office building.
2- *Fenestration Type*: Courtyard type.
3- *Relation to Surface*: Semi-subterranean (For the below grade part).
4- *Depth*: Shallow building (5meters)
5- *Project Scale*: Large sized building scale.

Earth Cover: 100 percent of exterior walls on first level below grade are covered (not including courtyards), 100 percent of exposed roof on first level is covered with 0.25m to 0.9m of earth.

Reason for going Underground(1)**:**

With energy conservation as a primary requirement the California State architect's office held a national competition for the design of a government office building. Completed in 1982, the winning design by the Benham Group demonstrated a wide range of energy-related concepts and systems. In addition, making a portion of the building below grade resulted in an open space within the city center Fig (2-42).

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(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.85

Fig (2-42): California State Office Building exterior view.

Project Description(1)**:**

Covering approximately 1.50 city blocks, the site is bounded by streets on the south, east, and west. Another east-west street separates the site into a full city block on the south side and a half-block to the north.

In order to resolve many of the constraints of the site and maximize opportunities for energy conservation, the design consists of two distinct parts - a one-storey underground building covering the city block on the south side of the project, and a six-story building rising along the northern edge of the site. A long narrow sunken courtyard forms an outdoor circulation spine through the underground building, extends under the street and ties together the two parts of the site divided by the street. On the rooftop of the underground structure is a public park with an outdoor amphitheater Fig (2-43).

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(1) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P.128

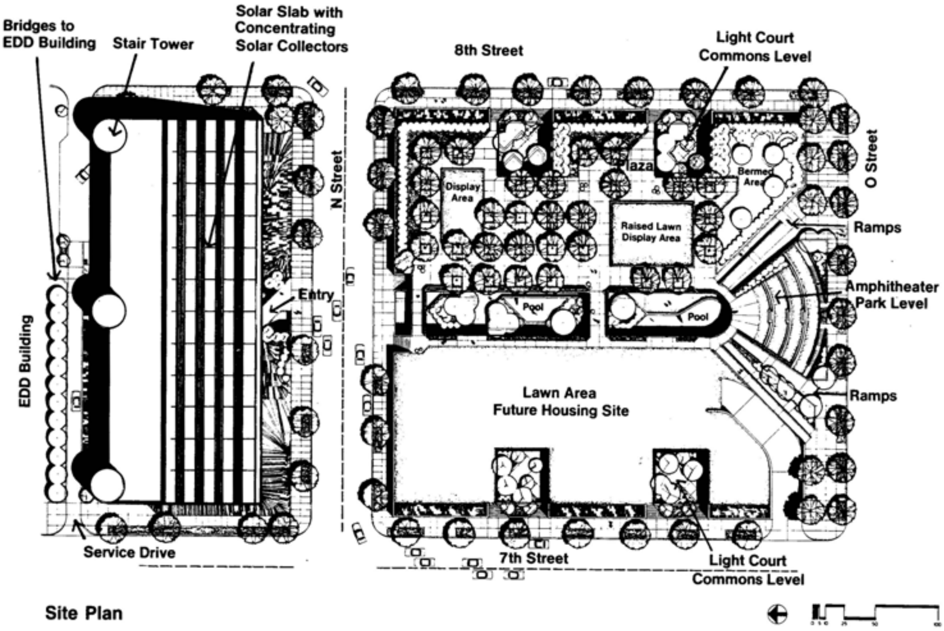


Fig (2-43): California State Office Building site plan.

The six-storey structure on the northern edge of the building supports 2325m^2 of concentrating solar collectors. By stepping the floors back at a 45-degree angle to form a sloping southern façade, solar collection is more efficient Fig (2-44).

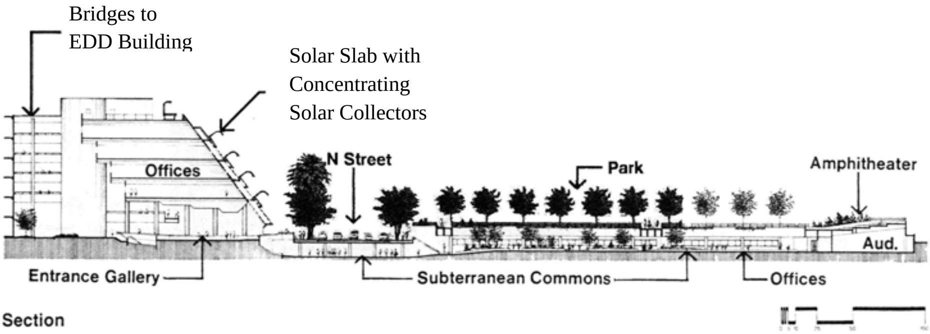
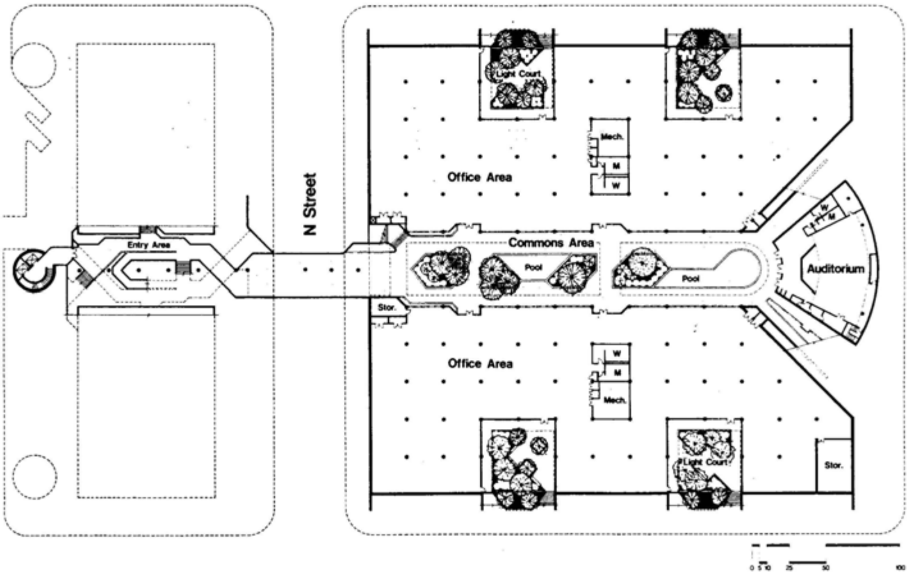
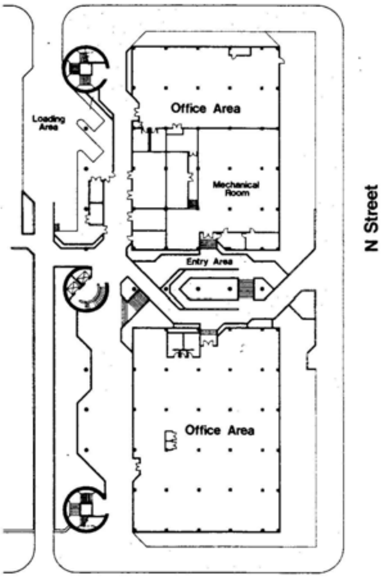


Fig (2-44): California State Office Building section.

On the southern edge of the site, pedestrians enter the below grade portion of the complex through two diagonal ramps leading to the central outdoor narrow courtyard. A 150 seat auditorium is located at the south end of the project, and underground office areas are entered from the central spine. The underground office area is divided into two separate buildings, each with windows that face the central walkway, providing some natural light and exterior views. Offices also have windows facing into four sunken courtyards located on the perimeter of the site Fig (2-45).





Above: One level below grade showing the central courtyard providing the offices with daylighting and linking the two parts of the building.

Left: First level above grade showing the main entrance of the below grade part.

Fig (2-45): California State Office Building Plans.

Daylighting Concept[1]**:**

Providing natural lighting in this building required special attention in the underground areas to provide adequate daylighting levels in the offices area and avoid glare problems. In order to explore the potential of substituting artificial light with natural lighting, the designers used scale models to simulate and predict lighting level.

Daylighting was provided to the underground offices through the narrow, tall central walkway and four sunken courtyards in the corners of the building thus placing the majority of the office area within view of the windows. In order to maximize the amount of natural light, highly reflective surfaces are used in the courtyards Fig. (2-46).

Fig (2-46): Central sunken courtyard at the level of the underground offices.

In addition to the sunken courtyards, perimeter daylighting is provided to the underground offices since the rooftop plaza is actually raised one half levels above grade thus providing high windows in the exterior walls.

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(1) ibid, P.132

In order to efficiently use natural lighting, photoelectric cells detect light levels and shut off part or all of the artificial lights when they are unnecessary.

Daylighting Analysis:

1- *Daylighting Method:* One central courtyard and 4 additional courts at the corners of the building.

2- *Orientation:* All of the courtyards are oriented north-south, east-west thus all orientations are available for the office spaces.

3- *Shape and Geometry:* The central courtyard is a 4-sided linear court while the others are 3-sided square shaped courts. All the courts are 1 storey deep.

4- *Floor and Walls Surface Reflectance:* Highly reflective surfaces- white stucco walls and light-colored concrete paving.

5- *Adjoining Spaces:* Glass partitions are used to permit light and view to penetrate to areas not immediately adjacent to the windows.

2-6-3 Nathan Marsh Pusey Library

Location: Cambridge, Massachusetts.

Architect: Hugh, Stubbins and Associates, Inc. Cambridge

Construction Date: 1976.

Project Size: 8100m^2

Underground Classification:

1- *Function*: Non-Residential / Institutional / Library.

2- *Fenestration Type*: Courtyard type.

3- *Relation to Surface*: Subsurface building.

4- *Depth*: Moderate (12meters).

5- *Project Scale*: Large sized building scale.

Earth Cover: 90 Percent of exterior wall area is covered, 100 percent of total roof is covered with 0.3m to 0.9m of earth.

Reason for going Underground(1):

The decision to place Pusey library underground was based on aesthetics and land-use efficiency. Any new structure inserted into the historical setting of the Harvard Yard requires great sensitivity and restraint in its design. By placing the 8100m^2 building almost completely underground, not only is the character and open space of the Harvard Yard preserved, but the new building serves as a link between three other adjacent libraries. The subsurface design also contributes to the security of the building, with limited and well-controlled points of access. Sound reduction is another benefit of underground space that can be appropriately utilized in a library structure Fig (2-47).

Fig (2-47): Nathan Marsh Pusey Library exterior view showing the main entrance and the Harvard Yard.

Project Description(2):

Completed in 1976, the Pusey Library provides major expansion space for the Harvard University library system. The original site of the library sloped downward from south to north.

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(1) Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.83.

(2) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P.60

By changing the landscaped roof to be basically flat surface this exposes the northwest corner of the building where the main entry occur Fig (2-48). At this point, the upper floor of the library is only 0.9m below existing grade, whereas the same floor level is 3.6m to 4.2m below grade on the southeastern corner of the site. A secondary entry occurs on the south western corner of the site. In the center of the open space is a square sunken courtyard extending down two levels into the library Fig (2-49).

Fig (2-48): Nathan Marsh Pusey Library main entrance at the northwest corner of the building.

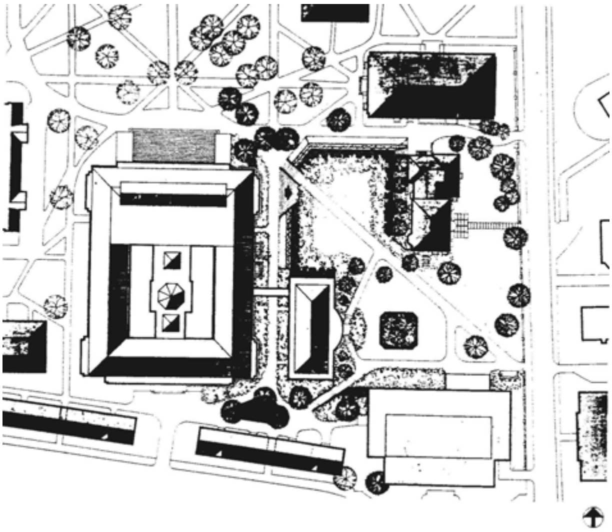

Fig (2-49): Nathan Marsh Pusey Library site plan showing the square sunken courtyard.

The various functions and collections on the three levels of the Pusey Library are arranged to facilitate access and provide light and view where appropriate to the most heavily used areas. On the upper level, a major corridor directs one past displays, lounges, and the main reading rooms of three special collections housed in the building: the Harvard University Archives, Theatre Collection, and Map Collection. The reading rooms and offices on this level all have large window areas facing the moat around the building (providing high windows in walls of exterior spaces) or the central sunken courtyard Fig (2-50). The stacks for the university archives and manuscript stacks from the general collection occupy most of the second level below ground. On this level, entrances to the three adjacent library buildings occur and faculty studies are located on three sides of the central courtyard Fig (2-51). The lowest level only about half the area of the upper two levels contains more stacks of the general collection.

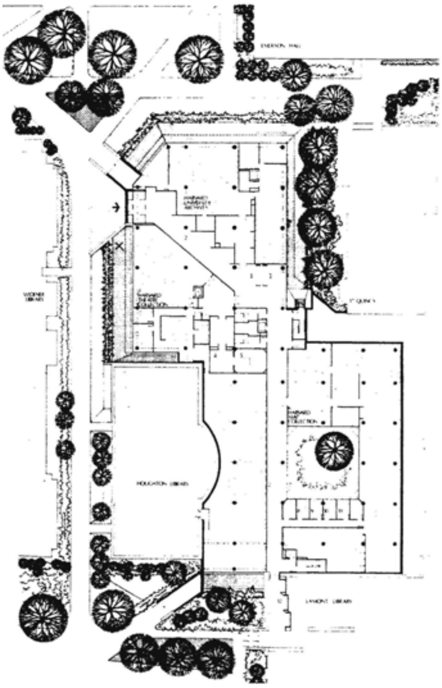

Fig (2-50): One level below grade plan showing the various functions within this level and the daylighting perimeter moat.

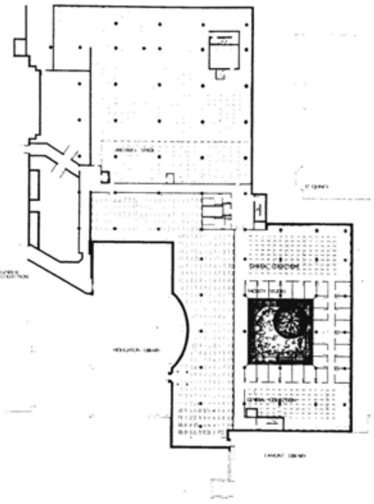

Fig (2-51): Two levels below grade plan showing the sunken square courtyard used to daylight this level.

Daylighting Concept⁽¹⁾:

Once inside the building, any negative associations with being in an underground space are offset by the variety of opportunities for natural light and exterior views. On the upper level, light and view are provided to a majority of spaces through the glass walls facing the perimeter moat and the sunken courtyard thus having more reflected light than direct sunlight Fig (2-52). The courtyard view and source of light occurs along the main corridor of both upper levels Fig (2-53). The majority of the middle level and all of the lower level (third underground level) are windowless and are appropriately for stacks. All the windows overlooking the sunken courtyard and the moat are triple glazed, not for energy conservation, but to aid in the careful control of humidity required to preserve documents in the building.

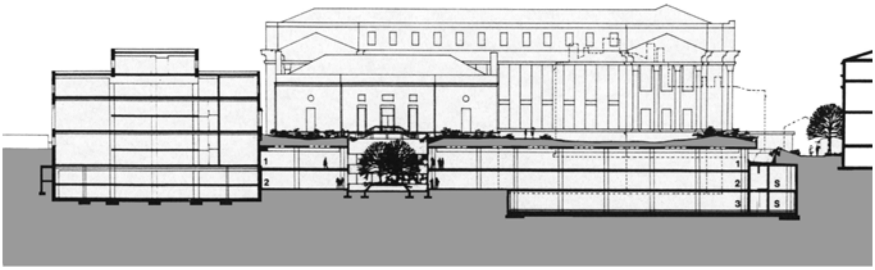

Fig (2-52): Nathan Marsh Pusey Library longitudinal section showing the daylighting concept (The sunken courtyard and the perimeter moat).

Fig (2-53): Exterior view of the famous Harvard Yard showing the sunken courtyard.

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(1) ibid, P.63

Daylighting Analysis:

1- *Daylighting Method*: One central sunken courtyard and additional windows overlooking the perimeter moat.

2- *Orientation*: The courtyard is oriented north-south, east-west thus allowing a variety of orientations suitable for the functions in the adjoining spaces.

3- *Shape and Geometry*: 4-sided, square shaped sunken courtyard 2 stories deep.

4- *Floor and Walls Surface Reflectance:* Light-colored floor and walls to maximize the light reflected to the adjoining spaces.

5- *Adjoining Spaces:* Variable glazing size in order to control the quantity of light entering each space according to its function.

2-6-4 Williamson Hall

***Location*:** University of Minnesota, Minneapolis, Minnesota.

***Architect*:** BRW Architects, Inc., Minneapolis, Minnesota.

***Construction Date*:** 1977 for the original building, 1982 for addition

***Project Size*:** 8035m^2 including 1982 addition

Underground Classification:

1- *Function*: Non-Residential / Institutional / Office building and campus bookstore.

2- *Fenestration Type*: Courtyard type

3- *Relation to Surface*: semi-subterranean

4- *Depth*: Shallow building (10meters).

5- *Project Scale*: Large sized building scale.

Earth Cover: 98 percent of exterior walls are earth covered, 7 percent of roof area is covered with 0.75m of earth (remaining areas of roof are 18 percent conventional roof and 75 percent precast concrete pavers.

Reason for going Underground:

Williamson Hall is an excellent illustration of an underground design resulting from a diversity of site-related, programmatic, and energy-related concerns.

One predominant feature of the site is the presence of several historic buildings clustered around it. On this particularly crowded area of the Campus, it was desirable as much open space as possible(1). By placing the new building almost completely underground, these objectives were met while the character of the area was preserved by avoiding any aesthetic conflict arising from placing older and more recent structures in close proximity. In addition, it became possible to place a relatively large building on a very constrained site, resulting in efficient land use(2) Fig (2-54).

Fig (2-54): Williamson Hall aerial view showing the underground building and the historic site.

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(1) DJB ARCHITECTS Ltd., David J. Bennett, FAIA New York, Minneapolis (http://djbarchitects.home.att.net)

(2) Brown, G., Dekay, M.; "Sun, Wind, & Light: Architectural Design Strategies", P.204

Project Description(1):

Williamson Hall serves as the student bookstore and contains the admissions and records offices for the university. The building is 95 percent below grade, the majority of the space is on two subsurface levels with only a small lounge and entry area above ground surface on one edge of the flat site. Included in the total area of 8035m^2 is the original building completed in 1977 and a 650m^2 storage area on two below grade levels that was added to the south side of the structure in 1982 Fig (2-55).

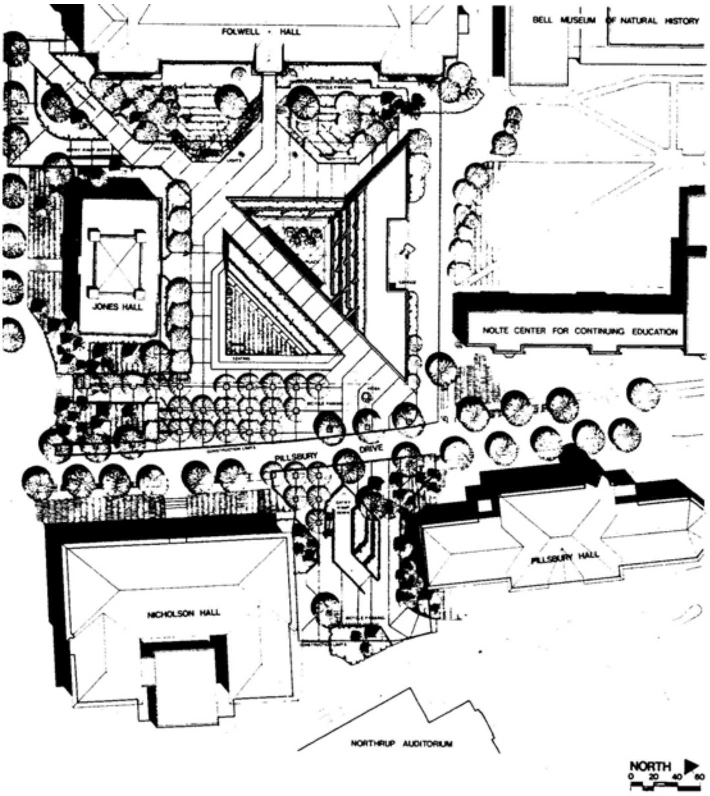

Fig (2-55): Williamson Hall site plan showing the new building and original existing historic buildings.

An important site constraint was the desire to preserve cross-site circulation. The site is basically square with a

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(1) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P.118

considerable amount of pedestrian traffic moving diagonally across it. This movement results from the location of the site between a campus commercial area with major mass transit stops and the remainder of the campus. Thus, the underground design provides an advantage over an above ground structure by permitting the circulation to continue uninterrupted over the building. In fact, the diagonal cross-site circulation is one of the major form determinants of the design Fig (2-56).

Fig (2-56): View of the pedestrian diagonal cross-site circulation.

The pedestrian walkways through the center of the building essentially separate its two distinct functions bookstore and office space. The differing requirements of the two functions are reflected in the design. The bookstore is mainly covered by glass and plaza areas on the surface except for a single row of clerestory windows providing light and view into the store. The half of the building containing the office areas, on the other hand, is designed with extensive windows that surround a sunken courtyard, which provide light and view out for the office workers Fig (2-57).

The building is actually designed with three major entrances. Two of them are located at either end of the site with ramps or stairs on the exterior leading to the major pedestrian walkway through the building. The third entrance is located in the small above grade portion of the building leading to an interior staircase and elevator. Once inside the building at the first level below grade, escalators provided convenient access to the second level down, where the bookstore and most public offices are entered Fig (2-58).

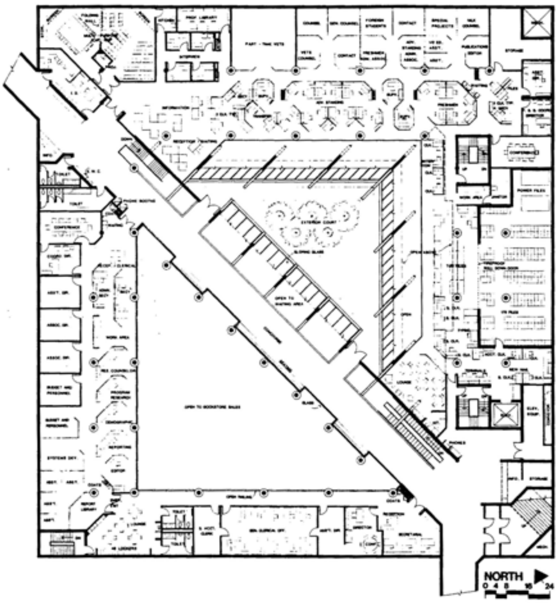

Fig (2-57): One level below grade plan showing the two main functions within the building (the bookstore and offices) and the diagonal walkway.

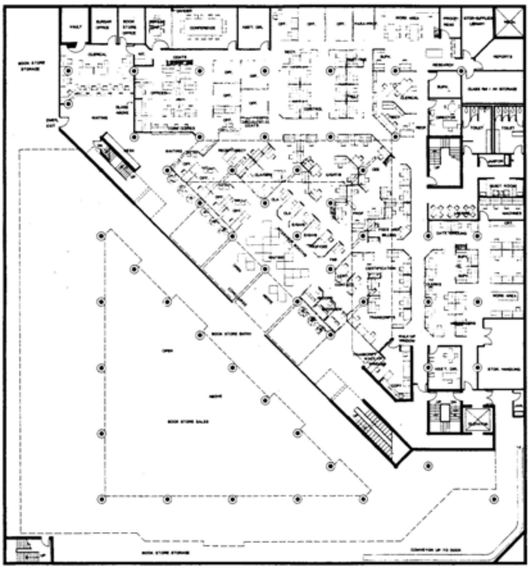

Fig (2-58): Two levels below grade plan showing the bookstore sales and the main office area.

Daylighting Concept(1):

The interior design of Williamson Hall is intended to create a feeling of openness and maximize the available light and view. Consequently, the bookstore is basically one large open space, two stories high with clerestory window providing light to the whole space. Even more effective is the light and view that penetrate the bookstore area from the sunken courtyard through the glass enclosed walkway Fig (2-59).

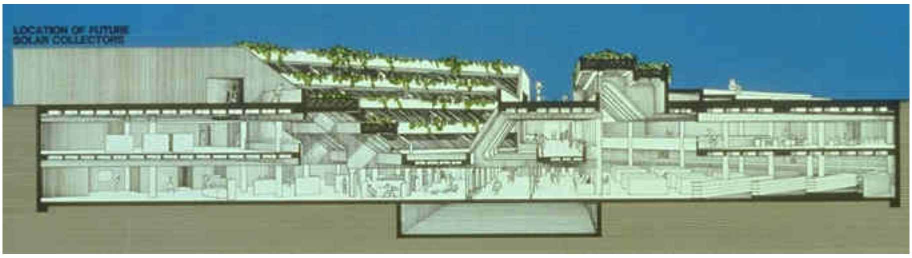

Fig (2-59): Williamson Hall cross section.

Although lacking windows to the outside, offices on the upper levels around the perimeter of the bookstore receive light through their glass walls and overlook the larger space. In a similar manner, much of the office space in the other half of the building is open, with lower partitions not only providing flexibility, but permitting light and view Fig (2-60).

Fig (2-60): Interior view of the offices area showing the daylighting fenestrations used.

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(1) ibid,P.121

This building has no horizontal skylights overhead. All of the glazing is sloped. Considering the relatively small area of glazing in the building - 3 percent of the total floor area ($235m^2$), all double glazed - it is remarkable that the majority of the building is daylit and open exterior views are available in most spaces Fig (2-61).

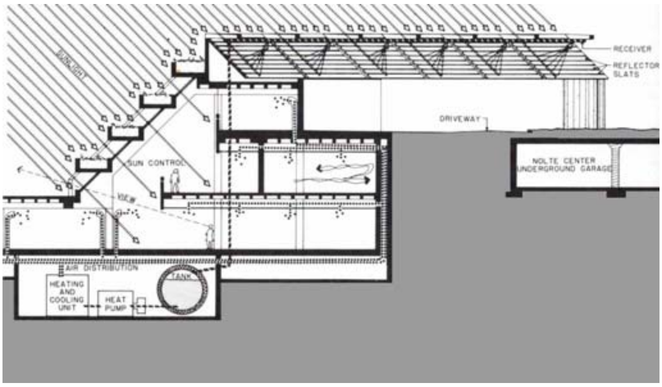


Fig (2-61): Detailed section showing the 45-degree sloped glazing.

Because of the potential for glare and overheating in summer tiers of planters are placed over the major areas of south-facing glass. The Engleman ivy plants that hang from these planters provide shade in the summer but drops it leaves in the winter to permit greater daylighting and solar heat gain values Fig (2-62).

Fig (2-62): View of the court showing the tiers of planters with the Engleman ivy plants used to shade the glazing in summer.

Daylighting Analysis:

1- *Daylighting Method*: One sunken courtyard with clerestory overlooking the diagonal pedestrian walkway providing light to the bookstore.

2- *Orientation*: Most of the glazing in Williamson Hall is oriented to the south and west providing natural daylighting and passive solar heat gain.

3- *Shape and Geometry*: The courtyard is triangular shaped with spaces overlooking all of its sides.

4- *Floor and Walls Surface Reflectance*: Light-colored surfaces to maximize daylight penetration to the side spaces.

5- *Adjoining Spaces*: Most of the glazing is sloped at a 45-degree angle to permit greater light penetration and view to the lower level while still maintaining horizontal views out of the building into the courtyard

2-7 Conclusions

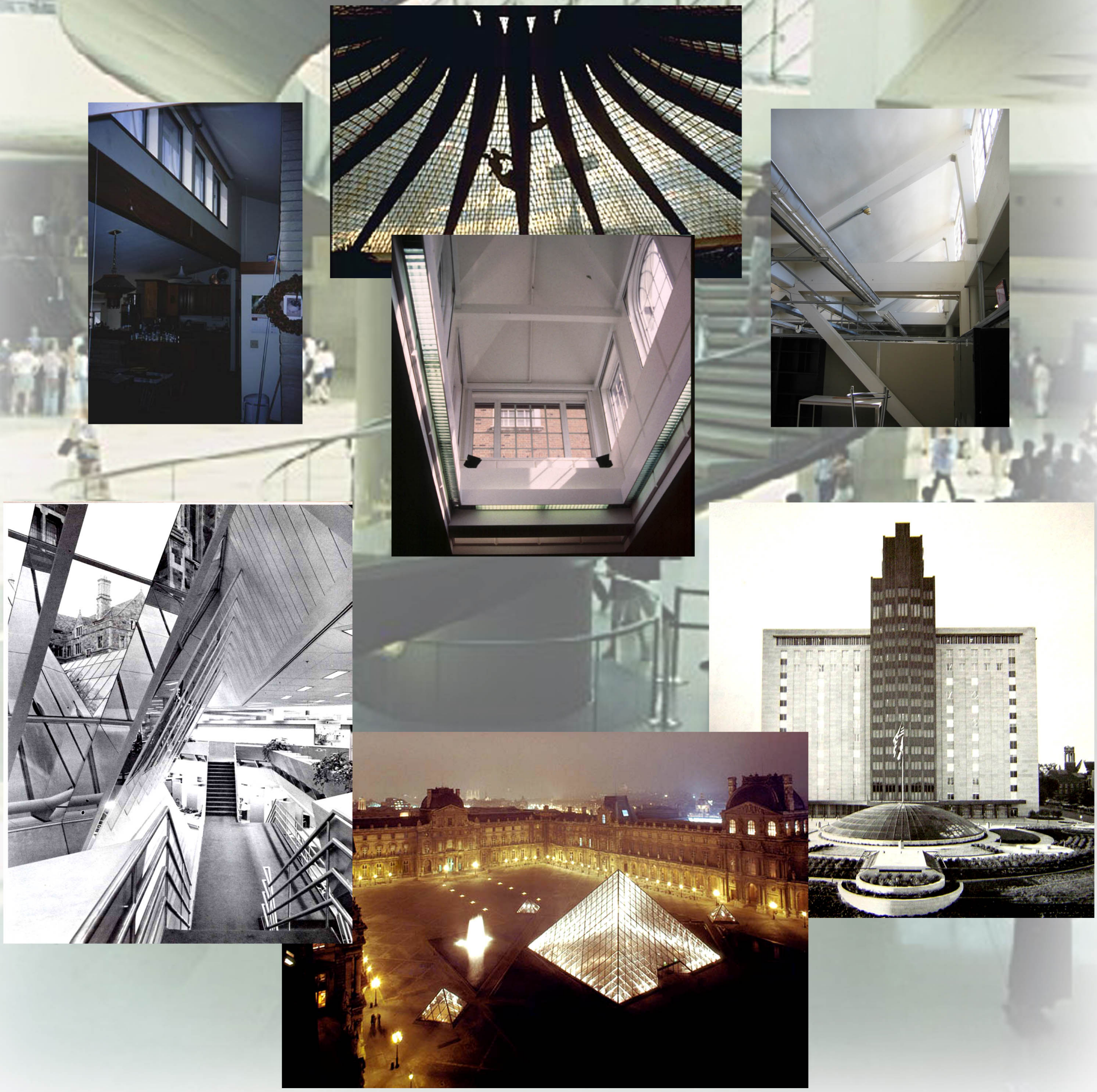
Daylighting is an essential need for all living organisms and have been profoundly related to architecture since the beginning of time. All the building developments (architectural and structural) reflected one main goal: increasing the daylight in the interior spaces. Daylighting has many significant benefits concerning the provided view, health aspect, light quality, and energy conservation.

Daylighting the underground space can be achieved by a number of traditional concepts and innovative systems. Traditional concepts include courtyards, atria, and top-lighting methods. Innovative systems include: heliostats, light pipes, and fiber optics daylighting systems.

Courtyards are one of the traditional methods that are used to daylight shallow underground spaces. Their orientation plays a significant role in the daylight penetration to the adjoining spaces and depends on what functions inhibit which sides. The courtyard size depends upon its intended function and the courtyard form is dependent on the building’s architectural concept and can be two-sided, three-sided, or four-sided. In the daylighting analysis of the courtyard the following aspects should be given a special concern: the courtyard proportions (length, width, and height), the walls and floor surface reflectance, and finally the proportions of the adjoining spaces.

The atrium is another traditional method that can be used to daylight shallow and deep underground spaces. Atria are similar to courtyards in many aspects except for two major points: the atrium roof and its thermal performance. The daylight penetration in the atrium is affected by many parameters. Those parameters include the atrium orientation and its shape, the atrium geometrical proportions, the atrium roof, and the atrium interior surfaces reflectance. Some design strategies can be used to increase the daylight penetration deeper into the atrium and the adjoining spaces. The main problem with the atrium thermal environment is the glazing used in the roof of the atrium which requires special treatment to control the heat loss or gain.

Chapter(3)
Top-lighting Concepts for Daylighting Underground Spaces



Chapter (3)

Top-lighting Concept for Daylighting Underground Spaces

3-1 Introduction

Top-lighting technique is one of the concepts that are used to deliver daylight to the underground buildings especially the shallow ones. It is used to daylight one or two stories - at the most - below ground. Although the top-lighting concept is not included in the underground buildings classification according to the fenestration type, it can be used to admit daylight to the underground spaces. It can be used as the only light source for the space or it can be used with side-lighting from courtyards or atria to enhance the daylight penetration to the relatively deep and large spaces.

Top-lighting concept offers a better illumination in terms of quality and quantity since the daylight can be controlled as desired. Top-lighting could be divided into horizontal top-lighting technique which includes horizontal skylights and vertical top-lighting techniques which include monitors, sawtooth and clerestories.

This chapter reviews the top-lighting techniques used to admit daylight to the underground spaces. Their benefits, basic components, their configuration and many other characteristics concerning the quality and quantity of daylight admitted into these spaces are reviewed. Then, several underground buildings using top-lighting concepts as a daylight source are presented and analyzed.

3-2 Top-lighting Concept as a Daylight Source for Shallow Underground Spaces

3-2-1 Top-lighting Definition

Top-lighting concepts are those in which the daylight penetrates an underground space from openings that are located above the ceiling line and usually constitute part of the roof of the building(1). Top-lighting concepts are often used in cases where the design concept or light criteria make side-lighting from courts and atria inappropriate. They can be also used to enhance the depth of penetration of side-lighting apertures.

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(1) Robbins, C.; "Daylighting: Design and Analysis", P.87

Often, top-lighting concepts are used in areas where security requirements reduce the desirability of side-lighting or where a view in or out is inappropriate or in case of using a courtyard or atrium is not an option. There are four traditional top-lighting concepts that use the clear or overcast sky as an interior illuminant Fig (3-1). The four top-lighting concepts are:-

1- Horizontal skylights
2- Sawtooth lights
3- Monitor lights
4- Clerestories

Each of these concepts involves a different architectural treatment of the building form and interior design, and each provides a different and unique lighting character and distribution patterns that differ from all the other lighting concepts(1).

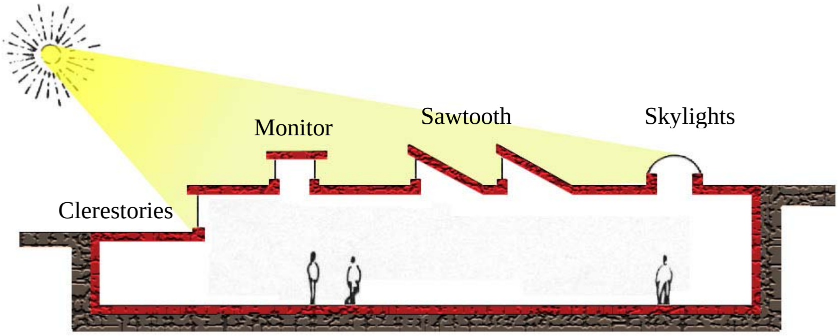

Fig (3-1): The different top-lighting concepts used to daylight underground spaces(2)

3-2-2 Top-lighting Concept Potentials

The use of top-lighting concepts has grown in recent years because they can save energy through daylighting, and the quantity and quality of light they deliver is different from any other lighting concepts(3) .

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.54

(2) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.320

(3) CADDET; "Saving Energy with Daylighting Systems", P.4

Top-lighting concepts can make a number of major contributions to the underground built environment since they:

- Provide excellent lighting conditions to the underground spaces.
- Reduce the use of electric lighting to save energy and reduce peak electric loads when combined with photo controls.
- Satisfy human needs for contact with the outdoors.
- Provide emergency smoke vents.

As for the quantity and quality of daylight delivered by top-lighting concepts, they are excellent devices for picking up large quantities of light with minimum sized openings(1). The illumination falling on the horizontal plane of the roof provides approximately three times illumination greater than that striking the vertical plane of the window wall in any court even under an overcast sky(2).

Top-lighting concepts are effective tools for delivering daylight deep into interior areas of a single storey building or into the top floors of multi-storey buildings(3). They can also provide fairly uniform illumination over large interior areas, while daylighting with side windows is limited to about 4 to 6m depth(4) Fig (3-2).

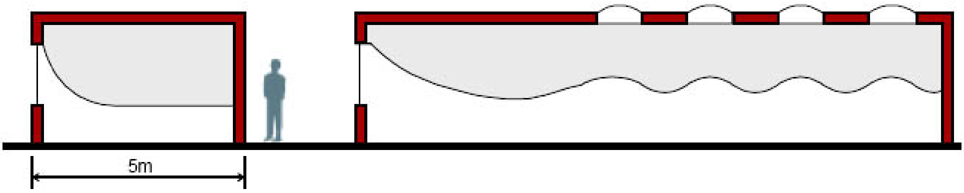

Fig (3-2): Top-lighting for large interior areas(5)

It should be noted that all overhead lighting sources have the potential to create veiling reflections which are best avoided by keeping

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(1) Schiler, M.; "Simplified Design of Building Lighting", P.89

(2) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.61

(3) Carmody, J., Sterlling, R.; "Underground Space design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.271

(4) Ruck, N.; "Building Design and Human Performance", P.192

(5) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.320

light sources out of the offending zone(1) Fig (3-3). The best solution for those reflections is to carefully diffuse the light so that no bright sources exist. The diffusion can be accomplished by reflecting the light off the ceiling or by using baffles to shield the light sources(2).

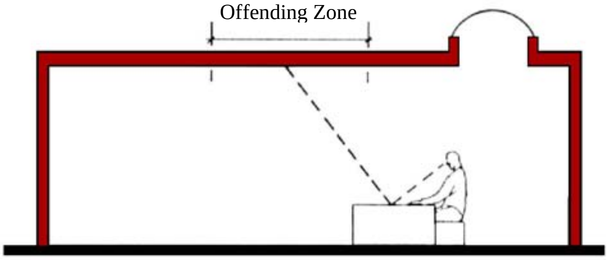

Fig (3-3): Veiling reflections are avoided when skylights are placed outside the offending zone.

3-3 Top-lighting Concept Analysis

When analyzing daylight distribution resulting from top-lighting concepts two main issues should be given special concern. The first issue that will be discussed in top-lighting concepts is the daylight penetration and spread, while the second issue will be the lighting zones resulting from the light penetrating the top-lighting openings.

3-3-1 Daylight Penetration and Spread in Top-lighting Concept

The daylight distribution pattern in case of top-lighting concepts is described according to its penetration and spread(3). In top-lighting the light penetration is not a primary concern because, in most cases, the distance between the floor and ceiling is within the optimum penetration range of 2.5 to 6ms. In addition, top-lighting concepts usually have a view of a larger portion of the sky dome or zenith, and consequently the available exterior illuminance is often much greater than in other lighting concepts.

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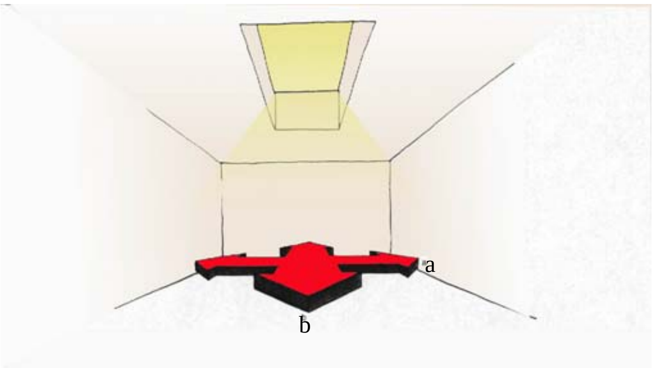
(1) Public Works and Government Services, Canada; "Underground Guide for Canadian Commercial Buildings", P.32

(2) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.61

(3) Robbins, C.; "Daylighting: Design and Analysis", P.89

In top-lighting concepts, longitudinal and latitudinal spreads are the key of the daylighting distribution concern Fig (3-4). Longitudinal spread is used to describe the daylight distribution along the length of the opening, while latitudinal spread describes the daylight distribution normal to the length of the opening. Vertical spread is used to describe light distribution on vertical surfaces⁽¹⁾.



(a) Latitudinal spread (b) Longitudinal spread

Fig (3-4): Daylight spread from top-lighting concepts⁽²⁾.

3-3-2 Light Zones in Top-lighting Concept

The light zone is a term used to describe areas having the same illumination levels. Most often, light zones are established to represent proportions of the room that can be illuminated to task, background, or general illuminance levels.

In case of top-lighting concepts the primary lighting zones, area having the highest illumination level, are located under the openings, away from the perimeter of the space. The primary lighting zone for top-lighting concepts is often larger than in any other lighting concept. Because the primary lighting zone is located on the interior of the underground space, the secondary or teritary lighting zones that might be used for circulation spaces are located on the perimeter of the underground space⁽³⁾ Fig (3-5).

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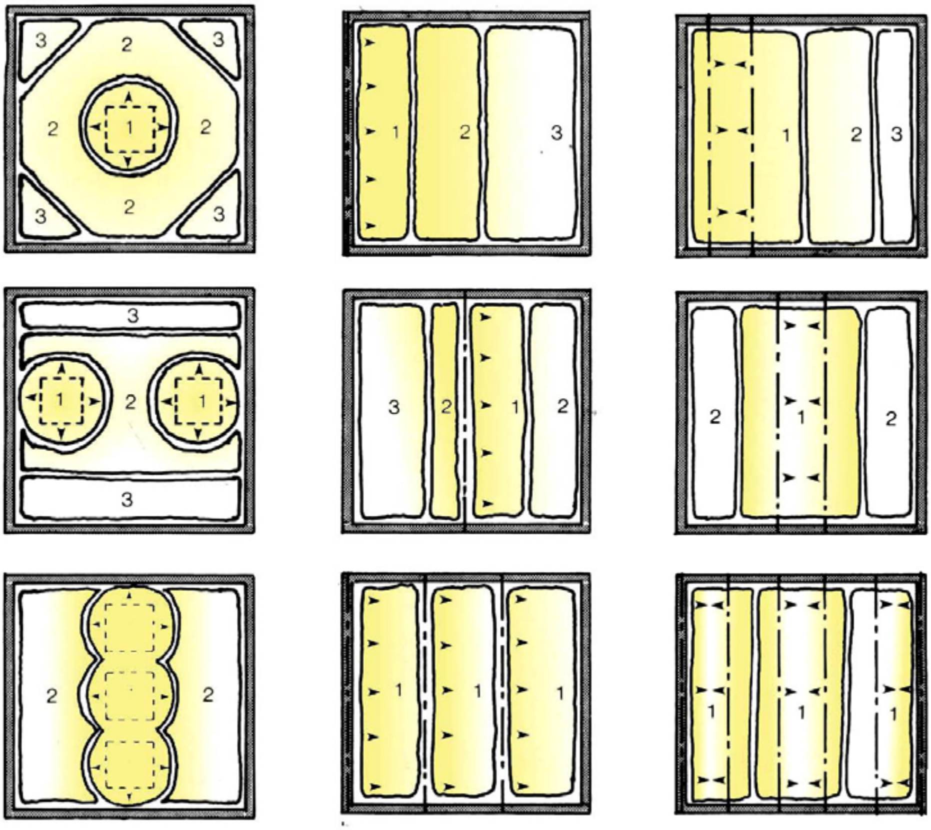
(1) ibid

(2) ibid

(3) ibid



Skylights Sawtooth Monitor

Fig (3-5): Lighting zones produced by different top-lighting concepts[1].

3-4 Using Top-lighting Concepts for Daylighting Underground Spaces

3-4-1 Horizontal Top-lighting Concept: Skylights

3-4-1-1 Skylights Definition

Skylights are horizontal or slightly slopped openings in the roof[2] Fig (3-6). Skylights provide a relatively uniform level of illumination throughout a space and allow for the use of both sky light and sunlight as interior illuminants, although the use of sunlight

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[1] ibid, P.90

[2] Schiler, M.; "Simplified Design of Building Lighting", P.89

(direct sun) is often discouraged⁽¹⁾. Skylights can be used to provide general illuminance or to illuminate a three dimensional display or a piece of art but they are less likely to be satisfactory where paperwork occurs, as in offices, drafting areas, and reading rooms⁽²⁾. The wide range and fluctuations of sunlight intensity are more noticeable in applications that require concentration on text⁽³⁾.

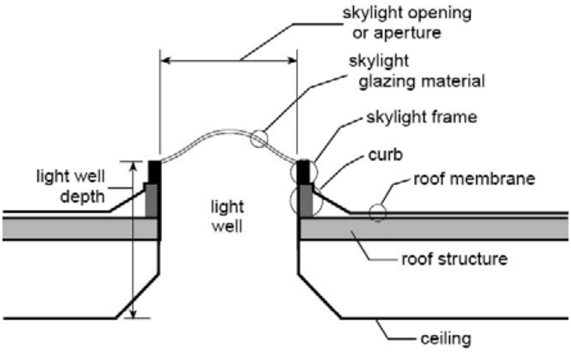

Fig (3-6): Components of a typical skylight.

There are several considerations for the designer to take into account when designing a skylight system for daylighting⁽⁴⁾. Those considerations include:

- Visual and thermal comfort.
- Seasonal and daily shifts in daylight availability.
- Integration with electric lighting system.
- Integration with the HVAC design.
- Structure and safety concerns.

3-4-1-2 Skylights Potentials

In terms of illumination quality, the major advantage of skylights is the ideal color rendition of daylight. Skylights must be located where the sun can shine on them directly. A skylight doesn't produce a useful amount of daylight if it is shaded by adjacent

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.34

(2) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.330

(3) Wulfinghoff, D.; "Energy Efficiency Manual: Measure 8.3.1Install Skylights or Light Pipes", P.966

(4) Energy Design Resources [http://www.energydesignresources.com/docs/sg-1-deign.pdf]

structures. Retrofitting skylights in existing buildings should be given a special concern because of the cost and structural interference.

Conventional skylights are related to problems associated with heat gain(1). However, sunlight has a better ratio of light-to-heat than any type of electric lamp. Therefore, if the light from the skylights is distributed efficiently and skylights are not oversized, they may not substantially increase the cooling load. Skylights can provide significant passive heating during cold weather(2).

3-4-1-3 Skylights Sizes and Shapes

Skylights are available in a wide variety of sizes and shapes to match nearly any building need. They range from simple rectangles to complex polygons. They can be small or large enough to run the length of a building(3). The glazing can be used in a simple plane or in a multi-face framing system that assumes various pyramid shapes Fig (3-7). Plastic glazing can be molded in dome or pyramid shapes for greater stiffness(4).

Built-up skylights can be made in virtually any size. Materials that cannot be bent easily, such as glass and fiber-reinforced plastic, are usually made into skylights this way(5). Molded and curved skylights are limited in size, but they can be grouped together to create a skylight of any size. Individual units can be molded to overlap curbs, an excellent method of avoiding leaks. Large skylights can be made of sheets of reinforced plastic that are curved in one direction(6).

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(1) Muhs, J.; "Design and Analysis of Hybrid Solar Lighting Full-Spectrum Solar Energy Systems", P.8

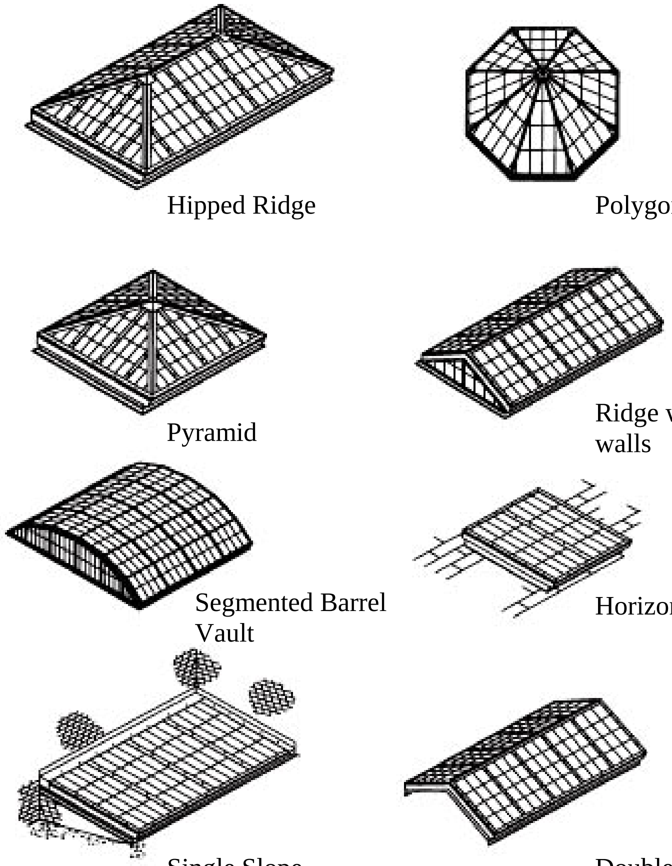
(2) ibid

(3) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

(4) Wulfinghoff, D., "Energy Efficiency Manual: Measure 8.3.1Install Skylights or Light Pipes", P.973

(5) Oikos, Green Building Resource [http://oikos.com/library/eem/skylights/#anchor-where-41350]

(6) Wulfinghoff, D., "Energy Efficiency Manual: Measure 8.3.1Install Skylights or Light Pipes", P.973



Hipped Ridge

Polygon

Pyramid

Ridge with end walls

Segmented Barrel Vault

Horizontal

Single Slope

Double Slope

Fig (3-7): Skylights Shapes.

