THE LIVING ATRIUM—
Design guidelines for quality atriums

by
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ABSTRACT

Modern technology has made it ecomically feasible to span large glass-enclosed structures which are socially sufficient and convenient for less mobile groups of the society like handicapped, elders and children to virtually spend days, weeks or even months in a comfortable indoor climate. However, it is plausible that any positive effects of a manipulated environment can turn sour if the created climate is not closely simulating natural conditions. There is a danger of building in faulty and shortsighted presumptions neglecting the close relationship that exist between social, biological, medical, technical and aesthetical needs.

This thesis, divided in two parts, has the broad aim to strengthen the architectural and technical foundation for a good atrium design in order to provide a suitable environment for the coexistence of people and plants in relation to comfort, health, climate, technique, aesthetics, and energy consumption. The scientific purpose is to establish new design criteria and methods in order to create a useful base for intelligent decisions in fulfilling the ultimate vision of a living atrium. The study will specifically focus on design guidelines with respect to climatic conditions affecting plant growth and human health and comfort within atriums.

Part one is a discussion regarding major variables affecting human health, comfort and plant growth in atriums. Also included is a detailed study, recently conducted by the author, investigating the impact of new glazing technology on plant growth.

Part two presents various useful design guidelines which can be used to moderate climatic conditions and enhance plant growth in atriums. A detailed lighting investigation, conducted by the author, is also presented as a design tool for determing the distribution of illumination levels in top-lit atriums during overcast conditions. The method can be used to rapidly identify plant growth zones in an arbitrarily porportioned and top-lit light-well.

Thesis Supervisor: Timothy Johnson

Title: Principal Research Associate

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PREFACE

Almost ten years ago, when I was working on a project for new university facilities in Port Harcourt, Nigeria, I first encountered many intriquate design problems which were intirnitely linked to climate. Paradoxally I found that different economical and technical limitations, such as a rather tight budget as well as an unreliable and sparce supply of electricity for air-conditioning and lighting, seldom put any aesthetical constraints on the design. On the contrary, these restrictions necessitated a sensitive play with massing, forms and detailing, which utilized passive means for climate control, while giving the buildings character and high levels of comfort and convenience.

Today, I'm increasingly convinced that a sensible understanding of natural climatic resources, like the sun and the wind, and a well founded consciousness of the physical and biological environment around us is an asset in the design process, not only in developing countries, but all around the globe independent of technical and economical standards. This knowledge will supply the designer with a sharp chisel for expressing fascinating architectural forms indeginous to the specific site, while meeting all the technical, economical, and functional demands of a modern society. "The Living Atrium" is only one aspect of the designed environment, however, the expected extensive use of atriums in the future and the implications this might impose on the society, makes it well worth an interrogative exploration.

Note: Coincidentially, Richard Saxon has devoted a section in his book, "Atrium Buildings- Development and Design", to "the living atrium". The author acknowledges this, but believes that the concept hasbeen brought a step further in this thesis than in his version of the theme.

ACKNOWLEDGEMENT

No knowledge is derived out of nothing and obviously I have many to thank for their contribution to this thesis. Some have been specifically essential for my understanding of the varied and often extensive academic and technical material that forms the spine of my investigation. However, much -if not all- of my studies would have been severely hampered without an economic base to start from. I'm deeply grateful to Dean John de Monchaux, head of the School of Architecture and Planning at the Massashusetts Institute of Technology, for granting me money from the Cabot Fund, which enabled me to carry on my quest for knowledge beyond the usual limits in exceedingly strainful economic conditions. Also, scholarships granted by the Fulbright Commission and the Swedish-American Foundation, though not directly linked to this thesis, have formed a substantial financial and emotional core of my studies at the Massashusetts Institute of Technology and I'm forever thankful for their support. The elaborate study of plant response to the impact of light transmitted through various glass types would not have been possible without all the glass samples kindly offered by Guardian Industries Corporation, and I especially thank Product Development Engineer Jason Theios for turning the administrative wheel and supplying me with needed data.

Among the different responses to my interrogative questions there are some that crystilized and stood out a little further, though I've highly appreciated them all. However, comments and suggestions by Photobiologist Christos Mpelkas, Manager-Photobiological Applications at GTE Products Corporation, Sylvania, have been extremely valuable for a more thorough understanding of plant responses to different environmental conditions. Mr. George Clark, former President of the Illuminating Engineering Society, has helped me to set up contacts within his field. Associate professor Harvey Brian at the Massashusetts Institute of Technology has given me significant academic support as well as suggestions regarding daylight research methods. Mr. Charlie Tilfor at Southwall Technologies Inc. has supplied me with new research results on plant response to heat absorbing glass. I dearly appreciated the time and effort spent by Dr. Richard Wurtman and Dr. Harry Lynch at the Massashusetts Institute of Technology for explaining the intricate effects of light on the human body. There are also colleagues and friends across the Atlantic who have offered me useful comments on the content of my thesis. Professor Anders Liljefors at the Royal Institute of Technology in Stockholm, Sweden, has supplied me with insights regarding the important influence of psychological factors on the human interpretation of light quality. Landscape architect Jan Strömdahl, gave me the first lessons in plant response to light and the importance of balancing all influencing climatic factors for a healthy plant growth. I also want to extend my gratitude to my collegue and friend, Architect Håkan Björk, for accompanying me on a sometimes stressful but tremendously interesting atrium tour thoughout northern America during the summer of 1985.

Of course, my deepest appreciation is reserved for my advisor Timothy Johnson, Principal Research Associate at the Massashusetts Institute of Technology. His sturdy knowledge of general research methods and technical issues has guided me past many possible pitfalls, but I'm also grateful for his personal belief in the importance of the topic and his encouragement at critical moments.

It is common, and this thesis is certainly no exception, to designate the last part of the acknowledgement to your deerest. So, it is with delightful joy I take this opportunity to express my sincere respect and love for my wife and thank her for supporting me whole-heartedly throughout this hectic period despite a sometimes neglected family life.

INTRODUCTION

During the last half decade there has been a revival throughout the western world of large glazed enclosures often referred to as atriums. The traditional use of central top-lit cores for bringing daylight deep into the stucture has, in the wake of new technology, been expanded to meet modern demands for multi functional open spaces serving technical and human needs. It could be argued that this concentration of amenities and circulation paths to a glazed court is an architectural whim with modern technology and trends trespassing hand in hand over adventurous land to meet business demand for rentable commercial spaces. Large office blocks with interconnecting glazed atriums have thus been popping up like mushrooms in, a flourishing but economically hardening market. The growth has been fast, usually combined with either a shrewd unwillingness or a lack of professional knowledge to foresee eventual drawbacks and interrelated problems. The use, or misuse, of the word "atrium" has kicked off expectations of profitable and functional common spaces trigged by the extra amenity of a multifarious large room. The response to the historically reborn interest in glazed rooms has been immediate and many times superficial, without the necessary understanding of the underlaying complexity of the matters, creating architectural spaces with severe problems not coping with the intricate balance between aesthetics, comfort and economy. Regardless of technical flaws there is strong support for the notion that the concept will be in tune with commercial and public requirements for a functional environment and presumably will survive in a competitive market. However, the continuing demand for atriums is largely dependant on successful design solutions portraying high technical performance, relevant costs, human comfort and convenience-all integrated to create a positive total experience.

Modern technology has made it ecomically feasible to span large glass-enclosed structures which are socially sufficient and convenient for less mobile groups of the society like handicapped, elders and children to virtually spend days, weeks or even months in a comfortable indoor climate. However, it is plausible that any positive effects of a manipulated environment can turn sour if the created climate is not closely simulating natural conditions. There is a danger of building in faulty and shortsighted presumptions neglecting the close relationship that exist between social, biological,medical, technical and aesthetical needs.

For instance the abundant architectural use of exterior tinted and reflecting glass for new and old construction does not only have an obvious visual impact on the urban environment but might also have subtle psychological, medical and biological effects on man and plants as transmitted light has varied spectral qualities depending on glass type.

This raises concern as there are escalating indications that human medical and biological responses to solar radiation, including wavelengths within the visual spectrum, are more diverse than visioned only a decade ago. Spectral quality and intensity might be related to seasonal affective disorder, melatonin secretion affecting sexual growth, sleepiness, the biological clock, and possibly ovulation.Infant jaundice, psoriasis, calcium metabolism, muscle strength and even cancer are other biological effects purportedly linked to electromagnetic radiation. The science of photobiology is still quite young and the gathered data is not yet conclusive, but the indications are calling for attention and are strong enough to "support the view that the design of light environment should incorporate considerations of human health as well as visual and aesthetic concerns" (Dr Wurtman, The Effects of Light on the Human Body, p.77)

There is also reason to believe that the spectral composition of transmitted light is essential for a healthy plant growth. Even though there is a massive experience regarding plant growth both from research and simple observations, there are still many phenomena not completely explained. The use of modern glazing materials has created conditions which find no actual comparisons with traditional techniques. Aesthetical and technical reasons have tempted designers to use tinted or reflective glass to minimize heat gain without investigating eventual side effects on plants. Hypothetically it is logical to assume that the proportions of active wavelengths penetrating the transmitting media is affecting plant response in a similar manner as direct radiation from a light source, but so far there is no compounded research to prove it.

With the expected increasing numbers of atriums -both for public and commercial use- it seems necessary to scrutinize pertinent architectural issues related to atriums which have not been properly addressed in order to fully understand the potential impact of possible design solutions. Recent projects show for the most part that the interest for atriums is revolving around their spatial and sometimes majestic expressions, often neglecting sensual qualities and requirements supporting the important interrelation between people and plants. Specifically there is a lack of awareness of the climatic prerequisites that exist for plants to grow, and grow well, within a man-made environment. Plants often serve as movable afterthoughts, placed in nonusable spaces with inadequate daylight. Architectural voids under staircases are used as flower pots, at best lit by restrained artificial light. Usually there is no correlation between plant species and offered climatic areas. Structures are unintentionally polluted by late decisions to increase illumination levels with grow-lamps instead of being designed at an early stage for adequate natural daylighting and if necessary supplementary artificial lighting. The conditions for the cohabitation of plants and people are also insufficiently addressed and there is definitely a great danger that many atriums, with the intent to be a functional transition zone between the inside and the outside, will not live up to envissaged long term expectations. There is a need for a different approach, regarding climatical functional atriums, coupled with new design tools and pioneering techniques readily accessible, understandable, and usable in order to push for a change towards better solutions.

Within the realm of these notions there are specific issues, hitherto insufficiently investigated, which need to be further discussed in order to establish criteria and design methods for a good atrium design.

This thesis, divided in two parts, has the broad aim to strengthen the architectural and technical foundation for a good atrium design in order to provide a suitable environment for the coexistence of people and plants in relation to comfort, health, climate, technique, aesthetics, and energy consumption. The scientific purpose is to establish new design criteria and methods in order to create a useful base for intelligent decisions in fulfilling the ultimate vision of a living atrium. The study will specifically focus on design guidelines with respect to climatic conditions affecting plant growth and human health and comfort within atriums.

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It has to be pointed out that as well as it is necessary to describe the goal of this thesis it is equally important to set the limits in order to prevent any misunderstanding of presented material as there are an abundance of different parameters affecting a successful atrium design. Many of these variables are possible to track and define and this thesis deals with some of them. Without any doubt the scrutinizing and interpretation of "all" influencing factors lie in the hands of a responsible design team. The members professional skill and artistic intuition as well as their knowledge of the individual components will ultimately affect the quality of the final design and possibly show the way to a living atrium.

At last it should be mentioned that it is not within the scope of this thesis to list historically significant atriums as such information easily can be obtained in the litterature.
However, it is relevant for the understanding of this study to recognize the differences between the traditional Roman atrium defined as an enclosed courtyard open to the sky and compare it to the transformed modern use of the concept where almost any glass-covered structure is considered an atrium. Two important relatively recent atriums claimed to have been influencing later development can serve as examples for the two directions. John Portman's Hyatt Regency Hotel in Atlanta Ga, erected in 1967, is an extension of the original concept. It is a tall construction with top-lighting and an interior courtyard enclosed on all sides with opaque walls.Roch's and Dinkeloo's Ford Foundation Headquarters in New York City, built in 1968, is close to a built in conservatorium where the outside and the inside only are separated with a thin climatically shielding glass wall.This thesis will make no destinction between these definitions but adopt the broader use of the word without disregarding the philosophical, historical and emperical differences between the concepts.

It is interesting to note that research is going on world wide in order to find some answers to plant response in atriums with fluctuating temperatures. It is raising interest especially in countries with temperate climate where it is beneficial to extend the mild season without high costs for climate control. The Swedish Institute for Building Research will deliver a paper on the subject in the fall of 1986.

To put this thesis in perspective it is necessary to mention a few but certainly important and for the context pertinant steps in the history of mankind. The earth, as is generally understood, has existed for millions of years. The evolution from micro organism to plants and animal life has been a slow process leading to the adjusted metabolism and adapted behavior that is seen today. The struggle for survival and enhanced living conditions has governed human exploration of the unknown. Technological border lines have limited the architectural expression. From living in the open to caves to contemporary constructions of modern life. The small openings penetrating the walls of antique and medevial dwellings were just large enuogh to maintain a relatively decent energy balance.The inventors of the hanging gardens of the Roman empire used vegetation and water to modify a harsh climate. New building techniques of the gothic and islamic cultures opened the wall and exposed the structure with the introduction of glass as a building material. Large glass windows brought mysterious and life enhancing light deep into the buildings..The industrial revolution made it possible to mass produce cheap building material accomodating the labor force in poorly lit and hastily built stacked houses while kings and despots surrounded themselves with highly articulated gardens and manipulated wild landscapes. The 19th century development of glass and iron manufacturing made it possible to span transparent skins over vast greenhouses and exebition areas. In the wake of medical insights during this enlighted century was the introduction of beneficial light in hospitals as a valuable control-factor of diseas. Dense urban housing developments in smog polluted cities were seriously questioned at the turn of last century as a human environment and city blocks were torn down to give room for light and air. The garden city with smaller individual houses was presented as an alternative. The functionalistic era furthered the concept and placed large appartment agglomerates in the landscape. Here in the present we have atriums as a climatic buffer creating resemblances and indications of life outdoors. Future development might lead to cities completely covered with a transparent skin as visioned by the late Buckminster Fuller. The living atrium is not only a glass covered enclosed private courtyard. It is also the evolution of mankind's striving for a better life. However, without an understanding of the different environmental factors that are prerequisites for a comfortable and healthy life, it will not be possible to get there.

PART 1: MAJOR VARIABLES AFFECTING PLANT GROWTH AND HUMAN HEALTH AND COMFORT

- A CALENDER OF CURRENT KNOWLEDGE REGARDING INFLUENCING PROPERTIES AND THEIR RELATED RESPONSES

CHAPTER 1: PROPERTIES

DISCUSSION

Through time and evolution man and plant have adjusted to the specific environment immediately surrounding them. Climatic conditions like temperature, relative humidity, solar radiation, light, soil quality, access to water, and air to breath have all had a profund impact on their development. Time has made it possible for man to migrate to climatically more favourable locations attuned to his needs in order to avoid exessive climatic stess and million years of evolution has changed the human physiology to correspond to life-sustaining requirements. Early plants found their appropriate environment by following a stream of water or a whisk of the wind. Evolution introduced more intricate means of survival and reproduction. Animals inadvertilly transported seeds to new domains with sometimes different prerequisites starting a new process of adjustment. Man and plants still continue this quest for an environment in equilibrium with their requirements. It is not possible in this study to linger over these thoughts except for shortly stating that man and plants today live under similar conditions that existed millions of years ago. The sky, the clouds, the sun, the soil, the oxygen, the carbon dioxide, and the water are still prerequisites for life. This chapter will touch on a range of major properties that affect conditions in atriums.

A: ATMOSPHERIC PROPERTIES

GASES

The earth is surrounded by an approximately 20 miles thick layer of atmospheric gases. Permanent gases like oxygen (20.95%) and nitrogen (78.08%) appear in almost the same proportions anywhere around the world. The remaining share is split between argon (0.9%), small portions of krypton, neon and xenon and a fluctuating amount of carbon dioxide, which is usually around 0.03%. This small portion of CO_2 is tremendously important for plant growth. There are also traces of ozon and water vapor (0.4%) which affect life on earth indirectly through their filtering and reflecting properties.

The proportions of oxygen and carbon dioxide in the air are decisive factors influencing plant respons. Surprisingly, it is evident that too much oxygen has negative effects and even the normal 21% is inhibiting photosynthesis. On the other hand, low carbon dioxide content has limiting effects on the photosynthetical process, which actually would be speeded up proportionally if the carbon dioxide were higher than the normal ambient concentration.[4]

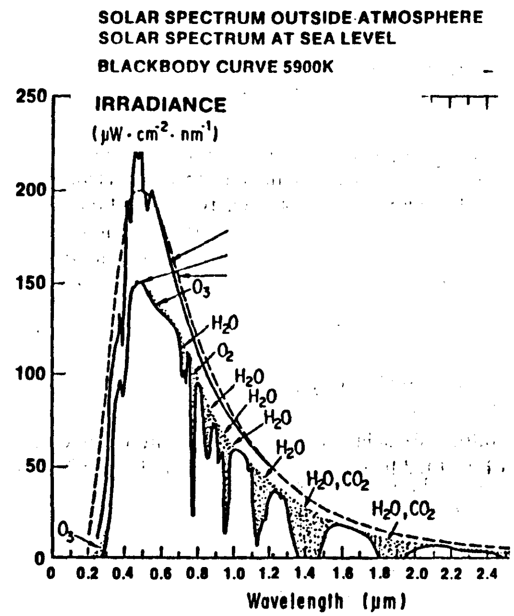
SOLAR RADIATION

The sun is constantly emitting energy in the form of electromagnetic radiation usually measured in quantas or photons expressed as a factor of frequency times Planck's constant(h). The frequency(f) does not change when radiation is transmitted through or in reflected by a specific medium it only decreases or increases when it is absorbed. Wavelengths(1) and velocity(c) change proportionally as they are reciprocals in a simple equation hf=c/1. Hence the energy content in a photon increases with shorter wavelengths which means that ultraviolet radiation contains more energy than infrared radiation.

The electromagnetic spectrum spans the range between shortwave cosmic rays and longwave radio waves. The wavelengths pertinant for atrium design form narrow band ranging from ultraviolet radiation(UV) over visible radiation(VR) to infrared radiation(IR). Their respective internal proportions being around 7%, 52% and 41%. (See fig.)

There are several conventional ways of expressing the unit for wavelengths. For this study namometers (1nm=10-9 meters) are choosen.

The amount of solar radiation hitting the atmospheree is approximately 430BTU/ft2hr or 1367 W/m2. This figure, known as the solar constant, is decreased to around 295 BTU/ft2hr or 938W/m2 at sea level as the incoming radiation is attenuated by the earth's atmosphere. It is partly absorbed and scattered depending on wavelength by oxygen, carbon dioxide, water vapor and the thin layer of ozone, or reflected back to outer space by water liquid content in the cloud cover. (See fig 2, The Medical and Biological Effects of Light, L. Thorington, p.30)



There is a controversy over the proper way of expressing illumination levels pertinent for plant growth and seeing. Commonly, footcandles or the SI equivalance lumens/m2=lux is used. (1fc=10.76lux.) However, some argue that irradiance expressed as W/m2 is the correct radiometric term for light intensity.[5] Others contend that W/m2 / nm is the adequate approach for plants, as they do not respond to light quantity per se but to the energy content in each band of the spectrum. There is a convincing tone in the remark that "it is reasonable to expect equal numbers of absorbed photons of different wavelengths to be equally effective , not equal quantities of energy." (Physiolgical Plant Ecology I, p.43) However, at this stage I am ready to question the more elaborate definition, even though I am prepared to accept its impact on photosynthesis.This is due to the fact that plants seem to be responding to the proportions of active wavelengths, hence not the accumilated effect of energy, nor photons, but rather to the interacting stimulation of different frequencies. The introduction of the unit "photon" portraying a function of frequency and Planck's constant is maybe one way of closing in on a relevant expression, but for now footcandles(fc) will be used accompanied with a description of spectral quality. It is also possible to describe the efficiency of light for various wavelengths by an "action spectrum", where energy is expressed as an inversely propo tional function of quantas and wavelengths.

Energy=Quanta/wavelength

This approach is said to be the most accurate as it describes the potential effect of different wavelengths on photosynthesis. From the formula it can be extracted that red wavelengths contain more quanta than blue wavelengths for a given amount of energy.[101] The same source advises that for practical purposesit is adequate to convert quantas to joules, or use the old standard of lux or footcandles, as it is easier to interprete the values.

ULTRAVIOLET RADIATION

Most ultraviolet radiation is absorbed by the ozone in the atmosphere. Only wavelengths longer than approximately 290 nm strikes the earth. Garrison et al has measured wavelengths down to 289nm, but ultraviolet radiation is usually effectively absorbed below 295nm. [7,102] The intensity varies depending on the oblique angle at which the sun's rays have to penetrate the ozone layer and the layers thickness. This is most vividly encountered when the sun's altitude is low as in the winter or at dusk and dawn. There might be seasonal differences of up to fifteen times more radiation in the summer than in the winter.[8] 8Others claim this difference to be about sevenfold.[9] However, there seem to be only relatively small spectral differences in the distribution of global irradiance reaching the earth's surface independent of season, time of day, sun angle, cloud cover and turbidity.[10] It is however important to note that scattered sky radiation has proportionally higher content of UV-B than direct sunlight.[11] and that heavy cloud cover can produce as high UV-B radiation as clear days. According to new studies it could be expected that between 40 % to 75 % of the total ultraviolet radiation, especially UV-B, reaches the earth through diffused skylight.[103]

There are three different UV-bands:

UV-A 315-400 nm
UV-B 280-315 nm
UV-C 100-280 nm

For this study mostly UV-A and UV-B will be considered except for the remark that UV-C has a strong germicidial effect and energy radiated at 253.7nm is more than 90% effective. It might also cause materials to spelling. High energy wavelengths less than 200nm can change oxygen in the air to ozone.
UV radiation has low tissue penetrating properties and UV-A is less effective than UV-B.[12,13]

VISIBLE RADIATION

Visible radiation spans a range between approximately 380-780nm. It is possible for the human eye to perceive radiated energy as light and colors within that wavelength range depending on intensity.