Sloped skylights could be used to improve light balances between winter and summer months. A sloped skylight will collect more winter light and less summer light(1) Fig (3-8). For north-facing skylights, the slope of the skylight (from the horizontal) should be the site latitude plus 23.5° to receive the maximum daylight with a minimum amount of direct sunlight entering the building(2) Fig (3-9). For

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(1) Seif El Nasr, S., "Daylighting Design Process in Buildings: An Approach for Integration of Daylighting in The Design Process", P.64

(2) Public Works and Government Services, Canada; "Underground Guide for Canadian Commercial Buildings", P.34

south-facing skylights, the slope of the skylight should be greater than the site latitude plus 23.5˚(1).

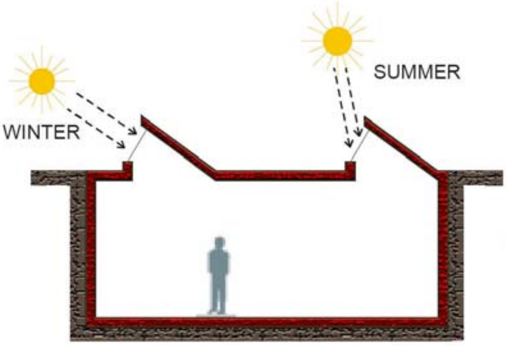

Fig (3-8): Skylights exposure in winter and summer.

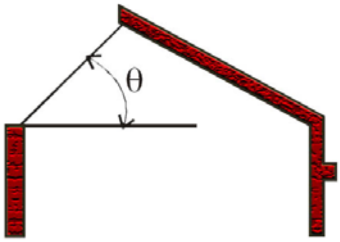

Fig (3-9): Skylight slope

3-4-1-4 Skylights Layout and Spacing

The skylight layout is primarily dictated by the design concept for the space. However, when skylights are provided in order to create uniform lighting in large open spaces, careful attention to spacing is important. Large widely spaced skylights are usually the most economical to install, but may produce bright conditions and cause glare under the skylights and relatively dark conditions in between. This results in uneven light distribution, reduced energy savings, and possible glare problems. Small, closely spaced skylights, on the other hand, will provide more uniform lighting conditions and greater energy savings, but will be more costly to install Fig (3-10). The differences in illumination level between locations directly under the skylights, compared to locations between skylights will be greater as the skylights become wider.

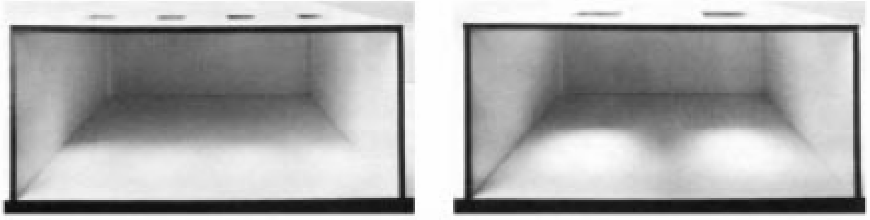

Fig (3-10): Skylights spacing affects the uniformity of light distribution.

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(1) ibid

In case of the absence of side-lighting apertures, the general rule of thumb is to space skylights at 1.0 to 1.5 times ceiling height (center to center in both directions)(1) Fig (3-11). In case of using side-lighting with the skylights, the general rule of thumb is to space the skylight next to the aperture at a distance 2H from the side aperture(2) Fig (3-12). This assumes a highly diffusing glazing and a modest depth for light wells. Skylight placement must also be coordinated with the structural, mechanical and lighting systems. Other variables come into consideration, such as glazing type, light well design, controls and other factors are discussed later.

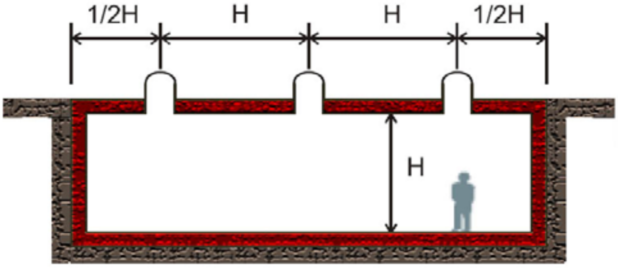

Fig (3-11): Recommended spacing for skylights without side windows(3).

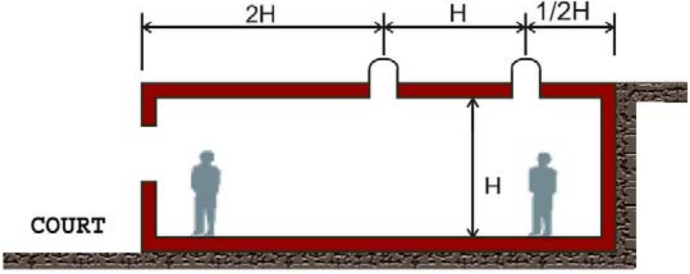

Fig (3-12): Recommended spacing for skylights with side windows(4).

3-4-1-5 Skylights Glazing

Common glazing materials for skylights include a variety of plastics and glass(5). The common plastic materials include acrylics, polycarbonates, and fiberglass. The advantages of glass include

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(1) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects", P.330

(2) ibid

(3) ibid

(4) ibid

(5) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

unlimited life, high light transmission, hardness, and rigidity. Glass can be treated to reduce cooling load by selectively absorbing the infrared portion of sunlight⁽¹⁾. The main problem of using glass is its vulnerability to breakage, along with the safety hazard that falling glass creates. Glass can be made more resistant to shattering by increasing its thickness, and by combining it with reinforcing materials⁽²⁾. Plastic materials are much lighter in weight, and they are resistant to shattering so they pose only a minimal safety hazard. Plastic skylights can be easily fabricated with multiple layers of glazing to improve thermal resistance. Plastics can be reinforced with fibers of various materials but the fibers cause some light losses⁽³⁾. Reinforced plastic is more difficult to mold into compound shapes. It is normally made in flat sheets, which can be curved only in one direction. Polycarbonates are stronger, but acrylics are more resistant to degradation by the ultraviolet component of sunlight⁽⁴⁾. All plastics deteriorate in strength and light transmission over a number of years. The main causes of deterioration are the ultraviolet light portion, heat and oxidation. The service life of plastic glazing can be extended greatly with additives.

Glass and plastic can be combined in larger skylights to minimize their respective weakness. Glass is used for the outer sheet, where it can provide considerable protection to the plastic, while the inner plastic sheet protects against glass breakage. Ordinary glass strongly absorbs the damaging ultraviolet portion of sunlight, so a plastic material will survive longer if it is installed inside glass.

The glazing area is usually between 3% to 12% of the floor area⁽⁵⁾. The lower limit of this range is used for spaces with high

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(1) Ruck, N.; "Building Design and Human Performance", P.204

(2) Oikos, Green Building Resource [http://oikos.com/library/eem/skylights/#anchor-where-41350]

(3) Wulfinghoff, D., "Energy Efficiency Manual: Measure 8.3.1Install Skylights or Light Pipes", P.973

(4) ibid

(5) Seif El Nasr, S., "Daylighting Design Process in Buildings: An Approach for Integration of Daylighting in The Design Process", P.55

air conditioning or heating loads, and the higher limit is used for temperate climates with more overcast skies⁽¹⁾.

The choice of the glazing material for a skylight can have an enormous effect on the quality of the light provided and the energy efficiency of the design. Factors to consider include:

- How much light is transmitted through the glazing - measured by the Visible Transmittance (T_{vis})
- How much of the direct beam sunlight is diffused - measured by the Transparency of the material.
- How much of the sun's radiant heat is transmitted through the glazing - measured by the Solar Heat Gain Coefficient (*SHGC*)
- How much heat from the air will pass through the glazing

There are two properties that should be given a particular attention concerning the skylight glazing:

I) Transmission of light II) Transmission of heat

I) *Transmission of Light*

In terms of the lighting performance of a skylight, the two most important properties are how much light it allows to pass through (transmittance) and how much it diffuses the sunlight that strikes it (transparency)⁽²⁾. Most people assume that the more transparent a piece of glazing is the more light will pass through it. However, the two properties are not directly related.

In general, the higher the visible transmittance of the material, the more efficiently the skylight can provide light to the room below. Diffusion of beam sunlight is important to avoid "*Hot Spots*" ⁽³⁾, where sunlight is more concentrated and creates areas that are both too bright and less comfortable due to the radiant heat of the sun.

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(1) ibid

(2) Laouadi, A., "Design Insights on Tubular Skylights", P.2

(3) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

Highly diffusing skylights are needed to achieve uniform illumination, allowing the overall lighting system and controls to be more efficient.

II) Transmission of Heat

The choice of glazing also affects the amount of heat that passes both in and out of the skylight. There are two important characteristics here: the relative proportion of the sun's radiant heat that is blocked by the glazing material, measured by solar heat gain coefficient (*SHGC*), and the overall resistance of the skylight unit to all types of heat flow, measured by *R-value*(1).

How much of the sun's radiant heat passes through a skylight is largely a function of the chemical structure of the glazing material. Various materials react differently to different portions of the sun's spectrum. Some wavelengths will be reflected, some will be absorbed and some will be transmitted. If most of the wavelengths in the infrared and ultraviolet portions of the spectrum are also largely transmitted, then the glazing material will allow almost all of the sun's radiant energy to pass through into the space below, and it will have a very high *SHGC*. If more of the non-visible radiant energy is reflected, then the material will have a lower *SHGC*(2). If the non-visible components of solar radiation are absorbed, rather than reflected or transmitted, then the glazing material itself will heat up. Part of the heat will be conducted downward into the space. The rise in temperature of the glazing material may also cause it to expand and deform.

In general, the most efficient skylight glazing material will allow the maximum amount of light to pass through, while rejecting the non-visible wavelengths of solar radiation (i.e. high transmittance glazing). High transmittance glazing, sometimes known as "*Low-emittance glazing*", has good optical clarity, high solar transmittance to admit sunlight in winter, and low thermal conductance. Low-e coatings have a high visible transmittance, being predominantly

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(1) ibid
(2) ibid

transparent over the visible wavelengths and are reflective in the infrared region(1).

The concept of an efficient glazing material for daylighting, based on a relatively high visible transmittance in conjunction with a comparatively low *SHGC* is described by the term "*Glazing Efficacy*". Glazing Efficacy(2) is the measure of how much light penetrates all the layers of the glazing material in relation to how much solar heat gets through. It is important to understand that it is not just one property or the other that is important, but the relationship between the two that determines how efficiently the glazing material will perform.

The other way that glazing materials affect heat transmission is described by their thermal resistance to all three forms of heat flow: conduction, radiation and convection. Adding layers of glazing to create insulating air spaces is the most common way to improve a skylight's resistance to heat flow (e.g. double and triple glazing). Since each glazing layer inevitably represents additional cost and loss of light, there is obviously a point at which added insulation is not cost effective. This balance point is highly dependent upon the local climate conditions, the design and operation of the building, and the relative costs of electricity and heating fuels.

3-4-1-6 Skylights Placement

The majority of skylights are installed on flat roofs where the skylight can use almost the full hemisphere of the sky. A top-lighting opening on a sloped roof cannot see the full sky hemisphere, but only a partial view determined by the slope of the roof. Furthermore depending upon the angle and orientation of the sloped roof, the sun may not reach the skylight during certain times of the day or year(3) Fig (3-13)

The shape of the skylight also affects how much daylight it can provide at different times of the day. The slope and

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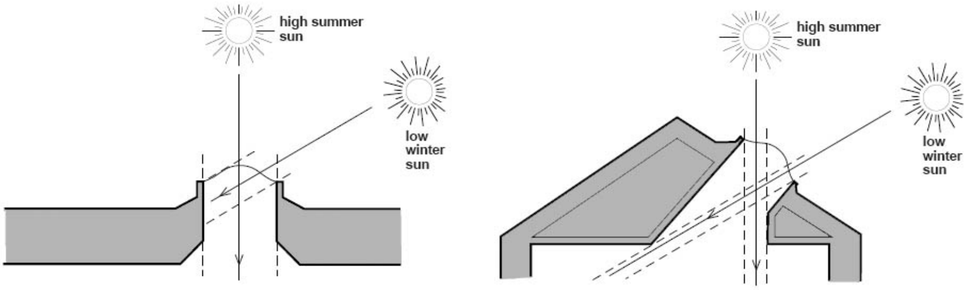
(1) Ruck, N.; "Building Design and Human Performance", P.204

(2) ibid

(3) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

orientation of the roof and the light well have a major impact on how much sunlight penetrates into the interior of the building.



Flat roof Sloped roof

Fig (3-13): Penetration on flat versus Sloped skylights.

3-4-1-7 Skylights Wells

Skylight wells are a primary component of the skylighting systems. They bring the light through the roof and ceiling structure, and they simultaneously provide a means for controlling the incoming daylight before it enters the main space. They are used to distribute the light and to shield the viewer from an overly bright light source. Skylight wells can be designed in a wide variety of shapes. The simplest are vertical sided shafts, the same size as the skylight opening. More elaborate wells have splayed or sloping sides that spread the light more broadly through the space(1) Fig (3-14).

The shape and size of the well is often determined by the roof and ceiling structure. Wells can be made from wood, gypsum board, ceiling tiles, or any other construction materials.

In some buildings, skylight wells consist only of the depth of the curb and the thickness of the roof structure but in buildings with dropped ceilings the skylight well can be deeper. On the other hand deep wells are an opportunity for greater control of the distribution of the daylight from skylights.

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(1) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

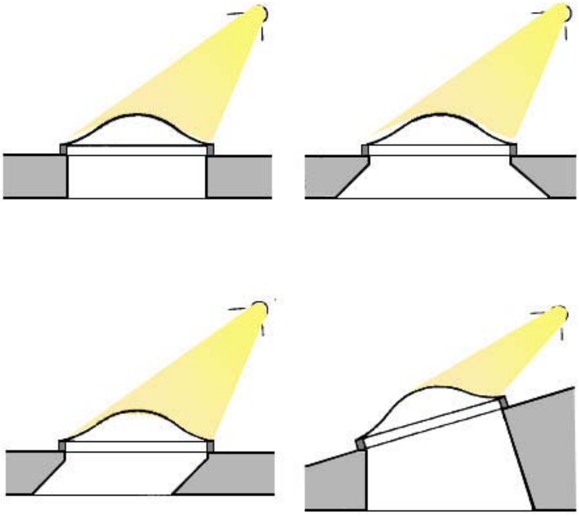
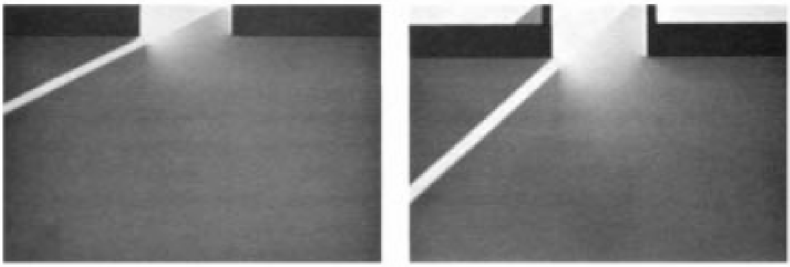


Fig (3-14): Types of light wells.

In designing wells for skylights, a number of factors must be considered:

I) *Solar Geometry*

The height and orientation of the sun change both daily and seasonally. The direct sun that enters a transparent skylight can be prevented from penetrating down to the task surface by light wells; conversely, the wells can reflect the sun light to a particular destination. To block high sun angles, the light well must be deeper than for low sun angles. With diffusing skylights, the angle of the sun is less of a concern, but the amount of light and heat entering the space will still be affected by solar geometry(1) Fig (3-15). If transparent glazing is used, the design of the light well must carefully consider sun angles. Light wells can provide a means of cutting off direct sun penetration.



Shallow light wells provide lower sun control

Deeper wells cut off higher sun angles

Fig (3-15): Shading of direct sun by light well. (Light wells can provide a means of cutting of direct sun penetration)

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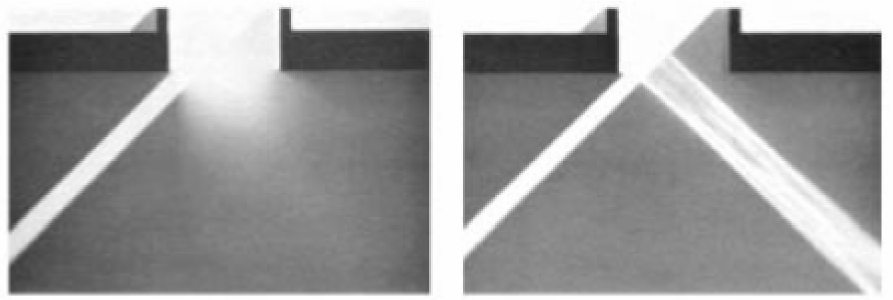
(1) ibid

II) *Surface Reflectance*

Skylight wells reflect and diffuse sunlight as it bounces from the skylight to the task surface. A highly reflective, diffusing surface (such as flat white paint) will help to provide a diffuse, broadly distributed light pattern below the skylight. On the other hand, a specular reflective surface, such as reflective foil, will not diffuse the light, but will reflect an image of the sun and sky on to a limited area below the skylight. Colored surfaces will distribute the light evenly, but will reduce its intensity and can dramatically shift the appearance of colors in the room below[1]. For applications where uniform light distribution is desired, a matte white surface is the best Fig (3-16).

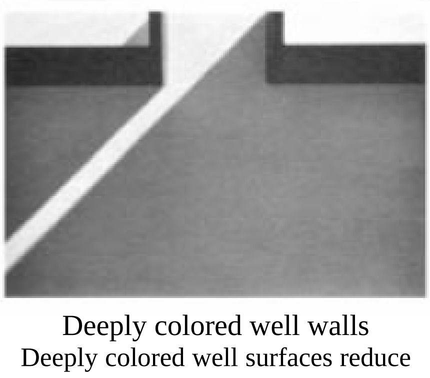


Diffuse well walls

Diffuse walls (e.g., flat or matte paints) reflect incident light in all directions, spreading the brightness

Specular well walls

Specular walls (e.g., mirror surfaces) reflect a direct image of the sun or skylight to the space below



Deeply colored well walls

Deeply colored well surfaces reduce nearly all light scattering, and tend to admit only direct sunlight

Fig (3-16): Reflective properties of well surfaces.

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[1] ibid

III) *Skylight Well Wall Slope*

The slope of well walls help to determine the distribution of light in the space(1). The broader the base of the well, the larger the task area in the space having a direct view of the skylight. This is an advantage under overcast sky conditions or with a diffusing skylight, but it can be a serious disadvantage with a transparent skylight when direct sunlight is present. Deep wells with vertical walls prevent direct view of the skylight and block low angle beam sunlight, but tend to keep the light concentrated in a smaller area and provide less uniform light distribution Fig (3-17). Splayed well walls allow a larger area of the space to view the skylight surface. With diffusing glazing, this helps to provide uniform illumination. With transparent glazing, splayed walls allow greater penetration of beam sunlight.

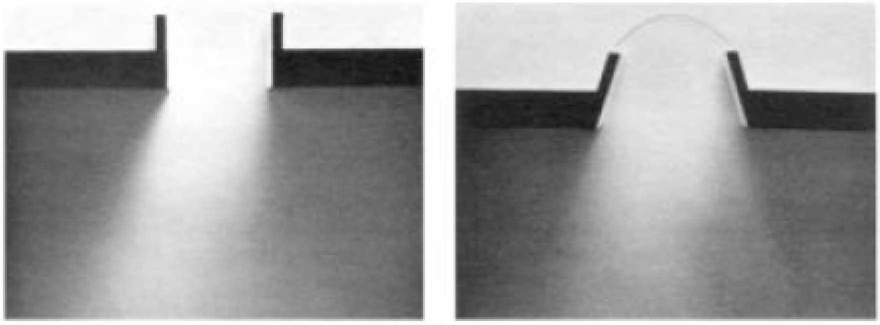

Fig (3-17): Splayed well wall effect

IV) *The Well Index*

The inter-reflections of light that occurs between the side walls of a skylight well absorb the light and decrease the overall daylight transmission to the space. The efficiency with which the well transmits daylight is a function of the well wall reflectance and the shape of the well. Tall narrow wells are less efficient. The lower the efficiency of the well, the larger the skylight must be to provide the same light level(2).

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(1) ibid

(2) Brown, G., Dekay, M.; "Sun, Wind , and Light: Architectural Design Strategies", P.233

The well Index (*WI*) is a geometrical proportion that relates the three geometrical proportions of the well. It is defined as⁽¹⁾:

$$WI = \frac{H(W + L)}{2(W \times L)}$$

Fig (3-18) uses the well index and the skylight well wall reflectance to estimate the efficiency of the skylight well. First, the well index is determined. Then, the graph is entered vertically from the horizontal axis until it meets the specific well reflectance. Finally, the efficiency of the skylight well is determined by moving horizontally until it intersects the vertical axis.

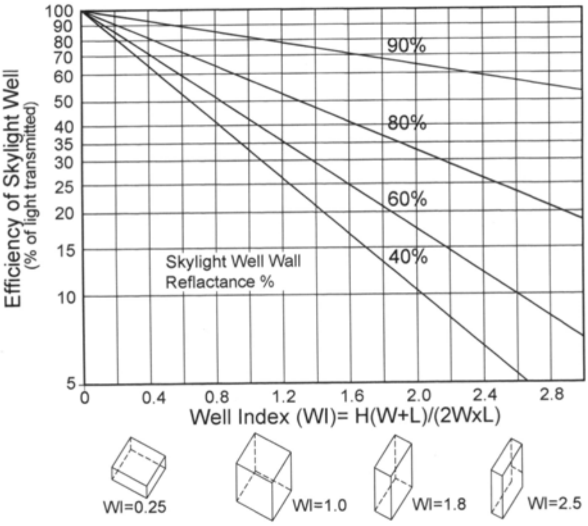

Fig (3-18): The well index and the efficiency of the skylight well.

3-4-1-8 The Skylight Geometrical Proportions and The Light Distribution Pattern.

The light distribution pattern resulting from skylights depends on its geometrical proportions (length, width, and height of the well). The height of the well through which the daylighting must penetrate have a significant impact upon the distribution and quantity of natural light in the room⁽²⁾.

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(1) Schiler, M.; “Simplified Design of Building Lighting”, P.108

(2) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

The light distribution pattern resulting from a single skylight in the base case takes on a bell shape curve under either a clear or an overcast sky(1) Fig (3-19). It should be taken in consideration that the impact of the direct sun is not included because the sun continuously changes position in the sky, the quantity of interior illuminance changes too, and the point of maximum illuminance moves with the movement of the sun. This occurs even if no direct sunlight enters the space; if the direct sunlight does enter the space, two points or more of maximum illuminance appear; one from the sun, and the other from the sky plus reflected sunlight. Since the impact of the direct sun is not included, the point of maximum illuminance – in the base case- is directly below the center of the opening in both cases (clear and overcast sky). The slope of either curve is steep, and the contrast between the points of maximum and minimum illuminance is usually very high.

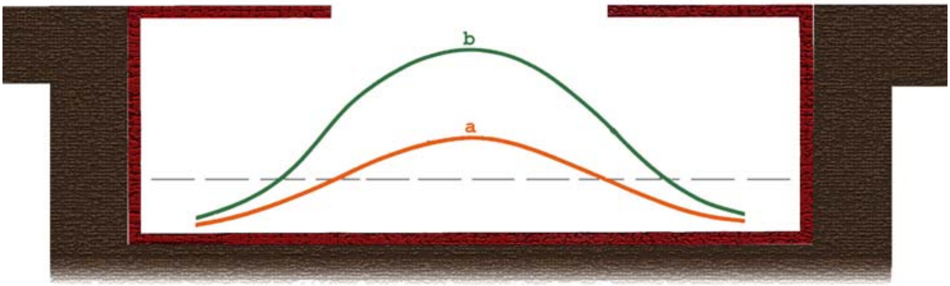

Fig (3-19): Typical light distribution pattern (the base case) in a room with a horizontal skylight under (a) Clear Sky or (B) Overcast Sky(2).

The changes in absolute illuminance that can occur between winter and summer under both clear and overcast conditions are illustrated in Fig (3-20).

It should be noted that the level of interior illuminance under an overcast sky is significantly greater than that under a clear sky (without sun) during either winter or summer(3).

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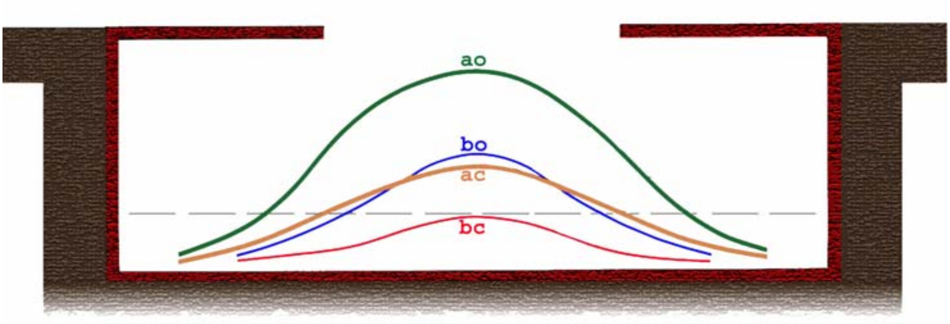
(1) Robbins, C.; "Daylighting: Design and Analysis", P.90

(2) ibid, P.91

(3) ibid, P.92



(ao) Summer Overcast Sky (bo) Winter Overcast
(ac) Summer Clear Sky (bc) Winter Clear Sky

Fig (3-20): Comparison between (a)Summer and (b)Winter performance characteristics for a horizontal skylight in absolute illuminance[1].

When studying the impact of changing the horizontal skylight geometrical proportions on the light distribution pattern it should be noted that the parameter that will be studied is the only variable and the other parameters are kept constant.

I) *Skylight Width*

By reducing the skylight width and keeping the other parameters constant (well length, depth, floor-to-ceiling height, orientation and, finishes), the point of maximum illuminance is reduced in comparison to the base case and the slope of the curve flattens at the ends[2] Fig (3-21) and vise versa.

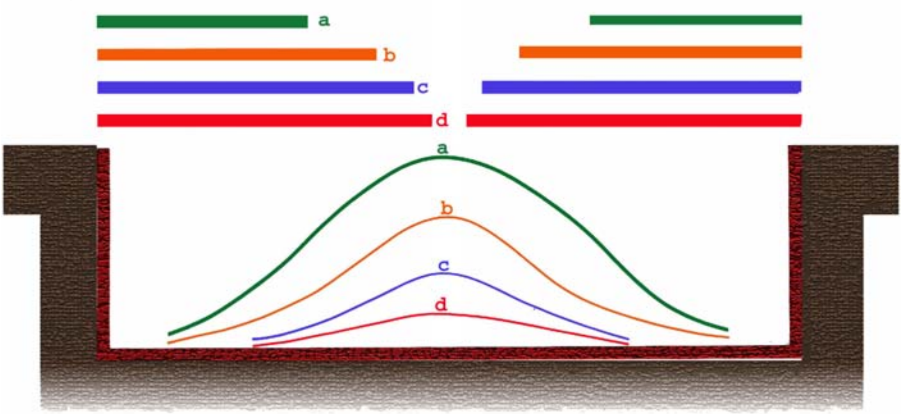


Fig (3-21): Impact of varying the skylight width on the light distribution pattern[3].

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[1] ibid
[2] ibid
[3] ibid

II) *Skylight Length*

By varying the skylight length and keeping other parameters constant this leads to affecting the longitudinal spread. The longitudinal spread is directly proportional to the skylight length.

III) *Depth and Slope of the Well*

One of the most significant factors affecting daylight distribution resulting from horizontal skylights is the depth and slope of the skylight well. Changing the depth and slope of the well affects both the spread of light and the point of maximum illuminance from an overcast sky⁽¹⁾. It should be noted that by increasing the well depth this leads to decreasing the point of maximum illuminance in comparison with that in the base case and flattens the bell shaped curve at both ends Fig (3-22). Increasing the slope of the well - from the vertical position - increases the point of maximum illuminance to a certain extent and distributes the daylight more evenly Fig (3-23).

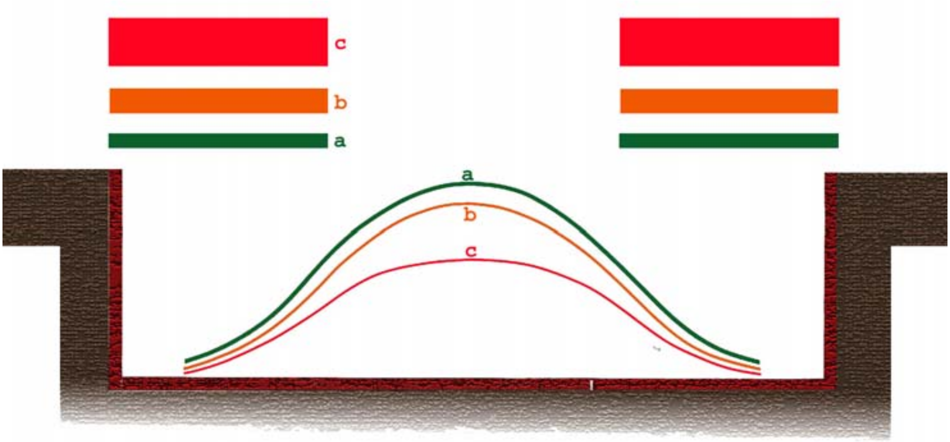

Fig (3-22): The impact of varying the skylight well depth on the light distribution pattern⁽²⁾.

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(1) ibid, P.93

(2) ibid

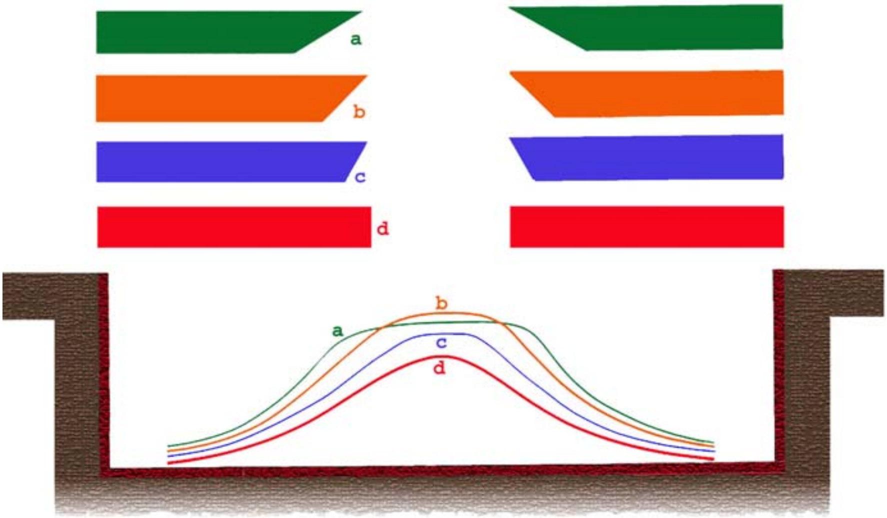
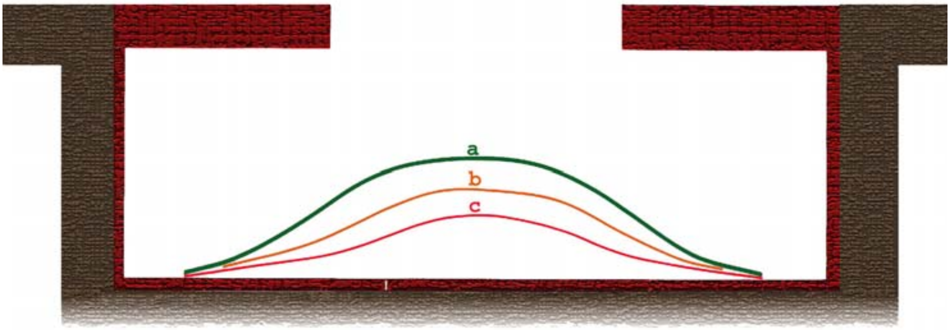


Fig (3-23): The impact of varying the slope of the skylight well on the light distribution pattern(1).

IV) *Well Reflectivity*

By varying the well reflectivity and keeping the other parameters constant this affects the distribution pattern as shown in Fig (3-24). Increasing the well reflectivity leads to increasing the point of maximum illuminance while the ends of the distribution patterns are almost the same(2).



(a) 80 percent reflective well (b) 60 percent reflective well
(c) 40 percent reflective well

Fig (3-24): The impact of varying the well reflectivity on the light distribution pattern(3).

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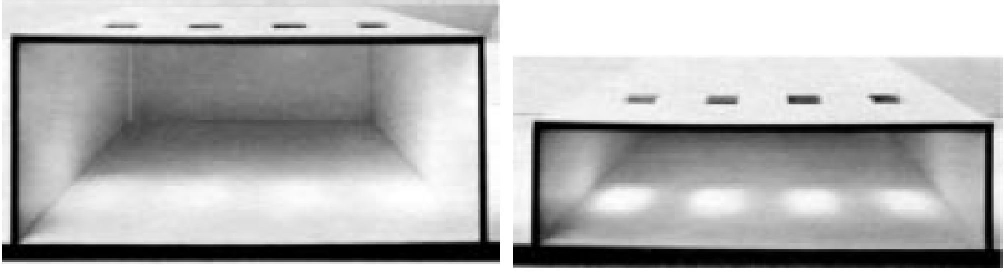
(1) ibid, P.94
(2) ibid
(3) ibid, P.93

V) *Angle of Glazing Material*

The angle of the glazing material in a horizontal skylight does not seem to be as critical as the other geometrical proportions of the skylight and the well.

VI) *Ceiling Height*

With skylights, the ceiling height strongly influences the daylight distribution within the space. Depending on skylight size, spacing, and well design, varying the ceiling height may increase or decrease the uniformity of the daylight distribution. By changing the ceiling height and keeping the other parameters constant, it is found that as the ceiling height is increased, the light transmitted by the skylight is distributed over a larger floor area and working plane. This generally results in more uniform skylighting while decreasing the ceiling height result in less uniformity with brighter areas under the skylights and darker areas in between(1) Fig (3-25).



For the same skylight spacing, a higher ceiling height will result in more uniform illuminance levels at the work plane (above left). Lower ceiling heights exhibit darker areas between and brighter areas under the skylights (above right).

Fig (3-25): The effect of the ceiling height on the light distribution pattern.

3-4-2 Vertical Top-lighting Concept

Monitors, clerestories, and sawtooth are all vertical top-lighting methods that use vertical or steeply sloped glazing on the roof(2) Fig (3-26). They are excellent daylighting concepts to use when uniform interior illuminance is needed over a large underground working space.

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(1) Energy Design Resources [http://www.energydesignresources.com/docs/sg-2-deign.pdf]

(2) Moore, F.; "Concepts and Practice of Architectural Daylighting",P.95

Although originally designed for large open spaces, they can be used with equal success in small or large underground spaces. When they face south, they collect more sunlight in the winter than the summer, which is generally the desired condition(1). Vertical south-facing openings can also be shaded easily from unwanted direct sunlight(2). North-facing openings deliver a low but constant source of skylight with little or no glare. East and west openings are usually avoided because of the difficulty of shading the low sun(3). Another advantage of those types of top-lighting is the diffused nature of the light, since much of the entering light is reflected of the ceiling. Because the light can be easily diffused once it is inside, the glazing can be transparent(4).

Sawtooth top-lighting method, along with monitors, was very common during the nineteenth and early twentieth century as a mean of illuminating the interior of industrial spaces(5).

Nowadays, they are used in a wide range of modern above or below ground building types and they seem to function well in any low or high-ceilinged single-storey underground building in which the primary lighting zone makes up a significant portion of the floor area such as libraries, department stores, computer assembly plants, as well as many other buildings.

Monitors daylighting technique

Clerestorey daylighting technique

Sawtooth daylighting technique

Fig (3-26): Different vertical top-lighting methods.

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(1) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects",P.333

(2) Seif El Nasr, S.; "Daylighting Design Process in Buildings: An Approach for Integration of Daylighting in The Design Process", P.68

(3) Public Works and Government Services, Canada; "Underground Guide for Canadian Commercial Buildings", P.36

(4) Moore, F.; "Environmental Control Systems: Heating, Cooling, Lighting",P.311

(5) ibid

3-4-2-1 Sawtooth Top-lighting Concept

I) *Sawtooth Spacing and Placement*

When designing a sawtooth top-lighting opening its placement is decided primarily according to the design concept of the underground space which is usually reflected from the function of that space. However, careful attention should be given to its spacing in order to create a uniform daylighting distribution pattern in the space below.

The general rule of thumb for sawtooth top-lighting openings is to space the openings at two and a half times the ceiling height (center-to-center) and the height of the opening should be half the height of space(1) Fig (3-27).

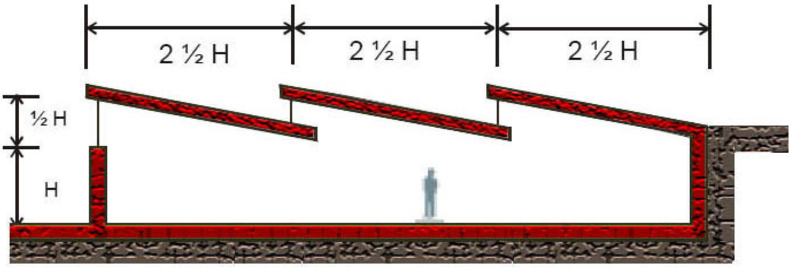

Fig (3-27): Typical sawtooth top-lighting method spacing(2).

II) *Sawtooth Light Distribution Pattern*

There are four important characteristics that need to be recognized concerning the distribution pattern for a series of sawtooth top-lighting concepts(3). Those characteristics are:

- The distribution pattern is different for a series of apertures than for a single one.
- For both clear and overcast sky the location of maximum and minimum illuminance points is at a different location from a single opening than a serious of openings.

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(1) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects",P.334

(2) ibid

(3) Robbins, C.; "Daylighting: Design and Analysis", P.98

- The end conditions are different; that is the daylight below the first opening in a serious is different from that under the last opening in the series. The distribution pattern is different in shape depending upon the sky conditions.
- The characteristic distribution light pattern from a sawtooth cannot be established with less than three opening in a series.

The daylight distribution pattern under a clear or overcast sky presents different spread patterns(1) Fig (3-28). In other top-lighting methods, even though the maximum illuminance or the slope of the distribution curve was different, the basic patterns for the two sky conditions were very similar.

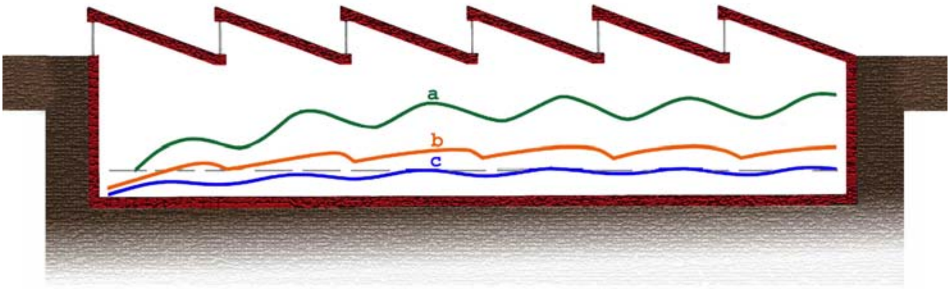

Fig (3-28): Sawtooth daylight distribution pattern (the base case), and sky conditions vary as follows: (a)Clear sky, opening facing the sun, (b)Overcast sky and (c)Clear sky, opening opposite the sun(2).

In the base case, a sawtooth opening produces different slopes of light distribution on both sides of the point of maximum illuminance. The location of the point of maximum illuminance for a series of sawtooth openings under a clear sky is about two-thirds the distance from the plane of the opening while the point of minimum illuminance is about one-third the distance from the opening to the end of the sloped roof. It should be noted that the location of the points of maximum and minimum illuminance varies with the orientation

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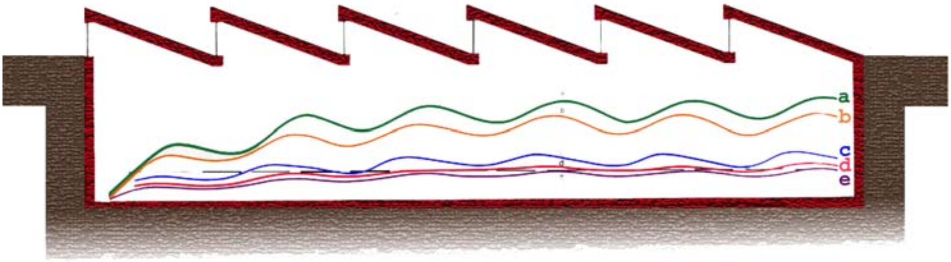
(1) ibid

(2) ibid, P.99

of the opening with respect to the sun from that in the base case of a clear sky Fig (3-29).



(a)aperture orientation 0° with sun (b) aperture orientation +/-45° with sun
(c) aperture orientation +/-90° with sun (d) aperture orientation +/-135° with sun
(e) Aperture orientation 180° with sun

Fig (3-29): Sawtooth daylight distribution pattern under a clear sky for various aperture orientations with respect to the sun(1)

On the other hand, under an overcast sky, the point of maximum illuminance is very close to the point of minimum illuminance that appears to be directly under the end of the sloped roof surface of the opening(2) Fig (3-30). Light distribution does not vary with the opening orientation under an overcast sky.

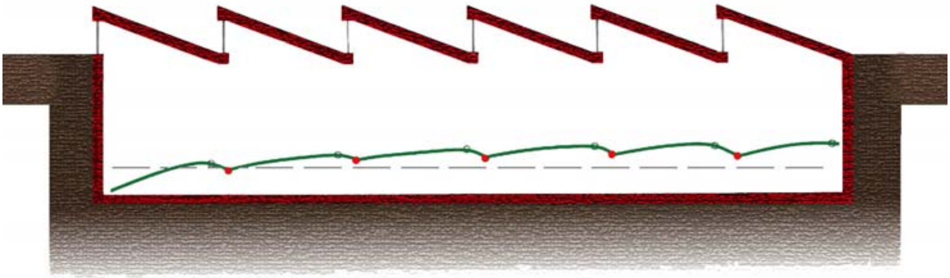


Fig (3-30): Location of points of maximum and minimum illuminance for the base case sawtooth openings under an overcast sky(3).

Most openings under a clear sky pass, in a single day, through several of the distribution patterns. Points of maximum and minimum illuminance exist for each opening allowing multiple task areas to be created in the space under a series of sawtooth. The primary lighting zone can be based on the maximum illuminance, the minimum

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(1) ibid, P.100
(2) ibid
(3) ibid, P.99

illuminance, or something in between according to the function of the space below.

III) *Sawtooth Geometrical Proportions and it Impact on the Daylight Distribution Pattern*

The geometrical proportions of the sawtooth top-lighting method influence greatly the daylighting distribution pattern and the points of maximum and minimum illuminance in the space below. Changing the length, width, openings spacing, and the glazing slope has a direct impact on the distribution pattern.

1-*Sawtooth Spacing*

Varying the sawtooth spacing changes the distribution pattern significantly from that in the base case under either clear sky or overcast sky. The sawtooth spacing is directly proportional to the distribution pattern(1) Fig (3-31).

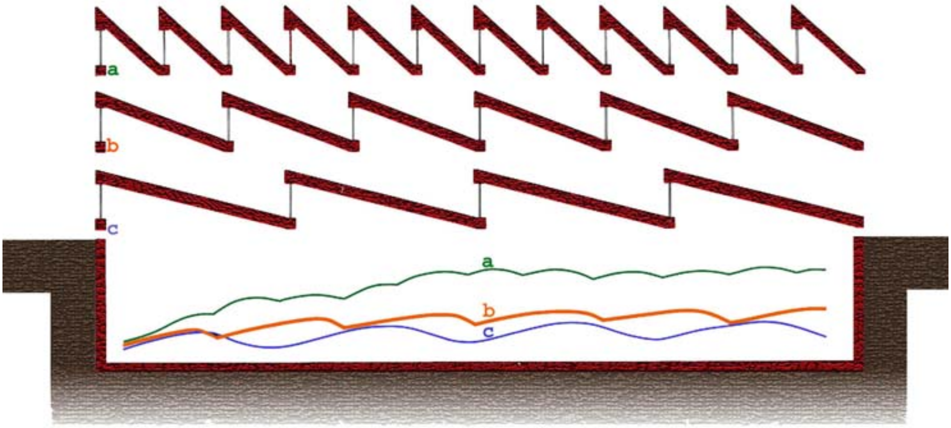

Fig (3-31): Sawtooth spacing variation and its impact on the light distribution pattern under an overcast sky(2).

Adding a horizontal spacing in-between the sawtooth openings affects the distribution pattern. As the horizontal spacing increase the difference in between the points of maximum and minimum illuminance increase till reaching a certain point where each of the sawtooth openings works in a single manner Fig (3-32).

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(1) ibid

(2) ibid, P.101

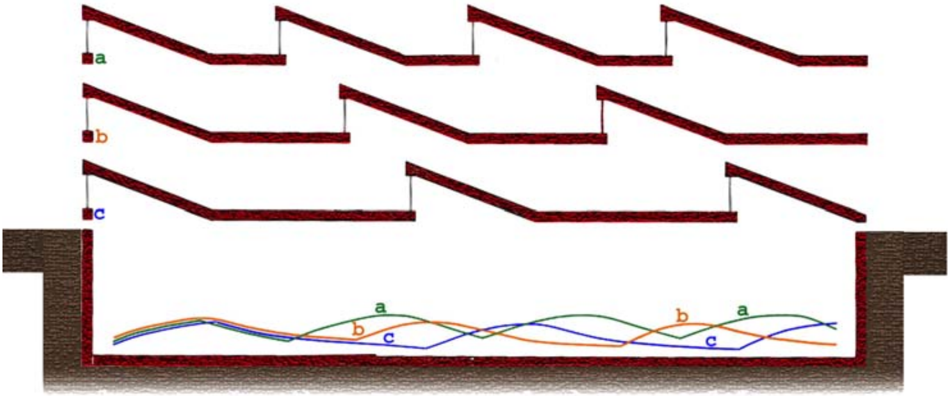

Fig (3-32): Impact of adding a horizontal spacing in-between the sawtooth openings on the light distribution pattern under an overcast sky[1].

2- *Glazing Slope*

Changing the glazing slope of a sawtooth top-lighting has a significant impact on the distribution pattern. As the slope of the glazing increase the interior illuminance increase and the difference between the points of maximum and minimum illuminance increase[2] Fig (3-33).

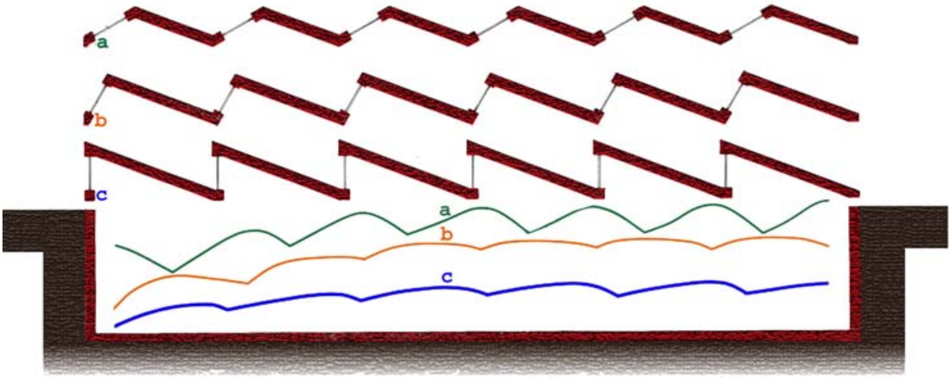

Fig (3-33): Sawtooth slope variation and its impact on the light distribution pattern[3].

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[1] ibid, P.102

[2] ibid

[3] ibid, P.103

3-4-2-2 Monitors Top-lighting Concept

I) *Monitors Spacing and Placement*

The monitor top-lighting method is an excellent daylighting concept that can be easily controlled to allow specific daylighting levels into a room. Careful design of the openings can lead to a very distinct illumination levels allowing the entire underground space to be treated as one lighting zone; or it can produce substantial variation in illuminance, allowing establishment of two or more lighting zones. Like the sawtooth method the monitor is a complex method and can be varied in numerous ways. It is also possible to design monitors with three or four glazed surfaces or to have two glazed surfaces that are not opposite to each other; these cases add additional dimensions to the analysis of the daylighting distribution patterns.

Typically, north-facing monitors employ clear glazing for maximum transmission since diffusion is inherent in the sky light and roof-reflected sunlight. South-facing monitors must employ translucent glass to diffuse direct sunlight(1).

As for monitors top-lighting, the general rule of thumb is to space the opening at two and a half times the ceiling height from the side walls with a spacing four times the ceiling height in between the two ends of the monitor and the height of the monitor is half the room height Fig (3-34).

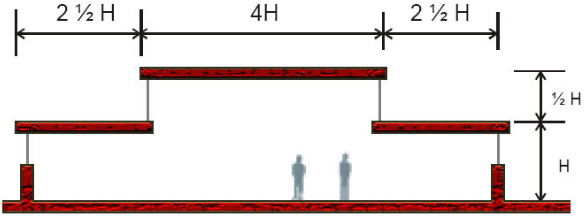

Fig (3-34): Typical Spacing of monitors' top-lighting method(2).

Sawtooth and monitors placement must be coordinated with other building systems such as structural, mechanical, and lighting systems.

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(1) Moore, F.; "Environmental Control Systems: Heating, Cooling, Lighting",P.311

(2) Lechner, N.; "Heating, Cooling, Lighting: Design Methods for Architects",P.334

II) *Monitors Light Distribution Pattern*

Under an overcast sky, the illuminance from the monitor top-lighting takes the bell shaped curve in which the light spreads an equal distance in both directions. When the sky is clear, the distribution pattern reflects the fact that the opposing openings have different views of the sky(1). The base case for daylighting penetration from a single monitor is shown in Fig (3-35).

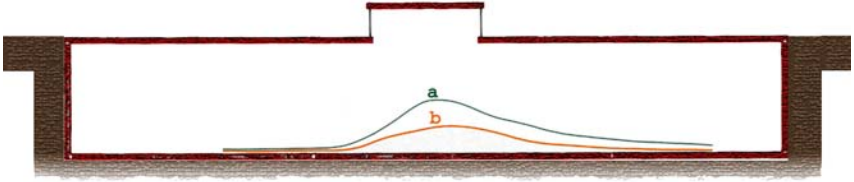

Fig (3-35): Monitor light distribution pattern under: (a)Clear sky (b)Overcast sky(2).

Light distribution under a series of monitors is very different from what it is under one monitor. Because the spacing between monitors, only two sets of monitors in a series are needed to establish the distribution pattern that typifies this kind of top-lighting technique under an overcast sky; three sets of monitors are needed to accomplish the same purpose under a clear sky.

The point of peak distribution varies with sky type and orientation. Under an over cast sky, the point of peak illumination becomes a plane of peak illumination; similarly; the point of minimum illuminance extends over a plane. Under a clear sky, recognizable points of maximum and minimum illuminance can be found(3) Fig (3-36).

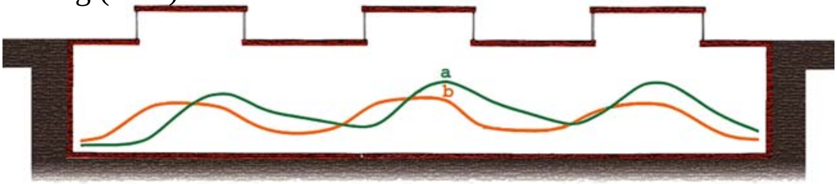

Fig (3-36): Light distribution pattern for a series of monitor openings and sky conditions are as follows: (a)Clear sky, openings facing and opposite sun, (b)Overcast sky(4)

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(1) Robbins, C.; "Daylighting: Design and Analysis", P.105

(2) ibid

(3) ibid, P.106

(4) ibid

The end conditions under the first and last set of monitors in a series can vary depending upon whether the edge of the opening aligns with the perimeter of the building or whether a space equal to the spaces between monitors is next to the perimeter of the building.

III) *Monitors Geometrical Proportions and their Impact on the Daylight Distribution Pattern*

1- *Monitors Height*

The monitors' geometrical proportions influence greatly the light distribution pattern. One of the most important proportions that play a significant role in the light distribution pattern is the height of the monitor. By varying the height of the monitor and keeping the other parameters constant, this leads to varying the interior illumination level in a direct relation to the height(1) Fig (3-37).

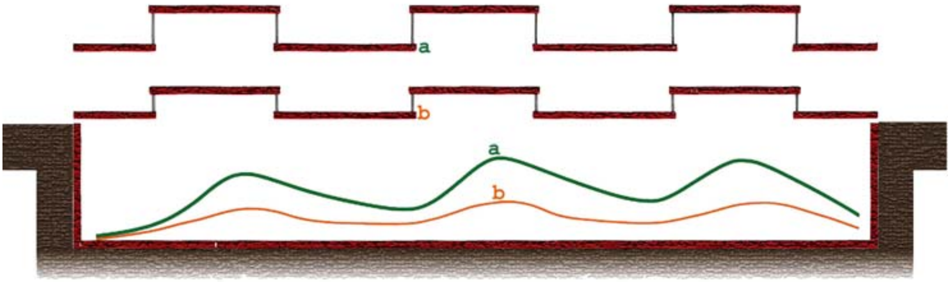

Fig (3-37): The monitor's height variation and its impact on illuminance under an overcast sky(2).

2- *Spacing between Monitors*

When changing the spacing between monitors and keeping the size of the monitor constant the points of maximum and minimum illuminance increases by reducing the spacing. While increasing the spacing leads to decreasing the points of maximum and minimum illuminance and flattens the curve(3) Fig (3-38).

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(1) ibid, P.107
(2) ibid
(3) ibid, P.108

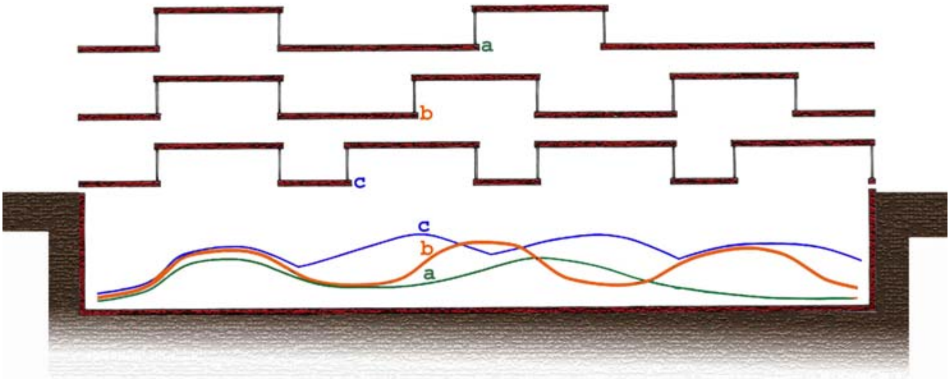

Fig (3-38): Impact of varying the spacing between the monitors on the light distribution pattern(1).

3- *Monitor Slope*

The illuminance in the space can be increased without shifting the point of maximum illuminance by varying the slope of the glazing. As the glazing slope increase, the internal illuminance increases and the size of the secondary lighting zone decrease(2) Fig (3-39).

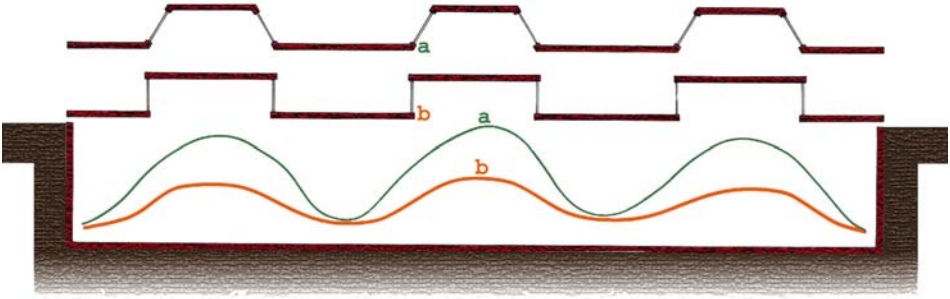

Fig (3-39): Impact of varying the monitors slope on the light distribution pattern under an overcast sky and the slope of the openings is varied as follows: (a) 60˚ slope (b) 90˚ slope(3)

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(1) ibid
(2) ibid
(3) ibid

3-5 Examples of Underground Buildings using Top-lighting as a Daylighting Concept

3-5-1 University of Michigan, Law Library Addition

Location: Ann Arbor, Michigan.

Architect: Gunnar Birkerts and Associates, Birmingham, Michigan.

Construction Date: 1981.

Project Size: 7150m^2 includes 1350m^2 of unfinished space.

Underground classification:

1-*Function*: Non-Residential / Institutional / Library.

2-*Fenestration Type*: Vertical top-lighting.

3-*Relation to Surface*: Subsurface building.

4-*Depth*: Moderate (17meters)

Earth Cover(1)**:** 90 percent of total roof area is covered with 0.45 to 1.40 meters of earth, skylights are the only exposed area; 100 percent of exterior wall area is in contact with earth (assuming glazed areas are included in roof area).

Reason for going Underground:

The buildings forming the original Law Quadrangle, constructed between 1924 and 1933, were designed in a Gothic style, modeled after the Inns of Court of London. In order to harmonize with the historical character of the surrounding buildings and to preserve open space on the surface, the University of Michigan law library addition is placed completely below grade. In addition to the noise isolation that the earth provides for such a function(2) (library)

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(1) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Buildings", P. 74

(2) Baker, M.; "Using the Earth to Save Energy: Four Underground Buildings",P.62

Project Description:

The master plan for the Law School, which occupies an entire city block, was completed in its final form except for the southeastern corner of the complex. This area was designated as the site for the proposed law library addition Fig (3-40). The site is completely flat, and no portion of the building extends above grade except for railings around the sunken skylights[1] Fig (3-41).

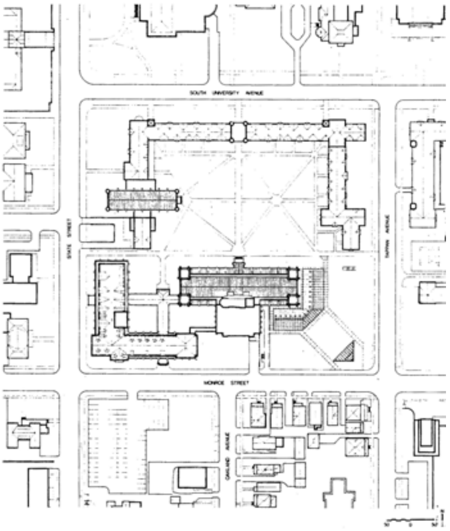

Fig (3-40): Law library site plan showing the L-shaped underground extension.

Fig (3-41): Law library exterior view from the east showing the original building and the L-shaped skylight of the new extension.

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[1] Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Buildings", P. 68

The entry to the new addition from outdoors occurs in the conventional sequence through the older building. The new building is actually entered by descending a wide stairway from the lower level of the older building. This entry leads directly to the dramatic central space along the sloping light well Fig (3-42).

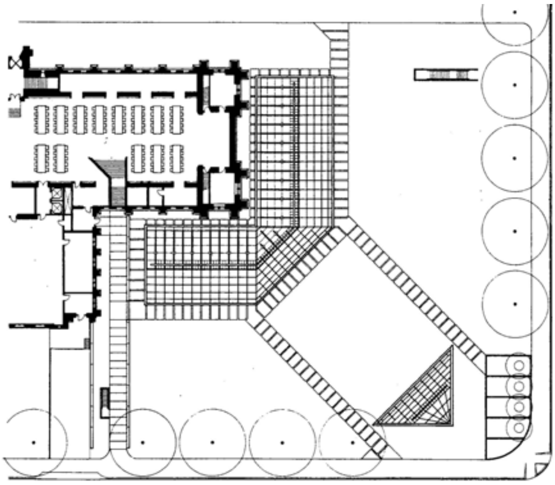

Fig (3-42): Law library grade level plan showing the entrance from the original building to the new addition.

The building floor plans are L-shaped with the busiest areas of the building - card catalogs, offices, and reading rooms - on the top floor[1] (level one below grade) Fig (3-43).

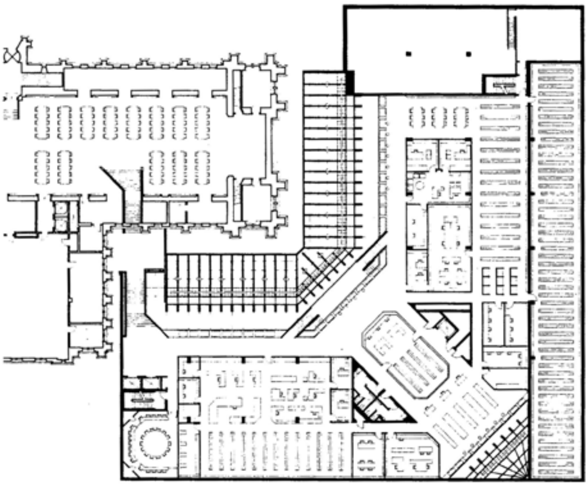

Fig (3-43): Law library level one below grade plan showing the different sections of the library

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[1] Baker, M.; "Using the Earth to Save Energy: Four Underground Buildings",P.62

The second level contains mainly stacks and individual carrels, while the lowest level - at a depth of 17meters beneath the surface - has more stacks, offices, and a student lounge illuminated by a smaller triangular shaped skylight Fig (3-44) at the southeast corner of the building.

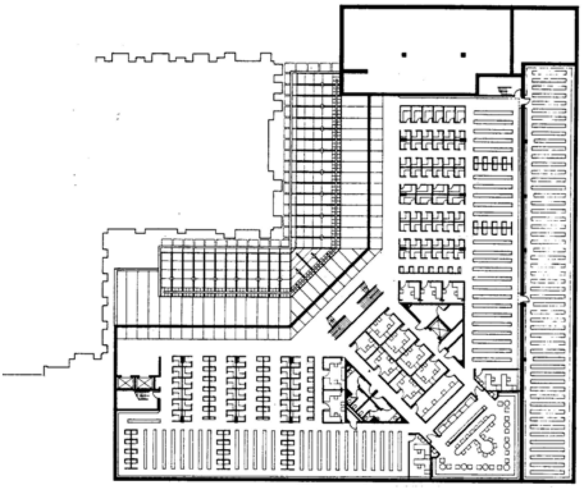

Fig (3-44): Law library three levels below grade plan showing the student lounge at the southeast corner of the building

The building is designed to accommodate approximately 500 people (246 in carrels), with 180,000 volumes in finished space and 200,000 to 3000,000 volumes in unfinished space⁽¹⁾. For many of the inwardly oriented activities in a library, the underground location with its limited exposure to the outside is not considered a detriment⁽²⁾.

The central feature of the building from both the exterior and interior is a sloping skylight facing the older building from within a V-shaped moat. Although the sloping skylights only extend down to the level of the upper floor, all levels are set back from the light well, forming balconies and permitting the light to enter the lowest level Fig (3-45).

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(1) ibid,P.63

(2) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Buildings", P. 68.

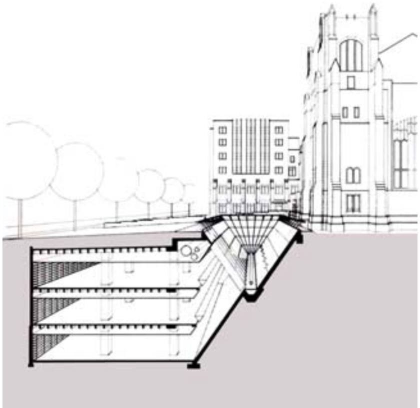

Fig (3-45): Law library addition section showing the V-shaped skylight.

Daylighting Concept[1]

Clearly the most notable aspect of the law library addition design is the manner in which natural light and exterior view are provided to the totally underground spaces. The sloping limestone wall forming the unusual skylight well and angled skylight above seem to direct the natural light down to all levels of the building while directing the view upward Fig (3-46). Mirrors are placed on the sloping supports of the glazed area (0.9m deep), providing a variety of reflections of exterior elements. In addition, the mirrors create complex patterns of light reflected onto the large sloping limestone wall Fig (3-47).

Fig (3-46): The sloping skylight viewed from the roof of the original building

Fig (3-47): Interior view of the skylight showing the 0.9 meter mirrors on the sloped glazing

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[1] ibid, P. 70

Since the light and view are concentrated in the light wells at the building edges, the library interior is designed essentially as one large open space to maximize the benefits from the dynamic central space[1]. Natural light can be seen from most areas of the building, although the open plan is less than ideal for acoustical control Fig (3-48).

Fig (3-48): Light reflected onto the sloping wall three levels below grade.

Two problems with overhead glazing - glare and excessive heat gain - are reduced by the presence of the older building to the west. In addition, fixtures near the light wells have photocell controls so they are automatically turned off when natural light is available at an adequate level.

Daylighting Analysis:

1-*Daylighting Method*: One large sized sloped skylight L-shaped in plan (45.75meters length by 8meters depth) and a smaller triangular shaped sloped skylight at the southeast corner of the building.

2-*Orientation*: The L-shaped skylight faces north, west and northwest while the triangular shaped skylight faces northwest.

3-*Glazing*: Both of the skylights uses clear glazing. In the L-shaped skylight the original building is used to diffuse the light and shade the undesired sun angles.

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[1] Carmody, J., Sterling, R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P. 74.

4-*Skylight Well*: The L-shaped skylight employs an unusual sloping limestone wall which is V-shaped in section and acts as the skylight well. Light colored finishes are used to increase the illumination levels in the underground spaces.

3-5-2 Mutual of Omaha Headquarters Addition

Location: Omaha, Nebraska.

***Architect*:** Leo A. Daly Company.

***Construction Date*:** 1979.

***Project Size*:** 17,100 m^2

Underground Classification:

1- *Function*: Non-Residential / Institutional / Office building including employee cafeteria and lounges.

2- *Fenestration Type*: Top-lighting.

3- *Relation to surface*: Subsurface.

4- *Depth*: Moderate (14m).

5- *Project Scale*: Large sized building scale.

Earth Cover: 100 percent of exterior walls are covered; 90 percent of roof is covered with 0.3 to 0.45m of earth.

Reason for going Underground(1)

A major addition to an existing building, particularly one with a very definite character and image, can be a difficult architectural problem. Conflicts may arise from connecting buildings of different styles, and the form of the older structure and spaces around it may be significantly altered.

In the case of the 17,100 m^2 addition to the Mutual of Omaha International Headquarters, these potential problems were resolved by placing the building completely underground. The familiar image of the Omaha, Nebraska, insurance company

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(1) Carmody, J., sterling, R.; "Underground Building Design: Commercial and Institutional Buildings", P. 142

building was important to preserve, and the style of the older building is difficult and expensive to duplicate. In addition, creating a landscape plaza on the flat site rather than another massive building enhanced the company's image with the surrounding residential community Fig (3-49).

Fig (3-49): Exterior view of the original building and the new addition.

Along with the visual and image-related benefits of the underground design, several very practical advantages emerged as well. First, the company was able to use existing property, saving land acquisition costs for the new facility. The underground design also increases land-use efficiency: the building mass exceeds, normal setbacks, but below grade, its exterior walls can be extended to nearly the edge of the property.

Second, the new structure, housing employee services as well as record storage, could be located in close proximity to the existing office building complex that it serves. Also, the underground design contributes to energy conservation and is considered to be less expensive to build than an above grade structure in the style of the existing headquarters building.

Project Description(1)

The basically flat site is dominated by the symmetrical monumental form of the older headquarters building. In response to this, the design of the rooftop plaza is also quite geometric and symmetrical Fig (3-50). The glass dome rising from the plaza, however, not only indicates the presence of a structure below, but is the central focus of the entire landscape design. At night the light from inside glowing through the dome creates an attractive effect Fig (3-51).

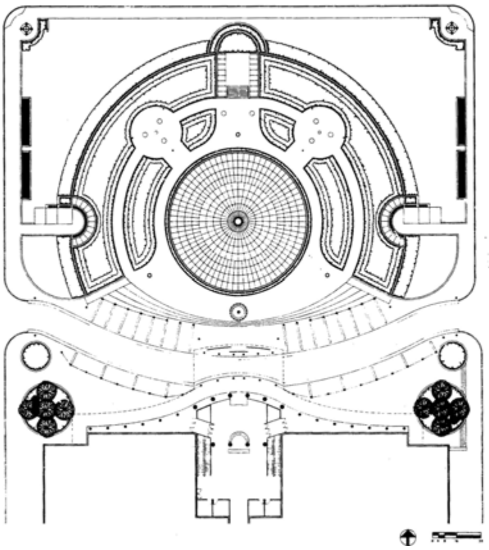

Fig (3-50): Grade level plan showing the symmetrical design of the roof plaza.

Fig (3-51): The underground addition viewed from the roof of the original headquarters building showing the glass dome.

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(1) ibid

Entered from the lowest level of the existing high-rise building, the addition consists of three levels completely below grade. On the first level below grade is the central feature of the addition a glass dome rising above the rooftop plaza level. The glass dome covers a garden court with a fountain and trees. Surrounding the garden court is a 1,000 seat employee cafeteria, library, lounge, kitchen, and a conference and training center. These facilities serve 5,000 workers from the entire headquarters complex Fig (3-52).

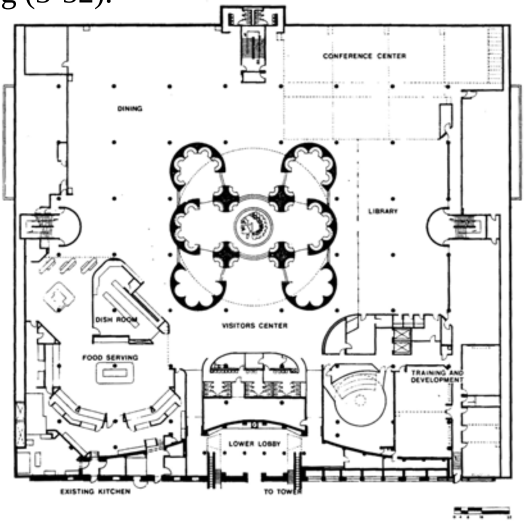

Fig (3-52): One level below grade plan showing the different functions in this level.

The second and third levels of the addition are large, open-plan office spaces with no direct connection to the surface. Machine repair, files, and some offices are on the middle level Fig (3-53). Record storage covers the lower level. Continuous transfer of files can occur between this area and the older building using a conveyor system.

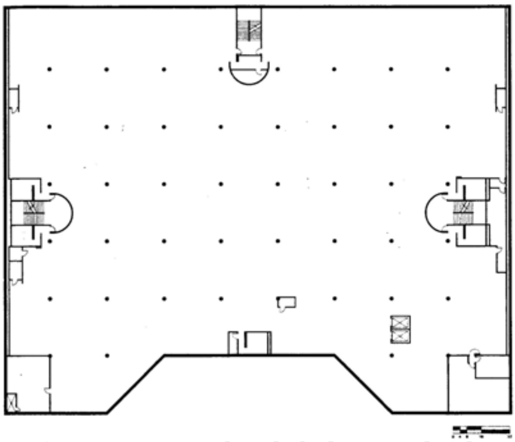

Fig (3-53): Two levels below grade plan.

Daylight Concept[1]

The underground addition to the Mutual of Omaha Headquarters Building houses several functions. Some are treated quite differently than others with respect to natural light and view. For one group of functions - employee cafeteria, library, and lounge - the goal was to create a very attractive environment that would provide a pleasant break from the typical office spaces. This is achieved by placing these functions around the glass-covered garden court, which is large enough to provide amenities and light for the entire upper floor Fig (3-54).

Fig (3-54): Interior view of the garden court showing the main daylighting theme - the glass dome.

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[1] ibid, P.144

The library, located on the upper floor, is separated from the court by a glass partition wall that provides an acoustical barrier without diminishing natural light from and view of the courtyard Fig (3-55). A conference and training center, also on the upper floor, is appropriately enclosed in windowless space on this level.

Fig (3-55): Library interior with glass partition wall permitting a view of the garden court.

On the two lower floors of the addition, functions such as record storage, offices, and machine repair are placed in completely windowless space. Access to these levels occurs through elevators and stairs from the courtyard level above Fig (3-56).

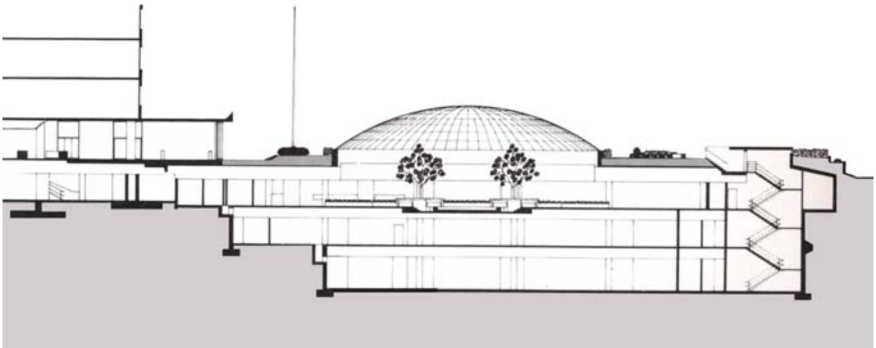

Fig (3-56): Mutual of Omaha Headquarters Addition section.

Daylighting Analysis:

1-*Daylighting Method*: One horizontal skylight, dome-shaped, 27.5meters in diameter, and 4.5meters above the roof level.

2-*Orientation*: The horizontal skylight sees the full hemisphere. The original building, that is located to the south of the dome, provides shading and diffusion of the direct sun.

3-*Glazing*: The dome uses two layers of tempered glass. Consisting of 505 glass panels, the outside layer is solar bronze glass - used to diffuse and reduce summer heat - and the inside layer is clear glass with 1.25cm of air space separating the two layers.

4-*Skylight Well*: With such huge aperture size, the effect of the well shape and size is almost negligible. The well walls are vertical, 2meters deep, and finished with light colored paints.

3-5-3 The Grand Louvre Extensions

Location: Paris, France.

Architect: PEI COOBB FREED & Partners (Architects LLP) - I.M.PEI senior designer

Construction Date: Phase I: Completed 1989
Phase II: Completed 1993

Project Size: Phase I: Site 90,000 m^2
Gross floor area: 61, 990m^2
Phase II (Richelieu Wing): Site 15, 600m^2
Gross floor Area: Demolition of 6 levels with a total area of 55,000m^2, new construction of 3 levels with a total area of 50,000m^2

Underground Classification:

1-*Function*: Non-Residential / Recreation and Commercial / Museum and Mixed-use Complex.

2-*Fenestration Type*: Top-lighting (Horizontal skylights)

3-*Relation to Surface*: Subsurface building.

4-*Depth*: Moderate (15meters)

5-*Project Scale*: District scale.

Earth Cover: 100 percent of the external wall area is in contact with earth, 100 percent of total roof area is used as a public plaza (skylights are the only exposed area).

Reason for going Underground

The Louvre in Paris, France, was built, enlarged and rebuilt almost constantly between 1546 and 1870. Originally a palace, it was converted to a public art museum in 1793 in the wake of the French Revolution. Despite of its enormous size, the museum was bursting with an art collection too vast to display. In addition, there was virtually no space to accommodate researchers and restorers, much less the 10,000 visitors who streamed through each day. These practical concerns led to launch an expansion project in 1981(1).

Of course, the problem was how to design a structure that would not compete with, or detracts from, the historic buildings that were begun in 1546. Thus, the architects felt the best solution was to go underground, build connecting links under the inner court of the U-Shaped complex, and construct an entrance in the middle of the plaza, the "*Cour Napoleon*". They chose a pure geometric form as their solution - a glass pyramid(2) Fig (3-57).

Fig (3-57): Exterior view showing the "*Cour Napoleon*" plaza and the main historic buildings versus the new entrance.

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(1) Chow, F., Paul, T., Vahaaho, I., Sellberg, B., Lemos, L.; "Hidden Aspects of Urban Planning: Utilisation of Underground Space", P.2

(2) Cottom-Winslow, M.; "Architecture and Technology: The Best of Environmental Design", P. 44

Project Description:

The Louvre expansions included a two-phase enlargement that added 80,825 m^2 of space to the Louvre beneath both the central courtyard and its extension past the original buildings. A centrally located glass pyramid forms the new main entrance and provides direct access to galleries in each of the museum’s three wings. Critically, the pyramid also serves as a skylight for a very large expansion building constructed under the courtyard to provide all the public amenities and technical support required in a modern museum Fig (3-58).

Fig (3-58): Exterior view of the glass pyramid that shape the entrance to the new extension.

Phase (I) (1)

The main objective of this phase is the expansion, modernization, and reorganization of the original Louvre and adding new operational infrastructure for the entire museum Fig (3-59).

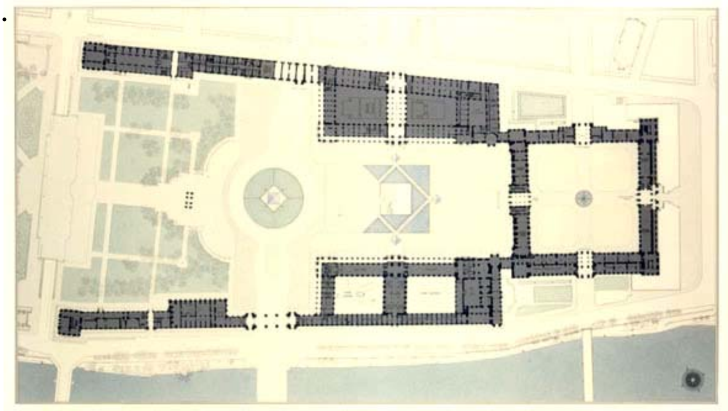

Fig (3-59): The Louvre ground floor plan showing the original U-shaped building and the entrance to the underground extension.

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(1) PEI COOBB FREED & Partners, Architects LLP [http://www.pcfandp.com/a/p/8315/s.html]

Phase (I) Major Components

29,000m^2 public plaza with fountains; 21.6m high pyramidal main entrance; 5m high three pyramidal skylights (one over each underground link to the three museum wings); 61,690m^2 Hall Napoleon with 290m^2 belvedere, 20,800m^2 mezzanine; 24,900m^2 main reception, 420-seat auditorium, 16,000m^2 technical level; Public spaces of total area 17,640m^2 (reception - circulation - research - cafes/restaurants - museum shop - temporary exhibition - Louvre history exhibition - commercial boutiques - workshops - staff workshops - security - medical services) Fig (3-60).

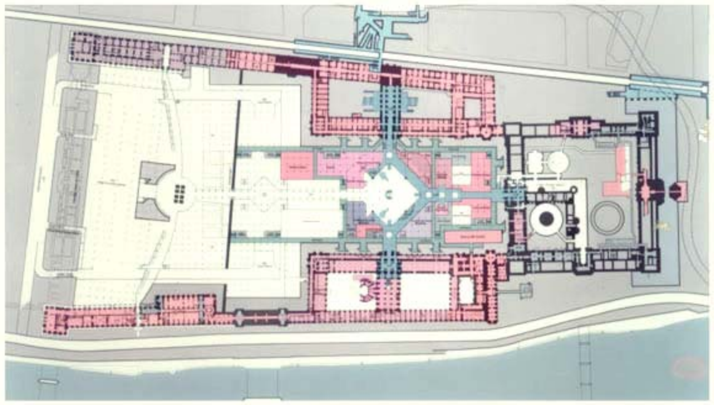

Fig (3-60): The Grand Louvre underground extension plan showing Phase (I) major components.

Phase (II)(1)

The main objective of this phase is the conversion of government offices into exhibition galleries and related projects. Phase (II) required the creation of new space within an historic shell. Work included the cleaning and restoration of facades and exterior sculpture, conversion of three interior courtyards into skylit sculpture courts, and demolition of 48,560m^2 of government offices compressed into 6 floors.

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(1) PEI COOBB FREED & Partners, Architects LLP [http://www.pcfandp.com/a/p/8401/s.html]

Beyond conversion of the Richelieu Wing, Phase (II) included the underground mixed-use complex known as the "*Carrousel du Louvre*", the "*Pyramid Inversee*" that brings the light into its center, the connected underground parking garage, and a series of related surface projects designed to actively reclaim the Louvre as a vital pedestrian precinct in the heart of Paris.

Phase (II) Major Components

Richelieu Wing; "*Pyramid Inversee*" 22,000m^2; "Rond Point Carrousel" 10,400m^2; "Terrasse Tuileries" 5,525m^2; "Carrousel du Louvre" 55,000m2 including retail, restaurants, food court, 600-seats amphitheater, and laboratories Fig (3-61).

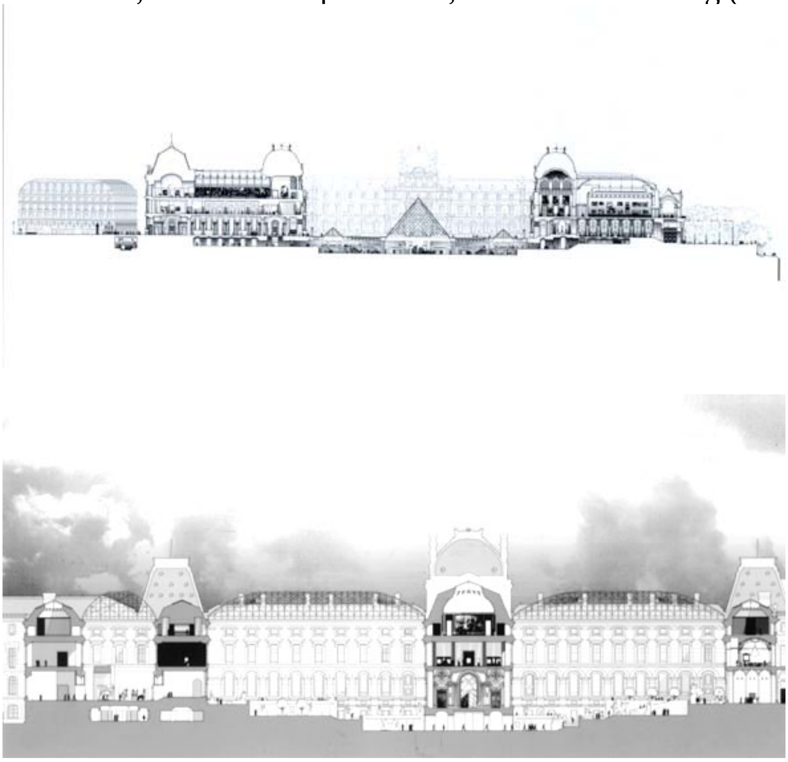

Fig (3-61): The Grand Louvre sections.

Daylighting Concept:

The monumental skylight that Pei proposed to crown the new subsurface reception area is the center of the daylighting theme in the new extension. Wanting to admit plenty of light to the two-storey underground addition and feeling that it was important to mark the museum's new entrance with a sufficiently impressive façade, Pei suggested topping the reception area with a large glass pyramid. The skylight rises only two-third as high as the historic Louvre. The pyramid is glazed with clear glass. The structure of the pyramid is solid stainless steel, custom crafted(1) Fig (3-62).

Fig (3-62): The glass pyramid glazing detail showing the aluminum frame and the clear glass used.

Besides expanding the underground space upward and allowing sunlight to pour through, the glass pyramid also provides views of the historic buildings that surround it Fig (3-63).

Fig (3-63): View of the historic buildings from inside the glass pyramid.

The pyramid's base is aligned with the existing buildings, but the 25m^2 reception area underneath is shifted so that its corners

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(1) The Hidden Worlds under Pei's Pyramids [http://www.subsurfacebuildings.com/page3.html]

point toward the surrounding structures. Passageways from each corner carry visitors to various parts of the museum as well as underground shaping and parking facilities. Each of the four passageways is flooded with light from a smaller glass pyramid(1). The skylights topping the three paths to the museum buildings rise 2 meters above the courtyard Fig (3-64).

Fig (3-64): Exterior view of the "Cour Napoleon" at night showing the main glass pyramid and the three skylights used to daylight the paths to the original museum buildings.

In the fourth direction lies the new underground commercial sector called "*Carrousel du Louvre*". The skylight designed for this sector is an inverted pyramid that hangs from the ceiling and reaches nearly to the floor of the spacious commercial wing(2) Fig (3-65). A dramatic feature inside the underground space, this inverted skylight is unnoticeable from the surface, where it is situated in a circular island in the middle of the divided road that crosses the courtyard's extension. The edges of the diamond shaped glass panels that cover the upturned base of the pyramid are designed to draw sunlight downward through the fixture(3).

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(1) Cottom-Winslow, M.; "Architecture and Technology: The Best of Environmental Design", P. 45

(2) Anthony's home page [http://www.atkielski.com]

(3) The Hidden Worlds under Pei's Pyramids [http://www.subsurfacebuildings.com/page3.html]

Fig (3-65): the "*Pyramide Inverse*" at the "Carrousel du Louvre" used to provide daylighting to the underground commercial center entrance.

Daylighting Analysis:

1-*Daylighting Method*: Daylighting, in this project, is provided to the underground spaces through the use of the horizontal top-lighting concept. The daylighting theme consists of one large glass pyramid 21.65m high. Another Three smaller glass pyramids, 5m high each, are used to daylight the passageways from the underground extension to the wings of the original building. An inverted pyramid, 7.6m high, is used to daylight the entrance to the commercial underground center.

2-*Orientation*: The large glass pyramid and the inverted pyramid are shifted with a 45° to the north. The three small pyramids are oriented to the north.

3-*Glazing*: All of the pyramids are glazed with laminated "white" glass sealed with structural silicone. Each glass panel is set into an aluminum frame with minimal mullions, engineered to be flush with the glazed surface.

4-*Skylight Well*: The designer used a shallow well with vertical walls and light colored finishes in order to increase the daylight penetration into the underground spaces.

Table (3-1) illustrates the main differences between the two top-lighting methods, horizontal and vertical top-lighting, used for daylighting shallow underground spaces.

	Horizontal Top-lighting **(Skylights)**	**Vertical Top-lighting** **(Sawtooth-Monitors-Clerestories)**
Main Concept	- Horizontal or slightly slopped openings in the roof that provides a relatively uniform level of illumination throughout a space.	- All Vertical top-lighting methods use vertical or steeply sloped glazing on the roof. - Include Monitors, Sawtooth, and Clerestories.
Main Potential	- Provides illumination levels three times higher than any vertical openings.	- The main advantage of this type is the diffused nature of the light entering the space since much of the entering light is reflected of the ceiling.
	• **Layout, Spacing, and Placement** - The skylight layout is primarily dictated by the design concept for the space. - Large widely spaced skylights cause glare, and result in an uneven light distribution. - Small, closely spaced skylights provide more uniform lighting conditions. - The general rule of thumb provides the best light distribution (in the presence or absence of side-lighting) - Skylight placement must be coordinated with the structural, mechanical and electrical lighting systems.	• **Layout, Spacing and Placement** - The general rule of thumb, for the sawtooth and monitors, spacing provides the best light distribution. - Their layout and placement is decided primarily according to the design concept and the function of the space.

	Horizontal Top-lighting **(Skylights)**	**Vertical Top-lighting** **(Sawtooth-Monitors-Clerestories)**
	• **Sizes and Shapes** - Shapes range from simple rectangles to complex polygons. Sizes range from small to large. Built-up skylights can be made in virtually any size. • **Glazing** - The glazing area is 3% to 12% of the floor area. - Glazing characteristics: *I) Transmission of light* - The glazing transmittance and the glazing transparency. - The higher the visible transmittance of the material, the more efficiently the skylight can provide light to the space. *II) Transmission of Heat* - The solar heat gain coefficient (SHGC). - The most efficient skylight glazing material allows the maximum amount of light to pass through, while rejecting the non-visible wavelengths of solar radiation. • **Skylights Wells** - The skylight well is used to	• **Sizes and Shapes** - Sawtooth and monitors shapes are fixed but they can use sloped glazing. - They Can be used in small or large buildings. • **Glazing** - Sawtooth and monitors can use clear glazing since the light diffusion is inherent in the incoming light.

	Horizontal Top-lighting **(Skylights)**	**Vertical Top-lighting** **(Sawtooth-Monitors-Clerestories)**
	bring the light through the roof and ceiling structure. It can be used to control the incoming daylight before it enters the main space. *I) Well Surface Reflectance* - A highly reflective and diffusing surface provides a diffuse and distributed light below the skylight. - A specular reflective surface will not diffuse the light and might cause glare. - Colored surfaces distribute the light evenly, reduce its intensity, and shift the appearance of colors in the space below. *III) Well Wall Slope* - It can be vertical or splayed at an angle. - The broader the base of the well, the larger the task area in the space having a direct view of the skylight *IV) The Well Index* - The well Index (WI) is a geometrical proportion that relates the three geometrical proportions of the well. - The WI and the well reflectance are used to determine the efficiency of the skylight well.	

	Horizontal Top-lighting **(Skylights)**	**Vertical Top-lighting** **(Sawtooth-Monitors-Clerestories)**
	• **The Light Distribution Pattern.** - ***Skylights*** - The light distribution pattern is symmetric under the overcast sky condition. - In clear sky, the direct sun penetration results in the presence of an additional maximum point of illuminance. - The contrast between the points of maximum and minimum illuminance is usually very high. - The level of interior illuminance under an overcast sky is significantly greater than that under a clear sky (without sun) during either winter or summer.	• **The Light Distribution Pattern.** - ***Sawtooth*** - The light distribution pattern is different for a series of openings than for a single one. - The daylight distribution pattern under a clear or overcast sky presents different spread patterns. - A sawtooth opening produces different slopes of the light distribution on both sides of the point of maximum Illuminance. - Under clear sky conditions, the orientation of the opening affects the point of maximum illuminance. - Under an overcast sky, the point of maximum illuminance is very close to the point of min. illuminance. - ***Monitors*** - Under an overcast sky, the light distribution pattern for a single monitor is symmetric below the monitor. - Under clear sky, the opposing openings have different views of the sky thus the light distribution is

	Horizontal Top-lighting **(Skylights)**	**Vertical Top-lighting** **(Sawtooth-Monitors-Clerestories)**
	• **The Horizontal Top-lighting Geometrical Proportions & the Light Distribution Pattern.** - ***Skylights*** *I) Skylight Width* - The skylight width is directly proportional to the internal illuminance. *II) Skylight Length* - The skylight length is directly proportional to the longitudinal spread. *III) Depth and Slope of the Well* - The depth of the well is inversely proportional to the internal illuminance. - The slope of the well is directly proportional to the internal illuminance. *IV) Angle of Glazing Material* - The angle of the glazing material in is less critical	asymmetric. - Light distribution under a series of monitors is very different from what is under one monitor. - The point of peak illuminance varies with the sky type and orientation. • **The Vertical Top-lighting Geometrical Proportions & the Light Distribution Pattern** - ***Sawtooth*** *I) Sawtooth Spacing* - The sawtooth spacing is directly proportional to the light distribution pattern. - Adding a horizontal spacing in between the sawtooth openings leads to increasing the difference bet. The points of max. & min. illuminance. *II) Glazing Slope* - As the slope of the glazing increases, the interior illuminance increases and the difference between the points of maximum and minimum illuminance also increase. - ***Monitors*** *I) Monitors Height* - The interior illumination level is directly proportional

	Horizontal Top-lighting **(Skylights)**	**Vertical Top-lighting** **(Sawtooth-Monitors-Clerestories)**
	than the other geometrical aspects. *V) <u>Ceiling Height</u>* - Increasing the ceiling height results in a more uniform light distribution while decreasing the ceiling height results in a less uniform light distribution with brighter areas under the skylight and darker areas in between.	to the monitor height. *II) <u>Spacing between Monitors</u>* - In a series of monitors, the interior illumination level is directly proportional to the spacing bet. The monitors. *III) <u>The Monitor Slope</u>* - As the glazing slope increases, the internal illuminance increases and the size of the secondary lighting zone decreases.

Table (3-1): Horizontal and vertical top-lighting methods comparison.

3-6 Conclusions

Top-lighting concepts can be used to daylight single-storey or the top floor of multi-storey underground buildings. They are best suited for lighting general tasks rather than a specific task. In addition to daylight, all top-lighting concepts are a source of heat and glare that should be dealt with and avoided. Top-lighting apertures produce more than one lighting zone each can be used to illuminate a different function. Top-lighting concepts are divided into horizontal and vertical top-lighting methods.

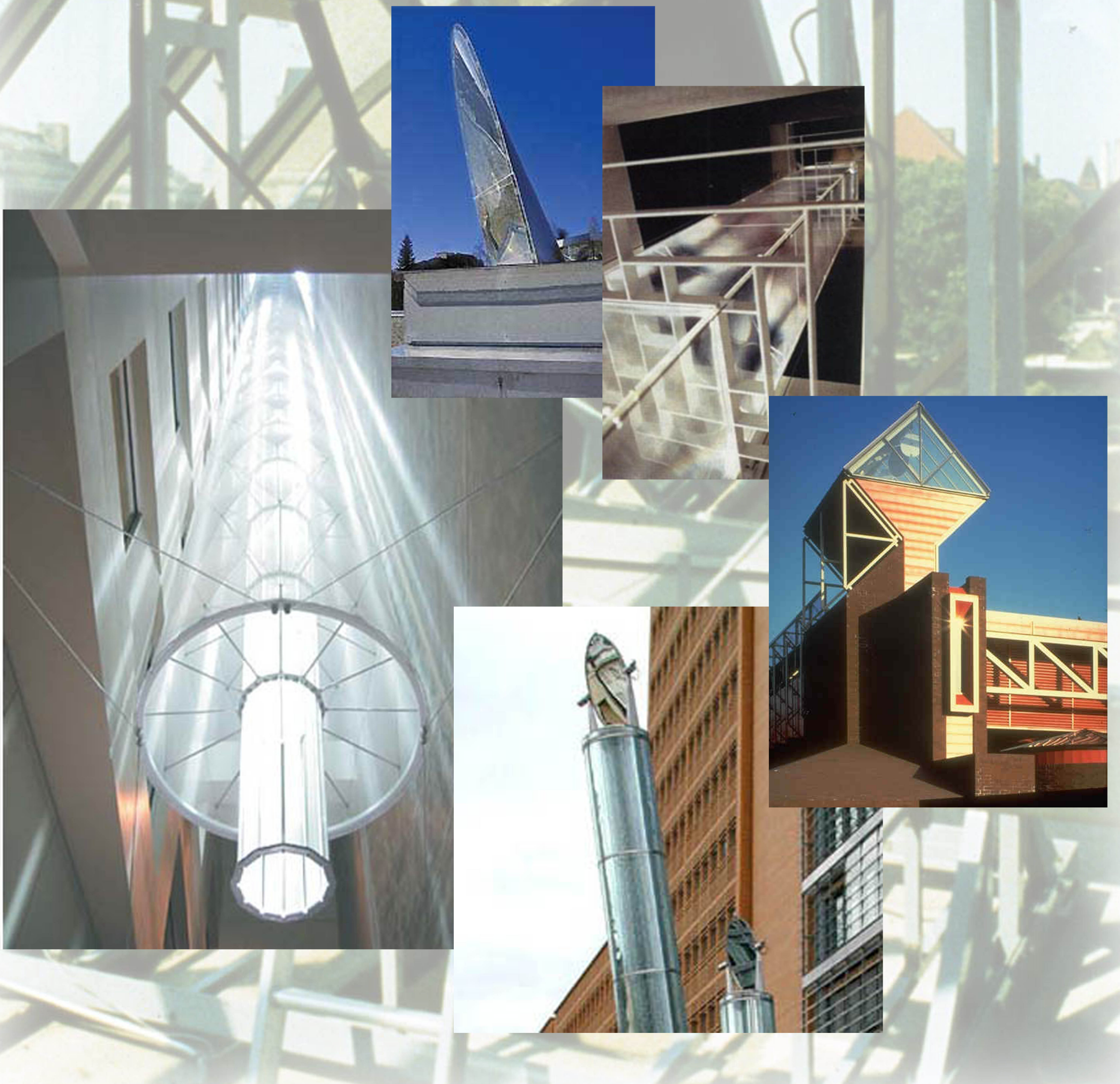
Horizontal top-lighting includes skylights which use horizontal or near horizontal glazing. Skylights provide illumination levels that are three times greater than any vertical aperture and can take a variety of shapes (simple or complex). Skylights use a variety of glazing materials which include glass or plastic materials (clear or translucent). Direct sunlight should be avoided either by using a diffusing glazing materials or by placing light diffusers above or below the skylights.

The light distribution pattern of the skylights depends greatly on the sky condition: clear or overcast sky. In addition to the sky condition, the geometrical proportions of the skylight should be given a special attention to obtain the best light distribution in the space. In addition, The skylight well properties - size, shape, slope, and well finishes - affect the light distribution pattern significantly.

Vertical top-lighting concepts include sawtooth, monitors, and clerestories. They can use clear glazing since the light entering the aperture is diffused by the roof, before it enters the aperture, or by reflection on the aperture wall after entering the space and before reaching the occupants. Vertical top-lighting can be oriented as desired. North facing apertures provide a constant but low illumination level and needs no shading devices. South facing apertures provide a higher illumination level but need an overhang for shading the undesirable sun. East and west apertures should be avoided as they are difficult to shade. Vertical top-lighting glazing slope plays an essential role in increasing or decreasing the illumination levels. Also, their geometrical proportions can be used to vary the daylight distribution pattern as desired.

Chapter (4)

Innovative Daylighting Systems For Underground Buildings



Chapter (4)

Innovative Daylighting Systems For Underground Spaces

4-1 Introduction

Daylighting the deep underground spaces have been relatively a new field of research for architects and occupants until recently. At first, underground spaces were limited to shallow ones in old civilizations and applications until researchers started invading this field of work.

At the beginning traditional methods, such as light courts, atria, and top-lighting concepts, were used to deliver daylight to the unlit underground spaces but they had limited capabilities and some drawbacks related to the depth of the building and their thermal performance. In many cases, however, underground spaces are isolated and are only accessible through tunnels or shafts, so natural light from traditional methods is not possible. In recent years the emphasis has been on developing new systems of transmitting maximum levels of indirect daylight into unlit spaces whilst avoiding the problems of glare and heat gain.

Nowadays, innovative daylighting systems are used to admit daylight into shallow and deep underground spaces. Those systems include active or passive heliostats, light pipes, and fiber optics systems. One of the primary advantages of using those systems is their ability to deliver daylighting to relatively long distances and deep underground spaces.

This chapter presents a general overview of the innovative daylighting systems concerning their theoretical concept, main components, potentials, and their present applications in the field of architectural daylighting.

4-2 Innovative Daylighting Systems used to Deliver Daylight to Underground Spaces: Main Concept and Components.

The use of innovative optical systems to improve daylighting performance is not a new concept. Numerous examples of the use of optical systems to enhance daylight performance in buildings have been recorded in patent literature as for back as the 1880's(1) Fig (4-1). Most of these systems depend on the redirecting of sunlight using mirrors, or lenses via overhead or other glare-free paths. In most cases tracking or some form of automatic adjustment is required for the daylight collection. After collecting the light, it is concentrated and transmitted to the required location. Finally, the light is redistributed in the space(2). It is worth notice that innovative daylighting systems should be supplemented, in most cases, by an electrical light source since their main light source is the sun which is a variable and an unstable source(3).

Fig (4-1): The optical system "Heliostat" designed by the Frenchman J.T. Silbermann in 1843.

The basic components of the innovative daylighting systems are reviewed in the following points.

4-2-1 Light Collection

To collect daylight in an efficient way it is necessary to understand that daylight comes - as mentioned before - in two forms, diffuse and direct(4) . The direct light from the sun is available when the sun is visible. The diffuse light is sunlight scattered by the atmosphere.