The visible spectrum is made up of narrow bands of wavelengths interpreted as colors by the human eye.

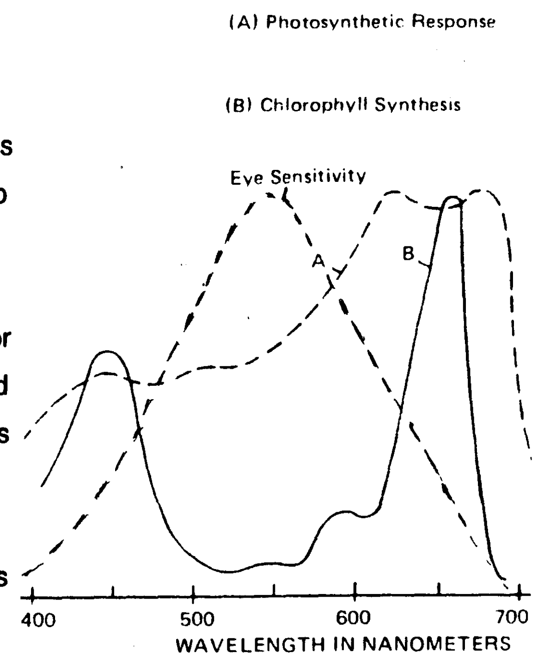
380-436nm violet
436-495nm blue
495-566nm green
566-589nm yellow

589-627nm orange
627-780nm red

Though not the most evident property of visible radiation it has been shown that "visible light is apparently able to penetrate mammalian tissues to considerable depth"[14] and that can lead to a wider interpretation of "visible radiation" in the future.

It has been long known that wavelengths within the visible spectrum is eminently important for plant survival. Both intensity and spectral quality as well as duration of radiation have profound impact on plant response. (See fig. demonstrating sensitivity of the eye contra photosynthesis and clorophyll synthesis. Sylvania Bulletine 0-352, p.2)

For a more detailed discussion regarding biological phenomena see subheading B in this chapter and chapter 2: Biological Responses.



INFRARED RADIATION

Long wave global radiation with internally different properties usually referred to as near and far infrared radiaton.

Near IR 780nm to 3200nm
Far IR 3200nm to 10^6nm

Near Infrared radiation.

Near infrared radiation is energy directly emitted by extremely hot objects like the sun or reflected by a radiated surface and has the strongest heating effect of all types of radiation. It penetrates tissues easily and raises the temperature of absorbing tissues due to direct impact.

Oxygen, water vapor and carbon dioxide in the atmosphere strongly absorb much of the short wave infrared radiation emitted by the sun. The infrared radiation reaching the globe has a range between approximately 780-3200nm.

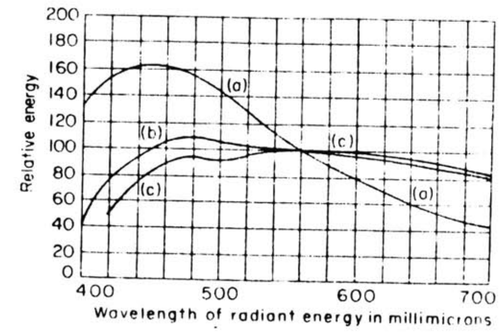
Far infrared radiation

There is a significant difference between near infrared radiation and far infrared radiation. Far infrared, sometimes referred to as thermal radiation, is energy radiating from all warm surfaces like furnaces, radiators, people, plants, animals, and artificial light fixtures. Object which have absorbed near IR reradiates the energy as far IR. Far IR indirectly raises the ambient air temperature by heating surfaces which conduct and convect the absorbed energy to the air. The wavelengths vary between 3200nm to 10^6nm.

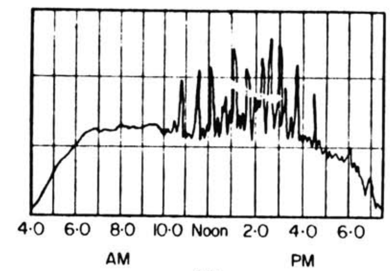
Daylight

The psychological perception of intensity level and color temperature of daylight is seemingly inert to quite big changes, unless there is an abrupt braeak in the regular pattern, like the sun suddenly peeking through a hole in the cloud cover or swiftly disappearing behind a passing cloud. However, the intensity varies constantly, but the eye is raesonably able to adapt to oscillating levels and alleviate some of the differences. It has been claimed that daylight, made up of direct sunlight and diffuse skylight, has a characteristically uniform spectrum.[16] That seems to be only partially true. The fact is that pure solar radiation, excluding the sky component, incident on a horizontal surface above the atmosphere follows a smooth curve,

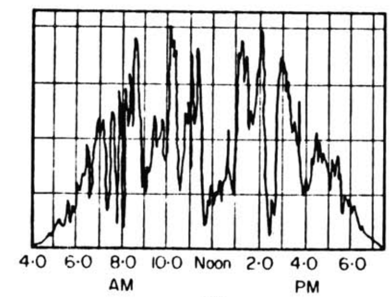
but it is also evident that atmospheric conditions change the intensity as well as the color temperature of transmitted radiation quite dramatically within only small time intervals. (See fig 11, 12, 13, The Medical and Biological Effects of Light, L. Thorington, p.40-41) (Phillips, Lighting in Architectural Design, p.71 and figs 7.3and 7.4). The thickness of the cloud cover, moisture in the air, and pollution have different impact on the spectral distribution. Cloudy days show an increased proportion of blue wavelengths with only partial discrepancies in the red spectrum compared to daylight with clear skies. Overcast conditions with haze and dust, on the other hand, result in a proportional reduction of blue wavelengths and an increase in red wavelengths. It is not surprising that the altitude of the sun also affects the spectral distribution. Actually, solar altitudes below 10° change the spectrum radically. This mode of daylight, referred to as twilight, has a striking emphasis on blue wavelengths, due to scattered skylight, and far red wavelengths, due to refracted sunlight.
(Physiological Plant Ecology I, D.C.Morgan and H.Smith, p.111) (See fig 4.1 p.111)
(See fig 16, The Medical and Biological Effects of Light, L. Thorington, p.14) Other studies indicate varying energy levels for blue and red wavelengths at twilight with a shift towards the red spectrum. (Physiological Plant Ecology I, F.B.Salisbury, p.152) (See fig 5.3 p.152)



Exterior illumination levels taken in Great Britain on two days in the same month. (A) Cloudless sky until 10 A.M., then solitary white clouds at about half-hour intervals. (*From Parry Moon, Lighting Design.*) (B) Overcast day with squalls and showers: rapid fluctuations due to heavy rain clouds. (*From W. H. Stevens, Principles of Lighting.*)



(A)



(B)

B:ENVIRONMENTAL PROPERTIES

Environmental discussion

Man has adjusted culture and physiology depending on climate. Differences in skin color, clothing and building technology have gradually progressed to give maximum protection and benefits from the impact of climatic forces. Religions and philosophies have been marked by the wonders of the world and miracles of the sky. The sun has been worshiped for its lifegiving light and heat, the moon for its subtle light, the stars for their guidence, the clouds for their rain, the tree for its shade and the earth for its food. Cultural, social and individual needs have risen out of these natural phenomena depending on access. Cultures, with an abundance of solar radiation,have naturally not been as prune to regard direct sunshine as equally favorabe as those which more evidently depend on the sun for survival. That is to say that the present intensity, duration and quality of light as well as shade, temperature, and humidity is regarded differently depending on cultural, social and genetic background.

Climatical properties

Sunlight impact depends on the position of the sun in the sky, (its seasonal average altitude above the horizon which affects the duration, intensity and spectral quality of daylight.) Several other factors, such as the thickness of the cloud cover, air pollution, and other atmospheric properties not mentioned above, have together with the orientation of the radiated object as well as the quality and quantity of shading obstacles modifying effects on the climatic environment. Nocturnal radiation, elevation above the sea level, and distance from influencing sea currents also moderate or accentuate the ambient air temperature. Wind direction and velocity, access to open water,and vegetation have impact on relative humidity and ambient air temperature. Topography,soil quality heat storage capacity in surrounding material and masses whether soil, rock or water are all basic ingredients in a development of regional climatic zones. Innumerable variations and proportional changes of individual components have created a range of different climatic conditions for plant growth, animal life and subsequently human settlement. The climatic zones, as they are evident today, have not been stable but part of a slow and oscillating process creating changing but rather narrow prerequisites for life and survival.

Geographical zones.

There are several theories regarding the nomenclature and classification of various geographical zones. However, according to W. Koppen there are five defined climate zones ranging depending on vegetation, latitude and altitude from tropical-rainy, dry, warm-temperate, cool-snow-forest and polar.[17] Others refer to tropical as hot-humid, sub-tropical as hot-arid or warm-humid, temperate as moderate-cool and arctic as cold.[18] The intent is not to ponder about different vegetational geographical areas but to point to the fact that macro-climatic variations have been the fundamental cause for the development of the fauna as it is seen today.

Comfort zones

It is interesting to note how the definition of comfort zones changes around the world. British Drs. H.M. Vernon and T. Bedford state the ideal temperature in the summer to be 66.1°F but differ in their opinion on how high a pleasant indoor temperature should be in the winter. Bedford suggests 64.7°F while Vernon is content with 62.1°F. Other sources give data for comfort zones in Britain to range between 58-70°F while it increases in the United States to 69-80°F and in the tropics to 74-85°F.[19] It is clear from Victor Olgyay's data that prefered temperatures and relative humidity is highly dependant on geographical location, sex, age, individual acceptance, type of activity and clothing. Research conducted in Denmark by Fanger, adopted by A.S.S.A.E., indicates a more favorable reaction to faster air movement, as a counteracting factor to high relative humidity, than what is advised in Victor Olgya's bioclimatic chart. All this goes to say that is is necessary to look at regional preferences in order to assess any value to given climatic zones.

Atrium design related to climatic properties

There are several climatic properties which have to be considered in atrium design, if the goal is to errect a building which is energy efficient, comfortable, economical, regional, and sensitive to human needs. The understanding of these conditions will create an architecture which is unifying technology, economy, ecology, biology, psychology, and even medical considerations in an aesthetic experience. It is obvious that descibed macro-climatical conditions creates a first base from where it is possible to make judgements towards an adapted design. At the local site it is necessary to know the detailed conditions.

Location

The possible impact and affect of solar radiation on any surface depends on the incident angle and the intensity of the radiating rays as well as the insulating, absorbing, transmitting, and reflecting properties of the material. Any shading external components like protruding constructions, vegetation, neighboring buildings and site topography also affect the outcome as well as reflections from surrounding surfaces. In this chapter only the intensity of the sun at different locations will be considered.[105]

Orientation

The orientation and tilt of radiated surfaces affect the efficiency of the solar radiation penetrating the atmosphere. Accordingly, the total amount of possible radiation striking a surface is a compounded factor of atmospheric conditions, season, time of day, location, orientation and tilt of surface. Architectural features can only, but powerfully, modify these terrestial conditions.

Climatic data

The table below does not pretend to give any complete climatic data but merely points at general differences in our natural environment.

Origin	Temperature	Humidity	Daylength
Tropics	Steady 75-95°F Mean 81°F Fluctuating at higher altitudes	High 80%	Even 12-14 hours year round
Subtropics	Moderate seasonal differences Desert arid areas have wide daily temperature spans	Dry summers Wet winters	Moderate seasonal differences
Temperature	Wide fluctuations Warm to mild	Moderate 60-80%	Wide fluctuations 16-20 hours

	summers		
	Cold winters	30-40%	6-10 hours
Arctic	Mild summers Cold winters	Regular precipitation	Wide fluctuations Summer 18-24 h Winter 6-0 h

C:BIOLOGICAL PROPERTIES

Biological properties related to man and his need for solar radiation.

Discussion

It is obvious that our eyes are vitally important for our performance whether it is for executing a task or viewing an object. However, along with the retinas role as a photoreceptor, there are new discoveries indicating that our eyes not only have the capacity of transmitting visual information to the brain but also act as intermediate links to the pineal gland, the adrenal medulla and the pituitary gland affecting the production of melatonin, adrenaline and tropic hormones. (R.Wurtman, The Pineal, p.9) As a curiosa it is interesting to note that even though these findings have surfaced during the last years there has been an ancient mystique surrounding their bodily functions. The pineal gland was early considered by Descartes as the center of the soul. (Webster's Encyclopedia) Today these "neuroendocrine transducers" are, in the light of modern science, claimed to be controlled by nervous signals generated by environmental lighting. (R.Wurtman, The Pineal, p.9) Other biological functions mainly affected by ultraviolet radiation are synthesis of vitamin D_3, erythema or reddening of the skin, melanin synthesis or darkening of the skin caused by pigmental changes, thickening of the epidermis of skin exposed to sunlight, photosensitization affecting rashes on the skin, and control of psoriasis and herpes virus. Blood producing organs as well as the ovaries and the liver are also affected. (The Effects of Light on the Human Body, R.Wurtman, p.68) Jaundice in newborn infants has been succesfully proven to be affected by light until the liver is capable to metabolize bilirubin. What part of the spectrum that is most efficient is under investigation. Blue light is most effective in decomposing bilirubin but full-spectrum white light is, regardless of reasonable spectral distrubution of blue wavelengths, capable of lowering plasma-bilirubin levels. (The Effects of Light on the Human Body, R.Wurtman, p.74) Recently it has been documented that natural or artificial sunlight incuding, ultraviolet radiation, has a positive effect on working capacity, physical fitness and muscular strength. (An Examination of the Beneficial Action of Natural Light on the Psychobiological System of Man, Ph.C.Hughes, p.D603/3).

The eye.

Structure

The structure of the eye is briefly made up of the cornea, the iris, the lens, the ciliary body, the vitreous humor, the retina, the fovea, the macula, and the optic nerve connected to the eye at the blind spot.

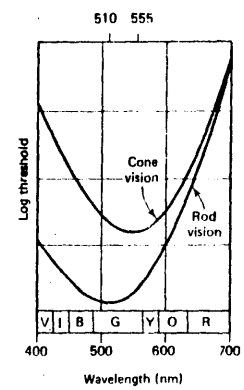
Optics

The lens and the iris are the the major optical components of the eye. Muscles in the ciliary body cause the lens to accommodate in order to bring an object into focus.

Light-sensation

The retina is the receiving light-sensitive component of the eye. It consists of two different kinds of light-sensitive nerv endings, cones and rods, which are activated depending on the light intensity.

The cones are concentrated to the fovea and are efficient for daylight vision only. They are reacting to intensities above a luminance level of 3cd/m^2 (Lighting Manual, PHILIPS, p.19.2.1) or 0.01fL (Illuminating Engineering for Energy Efficient Environments p.7) The property of the eye to respond to luminance above 1fL is called "photopic vision" and is most sensitive to wavelengths around 555nm and capable of distinguishing colors and producing sharp images.



The rods are increasing in numbers from the fovea and are sensitive to low luminance levels roughly between 10^{-6}fL to ~ 1fL. This property of the eye to see in the dark, especially with increased peripheral vision, is called "scotopic vision" and is dominantly reacting to movement and flicker. It peaks at 510nm with the eye adapted to 0.05cd/m^2, which is about the upper limit of moonlight illumination. (Lighting Manual, PHILIPS, p.19.2.1) (See fig 1-10, 1-11, Illuminating Engineering for Energy Efficient Environments p.12-14) (See fig 1.4 and The Ergonomics of Lighting, R.G.Hopkinson, p.23.)

There is an intermediate luminance zone at twilight where neither the cones nor the rods are fully efficient. This property is called "mesopic vision.

Adaptation

Adaptation to light or dark conditions does not happen instantaneously, but varies for different light levels. Generally it takes only seconds to adapt to brighter light levels while it is a matter of minutes and maybe up to 1 hour to completely adjust to low light levels. (The Ergonomics of Lighting p.20+ fig1.3) (fig1.4 p.21)

Interpretation

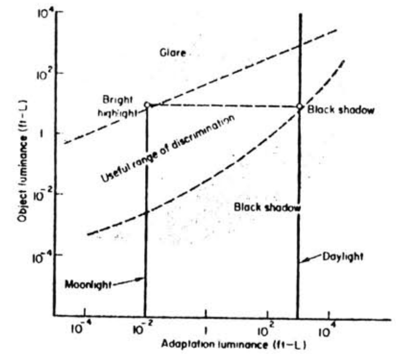
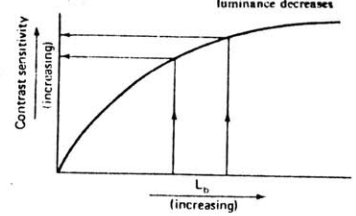


Fig. 1.4 *Schematic diagram showing the range of discriminable luminance at any given level of adaptation*

The limit lines shown are in no sense sharp boundaries—glare and loss of highlight detail gradually increase as luminance increases; loss of shadow detail gradually merges into subjective black as luminance decreases

Interpretations of these values indicate that the human eye is shifting its sensitivity from the green-yellow part of the spectrum towards the blue-green with diminishing light intensities and that the rods and cones are nearly equally sensitive to red wavelengths. It can also be questioned whether other visual properties than those related to photopic vision have any impact on atrium design.

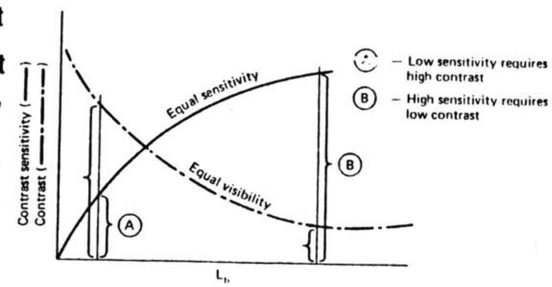
Human visibility



Contrast Sensitivity versus L_b *over Normal Indoor Ranges*

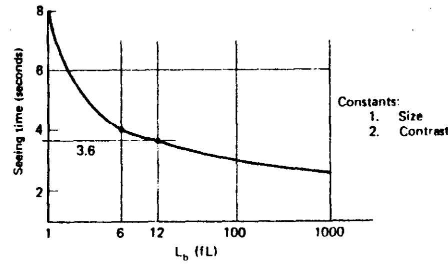
The possibility for the human eye to detect information is affected by visual acuity which is depending on mainly four variables: Size, luminance, contrast and time. Some data interesting for atrium design is that the maximum visual efficiency occurs when the surrounding luminance is between 1 to 0.1 times the luminance of the displayed object and that an object brighter than the background presents the highest visibility.

There is, however, a drop off in visual efficiency if the light level increases above a certain limit as the eye is not infinitly and evenly sensitive to contrast differences. "As the level of contrast sensitivity increases, the visual system needs less contrast for a certain level of visibility." (Illuminating Engineering for Energy Efficient Environments p.23) (See fig 1.19 and 1.21) It is also interesting to note that the time factor affecting visibility evens out at a luminance levels of approximately 12 fL. Some caution regarding the interpretation of this infomation is needed as the data available does not indicate size of the viewed object, which most definitely has to



Contrast Sensitivity versus Contrast

affect the critical time required. (Illuminating Engineering for Energy Efficient Environments p.25) (See fig 1.23)



Time versus L_b

Other Biological properties related to man

Biological properties like sex, age, color of skin are generally known to profoundly affect individual needs at the same time as it might lead to faulty conclusions to generalize differences. Each individual has his or hers preferences generated from cultural, social and genetic roots and it is complicated to measure these values. One rather easily obtained source of information, not based on subjective value judgement, is data describing the impact of UV-B radiation on human skin. As might have beenn expected black skin needs a larger dose of radiation to produce vitamin D3. Up to six times as much as caucasian skin according to a study related by Mickael F. Holick. (B.M.E. of Light, p.9). The same study states that wavelengths between 295-300nm are most effective in converting energy to vitamin D3 and that natural selection had favored the evolution of black skin in people living near the equator and light skin in those living in areas distant therefrom. "(p.5).

Affects of aging on the eye

The eye's possibility to act as photoreceptors is affected by aging. "The older one gets, the more light is required to perform the same task." (Derek Phillips, Lighting, p.29.) Young children have the best vision while acuity, range of adaptation, accomodation and distance resolution is diminishing with growing age. Presbyopia or the diminishing ability to focus clearly on close objects, due to weakening lens muscles, is the most evident difference. (Lighting, D.C.Pritchard, p.8) Others claim that blurred near vision beginning at the age of about 40 is "due to a hardening of the lens substance". (Illuminating Engineering for Energy Efficient

Environments p.5) Changes also take place in the retina requiring more stimulating radiation to see well. Cataract is a serious problem for elderly persons as the optic media in the eye, due to clouding over of the lens, is scattering more light causing sensations of glare and impaired vision. (Lighting, D.C.Pritchard, p.8) The yellowing of the lens and central portions of the retina is decreasing the old eye's sensitivity to blue wavelengths. However, it is also argued that these old-age syndroms are counteracted by an increased experience of details and inteligent intepretations of the surrounding environment. (The Ergonomics of Lighting, R.G.Hopkinson, p.23.) These findings have governed regulations for illumination levels throughout the world and the IES Lighting Handbook correlates for the age factor. Still, other relatively recent studies disclose that no significant discrepancies in performance due to light levels, within a span of1fc to 450fc, could be detected for different age groups. On the contrary it was concluded that "morale or sense of well-being" will "have a greater effect on performance than simple illumination levels." (The Effects of Light on Health, P.M. Coxe, P.B.Reiser, W.M.Lam, p.27) Reduced glare, increased contrast and better physical organization were also regarded as superior solutions to safety problems.(The Effects of Light on Health, P.M. Coxe, P.B.Reiser, W.M.Lam, p.22)

PROPERTIES RELATED TO PLANTS

Similar theories can be adopted to plants. Adjustment to prevailing conditions by selection has probably caused the development of different genera and species according to their varying needs of climatic stimuli. However, these needs might vary depending on time of day and season. Most plants regularily used indoors have originated from the tropics and the subtropics with relatively favorable stable climate. Tropical plants accustomed to steady temperatue, humidity and similar light conditions throughout the year are more sensitive to changes than plants used to seasonal and diurnal fluctuations. The latter adjusting more easily to the restrained conditions inside. *(Exotic Plant Manual, p.6). It has to b pointed out that most common indoor plants come from higher altitudes in the tropics where temperature fluctuations are relatively wide and temperatures generally dropping at night. *(EPM, p.27). Research is going on right now in order to investigate plant respons to extreme fluctuations. *(SBFR Sweden)

Even though plants do best in their natural or similar environment, they can adjust their biological properties to fit less favorable conditions by a gradual acclimatization process. The range within which the plants can adjust is depending on genotypes and individual species in accordance with the discussion above.