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(1) Ruck, N.; "Building Design and Human Performance", P.195

(2) ibid, P.199

(3) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.40

(4) Muhs, J.; "Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems", P.1

The sun is a high-density light source, but using it for daylighting means that one have to take into account its movement. This calls for an active collecting system; some kind of tracking sunlight collector, for example a heliostat(1). All kind of tracking and moving collecting systems are referred to as active systems. Non-moving systems are called passive systems.

4-2-2 Concentration of Light

Different collecting strategies can be adopted to meet the two forms of light. Direct sunlight has nearly a uniform direction and is therefore possible to concentrate. Diffuse light has multiple directions - it is coming from the whole sky. In fact the skylight can be characterized as the integration of an infinite number of point light sources(2). Therefore it is not possible to concentrate; at least there are limits for how much. Also no technique was found where diffuse light can be concentrated and in addition to this be given a uniform parallel direction.

The concentration can be done by several different techniques using optical aberration and reflection. The most common techniques are Fresnel lenses and reflecting parabolas. Other possible techniques for light concentration include heliostat arrays and wedge shaped light traps, where the latter is intended for photovoltaic cells.

4-2-3 Transmission of Light

Once collected the daylight should be transmitted to where it is needed, concentrated or not. However, transmission to remote spaces or rooms is typically intended for concentrated light. It takes up less cross-sectional area and because of that less space demanding when transmitted. Non-concentrated light is generally used closely to where it is collected. Concentrated light can be transmitted in several ways: an empty shaft with high reflectance, metal tubes, hollow light guides, optical fibers, and liquid light guides.

Common for all of the transmission techniques is that some portion of the light will be lost in the transmission. This is due to

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(1) Robbins, C.; “Daylighting: Design and Analysis”, P. 215

(2) Lechner, N.; “Heating, Cooing, Lighting: Design Methods for Architects”, P. 313

reflections, absorptions, etc. When choosing a light guiding technique the economy, space demand, durability, and capacity of the guide have also to be considered(1).

4-2-4 Use of Light

Light from daylighting systems can be used for several different purposes. It can also be delivered to the illuminated space with a variety of methods, depending on the purpose and the transmission technique.

4-2-4-1 Redistribution

The transmission method is important for determining which way the light will be distributed in the room. Concentrated light admits other possibilities than non-concentrated light.

The redistribution of concentrated light can occur by a variety of methods such as end-emitting or side-emitting optical fibers, hollow light guides, lenses, and prisms.

If it is a matter of non-concentrated light, the distribution method most often is directly given by the collecting method or it can be done by directing the light onto a highly reflective diffuse surface, e.g. a white wall or the ceiling(2).

Choosing what kind of distribution also depends on the purpose of the daylighting illumination. Task illumination at work places or spotlighting demands a concentrated and collimated light beam. General lighting of a whole room on the other hand could be provided with diffuse and not concentrated light.

Another important aspect of daylighting is glare from bright sources. If a high amount of light falls on the redistribution tool this can create glare for the inhabitants of the building. This could be avoided by increasing the illumination level indoors. One way of dealing with this could be redirecting the light creating the glare so it is utilized for illumination rather than creating bright spots.

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.39

(2) ibid, P.40

4-2-4-2 Mixing Daylight with Electrical Light Sources

As mentioned above, daylighting is most probably to be used in combination with other light sources, i.e. electrical lighting. The main reasons for this are the unpredictability of daylight availability and difficulties in distributing daylight evenly and deep into spaces. Thus a supplementary light source is needed(1).

Combining electrical light with daylighting can be done in several ways. There is a choice of where to put the electrical light source and also how to control it. If daylight is being piped by some kind of light guide there are mainly two concepts of where to put the backup light source. Either using a central electrical light source that can be placed so that the light guide pipes the light or lamps could be placed in the illuminated rooms. The first concept means that light losses along the light guide has to be considered. The latter one means that either a double set of luminaires have to be used or that electrical and daylight fittings have to be somehow integrated in the same luminaires. Either way, means of providing the same light distribution for electrical and natural light has to be considered(2).

Controlling the lighting level can be done in two steps: first measuring the present illumination and second adjusting the light output so that the desired illumination level is maintained.

Most often this is done by our own visual judgment and manually switching on or off available lamps in the room. In some cases there are also dimming devices to make it possible to adjust the light output from a lamp. This is called a manual control system.

Automatic control systems can be of mainly three different types: on/off, multistep, and continuous dimming. For all of these the room in question can be divided into different control zones depending on the available daylight.

On/off control systems simply switch on the electrical light when the available daylight is not sufficient to reach the

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(1) CADDET; "Saving Energy with Daylighting Systems", P.7

(2) ibid

required illuminance level. This means that the total illuminance level can become very high if the available daylight is just below the limit and the electrical light is switched on⁽¹⁾.

Multistep systems make use of daylight even when this is not enough to provide all of the required light. Electrical light is turned on in steps depending on the daylight level. The steps depend on the number of lamps in each lummaire and the manner in which these are wired or ballasted⁽²⁾.

Both on/off and multistep systems will give sudden changes in illuminance when electrical lighting is turned on or off. A change in illuminance of 50 lux or less is usually unnoticeable. Bigger changes are noticeable and if they are over 200 lux they can be very annoying.

Continuous dimming control systems can be in two forms. Simple dimming controls which can vary the electrical light output in response to the available daylight. More advanced dimming controls also include the possibility to turn off the electrical light⁽³⁾.

For all of these systems the available light needs to be measured. This can be done with the use of photosensors. These are electronic control devices made up of a photocell connected to a circuit that sends out a control signal in response to the detected illuminance. They can be placed on the ceiling or directly above a work surface that receives a representative amount of light.

4-3 Heliostats

4-3-1 Heliostat: Definition, Main Concept and History

A “Heliostat” is a device consisting of movable mirrors that tracks the sun as it crosses the sky, thus constantly reflecting direct

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(1) Andre, E., Schade, J.; “Daylighting by Optical Fiber”, P.41

(2) ibid

(3) ibid

sunlight to any desired location within the building by means of other fixed mirrors(1) Fig (4-2).

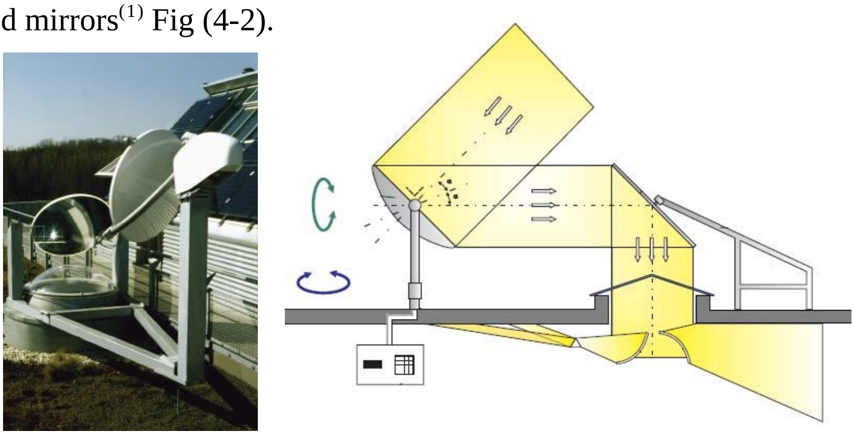

Fig (4-2): Heliostat concept - schematic sketch.

The simplest heliostat devices use a clock mechanism to turn the mirror in synchronization with the rotation of the earth. More complex devices need to compensate for the changing elevation of the sun throughout a solar year. Even more advanced heliostats track the sun directly by sensing its position throughout the day(2).

The heliostat main concept is the concentration or the reflection of the direct illuminance into the building by imaging the solar disk(3).

The heliostat was originally developed as an instrument for use in surveying, allowing the accurate observation of a known point from a distance(4). Afterwards, the heliostat was used in solar optics applications. It was used in the thermal and lighting fields to concentrate the solar energy producing huge amounts of heat energy and to redirect the sun's light to any desired location.

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(1) Guzowski, M.; "Daylighting for Sustainable Design", P. 246
(2) Wikipedia, The Free Encyclopedia [http://em.wikipedia.org/wiki/Heliostat]
(3) Robbins, C.; "Daylighting: Design and Analysis", P.215
(4) Wikipeda, The Free Encyclopedia [http://en.wikipedia.org/wiki/Heliostat]

The word “*Heliostat*” was originated from the Greek words for sun and stationary⁽¹⁾. Many small heliostats were designed and built since the 1800’s Fig (4-3).

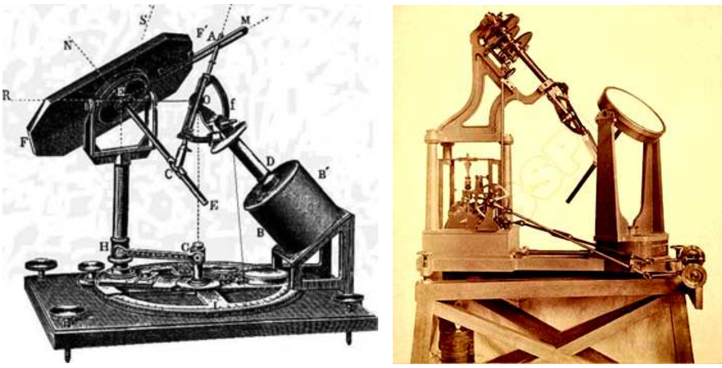

Fig (4-3): Early mechanical heliostat designs used in solar optics applications.

4-3-2 Heliostat Potentials

The heliostat daylighting system offers a variety of advantages in addition to the system potentials. First of all, heliostats deliver daylight to unlit spaces (above or below grade) thus increasing the quality of life and the environment of these spaces by the use of sunlight⁽²⁾. Top quality electrical energy may be saved by using primary energy available free of charge (daylight) for illumination purposes. The cooling loads in the building are reduced because of the efficiency of sunlight (IR-filtered) is considerably higher than that of artificial light. The potential savings of energy is in between 20% and 60% (depending on the used system) in the form of indirect energy savings (decrease of electric consumptions and HVAC loads)⁽³⁾.

4-3-3 Heliostat System Components

The basic structure of a heliostat has remained unchanged for many decades⁽⁴⁾. Active Heliostats that direct daylight in any

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(1) http://physics.Kenyon.edu/Early Apparatus/ Optics/ Heliostat/ Heliostat.html

(2) Pohl, W.; “Guided Sunlight for Room Illumination”, P.1

(3) Pohl, W., Anslem, C.; “Room Illumination by Controlled Sunlight”, P.3

(4) Chen, Y., Kribus, A, Lim, B., Lim, C., Chong, K., Karni, J., Buck, R., Pfahl, A., and Bligh, T.; “Comparison of Two Sun Tracking Methods in the Application of a Heliostat Field”, P.638

direction through the interior of a building and over longer distances require three major elements: a collection system to gather and concentrate available light, a light guide system to transmit the light to the point of use, and a distribution system consistent with the end use of the lighting in that portion of the building(1).

4-3-3-1 Collection and Concentration Systems

Daylighting heliostats consist of (a) a primary reflector that directly illuminates the interior of the building (Simple passive heliostat or one-mirror heliostat) or (b) a combination of a primary reflector that tracks the sun in some fashion, and a fixed secondary reflector that reflects the daylight into the building (Active or two-mirror heliostat)(2) Fig (4-4).

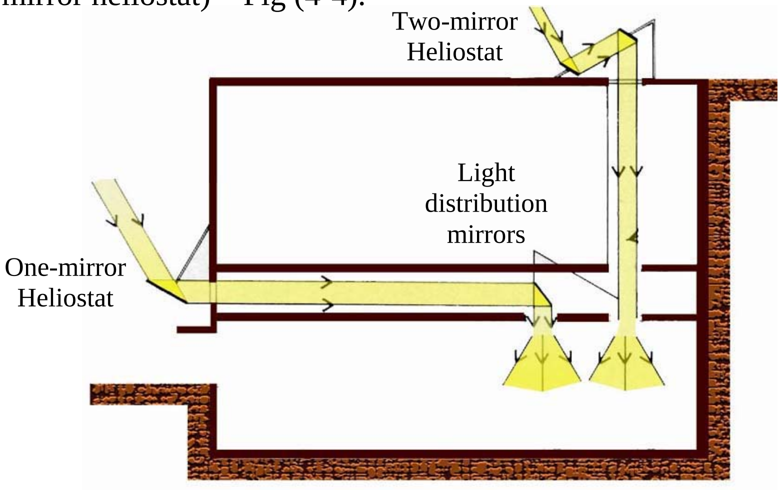

Fig (4-4): Passive and active solar collection systems.

Although a number of different heliostat systems can be used for solar applications, only three have been developed that use active heliostat for daylighting purposes. These are:

1-Azimuth-tracking, fixed-altitude systems.
2-Altitude-tracking, fixed-azimuth systems.
3-Altitude/azimuth-tracking systems.

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(1) Salem, D., “The Study of Natural Lighting in the Atrium Buildings within the Local Environment Level to Reach the Optimum Performance by the Aid of Computer”, P. 108

(2) Ruck, N.; “Building Design and Human Performance”, P.200

In azimuth-tracking, fixed-altitude heliostat systems, the primary reflector continuously tracks the solar azimuth while the slope of the primary reflector remains fixed at a specific angle (usually equal to the latitude of the location) and can not track the change in solar altitude(1).

In altitude-tracking, fixed-azimuth heliostat systems, the primary reflector continuously tracks the solar altitude by rotating about a horizontal north-south axis but is fixed to a specific solar azimuth(2).

In altitude/azimuth-tracking heliostat systems, the primary reflector continuously tracks both solar altitude and azimuth by rotating about two axes (east-west/north-south) with continuous adjustment to keep the surface normal to the incidence illuminance at all times(3) Fig (4-5).

In all of these systems, the secondary reflector is fixed in position. Furthermore, in order to be able to track altitude and/or azimuth continuously, the heliostat must have an automatic control system: it can not be manually driven.

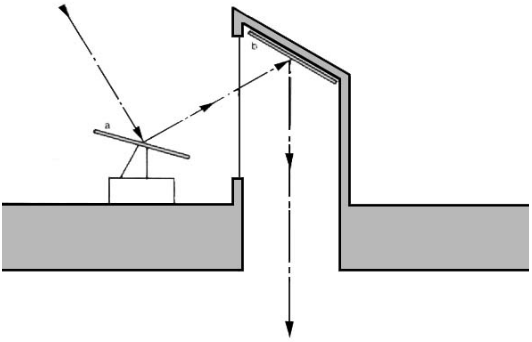

Fig (4-5): Schematic diagram of an azimuth/altitude-tracking daylighting heliostat.
(a) Primary reflector, tracking the sun; (b) Secondary reflect or, stationary

The opening through which the daylight from the heliostat must pass can typically be located in any of three locations:

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(1) Robbins, C.; "Daylighting: Design and Analysis", P 216
(2) ibid, P.217
(3) ibid

infront of the primary reflector, between the primary reflect or and the secondary reflector, or between the secondary reflector and the building.

If the opening glazing is located infront of the primary reflector, the heliostat is inside the building, and the performance characteristics of the heliostat system must be altered to represent the fact that any illuminance striking the primary reflector has already passed through the building glazing. If the glazing is placed between the primary reflector and the secondary reflector, light losses occurs after the light is reflected from the first mirror and before reaching the secondary mirror. If the glazing is located after the secondary mirror thus light losses occur after the light reflections and during entering the building. Each of the above locations of the glazing requires different handling solutions to obtain an efficient heliostat system.

The quantity of visible flux (in lumens) entering a building after being reflected from the primary reflect or the secondary reflector and from the secondary reflector into the building is called the luminous output of the heliostat. Luminous output is a variable used to determine the performance characteristics of most electric lighting systems. The luminous output from any of the three types of tracking heliostat systems is a function of the reflectivity of the primary and secondary mirrors, their size, the luminous flux incident on the primary reflector, and the properties and position of the glazing(1).

The mirrors used could be made of acrylic or glass materials. The measured reflection of the acrylic mirror is lower than that of the glass mirror in the ultraviolet ray region. This is attributed to an ultraviolet absorber contained in the acrylic material. The ultraviolet absorber must be contained to guarantee the strength of the mirror. The reflection efficiency of the glass mirror is recognized to be lower than that of the acrylic mirror in the visible light region but the reflection from the acrylic mirror is unstable in the infrared region(2).

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(1) ibid, P.216

(2) Hane, T.; "Application of Solar Daylighting Systems to Underground Space", P.466

As for the light concentration, a fluorescent concentrator, in which a fluorescent dye absorbs incident light and then readmits light within a narrow set of wavelengths, could be used but it has limited potential. Multiple fluorescent plates would improve overall efficiency. A second option is the use of holographic coatings to collect the light(1).

4-3-3-2 Transmission Systems

Light guide systems are necessary to transmit the light collected and concentrated by any collection systems to the target area. Five methods could be used to transmit the light Fig (4-6):

I) *Traditional clear "light ways" or shafts*

This is simply an empty shaft through which a collimated light beam can travel. The method of simple propagation across clear airspace or down a shaft is prone to ray scattering because of the dust in the air and passageways, resulting in deviation and loss of efficiency(2).

II) *Light ways with collimating lenses or lens guides*

Lenses can be included in the shafts or ducts to keep the beam concentrated. Collimating lenses also collect dust and suffer from reflections at each interface, also resulting in the reduction of the intensity and efficiency of the light. Some of these losses can be eliminated by the use of antireflection coatings(3).

III) *Mirrored or reflective metal ducts*

Hollow reflective light guides have considerable potential. These guides, either circular, rectangular, triangular, or square in cross-section, have a highly reflective coating on the interior surface. The application of a dielectric reflector film in place of metal spraying produces reflectance of up to 99 percent and an

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(1) Ruck, N.; "Building Design and Human performance", P.201

(2) Littlefair; "Innovative Daylighting: Review of Systems and Evaluation Methods" P.5

(3) ibid

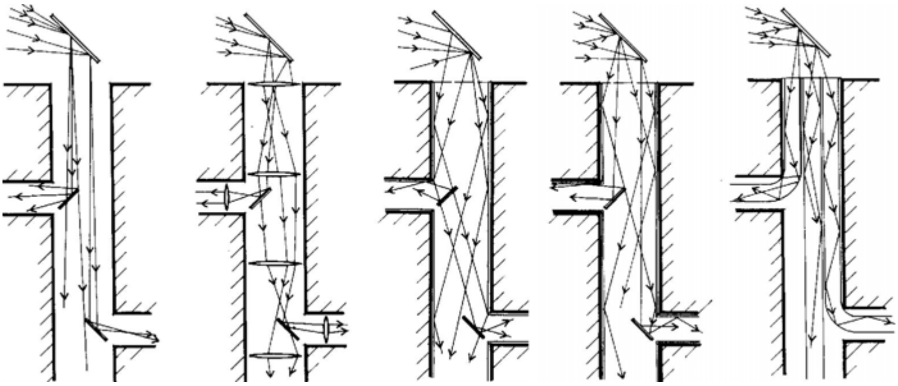
estimated efficiency for a 50m long and 1m diameter sealed unit of at least 50 percent. Silver has been found to be one of the most practical materials to use in a hollow light guide of small diameter and moderate length. If protected by a thin acrylic coating the efficiency of the light guide is increased depending on diameter(1).

IV) *Prismatic or refractive ducts*

A hollow guide with a prismatic cross-section traps the light by total internal reflection and redirects it back down the core of the light guide. The light lost in transmission is scattered out into the surrounding space, and therefore, this type of guide can be used as both a transport and distribution device(2).

V) *Optic fiber bundles/ Solid core optical fibers/ Liquid light guides*

These use the principal of total internal reflection as they transmit light along thin cables. Fiber optic system have the potential benefit of the use of flexible cables that can be routed as desired (flexible as electric cables)(3).



Plain duct Lens duct Mirror duct Prismatic duct Fiber optic

Fig (4-6): Transmission systems for deep building interiors

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(1) Ruck, N.; "Building Design and Human Performance", P. 202

(2) Salem, D.; "Daylighting as A Primary Element in the Design of Commercial Centers", P.112 (Arabic thesis)

(3) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.39

4-3-3-3 Redistribution Systems

Distribution design is basically influenced by the type of light guide system employed(1). In general, the distribution is done by one of two methods: directly by the use of diffuse luminaries Fig (4-7) or indirectly by reflecting the light to the ceiling then into the space(2).

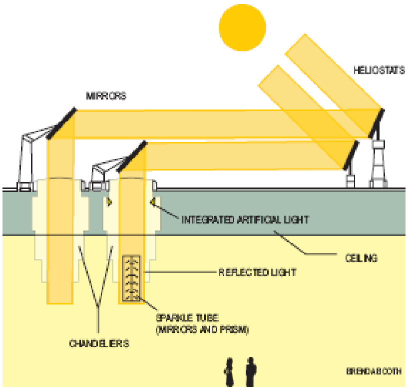

Fig (4-7): Direct light distribution by the use of diffuse luminaire in Manchester Airport, Great Britain.

4-3-4 Heliostat Systems Scale and Specifications.

At the present, three types of heliostat daylighting systems are available(3): a small-scale system for houses and dwellings; a mid-scale system for medium buildings; and a large-scale system for office buildings.

4-3-4-1 Small-scale Heliostat Daylighting Systems

This small-scale, mass produced system is intended as a low-cost, energy conservation system for applications in house courts, rooms facing north, and basements. Actual application examples are a system installed on a roof to direct sunlight into the rooms of a house; and a system installed on supports built in a garden, to provide daylight from the outdoors through a window Fig (4-8).

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(1) ibid

(2) Bomin solar GmbH [http://www.bomin-solar.de]

(3) Hane, T.; "Application of Solar Daylighting Systems to Underground Space", P.465

Fig (4-8): Small-scale heliostat system (garden and roof type).

4-3-4-2 Mid-scale Heliostat Daylighting System

The size of a mid-scale system is adjusted to match the building design, and is distinguished from a large-scale solar heliostat system by its mechanism. An example of such a system is the daylighting system that brings light into the Civil and Mineral Engineering Building of the University of Minnesota Fig (4-9).

Fig (4-9): The Civil and Mineral Engineering Building (an example of the mid-scale system is the passive system used in this building).

4-3-4-3 Large-scale Heliostat Daylighting Systems

The large scale system has been developed in order to bring natural light into a wide area by combining a number of reflecting mirrors. Such system can introduce daylight into a site approximately 5m x 5m to 30m x 30m. The system employs 1.5mm-thick reflecting mirrors, with high reflectance quality in order to make the daylighting more efficient and the system lighter in weight. The system power is self-supplied, using solar cells to meet its power consumption needs.

Table (4-1) illustrates the specifications of the three heliostat system scales(1).

Type of System	Mirror Area	Main Body Weight	Power Supply
Small-scale	0.464m^2	25 Kg.	AC100V/6W
Mid-Scale	3.1m^2-4.9m^2	450-950 Kg	AC/100V/20-25w
Large-scale	15m2	1200Kg	Solar cell DC 12V/72 W

Table (4-1): Specifications of solar daylighting system(2).

4-3-5 Overview of Existing Systems using the Heliostat Concept.

4-3-5-1 Lightron Heliostatic System(3), Germany

System Principle: A heliostat, automatically tracking the sun as it crosses the sky, constantly reflects direct sunlight to a secondary reflector that redirects the light to any desired location or to the distribution system within the building. Precise tracking is ensured by a built-in microprocessor control system Fig (4-10).

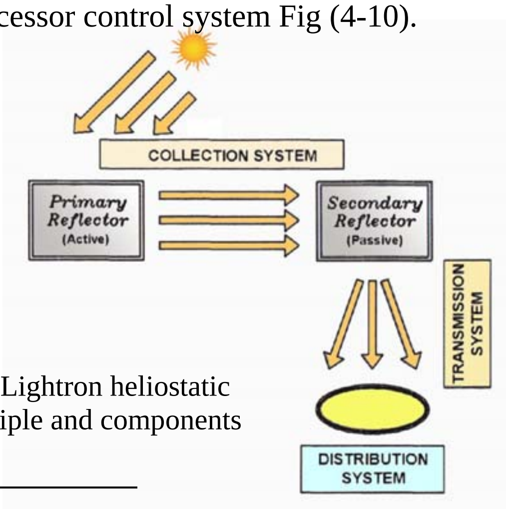

Fig (4-10): Lightron heliostatic system principle and components

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(1) ibid, P.469

(2) ibid

(3) Bomin solar GmbH [http://www.bomin-solar.de]

Application Fields: Interior lighting in museums, Banks, offices, shopping malls, hotels, hospitals, Airports, Public buildings, and underground spaces. Decorative effects for exhibitions and showrooms.

Existing Example (1).

- *Project Name*: Underground station - Altenessen.
- *Location*: Altenessen - Mitte, Deutschland.
- *Architects*: KZA, Koschany, Zimmer & Associates GmbH, Essen.
- *Construction Date*: 2001.
- *System Components*: the heliostat principle is used to daylight a moderate depth underground station Fig (4-11).

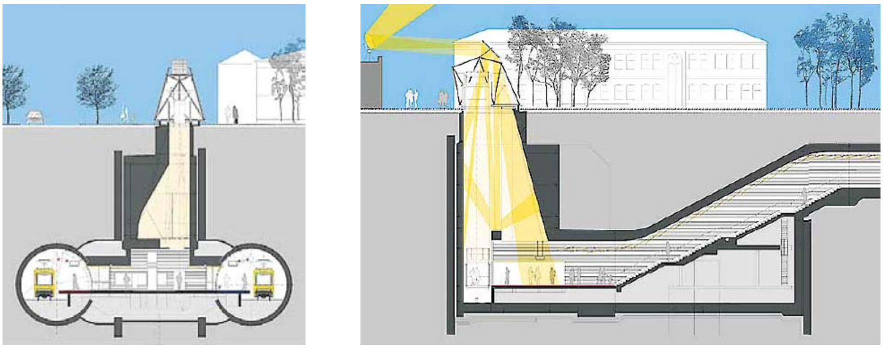

Fig (4-11): Cross and Longitudinal section of the underground station, Altenessen.

The lightron heliostatic system in this project consists of a primary heliostat lightron (1.6m x 1.6m) Fig (4-12) that tracks the sun and redirects the daylight onto a secondary reflector consisting of 24 redirection mirrors (0.37m x 0.37 m each) Fig (4-13). The secondary reflectors redirect the daylight to the underground space Fig (4-14).

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(1) ibid

Fig (4-12): Exterior view of the lightron system showing the primary and secondary mirror.

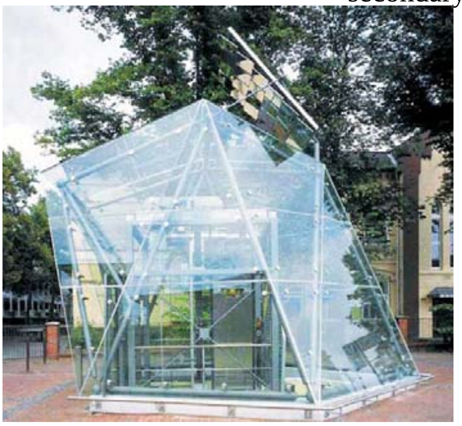

Fig (4-13): Exterior view of the system showing the secondary reflecting mirror.

Fig (4-14): Interior view of the station showing the resultant daylight within the underground space.

4-3-5-2 Sun Lighting System (SLS)(1), Austria

System Principle: The direct sunlight, captured by means of a movable heliostat, is aimed to a fixed mirror which redirects the sunlight to a concentrator. After compression, the sunlight is coupled into a hollow light guide and finally reaches a sun-luminaire which distributes the sunlight into the Basement Fig (4-15).

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(1) Bartenback LichtLabor GmbH [http://www.bartenbach.com]

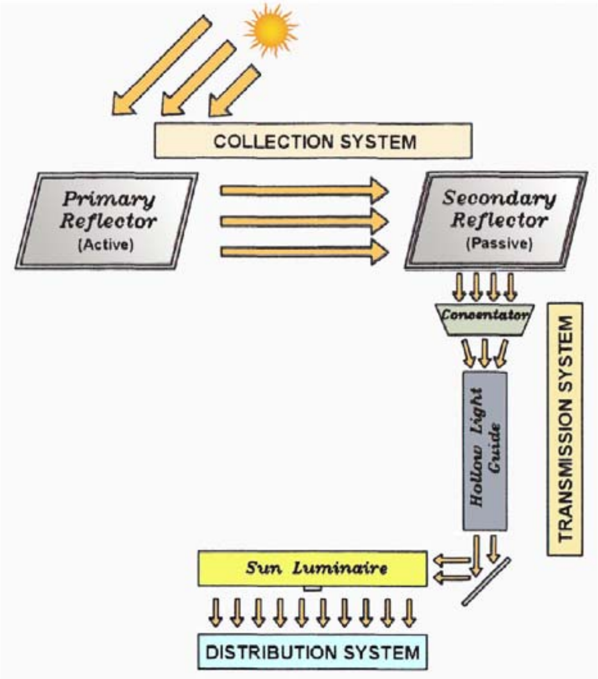

Fig (4-15): Sun lighting system main principle and components

Application: illumination of unlit underground spaces with natural sunlight.

Existing Example⁽¹⁾.

- *Project Name*: Bartenbach LichtLabor SLS
- *Location*: Rinner strabe, Aldrans, Innsbruck, Austria.
- *Construction Date*: 2001.
- *System Components*: Within the work of a European Commission (EC) funded research project a pilot installation has been erected at Bartenback lichtlabor's company site to illuminate an unlit cellar with natural sunlight Fig (4-16).

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(1) Pohl, w.; "Guided Sunlight for Room Illumination", P.1

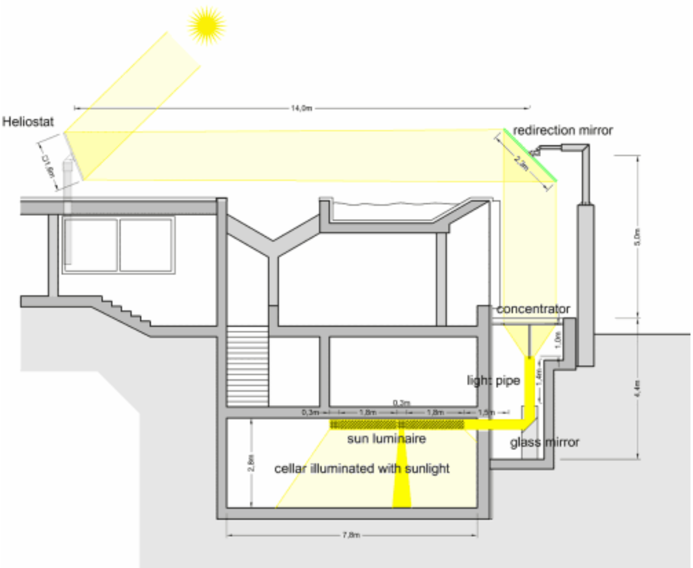

Fig (4-16): Schematic cross-section of the pilot installation at Bartenbach LichtLabor.

Two adjustable Fresnel lenses are used to capture the sunlight Fig (4-17). A secondary mirror redirects the light vertically Fig (4-18). Then the light is concentrated by the use of a collimator which increases the density of the incoming sunlight by a factor of 35 Fig (4-19). This guarantees an optimum coupling into the tubular hollow light guide (30 cm diameter) fitted with prismatic layer Fig (4-20). A 90 degree redirection element (knee) guides the sunlight into the sun-luminaire positioned in the cellar.

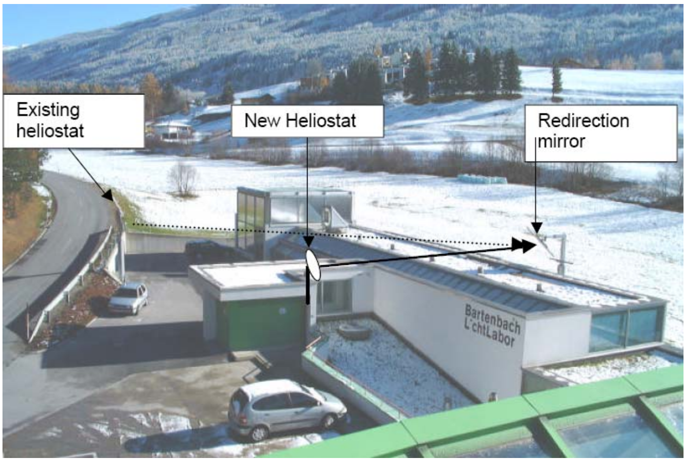

Fig (4-17): The pilot installation of the SLS at Bartenbach LichtLabor.

Fig (4-18): The secondary redirecting mirror

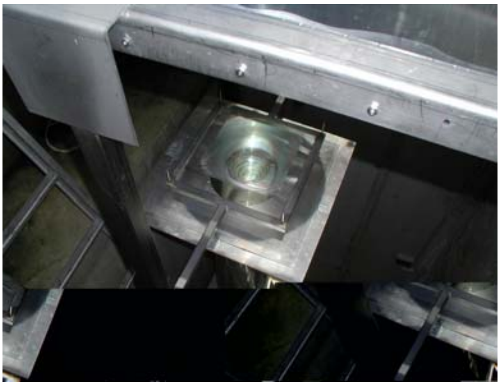

Fig (4-19): The sun collimator

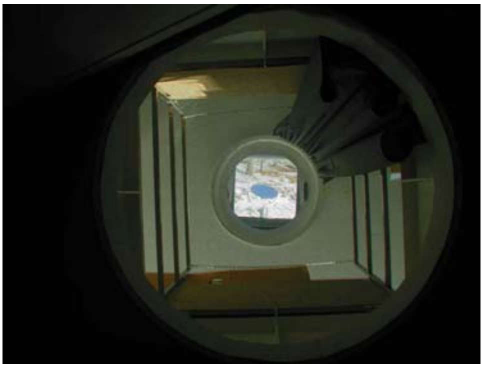

Fig (4-20): Looking-up through the hollow light guide lower opening.

The tubular sun-luminaire consists of two longitudinal elements and a central element Fig (4-21). By means of reflective optical components the longitudinal elements of the sun-luminaire distribute sunlight and limit the glare possibilities all over the cellar. Simultaneously, the central element extracts sunlight causing a bright spot on a table below thus creating a visual (psychological) link to the outside Fig (4-22). Alternative color effects can be created by adding prismatic elements below the central element.

Fig (4-21): The sun-luminaire showing the longitudinal and central elements in addition to the artificial lighting.

Fig (4-22): Cellar illuminated by sunlight.

Supplementary to the distributed sunlight, fluorescent lamps incorporated in the longitudinal elements are automatically dimmed to zero in case of shiny outdoor conditions. During night or in case of less sun shine the lamps are automatically turned on to guarantee stable indoor illuminace. By means of this technology building areas of lower quality (e.g. basements, store areas, and corridors) can be transformed into areas of high quality which allow an occupation (at least temporary e.g. conference rooms).

4-3-5-3 Heliobus, Switzerland

System Principle(1) The operation principle is as follow: solar light rays, captured by a light collector, are directed through an intermediate device (by its spectrally reflecting surfaces) into the input end of a vertical hollow light guide. Solar light travels inside and along the light guide by total internal reflection. When the rays strike an extractor, they are diffused and reflected back to light guide walls Fig (4-23).

Applications: It could be used in almost all applications of daylighting above and underground buildings.

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(1) Heliobus Tageslichtsysteme [http://www.heliobus.com]

Existing Example:

- *Project Name*: Pilot project in St. Gallen.

- *Location*: Bopartshoff School, St. Gallen. Switzerland.

- *Construction Date*: 1996

- *System Components*: the main objective of the used system (Heliobus) was illuminating the central part of Bopartshoff School built in 1966 in St.-Gallen (Switzerland) by using both solar and artificial light. It is a four storey building (three above ground floors and one underground floor), nearly square at the plan view.

The system has the following components[1] Fig (4-24):

1. A solar collector (heliostat)
2. An intermediate element
3. A unit containing electric light sources
4. Ballasts
5. A vertical hollow light guide
6. Extractor
7. A diffuser

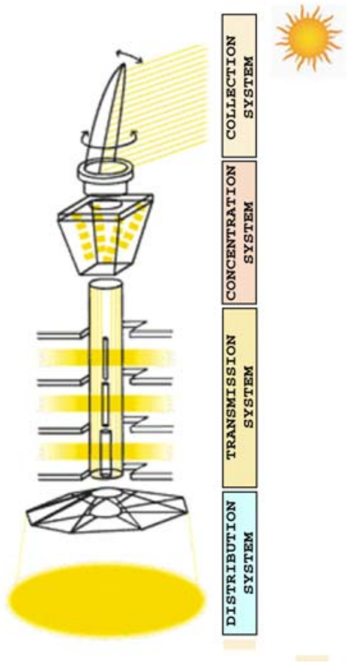

Fig (4-23): Heliobus system principle.

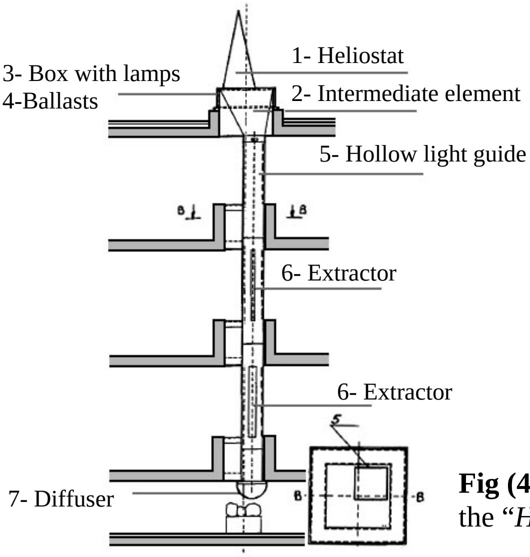

Fig (4-24): Cross-section showing the "*Heliobus*" basic components.

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[1] Aizenberg, J.; "Principal New Hollow Light Guide System "Heliobus" for Daylighting and Artificial lighting of Central Zones of Multi Story Buildings", P. 24

The Heliobus daylighting system components are:

The solar light collector (*Heliostat*)

The shape of the heliostat is optimized in order to gather and redirect the largest possible amount of daylight(1) Fig (4-25). The static, specially designed heliostat, is made of aluminum sheet with the inside coated by specularly reflecting material, which has a reflectance of 0.95. A protective screen is made from transparent ploy methyl metha Acrylate (PMMA) is used to protect the heliostat. The internal cavity of the collector is well sealed to prevent the accumulation of dust. The collector dimensions are: 2.25m (height); 1m (base diameter).

The Intermediate Element

The intermediate element is located directly above the input end of the light guide. It houses three mirror metal halide lamps. The lamps are positioned vertically with their caps directed upward(2) Fig (4-26).

Fig (4-25): Exterior view of the heliostat.

Fig (4-26): The intermediate element housing the artificial lighting.

The vertical hollow light guide with a height of approximately 10m and a square cross-section (0.625m x 0.625m) has an envelope from a transparent material, 10mm thick sheet PMMA, which protects it from

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(1) Trauthwein, C.; "Back to Basics: Daylighting", P.4

(2) Heliobus Tageslichsysteme [http://www.heliobus.com]

possible external damages Fig (4-27). From the inside, the walls of the light guide are covered by a prismatic film that carries out a transporting function. The light striking the film from specific directions undergoes the total internal reflection and extends along a light guide practically not coming out(1). For most of the reflected rays, the conditions of total internal reflection are violated, so they are subjected to refraction on the walls of a light guide and go outside into illuminated rooms located at different floors of the building.

Without light transmission With light transmission

Fig (4-27): The transparent light guide.

The Extractor

The extractor is made of extruded plastic tubes of different diameters. It is a diffusing rod, which alters the path of the light beam so that it can leave the light guide(2). It is not necessary to make extraction between floors. At the basement floor a bulb diffuser is fixed on the ceiling to provide the illumination and makes a suitable end for the light guide(3). At dusk or night, light bulbs placed at the top of the light guide are turned on which allow the light distribution through the same mechanics along the light guide Fig (4-28).

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(1) Aizenberg, J.; "Principal New Hollow Light Guide System "Heliobus" for Daylighting and Artificial lighting of Central Zones of Multi Story Buildings", P.241

(2) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.31

(3) ibid

Fig (4-28): The light guide tube illuminating the core of the building

4-3-6 The Civil and Mineral Engineering Building: An Example of Underground Building using Innovative Daylighting System.

Location: University of Minnesota, Minneapolis, Minnesota.

Architect: BRW architects, Inc., Minneapolis, Minnesota**.**

Construction Date: 1982

Project Size: 14,000m^2 (including 4,460m^2) in mined space.

Underground Classification

1-*Function*: Non-Residential/ Institutional/ Classrooms, laboratories and office building.

2-*Fenestration Type*: The mined space: chamber type
Remaining spaces: atrium/ Elevation type

3-*Relation to Surface*: Semi-subterranean / Subterranean.

4-*Depth*: Deep underground building (35 meters below grade)

5-*Project Scale*: Large sized building scale

Earth Cover*:* In the portion of the building above bedrock, 90 percent of total wall area is covered; 37 percent of the roof is covered with 0.3-1.2m of earth (remainder of the roof is 48 percent plaza and 15 percent conventional roof); entire envelope of mined space is in contact with the bedrock(1).

Reason for going Underground:

Placing the Civil and Mineral Engineering Building (CME) below 95 percent of grade is not only an energy conservation strategy, but also provides open space on the densely built campus and significantly reduces the mass of the structure(2).

Project Description:

The CME Building on the Minneapolis campus of the University of Minnesota represents one of the most innovative underground structures. The structure includes classrooms and laboratories as well as department and faculty offices(3) Fig (4-29).

Fig (4-29): Aerial view of the CME building.

The organization of the site plan and the resulting form of the building are determined mainly by a few key features of the site combined with special program requirements. In particular the site was designed to serve as a major bus terminal for the campus

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(1) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P. 93.

(2) Barker, M.; "Using the Earth to Save Energy: Four Underground Buildings", P. 60.

(3) Hane, T.; "Applications of Solar Daylighting Systems to Underground Spaces", P.465

and as the northern gateway to the institute of technology portion of the campus(1) Fig (4-30).

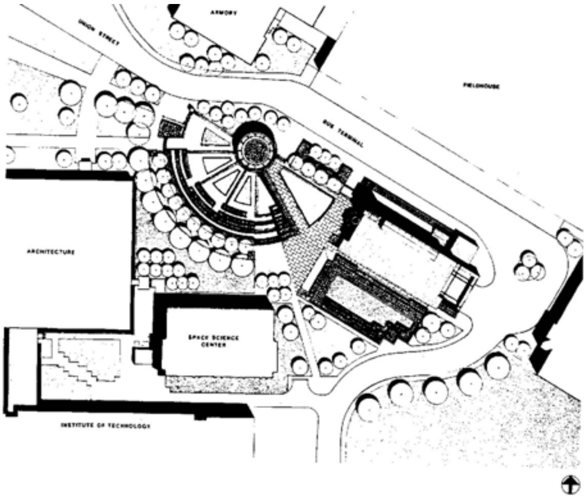

Fig (4-30): The CME building site plan

The site and program issues are resolved by dividing the building into distinct portions with differing functions. On the western half of the site, classrooms with connections to the adjacent structures are placed completely underground(2) Fig (4-31)

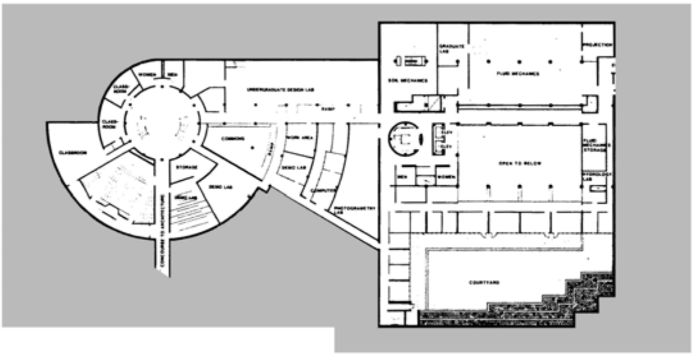

Fig (4-31): Two levels below grade plan showing the arrangements of the different functions.

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(1) Jankowski, W.; “The Best of Lighting Design”, P. 214

(2) Carmody, J. Sterling, R.; “Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces”, P. 273

On the surface is a spiral shaped courtyard that provides open space and serves as the major building entry Fig (4-32). On the eastern half of the site are the laboratory and office spaces requiring solar exposure. A central feature of this portion of the building is the four-storey-high main structures laboratory. The roof of the main structures lab projects above grade, although the floor of the laboratory is three levels below grade. To the south of the laboratories are the faculty offices clustered around a sunken courtyard(1).

Fig (4-32): View of the spiral shaped courtyard showing the main entrance of the CME building.

Because of the unique geology of the Minneapolis-St. Paul area, the CME building includes two distinct types of underground space: the conventional cut-and-cover space near the surface and the deep mined space in the bedrock Fig (4-33). The mined space is connected to the building above by two shafts through the limestone. The resulting space, used mainly for laboratories with some offices, is on two levels with the lowest floor level 35 meters beneath the surface(2) Fig (4-34). At this depth there is virtually a constant moderate temperature and complete isolation from surface noise and vibration.

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(1) Barker, M.; "Using Earth to Save Energy: Four Underground Buildings", P.61.

(2) Hane, T.; "Applications of Solar Daylighting Systems to Underground Spaces", P.469

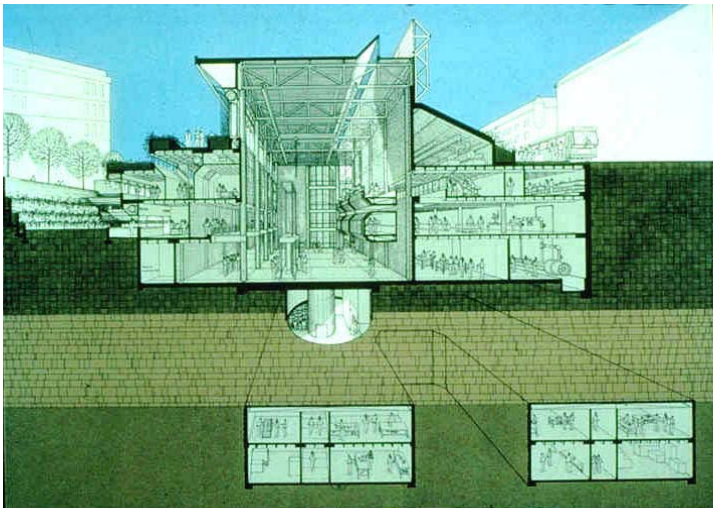

Fig (4-33): Isometric section of the CME building showing the different sections and functions in the building.

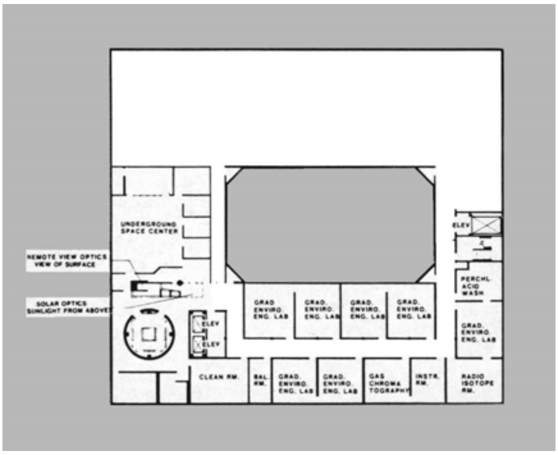

Fig (4-34): Mined space floor plan housing the mined and environmental engineering laboratories.

Daylighting Concept:

In this large underground building with limited window area, variety in the size and arrangement of interior spaces and the maximum use of the available natural light are essential for orientation and for habitability of the spaces. The actual distribution of windows is closely related to the functions in the building. Most of the faculty offices have exterior windows with views into the sunken courtyard. Offices that are not located on exterior walls have clerestory windows that provide natural light from the corridors or public spaces with exterior windows. The interior design of the office area employs glass partitions between the private offices and general open plan office area, as well as between the corridor and office complex, to increase the quantity of light in the offices that are not adjacent to exterior walls. Natural light in most of the classroom and laboratory spaces in the building is considered not only unnecessary but undesirable in many cases(1).

Many of the traditional daylighting design techniques evident in the conventional cut-and-cover portion of the building - skylights, courtyards, and borrowed light - are commonly used in underground buildings near the surface(2). However, the mined space in the CME building presents unusual constraints. The only connection to the surface is through two shafts containing stairs and elevators so more innovative daylighting systems had to be used(3).

Two kinds of innovative daylighting systems are used: active and passive heliostats Fig (4-35). The passive heliostat system that brings daylight rises 15m above ground. The passive solar system, mounted on the roof, collects sunlight on stationary mirrors which reflect it through high, narrow windows on the first floor. Another series of mirrors then transmits this light to the target zone-an east-west strip that cuts across the upper region of the lab(4) Fig (4-36). Surprisingly, even on a gloomy day, a fair amount of daylight is reflected inside Fig (4-37). Supplementary lighting in the lab is provided by fluorescent luminaries Fig (4-38).

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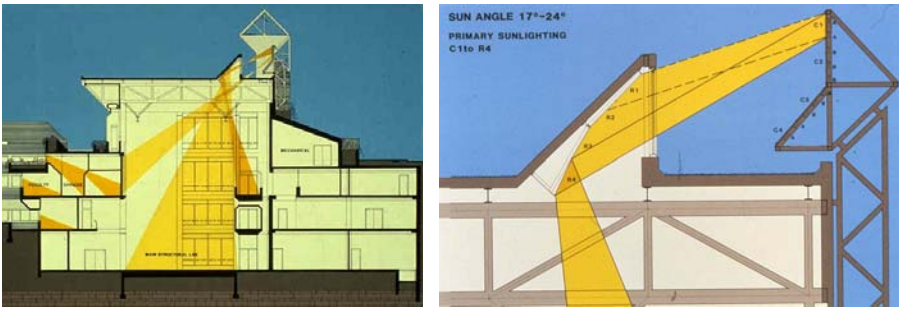
(1) Carmody, J., Sterling, R.; "Underground Building Design: Commercial and Institutional Structures", P. 89

(2) ibid

(3) Barker, M.; "Using the Earth to Save Energy: Four Underground Buildings", P. 61

(4) Jankowski, W.; "The Best of Lighting Design", P. 214

Fig (4-35): The Active and Passive heliostat systems at the CME Building.



Above: Cross-section showing the illuminated zones
Below: Sun angle 24°-47°

Above: Sun angle 17°-24°
Below: Sun angle 47°-67°

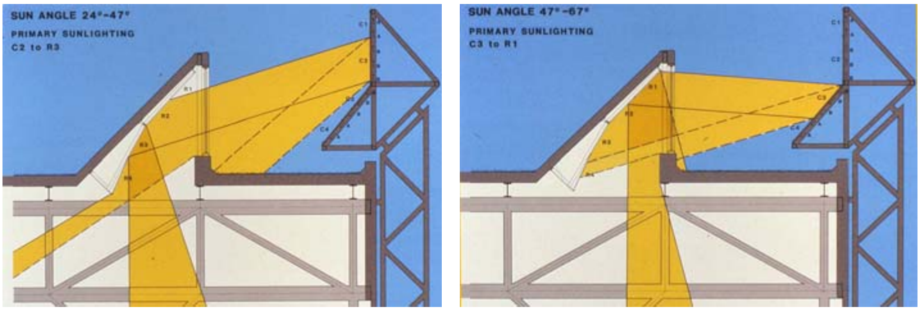


Fig (4-36): Passive heliostat diagrams of the light trace with the sun in different daily positions at 45° latitude in midwinter.

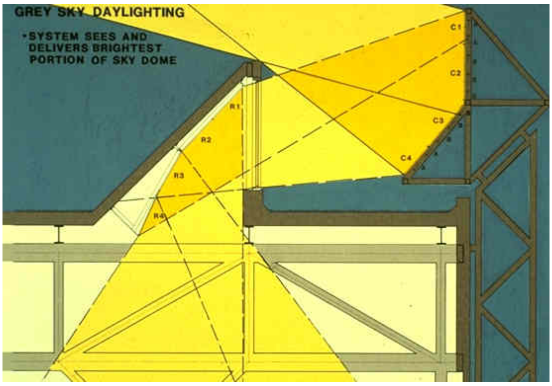


Fig (4-37): Passive heliostat during overcast sky condition.
(Overcast sky effect: Because some of the sun's rays are deflected through the clouds, those are not actually diffused come in at all angles simultaneously, lighting up the entire lens panel with the strongest light. The light is then reflected onto the secondary mirrors which direct the light into the targeted zone).

Fig (4-38): Walkway through the main structures lab illuminated by the passive solar system and supplemented by fluorescent luminaries.

The active heliostat system brings daylight to the insulated level far underground (mined space). Equipment for the solar system is housed in an above ground cupola Fig (4-39). Clock-driven mirrors are steered to constantly face the sun. The tracking is controlled with the use of Hewlett-Packard programmable calculator. The mirror face collecting the sunlight is a 1.5m wide by 2.2m high rectangle, which differs from the conventional circular type mirrors(1) Fig (4-40).

Fig (4-39): Exterior view of the cupola housing the active heliostat.

Primary mirror Secondary mirrors

Fig (4-40): View of the active heliostat from inside the cupola.

The sunlight collected by the mirrors is concentrated down through a shaft via a series of lenses and mirrors Fig (4-41). The sunlight emerges through a glass ceiling panel - similar to a conventional skylight - to illuminate an office seven stories below Fig (4-42). The system sends natural light of about 30,000 lux to the deep mined underground space - a total distance of 35 meters - during the day. At night, the system is designed to operate with an intense electric source - a xenon arc lamp(2).

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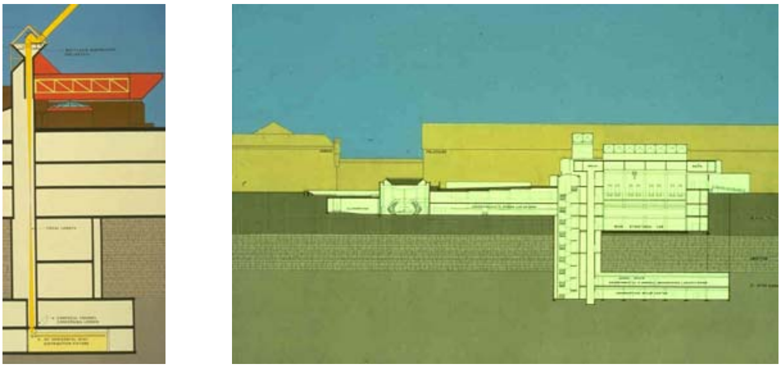
(1) Hane, T.; "Application of Solar Daylighting Systems to Underground Space", P. 469

(2) Jankowski; "The Best of Lighting Design", P. 214



Transmitted light detail Longitudinal section

Fig (4-41): Section through the building showing the transmitted light through the shaft to a total depth of 35 meters.

Fig (4-42): Skylight illuminating the offices area 35 meters below grade.

A few feet from the shaft is an “*Ectascope*”. It is a simulated window that offers a view of a lecture hall above ground surrounded by lawn and trees. It operates like a periscope to provide the underground occupants with a link to the above ground world(1) Fig (4-43).

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(1) Barker, M.; “Using the Earth to Save Energy: Four Underground Buildings” P.61

Detail of the Ectascope concept View from the Ectascope.

Fig (4-43): A view from the Ectascope, seven floors below ground, to a part of the campus above ground.

Daylighting Analysis:

- *System Type*: Passive heliostat system for the semi-subterranean part of the building. Active heliostat system for the deep mined subterranean spaces.
- *System Scale*: Passive heliostat is a mid-scale system (without mechanism). Active heliostat is a large-scale system (with mechanism).
- *Depth*: Passive heliostat delivers light to seven stories deep (four stories above grade and three stories below grade). Active heliostat delivers light to 35 meters below grade.
- *System components*: The passive heliostat consists of a series of primary mirrors elongated east-west on the roof of the building (outside the building). The primary mirrors reflect the light onto the secondary mirrors (inside the building) which in its turn directs the light to the targeted zones.

The active heliostat, which is totally inside the building, consists of a primary dual-axes rectangular mirror that tracks the sun. The primary mirror reflects the captured rays onto the secondary circular mirrors that concentrate the light into the shaft. The shaft includes collimation lenses that keep the guided light concentrated. The collected light is redistributed to the deep underground space through a diffuse skylight similar to the ones used above ground.

4-4 Light Pipes

4-4-1 Light Pipes: Definition and Main Concept

A light pipe (also known as light tunnel or light duct) is a rigid device designed to transmit daylight deep into the interior of a building(1).

The main concept of the light pipe depends on channeling the daylight incident on an exterior collector (usually a dome) to an interior diffuser (in the space) via multiple internal reflections in a pipe(2) Fig (4-44). In general, a light pipe can not deliver more light energy to the space than the light it collects from the outside of the building.

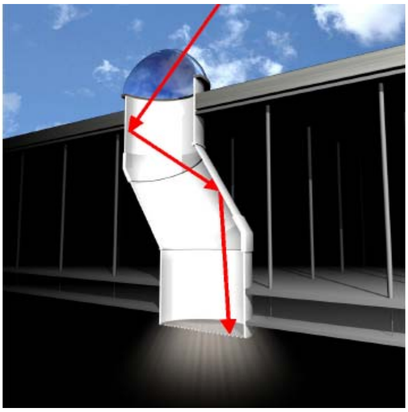

Fig (4-44): Daylighting light pipes main concept.

4-4-2 Light Pipes Potentials

Light pipes offer considerable advantages. Daylight can be transmitted to virtually any space throughout the building, regardless of the proximity to, or access to, the exterior thus offering large savings in electricity usage up to 20-30% of the total building energy consumption(3). Compared to other traditional daylighting concepts (top-

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(1) Center for The Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), "Saving Energy with Daylighting Systems", P. 9

(2) Ellis, P., Strand, R., Baumgartner, K.; "Simulation of Tubular Daylighting Devices and Daylighting Shelves in Energyplus", P. 1

(3) Oakley, G., Riffat, S., Shao, L.; "Daylight Performance of Light Pipes", P. 89

lighting, windows, atria, etc), the light pipe transmits less solar heat on to the illuminated surfaces(1). However, the benefits of light pipes also include occupants' satisfaction and a healthier and improved indoor environment. The attractiveness of the light pipe, compared with skylight, lies in its flexibility in going through the roof, lower heat loss during the winter season, more uniform light distribution and its potential for application in multistory buildings (using large diameter pipes)(2).

4-4-3 Light Pipes Components

Light pipe systems have three components(3) Fig (4-45): an outside collector (usually on the roof), the light pipe itself, and an emitter of luminaire that releases the light into the interior space (light diffuser).

Together the dome and the diffuser become "receiver and "transmitter", i.e. radiation entering the dome ends up exiting the diffuser(4).

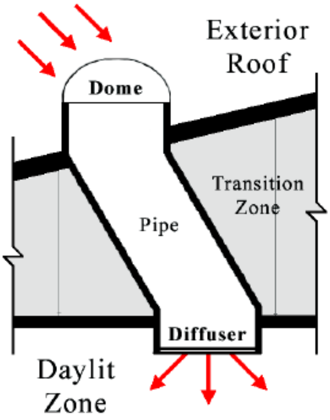

Fig (4-45): Light pipe schematic diagram showing the major components of the system.

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(1) Shao, L., Riffat, S., Hicks, W., Yohannes, I.; "A study of Performance of Light Pipes Under Cloudy and Sunny Conditions in the UK", P. 155

(2) ibid

(3) Oakley, G., Riffat, S., Shao, L.; "Daylight Performance of Light Pipes", P. 89

(4) Ellis, P., Strand, R., Baumgartner, K.; "Simulation of Tubular Daylighting Devices and Daylighting Shelves in Energyplus", P. 2

4-4-3-1 Collection System

The collector is usually hemispheric (dome shaped) and made up of clear glazing. The glazing could be made of glass, plastics, or any other material that have a high light transmittance, anti-yellowing and durability properties. The collector glazing removes the harmful ultraviolet radiation and prevents the ingression of rain water and dust. The collector may also include devices to enhance the lighting output of the light pipe especially at low sun altitude angles(1).

4-4-3-2 Transmission System

The light pipe is used to guide sunlight and daylight into the occupied spaces. The pipe may be rigid or flexible(2) Fig (4-46). Flexible pipes are easier to install but they suffer more light losses from the increased reflection and scattering inside the pipe. Rigid pipes may be straight or bent. Light pipes use the principle of high efficiency reflection, and as a result straight light pipes perform better than angled ones as light energy decreases with increased reflections. Each light pipe bend may reduce light output by approximately 8 percent(3). The coating on the internal surface of the light pipe is composed of highly reflective materials, such as anodized aluminum or coated plastic films such as Alcoa Everbrite and Silverlux, which have reflectances greater than 95 percent(4).

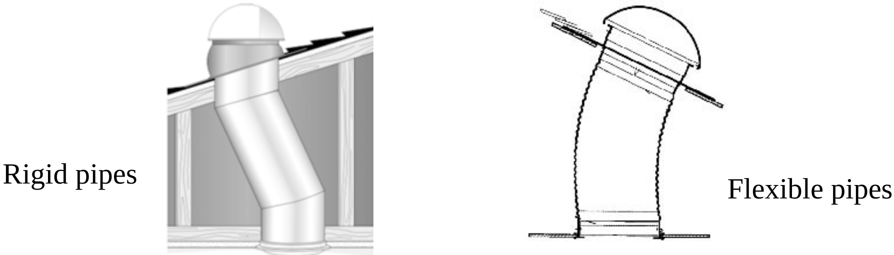

Fig (4-46): Rigid and flexible light pipe.

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(1) Laouadi, A.; "Design Insights on Tubular Skylights" P. 1

(2) Energy Efficiency Manual, "Measure 8.3.1 Install Skylights or Light Pipes", P. 977

(3) Oakley, G., Riffat, S., Shao, L.; "Daylight Performance of Light Pipes", P. 90

(4) Shao, L. , Riffat, S., Hicks, W., Yohannes, I.; "A Study of Performance of Light Pipes Under Cloudy and Sunny Conditions in the UK", P. 156

Recent designs of advanced light pipes now incorporate highly reflective polymer coatings or optical fiber cables. These reduce light losses along the length of the pipe and allow a higher percentage of the light entering the pipe to be transmitted to the space. This gives the added advantage that the length of the pipe becomes less significant, allowing longer lengths of pipe to be used(1).

The geometrical aspect of the light pipe can be characterized by the Aspect Ratio (*AR*)(2). It has the following expression:

$$AR = \frac{\text{Total Pipe Length}}{\text{Pipe Diameter}}$$

The aspect ratio is also a ratio between the reflecting lateral surface area of the pipe and the pipe external opening area. In general, the most effective light pipes are straight short ones with low aspect ratio, consequently, larger diameter light pipes would probably be more effective(3).

4-4-3-3 Redistribution System

The light diffuser distributes the light more evenly into the space the light pipe is illuminating(4). The diffuser is hemispheric or flat with translucent or clear glazing. Translucent glazing performs well in light diffusion, but it is not efficient in light transmission. On the other hand, clear glazing is efficient in light transmission, but usually requires lenses for light diffusion(5).

4-4-4 Light Pipes Performance Enhancement

Measurement of light pipe performance carried out in Australia has shown that an illuminance of 300 lux can be achieved in a room of 3x3x2m fitted with a single light pipe of 0.25m diameter without using any device to enhance light collection. The aspect ratio of the pipe,

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(1) CADDET; "Saving Energy with Daylighting Systems", P. 11

(2) Gugliermetti, F., Grignaffini, S.; "Shafts for Daylighting Underground Spaces: Sizing Guidelines", P. 184

(3) Oakley, G., Riffat, S., Shao, L.; "Daylight Performance of Light Pipes", P. 89

(4) Ellis, P., Strand, R., Baumgartner, K.; "Simulation of Tubular Daylighting Devices and Daylighting Shelves in Energyplus", P. 2

(5) Laouadi, A.; "Design Insights on Tubular Skylights", P.1

the reflectivity of the interior surface, and the solar altitude were 7, 95% and 60% respectively. The corresponding external illuminance was not reported⁽¹⁾.

The light pipe performance could be enhanced by dealing with the losses that occur due to the multiple reflections that the rays undergo within the pipe. A movable mirror or refracting system can be used to align the incoming sunlight with the axis of the light pipe, minimizing reflection losses. A light pipe with this feature is called a "*Sun Tracker*" Fig (4-47).

Fig (4-47): Sun tracking light pipes exterior view.

The Sun tracker is a traditional light pipe in addition to a rotating exterior head containing mirrors that reflect direct sunlight straight down the pipe Fig (4-48). However Sun Trackers may be less effective than simple light pipes for collecting sunlight from a diffuse sky as they are designed to collect light from the sun.

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(1) Shao, L., Riffat, S., Hicks, W., Yohannes, I.; "A Study of Performance of Light Pipes Under Cloudy and Sunny Conditions in the UK", P. 156.

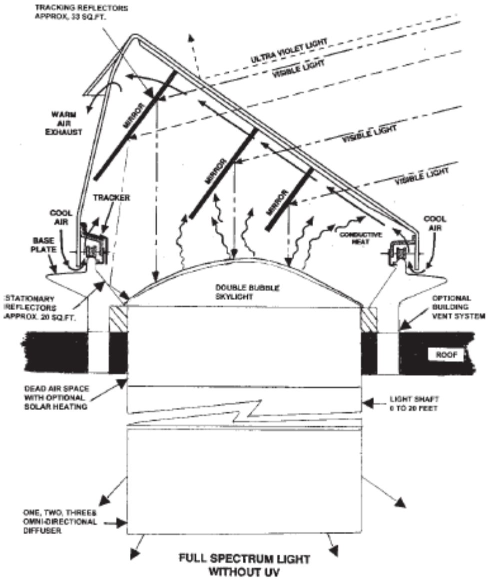

Fig (4-48): Cross-section of the Sun Tracker

4-4-5 Overview of Existing Systems using the Light Pipe Concept

4-4-5-1 Bomin Solar Light Pipe[1]

System principle: light is captured by the active heliostat system, guided down the space in the specially designed light pipe, emitting its light all over the place Fig (4-49).

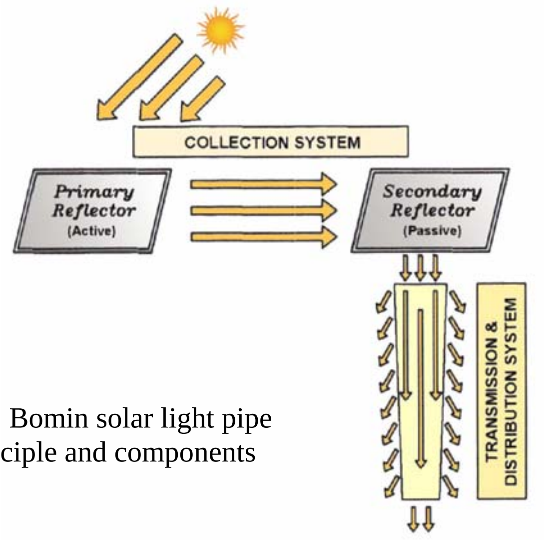

Fig (4-49): Bomin solar light pipe main principle and components

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[1] Bomin solar [http://www.bomin-solar.de]

Application: variety of applications especially the lighting of narrow deep unlit spaces.

Existing example[1]

- *Project Name*: Solar Light Pipe
- *Location*: Washington, D.C., USA.
- *Architects and Light Planners*: Carpenter & Norris Consulting, New York.
- *Construction Date*: 2001.
- *System Components*: The system consists of 1 active heliostat Lightron and 24 re-directional mirrors on swivel heads Fig (4-50).

Fig (4-50): The heliostat and the multiple re-directional mirrors (backside)

The heliostat tracks the sun throughout the course of the day and redirects the sun's light through the 36m long cone-shaped shaft Fig (4-51). The cone shaft is designed with a 1-degree slope so that the light would be evenly distributed along its length. The shaft upper diameter is 1.8m and the lower end is only 0.45m in diameter. The shaft consists of a prismatic film and surrounded with a nylon stocking Fig (4-52). Its sloped surface gives the direct beam of vertical sunlight a target to hit all along the length of the cone, allowing it to bend and refract horizontally to illuminate the entire shaft[2].

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[1] ibid

[2] ibid

In the 5-ton solar light pipe, the largest solar light fixture, the heliostat can only track the sun when the sky is clear. As a result the system is integrated with an artificial light source into the fixture that would produce qualities similar to those of the sun on overcast days or at night. When a cloud comes over the sun, the photo-cell senses a low light level and after a programmed period of time the computer signals the heliostat to tip down and switch the artificial system on. The electrical lighting system is programmed to dim, change color, and switch on through a computer controlled interface. Thus the occupants experience a consistent glow of light with the variability of natural sunlight.

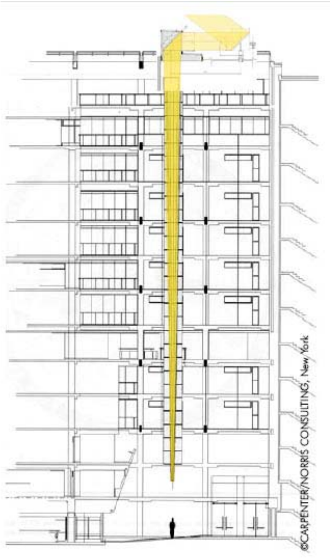

Fig (4-51): Section showing the cone-shaped pipe.

Fig (4-52): The solar light pipe.

4-4-5-2 Heliobus Light Pipes, Switzerland

System Principle: The Active heliostat follows the sun redirecting its rays through the pipes to the underground(1) Fig (4-53).

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(1) Andre, E., Schade, J.; “Daylighting by Optical Fiber”, P. 29.

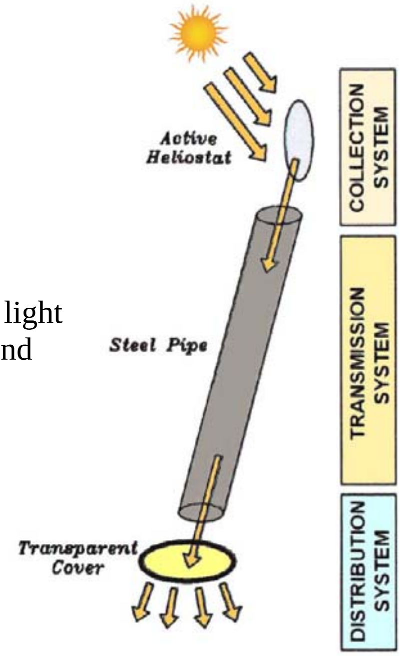

Fig (4-53): Heliobus light pipe main principle and components.

Applications: Lighting of underground spaces.

Existing Example (1)

- *Project Name*: light pipes on Potsdamer Platz.
- *Location*: Berlin, Germany.
- *Construction Date*: 2000.
- System Overview and Components:

Three light pipes extend high above the surface of the Potsdam Place in Berlin. During the day, these light pipes transport daylight from the outside into the station which is situated just below the place Fig (4-54). The light pipes direct daylight onto specific areas in the underground station. Therefore, the light pipes allow to make a connection to the outside weather and daylight changes may be observed below(2).

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(1) Heliobus Tageslichtsystems [http://www.heliobus.com]

(2) ibid

Fig (4-54): Light pipes on Potsdamer Platz in Berlin, Germany.

On top of each light pipe an oval shaped heliostat is mounted. The heliostat gradually follows the movement of the sun diverts the sunlight into the inside of the light pipe. The inside of the light pipe contain a steel pipe whose walls are covered with highly reflective foil. This allows sunlight to be guided into the underground. At the bottom of the light pipe, a transparent cover allows the light to emanate into the station(1).

A glass pipe encloses the steel pipe at a certain distance. The outside of the steel pipe is covered by special highly reflective, transparent foil. Artificial light is added right where the pipe cuts through the ceiling(2). The artificial light illuminates both above and below ground level parts of the light pipe.

In the above ground section of the light pipe, the artificial light emanates from all sides of the light pipe at night giving the pipe a very distinct look Fig (4-55). On the underground portion of the light pipe the artificial light is guided down to the ground level Fig (4-56).

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(1) ibid

(2) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P. 30

Fig (4-55): Exterior view of the light pipe at night.

Fig (4-56): Interior view of the light pipes end.

4-4-5-3 Solatube, U.S.A

System Principle and Components:

The Solatube system is a passive light pipe system⁽¹⁾ Fig (4-57). The light collector for this system is simply a transparent dome with a reflector inside, which is placed on the roof. The collected light is transmitted through the roof by a tube with a highly reflective inside. The smallest model has a tube diameter of 0.25 m and the largest model has a diameter of 0.53m.

After the tube cut through the ceiling the light is released into the space through an acrylic diffuser Fig (4-58). Solatube ceiling diffusers are designed to be highly effective at diffusing the bright light transferred through the tubing. Three types of the diffusing materials are used: Frosted, Prismatic, and Optiview⁽²⁾.

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(1) ibid, P.35

(2) Solatube, the Miracle Skylight [http://www.solatube.com]

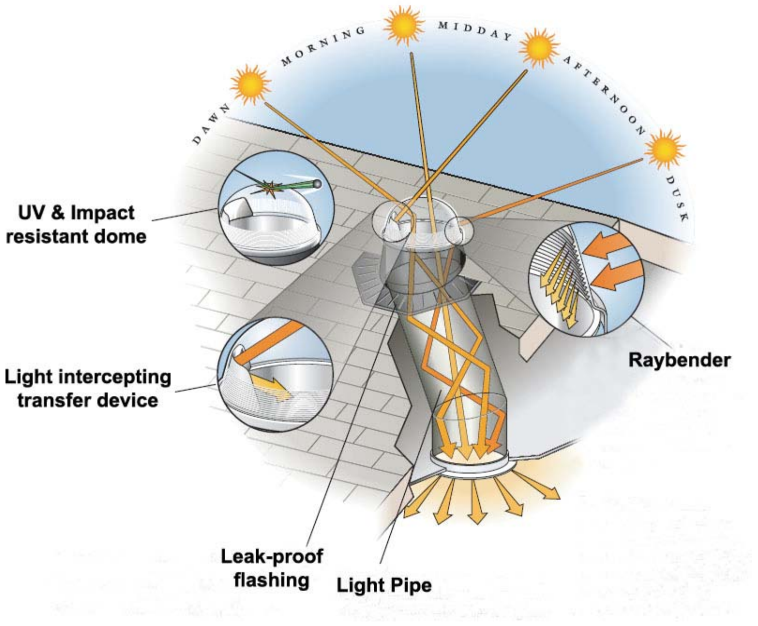
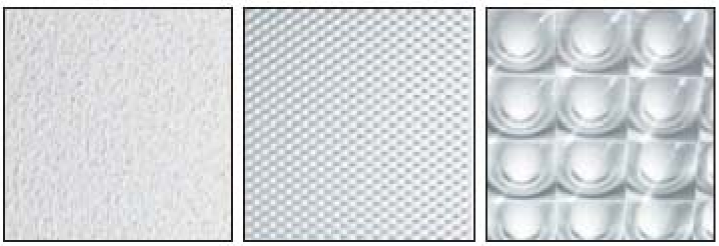


Fig (4-57): The Solatube system components.



Frosted Prismatic OptiView

Fig (4-58): Solatube ceiling diffusers.

System Applications(1): The system could be used in daylighting office, retail, healthcare, education, ware house, residential, and even underground buildings.

Solatube System Performance Chart(2)

Table (4-2) illustrates the performance of the Solatube system

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(1) ibid

(2) ibid

System Size	Relative light output (lumens)
Tube diameter 0.25m (Max. tube length 6m)	3,000 lumens up to 4,600
Tube diameter 0.35m (Max tube length 9m)	6,000 lumens up to 9,100
Tube diameter 0.53 m (Max tube length 12m)	13,500 lumens up to 20,500

Table (4-2): Solatube performance chart

(The Solatube relative light output is based upon 1.8m run (tube length) for the 0.25, 0.35, and 0.53 m diameters. Maximum and average values achieved over the peak 2,400 annual daylight hours for San Diego, California)

4-5 Fiber Optics Daylighting System

4-5-1 Fiber Optic: Definition and History

An optical fiber (or fibre in British English) is a transparent thin fiber for transmitting light. Fiber optics is the branch of science and engineering concerned with optical fibers⁽¹⁾.

In 1966 Charles Kao in his PhD thesis estimated that glass fibers need to have an optic signal attenuation of less than 20dB per kilometer to be useful for long distance communication. The first useful optical fiber was invented in 1970 by researchers Maurer, Keck, Schultz, and Zimar. The first telephone cable to use optical fiber went into operation in 1988⁽²⁾.

Nowadays, optical fibers are used in a variety of applications. They are used as light guides in medical and other applications where bright light needs to be brought to bear on a target without a clear line-of-sight path. Bundles of fibers are used along with lenses for flexible imaging devices called Endoscopes, which are used to view objects through a small hole (medical and industrial Endoscopes).

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(1) Bamboo Web Dictionary, Open Content Encyclopedia [http://www.bambooweb.com]

(2) ibid

In some high-tech buildings, optical fibers are used to route sunlight from the roof to other parts of the building.

4-5-2 Fiber Optics Daylighting Systems Potentials

Fiber optic lighting systems have the advantage to traditional light, that the light source is separated from the light output, and that there is no electricity transported into the fiber. No heat or current, no infrared and no ultraviolet radiation are led through the fiber, only light. This is for the most general used fibers in fiber optic lighting systems, but there are fibers, which are able to transmit a big part of the infrared radiation(1).

One advantage of the fiber optic lighting system is that it is possible to use it in contact with water, as there is no electricity transported, like for swimming pools or water fountains. Whenever electricity is present, the risk of explosion through sparks cannot be eliminated totally. As the fiber do not carry any electricity or heat, it is beneficial to use fiber light guides in such surroundings. It will improve the safety on, for example, oil platforms and many other buildings.

Usually the light fittings for a fiber optic lighting system do not have to be exchanged; these corrosion and acid resistant fittings are maintenance free. So problems associated with the replacing of lamps at inaccessible locations do not arise when fiber optics are used. The light source can be located in an easily accessible place from where it can power a great number of points of light. Thus maintenance will become considerably easier and cheaper(2).

If cold light is wanted, i.e. light with no ultraviolet or infrared, fiber optic lighting systems can be the solution. This makes such systems perfect for lighting objects and materials, which are sensitive to heat, ultraviolet or infrared rays, such as works of art, paper, leather goods, etc. This special quality also makes such systems feasible for exhibitions where cold light is wanted, like in museums or shops(3).

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(1) Ande,E., Schade, J.; "Daylighting by Optical Fiber", P.19

(2) Roblon, Fiber optics [http://www.roblon.com]

(3) Advanced Lighting Systems [http://www.advancedlighting.com]

4-5-3 Key Concepts for Fiber Optic Daylighting Systems

4-5-3-1 Optical Fibers Construction and Materials

I) *Construction*

Optical fiber is made out of transparent dielectric material, e.g. glass, which guides light. A cylindrical core is surrounded by, and in intimate contact with, a cladding of the same geometry. Surrounding the cladding is an overcoat for protection. Often another layer called buffer, which protects the fiber from damage, surrounds the overcoat Fig (4-59). Most optical fibers consist of two different types of optically conductive materials. The core that is 85% of the total fiber and carries the light has a slightly higher refractive index than the cladding(1).

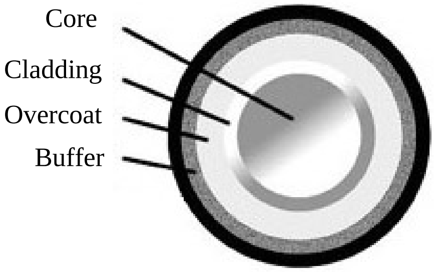

Fig (4-59): Typical fiber optic cable cross-section.

II) *Composition Material*

Optical fibers are commonly produced from glass, plastic or synthetic fused silica (often called silica or quartz fiber)(2). The different kinds of fiber have different properties, giving various advantages and disadvantages. In general silica fibers are used for data communication, but glass is still the most common choice for illumination applications. Plastic excels for ease of assembly in applications that have low operating temperatures. Solid core optical fiber is made of a combination of plastic and Teflon, and is commonly used for illumination. A solid optical gel could be used for the core (made from optical pure cast acrylic monomers)(3).

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(1) Schott Technical Specifications [http://www.us.schott.com]
(2) Fiberoptics Technology Incorporated [http://www.fti.thomasregister.com]
(3) Polyoptics Australia [http://www.fiberopticlight.com]

4-5-3-2 Fiber Factors

The optical fiber has no inherent brightness. The brightness of an optical fiber depends on many factors such as the amount of incoming light, color, refraction angle, viewing angle, and transmission loss.

One limitation to brightness is the losses that occur during the transmission of light from the source to the fiber. Another limitation is the transmission losses, which is given by the light accepting and carrying capacity of the fiber itself. The transmission losses mainly depend on the refraction indexes of the materials that the fiber is made of. Limitation of brightness is also depends on the heat enduring ability of the fiber. A service temperature, which is too high, will degrade the fiber over time. Illumination design can become very complex for this reason(1).

4-5-3-3 Transmission Characteristics

I) Transmission Characteristic of a Single Optical Fiber

The maximum light transmission for a single fiber in general cannot be higher than 75% because of how a fiber is constructed. Each fiber has a clad, which stands for 17-25% of the whole fiber cross sectional area. This part does not carry light. The surface reflection at the ends of the fiber is approximately 4% for glass fiber, and the attenuation in the glass fiber due to absorption and scattering is 13-16% per meter of light guide(2)``.

Because the attenuation depends on the material, plastic fibers have different numbers for absorption and scattering, but in general these are all higher than for glass fibers. This is why use of these is not recommended for longer distances than 15m. Solid core optical fibers have an attenuation of less than 5.3% per meter light guide. As usually silicate fiber, and glass fiber are recommended as the fiber with

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.48

(2) Fiberoptics Technology Incorporated [http://www.fti.thomasregister.com]

the lowest attenuation(1). The attenuation is even lower for the liquid light guides, with losses between 10 and 15% for 10meters.

II) Transmission Characteristics of Optical Fiber Bundles

The maximum transmission for an optical fiber bundle is lower than for a single fiber because of the space between the fibers, which are filled with epoxy. The epoxy fills 12 to 15% of the fiber bundle area and carries no light. The maximum transmission for a fiber bundles is approximately 60-65%(2).

4-5-3-4 Color Shift

For glass fibers shorter wavelengths will attenuate faster than longer wavelengths; this is due to Rayleigh scattering. Even the best glass fiber will have some color shifting. Color shifting represents the preferential attenuation of some wavelengths over others. Blue (short wavelength) may still appear as blue after 15.5m, but it might begin to fade over a distance greater than 23m, while colors with longer wavelengths will remain longer.

Plastic optical fiber and especially PMMA (Poly Methyl Methyl Acrylate), is more suited to transport shorter wavelengths because longer wavelengths will attenuate in them faster than shorter wavelengths. PMMA is a light guide material with good light transmission properties, especially for white light(3).

4-5-3-5 Bend Radius

The light will travel without major losses, if the bend radius is 8 times the fiber diameter or greater. If the bend radius is less than 8 times the fiber diameter, it will result in a loss of optical properties at the bend. This is because the internal reflection will fail.

Multiple bends at a larger radius have no detrimental effects. The light will follow the fiber and propagate without

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(1) Polyoptics Australia [http://www.fiberopticlight.com]

(2) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.48

(3) Roblon, Fiber optics [http://www.roblon.com]

losses due to the bends; the total internal reflection will be undisturbed. A very tight bend radius will cause a noticeable optical defect(1).

4-5-3-6 Diameter

The light transmission capacity of the fiber is directly proportional to the diameter. The thicker the fiber, the more light it can guide.

4-5-3-7 Moisture and Exposure to Ultraviolet Light

Fiber core should never be exposed to water, especially at the fiber ends. When the core absorbs water, the optical properties will change dramatically. However, the fiber end can be sealed for use in underwater applications(2).

Exposure to ultraviolet rays (UV) is another problem. It is not recommended to expose fiber to UV rays; especially plastic fiber will degrade if left in direct sunlight or other UV sources(3). If just the fiber ends are exposed to UV rays, an UV filter can be used, but the drawback will be in the form of higher light losses.

4-5-3-8 Heat Resistance

Standard fibers are designed for operation at a maximum of 177˚C. Above this temperature the fiber slowly starts to soften and will fail in a relatively short time Fig (4-60). With special manufacturing techniques, glass fibers that endure 482˚C can be created. Plastic fiber optics usually has an operation temperature of 79˚C. Solid core fiber optics has a maximum operation temperature of 120˚C(4).

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(1) Advanced Lighting Systems [http://www.advancedlighting.com]

(2) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.48

(3) ibid

(4) Polyoptics Australia [http://www.fiberopticlight.com]

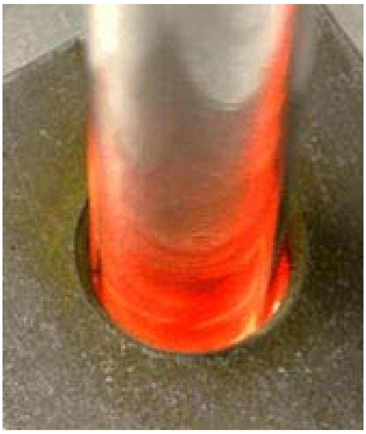

Fig (4-60): Fiber optic failure due to high operation temperatures.

4-5-4 Fiber Optic Daylighting System Components

The fiber optics daylighting system consists of five main components. The first component is the collection system which captures the daylight. The second component is the concentration system which concentrates the light since the fibers have a low acceptance angle. The third component is the separation system which isolates the visible spectrum from the non-visible spectrum. The fourth component is the controlling and mixing system which combines the daylight with the electric light and control the system output. The fifth and last component is the redistribution system which emits the light into the space.

4-5-4-1 Collection Systems

Tracker systems - as mentioned before - exist as single-axis (follows the path of the sun during the day across the horizon, from east to west) or double-axes tracker systems (follows the path of the sun during the day, and adjusts its horizontal angle throughout the year in response to the position of the sun in the sky as it changes from season to season). All two-axial systems return when night falls to the sunrise position; ready to immediately start tracking when the sun rises.

The one-axial system is not the best for fiber optic collecting system. Such a system needs a quite precise angle between the sun and the collector, to achieve the maximum efficiency for the light concentration into the fiber. Higher accuracy can be obtained with a two-axial system. The two-axial system is as an active solar tracking system Fig (4-61). The moving of the dishes can be controlled in several ways.

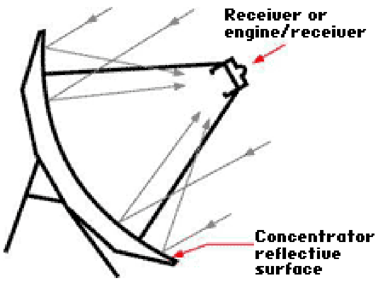

Fig (4-61): Two-axial tracking system.

The most common systems are electro-mechanical with controllers that use sensors for following the sun. The efficiency for such systems is dependent on position, quantity and accuracy of the sensor.

There are also combined systems, so the system uses the programmed astronomical data from the computer and combine them with the data from a sensor. Often those systems, which have a high accuracy, have a combination of a digital angle sensor and astronomical tracking system. The problem with the sensor controlled systems is the climate aspect. In very cloudy weather the system may not track at all. The computer controlled system is more expensive but giving the advantage that it also tracks the sun on a very cloudy day so even very diffuse light can be collected.

The self aligning system is able to observe the true sun position, looking for the maximum output of the system, and relating the observed sun position with the calculated position. At start up, the system scans around the calculated position looking for the maximum current output. This maximum current output position is compared with the calculated position and the right parameter is calculated. The most common problem for this system is the accuracy of the clock used as the time reference in computing the sun coordination. The drifts will have to be corrected for, to make the system efficient.

For all these different tracking systems, the accuracy is dependent on how smoothly the system can turn i.e. on how many small steps it can rotate.

4-5-4-2 Concentration Systems

I) Parabolas

The most common techniques to concentrate light are Fresnel lenses and reflecting parabolas. Parabolas have, because of their shape, special reflective properties. They reflect the incoming light to one point from every point of the parabolic dish surface Fig (4-62). Parabolas that are used for collecting light are usually made out of fiberglass with an embedded reflective foil.

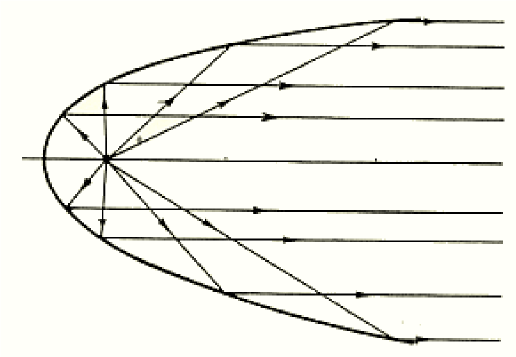

Fig (4-62): Concentration of rays reflected from a parabolic dish.

II) Lenses (Converging lenses)

A lens that refracts light is made of a transparent material. The lens that is used for collecting light is a converging lens. Because of the shape, converging lenses refract the light in such way that the light will be focused in one point. Converging lenses exist in different shapes, but in general a lens that is thicker at the centre than at the edges will function as a converging lens. This type of lenses is also known as convex lenses Fig (4-63).

The horizontal axis of a lens drawn through the optical centre is called the principal axis. If light travels parallel to this axis and passes through the lens the light will be focused one point that is the principal focus. The distance between the principal focus point and the centre of the lens is the focal length(1).

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.54

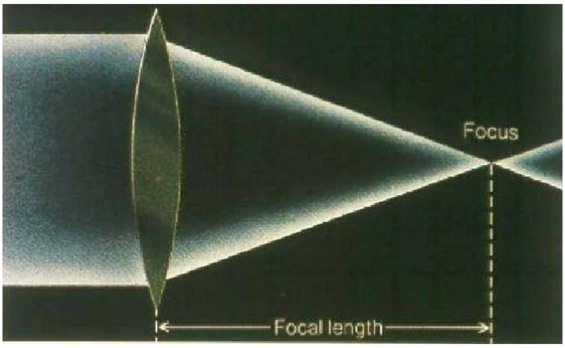
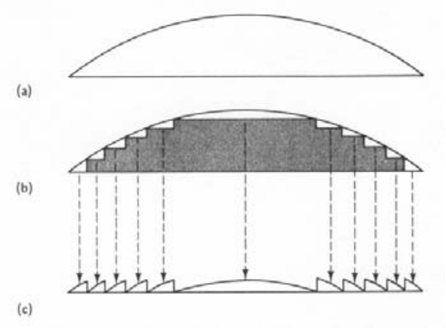


Fig (4-63): Converging lens with the principal focus.

III) Fresnel lenses

The Fresnel lens was developed during the 19th century by the French physicist Augustin Fresnel (1788-1827). His lenses were basically used for the lighthouses in that time. Fresnel lenses have a much lower image quality than a normal lens; but because the lens is thin, very little light is lost by absorption Fig (4-64). That makes Fresnel lenses very efficient for light gathering applications. The big advantage is that this lens is flat and light in weight when compared to a normal lens.



A schematic cut away diagram showing how a Fresnel lens is constructed

A real Fresnel lens

Fig (4-64): Fresnel lenses

IV) Reflecting Surfaces

When the surface of the objects is not smooth, diffuse reflection will occur. The reflected rays from a non-smooth surface leave the surface in multiple directions. If the surface of an object is smooth, such as glass or a mirror, the reflected rays will follow the law of reflection (angle of incidence is equal to the angle of reflection) (1).

To choose the right reflecting surfaces for a collecting system a few requirements have to be considered.

First, the choice of the material used depends on which wavelength should the material have a high reflection for. Different reflecting materials have better reflecting properties for different wavelengths. As the reflection of sunlight is the target, a material that has a high reflectance in the wavelength range of the visible solar spectrum, especially in the wavelength from the visible light, is needed. Good reflecting materials for solar radiation are silver, aluminum and stainless steel.

The reflectance can be measured in hemispherical reflectance and specular reflectance. Specular reflectance means that the light will be reflected in a narrow beam, while the hemispherical reflectance is more diffuse. For the fiber optics daylighting system the specular reflectance is the interesting one, as the light is collected nearly in one point.

The second aspect is the long-term stability. The material will be exposed to the environment: weather, direct pollution, etc. Most of the reflecting materials need for this reason a protective coating. If good reflecting materials such as silver or aluminum are unprotected and exposed to the outdoor conditions they will deteriorate quickly and after only two year exposure to the outdoor conditions an unprotected surface is no longer acceptable. Therefore the material has to be covered with a transparent layer, e.g. plastic, or anodizing the surface. The drawback of the necessary protective coating is the decrease of the reflectance properties. Another possibility is to choose a material that is stable, but with lower optical properties, like stainless steel(2).

Stainless steel does not have the optical properties as aluminum, the specular component decreased during 4 years from 51

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(1) ibid, P.55
(2) ibid, P.56

to 42%. But the mechanically durability make it interesting for reflectors and collectors. All these aspects should be weighed together.

4-5-4-3 Separation Systems

I) Selective Surfaces

If daylight is to be transmitted over fiber optics no heat is wanted. Cold mirrors are used in certain applications where the heat and the light components of the spectrum need to he separated. The cold mirror is a selective surface that reflects the visible component, while the heat portion is transmitted Fig (4-65). There are as well hot mirrors, designed to transmit the visible spectrum and to reflect the infrared.

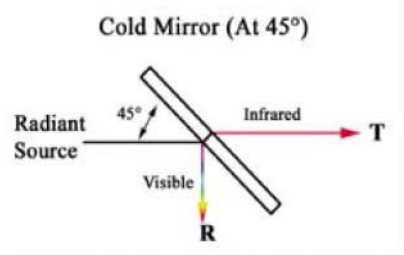
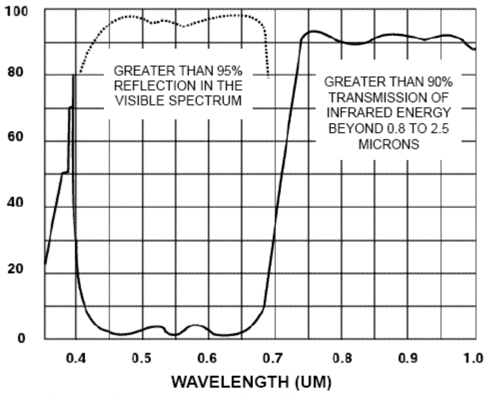


Fig (4-65): Cold mirror reflecting the visible light and transmitting the infrared portion.



Spectral reflectance (dashed) and transmittance (solid) of a “Cold Mirror”.

The basic idea about selective surfaces is that this surface reflects a certain range of wavelength and transmits a different range of wavelength. Most cold mirrors have an average transmission from 85-97% and an average reflectance from 95-97% under a certain incident angle(1).

The selective surfaces can be coated so that they can be exposed to a harsh environment. The operating temperature for a selective surface depends on the used material.

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(1) Optical Components, Inc.; “Dielectric Reflectors: Hot and Cold Mirrors” [http://www.ocioptics.com]

II) Lenses

For separation of different wavelengths the converging lens can be used. If sunlight passes through a convex lens, the focal point for the sunlight will not be exactly at one point. Different wavelengths have slightly different focal points behind the convex lens. The different focal length, give the possibility to eliminate the part of the sunlight which is unwanted(1) Fig (4-66).

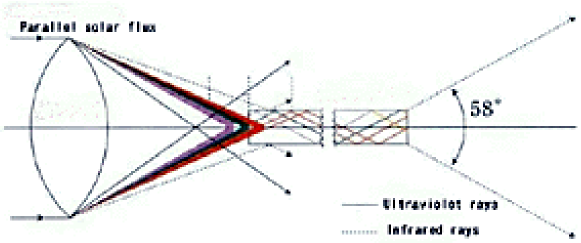

Fig (4-66): The different focal points for different wavelengths

III) Filter

Filter would be another possibility to separate a part of the collected sunlight. There are all kinds of filters for different wavelengths. For a fiber optic daylighting system the visible part of the sunlight is the desired part, whereas infrared rays and ultraviolet rays are the unwanted rays for a daylighting system. As it is not recommended to expose fiber optics, especially plastic fiber optics to the ultraviolet rays, elimination of these rays is needed. Infrared rays give the problem of unwanted heat, as fiber optics is not very resistant to heat. For this reasons it is good to eliminate infrared and ultraviolet rays.

The *IR*-filters are used as heat absorbing filters since they let the visible spectral range pass, while the infrared rays are blocked. An *IR*-filter blocks around 85% of the infrared radiation and transmits 85% or more of the visible light(2). *UV* filters block around 98% of the ultraviolet rays and transmit about 88% of the visible light. There are as well *UV/ IR* filters. This multi-coated interference filter blocks

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.58

(2) Optical Coatings Japan [http://www.techmark.nl]

98% of the unwanted *UV* radiation and 85% of the *IR* radiation. The transmission of the visible light is up to 90 %.

4-5-4-4 Controlling and Mixing

For controlling and mixing daylight with electrical light, light sensors and dimmers are needed. Photosensors are most commonly used in daylighting applications to dim electric lightning when the total illuminance exceeds a specific level. Other photosensors just switch on and off the light.

Photosensor control systems can be either existing in an open-loop system or in a closed-loop system. In an open-loop system, the photosensor is located on the outside of a building, for detecting the illuminance from the daylight. In a closed-loop system the photosensor detects both the electrical light in the room as well as the daylight in the space. Closed-loop systems are more common to use as it is more precise because the actual lighting in the room is measured. To have an efficient closed-loop system it is important to place the photosensor right. The photosensor could be placed in the ceiling near the luminaires it controls and directly above a work surface that receives a representative amount of daylight. Another solution is to aim the photosensor towards a wall to avoid the effect of changing reflectance on the work surface and sensing direct sunlight. A third solution is to locate the photosensor away from the window at a distance equivalent to approximately two thirds the depth of the area controlled by the photosensor(1).

4-5-4-5 Redistribution Systems

There are many possibilities for the distribution of the collected sunlight. For fiber optic systems a number of different fixtures exist. There are a lot of different shapes with or without optics as well as crystal fittings or even self-designed fittings Fig (4-67).

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(1) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.59

Fig (4-67): Various fiber optic daylight system distributors.

Another possibility would be to distribute the collected daylight with the help of light pipes, using a plastic tube with a special lighting film and white cylinders, extractors, inside the tube spread out the light evenly.

As fiber optic daylighting systems are usually controlled by the light generator (collectors), dimming and on-off switching will be not possible at all. The brightness of this lightning system will be dependent on the amount of incoming daylight. To switch a fiber optic lighting system off, the generator has to be switch off. To switch off the daylighting system the whole light collector has to be “turned off”. The other possibility would be to find a solution to cover the fiber ends when no light is wanted.

4-5-4-6 Cooling

Cooling will be needed, as heat will be generated when sunlight is collected and the fibers can work up to a certain temperature. There are probably different ways to cool the system. It might be possible to use a liquid cooling system, and to use this heat for other applications. A ventilation system would be another possibility.

4-5-5 Overview of Existing and Planned Systems using the Fiber Optics Daylighting System

The different systems can be divided - as mentioned before - into two areas: active and passive systems. Typically systems with moving parts are designed to collect direct sunlight instead of diffuse light from the sky. Hence they have sun collectors rather than light collectors. Passive systems can make use of direct sunlight, but are also dependent on other forms of daylight (diffuse light).

4-5-5-1 Himawari System, Japan

This is a daylighting system based on concentrating Fresnel lenses and glass optical fibers. It was developed in Japan in the late seventies by Professor Kei Mori and it was named after the Japanese word for "Sunflower". The first version, "Mono-lens HIMAWARI", first saw daylight in 1979(1) Fig (4-68).