PLANT PHYSIOLOGY

Basically a plant is made up of four major parts: The roots, the stem, the leaves and the flowers with growing points complementing roots and stems . They all fulfill important physiological functions in the life cycle of plants.

Aerial growing points

The main area of cell division where young tissues of leaves, stems and flowers are developed is concentrated to the aerial growing points. Major growing points also produce hormones to control rate of growth and shape of the plant. Some zones of the growing tips, together with young leaves, are active in detecting changes in day length thus controlling seasonal flowering. (S.Scrivens, Interior Planting in Large Buildings, p.15)

The stem

The function of the stem is not only to support the plant but also to act as a transporting media for nutrients, carbohydrates, and water. It is also a storage area for carbohydrates. Most stems are rigid and easily damaged by bending. Especially grasses and palmtrees
are sensitive as their conductive tissue can not be renewed. (S.Scrivens, Interior Pl5. See fig p.15.) Some photosynthetic reaction, though in lesser content than in leaves, also take place in branches and stems. (R.L.Gaines, Interior Plantscaping, p.14)

Leaf anatomy

Basic structure

The basic units of the leaves arranged from the upper surface are:
The upper cuticle, the upper epidermis, the palisade layers, spongy mesophyll, the lower epidermis,and the lower cuticle with stomatal apertures. (See fig p.14 and 16 in 15 and 16) The physical appearance of participating components are varying depending on climatic conditions. The leaves retain some carbohydrates as a reserve for functions during darkness. For an easy comparision it is logical to look at extreme leaf structures which according to their environment can be called sun leaves and shade leaves.

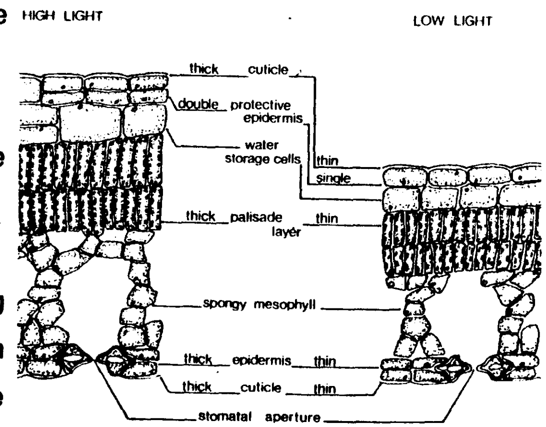
Cuticle

The upper cuticle is usually covered with a waxy film to protect from excesive solar radiation and consequently loss of water. In dry climates can systems of hairs and scales reduce this loss by creating a wind reducing layer of air as well as increase reflection. (!6 p.15)

Epidermis

The upper epidermis can have up to three protective layers reducing the impact of intense solar radiation, while it in shade laeves is reduced to one.(16, p.56)

(See R.L.Gaines, Interior Plantscaping, fig p.14 and S.Scrivens, Interior Planting in Large Buildings, p.16, fig 3.2)



3.2 Sections through leaves of Ficus benjamina *grown in high and low light conditions to indicate some of the variations in leaf morphology associated with extremes of light intensity*

Palisades

The palisade layers are made up of chloroplasts with light sensitive grana containing chlorophyll. The different components can position themselves and change form in accordance with the imposed light intensity. The chloroplasts can aligne themselves along the palisade cell, and the disks in a single granum can stack themselves on top of each other to minimize the exposed surface. Reversely, it is possible for the chloroplasts to squeeze together, and the grana to spread out like a toppled stack of coins, in order to gain maximum access to the radiated energy.(16, fig, p.57,60)

This process, however, is slow and usually takes up to four or five weeks.

Mesophyll

The spongy mesophyll contains some chlorophyll, but is less important than the palisade layer as a converter of light energy to chemical energy.

Its relatively large structural volume can be explained by the plant's need to expose a large surface for the exchange of gases and absorption of light. (R.van der Veen, Light and Plant Growth, p13)

Stomates

Stomates are small pores in the leaf to enable the plant to exchange gases -like oxygen, carbon dioxide, and water vapor- with the atmosphere. They are usually found on the underside of the leaf surrounded by two guard cells, which contain some chlorophyll. The apertures of the stomates are depending on the climatic conditions of the plants immediate environment. They are usually open during light hours and partially closed at low light levels. The dependance on balanced climatic conditions is strong and is affecting the rate of photosynthesis within the plant. Extreme conditions, like an inadeqate water supply, can limit the guard cell turgidity and make the leaves close the stomates completely. A collapsed aperture is reducing the necessary flow of carbon oxide and thus limiting photosynthesis and growth.

Pigments

Chlorophyll is a highly light-sensitive green pigment and the major stimulant in photosynthesis. There are several types of chlorophyll, usually referred to as (a) and (b), which are found in a ratio of about 3 to 1 in higher plants. Even (c) and (d) types are mentioned in the litterature, but the (a) type is the most prominent in the photosynthetical process. (R.van der Veen, Light and Plant Growth, p14.) The chemical structure of chlorophyll reveals that the nucleus is constituted of mineral elements like magnesium(Mg) and nitrogen(N) surrouned by carbon(C), oxygen(O),and hydrogen(H). Protochlorophyll, a green pigment similar to chlorophyll, is not photosynthetically active, but an important precursor for chlorophyll(a). The nucleus of the chemical structure of protochlorophyll is replaced with iron(Fe) instead of magnesium found in chlorophyll.

Chlorophyll forms only when protochlorophyll has been exposed to light.(Environment & Plant Response, M.Treshow, p.101) Other pigments such as phytochrome is essential for photoperiodism. "All organisms which are photosynthetically active contain chlorophyll". There are , however, other pigments as well, which effectively can transfer absorbed energy to the chlorophyll molecules, even though they do not directly participate in the photosynthetical process, (R.van der Veen, Light and Plant Growth, p21.) Plants that are red, yellow, brown, blue, and purple contain pigments such as carotenes (orange), anthocyanin (red), phycoerythrin, fucoxanthin, and phycocanin together with smaller amounts of chlorophyll. The action spectrum of these plants can thus be widened, though it appears that chlorophyll(a) is the only strictly essential pigment in photosynthesis. (R.van der Veen, Light and Plant Growth, p21.)

Roots

There are several components of the root system serving different functions. The main roots are responsible for the anchorage of the plant, major water and nutrient uptake, as well as food storage. The size of the root system is dependent on its environment and the activity of photosynthesis. A system in balance usually means that the top growth is approximately equal in volume to the subterranean growth. The relative proportions are often referred to as the root/shoot ratio. Function and efficiency of the root system is highly dependent on the quality and quantity of soil and water, as well as the oxygen content in the soil.

The growing points of the roots have the same rapid cell division capacities as their aerial counterparts.

The root hairs are spreading out close to the growing points. They only live for a few days until they are replaced after serving as collectors of water and mineral salts, absorbed from the soil by osmosis or diffusion.

Photosynthesis

Photosynthesis is directly and indirectly essential for the survival of any living organisms. Photosynthetically active plants and algaes convert radiant energy to chemical energy for their own growth making it possible for higher life forms to indirectly make use of produced carbohydrates and oxygen. It should be noted that the vast majority of photosynthetic activity takes place in living organisms in the oceans. Wherever there is chlorophyll there is a photosynthesis reaction to available light. This indicates that the most vital part of the plant for this process is a healthy leaf, but also that green stems are involved to some degree.

"The biochemistry of photosynthesis can be divided in two phases", as sometimes classified in the literature as "the light cycle" and "the carbon dioxide cycle". These cycles can not be performed without the presence of light energy, favorable temperatures, water, carbon dioxide, nutrients, and necessary enzymes. (R.van der Veen, Light and Plant Growth, p15.) Other more recent sources prefer to divide the process in a light and a dark reaction. (M.Treshow, Plant Response, p.103.) (S.Scrivens, Interior Planting in Large Buildings, p.17) The divisions are primarily the same, however, the following discussion will adopt the first mentioned principle to distinguish the photosynthetic reaction from photoperiod responses to "light and dark cycles".

1. The light cycle is initiated by a photochemical reaction to light energy and responsible for the production of phosphates. Only a small portion, maybe1% to 2%, of available energy is used in this process. (R.van der Veen, Light and Plant Growth, p11.) Most energy is reflected or absorbed by the leaf as heat and lost to the surrounding environment. A fraction of this absorbed energy, less than 1%, is reradiated, as chloropfyll fluoresces wave lengths in the red and far red within the leaf. The chemical conversion can briefly be explained as a reduction of H radicals and oxidization of OH radicals to free oxygen and hydrogen for the production of vitamin K.

2. The carbon dioxide cycle is the second step of photosynthesis and the actual process where carbon dioxide is absorbed to form different types of carbohydrates like glucose, and eventually cellulose, fats, and proteins. (R.van der Veen, Light and Plant Growth, p17.)

Normally about 75% of the produced carbohydrates are used for building up the plants cell walls and 15% to 20% for respiratory activities. The remaining share "serves as substrate for carbohydrate, fat and protein metabolism." (M.Treshow, Plant Response, p.103.)

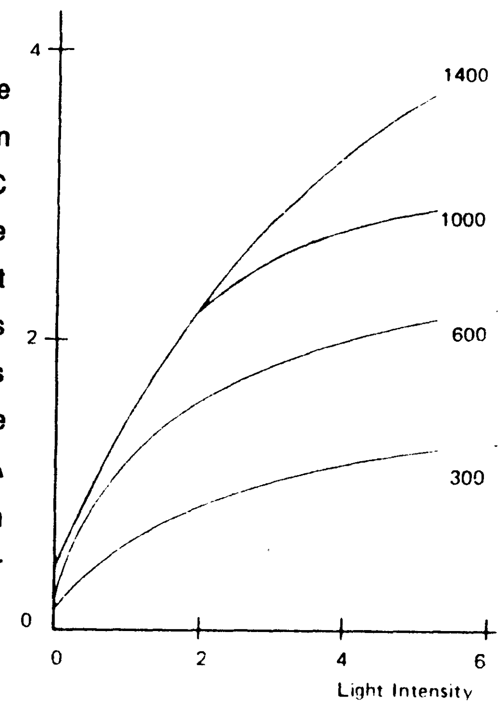
Chemical reaction

The total chemical reaction for photosynthesis can be expressed in a simplified formula:

$6CO_2 + 6H_2O +$ RADIANT ENERGY $= C_6H_{12}O_6 + 6O_2$

Photosynthetical activity

It is obvious that a limited amount of water, carbon dioxide, or radiated energy will affect the photosynthetical activity. More over, the prevailing temperature is also related to the carbon dioxide cycle, which seems to be most effective in a temperature range between 10°C to 30°C (50-85°F). (S.Scrivens, Interior Planting in Large Buildings, p.17) Other sources claim the photosynthetical temperature range to be between 4°C to 30°C. (Environment & Plant Response, M.Treshow, p29). The concentration of carbon dioxide is influenced by the access of fresh air within a closed environment. The optimal concentration of 1000ppm to 1500ppm is hard to maintain in the winter and can raise a problem especially during light hours when the plants are requiering carbon dioxide for photosynthesis. (Sylvania Bulletin 0-352, p.5, fig 5) A lower ratio than the normal 0.03% affects the photosynthetical rate and will probably slow down crop growth. On the other hand, an increased growth will presumably occur due to higher concentrations. (Sylvania Bulletin 0-352, p.4, fig 4) The intensity of radiated energy must, however, be classified as the most important factor influencing photosynthesis. It could be convenient to exclaim that the more energy the better, and this is true within limits. But, too



much light is as harmful as too little. It all depends on individual factors as well as their relative balance. Different kinds of data have to be investigated before it is possible to make a judgement. Influencing factors such as; type of plant exposed, length and quality of acclimatisation, dominent type of leaves- whether shade or a sun laeves, amount of water, amount of carbon dioxide, amount and type of nutrients, prevailing leaf temperature, soil temperature, air temperature as well as the general plant posture and age, have all a part in the photosynthetical process.

Defiencies

Plenty of absorbed light energy can initially promote increased photosynthesis. However, too much light will cause dehydration if the following transpiration rate excedes the plants ability to restore dissipated water or carbon dioxide and nutrients, and eventually impair photosynthesis. Extravagantly high intensities might also break down the chlorophyll molecules in a photooxidation process. Chlorophyll must be constantly synthetisized if the plant is going to stay green and aviod yellowing of the leaves. A defiency usually referred to as chlorosis.

Photosynthetically active radiation: PAR

Traditionally wavelengths between 400nm to 700nm, usually referred to as light, have been claimed to activate photosynthesis. It has also been stated that all wavelengths are not promoting photosynthesis with equal efficiency, but that the production is peaking in the blue spectrum at 435nm and in the red spectrum at 677nm. The typical double peak of the Hoover curve has since 1937 been the general conception of a photosynthesis action spectrum. However, Hoover's findings were based on pale green wheat leaves, and more detailed studies have indicated differences in the action spectrum depending on type of plants and possibly leaf thickness and color. Tree leaves show a more even photosynthetical response to the full spectrum compared to pale herb leaves like lettuce. (Physiological Plant Ecology I, K.J.

McCree, p.47 and fig 2.4 and 2.5) This seems to be confirmed by other reports indicating that the action spectra for a plant canopy is nearly flat.(Plant Response to Light Quality and Quantity,"H.M.Cathey and L.E.Cambell, p. 229)

Chlorophyll synthesis

Photosynthesis can not occur without the necessary formation of chlorophyll. That phase in the photosynthetical process is usually initiated by light impinging on protochlorophyll, and completed after its conversion to chlorophyll(a). The process seems to be reversed in darkness within about an hour. Some conifers and lower plants can manufacture chlorophyll in darkness. (R.van der Veen, Light and Plant Growth, p24)

Action spectrum for protochlorophyll to chlorophyll

The action spectrum for the transformation of protochlorophyll to chlorophyll is different than the action spectrum for photosynthesis. There are more distinct action bands affecting this so called chlorophyll synthesis and the curve is sharply peaking in the blue and red wavelengths at 445nm and 650nm. (Sylvania Engineering Bulletin 0-352, p.2 fig.1) Blue light seems to accelerate chlorophyll production in strong light while red and far red wavelengths are active in weak light. (R.van der Veen, Light and Plant Growth, p112) Some sources contend that the distinct dubbel peak for chlorophyll synthesis is much less pronounced for complete plants, and argue that the influence of other pigments and the scattering of the leaf cells cause the curve to even out. Correlating with earlier reports on the effect of leaf thickness on photosynthetical rate these findings show a similar respons for chlorophyll synthesis. (S.Scrivens, Interior Planting in Large Buildings, p.23 fig. 4.4)

Respiration

Respiration is very closely related to photosynthesis, but contrary to that process, it goes on all the time-day and night, with or without light. The carbohydrates manufactured in photosynthesis, and stored in the plant cells, are converted to energy and used for plant metabolism. The temperature of the surronding environment affects directly the rate of respiration independant of the plants need. Other factors such as water availability, nutrients, carbon dioxide and oxygen content also affect the activity. Oxygen is used for the process and carbon dioxide is released in a reversed scenario to photosynthesis.

Light compensation point

Plants need energy to survive and grow. They get this energy from photosynthetic activity , and they use energy for metabolism in the respiration process. These two processes are related as they can restrict each others activities but also independent as they can freely move within those limits depending on external conditions. The more carbon hydrates the plant is able to produce for metabolism and set aside for storage in its cell walls the better is its possibility for survival and growth. The optimum rate of photosynthesis and respiration is unique for every plant but generally depending on a combination of several factors such as environmental conditions, the plants native habitat and genetic disposition, age, leaf and root efficiency, and stage of acclimatization. Environmental factors include "light intensity, light quality, temperature, and moisture relationships". C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.128) At certain levels these factors coincide and the plant's photosynthetic activity produces as much energy as the plant requires for respiration and development of growth.

The light compensation point is the state, where the production level of carbon hydrates is in balance with the minimum requirements for maintaining life but not enough to support any growth. One way to describe the light level necessary to maintain this balance is measuring the amount of carbon dioxide used for metabolism. It has been found that the light saturated level of carbon dioxide uptake varies quite dramtically for sun species compared to shade species. Differences of up to ten times higher rates for sun species have been common. (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.126 and see fig.4.3 p.128)

Transpiration

Plants mainly absorb energy from direct solar radiation or reradiated far infrared radiation. A minor amount of energy is absorbed by conduction and convection. Energy not used in photosynthesis, and needed for maintaining a sufficient tissue temperature, has to be dissipated to prevent damage to the plant structure. Regularily up to 70% to 90% is reradiated back to the environment,while some heat is lost due to effects of conduction and convection. (Environment & Plant Response, M.Treshow, p.52) The remaining share of surplus energy is used to convert water to water vapor within the cell structure. Up to 65% of absorbed heat energy can be converted to latent energy in the evaporation process. (R.L.Gaines Interior Plantscaping p.24) The water vapor is tranferred to the atmosphere, mainly via the stomates and minutely through the cuticle, in a transpiration process, thus contributing to the plant's heat control. It has been shown that the transpiration rate is affecting the leaf temperature as much as up to 9° C (16°F). (Environment & Plant Response, M.Treshow, p.54, fig 5.1) The close relationship between the physical phenomena of evaporation and the physiological function of respiration makes it sometimes convenient to refer to the combined effect as an evapo-transpiration process. There might be other functions, related to transpiration, seemingly not conveyed in the literature. Water in the leaf cells has to be replaced once it is evaporated and dissipated. The accompanied pressure difference in the leaf cause water to be drawn from the roots bringing necessary nutrients, and carbohydrates needed for the metabolism into the cells, making transpiration an essential part of the growth cycle as well.

The effect of the environment on transpiration

There is a dual relationship between transpiration and the environment. The amount of energy absorbed depends on "leaf pigmentation and color, morphological characteristics of the plant,the exposure and orientation of the leaves to the sun", which affects the leaves capacity to reflect and transmit, and consequently to absorb the emitted energy.(Environment & Plant Response, M.Treshow, p.52)

The rate of transpiration is also dependent on atmospheric conditions like the water vapor pressure in the air, intensity of radiation, air movement and temperature differences between leaf tissue and the surrounding air.
The intensity of radiation is the main variable affecting transpiration, but it is the combined effect of all contributing factors during extreme conditions, that can have severe effects on plants. Bright light, high temperature, low relative humidity, and fast air movement, can spike the transpiration rate beyond the capacity of the roots and stem to supply the cells with new water. (R.L.Gaines Interior Plantscaping p.25)

Affects of high transpiration rate on plant growth

Too high transpiration rate can cause the plant to wilt and eventally die, if the amount of replaced water does not meet the plant's need. The immediate effect of this water stress is a diminishing turgidity of the leaf cells. The plant is counteracting the pressure deficiency, due to uncontroled water loss, by closing the stomates, however, at the same time shutting out carbon dioxide needed for the second phase of photosynthesis. Subsequently, retarded photosynthesis is slowing down growth and causing eventual decay. There is a natural screening of inefficient leaves and usually old leaves adjusted to previous conditions are affected first, while surviving greenery tend to obtain a darker shade due to a relative increase in chlorophyll density. (Partly R.L.Gaines Interior Plantscaping p.25)

PHOTOMORPHOGENESIS

There is some discrepancy regarding the classification of photomorphogenical responses. Any change in the shape of the plants due to light should logically be defined as a photomorphogenical response. However, the literature does not follow that defintion closely, but tends to separate between phototropism, photomorphogenesis and photoperiodism.(Physiological Plant Ecology I, D.C.Morgan and H.Smith, p.128) (Sylvania Bulletin 0-352, p.3.) (S.Scrivens, Interior Planting in Large Buildings, p.22)

◊Photomorphogenesis is referring to the plants reaction to the ratio of red to far red wavelengths. Some studies indicate that high energy blue light also effect photomorphogenesis. (Physiological Plant Ecology I, D.C.Morgan and H.Smith, p.127) (Sylvania Bulletin 0-352, p.3.)

◊Photoperiodism is plant response to seasonal changes in light quality, probably due to the same properties governing photomorphogenesis.

◊Phototropism is the plants reorientation towards a light source. (S.Scrivens, Interior Planting in Large Buildings, p.29 see fig 5.1 and 5.2) (Sylvania Bulletin 0-352, p.2, fig 2)

Photoreceptors

Three different types of photoreceptors are regarded to influence photomorphogenesis:

Chlorophyll, Phytochrome and the blue light receptor.

Chlorophyll has already been discussed. The effects of the blue light receptor is still quite unknown, but it has an action spectrum in the blue band between 350nm and 500nm with a peak at about 450nm.