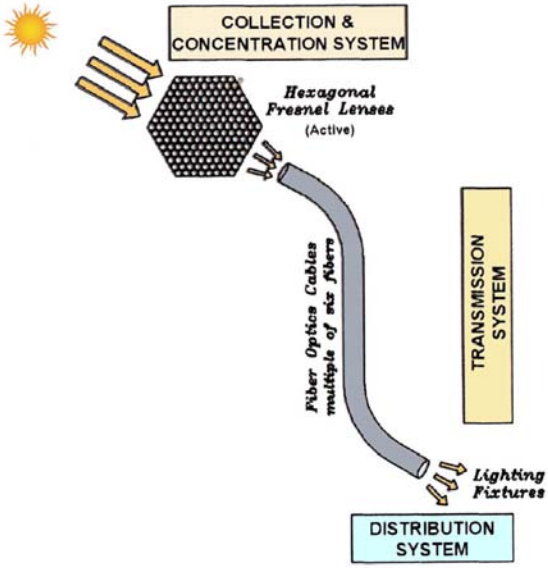

Fig (4-68): Himawari daylighting system main principle.

I) Light Collection

Himawari is a sun tracking system with a sun collector made up of several hexagonal Fresnel lenses, attached in a honeycomb pattern Fig (4-69). A sun sensor, an internal clock and a microprocessor carry out the sun tracking(2).

In fine weather the sun's exact position is determined by the sun sensor, which is mounted in the centre of the sun collector. When the sun is behind clouds the collector relies on the clock and the microprocessor to calculate how it should be directed. This

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(1) La Foret Engineering Co.,Ltd. [http://www.himawari-net.co.jp]
(2) ibid

makes it possible for the collector to always have the correct direction when the sun comes out from behind clouds. At sunset the system positions itself for sunrise and shuts down until next morning.

Fig (4-69): Different Himawari sun tracking system

II) Light Transmission

Each Fresnel lens focuses the sunlight onto the end of a glass fiber with a diameter of 1mm; six fibers are connected into one fiber optic cable. Thus the smallest available version of the Himawari system has six lenses in the sun collector. All the larger ones have a number of lenses dividable by six.

The fact that lenses concentrate the light is utilized to filter out some of the infrared and ultraviolet parts of the sunlight. This is possible because of the chromatic aberration that causes light with different wavelengths to focalize at different distance from the lens(1). The fiber ends are placed in the focus for the visible wavelengths where the infrared and ultraviolet light rays are less dense.

III) Performance

If the sun collector is receiving 98,000 lux of sunlight, each fiber can transmit a luminous flux of 1630 lm over a distance of 15m. The light disperses with an emission angle of 58˚ from the fiber end. If it is placed at a height of 2 m it will illuminate the floor below with 420 lux in average within a circle of 2.2m diameter (2).

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(1) ibid

(2) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.22

IV) *Luminaires*

Some ordinary down lights and a spotlight fitted at the end of an optical fiber could be used Fig (4-70).

Fig (4-70): Himawari lighting appliances.

V) *Applications*

This system can be used for a wide variety of applications⁽¹⁾: common room illumination, visual effects, aquariums, laboratories, etc. Fig (4-71).

Fig (4-71): The terrace of 19 lenses Himawari in Tsukuba EXPO'85

4-5-5-2 Hybrid Lighting System, U.S.A

The system main concept is the use of daylight for illumination and electricity generation⁽²⁾ (a parabolic sun collector providing both sunlight, transmitted within optical fibers, and electricity, generated by photovoltaic cells) Fig (4-72).

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(1) La Foret Engineering Co.,Ltd. [http://www.himawari-net.co.jp]

(2) CADDET, Energy Efficiency ; "Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings", P.1

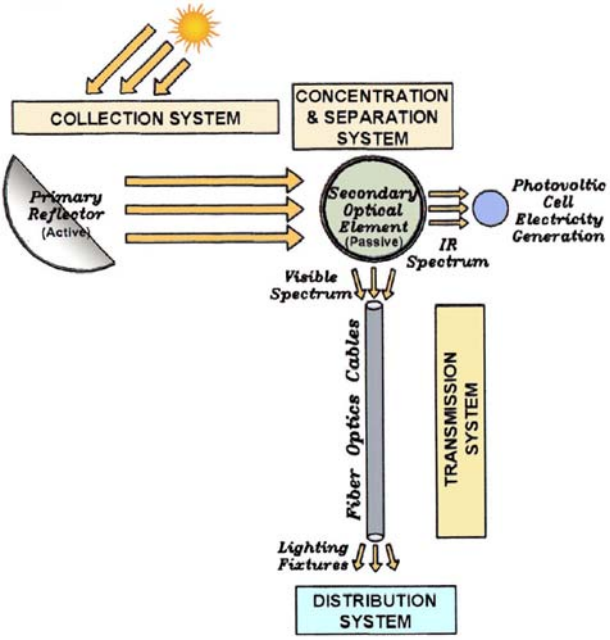

Fig (4-72): The hybrid lighting system main concept.

I) Light Collection and Electricity Generation

Similar to the Himawari system the Hybrid Lighting sun collector is a two-axis sun-tracking collector Fig (4-73). It is designed as a parabolic mirror (the primary mirror) that reflects direct non-diffuse sun light onto a secondary optical element (*SOE*), placed in focus of the parabola. The primary mirror has a radius of curvature of 3.675m. The *SOE* is a spectrally selective cold mirror, which separates the visible portion of the solar spectrum from the near infrared spectrum. It reflects the visible portion of the sunlight onto a number of large-core optical fibers placed in the centre of the dish. The infrared rays are transmitted through the cold mirror and are utilized by a photovoltaic cell to generate electricity. This solar cell is especially sensitive to the near infrared wavelengths. The primary mirror is approximately 1450 mm from the secondary(1).

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(1) Muhs, J.; "Design and Analysis of Hybrid Solar Lighting Full-Spectrum Solar Energy Systems", P.2

Fig (4-73): The Hybrid Lighting System sun collector.

II) Light Transmission

The *SOE* is divided into eight sections that reflect the light onto eight fiber ends placed in a circle, 54 mm in diameter, in the centre of the dish. The fibers are large-core plastic fibers with 18 mm diameter. The number of fibers used and their size is dictated by the size of the primary mirror(1) Fig (4-74).

Fig (4-74): Close-up view of the large-core optical fibers end.

III) Luminaires

The system is called "*Hybrid Lighting*" since it requires an alternative light source in cloudy weather or when the sun is below the horizon. The alternative light source is planned to be some

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(1) Muhs, J.; "ORNL's Hybrid Solar Lighting Program: Bringing Sunlight Inside", P.1

kind of electrical lamp mounted together with dispensers for the sunlight in hybrid luminaries(1).

This dual system will have a control system that ensures that the illumination remains constant even if the sun is temporarily hidden behind clouds. The control system employs ballast dimmers that adjust the electrical light according to how much natural light is available. In this way electrical energy is saved. It will also be possible to dim both the natural and electrical light and to switch it on and off(2).

In order to provide a good mix of light from the two sources it is important that they both have the same characteristics such as light color and spatial intensity distribution. It is also important that the control system responds quickly to intensity fluctuations in the natural light, due to changing cloud coverage for example, so that constant illumination can be ensured.

Two different light dispersing techniques that allow fiber optic end-emitted light to mimic the light from a standard cylindrical fluorescent light tube have been investigated.

One technique is to employ cylindrical diffusing rods placed adjacent to the ordinary light tubes in the luminaires. Light is emitted from the end of this rod with a diameter of 2.54 centimeters. The half of the rod that faces the floor is clear and transmits light, while the upper half is diffuse and scatters light downwards Fig (4-75). The opposite end of the rod to the fiber end contains a concave mirror that further improves the light scattering. A drawback with this concept is that optical efficiency was low for the rod, only 50%, and the inclusion of the rods also decreased the efficiency of the electric lighting for the fixture from 64 to 53%(3).

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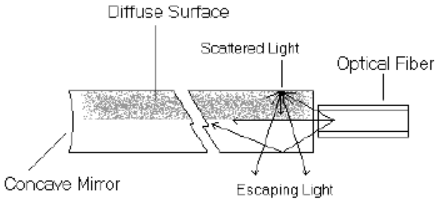
(1) Andre, E., Schade, J.; “Daylighting by Optical Fiber”, P.23

(2) Earl, D., Muhs, J.; “Preliminary Results on Luminaire Designs for Hybrid Solar Lighting Systems”, P.2

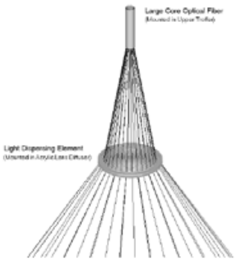
(3) Muhs, J.; “Design and Analysis of Hybrid Solar Lighting Full-Spectrum Solar Energy Systems”, P.1



Above: Designed cylindrical diffusing rod
Right: Constructed cylindrical diffusing rod

Fig (4-75): Cylindrical diffusing rod (designed and constructed rod)

A More promising technique used is based on dispersing elements in the luminaire's acrylic lens diffuser. The light dispersing elements are 15 centimeters in diameter with micro-optic structures to disperse light coming from the fiber-end mounted above pointing downwards Fig (4-76). The optical efficiency of this design has been estimated to 90%. The overall optical efficiency for the luminaires was lowered by the dispersing elements from 76 to 73%(1).



Right: Light dispersing element main concept.
Above & Left: Installation of the light dispersing element

Fig (4-76): Typical configuration of light dispersing element and optical fiber. (Main concept and installations)

IV) Performance

Based on performance values for the different components the total performance has been estimated to be approximately 50% for a single-storey application and 30-35% for

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(1) ibid, P.3

second-storey(1). This means that half of the light or more will be lost due to losses in the primary mirror, *SOE*, fiber entrance, transmission and luminaires. Aging of components and build-up of dirt was included in this evaluation(2)Fig (4-77).

Fig (4-77): Interior view of a laboratory being illuminated by distributed sunlight (left) and standard fluorescent lamps (right).

4-5-5-3 Solux Lighting System, Germany

This is a Fresnel lens-based daylighting system developed by the German company Bomin Solar Research (*BSR*). The collected sunlight is transmitted by liquid light guides Fig (4-78). Remote artificial backup light is added to maintain the flux output of the luminaire at night and when the sun is obstructed by clouds.

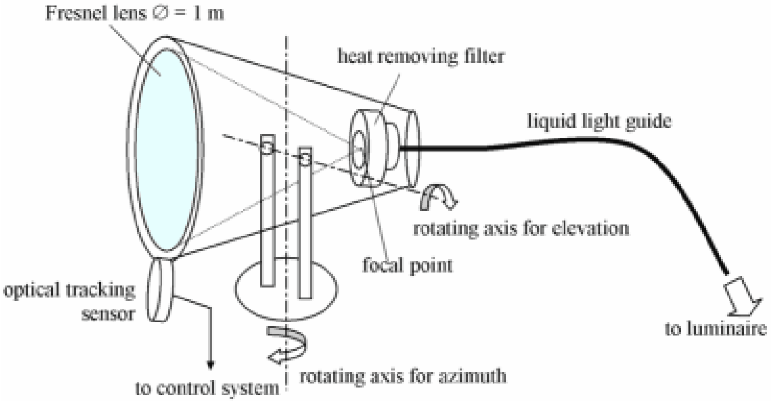

Fig (4-78): Solux Lighting System main components

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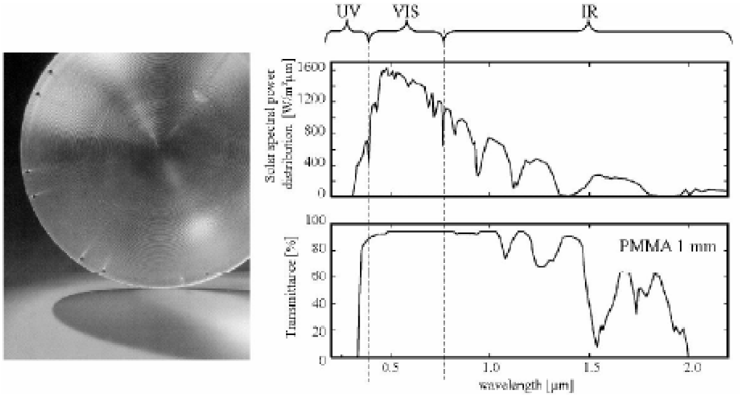
(1) Andre, E., Schade, J.; “Daylighting by Optical Fiber”, P.25

(2) CADDET, Energy Efficiency ; “Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings”, P.2

I) Collector

The collector is a sun tracking two-axis turning unit Fig (4-79). The plastic Fresnel lens is 1m in diameter and concentrates the sunlight 10,000 times Fig (4-80). Such dimensions are difficult to realize with glass but offhand possible with the transparent synthetic material *PMMA*. Transmission losses in the visible range are negligible at such small lens thickness, of about a few millimeters, thus transmission losses is only restricted to reflection losses(1).

Fig (4-79): Solux Lighting System heliostat.
(With and without the acrylic dome)



Left: A Fresnel lens made of transparent PMMA,
Right, top: Spectral power distribution of the global solar irradiation,
Right, bottom: Transmittance characteristic of PMMA

Fig (4-80): A Fresnel lens with the spectral transmittance properties.

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(1) Wilson, M., Jacobs, A., Solomon, J., Pohl, W., Zimmermann, A., Tsangrassoulis, A., and Fontoynont, M.; " Creating Sunlight Rooms in Non-Daylit Spaces", P.2

A filter that the light passes through before it enters the liquid light guide extracts heat; there have been ideas about designing concepts for using the extracted heat. The heat is removed by absorption in a water filter or due to specific IR-reflection on a hot mirror. The Fresnel lens is guided to be permanent perpendicular orientated to the sun so that the effective light gathering area is maximized(1).

The sun tracking is carried out by a dual system which is a self-learning system. It is made up of a solar direction sensor and a microprocessor calculating the position of the sun.

When mounted at a roof a clear acrylic dome to protect it covers the whole collector. This is an extra source of light losses. However, the protection also makes it possible to employ a less robust design and thus a less expensive design.

II) Light Transmission

The concentrated and filtered sunlight from the collector is fed to a liquid light guide. This is a flexible pipe, 2 centimetres in diameter, filled with an optical clear liquid made up of several components. The light transport in liquid light guides is based on total internal reflections in the liquid core. They are more efficient and less expensive than glass fiber bundles and sealed with glass windows at both ends. Even at lengths of up to 30m the spectral distribution of the emitted light is still similar to that of the light source itself and therefore well suited for the light transport over longer distance. There is also no undesirable red-shift of the spectrum as observed with fiber bundles. At such long distances the total transmission is lowered to 50% (70% at 15m) but is still sufficient compared to other systems(2).

III) Luminaires

One solution to distribute the transmitted light, through the liquid light guides, is to release the light into a diffusing tube

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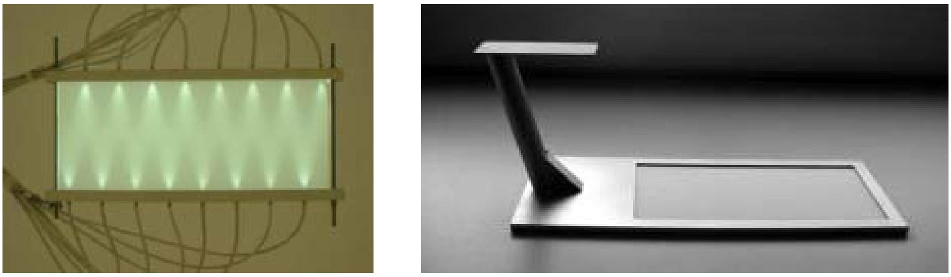
(1) ibid, P. 3

(2) Wilson, M., Jacobs, A., Solomon, J., Pohl, W., Zimmermann, A., Tsangrassoulis, A., and Fontoynont, M.; " Sunlight, Fibers and Liquid Optics: The UFO Project", P.4

that spreads the light in the room. Because of the transmission through the liquid the light is somewhat greenish. The diffusing tubes are about 5-7meters in length and approximately 20 centimeters in diameter. Natural light from the collectors enters one end and at the other end an electric lamp is used when the sunlight is not sufficient⁽¹⁾.

Another solution is to use a flat panel emitter. The flat panel emitter is a sheet of Perspex material with a white dot pattern screen printed on it Fig (4-81). The dots will allow the light which is trapped inside the panel, through total internal reflection, to break out. By varying the size and distance of the dots, any desired distribution of illuminance across the surface can be created. An optimized dot pattern will ensure an even illuminance across the whole panel. The flat panel emitter was found to have a high efficiency of between 70 and 90%, depending on the configuration⁽²⁾. This was determined by comparing the light output from the emitter with the output of the bare ends of the fiber optic cable.



An early prototype of the flat panel emitter   Final version of the flat panel emitter

(In the final version, all fibers will be attached to the short side of the panel, virtually eliminating the scalloping patterns on the surface of the emitter)

Fig (4-81): Flat panel emitters

The end of fiber optic cables can be considered a point source with a certain beam angle which depends on the type of the transmission material Fig (4-82). In typical fiber optic installations, a

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(1) ibid

(2) Wilson, M., Jacobs, A., Solomon, J., Pohl, W., Zimmermann, A., Tsangrassoulis, A., and Fontoynont, M.; " Creating Sunlight Rooms in Non-Daylit Spaces", P.4

fixture is usually attached to the fiber end in order to modify the distribution or make for an attractive fitting(1).

IV) Performance

The light loss in the liquid light pipes is about 10-15% per 10m(2).

Fig (4-82): A fiber optic projector

Table (4-3) illustrates the main differences between the three innovative systems, heliostats - light pipes - fiber optics, used for daylighting underground spaces.

	Heliostat	**Light Pipe**	**Fiber Optics**
Main Concept	-Light is collected by mirrors and reflected to the desired location in the building.	-Light is captured by an external element, channeled down through a highly reflective pipe, then released and distributed into the space.	-Light is collected by specially designed exterior concentrators, transmitted through fiber cables and redistributed by some specially designed diffusers.
Main Advantages	-Daylighting spaces that could not be lit by traditional methods.	-An alternative for the traditional skylights without the accompanying heat gain. -Less expensive than the other two systems. -Relatively flexible in going through the roof.	-Separated light source and light output. -Flexibility. -Small cable size. -Light can be transmitted to long distances that can reach 30ms and more.

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(1) Wilson, M., Jacobs, A., Solomon, J., Pohl, W., Zimmermann, A., Tsangrassoulis, A., and Fontoynont, M.; " Sunlight, Fibers and Liquid Optics: The UFO Project", P.5

(2) Andre, E., Schade, J.; "Daylighting by Optical Fiber", P.27

	Heliostat	**Light Pipe**	**Fiber Optics**
System Compo-nents	**1-<u>Collection System</u>** -Heliostats may be passive that uses a stationary mirror or active that tracks the sun with a mechanism. -Active Heliostat: i) Azimuth-tracking ii) Altitude-tracking iii) Altitude/ Azimuth tracking. -Light collection is done by the use of reflectors (Glass, Acrylic, ...). -In the active heliostat, the primary mirror tracks the sun and the secondary mirror is stationary. -Heliostat position. i) Inside the building. ii) Outside the building iii) Partially in/out (primary mirror outside the building and	**1-<u>Collection System</u>** -The exterior collector is usually hemispheric shaped and made of clear glazing. -Glazing is made of glass, plastics, or any other material with high light transmittance, anti-yellowing, and durable. -The collector is outside the building (usually on the roof). -To enhance the light pipe collection system a “sun tracker” may be used to align the incoming light rays with the pipe axis thus lowering the losses due to the internal reflections.	**1-<u>Collection System</u>** -Light collection can be in the form of a single-axis or a dual-axes tracking systems -The collection system consists of primary and secondary mirrors. -After collecting the light and before entering the fiber optic transmission system light must be concentrated and the different components of the solar spectrum must be separated. -Light concentration is done by i) Parabolas. ii) Converging lens. iii) Fresnel lens. iv) Reflecting surface. -To separate the visible portion of the spectrum from the UV and IR spectrum this is done by: i) Selective surfaces.

	Heliostat	Light Pipe	Fiber Optics
	the secondary mirror inside) -Heliostat system scale i) Small-scale ii) Mid-scale iii) Large-scale **2-<u>Transmission System</u>** -The Light ducts could take one of the following forms: i) Traditional clear shafts. ii) Shafts with collimating lenses. iii) Mirrored or reflective metal ducts. iv) Optic fiber bundles, solid-core optical fibers, liquid light guides. -System of up to 35ms depth is used in the C.M.E building.	**2- <u>Transmission System</u>** -The light pipe can be flexible or rigid. -Rigid pipes could be straight or bent. - Straight pipes are better due to the lower internal reflections. -Each bend reduces the light transmission by 8% -The pipe inner coating is made of a highly reflective material such as Anodized Aluminum or Plastic coating film or Silver. - Pipe geometrical aspect $AR = \frac{\text{Pipe Length}}{\text{Pipe Diameter}}$ -Straight, short pipes with large diameters are more effective.	ii) Lenses. iii) Filters. **2-<u>Transmission System</u>** -Light is transmitted through fiber optics bundles. -Fibers are made out of transparent dielectric material (glass, plastics, synthetic fused silica) -Fibers consist of core, cladding, overcoat, and buffer. -A single fiber transmits max. 75% of the light. -Fiber bundles max. transmission is 60-65% -Color shift is due to the attenuation of some wavelengths over others. -If the bend radius of the fiber is 8 times the fiber diameter or greater thus no major

	Heliostat	**Light Pipe**	**Fiber Optics**
	3-<u>Light Redistribution</u> i) Directly by the use of diffuse luminaines ii) Indirectly by reflecting the light to the ceiling then into the space.	-In general, light pipes are efficient for a max. length of 10-12 ms. **3-<u>Light Redistribution</u>** -The diffuser could be hemispheric or flat, translucent or clear glazing. -Translucent glazing has better light diffusion and lower light transmission. -Clear glazing has better light transmission and lower light diffusion.	losses occur. -The thicker the fiber, the more light it guides. **3-<u>Light Redistribution</u>** -By prefabricated or specially designed fixtures. -By light rods consisting of plastic tubes, lighting film, and extractors **4-<u>Controlling and Mixing</u>** -Controlling and mixing of artificial light with daylight is done by sensors and dimmers.

Table (4-3): Innovative daylighting systems comparison

4-6 Conclusions

Innovative daylighting systems are used to deliver daylight to shallow and deep underground spaces but in most cases they are used for deep ones. The basic components of the innovative systems are: light collection and concentration, light transmission, and light redistribution.

Light collection is done by the use of active or passive systems that capture the direct sunlight. Captured light is concentrated by the use of optical aberration and reflecting devices. The concentrated light is then transmitted through the light guiding system. Finally, the light is redistributed back into the underground spaces directly or indirectly. All innovative systems are supplemented in most cases by an electrical light source.

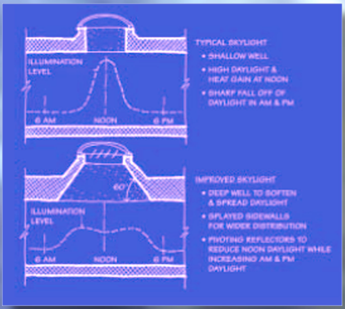
Innovative daylighting systems for daylighting underground spaces include heliostats, light pipes, and fiber optics daylighting systems.

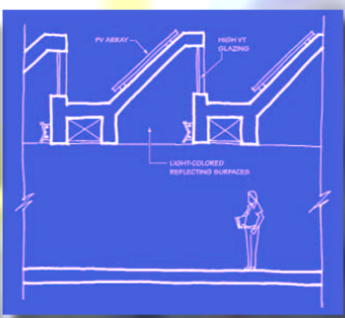
Heliostats consist of light collection, light transmission, and light redistribution systems. Light pipes consist of an exterior collector, the light pipe, and the light diffuser. Fiber optics daylighting systems consist of the light collection system, the concentration system, the separation system, and the light redistribution system.

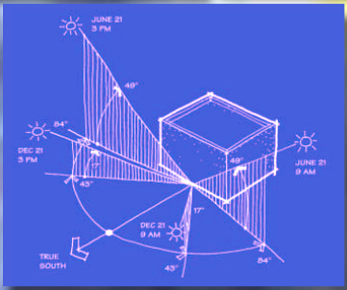
Several existing examples of the above mentioned systems are found world wide that demonstrates the potentials of using the innovative daylighting systems to deliver natural light to underground spaces.

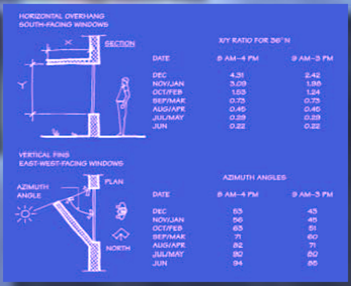
Chapter (5)

Design Guidelines For Daylighting Underground Buildings









X/Y RATIO FOR 36°N

DATE	8 AM–4 PM	9 AM–3 PM
DEC	4.31	2.42
NOV/JAN	3.09	1.98
OCT/FEB	1.53	1.24
SEP/MAR	0.73	0.73
AUG/APR	0.45	0.45
JUL/MAY	0.29	0.29
JUN	0.22	0.22

AZIMUTH ANGLES

DATE	8 AM–4 PM	9 AM–3 PM
DEC	53	43
NOV/JAN	56	45
OCT/FEB	63	51
SEP/MAR	71	60
AUG/APR	82	71
JUL/MAY	90	80
JUN	94	86

Chapter (5)

Design Guidelines For Daylighting Underground Buildings

5-1 Introduction

In this thesis, identifying the architectural parameters to integrate the daylight in the underground spaces in order to establish daylighting design guidelines for the architects to use is the main goal. Thus, underground buildings were classified into shallow and deep ones and the daylighting methods were classified into traditional and innovative concepts Fig (5-1).

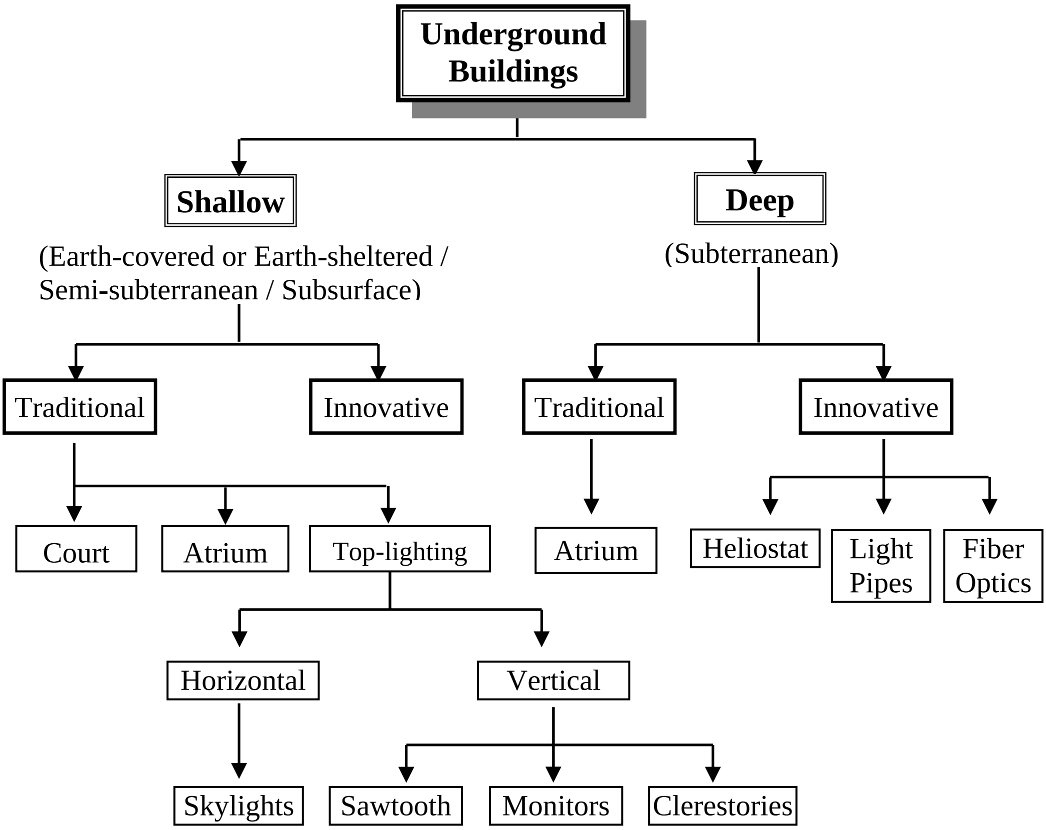


Fig (5-1): General classification of underground buildings and the used daylighting methods.

This thesis focused on the relation of the underground building to the surface and the depth of the building. It is worth notice that the methods used for daylighting the deep underground buildings (the atrium and innovative systems) could be used to daylight the shallow ones but not vice versa table (5-1).

Daylighting Concept / **Type of underground space**	**Traditional**				**Innovative**		
	Core Daylighting		**Top-lighting**		**Heliostat**	**Light Pipes**	**Fiber Optics**
	Court	**Atrium**	**Horizontal**	**Vertical**			
Earth-covered Or Earth-sheltered	▒	▒	▒	▒	▒	▒	▒
Semi-subterranean	▒	▒	▓	▓	▒	▒	▒
Subsurface	▒	▒	▒	▒	▒	▒	▒
Subterranean	▓	▒	▓	▓	▒	▒	▒

▒ Applicable ▓ Not applicable

Table (5-1): Daylighting methods and types of underground spaces showing where to use each type

In order to accomplish the main goal of this thesis, some design guidelines were established to help the designer in choosing which type of daylighting concept suitable for the space and how to use it. The established design guidelines took into consideration the different architectural and daylighting parameters when designing for underground buildings. All of these parameters are closely related and interfere with each other. Each of the used daylighting methods is studied separately to identify the parameters of each concept. More than one of the daylighting concepts could be used in the same underground building. This depends primarily on the designer and the architectural design concept, the site features, and finally the functions of the spaces.

5-2 Traditional Daylighting Concepts

5-2-1 The Courtyard

In the courtyard design guidelines the "***Radiance***" simulation program(1) was used to study the different parameters of the

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(1) Program Version: Desktop Radiance 2.0 BETA

courtyard that affect the daylight penetration into the adjoining space in order to specify the strength and effectiveness of each parameter. Those parameters were obtained from the courtyard concept analysis in chapter (2) and are used in the design guidelines. The courtyard concept was chosen to be simulated since it is considered to be the most widespread concept used in Egypt through out the history and in the present day. Thus the main aim of this study is to obtain accurate results (from the simulations) which are used in designing the courtyard guidelines. It is worth notice that the study of the daylighting levels in the spaces adjoining the court can take one of the followings forms: a quantitative study or a qualitative study or both. This study focuses on the quantitative aspect of the daylighting.

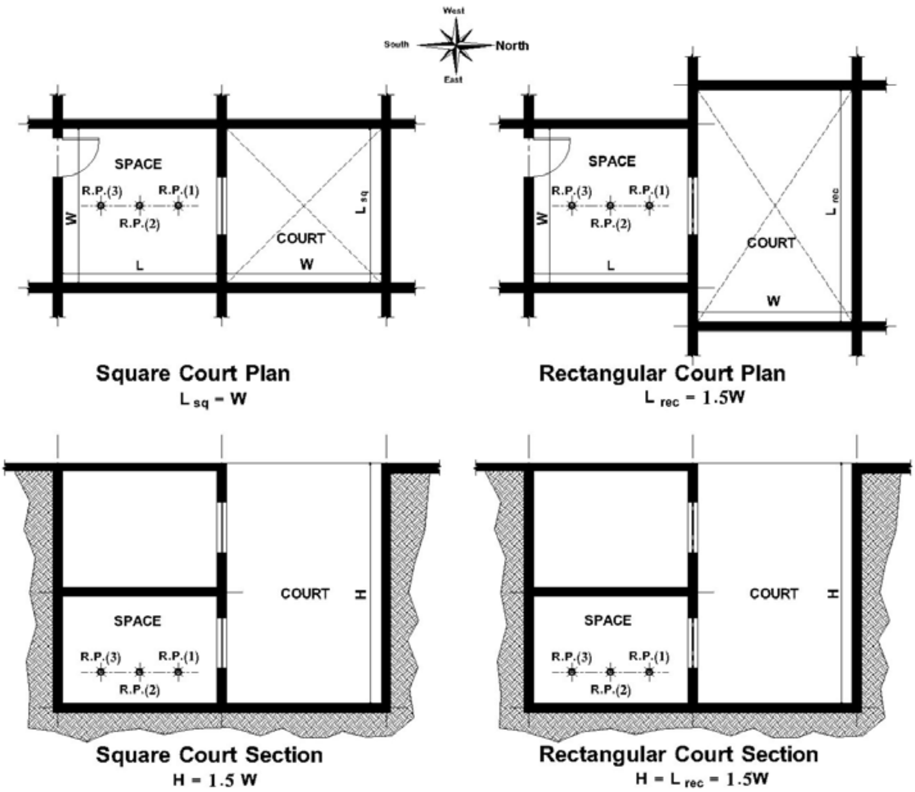
5-2-1-1 Simulation Study Limitations

In this simulation study, two base cases were established (one for the square court and one for the rectangular court) and three reference points [R.P.(1), R.P.(2), R.P.(3)], for each base case, were defined in the adjoining space. The study consists of a number of design assumptions, in the base case, in order to reach to some accurate results. It is worth notice that there are an infinite number of assumptions for each parameter which leads to an infinite number of results for the daylighting simulation study.

The court parameters include the court shape, orientation, geometrical proportions and surfaces reflectance. In each simulation only one of those parameters is changed and the other parameters are kept constant as those in the base case. At the end, each simulation result is compared to its previously assumed base case. The adjoining space parameters were not included in the study since the main aim of the study is to examine the parameters of the daylighting method used. The adjoining space parameters include the interior space surfaces reflectance (walls, floor and ceiling), the opening orientation, the glazing type and its transmittance, the space geometrical proportions and the used furniture.

5-2-1-2 Base Cases

In the two base cases some design assumptions were made. Those assumptions are shown in Fig (5-2) and include:



Square Court Plan
$L_{sq} = W$

Rectangular Court Plan
$L_{rec} = 1.5W$

Square Court Section
$H = 1.5\ W$

Rectangular Court Section
$H = L_{rec} = 1.5W$

Fig (5-2): The two base cases (plans and sections) showing the design assumptions

1- *Location*: Cairo, Egypt.

2- *Sky Condition*: Clear sky.

3- *Date and Time*: 21 June, 12:00 Noon.

4- *Orientation*: North.

5- *Court Dimensions*: The rectangular and square courts have the same width and height.

Rectangular court: $L_{rec} = 1.5\ W$ $H = L_{rec} = 1.5W$
Square court: $L_{sq} = W$ $H = 1.5\ L_{sq} = 1.5W$

6- *Court Surfaces Reflectance*: In the two base cases the walls and floor were assumed to be medium colored finishes(1).

7- *Adjoining Space Dimensions*: The adjoining space is square shaped and has the same width as the rectangular and the square court.

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(1) Walls medium colored finishes (50 %< reflectance< 85%)
Floor medium colored finishes (20 %< reflectance< 60%)

8- *Adjoining Space Surfaces Reflectance*: Walls and floor: medium colored finishes. Ceiling: light colored finish(1).

9- *Opening Size and Location*: 0.12% of the adjoining space floor area, in the middle of the north facing wall.

10- *Glazing Type*: Transmittance 73%

11- *Reference Points*: The Reference Points (R.P.) are taken at a height of 0.80m above the floor. R.P(1), R.P(2), R.P(3) are located at a distance of 1m, 2m, 3m respectively from the middle of the opening.

5-2-1-3 Simulation Studies

In the simulation studies, some parameters were taken as constant parameters (i.e. parameters that were not changed during the whole study). Those parameters include:

- The location, sky condition, the date and time of the study.
- The adjoining space surfaces reflectance and geometrical proportions.
- The opening glazing type, size, and orientation.

Other parameters were taken as variables. Those parameters are:

- The court shape.
- The court orientation.
- The court geometrical proportions and reflectance.

5-2-1-4 Simulation Results

The following results are based on the courtyard simulation studies that were carried out(2).

- ***Shape***

  -General Results: the courtyard can take any shape but the square and the rectangular shapes are the most popular. For courtyards having the same area, orientation, surfaces reflectance, and height but different shapes the internal illuminance distribution through out the adjoining space differs according to the court shape.

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(1) Ceiling light colored finishes (reflectance> 85%)

(2) For detailed results refer to Appendix (B): "Courtyard Simulation Study Detailed Results"

- ***Detailed Results:*** In this simulation study, a rectangular court and a square court having the same area and same conditions were simulated. By comparing and analyzing the results it was found that the square shape provides more internal illuminance by 28% especially near the window wall and the difference in the internal illuminance decreases until being almost neglected near the back wall Fig (5-3).

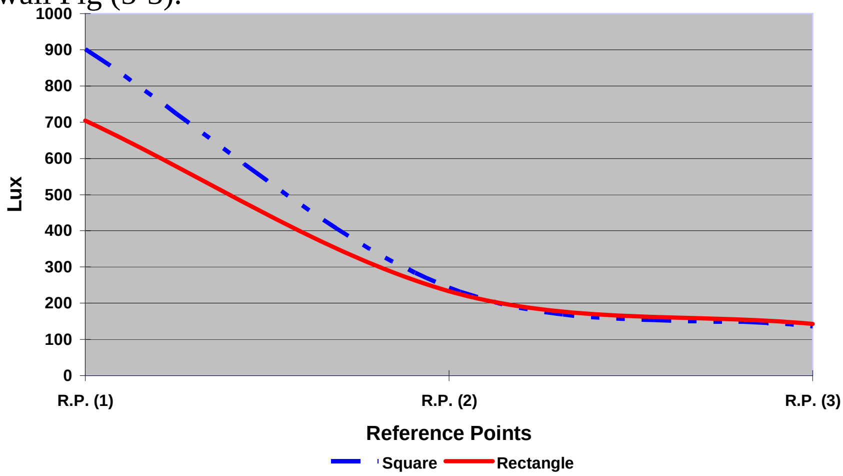
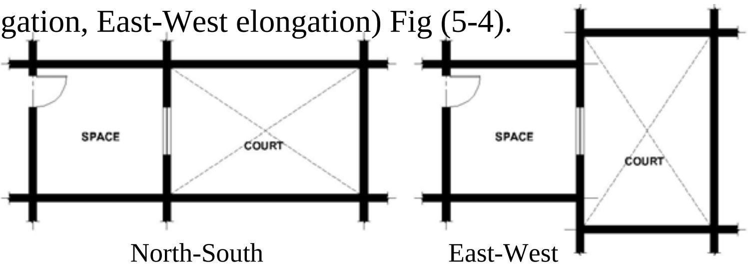


Fig (5-3): The square versus the rectangular shaped court showing the difference in the internal illuminance from the window wall to the back wall

- ***Orientation***

- ***General Results:*** The court can be oriented as desired (according to the design concept and the functions of the adjoining spaces). The orientation of a rectangular court is far important than that of a square one (since both sides of the square are equal).

- ***Detailed Results:*** In this simulation study, two orientations for the rectangular court were chosen and simulated (North-South elongation, East-West elongation) Fig (5-4).



North-South East-West

Fig (5-4): Rectangular court elongated north-south versus rectangular court elongated east-west.

By comparing and analyzing the simulation results it was found that the rectangular court elongated north-south provides a higher illumination level in the adjoining spaces near the window wall by 46% than those elongated east-west. The difference in the internal illuminance decreases in the middle of the space until it coincides at the back of the space and becomes neglected Fig (5-5).

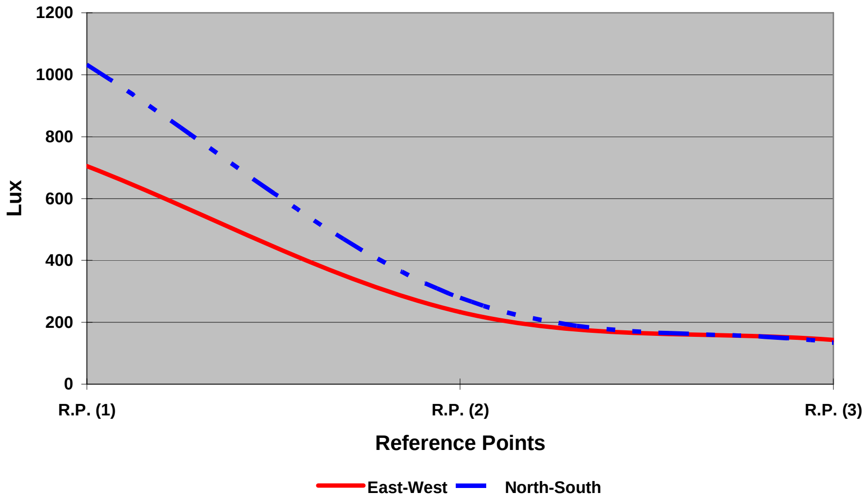


Fig (5-5): The distribution of the internal illuminance resulting from a rectangular court elongated north-south versus a rectangular court elongated east-west from the window wall to the back wall.

- ***<u>The Geometrical Proportions and the Surfaces Reflectance</u>***

- In this study, the different court heights were simulated separately at first, and then the impact of the different court surfaces reflectance was added and simulated.

- ***<u>The Court Geometrical Proportions</u>***

- ***General Results:*** The internal illuminance in the spaces adjoining the court is inversely proportional to the court height. The difference in the internal illuminance in case of increasing or decreasing the court height is variable and effective through out the space.

- ***Detailed Results:*** To determine the effect of the court height on the internal illuminance three different heights, for each base case, were chosen and simulated. The different heights represent the minimum court depth (shallow court) where H_2=0.5H, the intermediate court depth (moderate depth court and in the same time the base case) where H=1.5W, and the maximum court height (deep court) where H_1=1.5H(1) Fig (5-6).

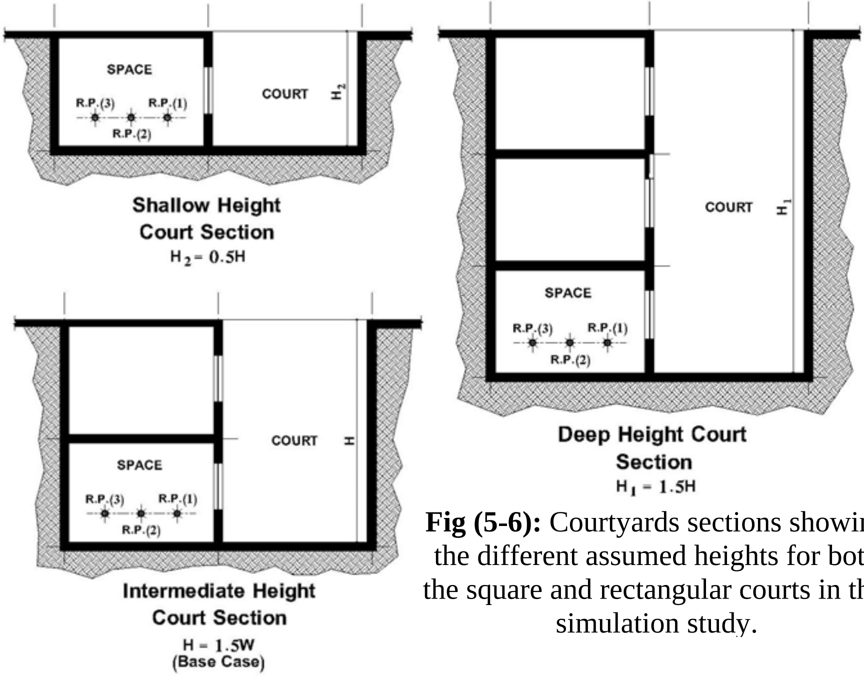


Fig (5-6): Courtyards sections showing the different assumed heights for both the square and rectangular courts in this simulation study.

By comparing and analyzing the simulation results it was found that for both the square and the rectangular courtyards having the same height, the distribution of the internal illuminance increased or decreased by almost the same percentage.

The shallow court provided more internal illuminance through out the space (especially the square shaped court) than the intermediate and deep court and the most affected area by decreasing the court height was the area near the back wall. The increase in the internal illuminance near the window wall was considerable but not as that near the back wall.

For the ***rectangular*** courtyard, the shallow court provided more than 4 times the internal illuminance provided by the deep court

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(1) The different court heights (shallow, moderate and deep) were determined form the courtyard analysis in chapter (2).

near the window wall and more than 8 times near the back wall Fig (5-7).

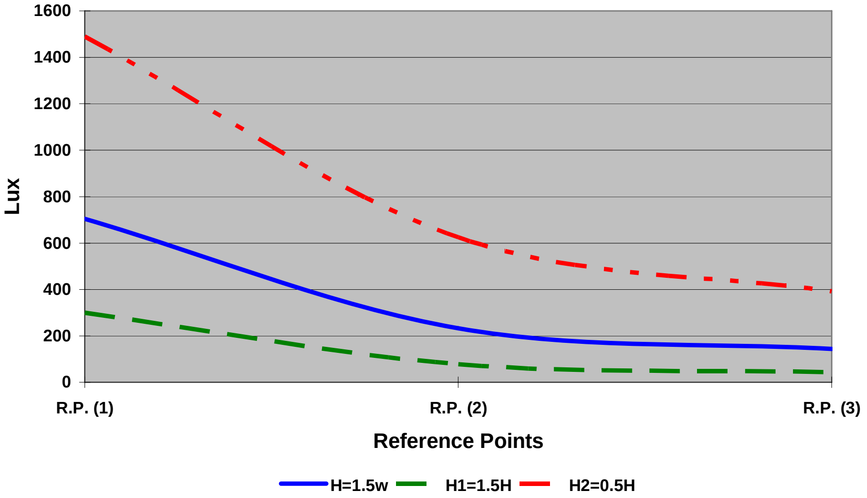

Fig (5-7): The internal illuminance distribution in case of a rectangular courtyard for the different assumed heights in this simulation study.

For the ***square*** courtyard, the shallow court provided more than 9 times the internal illuminance provided by the deep court near the window wall and more than 19 times near the back wall Fig (5-8).

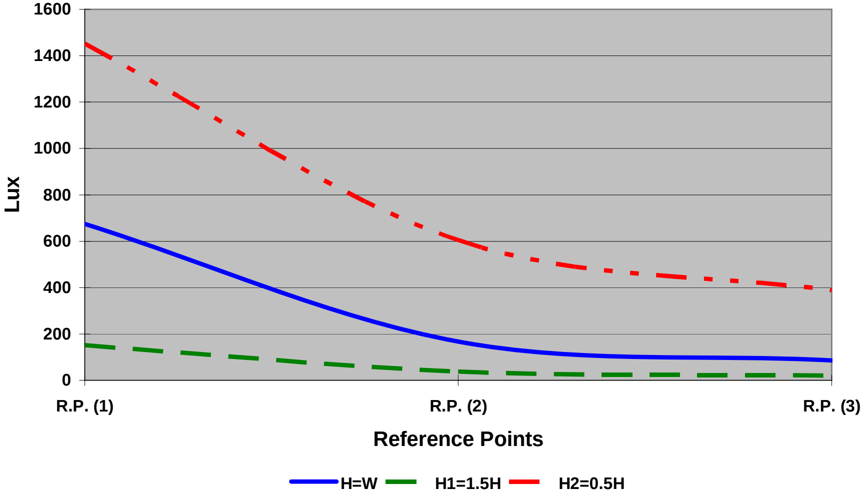

Fig (5-8): The internal illuminance distribution in case of a square courtyard for the different assumed heights in this simulation study.

- ***The Surfaces Reflectance***

- ***General Results:*** The court surfaces reflectance is directly proportional to the court height i.e. as the court height increases the more dependent the court becomes on the surfaces reflectance.

- For the low height courts (H_2<W), the surfaces reflectance can be as desired (dark, medium, or light finishes). For the intermediate height courts (H=1.5W), the surfaces reflectance can be medium or light colored finishes. For the deep courts (H_3>1.5W), the surfaces reflectance should be light colored finishes especially the walls.

- The court walls reflectance is more effective in increasing or decreasing the overall internal illuminance in the adjoining space than the court floor for the different court heights (low, intermediate, and deep courts).

- ***Detailed Results:*** In this simulation study, in order to determine the impact of the court surfaces reflectance on the internal illuminance in the previously mentioned heights several simulations were carried out. For each height the walls and floor reflectance, each at a time, was varied between light colored, medium colored (base case) and dark colored finishes(1).

For the ***rectangular*** and ***square*** courts, the impact of varying the court surfaces reflectance (walls and floor) for the intermediate (H=1.5W) and deep (H_1>1.5W) courts was very similar. The walls with high reflectance increased the internal illuminance by 25-30% near the window wall while the impact of the high floor reflectance was almost neglectable Fig (5-9). On the other hand, the walls with low reflectance decreased the internal illuminance by 40-45% near the window wall while the floor low reflectance decreased the internal illuminance near the window wall by 10% Fig (5-10).

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(1) Walls dark colored finishes (reflectance< 50%), Floor dark colored finishes (reflectance< 20%)

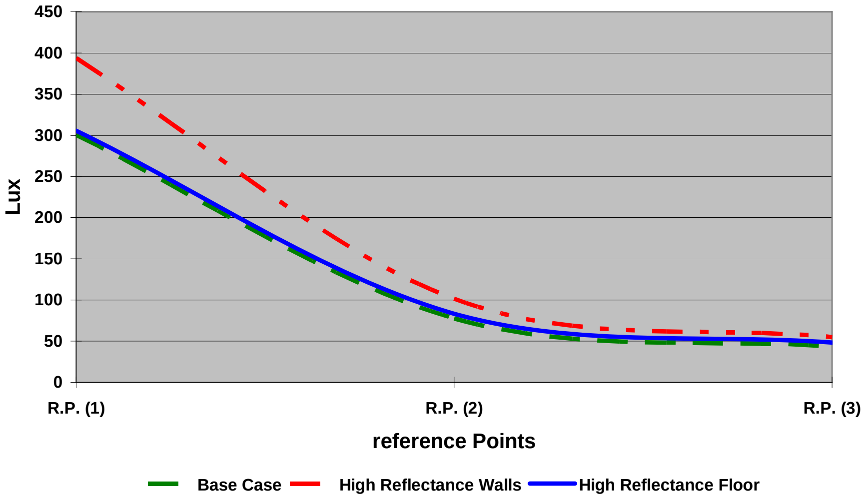


Fig (5-9): The internal illuminance distribution in case of a deep rectangular courtyard with high surfaces reflectance.

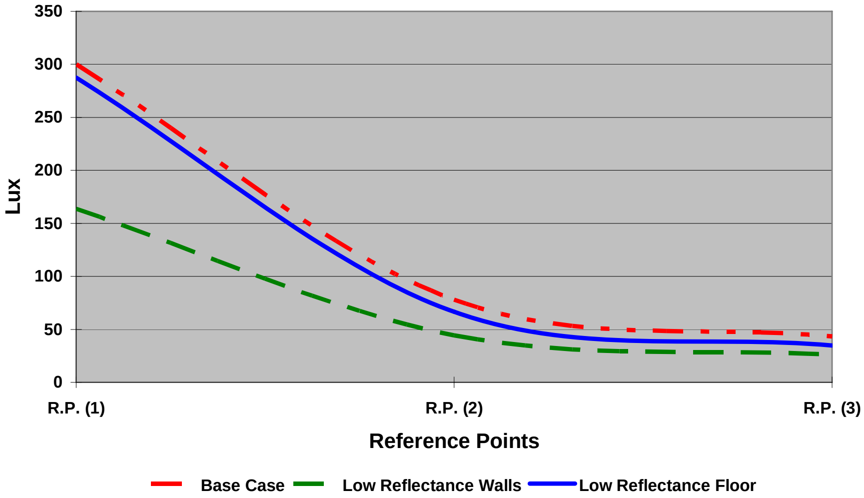


Fig (5-10): The internal illuminance distribution in case of a deep rectangular courtyard with low surfaces reflectance.

For the ***rectangular*** shallow court (H_2<W), the impact of varying the court surfaces reflectance (the walls and floor) was very similar. The walls (or floor) with high reflectance increased the internal illuminance by 10% near the window wall Fig (5-11). On the other hand, the walls (or floor) with low reflectance decreased the internal illuminance by 10-20% near the window wall Fig (5-12).

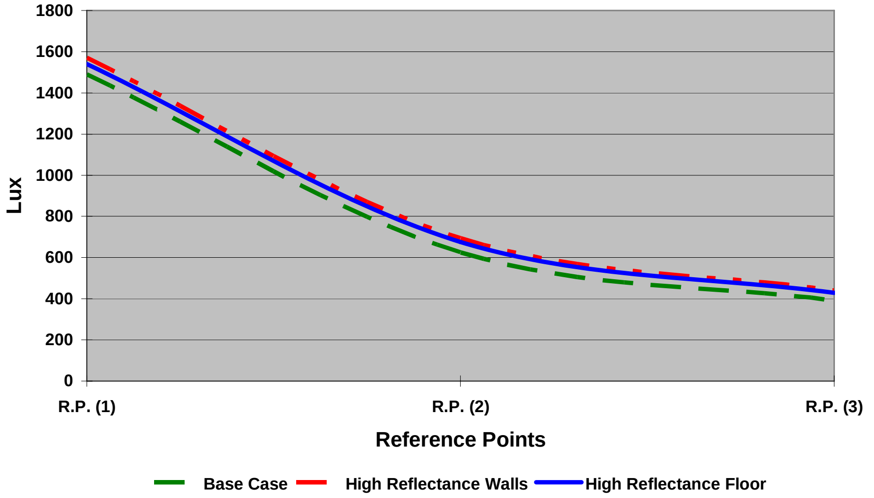


Fig (5-11): The internal illuminance distribution in case of a shallow rectangular courtyard with high surfaces reflectance.

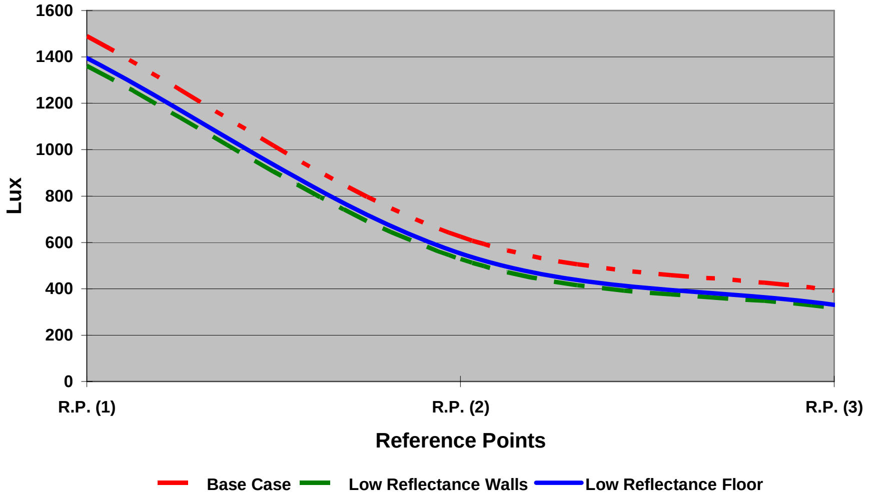


Fig (5-12): The internal illuminance distribution in case of a shallow rectangular courtyard with low surfaces reflectance.

For the ***Square*** shallow court (H_2<W), the impact of varying the court surfaces reflectance (the walls and floor) was different and the impact of using the low reflectance floor was the most critical. The walls with high reflectance increased the internal illuminance by 10-15% near the window wall while the impact of the floor with high reflectance was neglectable Fig (5-13). On the other

hand, the walls with low reflectance decreased the internal illuminance by 10% near the window wall while the floor with low reflectance decreased the internal illuminance by 50% near the window wall while the area near the back wall was not affected Fig (5-14).

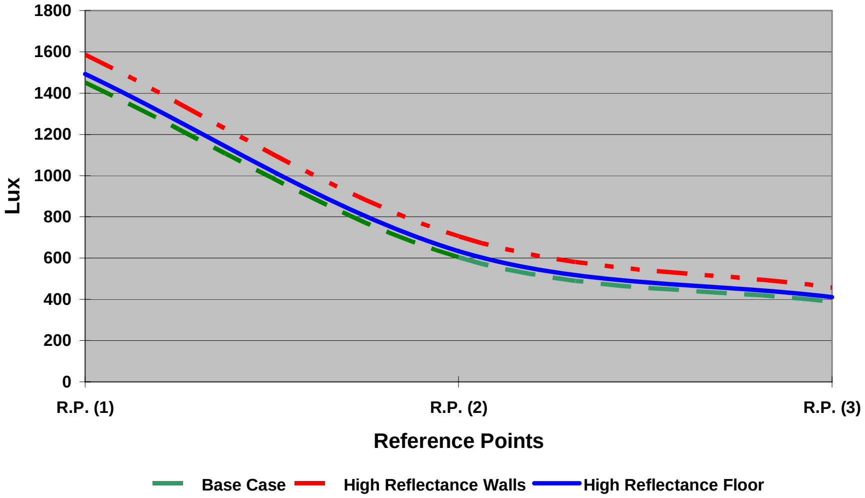


Fig (5-13): The internal illuminance distribution in case of a shallow square courtyard with high surfaces reflectance.

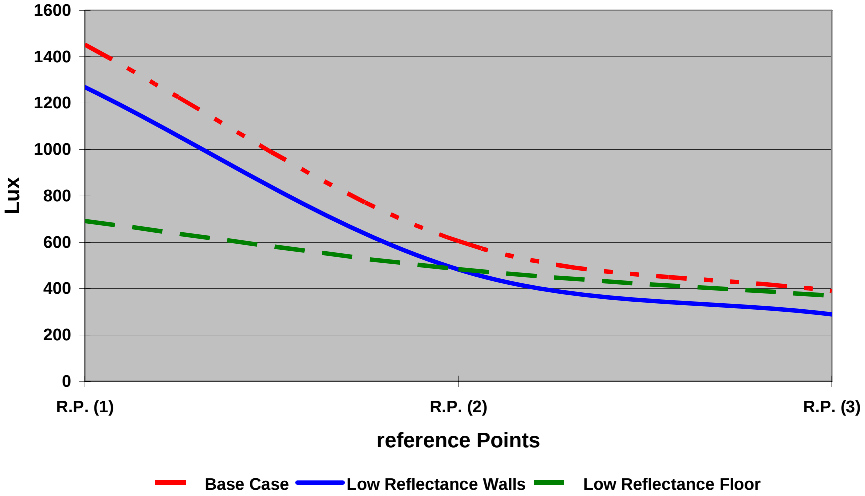
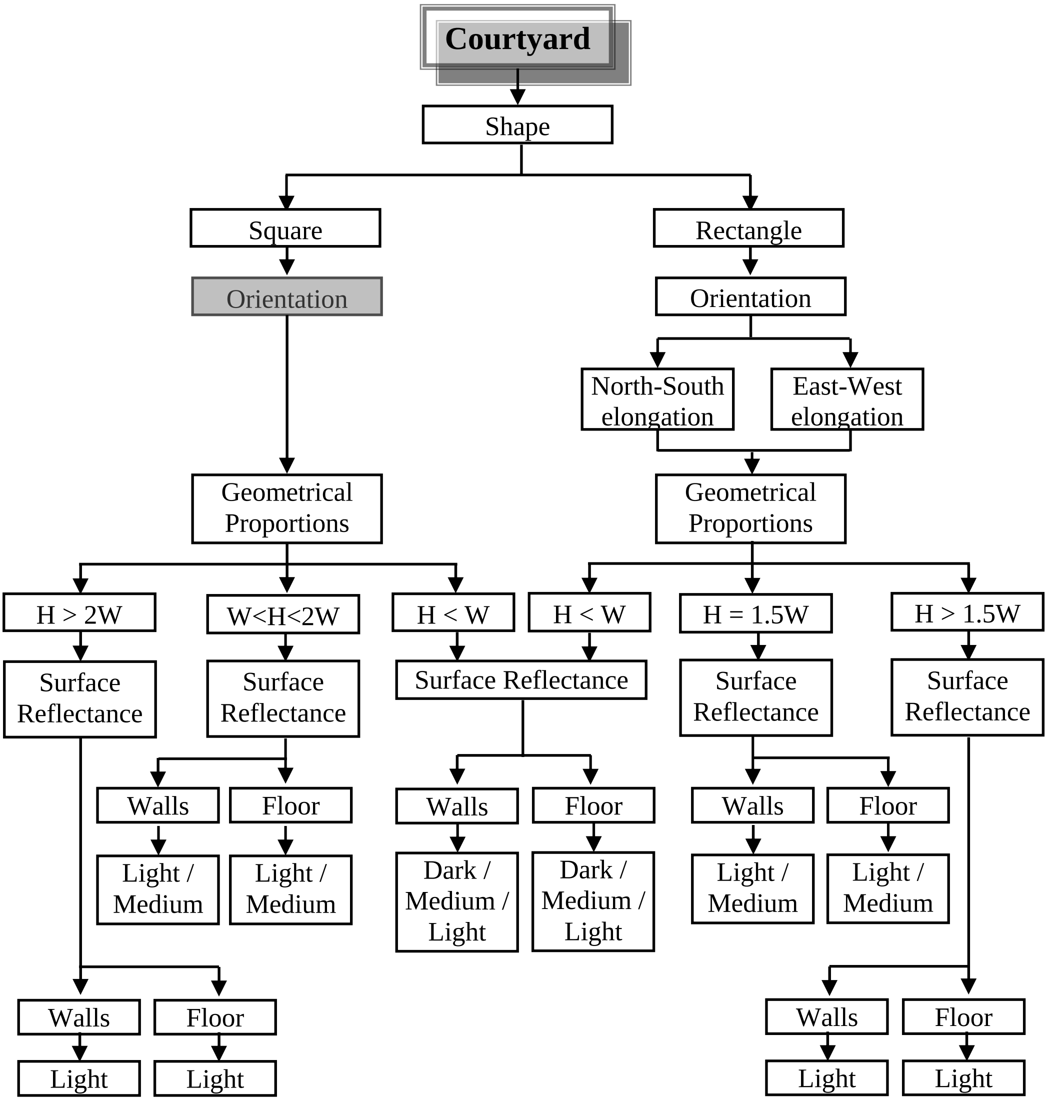


Fig (5-14): The internal illuminance distribution in case of a shallow square courtyard with low surfaces reflectance.

The courtyard daylighting design guidelines are summarized in Fig (5-15).



Legend

- H = Court Height, W = Court Width.

- *The **walls** surface reflectance*: Dark colored finishes (reflectance<50%), Medium colored finishes (50 %< reflectance< 85%), Light colored finishes (reflectance>85%)

- *The **floor** surface reflectance*: Dark colored finishes (reflectance<20%), Medium colored finishes (20 %< reflectance< 60%), Light colored finishes (reflectance>60%).

Fig (5-15): The courtyard daylighting design guidelines.

5-2-2 The Atrium

The atrium is used mainly to daylight deep underground buildings but it can be used to daylight shallow ones. The atrium design guidelines are as follow:

- *Orientation*: The orientation of rectangular atrium is for more important than a square one.

  - The east-west elongation provides daylight penetration to the upper floors of the south facing façade while the north-south elongation provides daylight penetration to the base of the atrium but not to the adjoining spaces.

- *Geometrical Proportions*: The geometrical proportions of the atrium include: the atrium width, the atrium interior surface area to volume ratios and the H / W proportion.

  - The atrium width is directly proportional to the daylight penetration thus maximize the width as possible.

  - Choose a shape that has the least interior surface area to a given volume to increase the *IRC* (circle - square - equilateral triangle - rectangle) thus the summation of the interior surface area should be as low as possible.

  - For the H / W proportion, if H < W (i.e. shallow and wide atrium) the daylight penetration in the atrium is high thus the atrium requires low surface reflectance materials and the floor plan shape is less critical. If H > W (i.e. deep atrium) the daylight penetration is low and requires high surface reflectance materials.

  - The square shaped plan provides 7-10% more daylight than the rectangular shaped atrium.

- *Location*: The location of the building affects the atrium area. Buildings at higher latitudes require larger plan area than those at lower latitudes.

- *Atrium Roof*: The roof of the atrium is an important parameter. It includes the roof glazing and the roof structure.

- The roof glazing transmittance can be controlled as desired. A single glazed clear glass transmits 85% of the incident light while the double or triple glazing transmits lower amounts (60 – 70%).

- The type of the glazing material affects the daylight penetration. The transparent glazing increases the daylight penetration while the diffusing glazing provides uniform light but lower light transmittance.

- Minimum roof structure reduces the light admitting area by 8-10% thus the roof structure should be as simple and small as possible.

- *Atrium Walls*: The shape of the atrium walls could be straight or splayed. A 10˚ to 30˚ splay from the vertical increases the daylight penetration by 25% to 30%.
- *Atrium Surfaces Reflectance*: The surface reflectance of the walls and the floor of the atrium is one of the parameters affecting the daylight penetration into the atrium.

- The area of the fenestration in the interior walls should be increased gradually from top to bottom (minimum at top and maximum at bottom). A 50% glazing reduces the *IRC* by 50% while 100% glazing (curtain wall) reduces the *IRC* to 1/3.

- The interior walls can be a diffuse reflecting material which reduces the quantity of light reaching the lower part of the atrium. It can be a specular reflecting material which performs better but increase the opportunity of glare. Dark finishes can be used but they reduce the average internal reflectance.

- The effect of the floor surface reflectance is limited to the lower levels. In shallow atria, a medium reflectance material can be used. In deep atria, a highly reflective material should be used.

The atrium daylighting design guidelines are summarized in Fig (5-16).

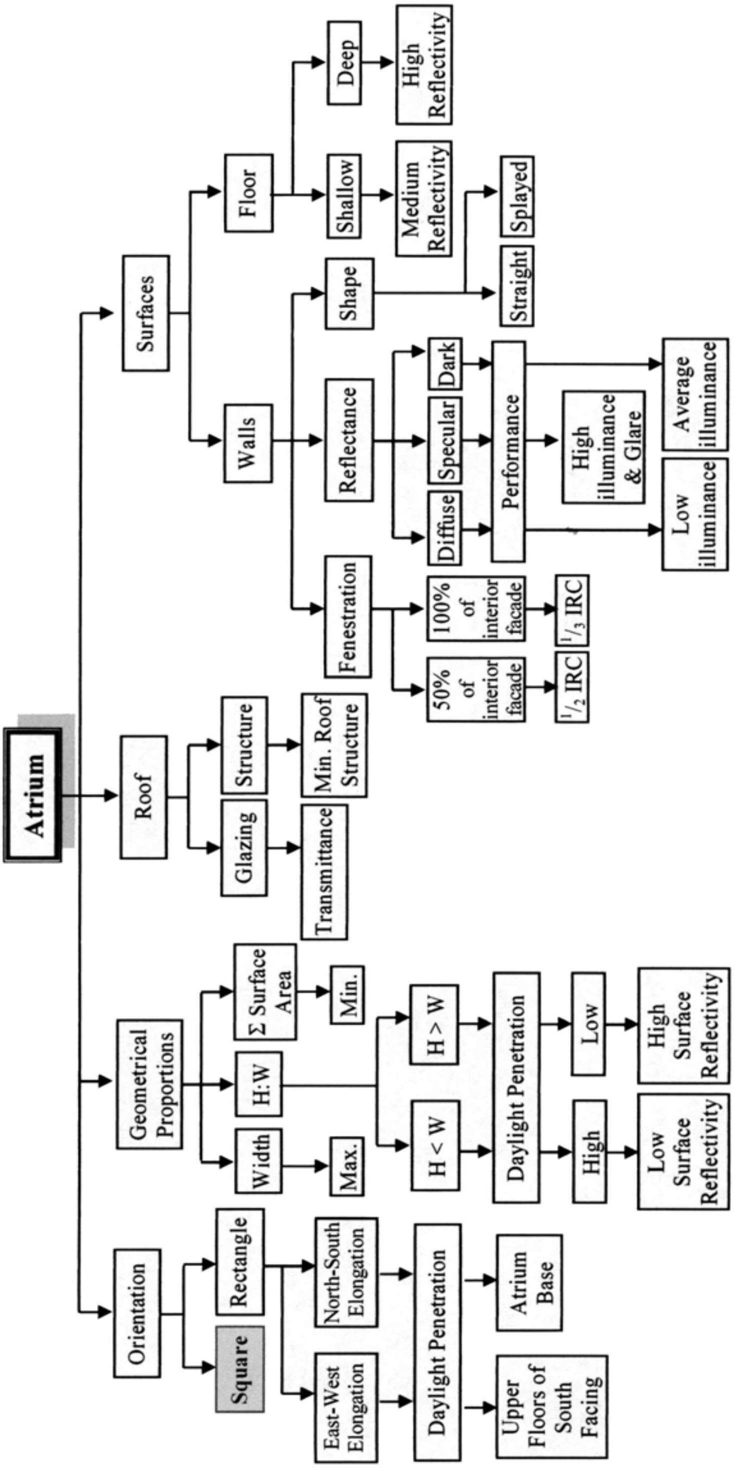


Fig (5-16): The atrium daylighting design guidelines.

5-2-3 Top-lighting Concept

I) Horizontal Top-lighting (Skylights)

Skylights are used to daylight the top floor of shallow subsurface buildings. The horizontal top-lighting design guidelines are as follow:

- *Shape and Layout*: Skylights can take any shape simple or complex. Its size and layout are primarily dictated by the architectural design concept.
- *Spacing*: Large and widely spaced skylights results in an uneven light distribution and cause glare. Small and closely spaced skylights results in a more uniform light distribution. The general rule of thumb is the optimum for the quality of light.
- *Light Distribution Pattern*: The light distribution pattern resulting from a skylight in an overcast sky condition is symmetric while that under a clear sky is also symmetric except for the presence of an additional point of maximum illuminance due to the direct daylight component.
- *Geometrical Proportions*: The geometrical proportions of the skylight impacts the light distribution pattern as follows:
  - The width of the skylight is directly proportional to the maximum illuminance.
  - The length of the skylight is directly proportional to the longitudinal spread.
  - The Angle of glazing is not as critical as the other proportions.
- *Ceiling Height*: A high ceiling results in a more uniform daylight distribution pattern while low ceiling results in a less uniform pattern.
- *Glazing*: The skylight glazing is one of the parameters that play an important role in the daylight penetration.
  - The glazing material can be glass, plastics, or glass and plastics. Each type has its potentials and drawbacks.

- The glazing area ranges from 3% to 12% of the floor area. The lower limit is used for spaces with extreme climates (hot or cold) while the upper limit is used for spaces with temperate climates with overcast sky.

- The glazing properties include the transmission of heat and light. The transmission of light is determined by the glazing transmittance and the glazing transparency while the transmission of heat is determined by the solar heat gain coefficient (*SHGC*).

- The most efficient skylight glazing allows the maximum amount of visible light to pass through and rejects the non-visible wavelengths of the solar radiation.

- *Skylight Well*: The minimum size of the well is determined by the roof and ceiling structure.

- The shape of the well can be straight with vertical sides or splayed with sloped sides. Splayed wells have a larger task area in the space having a direct view of the skylight.

- The skylight well can be used to control the distribution of light. Deeper wells block high sun angles and control the daylight distribution better while shallow wells are used to block low sun angles.

- The surface reflectance of the skylight well can take one of the following forms:

1- A highly reflective diffusing surface that provides a diffuse and broadly distributed light pattern below the skylight.

2- A specular reflecting surface that provides an image of the sun and the sky on to a limited area below the skylight.

3- Colored surfaces distribute the light evenly but reduce its intensity and shift the appearance of the colors in the space below

The horizontal top-lighting design guidelines are summarized in Fig (5-17).

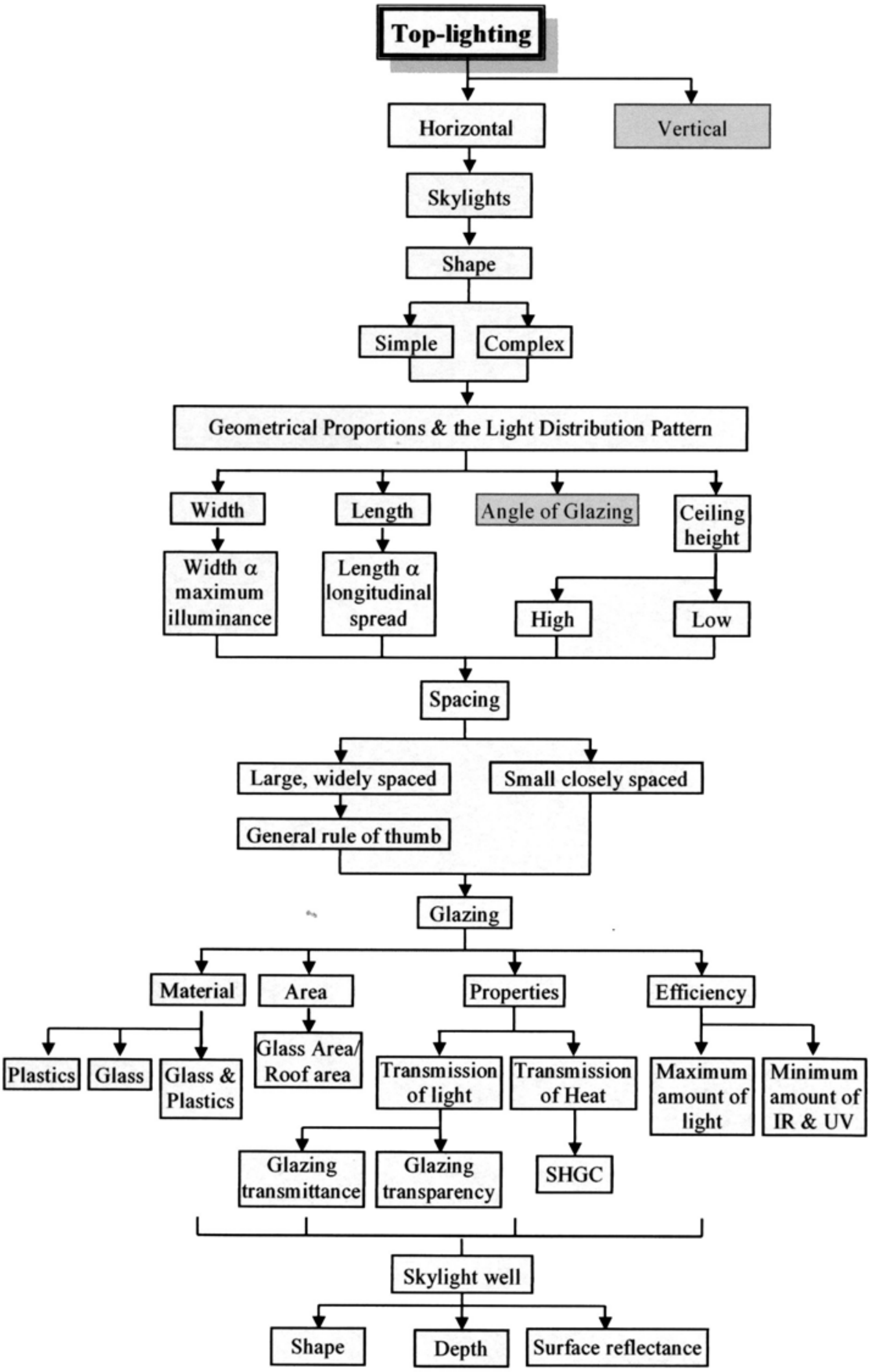


Fig (5-17): Horizontal top-lighting design guidelines.

II) Vertical Top-lighting (Sawtooth / Monitors / Clerestories)

1- **Sawtooth Top-lighting**

- *Placement*: Depends on both of the architectural design concept and the function of the space.
- *Spacing*: According to the general rule of thumb.
- *Light Distribution Pattern*: The light distribution pattern is asymmetric and varies for a single opening than for a series of openings under both clear and overcast skies.

  - Points of maximum and minimum illuminance vary with the orientation. Most openings under a clear sky pass, in a single day, through several of the distribution patterns.
- *Sawtooth Geometrical Proportions and the Light Distribution Pattern*: Both of the sawtooth spacing and glazing slope are directly proportional to the resulting daylight distribution pattern.

2- **Monitors Top-lighting**

- *Placement and Spacing*: The monitor's placement is primarily dictated by the architectural design concept and the spacing is according to the general rule of thumb.
- *Orientation and Glazing*:

  - North-facing monitors are the best orientation and do not require shading. It employs clear glazing for maximum transmission since diffusion is inherent in the incoming light.

  - South-facing monitors are the second choice. They require simple overhangs to shade them and employ translucent glazing to diffuse direct sunlight.
- *Light Distribution Pattern:* In over cast sky condition, the light distribution pattern for a single monitor is symmetric while in case of clear sky the light distribution pattern is asymmetric due to the different orientation of the opposing openings.
- *Monitors Geometrical Proportions and the Light Distribution Pattern:*

- The monitors’ height is directly proportional to the internal illuminance.

- The spacing between monitors is inversely proportional to the internal illuminance.

- Monitor's slope is directly proportional to the internal illuminance.

The vertical top-lighting design guidelines are summarized in Fig (5-18).

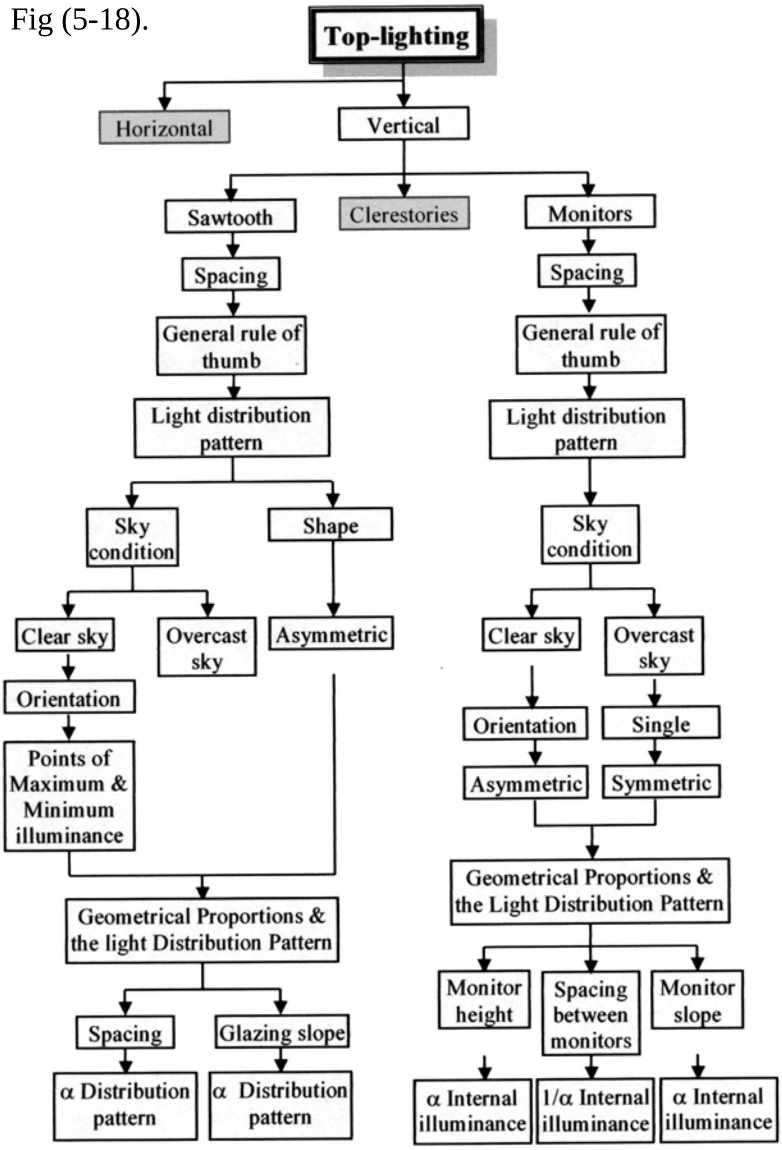


Fig (5-18): Vertical top-lighting design guidelines.

5-3 Innovative Daylighting Concepts

5-3-1 Heliostat

- **Collection System**

- The collection system can be active (movable) or passive (stationary).

- *Collector Components*: The collector can be simple or one-mirror heliostat which is considered to be a passive system or it can be a two-mirror heliostat which is considered to be an active system.

- The two-mirror heliostat can be one of the following types:

1- Azimuth tracking, Fixed altitude in which the primary mirror is movable and tracks the solar azimuth while the secondary mirror is stationary.

2- Altitude tracking, Fixed azimuth in which the primary mirror tracks the solar altitude.

3- Azimuth / Altitude tracking in which the primary mirror tracks both the solar azimuth and solar altitude.

- *Collector Position*: For the one-mirror heliostat the collector can be outside or inside the building.

- For the two-mirror heliostat the collector can be inside the building (both of the primary and secondary mirrors are inside) or it can be outside (both of the primary and secondary mirrors are outside) or it could be partially inside and partially outside (primary mirror is outside and secondary mirror is inside the building).

- *Reflector Material*: The reflector material can be acrylic or glass.

- Acrylic reflectors provide better reflection in the visible spectrum than glass reflectors but their reflection is lower in the *UV* spectrum and is considered unstable in the *IR* spectrum.

- *System Scale*: The heliostat scale can be: small, medium, or large-scale.

- The small-scale system is a passive one-mirror system with mirror area of 0.464 m^2 and limited in use.

- The mid-scale is a passive two-mirror system without mechanism and the mirror area is between $3.1m^2$–$4.9m^2$.

- The large-scale is an active system with two-mirrors. The mirror area is around 15 m^2.

- **Transmission System**

- *Traditional clear shafts*: Dust reduces its efficiency.

- *Light ways with collimating lenses or lens guide*: Dust reduces its efficiency and light intensity is reduced at each interface.

- *Mirrored or reflective metal guide*: mirrored guides can be in the form of di-electric reflector film with reflectance up to 99%. Reflective metal guides can be made of silver material which is characterized by a small diameter, a moderate length, and high efficiency.

- *Prismatic ducts*: Depend on total internal reflection. They are used as both transport and distribution device.

- *Optic fiber bundles or liquid light guides*: Depend on total internal reflection. They are used for long distances.

- **Distribution System**

- *Directly*: by diffuse luminaries.

- *Indirectly*: by reflecting the light onto the ceiling then into the space.

The heliostat daylighting system design guidelines are summarized in Fig (5-19).

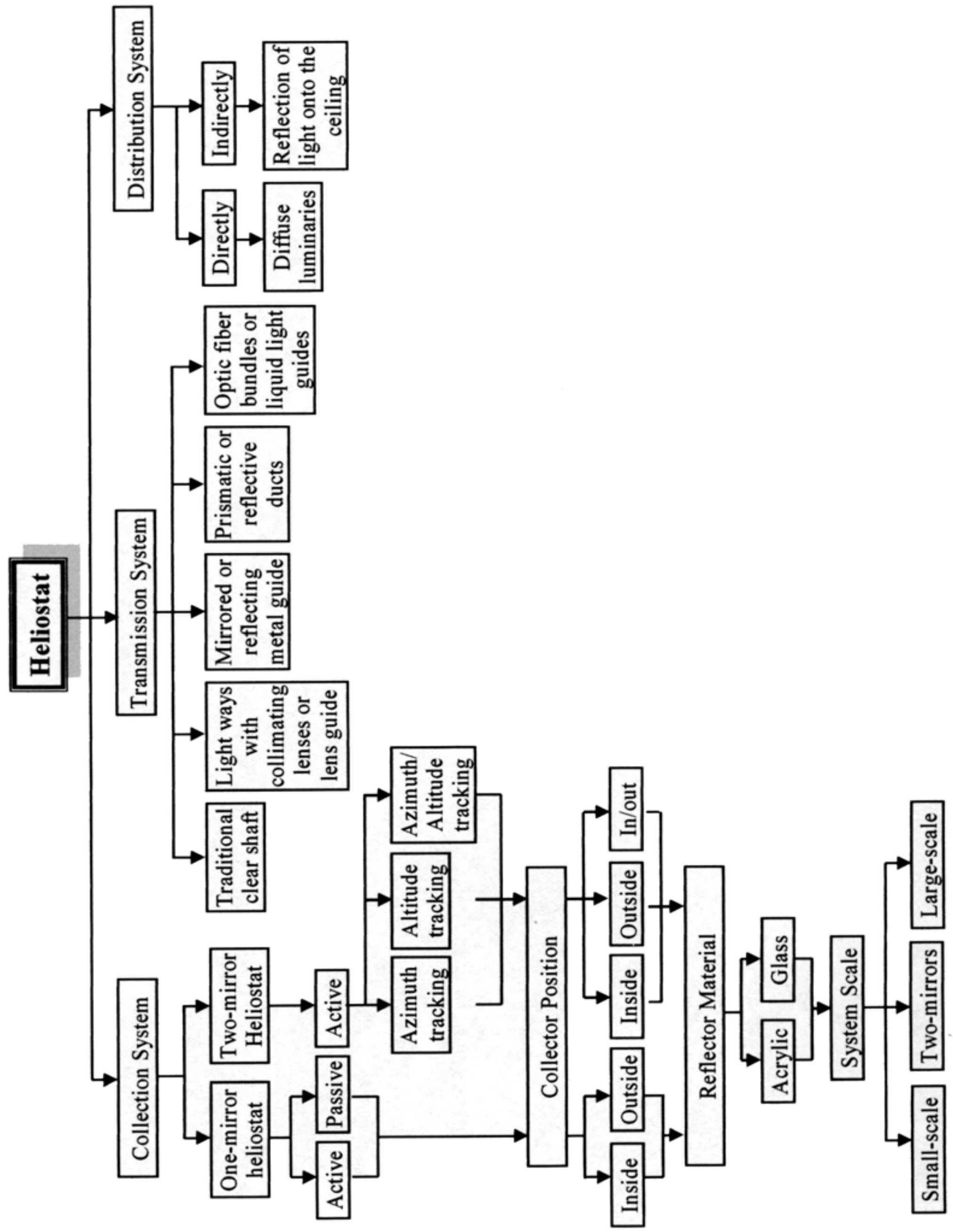


Fig (5-19): Heliostat daylighting system design guidelines.

5-3-2 Light Pipes

- **Collection System**

- Stationary, exterior unit.

- Shape is usually hemispheric (dome shaped)

- Glazing material can be glass, plastics, or any other durable material with high light transmission, usually clear glazing.

- The collection system can be enhanced by the use of low sun angles catchers or a "Sun Tracker" to align the incoming light with the axis of the light pipe.

- **Transmission System**

- The transmission system is the light pipe itself; it can be flexible or rigid.

- Flexible light pipes are easier to install but result in more light losses.

- Rigid light pipes can be straight or bent. The straight pipe performs better than the bent light pipe since each bent reduces light by 8%.

- Transmission system coatings can be a highly reflective material or polymer coatings.

- **Distribution System**

- The distribution system can be in the form of a hemispheric diffuser or a flat diffuser.

- The glazing material may be clear or translucent glazing. Translucent glazing provides a better light diffusion but a lower light transmission.

The light pipe daylighting system design guidelines are summarized in Fig (5-20).

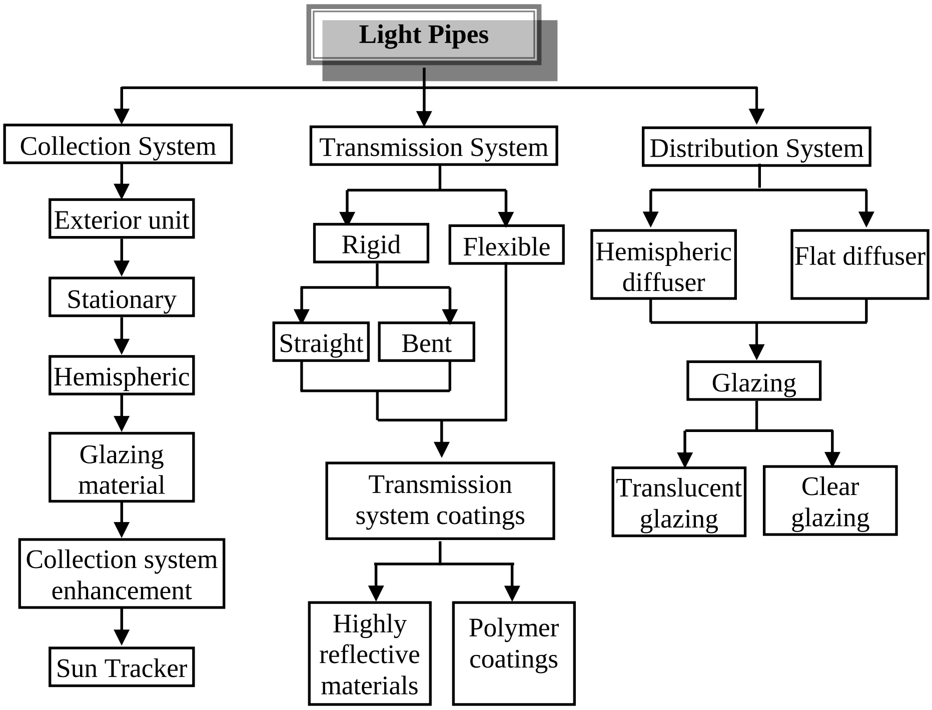


Fig (5-20): Light pipe daylighting system design guidelines.

5-3-3 Fiber Optics Daylighting System

- **Key Concept for Fiber Optics Daylighting System**

- When using a fiber optic daylighting system the designer should be aware of the following key concepts:

- The fibers materials, construction, and composition.
- The transmission characteristics for a single fiber and for a bundle of fibers.
- The color shift that may result due to the attenuation of some wavelengths over others according to the fiber material.
- The impact of the bent radius on the light losses and the direct relation between the fiber diameter and the transmission capacity of the fiber.
- The degradation that results from the exposure of the fiber to moisture and *UV* radiations

  - The maximum heat that the fiber can endure.

- **Collection System**

  - In the form of a single-axis or double-axes.

  - Single-axis is a passive system which results in a low collection system efficiency.

  - Double-axes is an active system, more accurate, and more efficient. It can be a programmed system only or light sensors can be added to the system.

- **Concentration System**

  - Concentration can be done by one of the following methods: 1- Parabolas 2- Converging lenses 3- Fresnel lenses 4- Reflecting surfaces.

  - The concentration system is needed due to the low acceptance angle of the fiber optics.

- **Separation System**

  - The separation system is used to separate the visible spectrum from the UV and IR spectrum that deteriorates the care of the fibers.

  - Separation is done by one of the following methods:
    1- Selective surfaces: cold and hot mirrors.
    2- Lenses: convex lenses
    3- Filters: UV-filters, IR-filters, or UV/IR-filters

- **Distribution System**

  - Distribution is done by the use of fixtures or light rods.

  - Fixtures can be pre-fabricated or self-designed.

  - Light rods consist of a plastic tube, lighting film, and extractors.

The fiber optics daylighting system design guidelines are summarized in Fig (5-21).

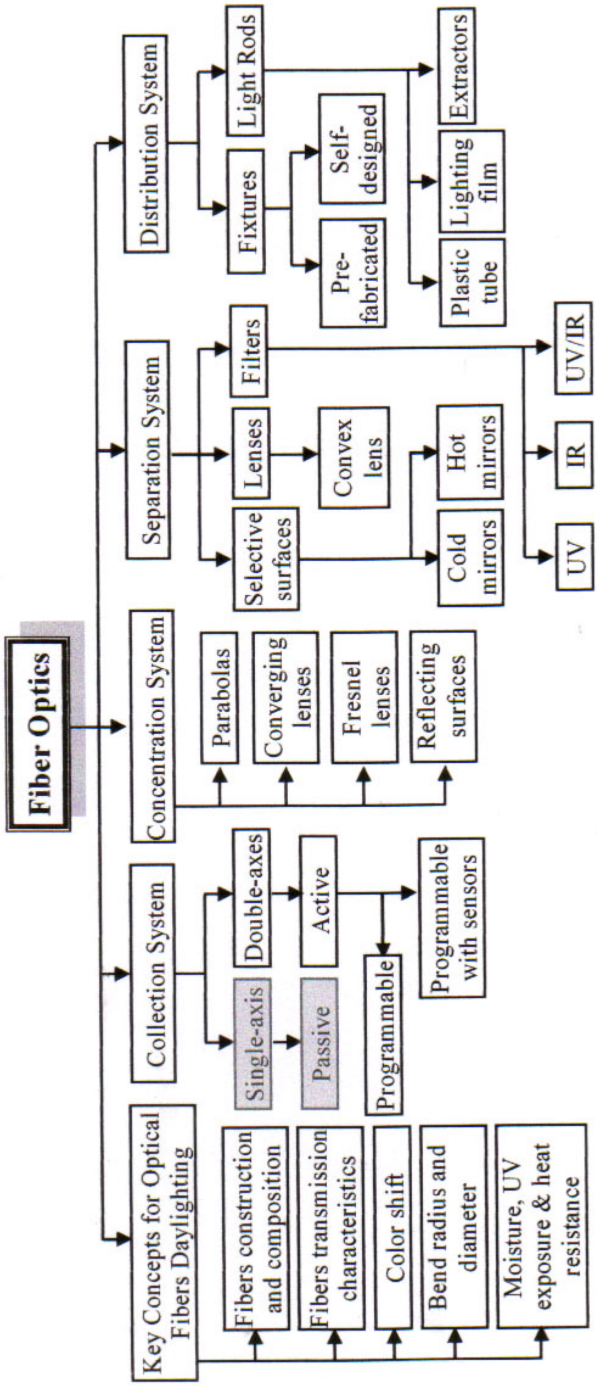
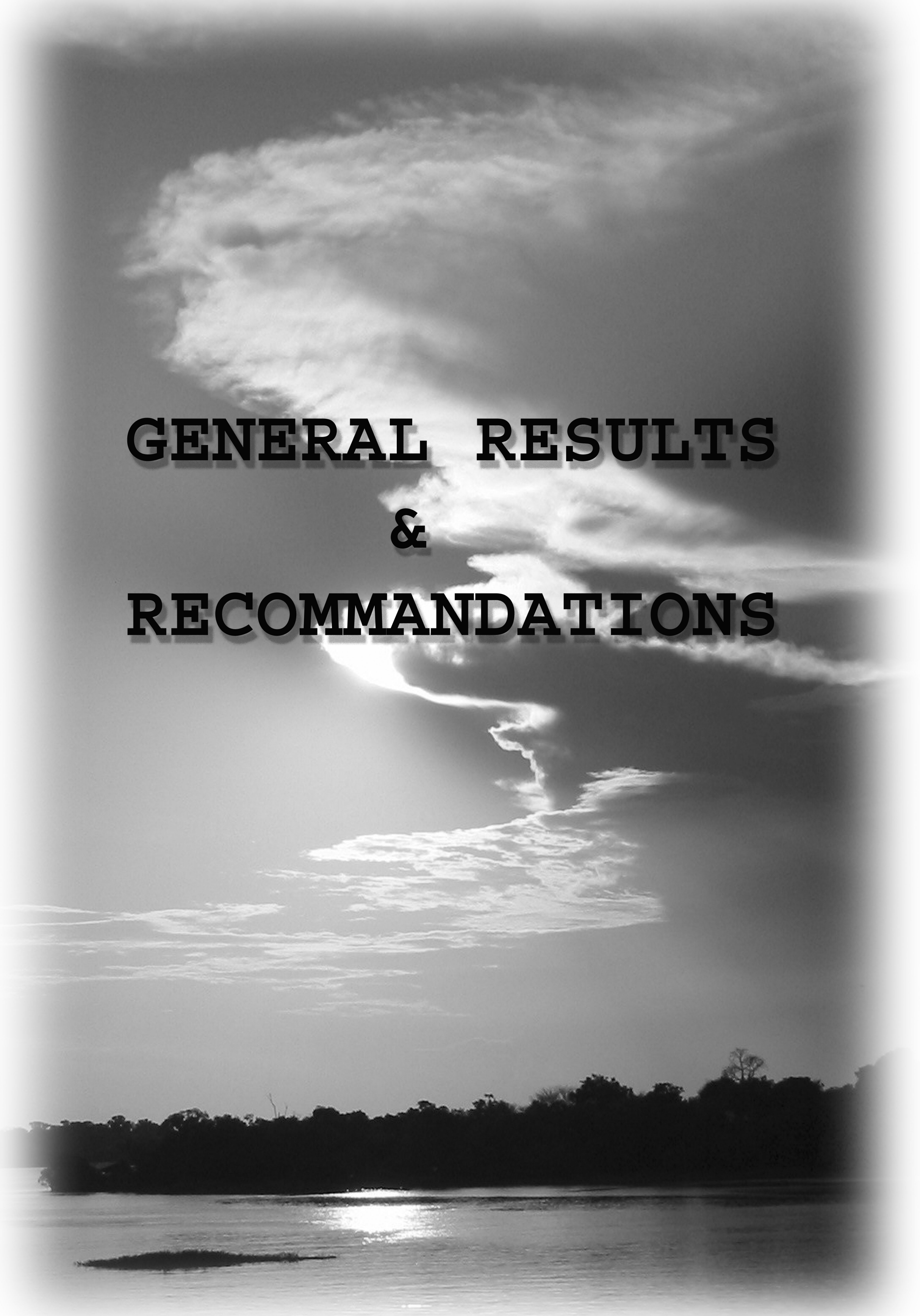


Fig (5-21): Fiber optics daylighting system design guidelines.

GENERAL RESULTS
&
RECOMMANDATIONS



GENERAL RESULTS

- All the traditional and innovative concepts can be used to daylight shallow underground spaces but only the atrium and the innovative concepts are used to daylight deep underground spaces.
- Courtyards and atria can be used to increase the underground building aesthetics in addition to being a natural daylight source.
- Top-lighting concepts are used to daylight large tasks rather than lighting specific tasks.
- Top-lighting concepts are used for high illumination levels.
- The changes in daylighting levels should be considered due to the different solar angles throughout the day in all the concepts used.
- North exposure should be maximized to take full advantage of the naturally diffused light.
- The east and west exposures should be minimized because of the large summer heat gain and serious glare problems from low sun angles.
- Appropriate room size and geometry should be selected according to the used daylighting concept.
- Spaces with low daylighting requirements (i.e. service areas) should be located at the perimeter of the underground building.
- Total light diffusion, especially in spaces where non-specific tasks occur, can be psychologically boring.
- This research is an attempt to point out the value of using the innovative daylighting systems for the future underground projects in Egypt especially that Egypt’s location is characterized by a clear sky most year round.

RECOMMENDATIONS

- Taking full advantage of the daylighting in improving the underground space, regarding the quality of light, the view, the building aesthetics, and the occupants comfort is a must.
- Getting as much high quality daylight as possible into the underground spaces should be the main target (i.e. no glare or veiling reflections).
- Use different daylighting concepts, traditional and innovative, to meet the internal illuminance targets needed to perform various tasks in different spaces of the underground buildings.
- Avoid over sizing of the daylighting methods used in order to prevent the thermal problems that may result from increasing the glazing area.
- All the daylighting concepts for the underground buildings, traditional and innovative, should supplement each other rather than replace one another.
- Use innovative daylighting systems when traditional methods are not efficient or when they are unattainable.
- Maintenance of the innovative daylighting systems should be scheduled periodically.
- More detailed researches and investigations concerning the innovative daylighting concepts should be carried out.
- Under-graduate and post-graduate students should be aware of the innovative daylighting systems potentials to use them in their architectural design projects during their study and in their practice.
- Academic research laboratories for the innovative daylighting concepts should be launched.
- Collaboration among foreign universities concerning the innovative daylighting concepts should be encouraged especially using well equipped laboratories for more advanced research.
- Daylighting simulation programs should be introduced to the under-graduate students in their courses. In addition, they should be used to predict and calculate the daylighting levels in the students’ projects as a part of the environmental design process.

- More simulation studies concerning the courtyard concept should be carried out with different assumptions than those included in this thesis in order to identify the real effect of the complex and interfering parameters of the court.
- Other daylighting concepts for daylighting underground spaces that were not included in the computer study in this thesis should be simulated and the strength and effectiveness of each parameter should be identified.
- Building codes and regulations for the underground spaces should be established and specific attention should be given to the daylighting process.
- Integration between daylighting and electrical lighting should be investigated thoroughly especially in all underground spaces.
- Uniformly distributed light levels are more favorable than uneven light distribution levels when using daylighting, electrical lighting or both.

APPENDIX (A)

UNDERGROUND SPACE UTILIZATION

APPENDIX (A)

UNDERGROUND SPACE UTILIZATION

Underground space utilization is spread in almost all the continents of the world from the prehistoric cave dwellers to the present day and its use includes almost all the fields of the daily life. Some notable patterns of underground space utilization, both historically and recently, can be identified from the world map(1) in Fig (A-1).