Phytochrome

Phytochrome, a blue pigmented protein in the leaf cell, is an enzyme acting as a photoreceptor controlling photomorphogenesis. It exists in two reversable forms sensible to red (Pr) and far red (Pfr) wavelengths, peaking at 6600nm and 735nm respectively. The (Pr) form transmutes to the (Pfr) form under red light radiation, while the process is slowly reversed in the darkness. This last reaction, however, can be accelerated by far red light radiation, and is dependent on temperature. (R.L.Gaines Interior Plantscaping, see fig p.25) (Sylvania Bulletin 0-352, p.3)

It has been shown that the last exposure of far red or red light on plants is governing the response, and that far red is the active component. Plants radiated with far red light for 5 minutes after an 8 hour period in white fluorescent light "increased internode extension by up to 400%"If the plants, immediately after the far red light period, were exposed to red light for 5 minutes the effect was fully neutralized. (Physiological Plant Ecology I, D.C.Morgan and H.Smith, p.120)

PHOTOPERIODISM

Attuned responses

Plants are reacting to different ratios between light and dark hours, originally an attuned response to their natural habitat, in order to enhance propagation and chances for survival. The response to a seasonal light and dark cycle is called photoperiodism and is usually claimed to affect flowering, but other effects on plant growth are slowly beeing recognized as vastly significant. Recent studies (1981) point at a range of different responses other than flowering. They all are important to plant development, but it is intersting to note that "the vegetative gowth of a plant is extremely sensitive to photoperiod", especially stem elongation, leaf growth and shape. (Physiological Plant Ecology I, F,B.Salisbury, p.138) (R.van der Veen, Light and Plant Growth, p78.)

Daylength and night length

It has been shown possible to neutralize the effect of long nights by exposing plants for a short time in the middle of the dark period. The same effect can be obtained by illuminating plants with weak light after a period of strong light. (R.van der Veen, Light and Plant Growth, p.53 fig 35) The results can also be interpreted as a confirmation that the actual length of the dark period exerts the strongest influence on plant response to daylength. However, without discarding the general appropriateness in this notion, it has recently (1981) been concluded from work on the photoperiodism clock, that combinations of conditions during the day and night exert a combined effect on photoperiodism. (Physiological Plant Ecology I, F,B.Salisbury, p.161) The natural spectral conditions most likely to affect phytochrome occur at twilight, but other conditions, such as a vegetative canopy transmitting much in the far red range, can also influence photoperiodism.

Photoperiodic response types

Plants are regularily grouped into three photoperiodic types traditionally determined by their need for a certain period of daylength to flower.

1. day neutral, 2. short day, increasing night length 3. long day, decreasing night length. Sometimes a fourth group is added depicting; daylength intermediate, day-night limitations. (Plant Response to Light Quality and Quantity,¨H.M.Cathey and L.E.Cambell, p240) (Physiological Plant Ecology I, F,B.Salisbury, see fig 5.1 and 5.2 p.i37)

Adjustment to changes

Time has allowed different species to adjust to exact changes of day length. Studies in Nigeria on tropical plants have shown that slight differences of only 15 minutes can prevent or induce flowering. (M.Hunter and E. Hunter, The Indoor Garden, p.64) Interesting is that plants of the same genotype seem to be able to adjust to a wide range of variations in daylength. A relatively recent study in Scandinavia (1978) showed that plants at three different locations had adjusted their photoperiodical response, in this case shoot elongation, to the prevailing optimal light-dark ratio. The critical day for shoot elongation shifted from 14-16 hours at the most southern latitude to 16-18 hours at a mid range location and ended up reacting to 20-24 hours above the arctic circle. (Physiological Plant Ecology I, F.B. Salisbury, p.149) Although there are some exceptions, it is noteworthy that "cultivars produced by controlled breeding exhibit a wide range of photoperiodic types within a species." (Physiological Plant Ecology I, F.B. Salisbury, p.149)

Implications

The implication of these findings are more extravagant than loosely interpreted at first sight.
First of all, it can be concluded that plants can adapt, within reasons, to almost any day-night cycle.
Secondly, it is possible to breede and acclimatize more durable plant species less sensitive to extended light periods, reaching even 24 hours.

Other studies seem to support these indications claiming that flowering is not responding solely to the day-night cycle, but that "24-hour radiant energy from artificial sources can override the classical photoperiod responses". (Plant Response to Light Quality and Quantity,˜H.M.Cathey and L.E.Cambell, p240) Flowering can also be induced by "temperature,time, light or any combination of these". (R.L.Gaines Interior Plantscaping, p.25)

Quantitative and qualitative responses

Quantitative responses are "relatively independent of the spectral composition of the light source", except for certain plants -like a few species of lettuce- which are developing a pale foliage when radiated with extremely narrow wavelength bands. (Plant Response to Light Quality and Quantity,˜H.M.Cathey and L.E.Cambell, p240) In this case low pressure sodium lamps were used. However, it was found possible to restore the color with supplementry wide spectrum incadescent lighting. (Plant Response to Light Quality and Quantity,˜ H.M.Cathey and L.E.Cambell, see fig(a) p. 218 and fig(k) p.223). The same result interestingly evolved from increasing the ambient temperature level to 28°C (82°F). Some improvement in foliar deficiencies also occurred after spraying with minor elements, particularily iron ions(Fe^{+2}).

Observations

One observation, from the recited investigation, is of particular interest. It was found that no discoloration of foliage ocurred, if plants grown under low pressure sodium lamps were "exposed to even the dimmest sun of winter months". This implies that plants are responding favorably to a broad spectrum independent of proportional intensity levels. Another, more scrutinizing, interpretation could possibly indicate, that it is enough with only slight levels of photoperiodically active wavelengths to induce photoperiodism. In any case, the presence of all wavelengths in a spectrum radiating plants is beneficial to a healthy plant growth.

Reservations

It has to be pointed out that most plants grown in green houses today can show signs of "overshoot", if too much light is impinged on the leaf surface for too many hours. Light intensities of $24W/m^2$ (~400Fc) for 24 hours daily usually "develop chlorotic foliage and surpressed leaf and shoot development". Decreasing the "daylength" to less than 20 hours or diminishing the light intensity restores the green color to the leaves and resumes stem elongation. (Plant Response to Light Quality and Quantity,˜ H.M.Cathey and L.E.Cambell, p.241)

PHOTOTROPISM

Plants are usually seen to grow towards the light efficiently utilizing their leaf structure to absorb as much as possible of the available energy. It has been shown that photosynthesis could increase between 10% and 23%, due to efficient orientation of the leaves. (Physiological Plant Ecology I, D.C.Morgan and H.Smith, p.128) If the position of the light source changes the plant foliage responds with a movement towards the new direction. The stems get elongated and the leaves face again the brightest light source."This property whereby the direction of growth is determined not only by the light but also by the direction of the light"is termed phototropism. (R.van der Veen, Light and Plant Growth, p25.) This reorientation is governed by a plant growth substance called auxin, which seems to be sensible to mainly blue wavelengths around 450nm. It has been shown that irradiation on one side of a coleoptile tip promotes retardation of growth on that specific side, thus causing a bending towards the light source. (R.van der Veen, Light and Plant Growth, p.27 and see fig 16) . That particular response is termed positive phototropism. Conversely, the bending away from a light source is called negative phototropism, seen in roots of certain plants. Leaves are mostly exhibiting transverse phototropism, with the surface perpendicular to the light source, usually in a horizontal position. Some plants, like certain cacti in hot-arid climates, orient their leaves vertically so only the low morning and evening sun can shine on their surfaces. (R.van der Veen, Light and Plant Growth, p.32)

CHAPTER 2

DISCUSSION

People and plants are responding to the impact of the environment in a variety of ways. It is often difficult and fruitless to try to depict a single factor responsible for a certain response. The combined effect of two or multiple parameters can offset the impact of a major factor. Different genotypes, species and individual plants can portray diverse or similar responses to the same impact depending on age, season, and time of day. Human responses might seem easier to track down. Our conception of the environment and our needs are known from our own experience of just living, from employing our senses and from our ability to communicate. However, despite of all the million years that man has existed there are still unexplored scientific knowledge between impact and response. Some links are just surfacing while others are on the brink of being manifested. The reseach field is vast and this thesis makes no illusions about covering it all, but this chapter will concentrate on basic important responses and some significant indications with strong connections to the built environment and atrium design.

2A: RESPONSES TO SOLAR RADIATION

Without the sun life would not exist as we know it. It is the core which life is revolving around. Naturally, living organisms as a general rule have to respond favorably to the emitted energy, as it is a necessecity for survival. However, there are responses developed for the protection against harsh impact, and both people and plants have adopted specific responses to the different wavelengths of the solar spectrum reaching the earth. They have also aquired sensors to trace changes in intensity, and adjusted their rythm to the

phases of the sun and set their biological clock according to the time it takes for the earth to spin around its own axis.

There are three basic factors, as well as any combination of them, affecting the impact and the outcome of a certain response.

◊Intensity

◊Duration

◊Quality

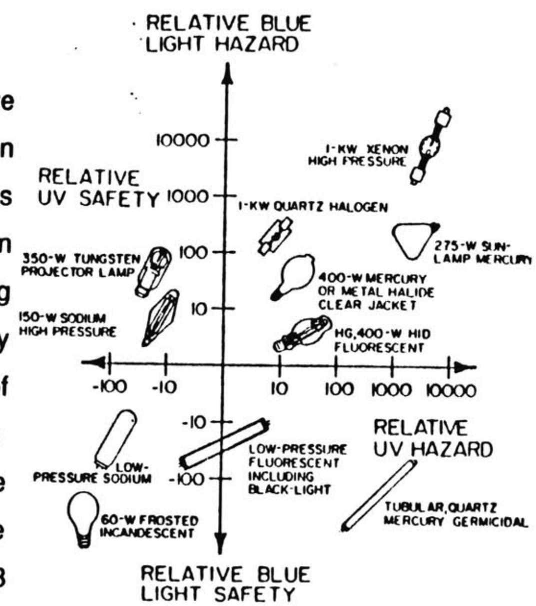
Quality, in this concept, is usually defined as the ratio between certain wavelengths.

Human biological responses to solar radiation

UV- ultraviolet radiation

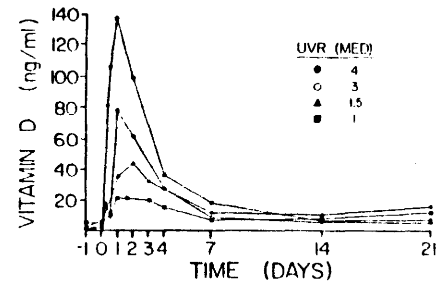
Negative effects

Ultraviolet radiation is often reported as having adverse effects on man. Several studies have been conducted to scrutinize possible damages, mostly concerning the effects of radiation on the skin, but also affects on the retina and the lens. There are normally no injuries to the retinas and corneas while out in the sun. However, it has been found that maligna, a form of skin cancer, can develop from exessive exposure to the sun and other radiating sources containing ultraviolet radiation. Other damages reported besides sunburn are, mutations, and chemically induced phototoxic and photoallergic reactions, irregular thinning of the epidermis, wrinkling of the skin, and graying of hair. (The Medical and Biological Effects of Light,M.A.Pathak p.329) Some studies have tried to classify the effect of radiation from artificial light sources, and have concluded that the risk for damage is related to the time the eye and skin are exposed to the luminare. The values given refers to relative hazards less than 1 meter from the source after 8 hours of exposure.(The Medical and Biological Effects of Light,D. H. Sliney p.117 see fig. 1)



Positive effects

There is new exitement regarding old knowledge. Solar radiation has been known to influence the production of vitamin D, and calcium metabolism for many years. The cause and cure for rickets was linked to the beneficial sunlight in the 1920's."It is now established that, during exposure to sunlight, ultraviolet photons with energies between 290 and 315 nm" penetrate into the skin where most of the previtamin D_3 formation occurs, culminating between 295nm and 300nm. (The Medical and Biological Effects of Light,M.F Holick p.4, see fig 4 p.7) The equilibration to vitamin D_3 takes three days and is independent of ambient air temperature. It is interesting to note that vitamin D has a relatively short action period. It has been shown that concentrations increases to a maximum value 24 hours after exposure to radiation and gradually returns to baseline values after 7 days. (The Medical and Biological Effects of Light,M.F Holick p.10, see fig 6 p.10) Indicating the importance of regular intake of vitamin D3, either ingested in the diet or through exposure to ultraviolet radiation. The melanin pigmentation in the skin is a decisive factor for vitamin D_3 formation . Melanin is an effective neutral filter absorbing and reacting to all wavelengths between 290nm and 700nm. Black skin needs up to six times more ultraviolet radiation to produce the same amount of vitamin D. This is proposed to be one of the reasons why rickets among black children is reemerging in cities in the northeastern United States. (The Medical and Biological Effects of Light,M.F Holick p.12) Also certain classes of Asian immigrants to industrial northern climates show an increased incidence of the disease. (The Effects of Light on Health, P.M. Coxe, P.B.Reiser, W.M.Lam, p.10) It has been shown that outdoor activities increase levels of vitamin D, presumably credited to utraviolet radiation in natural daylight. The generally higher concentration of ultraviolet radiation in sky light at locations closer to the equator or at higher altitudes also seem



to be contributing factors. (The Medical and Biological Effects of Light, R. M Neer p.17 see fig.2 and fig.3 p.17)

During the last fifteen years new findings have recognized a difference between endogenous skin production of vitamin D_3 and exogenous dietary vitamin D_2. Some claim vitamin D_2 to be less effective than vitamin D_3, while others contend they are biologically equivivalent. (The Effects of Light on the Human Body, R.Wurtman, p.73) (The Effects of Light on Health, P.M. Coxe, P.B.Reiser, W.M.Lam, p.10) Indications in Europe that D_2 is toxic in large doses has also curtailed its use. British studies confirm that food intake of vitamin D_2 is insignificant in Britain. Sunlight- stimulated skin production was concluded to be much more important as a vitamin D source than intestinal production. This can be compared with for instance the U.S, where heavy D_2 fortification of food is still prevailing. Yet, a study of white adults living in St. Louis concluded that sunlight, due to its capacity to produce vitamin D_3, was vastly more important than fortified food, as 70% to 90% of vitamin D in the blood of the tested was linked to the D_3 form.

What is interesting to know is the implications of these differences. The consequences of an air polluted environment, curtailing the solar radiation, was widely encountered during the industrial revolution. Today rickets is uncommon, but still exists. More significant is data indicating that a relatively high numbers of elderly are vitamin D-deficient in the northern U.S. Approximately 10% of the elderly in Boston have a vitamin D deficiency, and "among elderly individuals admitted to Massachusetts General hospital with fracture of the hip, 21% were vitamin D-deficient." (The Medical and Biological Effects of Light, R. M Neer p.19) Many elderly women suffer from osteoporosis, due to inefficient absorption of calcium, directly linked with

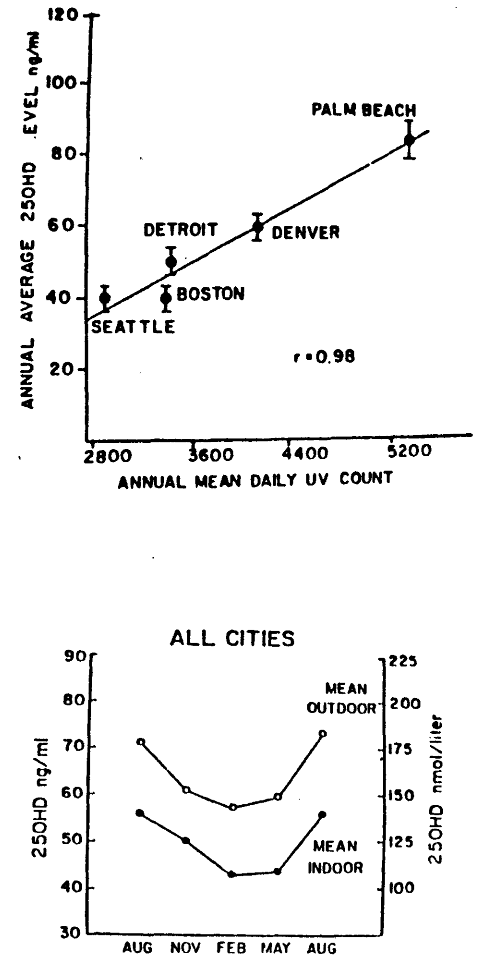


FIGURE 2. Average blood levels of 25-OH vitamin D middle-aged males working in Boston, Detroit, Seattle. city, half of the men worked indoors and half outdoors,

vitamin D deficiency. These data are noteworthy, but more data around the world has to be gatherd, to gain a complete picture of the current state. What is known is that vitamin D_3 deficiency still exists, despite readily available outdoor sunlight and vitamin D fortified food, especially in certain vulnarable groups of the population and that the problem might increase in the future. The implications of these findings indicate that, in some cases, it might be desirable to increase controlled utraviolet radiation, either through artificial means or exposure to daylight. It could be possible to alleviate the symptoms encountered in an enclosed environment, by incorporating certain types of transparent material transmitting UV- radiation.

Other biological affects of ultraviolet radiation include help for curing rare forms of leukemia and immune system disorders. (The State Journal-Register Sunday, December 9, 1984, p.35) Coal minors in U.S.S.R. are exposed to UV-radiation every day to protect against the development of black-lung disease. Patients with psoriasis can be successfully treated with exosure to 365nm UV-radiation after intake of an photosensitizing agent called psoralens, with the active ingredient curiously found in an Egyptian plant "used in ancient times to treat skin ailments". Also carrots, parsley and lime contain small amounts of it. (The Effects of Light on the Human Body, R.Wurtman, p.72)

VR-Visible radiation

Infant jaundice

Besides seeing, the obvious effect of visual radiation, there are more subtle indirect effects, which the human body is responding to.

Some years ago it was noticed by coincidence, that infant jaundice- the yellowing of the skin due to concentration of bilirubin in the blood stream- could be sufficiently remedied, if the newborn infants were placed near an open window. The beneficial effect was originally traced to the impact of sunlight and possibly ultraviolet radiation. However, it has been shown that blue light is the most effective radiation in decomposing bilirubin, although it has been proven that full-spectrum white light have equal effects regardless of the relative intensity of blue wavelengths. (The Effects of Light on the Human Body, R.Wurtman, p.74)

Light-dark cycles

According to new discoveries, there are strong indications that evolution has equipped man with biological clocks in rythm with differences in day light cycles. This indirect effect of light depends on the time the body is exposed to daylight, which varies with seasonal changes of day length as well as the day and night ratio. Several responses have been found to be associated with these light cycles. "Physical activity, sleep, food consumption, water intake, body temperature and the rates at which many glands secrete,and hormones all vary with periods that approximate 24 hours." (The Effects of Light on the Human Body, R.Wurtman, p.75 see fig p.74) The cortisol level also seem to vary with the same 24 hour rythm in healthy human beings, while it has been found that blindness upsets the synchronization with daylight. The factors governing the specific rythms are not completely known and psychosocial factors could be more important than light cycles. (The Effects of Light on the Human Body, R.Wurtman, p.76)

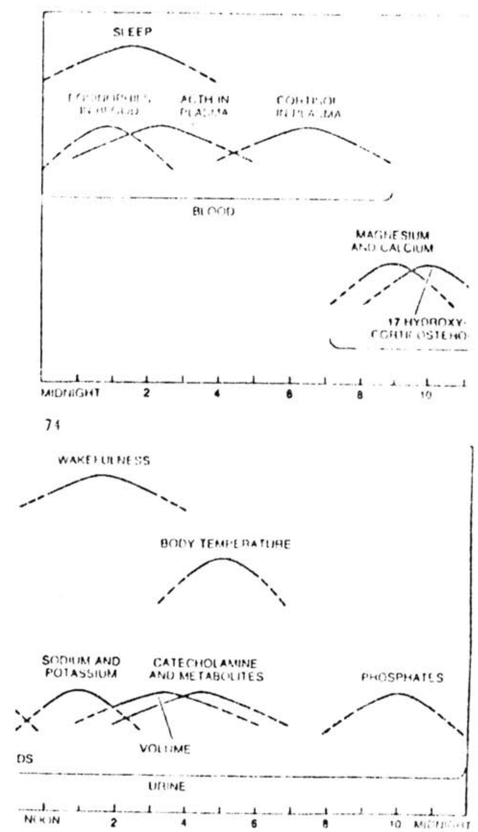
Sexual maturity

Observations of earlier gonadal maturation among blind girls compared to a normal score of girls, also point towards a connection between light and sexual maturity. (The Effects of Light on the Human Body, R.Wurtman, p.77) (R.Küller, Ljusets Biologi, paper presented at the solar conference held in Trondheim, May 1984 see fig.3 p.3)

Skin diseases

Visual light together with photosensitazation agents have been used to traet several skin diseases by causing damage to invading organisms, such as herpes virus and malignant cells.

Productivity



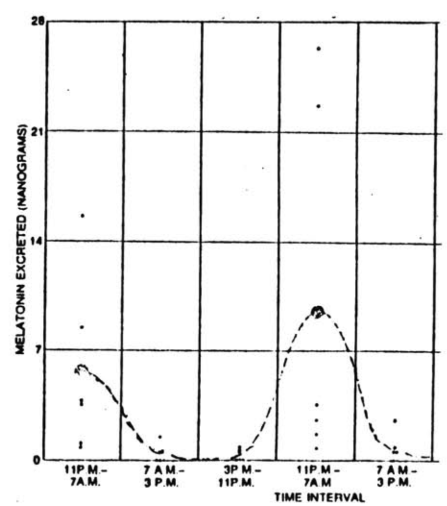
Dialy rhythms are characteristic of many human psychological functions. Whether these 24-hour rhythms are produced by the daily light-dark cycle or are simply entrained by that cycle remains to be unequivocally established. Each curve represents the typical daily peak for a physiological state or for the levels of particular substances that circulate in the blood or are excreted in the urine.

Several studies have been conducted in order to investigate the impact of light on worker productivity. Mostly they have tended to look at illumination levels. Dr.H.R.Blackwell's studies of productivity, performed in a laboratory setting, has rendered much interest but also citicism. His work forms the basis for lighting codes in the U.S. and Canada.(The Effects of Light on Health, P.M. Coxe, P.B.Reiser, W.M.Lam, p.26) In a later statement Dr. Blackwell claims that light from full spectrum luminares could increase worker productivity close to 12%. Unfortunately the study conveying his remarks neglect to give any information regarding the comparable source. (The State Journal-Register Sunday, December 9, 1984, p.36) Other studies in Sweden regarding the impact of artificial light with different spectrum, show that fluorescent luminares with a daylight spectrum gave the workers less visual problems and eye fatigue than personel working in traditional cold white light. The same study shows that the cortisol level was linked to the access of daylight, with decreased levels for personel working far away from the windows, especially during the summer.

Effects of light on the melatonin level and depression.

The most intriguing discovery, and what can prove to be a new understanding of the indirect effects of light, is the inhibition effect light has on the melatonin level. The exact role of melatonin is still to be established. Its effect on the brain has so far been linked to sleepiness and inhibition of ovulation. Other functions include raising the levels of serotonin- a neurotransmitter, and modifying the secretion of other hormones and the electroencephalogram. It has been found that the melatonin level in the urin is cyclically much higher at night between 11:00P.M. to 07:00 A.M. than during the rest of the day. (The Effects of Light on the Human Body, R.Wurtman, p.77 see and correct fig p.77)

The melatonin concentration in humans is not only responding to diurnal light-dark cycles, but also show annual variations. The concentration is lower in the spring and in the fall, and the nocturnal peak is about two hours broader in the winter than in the summer with a delay occurring in the morning concentration only, according to preliminary data from Stockholm.



RHYTHM IN MELATONIN SECRETION in human beings has be

(The Medical and Biological Effects of Light, D.F.Kripke, p.277) The seasonal changes in concentration can possibly be traced to affect human physiologic and behavioral actions in diverse and drastic ways. The annual rythms seem to be strongly related to the avilability of sunshine. Hospitalization and suicide rates tend to peak in the spring and in the fall. Conception might be linked to a photoperiodic control as studies in Europe indicate that patterns of births seem to correlate with differences in latitude. There are even claims that menstruation among Eskimo women may cease during the long arctic night. (F.Birren, Color & Human Response, p.21) Dysfunction of the circadian rythm can cause severe depressions due to seasonal changes and it has been shown that the melatonin level is abnormally low among depressed patients. "Patients with seasonal affective disorder-SAD are especially sensitive to the short days of winter, which induce them in a cluster of symptoms including fatigue,sadness, hypersomnia,overeating,carbohydrate craving , and weight gain." (The Medical and Biological Effects of Light, N.E.Rosenthal et al, p.267) Research also shows that depression can be treated with light, if the intensity of the radiated full-spectum light is above at least 250Fc. The duration of the treatment has to be longer than 3 hours, preferably 5 to 6 hous, and adjusted to the time of the day. Some studies state, that evening treatment is as effective as the combined effect of shorter morning and evening exposures, while others suggests that evening exposure is not as effective. (The Medical and Biological Effects of Light, N.E.Rosenthal et al, p.267) (The Medical and Biological Effects of Light, D.F.Kripke, p.277) Fact remains, that the treatment has proven to be successful. However, it is interesting to note that, the melatonin level in patients with seasonal affective disorder-SAD is lower at night than normally accounted for. This indicates that light treatment of depression is not actually suppresing the melatonin secretion as would have been logically expected, but "causes rebound increases in nocturnal melatonin". (The Medical and Biological Effects of Light, D.F.Kripke, p.278) This could possibly be explained by a form of supersensitivity to light in depressed patients and suggests that their dysfunction is a combination of this hypersensitivity to light and inadequat exposure to light during the day.

Jet lag and shift work

Ther are other more subtle effects of light exposure affecting healthy people. The human circadian rythm tend to be longer than 24 hours and can be utilized together with bright light exposure to manipulate the melatonin level for treatment of jet lag and maybe also for adjusting shift workers to changing working hours.

Physiological effects of color

The science of color is fascinating and has many different aspects. The psychological impact of color might well be more important than the physiological aspect, but new findings regarding the impact of light on human well-being can prove to increase the understanding of physiological factors and eventually find the links affecting psychological perception.

Every sensation in the brain of a color is originating with a light source seldom directed straight on to the eye, but often reflected off an illuminated object or transmitted through a more or less transparent material. The reflected or transmitted light is modified by the absorbing properties of the object. The eye is thus receiving redirected light with color qualities depending on the light source as well as the illuminated object, before the high energy photons strike the retina and is interpreted as colors. Many studies and philosophies are suggesting certain human behaviors tied to the perception of colors. However, this thesis will not go into any details, but just briefly cite one source.

"In human beings red tends to raise blood pressure, pulse rate, respiration, and skin response (perspiration) and to exitebrain waves. There is noticeable muscular reaction (tension) and greater frequency of eye blinks. Blue tends to have reverse effects, to lower blood pressure and pulse rate. Skin responses is less, and brain waves tend to decline. The green region of the spectrum is more or less neutral." (F.Birren, Color & Human Response, p.24) However, the same source cautions "that color effects are allways temporary" and bodily responses, after a longer exposure to the same color, might decline below normal. (F.Birren, Color & Human Response, p.23)

It is also necessary to point at cultural differences and other factors discussed earlier, which all can affect the perception.

Infrared radiation

Positive effects

Infrared radiation can be used therapeutically for sore muscles and other muscleskeleton injuries. (The State Journal-Register Sunday, December 9, 1984, p.35) It also has a tremendous importance as a direct heat source necessary for maintaning heat balance in the body, compensating ambient air temperature and metabolism.

Negative effects

High intensity exposure by infrared radiation can cause overheating. The body reacts by perspiring, increasing blood circulation and enlarging skin area. Sunstroke, brain damage and possibly death are ultimate reactions.

PLANT RESPONSES TO SOLAR RADIATION

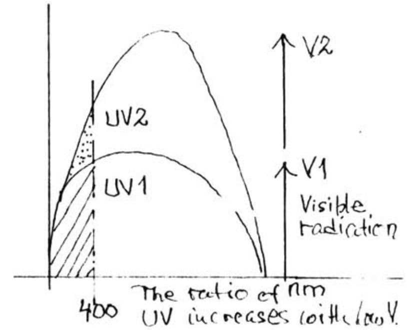
UV-Ultraviolet radiation

Positive effects

There are signs indicating that particularily long wavelengths of ultraviolet radiation can stimulate photosynyhesis. However, the general conclusion is that UV-radiation is detremental. Even though some sources maintain that ultraviolet radiation is a necessary part of a natural environment and basically positive.(J.Ott) This notion might be encouraged by a study on cacti and succulents, which claims that it is possible to induce flowering with supplemental ultraviolet radiation when cultivating these plants indoors. A response not previously known to be successful in an indoor environment. (Duro-Test Corporation, Form 815-7106R, 1971) Dr. John Ott has claimed that ultraviolet radiation caused apples he used for an experiment to turn red. However, other sources state that red coloration of apples is caused by strong blue light. (R.van der Veen, Light and Plant Growth, p113.) (C.Mpelkas, conversation)

Negative effects

All ultraviolet radiation, that is wavelengths below 400nm, are claimed to be harmful, and the shorter the wavelengths the greater the risk for damage. (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.114) Small doses of UV-C can be direct lethal and readily inhibit photosynthesis. Nonlethal, but damaging effects of UV-C radiation include genetic alterations, mutations and reduced growth. UV-B can cause a reduction in leaf enlargment and diminish the rate of photosynthesis. Chlorophyll reduction is apparent after extremely large doses, or after exposure to UV-B in an environment with relatively low visible radiation. Damage on leaves and reduction of photosynyhesis is caused by the cumulative effect of ultraviolet radiation, even if the doses are relatively small. One important feature, already touched but need to be stressed, is that the influence of UV-B on photosynthesis has shown to be totally dependent on the ratio of visible radiation to ultraviolet radiation rather than

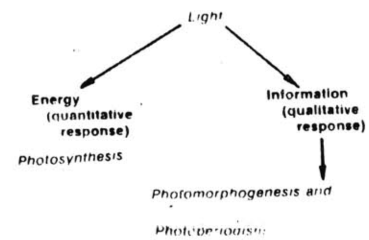


the actual intensity. (Physiological Plant Response I, M.M.Caldwell, p.186) (see own figure p.186)

It has been shown that the effects of exposure to UV-C can be somewhat alleniated if if the organisms are radiated with low intensity or visible radiation beforehand. The plant is responding to the impact of ultraviolet radiation either by avoidence or adaption. There is some evidence that plants adjust their leaf inclination to protect from direct UV impact by declining their leaves slightly. This response is increasingly pronounced with lower latitudes. However, even totally vertical leaves receive around 70% of the possible total irradiation as most UV-B radiation, 40% to 75%, is part of the scattered sky component. Absorption of UV radiation and different types of synthesis reactions in the leaves may also participate in the acclimatization process. Changes in cuticular thickness and mesophyll structure also take place. Plants previously not subjected to ultraviolet radiation are very sensitive to the high energy wavelengths, which are rapidly damaging the leaves and eventually will fall off. On the other hand, leaves grown in an environment with ultraviolet radiation are more prone to withstand its impact. The leaves become smaller, hardy, sometimes hairy, and develop a thicker cuticle. (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.114)

VR-Visible radiation

The overwhelming part of the plants' active spectrum lies in the visible radiation range. Both quantitative and qualitatative responses are basically depending on light. Photosynthesis and chlorophyll synthesis are generally quantitative responses increasing with light intensity. Photosynthesis is active over the whole spectrum with peaks in the red and blue. Chlorophyll synthesis is predominantely a two-peak-curve in the red and blue ends of the spectrum. Qualitatative responses react to slight changes in wavelength ratios often independent of intensity levels. The phototropic response is activated by blue wavelengths. Photoperiodism



and photomorphogenic responses are reacting to red, and far red, and possibly high energy blue wavelengths.(S. Scrivens, Interior Planting in Large Buildings, p.29 see fig.5.1 and 5.2)

Plant response to light quality

Germination

Light does not affect seed germination for most cultivated plants, except for small-seeded species which require wavelengths in the red spectrum, between 560nm to 690nm, with a peak at 660nm to effectively germinate. Germination for a few species are inhibited by light and some still inhibited by long exposures to far-red.

Seedlings

All seedlings most effectively develop a compact growth as a response to red wavelengths at 660nm. (Plant Response to Light Quality and Quantity,"H.M.Cathey and L.E.Cambell, p.238)

Plant response to illumination levels

Too little as well as too much light can be harmful to plants. The exact detramental levels are influnced by a variety of parameters, such as temperature, fertilization, and most important time and intensity. Most plants can sustain shorter periods of extreme light conditions. Longer periods of high or low light levels will drastically diminish and even inhibit efficient photosynthesis. The rate of photosynthesis is directly linked to the intensity and will cease, if the light intensity is not enough to induce the convertion of protochlorophyll to chlorophyll, and eventually cause -chlorosis- yellowing of the leaves. Too much light will inhibit photosynthesis and induce photo-oxidation, or bleaching of the chlorophyll, reversing the synthesis back to protochlorophyll. High light levels also increase transpiration, risking dehydration, scalding and scorching of the leaves and eventually necrosis, if the plant's capacity to replace the dissipated water is inadequate.

The following material is developed from "Plant Response to Light Quality and Quantity" by H.M.Cathey and L.E.Cambell, p.244 to 248. Also A.S.H.R.A.E, 1981, chapter 9.12-13, contain the same basic data. It should only be interpreted as a general description of plant response to certain light levels. It is obvious that different types of plants have different preferences. See chapter1 and chapter 5.

Display 0.3W/m^2 (5 Fc)

The plants can be displayed for a shorter time, but no growth expected.

Photoperiod 0.9W/m^2 (15 Fc)

This low light intensity, in combination with daylight, is adequate for activating the photoreversible blue phytochrome, thus regulating photoperiodic responses, such as growth and flowering. Plants will not survive for a longer period. Deciduous trees lighted with incadescent light at 0.9W/m^2 maintain vegetative growth over many months, while HID lamps cause discoloration and dormancy. Photoperiodic responses are dependent on wavelengths around 660nm and 730nm, making incadescent light with the main bulk in the red spectrum a suitable light source. Photomorphogenic responses require blue wavelengths, indicating a combination of light sources, or the use of broad spectrum luminares, as the best alternative.

Survival 3W/m^2 (50 Fc)

Plants can survive and the light intensity is enough to maintain the green color.
However, stems get elongated and leaves are reduced in size and thickness. Photoperiod responses do not function well and no new foliage is developed. Eventually the plants have to be replaced.

Maintenance 9W/m^2 (150 Fc)

Plants can grow for many months making it a convenient illumination base to start out from. It is possible to grow a wide range of plants in this light level. Most plants develop deep green foliage, large leaves, and exchange old leaves with new ones. It is possible to regulate growth by intruducing a 12 hour light-dark cycle, coupled with less frequent watering and fertilizing, slowing down the production of new leaves.

Minimum required light intensity for slow growth according to A.S.H.R.A.E. (A.S.H.R.A.E, 1981, chapter 9.12-13)

Propagation- slow growth 18W/m^2 (300 Fc)

Plants can be propagated rapidly in this light level if the plants are illuminated for at least 6-8 hours daily. Most plants can be brought to maturity, but the growth rate is still quite slow.

Greenhouse- growth 24W/m^2 (400 Fc)

Plants can be grown year round in a glazed environment, if the natural daylight is supplemented with this light intensity for 8-16 hours daily. By tradition this is the irradiance that best couples ambient sunlight with supplemental lighting boosting growth rates and creating a growing environment for rapid development and early flowering. Plants grown without supplemental light will grow much slower. Supplemental lighting for 8 hours a day is much less effective than 4 hours applied at night between 20.00 and 24.00.

Growth chamber 50W/m^2 (830 Fc)

This is the standard light level in growth chambers and can be used to simulate outdoor conditions. It is possible to grow most kind of plants in light intensities between 50-80W/m2, providing 10-20% is incadescent light with red and far red wavelengths and other affecting factors span a range between 8-24 hours daylength, 20-80% relative humidity, 9-35°C temperature,free air flow, and a carbon dioxide content of 300-500PPM.

Adequate light levels

Other studies indicate adequate plant growth at light levels between $13\mu Em^{-2}s^{-1}$(~90Fc) to $26\mu Em^{-2}s^{-1}$(~180Fc) for 12 to 18 hours daily. The quality of plant growth increased with light intensities and was best at $26\mu Em^{-2}s^{-1}$(~180Fc). (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.146)

Continous lighting

Continous lighting of some plants induces paling of foliage and loss of of pigments of the top-most leaves. The trees can survive for several weeks and eventually retreive their original posture by reducing the light period by at least 4 hours or by increasing the temperature 2-4°C. Mineral elements might also be used (Fe^{2+}). (Plant Response to Light Quality and Quantity, H.M.Cathey and L.E.Cambell, p.247). Other studies claim that constant light reduce plant quality. (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.145)

The effect of spectral distribution on plant growth

It has been observed that plants grow best when the spectral distribution is wide. Studies reporting on plant growth in interior environments claim that Cool White fluorescent plus incadescent luminares provide superior conditions for growth compared to only Cool White fluorescent. (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.145) Others assert that wide spectrum fluorescent lamps because of their property to closely imitate the spectral distribution necessary for photosynthesis is an efficient choice. (Sylvania Bulletin 0-285, p.3, fig.2) and covers the whole range of the visible wavelengths.

IR-Infrared radiation

Positive effects

About 50% of the solar radiation reaching the earth is near infrared radiation. The energy ratio actually impinging on plants is modified by the environment, and is also dependent on the absorbing qualities of the transparent material it is transmitted through. The ratio of IR emitted from artificial light is dependent on the light source. Far infrared radiation- thermal radiation- from the surround is not part of the solar spectrum. Some of this energy is absorbed by the plants as heat in order to obtain adequate tempertures necessary for metabolism and survival.

Negative effects

There are claims that exposure to near infrared radiation.cause elongation. But, again, other experiments indicate no actual effect. (R.van der Veen, Light and Plant Growth, p.97) High intensity infrared radiation can cause severe damage to the leaf structure, but the magnitude of the injuries are coupled to other environmental factors and the induced temperature within the leaves.

Psychological responses to solar radiation.

UV-radiation

The different expected and experienced physical responses to UV-radiation is probably affecting the psychological response. For instance, suntan is creating a positive response, while sunburn cause a negative response.

VR-Visible radiation-light

The psychological perception of direct and reflected visible radiation, in this case preferably called light, is a balanced interpretation of the total environment. Human individual factors , such as cultural and genetic backgrunds,sex, age, as well as adjusted behavior, play all a significant role in this process, together with the functional appropriateness of the created space. Different shades of darkness and brightness, light and shadow,glare and contrast, as well as colors in all nuances, have all a profound, but value judged, effect on our immediate perception of the physical environment. See also chapter1.

IR-Infrared radiation

The benefits from infrared radiation as a heat source to balance cold ambient air temperatures is appreciated. A negative psychological response can be expected if the ambient air temperature and infrared radiation coincide to create an uncomfortable hot environment.

The effect of light intensity on leaf shape

Leaves of plants grown under high light conditions are usually less green, thicker, shorter and smaller, than those grown in a low light environment. It has also been noticed, that sun grown plants posses twice as many leaves as shade grown plants. However, the larger area of each individual shade grown leaf offsets the quantitative advantage, making the shade grown plants total leaf area equal in size. (C.A.Conover and R.T.Poole, Acclimatization of Indoor Foliage Plants, p.145) For leaf structure, due to different light levels, see chapter 1)

The effect of color on leaf shape

The color of the radiating light appears to have the most striking effect on leaf development.

Leaves grown in red light seem to be larger, elongate and "aquire a knobbly surface in contrast to those grown in green or blue light", while blue, violet and near ultraviolet seem to be responsible for the more sturdier growth seen in plants developed in high light conditions . (R.van der Veen, Light and Plant Growth, p108-109) It has to be pointed out that the growth response to the different colors of the spectrum may vary for individual species. Green light seem to be neutral. However, there are two important observations. Plants can convert some of the green light energy, by fluorescence, to more efficient wavelengths utilized in photosynthesis, and at the same time affect photomorphogenesis.

Acclimatization to changing light intensities

Sun grown plants have adjusted their leaf structure to suit high light conditions. Position and orientation of the leaves, thickness of the cuticle, and disposition of the energy absorbing grana, are all in a protective mode. However, the abundance of energy has also developed an inefficient leaf, with a relatively small amount of chlorophyll and low utilization of absorbed energy. Changed conditions with lower light intensities will drastically impair the necessary production of carbohydrates, and the plant has to adjust in order to survive. It can basically react in two ways: 1. increase the chlorophyll content and change the disposition of the palisade layers and the grana to a more exposed mode. 2. exchange the old leaves for new more efficient leaves. Usually the plant respond in accordance with both propositions. The first process can take between 4 to 8 weeks, while the second process can be extended over months or years. The reversed acclimatization process requires even more drastic plant reactions. The cuticle is too thin to protect the leaf from high energy impact, and the plant can not react by changing leaf anatomy. Only retraction of the palisade layers and redisposition of the grana remain, often resulting in damage to the leaves.

Plants originally grown under shade conditions in greenhouses have proven to have a higher quality than acclimatized sun grown plants. (G.H.Manaker, Interior Plantscapes, p.200)

2B: RESPONSES TO AIR AND SOIL TEMPERATURE

The most immediate consequencies of solar radiation, light intensity and temperature levels, are probably the most important physical factors affecting life. It has been shown that the light intensity can vary quite drastically, without impairing necessary physiological functions. However, the margins for the impact of temperature are relatively narrow. It has to be pointed out, that the sensation of temperature is related to other parameters, such as the relative humidity, air movement as well as physiological and physical reactions aquired to protect from a harsh impact. It is also a physical and psychological experience of the combined effect of ambient air temperature and direct radiated energy. As explained in chapter 1, radiated heat energy can be divided in near infrared radiation and far, or thermal, radiation. This section deals with responses to temperature levels related to thermal radiation, conduction and convection .

Human biological responses to temperature levels

Every sensation of a comfortable temperature has to be explained in its relation to the surrounding environment, and individual physiological conditions and psychological preferences. However, there are general responses related to the human body. The deep body temperature is relatively constant between 36 to 38°C (97 to 100F°), while the skin temperature can change with the impact of the environment. The skin indoor temperature is usually around 32°C (90°F). For the body to function well, it has to obtain enough energy to maintain a constant temperature. This is performed by metabolism, physical work, and absorption of external heat energy. In the case of a heat intense environment, the body has to react by dissipating superfluous energy to prevent overheating. "The fundamental thermodynamic process in heat exchange with the environment can be described by the general heat balance equation." (A.S.H.R.A.E, 1981, chapter 8.1)

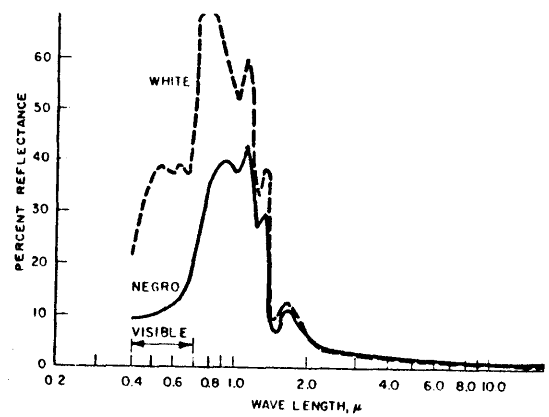
$S = M - (\pm W) \pm E \pm R \pm C$

$S > 0$ => rise in body temperature

$S = 0$ => thermal equilibrium

$S < 0$ => declining body temperature

Where the capacity to store(S) energy in the body is dependent on the balance between metabolism(M), mechnical work(W), evaporative(E) heat loss, heat exchange by radiation(R), convection(C) and conduction. When the body is not in thermal equilibrium it has to react to maintain balance. The rate of metabolism is rather constant, while radiation and convection is drastically related to the operetive temperature. The body almost always lose some energy through evaporative cooling, but the loss is sharply increasing at higher temperatures. (A.S.H.R.A.E, 1981, chapter 8.2, fig 1) The body responds to low temperatures by restricting the blood flow to the skin, and increases internal heat production by muscular tension, shivering, and spontanious activity. At high temperatures the blood flow to the skin increases, effectuating a more efficient heat loss through convection and conduction. The body also starts to sweat to enhance the effect of evaporative cooling (A.S.H.R.A.E, 1981, chapter 8.2) (A.S.H.R.A.E, 1981, chapter 8.12, fig.11) It is noteworthy, that the human body is reacting more dramatically to small changes in temperature levels above normal skin and body temperatures, than when experiencing temperature drops.