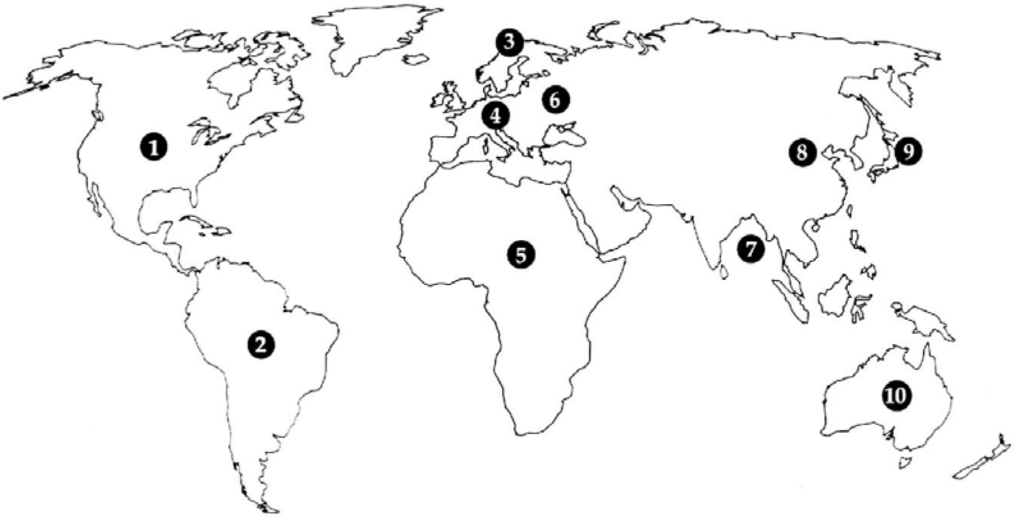


Fig (A-1): World map indicating notable patterns of underground utilization.

1. North America

- Indigenous housing utilized earth and rock structures
- Many examples of modem earth-sheltered housing and non-residential buildings such as libraries and museums.
- Subway systems in some larger urban areas including some with related underground commercial development (Montreal and Toronto, Canada).
- Scattered example of mined space use.

2. South America

- Limited number of uses outside of mining excavations.

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(1) Carmody, J., Sterling R.; "Underground Space Design: A Guide to Subsurface Utilization and Design for People in Underground Spaces", P.70

- Subway systems in some large cities.
- Hydroelectric schemes under development in mountain areas.
- Some experience with underground food storage.

3. Scandinavia

- Large variety of uses mostly in hard rock. Examples include churches, concert halls, sports facility, and archives.
- Many uses are dual-purpose civil defense/community facilities.
- Large number of underground hydropower facilities.
- Extensive oil storage caverns and other storage systems.
- Subway systems in capital cities.

4. Other western European countries

- Variety of urban uses including multipurpose commercial centers and parking facilities.
- Many interurban road and rail tunnels crossing natural barriers.
- Many underground portions of transit systems in major cities.
- Indigenous underground housing found in France, Spain, Italy, and Greece.

5. Africa

- Indigenous food storage in North Africa – notably Morocco.
- Extensive mining activities and some hydropower.
- Indigenous housing in North Africa (both current and historical). Examples include Matmata and Bulla Regia, Tunisia.

6. Eastern and western Europe

- Extensive metro systems in major cities.
- Use of Utilidors for some urban utilities.
- Civil defense facilities.
- Indigenous housing and religious structures - mostly historical. Examples found in Cappadocia in central Turkey.

7. Southern and southeastern Asia

- Cave temples such as Ajanta and EIlora in India.
- A few urban underground facilities including pedestrian underpasses and short road tunnels.
- Subway systems in some major cities including Calcutta and Hong Kong.
- Hydropower facilities in mountainous regions.

8. Eastern Asia

- Approximately 30 million people living in cave dwellings in north-central China.

- Extensive civil defense works in cities in China.
- Extensive interurban road and rail tunnels.
- Metro systems in some cities such as Beijing, Novosibirsk.

9. Japan

- Large metro systems in major cities.
- Extensive underground shopping centers connected to transit facilities.
- Urban uses for infrastructure purposes.
- Extensive interurban road and rail tunnels.
- Intense interest in a wide range of future uses.

10. Australia

- Housing and other building uses in outback mining communities.
- Building applications for environmental preservation in sensitive areas.
- Hydroelectric facilities in mountainous areas.
- Limited underground urban road and rail facilities.

APPENDIX (B)

COURTYARD SIMULATION STUDIES DETAILED RESULTS

APPENDIX (B)

COURTYARD SIMULATION STUDIES DETAILED RESULTS

SQUARE SHAPED COURTYARD

	R.P (1)		R.P (2)		R.P (3)	
Base Case **W<H<2W**	*675.02 Lux*		*167.64 Lux*		*86.28 Lux*	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**
Court Walls High	830.57	126%	216.18	128.95%	109.86	127.32%
Court Walls Low	438.79	65%	96.61	57.62%	50.65	58.7%
Court Floor High	683.52	101.25%	175.11	104.45%	90.81	105.25%
Court Floor Low	663.07	98.22%	157.14	93.75%	77.76	90.125%

	R.P (1)		R.P (2)		R.P (3)	
$H_1>2W$	*150.75 Lux*		*36.75 Lux*		*19.87 Lux*	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**
Court Walls High	200.96	133.3%	46.99	127.86%	24.83	125%
Court Walls Low	79.78	52.92%	21.74	59.15%	12.54	63.11%
Court Floor High	153.72	101.97%	38.90	105.85%	21.61	108.75%
Court Floor Low	146.58	97.23%	32.89	89.49%	17.11	86.10%

	R.P (1)		R.P (2)		R.P (3)	
$H_2<W$	*1451.4 Lux*		*603.53 Lux*		*388.15 Lux*	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**
Court Walls High	1586.25	109.29%	706.47	117.05%	457.95	117.98%
Court Walls Low	1269.64	87.47%	481.87	79.84%	289.33	74.54%
Court Floor High	1492.20	102.81%	633.82	105.01%	411.32	105.96%
Court Floor Low	690.99	47.6%	483.54	80.11%	368.05	94.82%

	R.P (1)	R.P (2)	R.P (3)
Square Court **(area $24m^2$)**	*902.12 Lux*	*243.26 Lux*	*136.07 Lux*

Table (B-1): The square shaped courtyard simulations results.

RECTANGLUAR SHAPED COURTYARD

	R.P (1)		**R.P (2)**		**R.P (3)**	
Base Case H=1.5W	***704.55 Lux***		***233.00 Lux***		***143.34 Lux***	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**
Court Walls High	862.87	122.47%	294.94	126.58%	179.43	125.17%
Court Walls Low	467.21	66.31%	137.42	58.97%	87.30	60.90%
Court Floor High	720.15	102.21%	243.59	104.54%	153.06	106.78%
Court Floor Low	681.04	96.66%	209.19	89.78%	125.59	87.61%

	R.P (1)		**R.P (2)**		**R.P (3)**	
$H_1>1.5W$	***300.17 Lux***		***77.87 Lux***		***43.53 Lux***	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**
Court Walls High	393.95	131.24%	101.62	130.5%	54.93	126.28%
Court Walls Low	163.49	54.46%	44.39	57.0%	26.03	59.79%
Court Floor High	305.38	101.73%	83.51	107.25%	48.08	110.45%
Court Floor Low	287.59	95.80%	66.63	85.56%	34.93	80.25%

	R.P (1)		**R.P (2)**		**R.P (3)**	
$H_2<W$	***1489.57 Lux***		***624.64 Lux***		***391.54 Lux***	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**
Court Walls High	1569.61	105.37%	693.17	110.97%	440.50	112.50%
Court Walls Low	1360.49	91.33%	527.01	84.37%	316.21	80.76%
Court Floor High	1540.89	103.45%	676.97	108.37%	428.48	109.43%
Court Floor Low	1394.94	93.64%	552.61	88.46%	331.68	84.71%

	R.P (1)		**R.P (2)**		**R.P (3)**	
North-South Elongation	***1032.98 Lux***		***279.01 Lux***		***134.38 Lux***	
	Lux	**Percent**	**Lux**	**Percent**	**Lux**	**Percent**

Table (B-1): The rectangular shaped courtyard simulations results

APPENDIX (C)

DAYLIGHTING DEFINITIONS

APPENDIX (C)

DAYLIGHTING DEFINITIONS

Acceptance Angle: In optical fibers the acceptance angle is the half-angle of the cone within which incident light is totally internally reflected by the fiber core.

Active System: A movable system that uses mechanical devices or electric power to perform its function.

Ambient Light: General illumination in a room, usually diffuse and often at lower illuminance than lighting for specific activities. See also Task Lighting.

Angle of Incidence: The angle of incidence is the angle between a beam incident on a surface and the normal (line perpendicular to the surface at the point of incidence). The beam can be formed by any wave: optical, acoustical, microwave, X-ray etc.

Angle of Refraction: The angle of refraction is the angle between the beam refracted at the boundary between two media of different refractive indices and the normal (line perpendicular to the surface at the point of the incidence). The beam can be formed by any wave: optical, acoustical, microwave, X-ray etc.

Aperture: The rough opening in the surface of a building that admits daylight. The aperture opening does not account for framing or glazing.

Artificial Light: The common name for all light sources except daylight and sunlight.

ASHRAE: American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Aspect Ratio: Ratio between two sides of an object, such as the height: width of a duct or an atrium.

Atrium (pl. atria): An interior, covered, open area in the center of a building.

Beam Daylighting: The intentional use of the direct (sunlight) component of daylight to illuminate a building.

Brightness: The subjective human perception of luminance, See also Luminance.

Cable: A cable is two or more wires bound together. A cable may be protected by a sheath which covers all the wires. Cables can also act as carriers for other media, including optical fibers.

CIE: Commission Internationale de l’Eclariage: International Lighting Commission, Headquartered in Paris, France.

Cladding: Regarding optical fiber, cladding is one or more layers of material of lower refractive index, in intimate contact with a core material of higher refractive index.

Clear Sky (CIE): A reference cloudless sky condition as defined by Kittler (1965) and adopted by the CIE in 1973.

Clear Sky (NOAA): A sky that has less than 30 percent cloud cover, with the solar disk unobstructed.

Cloudy Sky (NOAA): A sky having between 30 and 70 percent cloud cover, with the solar disk obstructed.

Contrast: A qualitative perception of the difference between two elements in the visual field, especially of their luminance.

Coefficient of Utilization (CU): The ratio of luminous flux (lumens) from a luminaire calculated as received on the work plane to the luminous flux emitted by lamps. When used with skylights, the coefficient of utilization is the ratio of the luminous flux from skylights received on the work plane to the daylight entering the room from the bottom of the light wells.

Color: The characteristics of light by which a human observer may distinguish between two structure-free patches of light of the same size and shape.

Core Daylighting: The use of daylighting techniques to illuminate areas of a building that are not part of the perimeter (exterior 6m) of the building.

Critical Angle: In geometric optics, the critical angle is the smallest angle of incidence at which total internal reflection occurs. The angle of incidence is measured with respect to the normal at the refractive boundary.

Courtyard: An interior, uncovered, open area in the center of a building.

Daylight: Illuminance from radiation in the visible spectrum from the diffuse sky, reflected light, and direct sun that lights a room.

Daylight Factor: A relative measure of daylight illuminance at a point on a given plane expressed as the ratio of the illuminance on the given plane at that point to the simultaneous exterior illuminance on a horizontal plane from the whole unobstructed sky. Direct sunlight is excluded from both interior and exterior values of illuminance.

Daylight Saturations: The condition where the interior daylight illuminance level equals or exceeds the specified design illuminance level and the lighting control system thus provides maximum lighting energy savings. At saturation, any further increase in daylight illuminance will not produce additional lighting energy savings.

Dielectric Waveguide: is a waveguide that consists of a dielectric material surrounded by another dielectric material, such as air, glass, or plastic, with a lower refractive index. An example of a dielectric waveguide is an optical fiber.

Diffuse (Lambertian) Surface: A surface that emits or reflects light in all directions and has a constant luminance regardless of viewing direction. See also Specular reflecting surface.

Diffuse Light: The visible radiation received on a surface from the sky, including background sky brightness, horizon brightness, and circumsolar brightness.

Disability Glare: Glare resulting in reduced visual performance and visibility.

Discomfort Glare: Clare producing visual discomfort that does not necessarily interfere with visual performance.

Dispersion: In optics, dispersion is a phenomenon that causes the separation of a wave into components with different frequencies, due to the dependence of the wave's speed on its frequency. It is most often described in light waves, though it may happen to any kind of wave that interacts with a medium or can be confined to a waveguide, such as sound waves. There are generally two sources of dispersion: material dispersion, which comes from a frequency-dependent response of a material to waves; and waveguide dispersion, which comes because the transverse mode solutions for waves confined laterally within a finite waveguide generally depend upon the frequency (i.e. on the relative size of the wave, the wavelength, and that of the waveguide).

External Reflected Component (ERC): The ratio of that part of the daylight illumination, at a point, that is received from exterior reflecting surfaces to the simultaneously measured exterior daylight on a horizontal surface.

Fenestration: Any opening or arrangement of openings for the admission of daylight, including any devices in the immediate proximity of the opening that affect distribution.

Glare: The sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss of visual performance and visibility.

Glazing: The transparent or translucent media in an aperture through which daylight is filtered.

Glazing Efficacy (GE): The measurement of the ability of the glazing material to transmit visible light, in relation to the amount of solar heat it admits into the building. Glazing efficacy is the visible light transmittance divided by the solar heat gain coefficient. Glazing efficacy is the same as the light-to-solar gain ratio (LSG).

Heliostat: A device that tracks the solar disk in order to redirect sunlight into a building for use as an interior illuminant.

High-performance glazing: Typically defined as glazing with $T_{vis} > SC$ (glazing efficacy > 1.0).

Illuminance: The density of the luminous flux incident on a surface, expressed in units of footcandles (or lux).

Illumination: The act of illuminating or state of being illuminated.

Internal Reflected Component (IRC): The ratio of that portion of the daylight illuminance received at a station point after being reflected one or more times from room surfaces to the exterior illuminance on a horizontal surface.

Latitude: The angular distance north or south of the earth’s equator, measured in degrees along a meridian. Latitudes farther from the equator have lower sun angles, less radiation and illuminance per hour, and more variation in sun path between summer and winter.

Light: Radiant energy that is capable of exciting the retina and producing a visual sensation. The visible portion of the electromagnetic spectrum extends from about 380 to 780 nm.

Low-emissivity (Low-e) Coating: A coating applied to glazing that selectively transmits short wave radiation (such as light) but reflects long wave (infrared) radiation. Lower heat losses and lower U-values result from applying low-e coatings to glazing.

Luminance (L): The luminous intensity of a light source or reflecting surface, including factors of reflection, transmission, and emission. Units are candelas per square foot (cd/ft^2), candelas per square meter (cd/m^2). An unobstructed sky of 1 foot-lambert luminance produces an illuminance of 1 foot-candle on a horizontal surface.

Luminous Efficacy (LE): A measure of the luminous efficiency of a radiant flux, expressed in lumens per watt. For daylighting, this is the ratio of visible flux incident on a surface divided by radiant flux on that surface. For electric sources, it is the ratio of the total luminous flux emitted divided by the total lamp or luminaire power input.

Lux, Ix: The SI unit of illuminance. One lux is one lumen per square meter.

Maintenance Factor (MF): The ratio of illuminance on a given area after a period of time to the initial illuminance on the same surface. Used in the daylight factor method of analysis.

Minimum Bend Radius: Minimum bend radius is the radius below which a cable should not be bent.

Opaque: Not able to transmit light; for example, unglazed walls.

Orientation: The relation of a building surface with respect to compass orientation. Usually expressed as either a compass heading or a degree heading.

Overcast Sky: The condition in which the sky is completely covered in clouds and the sun cannot be seen. Overcast skies generally have lower luminance, lower radiation, and create weak shadows and more diffuse lighting, relative to more clear conditions. The sky is about three times brighter at the zenith than at the horizon.

Partly Cloudy Sky: The sky condition between overcast and clear conditions, which varies from mostly cloudy with patches of clearness to mostly clear with a few clouds. Partly cloudy skies are highly variable and difficult to predict. **Passive System:** A stationary system that uses non-mechanical, non-electrical means to perform its function.

Perimeter Daylighting: The use of day lighting techniques to illuminate areas of a building that are part of the perimeter (exterior 6ms) of the building.

Photocontrols: Lighting control system that adjusts the electric lighting power in response to the amount of interior light or ambient light or ambient daylight available.

Quality of Light: Refers to the distribution of luminance in a visual environment. The term is used in a positive sense and implies that all luminances contribute favorably to visual performance, visual comfort, ease of seeing, safety, and aesthetics for the specific visual tasks involved.

Quantity of Light: The product of the luminous flux by the time it is maintained. It is the time integral of luminous flux.

Rayleigh Scattering: is the scattering of light by particles smaller than the wavelength of the light. It occurs when light travels in transparent solids and liquids, but is most prominently seen in gases. Rayleigh scattering of sunlight from particles in the atmosphere is the reason why the light from the sky is blue (named after Lord Rayleigh).

Reflectance: The ratio of radiation reflected by a surface to the radiation incident on it. Range is 0-1.0.

Reflection Loss: In an optical fiber, the loss that takes place at any discontinuity of refractive index, especially at an air-glass interface such as a fiber end face, at which a fraction of the optical signal is reflected back toward the source.

Refraction: is the change in direction of a wave due to a change in velocity. It happens when waves travel from a medium with a given refractive index to a medium with another. At the boundary between the media the wave changes direction, its wavelength increases or decreases but frequency remains constant.

Sawtooth: A roof aperture system in which the glazing is placed on the short, usually vertical, surface of a series of roof serrations.

Side Lighting: The use of daylight apertures on the walls of buildings to provide daylight that sweeps across tasks. Typically used to illuminate a horizontal work plane.

Sky Light: Daylight from the sky dome only, excluding the direct sun.

Skylight-to-Floor Ratio (SFR): The ratio of gross skylight opening area to day lit floor area..

Sky Component (SC): The ratio of that part of the daylight received at a work plane from the sky to the simultaneously measured exterior illuminance on a horizontal surface.

SkyLight: A roof window, horizontal or sloped.

Skylight Efficacy (SE): The measurement of a skylight system’s ability to transmit visible light, in relation to the amount of solar heat it admits into the building.

Solar Altitude: The vertical angular distance of the sun in the sky above the horizon. It is measured positively from the horizon to the zenith, from 0 to 90 degrees.

Solar Azimuth: The horizontal angular distance between the vertical plane containing the sun and true south.

Solar Equinox: Either of two times during the year when the sun crosses the celestial equator and when the length of day and night is approximately equal. The autumnal equinox is September 22; the vernal equinox, March 22.

Solar Heat Gain Coefficient (SHGC): The fraction of incident solar radiation (for the full spectrum) which passes though an entire window assembly, including the frame, at a specified angle. Range is 0-0.85.

Solar Solstice: Either of two times during the year when the sun reaches either the Tropic of Cancer or the Tropic of Capricorn and the length of the day is either the longest or the shortest of the year, depending upon whether one is in the northern or southern hemisphere. The winter solstice is December 21, the summer solstice is June 21.

Solar Transmittance: The transmittance of a glazing material or skylight assembly over the complete solar spectrum.

Specular Reflective Surface: A surface characterized by the reflectance of light rays striking and leaving the surface at equal angles.

Sunlight: Direct visible radiation from the sun. Called the direct component of daylight when considering the direct, diffuse, and ground-reflected components.

Task lighting: Light used to illuminate visually demanding activities such as reading.

Top-lighting: Daylighting concepts, in the roof of a building, that provide light from above to illuminate horizontal, sloped, or vertical work planes.

Translucent: The ability to transmit light but causing sufficient diffusion to eliminate perception of distinct images.

Transmittance: The ratio of the transmitted flux to the incident flux.

Transparent: The ability to transmit light with little distortion of images.

Ultraviolet Radiation: For practical purposes any radiant energy within the range of 10 to 380 nm.

Uniform Sky: An isotropic sky in which the luminance in all directions is equal. Used to describe both an overcast and clear sky, without sun. It assumes that brightness at zenith and horizon are equal.

Visible Transmittance (T_{vis} or VT): The transmittance of a particular glazing material or skylight assembly over the visible portion of the solar spectrum.

Wavelength: The distance between two successive points of a periodic wave in the direct of propagation, in which the oscillation has the same phase. In daylighting, wavelength is measured in nanometers.

Well Cavity Ratio (WCR): A parameter used to determine the light well factor. Well cavity ratio is a measure of the geometric shape of the well, and is calculated as follows:

$$\text{WCR} = \frac{5 \text{ x Well Height x (Well Length + Well Width)}}{\text{Well Width x Well Length}}$$

A light well with proportions of a cube always has a well cavity ratio of 10.

Well Factor (WF): The ratio of the amount of visible light leaving a skylight well to the amount of visible light entering the skylight.

Work Plane: The plane at which work usually is done, and on which the illuminance is specified and measured. Unless otherwise indicated it is assumed to be a horizontal plane 0.76m (30 inches) above the floor.

Zenith: The point at the top of a hemispheric sky dome.

REFRENCES

BOOKS

Ahrens, D., Ellison, T., and sterling, R.; "**Earth-Sheltered Homes: Plans And Designs**", Van Nostrand Reinhold, New York, 1981

Brown, G., Dekay, M.; "**Sun, Wind, And Light: Architectural Design Strategies**", John Wiley & Sons, Inc., 2nd edition, New York, 200

Carmody, J., Sterling, R.; "**Underground Space Design: A Guide To Subsurface Utilization And Design For People In Underground Spaces**", Van Nostrand Reinhold, New York, 1993

Carmody, J., Sterling, R.; "**Underground Building Design: Commercial And Institutional Structures**", Van Nostrand Reinhold, New York, 1983

Evans, B.; "**Daylight in Architecture**", Mc Graw-Hill, Inc., New York, 1981

Cottom-Winslow, M.; "**Architecture And Technology: The Best Of Environmental Design**", PBC International, Inc., New York, 1996

Golany, G.; "**Earth-Sheltered Dwellings In Tunisia: Ancient Lessons For Modern Design**", Associated University Presses, Inc., London, 1988

Golany, G.; "**Earth-Sheltered Habitat: History, Architecture, And Urban Design**", Van Nostrand Reinhold, New York, 1983

Guzowski, M.; "**Daylighting For Sustainable Design**", Mc Graw-Hill, New York, 2000

Jankowski, W.; "**The Best of Lighting Design**", PBC International, Inc., New York, 1987

Lechner, N.; "**Heating, Cooling, lighting: Design Methods For Architects**", John Wiley & Sons, New York, 1991

Moore, F.; "**Concepts And Practice Of Architectural Daylighting**", Van Nostrand Reinhold, New York, 1991

Moore, F.; "**Environmental Control Systems: Heating Cooling Lighting**", Mc Graw-Hill, Inc., Singapore, 1993

Phillips, D.; “**Lighting Modern Buildings**”, Architectural Press, Oxford, 2000

Ruck, N.; “**Building Design And Human Performance**”, Van Nostrand Reinhold, New York, 1989

Reynolds, J.; “**Courtyards: Aesthetic, Social, And Thermal Delight**”, John Wiley & Sons, Inc., New York, 2002

Robbins, C.; “**Daylighting: Design And Analysis**”, Van Nostrand Reinhold, New York, 1986

Saxon, R.; “**Atrium Buildings: Development And Design**”, The Architectural Press, London, 1983

Schiler, M.; “**Simplified Design of Building Lighting**”, John Wiley & Sons, Inc., New York, 1992

Soleri, P.; “**The City In The Image Of Man**”, MIT Press, Cambridge, Massachusetts, London, England, 1969

Steffy, G.; “**Architectural Lighting Design**”, John Wiley & Sons, Inc., 2nd edition, New York, 2002

Vale, B., Vale, R.; “**Green Architecture: Design For A Sustainable Future**”, Thames and Hudson, London, 1991

THESIS

Achi, A.; "**Design Criteria For Courtyards In The Architecture Of The Arab World**”, Ph.D., Faculty of Engineering, Cairo University, 1999. (Arabic Thesis)

Amer, N.; “**Atrium Buildings’ Design In Urban Context**”, M.Sc. Thesis, Faculty of Engineering, Cairo University, 1998

Andrea, E., Schade, J.; “**Daylighting By Optical Fiber**”, M.Sc. thesis, Department of Environmental Engineering, Lulea University of Technology, Porson, Lulea, Sweden, 2002

Ashley, J., “**Modification Of Atrium Design To Improve Thermal And Daylighting Performance**”, M.Sc. thesis, Center for Medical, Health, and Environmental Physics, School of Physical and Chemical Science, Queensland University of Technology

Konsowa, A.; “**The Architecture Of The Underground Buildings: An Analytical Study Of Buildings In The Underground And Its Ability To Be Used In Egypt**”, M.Sc. thesis, Chair of Architecture, Military Technical College, 2004

Michael, M.; “**Architecture Of The Underground Structures: The Influence Of Underground Subways**”, M.Sc. thesis, Chair of Architecture, Military Technical College, 2004

Salem, D.; “**The Study Of Natural Lighting In The Atrium Buildings Within The Local Environment Level To Reach The Optimum Performance By The Aid Of Computer**”, Ph.D. Thesis, Faculty of Engineering, Cairo University, 2001.(Arabic Thesis)

Seif El Nasr, S., “**Daylighting Design Process in Buildings: An Approach for Integration of Daylighting in The Design Process**”, M.Sc. Thesis, Faculty of Engineering, Cairo University, 2003.

CONFERENCE & WORKSHOP PROCEEDINGS

Aizlewood, M.; “**The Daylighting of Atria: A Critical Review**”, ASHRAE-Transactions, Vol.101 npt2, 1995, Proceedings of the 1995 ASHRAE Meeting, San Diego, CA, USA.

Boubekri, M.; “**The Energy Conservation Potential of Daylighting in a Four-Sided Atrium: A Simplified Calculation Procedure**”, Proceedings of the International Conference on Energy Research & Development (ICERD), Volume I, State of Kuwait, November 1998

Chow, F., Paul, T., Vähäaho, I., Sellberg, B., and Linos F.; “**Hidden Aspects of Urban Planning: Utilization of Underground Space**”, Proceedings of the 2nd International Conference on Soil Interaction in Urban Civil Engineering, Zurich, March 2002
URL: http://www.gcg.co.uk/features/utilisationofundergroundspace.pdf
[Accessed May 2005]

Earl, D., Muhs, J.; “**Preliminary Results on Luminaire Designs for Hybrid Solar Lighting Systems**”, Proceedings of Forum 2001: Solar Energy: The Power to Choose, April 21-25, 2001, Washington, DC
URL: http://www.ornl.gov/sci/hybridlighting/pdfs/AsmeLuminaire.pdf
[Accessed July 2005]

Ellis, P., Strand, R., Baumgartner, K.; “**Simulation of Tubular Daylighting Devices and Daylighting Shelves in Energyplus**”, SimBuild 2004, IBPSA-USA National Conference, Boulder, CO, August 4-6, 2004
URL: http://gundog.lbl.gov/dirpubs/SB04/sb05.pdf
[Accessed July 2005]

Muhs, J.; “**Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems**”, American Solar Energy Society’s, SOLAR 2000 Conference, Madison, Wisconsin, June 16-21, 2000
URL: http://www.ornl.gov/sci/hybridlighting/pdfs/Muhs_ASME_Paper.pdf
[Accessed June 20054]

PAPERS & TECHNICAL REPORTS

CADDET, Energy Efficiency, Energy Efficient Lighting; “**Hybrid Solar Lighting Doubles the Efficiency and Affordability of Solar Energy in Commercial Buildings**”, Newsletter No.4, 2000
URL: http://www.caddet.org/
[Accessed July 2005]

Center for the Analysis and Dissemination of Demonstrated Energy Technologies [CADDET], Maxi Brochure 14, “**Saving Energy with Daylighting Systems**”
URL: http://www.caddet-ee.org
[Accessed December 2003]

Chen, Y., Kribus, A, Lim, B., Lim, C., Chong, K., Karni, J., Buck, R., Pfahl, A., and Bligh, T.; “**Comparison of Two Sun Tracking Methods in the Application of a Heliostat Field**”, Transactions of the ASME, Vol. 126, pp.638-644,February, 2004
URL: http://www.eng.tau.ac.il/~kribus/Publications/ACTA-JSEE-04.pdf
[Accessed July 2005]

Godard, J., Sterling, R.; “**Geoengineering Considerations in the Optimum Use of Underground Space**”
URL: http://www.ita-aites.org/.../pdf/ItaAssociation/ProductAndPublication/ItaPositionPapers/Geoingineering/geo202.pdf
[Accessed May 2005]

Kribus, A., Meri, M., Yogev, A., Vishnevetsky, I, Sytnik, A; “**Continuous Tracking of Heliostat**”, Transactions of the ASME, Vol. 126, P.842-848, August 2004
URL: http://www.eng.tau.ac.il/~kribus/ Publications/cont-tracking-JSEE-04.pdf
[Accessed July 2005]

Muhs, J.; “**ORNL’s Hybrid Solar Lighting Program: Bringing Sunlight Inside**”, NCPV and Solar Program Review Meeting 2003
URL: http://www.nrel.gov/ncpv_prm/pdfs/33586085.pdf
[Accessed July 2005]

Parker, H.; “**Underground Space: Good for Sustainable Development and Vice Versa**”, International Tunneling Association (ITA) Open Session, World Tunnel Congress, Singapore, May, 2004.
URL: http://www.ita-aites.org/cms/fileadmin/filemounts/
general/pdf/ItaAssociation/ITAEvents/OpenSessions/HParker.pdf
[Accessed May 2005]

The National Renewable energy laboratory (NREL), Department of Energy Efficiency and Renewable Energy “**Earth Sheltered Houses”**
URL: http://www.eere.energy.gov/consumerinfo/factsheets/earth.html
[Accessed May 2005]

The European Commission Directorate-General for Energy (DGXVII); “**Daylighting in Buildings**”, A Thermie Action, Energy Research Group, School of Architecture, University College Dublin, Richview, Clonskeagh, Ireland.
URL: http://erg.ucd.ie/mb_daylighting_in_buildings.pdf
[Accessed August 2004]

PERIODICALS

Aizenberg, J.; “**Principal New Hollow Light Guide System “Heliobus” for Daylighting and Artificial lighting of Central Zones of Multi Story Buildings**”, Right Light 4, Vol.2, pp. 239-243, 1997
URL: http://www.iaeel.org/IAEEL/Archive/Right_Light_Proceedings/
Proceedings_body/BOK4/RL42aize.pdf
[Accessed January 2004]

Barker, M.; “**Using the Earth to Save Energy: Four Underground Buildings**”, Tunneling and Underground Space Technology, Vol. 1, No. 1, pp.59-65, 1986
URL: http://WorkingGroupsPublication/WG4/Tust_Vol_1_1_59-65.pdf
[Accessed June 2005]

Brogan, J.; “**Light in Architecture**”, Architectural Design, Profile No.126, 1997.

Calcagni, B., Paroncini, M.; “**Daylighting Factor Prediction in Atria Building Designs**”, Solar Energy, Vol.76, Elsevier Ltd., 2004

Gugliermetti, F., Grignaffini, S.; “**Shafts for Daylighting Underground Spaces: Sizing Guidelines**”, Lighting Research Technology, Vol.33, No.3, pp.183-195, 2001

Hane, T.; “**Application of Solar Daylighting Systems to Underground Space**”, Tunneling and Underground Space Technology, Vol. 4, pp.465-470, 1989

Kribus, A., Vishnevetsky, I., Yogev, A., Rubinov, T.; “**Closed Control of Heliostat**”, Energy, Vol. 29, pp.905-913, 2004
URL: http://www.eng.tau.ac.il/~kribus/ Publications/closed-loop-En-04.pdf
[Accessed July 2005]

Laouadi, A.; “**Design Insights on Tubular Skylights**”, Lighting, Vol.25, No.1, pp.38-41, February 2005
URL: http:// irc.nrc-cnrc.gc.ca/fulltext/ prac/nrcc47334/nrcc47334.pdf
[Accessed June 2005]

Littlefair; “**Innovative Daylighting: Review of Systems and Evaluation Methods**”, Lighting Research and Technology, Vol. 22 n.1, pp.1-17, 1990

Oakley, G., Riffat, S., Shao, L.; “**Daylight Performance of Light Pipes**”, Solar Energy, Vol.69, No.2, pp.89-98, 2000

Shao, L., Riffat, S., Hicks, W., Yohannes, I.; “**A study of Performance of Light Pipes Under Cloudy and Sunny Conditions in the UK**”, Right Light 4, Vol.1, pp.155-159, 1997
URL: http://www.iaeel.org/IAEEL/Archive/Right_Light_Proceedings/ Proceedings_body/BOK4/RL4shao.pdf
[Accessed January 2004]

Trauthwein, C.; “**Back to Basics: Daylighting**”, Architectural Lighting Magazine, April 2001
URL: http://www.lightforum.com/archives/2001/0401/technique2.html
[Accessed December 2002]

ON LINE DOCUMENTS

Advanced Lighting Systems, Technical Solid Core Information
URL: http://www.advancedlighting.com
[Accessed July 2005]

Anthony’s home page
URL: http://www.atkielski.com
[Accessed July 2005]

Bamboo Web Dictionary, Open Content Encyclopedia
URL: http://www.bambooweb.com
[Accessed July 2005]

Bartenbach L’chtLabor GmbH, Austria
URL: http://www.bartenbach.com
[Accessed January 2003]

BOMIN SOLAR GmbH, Germany
URL:http://www.bomin-solar.de
[Accessed July 2003]

DJB ARCHITECTS Ltd., David J. Bennett, FAIA New York, Minneapolis
URL: http://djbarchitects.home.att.net
[Accessed July 2004]

Energy Design Resources; “**Introduction To Skylighting**”
URL: http://www.energydesignresources.com/docs/sg-1-deign.pdf
[Accessed December 2003]

Energy Design Resources; “**Designing With Skylights**”
URL: http://www.energydesignresources.com/docs/sg-2-deign.pdf
[Accessed December 2003]

Energy Design Resources; “**Skylights: Specification Choices**”
URL: http://www.energydesignresources.com/docs/sg-3-deign.pdf
[Accessed December 2003]

Energy Efficiency Manual, “**Measure 8.3.1 Install Skylights or Light Pipes**”
URL: http://www.energybooks.com/pdf/966978.pdf
[Accessed January 2004]

Fiberoptics Technology Incorporated, Optical Fiber Principles
URL: http://www.fti.thomasregister.com
[Accessed July 2005]

HELIOBUS AG, Switzerland
URL: http://heliobus.com
[Accessed January 2004]

Heliostats
URL: http://physics.Kenyon.edu/Early Apparatus/ Optics/ Heliostat/ Heliostat.html
[Accessed December 2003]

International Tunneling Association (ITA-AITES); “**Why Go Underground?”**
URL: http://www.ita-aites.org/cms/117.html
[Accessed May 2005]

Iyer-Rangia, U.; “**Daylighting in Atrium Spaces**”
URL: http://www.art.bilkent.edu.tr/iaed/cb/Ozdamar.html
[Accessed July 2004]

La Foret Engineering Co., Ltd.
URL: http://www.himawari-net.co.jp
[Accessed July 2005]

Oikos, Green Building Source; “**Courtyard Characteristics: Exposure**”
URL: http://oikos.com/
[Accessed June 2004]

Oikos, Green building Source; “**Special Features of Light Pipes**”
URL: http://oikos.com/library/eem/skylights/lightpipes.html
[Accessed January 2004]

Oikos, Green Building Resource; “**Install Skylights or Light Pipes**”
URL: http://oikos.com/library/eem/skylights/#anchor-where-41350
[Accessed January 2004]

Optical Coatings Japan; Mirrors
URL: http://www.techmark.nl
[Accessed July 2005]

Optical Components, Inc.; Dielectric Reflectors: Hot and Cold Mirrors
URL: http://www.ocioptics.com
[Accessed July 2005]

PEI COOBB FREED & Partners, Architects LLP
URL: http://www.pcfandp.com/a/p/8315/s.html
[Accessed January 2005]

Pohl, W.; "**Guided Sunlight for Room Illumination**"
URL:http://www.bartenbach.com/homepage/en/Literature/R+D/Guided_sun.pdf
[Accessed July 2005]

Pohl, W., Anslem, C.; "**Room Illumination by Controlled Sunlight**"
URL:http://www.bartenbach.com/homepage/en/Literature/R+D/Room_illum_sun.pdf
[Accessed July 2005]

Polyoptics Australia
URL: http://www.fiberopticlight.com
[Accessed July 2005]

Public Works and Government Services, Canada; "**Underground Guide for Canadian Commercial Buildings**"
URL:http://www.enermodal.com/pdf/DaylightingGuideforCanadianBuildingsFinal6.pdf
[Accessed August 2004]

Roblon, Fiber Optics
URL: http://www.roblon.com
[Accessed July 2005]

Schott Technical Specifications
URL: http://www.us.schott.com
[Accessed July 2005]

Solatube, The Miracle Skylight
URL: http://www.solatube.com
[Accessed June 2005]

The Hidden Worlds under Pei's Pyramids
URL: http://www.subsurfacebuildings.com/page3.html
[Accessed January 2005]

Wikipedia, The Free Encyclopedia
URL: http://em.wikipedia.org/wiki/Heliostat
[Accessed July 2005]

Wilson, M., Jacobs, A., Solomon, J., Pohl, W., Zimmermann, A., Tsangrassoulis, A., and Fontoynont, M.; "**Creating Sunlight Rooms in Non-Daylit Spaces**"
URL: http://www.learn.londonmet.ac.uk/ about/doc/ufo_rightlight2002.pdf
[Accessed July 2005]

Wilson, M., Jacobs, A., Solomon, J., Pohl, W., Zimmermann, A., Tsangrassoulis, A., and Fontoynont, M.; "**Sunlight, Fibers and Liquid Optics: The UFO Project**"
URL: http://www.learn.londonmet.ac.uk/about/doc/ufo_epic2002.pdf
[Accessed July 2005]

Wulfinghoff, D.; "**Energy Efficiency Manual: Measure 8.3.1Install Skylights or Light Pipes**"
URL: http://www.energybooks.com/pdf/966978.pdf
[Accessed January 200]

Desktop Radiance 2.0 BETA
Source: Lawrence Berkeley National Laboratory (LNBL)
URL: http://radsite.lbl.gov/deskrad/downloadB.htm

النتائج و التوصيات

توصلت الرسالة إلى مجموعة من النتائج العامة لكل من الجزئيات التى شملتها. كما تضمنت مجموعة من التوصيات تتركز فى الاهتمام بعلم "الإضاءة الطبيعيه" فى تصميم المبانى بشكل عام و فى تصميم المبانى تحت سطح الأرض بشكل خاص.

النوعية من المبانى و الخلفية التاريخية لها و مدى انتشارها على مستوى العالم. و قد تم استعراض أنواع الاستخدامات المختلفة لهذه المبانى و فى نهاية هذا الباب تم عمل تصنيف لها من حيث علاقتها بمستوى سطح الأرض و قد ساعد هذا التصنبف فى تحديد العنصر المعمارى المناسب لتوصيل الضوء الطبيعى إلى الفراغات الداخلية تبعا لعلاقتها بسطح الأرض.

الباب الثانى: *إدخال الإضاءة الطبيعية إلى المبانى تحت سطح الأرض.*

فى هذا الباب تم دراسة المفاهيم الأساسية للضوء الطبيعى و مكوناته و فوائده و مدى ارتباطه بالعمارة على مر العصور. كما تناول الباب دراسة الفناء الداخلى و فراغ الأتريوم كطرق تقليدية لإدخال الضوء الطبيعى للفراغات الضحلة و العميقة تحت سطح الأرض. حيث اشتمل الباب على دراسه و تحليل و مقارنة هاتين الطريقتين. فى نهاية هذا الباب تم استعراض و تحليل بعض الأمثلة التطبيقية التى استخدمت هذه الطرق لإدخال الضوء الطبيعى للفراغات المجاوره.

الباب الثالث: *الإضاءة العلوية السقفية كمصدر للضوء الطبيعى فى المبانى تحت سطح الأرض.*

تناول هذا الباب دراسة طرق الإضاءة العلوية السقفية و مدى امكانية استخدامها فى إضاءة الفراغات الضحلة تحت سطح الأرض. كما تم تقسيم الإضاءة العلوية السقفية الى إضاءة علوية أفقية و إضاءة علوية رأسية و تم عمل تحليل لكل طريقة ومقارنة هاتين الطريقتين. فى نهاية هذا الباب تم استعراض و تحليل بعض الأمثلة التطبيقية التى استخدمت هذه الطرق لإدخال الضوء الطبيعى للفراغات المجاورة.

الباب الرابع: *الطرق الحديثة لإدخال الضوء الطبيعى الى الفراغات تحت سطح الأرض.*

فى هذا الباب تم دراسة الطرق الحديثة و التقنيات المتقدمة لإدخال الضوء الطبيعى الى الفراغات العميقة و المعزولة تحت سطح الأرض. من هذه التقنيات نظام الهليوستات ونظام الأنابيب الضوئية ونظام الألياف الضوئية. و قد تم التعرف على مميزات و طريقة عمل كل نظام من هذه الأنظمة. فى نهاية هذا الباب تم مقارنة هذه الأنظمة كما تم استعراض العديد من الأمثلة التطبيقية المستخدمة على مستوى العالم.

الباب الخامس: *المعايير التصميمية لإضاءة المبانى تحت سطح الأرض.*

فى هذا الباب تم استخلاص مجموعة من النتائج التى جاءت فى هيئة معايير تصميمية استرشادية لكل من الطرق السابق دراستها فى الأبواب المختلفة للرسالة و ذلك فى محاولة للتيسير على المصمم فى عمل نوع من التكامل بين الفكرة المعمارية للمبنى الموجود تحت سطح الأرض و طرق توصيل الضوء الطبيعى إلى فراغاته الداخليه. و تم كذلك فى هذا الباب عمل تجارب على برنامج متخصص للحاسب على الفناء الداخلى للوصول إلى نتائج أكثر دقة لتأثير المعايير التصميمية المكونة له على الإضاءه الطبيعيه فى الفراغات المطلة على الفناء.

عنصر اساسي في عملية تأدية الوظائف والمتطلبات كما انه يؤثر بصورة اساسية في حالة المنشآت تحت سطح الارض على شكل الموقع العام للمبنى.

من هذا المنطلق جاءت أهمية دراسة طرق إدخال الإضاءه الطبيعية إلى هذه المبانى. و بمراجعة الأبحاث السابقة وجد أن هذه النقطة لم تنل قسطا كافيا من الدراسة و التى تناسب مكانتها الحقيقية لذا وجب دراسة هذة النقطة المؤثرة و ذلك للتشجيع على استخدام وانتشار هذه المباني في تنمية المناطق الحضرية المزدحمة والمختنقة كعلاج لمشكلة الازدياد السكاني المستمر وتدهور البيئة في العالم بشكل عام وفي مصر بصورة خاصة وما يستتبع هذا الازدياد من الحاجة والضرورة الملحة لتوفير بيئة افضل .

الهدف من البحث

يهدف البحث لدراسة الطرق التقليدية و الحديثة لتوصيل وإدخال الإضاءة الطبيعية إلى الفراغات والمباني تحت سطح الأرض و مقارنة هذه الطرق للوقوف علي مدي الاختلاف بينهما ومدى نجاح كل منها في أداء وظيفتها وذلك للتشجيع على انتشار مثل هذه النوعية من المباني.

و بذلك يكون الهدف الرئيسى من البحث هو:

"تحديد الأساليب و المعايير التصميمية التى تعمل على توصيل الضوء الطبيعى إلى الفراغات الموجودة تحت سطح الأرض مما يساعد المعمارى عل اختيار الأسلوب الملائم و المناسب عند تصميمه لهذه النوعيه من المبانى ".

منهج البحث

ينقسم البحث إلى ثلاث أجزاء أساسية هى:

- **الجزء الأول** تناول دراسة المبانى تحت سطح الأرض وفيه تم جمع البيانات عن هذة المبانى و تصنيفها من حيث علاقتها بسطح الأرض.
- **الجزء الثانى** تناول دراسة الطرق التقليدية و التقنيات الحديثة لإدخال الضوء الطبيعى إلى المبانى تحت سطح الأرض. وقد تم تطبيق المنهج التحليلى و المنهج التحليلى المقارن فى دراسة هذة الجزئية.
- **الجزء الثالث** تم فية تحديد المعايير التصميمية الإسترشادية لكل من الطرق السابق دراستها و ذلك عن طريق تطبيق المنهج الإستنباطى لإستخلاص النتائج و الوصول إلى الهدف من البحث.

محتويات البحث

تتكون الرسالة من خمسة أبواب كالاتى:

الباب الأول: ***نظرة شاملة للمبانى تحت سطح الأرض.***

فى هذا الباب تم دراسة المبانى تحت سطح الأرض حيث تم التعرف على أهم المفاهيم و التعريفات الخاصة بالمبانى تحت سطح الأرض. كما تم التعرف على مميزات مثل هذه

مقدمـــة

إن الراحة والأمان هما أهم ما يبتغيه الإنسان دائما فى حياته ولتحقيق هذه الأحاسيس فإنة يجب توفير فراغات ملائمة لمعيشته وعمله ولكافة الأنشطة الأخرى التى يقوم بها كالتنقل وانتاج الطاقة وتخزينها وغيرها من الأنشطة المؤثرة فى الحياة اليومية للانسان. ولكن تحقيق هذه الرغبة فى توفير الفراغ الملائم تزداد صعوبة مع مرور الوقت نتيجة النقص المستمر فى الأراضى داخل المدن والازدياد المستمر والمتطرد لمعدلات النمو السكانى والحضارى والذى سيكون له تأثيرة القوى على حياة الإنسان فى المستقبل. فنتيجة ازدياد التعداد السكانى فى العالم ومحاولة كثير من الدول النمو والتطور وتحقيق مستوى معيشى أفضل لذلك وجب على العالم توفير المزيد من الأغذية والطاقة والموارد الأخرى الى جانب زيادة المسطحات الحضرية لمواجهة هذا الازدياد المستمر.

وصعوبة تحقيق ما سبق تأتى نتيجة ثلاث اتجاهات رئيسية في كافة أنحاء العالم وهى تحويل الأراضى الزراعية الى أراضى سكنية أو حضرية هذا الى جانب ظاهرة التحضر فى العالم وأخيرا الاهتمام المتزايد والمستمر للحفاظ على البيئة وتحسينها. لذلك فقد ازداد الاهتمام العالمى باستغلال الفراغات والمنشآت تحت الأرض فى شتى أنحاء العالم، فبنقل بعض الاستخدامات والوظائف تحت الأرض فإنه من الممكن استخدام سطح الأرض بطريقة أكثر فعالية فى توفير أراضى زراعية ومناطق ترفيهية تساعد على نمو العالم بأسره وليس جزء منه.

وعلى الرغم مما تشملة الفراغات تحت سطح الأرض من مميزات واستخدامات متعددة إلا أنه هناك العديد من المحددات التى تمنع وتؤخر انتشار هذه النوعية من المبانى بصورة كبيرة منها تكاليف الانشاء، عناصر ومتطلبات الأمان، الاضاءة والتهوية الطبيعية للفراغات وعزل هذه الفراغات وذلك قد يكون نتيجة عدم توافر التقنية المناسبة لانشاء هذه المبانى أو رد فعل المستخدم تجاه المبنى أو الفراغ وكلها عوامل تكون سلبية اذا لم يتم دراستها بعناية للتوصل الى أنسب الحلول لنجاح هذه المبانى فى تحقيق وظيفتها.

المشكلة البحثية

تعتبر الإضاءة الطبيعية أحد المحددات التي تساعد علي انتشار المباني تحت سطح الأرض و التى لها دور اساسي وهام في التأثير على تصميم هذه الفراغات ومدى نجاحها في تأدية وظيفتها وتشجيع مستخدمى الفراغ على التعامل بصورة ايجابية مع الفراغ. ونتيجة لعدم الاهتمام بالاضاءة الطبيعية في هذه النوعية من المباني فإنه من الشائع عند كثير من الناس الصورة السلبية للفراغات تحت الارض وارتباطها بالاحساس بالظلام والبرودة والخوف وذلك نتيجة افتقار هذه الفراغات في كثير من الأحيان إلى الإضاءة والتهوية الطبيعية.

والضوء الطبيعي يلعب دور أساسي وحيوي في توفير بيئة صحية سواء كانت أعلى أو اسفل سطح الارض. فالضوء هو الوسط الذي يتم من خلاله جميع التجارب والخبرات الفراغية البصرية وهو الذي يعطي الإحساس باتساع الفراغ ويعطيه تحديد وشخصية مميزة كما انه

التعريف بالباحث

اسم الطالب: **أشرف على إبراهيم نسيم**

تاريخ الميلاد: **مارس 1977**

الدرجة السابقه: **بكالوريوس الهندسة المعماريه**

جهة التخرج: **جامعة عين شمس**

تاريخ التخرج: **يونيو 2000**

الوظيفه الحاليه: **معيد بقسم العمارة – كلية الهندسة – جامعة عين شمس**

جامعة عين شمس
كلية الهندسة
قسم الهندسة المعمارية

اسم الطالب: **أشرف على إبراهيم نسيم**
عنوان الرسالة: **"الإضاءة الطبيعية فى المباني تحت سطح الأرض"**
الدرجه العلميه: **الماجستير**

لجنة الحكم و المناقشة	**التوقيع**
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التاريخ: 22 / 12 / 2005

الدراسات العليا

ختم الإجازة
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أجيزت الرسالة بتاريخ
....

موافقة مجلس الكلية
....

موافقة مجلس الجامعة
....

جامعة عين شمس
كلية الهندسة
قسم الهندسة المعمارية

"الإضاءة الطبيعية
فى
المباني تحت سطح الأرض"

رسالة مقدمة من:
المهندس / أشرف على إبراهيم نسيم
بكالوريوس الهندسة المعمارية – جامعة عين شمس 2000

للحصول على درجة
الماجستير فى الهندسة المعمارية

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