Average Values of Spectral Reflectance for White and Dark-Negro Skin

There are many individual factors affecting the response to the impact of absorbed heat. Clothing, skin color, sex, age and adjustment to the prevailing conditions all have a more or less strong influence on the perceived comfort level. (A.S.H.R.A.E, 1981, chapter 8.9, fig.5)

(A.S.H.R.A.E, 1981, chapter 8.14, fig.12) Other climatic conditions, such a، relative humdity and air movement are also directly linked to this effect. Many studies have tried to tie these factors together, often potraying the relationships in a graphical presentation. The pioneering work of V. Olgyay, and P.O.Fanger presents some of the basic bioclimatic charts. A.S.H.R.A.E. has developed a new comfort chart based on their principles, which can be complemented, for more detailed information, with diagrams depicting the combined influence of humidity, ambient air temperature, wind velocity, and mean radiant temperature. See apendix section.

Mean radiant temperature

Mean radiant temperature can balance the impact of the ambient air temperature, but there are limitations to its influence as discomfort can arise from extreme assymetric exposure. Under normal conditions with regular clothing that is business dress- ,there is a tolerance span of about ±5°C in relation to the ambient air temperature. (A.S.H.R.A.E, 1981, chapter 8.26)

Comfort and health

It has been shown that regulated indoor climates enhance comfort and health. (A.S.H.R.A.E, 1981, chapter 8.29) The margins for comfort are, as descibed, depending on several factors, but can be set within certain limits.

• Ambient air temperature: 20°C-28°C (68°F-82°F)

• Relative humdity: 20%-80%

• Air velocity: 0.1m/s-1.5m/s (0.3ft/s-5ft/s

(A.S.H.R.A.E, 1981, chapter 8.28-8.29, fig.22 and fig.23)

Plant response to air and soil temperatures

Most plant activities governed by light are also influenced by the temperature level,which

exerts a strong influence over plant development, both restricting and promoting growth. The magnitude of the influence and severity of the damages are dependent on the temperature level, duration, and speed of temperature changes allowing time for adjustment.
The effect of heat on plants is dependent on the transferring media, as well as the absorbing tissue. The temperature difference between the plants and the environment, and between the soil and the air, also play a significant role.
Plants are losing or gaining heat depending on the prevailing conditions. Heat is lost, either as transferred thermal radiation from the plant to the environment, including the nocturnal sky, or stipped off by air movement because of convection, or absorbed by the cooler soil due to conduction. Any combination is also possible.
Heat is gained, either as transferred thermal radiation to the plant from the environment, or as latent and sensible heat from the surrounding air, or absorbed by the stem from the warmer soil due to conduction. Any combination is also possible.

Effect of temperatures on photosynthesis

It can be argued that the ambient air temperature, and leaf temperatures, possibly affect the photosynthetical activity, through the temperature dependent second step in photosynthesis. On the other hand, it is also difficult to separate the temperature influence from other contributing factors. There are, however, indications pointing at an indirect association. Studies measuring the influence of temperature levels on photosynthesis, have been able to plot a saturation curve, showing the direct relationship between the rate of photosynthesis and light intensity, at different temperature levels. (R.van der Veen, Light and Plant Growth, p18, fig.9.) Other sources contend that the duration of high temperatures affects photosynthesis negatively. (R.L.Gaines Interior Plantscaping p.168, fig. p168) Some studies indicate an upper limit for photosynthesis at 32°C to35°C (90°F to 95°F), above which the rate will decline. (G.H.Manaker, Interior Plantscapes, p.75)

Effect of temperatures on respiration

Respiration is closely related to the temperature level. During normal conditions and within certain limits, a rising ambient air temperature promotes a faster respiration rate. The rate seem to double with every 10C° (18F°), or 10°F, temperature increase between 10°C to 30°C (50°F to 86°F), a phenomenon sometimes referred to as the Q-10 of respiration. (Environment & Plant Response, M.Treshow, p.54) (R.L.Gaines Interior Plantscaping p.168, fig. p169) However, the aftermath is also an increasing depletion of carbohydrates. That is, high temperatures can cause an unbalanced metabolic activity, by exceding the production of new chemical energy, or food, and exhausting stored energy, eventually wearing down the plant. Low temperatures will generally slow down respiration, and enable the plant to conserve energy and keep in balance with low light intensities. Extreme temperatures at both ends will reduce respiration. Night temperatures can preferably be 3°C to 5°C (5°F to 10°F) cooler than day time temperatures .

Effect of temperatures on transpiration

Transpiration is directly tied to temperature levels and relative humidity. High water vapor pressure in the air restricts the transpiration flow, but with rising temperatures the water vapor pressure will decrease, enabling an increased gas exchange. A combination of low relative humidity and a high temperature can be detramental to the plant. (Environment & Plant Response, M.Treshow, p.54, fig.5.1)

Effect of temperatures on photoperiodism

It is common for the photoperiodism activity to be linked with temperature, and responses change due to combinations of dalength and temperatures. Both flowering and dormancy seem to be affected according to some sources. "Flowering of many species is promoted by a brief to prolonged exposure to temperatures close to the freezing point." (Physiological Plant Ecology I, F.B.Salisbury, p.147) "A dormant condition can be maintained by keeping the plant at a *low temperature* ." (R.van der Veen, Light and Plant Growth, p.67)

Plant response to soil temperatures

"Temperatures directly influence the availability and absorption of mineral elements from the soil", as "nutrients are tightly bound to the soil at low temperatures". (Environment & Plant Response, M.Treshow, p.56.) The ability of the roots to absorb water is also influenced by the temperature, as the viscosity of water increases with decreasing temperature, making it more requiring for the plant to obtain necessary fluids and nutrients. (Environment & Plant Response, M.Treshow, p.56.) Seed germination is highly marked by the temperature. At 20°C (68°F) germination begin to decline and will eventually cease at 45°C (113°F). (Environment & Plant Response, M.Treshow, p75.)

Optimal temperature ranges

Foliage

Every plant can have a certain preferred tempereature level, but most plants seem to do well at a temperature range between 18°C to 24°C (65°F to 75°F). However, some plants, such as Cactus and Yucca prefer 13°C to 18°C (55°F to 65°F). Night temperatures should in both cases be about 5C° (10F°) lower. (G.H.Manaker, Interior Plantscapes, p.75)

Roots

Roots grown in soil temperatures of about 18°C (64°F) seem to do best. (Environment & Plant Response, M.Treshow, p58.)

2C: ATMOSPHERIC IMPACT

The quality of the air is a vital factor that has to be seriously considered. The amount of oxygen and nitrogen is relatively stable, and normally does not affect the climatic situation. However, more significant are the fluctuating proportions of carbon dioxide and water vapor. The relative humidity affects both people and plants, while carbon dioxide is mainly a concern for a healthy plant development. Ions and stale air can cause severe nuisance, and pollutants can play a small, but sometimes devastating role. Many types of pollution can cause toxic damage to sensitive plants as well as create an unhealhty environment for people. Carbon monoxide and hydrocarbons from neighboring carparkings and streets, cigarette smoke, chlorine from desinfection of water, ammonia from cleaning fluids, etc. (R.L.Gaines Interior Plantscaping p.172.) (S.Scrivens, Interior Planting in Large Buildings, p.22.)

Relative humidity for plants

There is naturally a wide discrepancy between optimal levels of relative humidity(RH), due to the original habitat of the plants. Most plants prefer high levels, maybe 70% to 90%, but it has also been shown that plants are relatively unaffected even at 20% relative humidity. Generally, plants thrive well at normal levels around 30% to 50%. (R.L.Gaines Interior Plantscaping p.172.)

Ventilation and carbon dioxide

Natural, or mechanical, ventilation should provide fresh untainted air for control of temperature and, if necessary, humidity. However, for a healthy plant growth, it is even more essential that plants are abundantly supplied with air containing carbon dioxide for photosynthesis. "The level of carbon dioxide should kept between 1000ppm to 1500ppm". (Sylvania Bulletin 0-351, p.4.)Because, stale air around plants is depleted of carbon dioxide and will impair growth. Also, a high content of water vapor dissipated in the evapo-transpiration process will exert a strong pressure on the intercellular walls reducing transpiration and eventually photosynthesis if the stale air is lingering close to the leaves. Any air movement will have beneficial impact on plant development.

2D: SOIL QUALITY

All the mineral elements, maybe 16 altogether, which are necessary for a healthy plant growth, are absorbed by the root system from the soil. The nutrients are continously demanded by the plant and have to be replaced once the supply around the plant gets depleted. It is especially essential to restore major elements such as nitrogen, phosphorus, potassium, sulphur, magnesium and calcium. Minor trace elements, including iron, are only needed in minute quantities, but can have a detremental impact if not supplied.

It is of vital importance that the soil is aerated and can supply the roots with oxygen needed in respiration. Too much water can drench the roots and kill the plant.

CHAPTER 3

IMPACT OF DIFFERENT GLASS TYPES ON PLANT GROWTH

A STUDY ON PLANT GROWTH RESPONSE TO DAYLIGHT TRANSMITTED THROUGH GLASS WITH DIFFERENT SPECTRAL ABSORPTION - CONDUCTED BY THE AUTHOR AT MIT THE SPRING OF 1986.

Discussion

With the advent of large glazed buildings, energy consciousness designers have resorted to technical and architectural solutions dependednt on glass with reflective and absorbing properties. Reflecting glass has popularized completely glazed curtain walls. However, the low daylight levels, as well as environmental conflicts with reflected glare have not always seemed adequate. Other design solutions have utilized tinted glass in order to cut down heat gain. New glass technology has enabled more ingenious methods, such as applying heat reflective coatings on the glass plate or suspended between plates. Though it seems unquestionable that technical problems including heat control and glare reduction have been well addressed, no actual study has been conducted exploring the possible biological concequences of the impact of the daylight transmitted through these glass types.

Objective

In the wake of these notions this study is intended to increase the knowledge of how plants respond to the solar spectrum when transmitted through the glass types used in large glazed constructions.

Hypothesis

There is strong and persistant evidence that a healthy plant growth is not only dependent on light for energy, but also depends on the combined effect of light intensity,duration, as well as the spectral composition, (sometimes referred to as light quality). Plant responses, such as photoperidism, phototropism, and photomorphogenesis are also tied to certain wavelengths.

It seems plausible, from studies available, to formulate an assumption that plants are extremely sensitive to small changes in spectral distribution. These nuances,which maybe not noticable to the eye, can presumably affect plant development.

Most research, often conducted in laboratory environment, has concentrated on exploring the impact of specific wavelengths on plant response. Only a few studies have looked at the influence of the transmitting media, and even fewer have touched the eventual impact of various glass types. In order to obtain more information, the author choose to conduct an experiment on site at The Massachusetts Institute of Technology.

Materials and methods

Glass types

Six specific glass types with different spectral properties, were obtained from Guardian Industries. All glass types, but one, were insulating units with Low-E coating. Two of the six were also laminated, as it was expected that laminated glass will be used in sky lights for safety reasons

Four commonly used tints were chosen assuming that varying spectral distribution would have an impact on the result: Clear, green, bronze and gray.

The glass delivered from Guardian Industries are grouped below in accordance with the number of the test cell, which they were placed on.

Outboard lite — Inboard lite

1. Low E on 1/4" green + 1/4" clear float glass
2. 1/4" clear float + 9/16" clear laminated

The laminated glass is made up of (1/4" clear, 0.060 vinyl, 1/4"clear)

3. Low E on 1/4" clear + 1/4" bronze
4. Low E on 1/4" clear + 1/4" gray
5. Low E on 1/4" clear + 1/4" clear
6. Low E on 1/4" clear + 9/16" clear laminated

It was also decided to cover one of the test cells with just 4mil polyethylene (rather than a glass sample), in order to observe if longwave ultraviolet radiation might have a possible influence on the result, and to enable a comparison with a previously tested material. Test cell 5 was thus divided into two separate parts: (5a), polyethylene and (5b), Low E on 1/4" clear + 1/4" clear as above.

The data obtained from the manufacturer showed transmission differences between glass types. Both transmitted ultraviolet radiation and total visual radiation, as well as near infrared radiation distinguished each glass type. Submitted spectrographs from Guardian also gave a graphic visualization of the inherent spectral properties.

Experimental method

The specific phenomenon, had to be separated from other influencing factors, in order to create a comparable environment. Thus, it was decided to neutralize the average daylight transmission differences in order to obtain a pure spectral comparison between the different glass types. It was also essential for the experiment to equalize air, and soil qualities between each test cells, as well as allow transmitted light and temperature levels to be evenly distributed. The plant choosen for the experiment should respond to the intended observations.

Site

A site had to be picked, which allowed unobstructed daylight to enter the testcells. After a few alternatives it was decided to place the test site on top of the existing Solar House, at the west end of Briggs Field.

Construction

Frame

The weather was expected to be cold during the the experimental period, and a weather tight construction with good insulating values was determined necessary. The size of the enclosure was dependent on the size of the choosen test cells. Each cell had to be 2ft x 2ft, in order to create enough space for an adequate numbers of plants to develop within each cell. It was also necessary to keep the size of the volume at a minimum for economical reasons. Thus, it was decided to use 3/8" thick and 4ft x 8 ft large waferboard as the basic construction material. It was utilized to its full extent as floor construction or cut to size and assembled as floor and wall panels filled with R11, $3^1/2$" thick insulation, fastened to a frame of 2" x 4" studs.

Roof

Clear ACRYLITE FF, 4ft x 8 ft sheets, from Cyro Industries was used as a transparent roof skin and screwed tightly to studs at each end of the base. Polyethylene, NBS voluntary standard PS17-69, 4 mil thick, was fastened on the inside of the pitched roof and spaced 2" from the acrylic, in order to diffuse the sunlight and minimize heat losses. The gables, made of acrylic sheet, were designed to be easily demountable, in order to enable ventilation and access to the testhouse.

Walls

The walls, 2ft high, were cladded with triple polyethylene to half the hight, to create a water tight soil basin and protect the plants from soluble salts in the waferboard. The remaining part of the walls, 1ft, were painted white with a latex coating to scatter the light and protect the plants from contact with the raw board. The test cells were separated with white painted waferboard, which did not quite reach the soil, but left some cracks for free air movement between the cells. The cracks were, however, covered with black rubberstrips to protect the from seeping light.

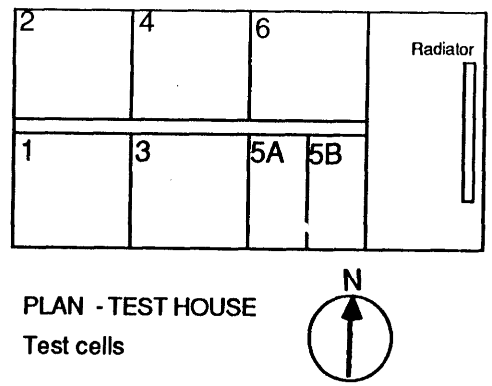
The glass plates were placed on top of weather strips and held down by their own weight.

Ventilation and drainage

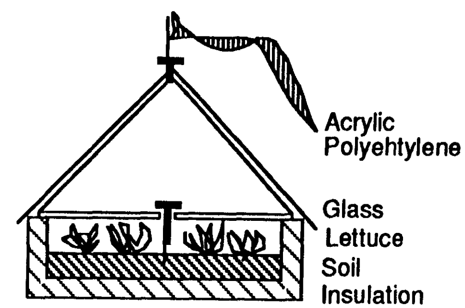
A horizontal 2" opening for drainage was arranged along the bottom end of the soilbasin. Small 1" holes were drilled out between each test cell to enable free air movement. Six inch long pieces of a 1" rubber hose were tightly stuck into the holes to protect the plants from seeping light. However, during the test period it was noticed that the ventilation needed to be improved and more holes, with similar details, were also drilled to the outside. Later improvements of the enclosure included a horizontal ventilation exhaust along the separating middle wall. It was also decided to cut out a 2ft x 3ft opening in the acrylic sheet to allow for longwave ultraviolet radiation to reach the test cells closest to the opening.

Layout

The size of the foorplan made it possible to place the test cells side to side in a 2 x 3 pattern and still allow for some free space at the opening. The created void was equipped with a 750W electric radiator and a gutter for drainage. The six cells were later expanded to seven, or actually five full test cells and two half test cells. The test house was oriented with the longer sides facing north and south respectively. Counting from west to east the test cells closest to the north side were number 2, 4, and 6. The south side test cells were numbers 1, 3, 5a, and 5b. (See fig of test house plan and section.)



PLAN - TEST HOUSE
Test cells



SECTION TEST HOUSE

Spectral Intensity

To neutralize the impact of varying intensity transmitted through the different glass types, it was necessary to measure the average transmitted light in each test cell. The manufacturers own data, indicating the magnitude of the transmitted light, was used as a first base. Actual light measurements were also conducted for each cell to complement these data. A Minolta light meter was used for these readings. The lightmeter is cosine and color corrected, but graded to be sensitive to the human eye's photopic spectrum. The data recorded was used to calculate necessary reduction of area for each glass type, in order to correlate and equalize the transmitted energy to each test cell. Regular duct tape was taped onto the glass in a symmetric pattern to allow an even light distribution.

Monitoring equipment

The changing external climatic conditions, and the possible impact of temperature differences on the plants, made it essential to install temperature recording equipment. 7 different thermistors were connected to 6 of the test cells and one was utilized to record the soil temperature. The air temperature in the test cell(5b) without a thermistor was estimated to equal the data obtained from its neighbors. Recordings of external minimum and maximum ambient temperatures, and percent of available sunshine, were also collected from the daily local newspapers.

Soil

The whole basin was filled with a 12" deep layer of sterile, weed free, fabricated Pro-mix soil; and carefully saturated with water. Any exess water was drained out.

Crop

It was decided to use a common, realatively fast growing lettuce seed, which could be easily monitored, and comparable, to other test results. Grand Rapids seeds, from Stokes Seeds

Ltd, which has a normal growth period of about 45 days and is well adapted to ultraviolet radiation , were sewn in small, $1^{3}/4"$ x $1^{3}/4"$ x 2", individual peat-pots and covered with 5mm soil mix. They were centrally placed, in bunches of ten, on top of the soil in each test cell, and the cells were covered with the tested glass types. The peat-pots, with an average of two seeds, evenly spaced in each test cell and transplanted after two weeks into the soil with the seedlings. A procedure was used to avoid root damage, and prevent transplant shock mortality, caused by mechanical transplanting.

Test period

The first crop was sewn Feruary 10, 1986, and cultivated April 30, 1986.
A second crop was sewn April 5, 1986 and is not cultivated at this time.

Observations

The seeds were planted February 10, and the weather was rather typical for the season, that is cold, and an approximately 50%/50% mix of overcast with snow, and blue skies with sunshine. The average sunshine for the germination period between February 10 to March 3 was actually calculated to 48% of available sunshine. This is also reflected in the relatively wide temperature swings of the peat pot soil, ranging between a minimum of 37°F to a maximum of 89°F. The soil temperature increased when the sun was shining. This could be expected, because at this stage the peat pots were still placed on top of the major soil basin and could hold very little mass. When the peat pots were submerged into the soil on March 3 the temperature span decreased drastically, between a minimum of 52°F to a maximum of 67°F. There were also signs of overheating of the ambient air in the test cells. This was noticed for the first time on March 15, when the maximum reading slightly crossed over the 100°F mark. It was decided to alleviate this phenomenon by flipping the glass plates to atrium mode, that is with the Low-E coating on the inside of the outer glass plate, or number 2 as seen from the outside so solargains would be minimized. The first tiny signs of cuttlings were noticed on March 15. The medium hight seemed to be between 2mm to 5mm, and test cell 6 was showing the least signs of sprouting. The decission to flip over the differrent glass plates did not seem to have any effect. The ambient air temperature was still high, and a second step to cut down the tendancy to overheat was implemented. Every test cell was connected with an upper and a lower 1" hole for better convection flows. The holes were tightly fitted with a 6" long rubber hose. and eventual cracks were sealed with caulking. The soil was still moist from the first watering. Recordings of the first existing cuttlings were made on March 16.

First observation

Test cell	No. of cuttlings	Hight (mm)	Comments February16, 1986
1.	9	5-8	Signs of grey mould
2.	15	~5	Cuttlings look healthy
3.	12	~5	Cuttlings are a little yellow
4.	6	3-5	Only a little mould
5.	5	5-8	Signs of grey mould
6.	7	3-5	Cuttlings a little yellowish

On that same day, a UV-window, 2ft x 3ft, was cut out of the acrylic roof facing south. Studs were mounted to support the edges and a polyethylene film was added as a replacement for the acrylic sheet, and fastaened with caulking to the existing acrylic. On February 17 and the 19, new scannings of the conditions revealed some very dramatic development.

Second observation

Test cell	No. of cuttlings	Hight (mm)	Comments February 17, 1986
1.	14		Some condensation on the glass
2.	17		A lot of condensation on the glass
3.	15		Some condensation on the glass
4.	12		Some condensation on the glass
5.	10		Most condensation on the glass
6.	16		Some condensation on the glass

Third observation

Test cell	No. of cuttlings	Hight (mm)	Comments February 19, 1986
1.	19		No condensation on the glass
2.	24		No condensation on the glass
3.	18	20	No condensation on the glass
4.	17		No condensation on the glass
5.	18		No condensation on the glass
6.	21		No condensation on the glass

February 23. A thermistor was pressed down about 20mm into one of the peat pots, to get better readings of the soil temperature.

February 25. It seems to be warmer in test cells along the south side.

February 26. Test cells 1 and 2 showed night time temperatures around the freezing point.

February 27. The peat pots in test cell 5 were divided into two groups, with five pots in each, and placed in two separate test cells, 5(a) and 5(b).

Fourth observation

Test cell	No. of cuttlings	Hight (mm)	Comments February 27, 1986
1.	23		Most developed cuttlings were 2.
	27		around 30mm tall, with two
3.	23	30	caracteristically heart-like
4.	21		shaped leaves. See fig.
5(a)	14		
5(b)	10		
6.	22		

March 3, it was time to transplant the peat pots. Pictures were taken of the plant development, but unfortunately they never came out right. However, some observations were interesting. Most developed cuttlings were around 50mm tall, with a third center leaf. However, plants in test cell 3 were clearly elongated and about 75mm tall.

Fifth observation

Test cell	No. of cuttlings	Hight (mm)	Comments March 3, 1986
1.	23	50	slow growth.
2.	27	50	-
3.	23	75	clearly elongated
4.	21	50	-

5(a)	14	50	fine sturdy growth
5(b)	10	50	the slowest growth.
6.	22	50	fine sturdy growth

After two weeks of fast development the growth seemed to slow down, but also maintained a steady pace.

There were, however still some problems with overheating, and new ventilation holes had to be drilled to the outside. The technique was the same as for interior holes. A 6" long rubber hose was fitted in a ø1" drilled hole and covered on the outside with a light trap to protect from direct light into the cells.

Documentation pictures were taken on three different occasions during the experiment. April 2, 21, and 30, 1986. (A set of pictures of the last photo session is included at the end of this chapter.) On all occasions it was possible to detect a few differences in plant growth between the test cells. A general estimation of the plant growth was also conducted the first two times.

Sixth, and seventh observation

Test cell	Comments April 2,and 21, 1986	
1.	Rather slow	Pictures were taken on all
2.	Well developed	occasions. Scale was indicated
3.	Elongated	with a ruler.
4.	Medium	
5(a)	Good development	
5(b)	Uneven development	
6.	Rather slow	

It was time to harvest the mature crop on April 30, 1986 because of high outside temperatures. Pictures, and measurements were taken and data was recorded as documentation. The fresh weight was measured with a regular balance scale. It is presumed adequate to measure fresh weight as living plants will be used in atriums. (See pictures of the last photo session at the end of this chapter.)

Eighth observation

Test cell	Number of stems	Fresh weight grams	Length avg. mm	Thickn. Ø mm	weight per stem	Comments April 30 1986 Color growth
1.	21	355	450	2-6	16.9	Even bushy growth Pale-green
2.	19	674	550	4-12	35.5	Rather even growth Pale green, whitish,at the bottom
3.	21	459	21.9	2-7	475	Bushy growth Whitish pale green Scorching at the top

4.	16	400	550	2-9	550	Uneven growth Pale green Scorching at the top
5(a)	13	445	34.2	7-10	575	Even strong growth Not so pale green
5(b)	8	211	26.4	3-10	450	The plants growing towards the light Pale green
6.	21	306	14.6	2-7	375	Uneven,bushy growth Pale green

Discussion

The scale of this experiment is for several reasons necessarily small,and the resources limited. It is plausible that all influencing factors have not been detected or satisfactorily remedied. However, the ambition to isolate the investigated variable, that is the spectral distribution, has been a prime concern. Some problems encountered are, for instance the relatively high temperatures in the test cells during sunny days, and low temperatures at some very frosty nights. It was necessary to increase the ventilation to modify the high temperatures, but also to increase the air movement in the test cells. Slow air movement could possibly affect the concentration of carbon dioxide and condensation could create conditions for fungi. Mould was actually observed at the beginning of the test period, but was seemingly satisfactorily controlled by new arrangements and technical solutions. Probably the most severe unaviodable factor, was the relatively low light levels, depending on the season but also the tested materials themselves. The experiment had to be executed during rather stable conditions, presumably inside, as it was essential to enable some control of the impact from foul climatic conditions,like rain, frost, etc. The shielding transparent test house had to be there, and the transmission values of the different glass types were given. The plant used for the investigation is the only factor that actually could have been changed. Lettuce often need light intensities up to 1500Fc, while the real levels inside the test cells at the worst occasions during an over cast day could reach approximately 200Fc. Considering all these hampering variables, there are still some major observations during the experiment that can be explained. For instance, the prolonged growth period, the spindliness among plants in some test cells, the often found uneven growth, but maybe most important the significant difference in growth between the test cells.

The long growth period is probably due to the relatively low light intensities. The light intensity was probably not not been high enough for an efficient photosynthesis, affecting the production of carbohydrates and the plant growth. However, there should not be a considerable difference between the test cells, as they had been calibrated to transmit equal amount of average daylightlight. A possibility remains that the actual calibration, due to the light meter measuring most efficiently in the green-yellow spectrum, did not consider actual differences in energy. It has to be reminded though, that the object of this experiment is to test plants in an environment simultaniously used by people as well as plants, why it is pertinent to use footcandles as an intensity unit for easy comparisons in a glazed construction.

It is probably relevant to point at the relatively low light intensity also, as the cause for the spindly and uneven growth. One other factor could be uneven distribution of light. Signs of phototropistic response could be traced in some plants search for light. The stems were pointing in the same direction towards the slightly brighter southfacing internal walls. However, this response was not observed in all test cells at all possible locations for this reaction.

The differences in plant growth between the test cells is the most striking observation. It must be feasable that differences in spectral distribution between the tested glass types cause this reaction. The early elongation of cuttling stems in test cell(3, bronze), might be an effect of a relatively high proportion of wavelengths between 600nm to 800nm. A high proportion of red wavelegnths is interestingly also found in light transmitted through, gray glass. There was some indication of elongated growth in the test cell(4) with that glass, but not as pronounced as in test cell(3). It is also posible to point at temperature differences as an affecting parameter. Test cells (3) and (4) seemed to run warmer than any other cells, maybe effectuating elongation. However, the temperature differences between the test cells and growth do not correspond. Growth in the warmer test cells (3) and (4) is intermediate between the poor and good growth of other test cells. What is even more remarkable, the average temperatures in test cell (1) and (2) are quite similar, still the yield is drastically different. (See fig of average temperatures)

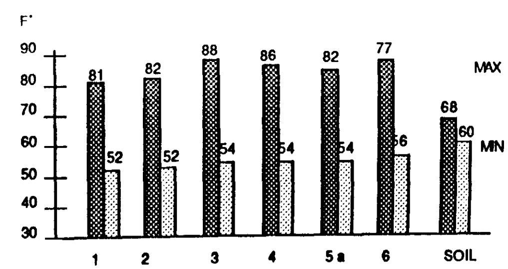
Looking at the different fresh weight data it is evident that the results can be placed in three groups:

A. Test cells (2, laminated clear) and (5a, polyethylene) with a high yield.

B. Test cells (4, Low-E, gray) and (5b, Low-E, clear) with a medium yield.

C. Test cells (1, Low-E, green) and (6, Low-E, laminated green) with a low yield.

Test cell (3, Low-E, bronze) is swirling between the low and medium yield.

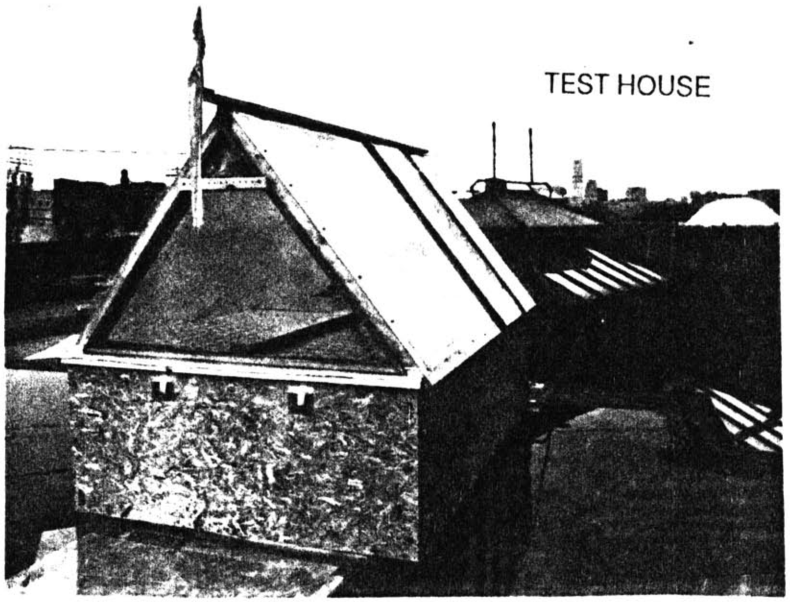


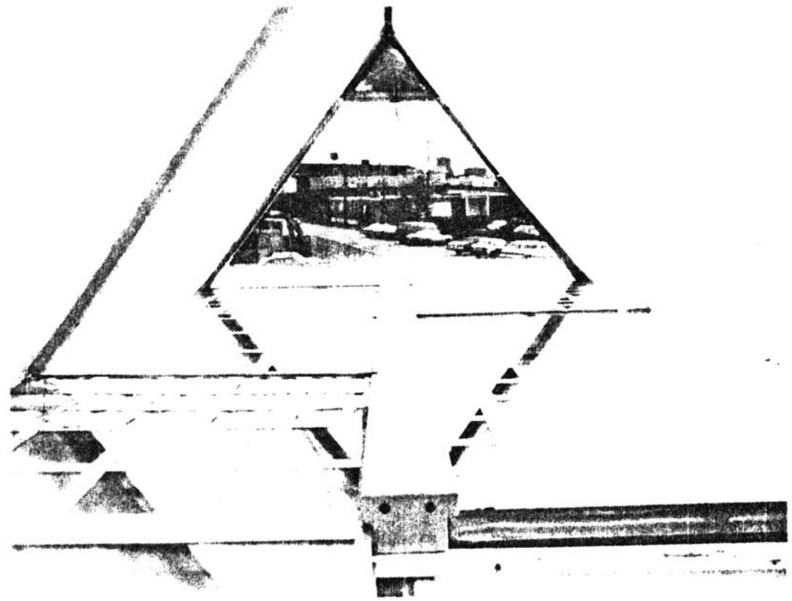
AVERAGE MAXIMUM AND MINIMUM TEMPERATURES FOR EACH TEST CELL MEASURED FOR THE WHOLE TEST PERIOD

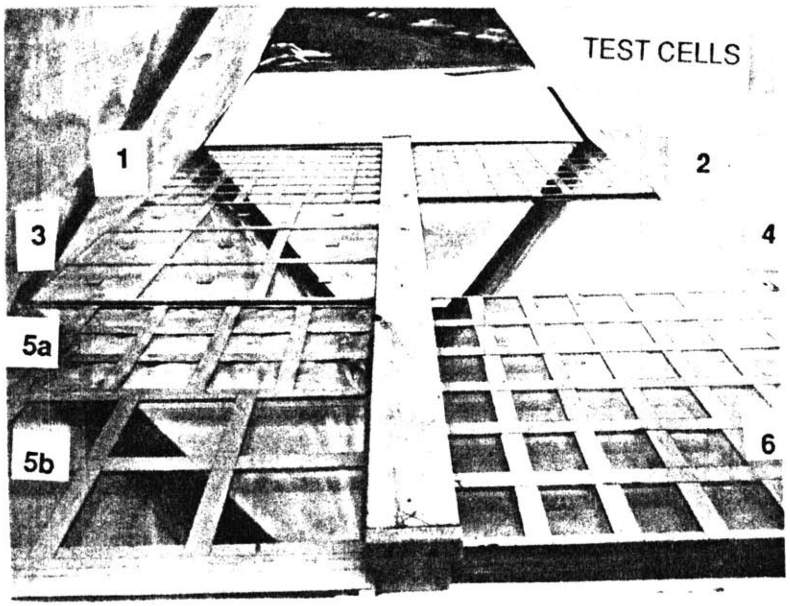
It is interesting that the glass types that let the spectrally least affected daylight through promote a higher yield. One result mediating this observation is the relatively poor plant growth in test cell (5b, Low-E, clear). This is possible due to the fact that very few stems eventually grew up in that cell. However, there is still a drastic difference between Low-E, clear and those transmitting relatively much in the green spectrum, which seem to perform the worst. This could possibly be explained by the specific properties of photosynthesis, regularily reacting more actively to wavelengths in the red and the blue spectrums. That is the plants could not efficiently utilize the energy in the green spectrum. There are indications that this is especially true for pale green plants like lettuce. Another interesting interpretation of the result is the fact, that ultraviolet radiation, insofar as it reached the plants, neither was beneficial nor damaging. The good yields of both test cell (2, laminated clear) and (5a, polyethylene), the latter exposed to longwave ultraviolet radiation, might support this interpretation.

Conclusions

It is possible that all the influencing factors affecting plant growth response to the spectral distribution of transmitted daylight through different glass types, have passed undetected in this experiment. One condition which could have affected the result is the differences in temperatures, though the test findings do not give any indication of correlation between yield and temperature. Other affecting factors might be differences in transmitted energy and the small scale of the project. However, the results indicate sufficiently a relation between the spectral ditribution and plant growth. It seems possible to attach a strong link between the full spectrum distribution, and a good plant growth. That is, panes with clear glass, or another material that lets untainted daylight through, will stand a better chance to support a strong and healhty plant growth.







The different glass plates on top of the test cells are shaded with tape in symmetrical pattern to compensate for varying transmission properties


1. APRIL 30

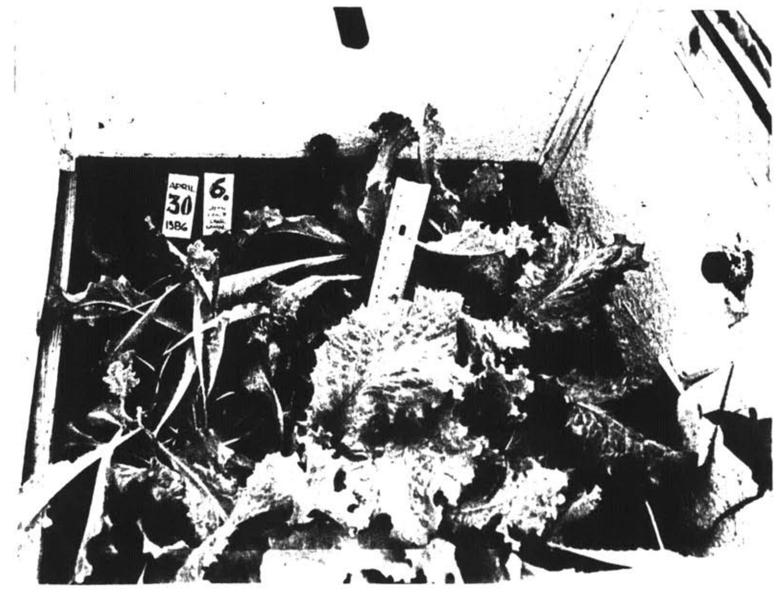

2. APRIL 30 1986


3. APRIL 30 1986


4.
APRIL
30
1986


APRIL
30
5A


APRIL
30
1986
5B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PART 2 : DESIGN GUIDELINES FOR A HEALTHY PLANT GROWTH AND HUMAN HEALTH AND COMFORT IN ATRIUMS

CHAPTER 4
MAJOR LIGHTING MEASURING METHODS

Discussion

It is not within the scope of this thesis to reprint different daylighting methods, the original sources are extensive and readily available. However, some general remarks regarding the usefulness and appropriateness of different methods are beneficial to the knowledge and experience of how daylight enters buildings.

First of all, it is essential to understand the physical, physiological, and psychological factors that govern our perception of light. Psychological factors in this case, is a broad generalization of several compounding variables, some of them mentioned in chapter 1. That is, illumination levels, may not have any influence at all over comfort, convenience, performance, or aesthetical preferences. However, as some light is necessary to even conceptualize forms, there is a logical agreement, that architecture is created from light. The intriguing questions could possibly be narrowed down to what quantity is sufficient to enable certain performances, and how the least amount of light should be distributed to enhance the perception of the environment.

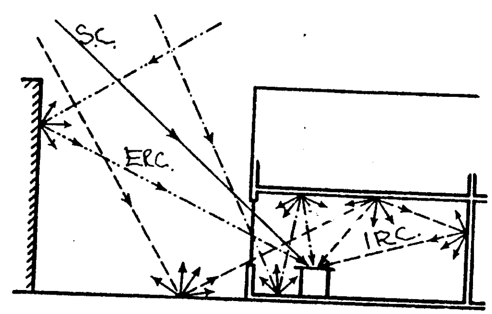
The second obstacle which has to be surmounted, once some creteria for a suitable illumination level has been settled, is how these lighting levels and quality perceptions should be predicted at the design stage. There are several methods for calculating the intensity of illumination , some which are more detailed than others. Traditional calculation methods, such as the point by point method, and the lumen method, have utilized formulas and tables. The point by point method is tideous, but useful in determining isolux contours as it allows for more detailed calculations. The size and the position of the window, as well as the position of the specific points, affect the calculated values, and usually maximum, average, and minimum levels are determined. The more crude lumen method will suffice if estimations of average intensities are adequate for the solution, but will not consider the impact of different window positions. Other methods include utilization of protractors to predict the sky component, and can be sufficiently accurate for measuring the influence of overhangs and vertical fins. Recently the useful range of the protractor method has been expanded to consider the impact of the sun and the orientation of the windows.

The introduction of low cost micro computers have spurred the development of several soft ware programs for daylighting, besides the more elaborate and expensive main ship in computer programs, the DOE-2, developed by the Department of Energy in the U.S. The different programs utilize graphics to visualize illumination contours, and can be monitored for quick alternatives. However, difficulties in supplying the computer with relevant information can lead to deceptively accurate measurements, maybe based on wrong assumptions.

The most accurate method today for daylighting calculations, despite modern technology, is physical modelling. The model can be hastily manufactured, without hampering the overall accuracy, and also supplies the designer with valuable information of subtle light qualities, such as shades,colors, contrasts, and textures. It is generally best to test the model under real sky conditions, but an artificial environment simulating the outside world, is advantageous if the weather does not permit regular testing. It is possible to build affordable artificial light-boxes, which are simulating overcast conditions satisfactorily. MIT, actually owns one and it was utilized for the experiment discussed in chapter 6. The idea behind the light-box is simply a bright artificially lit horizontal ceiling made of translucent sheeting with mirror-cladded walls. The scale of the model tested can vary depending on desired accuracy, but generally it is easier to get a reliable result from a large scale model of approximately 1: 50 (SI standard) or 1/4" = 1'-0" (U.S. standard). Photographs of the lighting model will enable good evaluation, and an often strikingly true-life atmosphere.

However, there are circumstances, especially early in the design process, when some rough estimations of conceived solutions would facilitate correct decisions. These rule of thumbs can often be handy in evaluating average illumination levels, and several methods have been suggested.

The regular approach, regarding illumination levels, is to describe the efficiency of the suggested design in daylight factors. When the external horizontal illumination changes, the interior light level changes simultaniously and proportionally with the combined effect of three different parameters. Namely, 1, direct sky component(SC) 2, external reflective component(ERC) 3, internal reflective component(IRC). (R.G.Hopkinson et al, Daylighting, p.69 fig3.3) The summation of these parameters, the daylight factor(DF) is expressed as the ratio between the internal daylight at a certain point to the available external daylight, and is usually quoted in percents. All these factors imply several influencing variables, which all should be known in order to get an exact result. It is obvious that a simplified method has to exclude many variables at the cost of less accuracy.



Sidelighting

Sidelighting is more affected than toplighting, as the external reflective component, is changing with the location. Obstructing buildings, vegetation, and different reflective ground material might influence the total daylight factor, beyond a rough estimate. However, one example of approximazation suggests a simple rule-of-thumb for single sided unobstructed rectangular rooms. The daylight factor is expressed as directly related to the ratio between the net glass area(Ag) to the total floor area(Af) multiplied by a factor of 0.2, for average illumination, and 0.1 for minimum illumination. (H.Bryan et al, Daylighting a Resourcebook, p.5-46, unpublished)

Sidelighting rule-of-thumb.

Method 1.

$D.F._{avg} = 0.2\ Ag/Af$

$D.F._{min} = 0.1\ Ag/Af$

The method seems to be related to Früling's formula, which expresses the average daylight factor as a product of a window factor(F) and coefficient of utilization(U) times the ratio between the net glass area(Ag) and the total floor area(Af). F= 0.5 for an unobstructed room, and U can vary between 0.2 to 0.5, but it is suggested to use 0.4. (R.G.Hopkinson et al, Daylighting, p280.)

The size of the room is necessarily an influencing factor to be considered. It can conveniently be calculated that any increase in room size, above a normal room ratio of 2:2:1 (length, depth, height), will effectuate a decrease in the daylight factor at 20 ft from the window, which is equal to half the proportional change of the total surface area. (R.G.Hopkinson et al, Daylighting, p277.)

$\Delta D.F. = \Delta A_{totsurface} \times 0.5$

The position of the opening also affects the illumination level. The higher the window head, the better the light penetration deep into the room. That is, a vertical window with the same area as a horisontal opening will allow less light deep into the room. The effect of a clerestory window could be an increase of about 50%. However, the same horizontal window placed as a low view window will cause a reduction of 50% compared to a normally placed window. (R.G.Hopkinson et al, Daylighting, p277.)

Another interesting formula for calculation of the average daylight factor is known as the Littlefair/ Plymouth expression. It is expressed as dependent on the total surface area instead of the floor area.

Method 2.

$D.F._{avg} = t\, A_{glass}\, ß \,/\, 2 \times A_{tot\ surface} \times (1-R^2)$

t= diffuse transmittance of glazing material.

ß= the angle subtended, in degrees, from the center of the window to the free sky. The use of this angle enables calculations where considerations can be taken regarding obstructing objects. (D.C.Pritchard, Lighting, p.108)

It is interesting to compare the two methods mentioned. Consider a room with all sides 10ft long and one wall completety covered with glass.

R= average reflectance of all room surfaces.

Method1.

$D.F._{avg} = 0.2\ Ag/Af$ and $Ag=100$, $Af=100$ gives $D.F._{avg} = 0.2$ or 20%

Method 2.

$D.F._{avg} = t\, A_{glass}\, ß \,/\, 2 \times A_{tot\ surface} \times (1-R^2)$

Assume t=1, ß=90 (no obstruction), R=50%

$D.F._{avg} = 1 \times 100 \times 90 / 2 \times 600(1-0.5^2) = 9000/ 900 = 10\%$

There is a difference of 100% between the methods and that might be expected

Toplighting

The Früling method can also be applied for estimations of toplighting, exchanging the sidelighting factors for others, associated with skylight monitors.

Toplighting rule-of-thumbs. 50% average indoor reflectance.

Method 3.

$D.F._{avg} = 0.20\ Ag/Af$ -for vertical monitors

$D.F._{avg} = 0.33\ Ag/Af$ -for north-facing sawtooth openings

$D.F._{avg} = 0.50\ Ag/Af$ -for horizontal skylights

Other sources suggest a little different approach, involving a room ratio, or sometimes called room index.

Room index = l x w / (l + w) x h

Method 4.

$D.F._{avg} = U \times Ag/Af$

U= coefficient of utilization dependent on room index, light-well efficiency, and other transmission loss factors.

The method could be useful for atriums, if the coefficient of utilization tables were expanded to include taller structures. As it is now, the room index only covers ratios up to 0.6, which is a space with a room height less than its sides. However, it seems possible to use the table for well efficiency to obtain a relatively reliable result. The results have been tested against emperical studies discussed in chapter 6. (H.Bryan et al, Daylighting A Resourcebook, p.5-46 fig.15, unpublished)

Method 5.

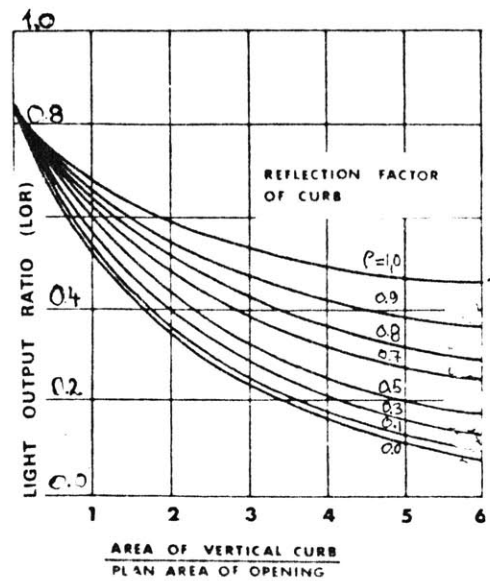
$D.F._{avg} = E_w \times Ag/Af$

E_w = efficiency of well

Well index = well height x (well width + well length) / 2 x well width x well length.

Table 1. (H.Bryan et al, Daylighting A Resourcebook, p.5-46 fig.15, unpublished)>

Still another approach is taking into account the shape of the skylight skirt along with the size of the opening and reflectance considerations. Lynes is expressing the daylight factor as variable dependent on LOR, or the light output ratio times the ratio of the glass area to the floor area divided by the impact of floor and ceiling reflectances. (Lynes, Principals of Natural Lighting, p.103)

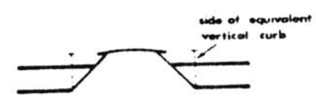


Light output ratio of rough-cast glass (

Method 6.

$D.F._{avg} = LOR \times A_{glass} \;/\; A_{floor} \times [1-(R_{floor} \times R_{ceiling})]$

LOR is calculated from a table, and is dependent on the ratio of the vertical curb area to the opening area, and the reflectance factor of the curb. (Lynes, Principals of Natural Lighting, p.102, fig8.2) It is also claimed that a splayed skirt will increase LOR to a value equivilent to the output ratio of an upright curb with the same ceiling opening as the horizontal internal area covered by the splayed skylight. (Lynes, Principals of Natural Lighting, p.101, fig8.1) A simple use of the table indicates that 2ft deep, 10ft by 10ft opening, is about 13 % more efficient than a vertical opening of the same size. The improved efficiency increase to appximately 33% if the depth of the opening is10ft. The average reflectance was assumed to be 50% and the splay 45°.



dome with splayed curb.

Another method to approximate daylight factors generated by toplighting in atriums has been investigated by the author and will be discussed in chapter 6 of this thesis.

There are many aspects of the distributed daylight that affect our perception. An efficient illumination is not necessarily bright. On the contrary, the problems related with too bright light, might overshadow the existing qualities of the space. A good daylighting design is funtionally efficient and enhances the shapes, the color nuances, the desired textures and the envisioned mood, and add a touch of mystery. Still, adequte light intensities for plants has to be maintained if a healthy growth is considered a part of a serious design. These sometimes diametrically opposite requirements might lead to conflicts that creates poor conditions for both people and plants.

CHAPTER 5
DESIGN GUIDELINES FOR QUALITY ATRIUMS

DISCUSSION

Any design starts with an envisioned function, with limitations set by the location as well as the technical and economical possibilities. A good design has merged the restraints into a functional living space with aesthetical qualities. It is possible to defy the impact of site related climatic conditions and pay the price of either high energy costs or hampered comfort. However, a concept in tune with the climate mediates and utilizes the influence of the sun and extreme temperatures, while responding to the influence of culture, tradition and the existing physical built environment. These notions form a first base for a good atrium design harvesting specific climatic conditions to create an architecture indigenous to the site.

Technical parameters affecting a good atrium design.

In the previous chapters it has been explained what biolocical, physical, and to a certain extent, psycolological cultural and social properties that set the limits for survival, health, and comfort in a built environment. But, how should these requirements be met and what are the possible technical and architectural solutions to balance several contradicting conditions, while creating a comfortable and pleasing indoor environment?

Daylight

Daylight affects our perception of a space in many ways. Efficient illumination is not necessarily bright. On the contrary, the problems related with too bright light might overshadow the existing qualities of the space, "because the quantity of light is not nearly as important as its quality". (Rasmussen, S.T, Experiencing Architecture, p.189) A good daylighting design is funtionally efficient and enhances the shapes, the color nuances, the desired textures and the envisioned mood, and adds a touch of mystery. Still, adequate light intensities for plants have to be maintained if a healthy growth is a part of a serious design. These sometimes diametrically opposite requirements might lead to conflicts that creates poor conditions for both people and plants.

Modes of daylight

Daylight has different modes, which all can be positively utilized if applied properly. It can create a sense of time, movement, orientation, tranquility or activity, and pronounce nuances of colors and shapes. The relatively uniform daylight of overcast skies gives a mellow, inactive, even light with few contrasts and an apparent feeling of spatiousness. Diffused sunlight is somewhat stronger in contrasts, more directional and warmer in color. Redirected sunlight creates a modified transition zone between the bright outside and the darker inside. Direct sunlight is an asset for intentional contrasts and playful manipulations with shadows and strong relationship with the outdoors. The rich range of shades enhances volumes, textures, directions, and promotes a strong sense of enclosure. Colors can also appear more saturated in sunlight, though reflections from sunlit surfaces can create a specular appearence, thus fading the sensation of color.

Location

The site choice in a rural landscape and sparcely urbanised areas is especially sensitive to the impact of microclimatic conditions. The topography as well as existing vegetation and wind directions affect the climate and has to be considered. An urban site is more uniform and the microclimate is dependent on existing buildings around the site. Access to fresh air and unobstructed views are limited. Surrounding tall buildings can cast shadows over the site diminishing the intensity of the sun as well as curtailing adequate access to daylight. Increased wind speeds and turbulence, due to escalated and fluctuating air pressure around tall buildings, can also affect the structure of the atrium, as well as the comfort and safety of entrances and pedestrian walkways.

Orientation

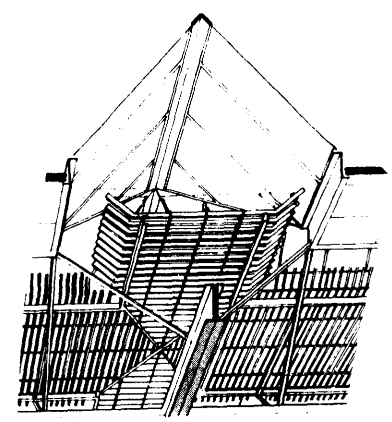
The massing and orientation of the volumes and glazing that embrace the atrium have a profound effect on the climatic performance. The balance of heating and cooling is mainly dependent on the existing climatic conditions, but proper massing and orientation can enhance or reduce the impact of the sun. Commercial structures have high internal energy loads, and it is usually advantageous in temperate climates to minimize the heat gain. Energy performance is directlty affected by the orientation and the tilt of glass surfaces. Seasonal changes and diurnal differences in solar altitude favor a longitudinal east-west orientation. Northfacing glass is the most attractive solution for reducing heat gain, but the high and hot summer sun shining from the south is also relatively easy to control. However, the eastern and western sun still maintains a high intensity, but at low elevations to the facade, making shading more complicated and energy savings less.

Daylight control

Glare

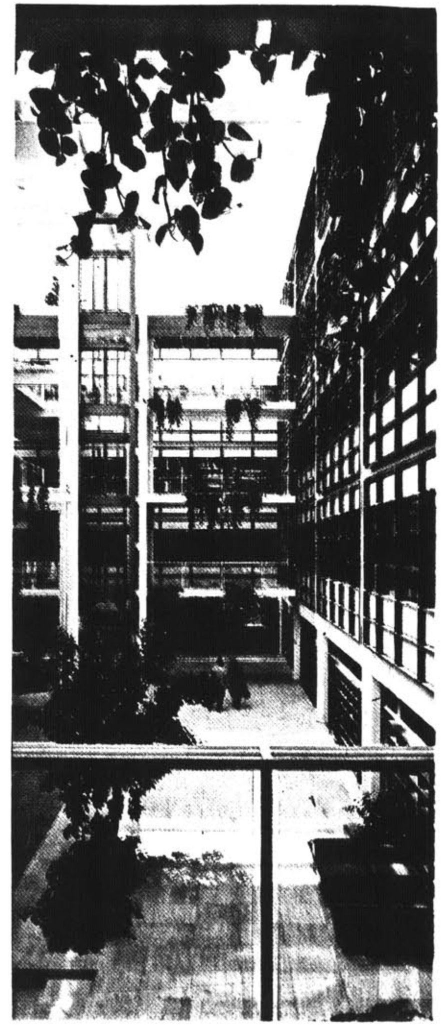
Many attempts to maximize the transmitted daylight is curtailed by glare problems as well as temperature related disorders. The solution in modern structures has often been the use of reflective and tinted glass. However, the sensation of glare is the relative experience of too bright light compared to darker surrounds, and emminently affected by the eyes ability to adapt. That is, even quite low light levels can impose a glare problem if the eyes have adopted to a lesser ambient light intensity in the occupied space. There are two ways to overcome the problem. Either an increase of the light level in the room, to adapt the eyes to a higher intensity, or a reduced brightness of the glare source. The approach to reduce the glare source, in this case daylight, has the effect that the light level in the room also decreases, why the annoying glare problem still might exist. The threshold for obtaining a perceived glare reduction requires that the daylight transmittance of the glass is less than 30%. (Hopkinson, R.G., Daylighting, p.325.) The possibly gloomy effect of low transmittance glass combined with a distorted spectrum reaching the interior can hamper human health and negatively affect plant gowth. See chapter 2.

There are other probably more rewarding solutions to glare, which can contribute to the architectural expression as well as the quality of light. The approach is dependent on the mood desired as well as heat gain considerations. Different methods can also have drastic implications for the aesthetical appearance, affecting both massing as well as detalings of the facade. Control devices can be integrated with the structure and the facade or be fixed to the exterior or the interior once the building has been errected. Shading can be applied to the exterior or the interior or within the transmitting media. They can be fixed or movable, automatic or manual, translucent or opaque, horizontal, vertical or eggcrate shaped. The shape of the building can be manipulated to allow self-shading and direct sunlight can be modified by bouncing it off external or internal walls. Some examples are L. Kahn's double wall systems in Bangladesh, I.M. Pei's City Hall in Dallas and an office building in London, 1 Finsbury Avenue by Arup Associates, and of course many traditional old buildings with deep reveals. See figs. The atrium itself can also serve as an indirect diffusing light source reflecting soft light to adjoining offices.



Interior daylight control

The interior of the atrium can be manipulated to reduce sensations of glare, and at the same time add richness to the architectural experience. Canopies of vegetation can be used as a buffer zone for modifing and diffusing the direct light. The more intense light close to glazed openings can be efficiently utilized by sun addapted planting material, while transmitting soft modified light to zones occupied by people and shade grown plants underneath. The translucent pale green bamboo canopies within the atrium of the IBM building in New York, N.Y. is a successful application of this approach. It should also be possible to create translucent "waterfalls" of vegetation close to vertical glazing, if the planting material is carefully choosen and the surface temperature of the glass controlled. Similar use of vegetation on the outside of the glazed fasade can allow for changes with the season, transmitting more direct light in the winter when the heat is needed.



Other daylight control methods involve the use of sunscreens of different material. One interesting examle is I.M.Pei's extension of the Museum of Fine Arts in Boston, U.S.A., where matt finished aluminum rods are placed close to the glass to reduce the direct impact of sunlight and articulate the shape of the roof structure. See fig. More apetizing solutions integrate the screening effect with other functions to create an even richer architecture. Some good examples are Gateway Two, at Basingstoke, and One Finsbury Avenue in London, both in England and designed by Arup Associates. See figs. New forms are developed out of the integration of several functions, such as maintenance and glare control to create aesthetic functional pleasure.

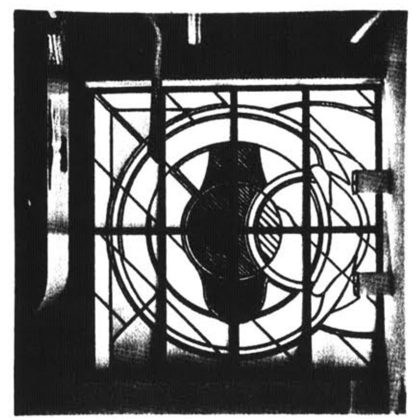
Artistic collaboration and architectural integration

There is also a world open to artistic collaboration and architectural integration with other arts.

The redirection of visual interest to special focal points, will enhance the spatial quality while perceptionally reducing glare. There are many different possible artistic methods to achieve this integration. For instance, textiles can be used as interior flags and banners for the purpose of diffusing as well as redirecting light. Diaphanous sculptures can create interest as well as be used for funtional reasons. Hanging glass prisms and mobiles can refract and redirect light to form changing patterns on surrounding surfaces. The glass surface can be treated with different stained glass methods to create the effect a translucent painting, as well as transmit a secondary image to floors and walls. The author suggests applied use of glass in architecture depending on its function. Transparent glass covering openings should transmit a natural spectrum, while treated glass could be used for special effects. Eggcrate louvres of stained glass can diffuse direct sunlight, while maintaining the valuable vertical light from toplighting during overcast conditions.

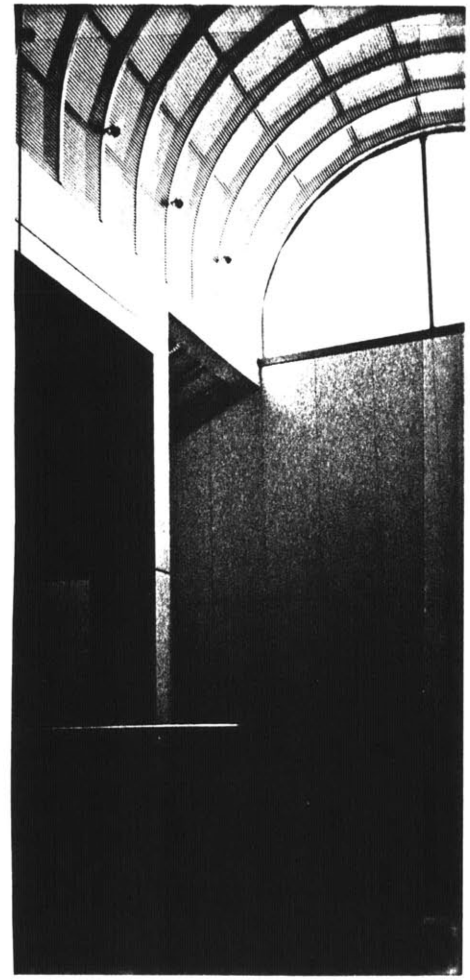
Energycosts

Atriums can contribute to energy savings. The experience from many built atriums is that costs for the total structure is not increased. (The American Institute of Architecture, General Procedings, Building Redesign and Energy Challenges, Boston, November,1984.) However, a general notion is that savings in the U.S., or in locations with similar climates, depend on the air-conditioning load and the desired indoor climate. Lightly conditioned atriums promote savings, while fully conditioned atriums seldom save on energycosts, unless the atrium is enclosed with heat reflective Low-E green glass. (Johnson, T., conversation, Thesis, MIT 1986.)



Fire

There are still many issues regarding fire prevention and smoke control that are unsolved. The natural chimney effect in tall structures may not be enough for smoke evacuation and could cause problems unless supported by powerful fans. Usually the regular return air system at the peak of the atrium is complemented by extra fans in case of a fire in order to evacuate smoke. Another approach is to limit the number of open stories facing the atrium. Fire codes in the U.S. suggest a maximum hight of three open stories. (U.S. BOCOA) The most recent development in Europe separates the function of the atrium, in the case of a fire. The atrium is exclusively utilized as a smoke exhaust channel, while the evacuation of people is concentrated towards fire escapes at the exterior facades. (Butt, L., Arup Associates, conversation London, 1986.)



Ventilation

The need for fresh air and temperature control, usually necessitates mechanical systems for ventilation. The cost for a totally climatized atrium, however, can be high, so natural ventilation should be utilized as much as possible. The authour has noticed that, the ambient air temperature in traditional naturally ventilated palm houses can be quite comfortable even during warm sunny days, if the convective air flow is adequate. For instance, the Temperate House at Kew Garden, London, is totally conditioned with outside air in the summer, and is only heated during the cold season. The Crystal Cathedral by Philip Johnson, in Los Angeles, is relying on natural convection and solar heat gain throughout the whole year. Outside air is allowed to enter through openings at the gradient level, while utilizing natural convection to exaust hot air at the roof top. The effect is caused by air pressure differences between the cooler outside air vis a vis the hotter air at the roof top, so its usefulness is limited to those conditions. However, ingenious techniques to passively increase the temperature difference could be a cost effective alternative to mechanical systems. For instance, solar radiation can be utilized to heat up effective heat absorbing exterior roof surfaces, causing pressure decrease at the roof top and subsequently increased convection. One very interesting energy reducing solution has been designed for the Royal Garden Hotel at Trondheim, Norway. The stratification of air is utilized to minimize airconditioning to the first couple of floors, while hot air is exhausted at the roof top. The concept was tested for an atrium in Dallas, Texas, in the Energy Conscious Design cource at MIT, 1985, with good result. (Gardestad, K., course notes, Energy Conscious Design, MIT 1985.)

Royal Garden Hotel, Trondheim

Temperature control

There are many interrelated factors linking daylight control and light quality with temperature control. Any attempt to mediate the influence of solar radiation on a transparent media has a subsequent effect on light quality. Problems and possibilities related to the use of different glass types has already been mentioned in the section discussing daylight control, which is relevant, because most often treated glass is born out of the sole purpose of reducing heat-gains without considering light quality. However, there are new glass technologies which utilize the different absorbing and reflecting properties of inorganic or organic coatings to reduce heat-gain, while maintaining most of the intensity of the transmitted daylight. (Johnson T., Vol IV, BOOK 2, chapter 2, U.S DOE Documentation Project, MIT Press, 1986.) Some of the emerging methods have not yet been commercially utilized, while others have made a fast move into the market. Most successful among different new technologies is Low-E glass, or low emissitivity glass, with coatings applied directly to the glass surface or to mylar films. The thin metal films, usually silver(Ag), reflects much of the far infrared radiation, while reducing thermal heat. The most effective application of far infrared reflective glass is for residential purposes, but atriums errected in climates with energy costs tied to heat-losses might find the method attractive. The combined properties of Low-E coatings and light green, iron rich, glass has the economically viable effect of absorbing near infrared radiation, while transmitting much of the visible radiation, thus reducing heat gain due to solar radiation. It is posssible to obtain a

daylight transmission of 64% while keeping the shading coefficient at 47%. (Johnson T., Vol IV, BOOK 2, chapter 2, not yet published.) It is about to claim a substancial nische in the commercial market. However, the natural property of green glass to increase the ratio of transmitted green wavelengths, might have negative consequences for plant growth. The possible effects are discussed in chapter 3. of this thesis, and indicates that especially green light, due less efficient photosynthesis, might impair plant development. It has to be pointed out that the small scale investigation is not decisive. Yet, it hints a possible connection.

Artificial lighting

It is not the intension of this thesis to advocate the use of artificial lighting in atriums. On the contrary, much emphasis is put on adequate utilization of natural light. However, in cases where artificial lighting is necessary to maintain a functional light level for photosynthesis, it is important to supply the environment with a full spectrum active light. This does not imply that one light source with this range is the best solution. Combinations of light sources with different wavelengths, might be as effective and at the same time enable adequate lighting of disparate functions. There are two consequential observations regarding lighting for plants, which the author wants to bring to life. It is widely considered to be of vital importance that plants are supplied with relevant light levels for an extended period in order to maintain a healthy plant growth. This is many times the cause for introducing artificial light in the atrium as the daylit period during the winter season is considered to be too short. However, that approach can be contested, for a simple but paradoxical reason. The author noticed at a visit to the Botanical Garden at Kew, London, the spring of 1986, that the Temperate House, built in 1862, had no supplemental artificial lighting, but totally relied on daylight. That was despite of abundant planting material from tropical latitudes expected to be especially sensitive to small changes in daylength. It has to be added that London, famous for its overcast conditions, is situated north of the 50'th latitude with more pronounced differences in daylength than experienced anywhere in the U.S. except Alaska. The conclusion may be daring, but the observation has to be interpreted as a support for the notion that plants in daylit atriums are not dependent on the daylength. Thus, artificial lighting seem to be redundant, as long as the light intensity aquired from daylighting is adequate. The second observation is more a compounded knowledge of phototropistic plant response gathered from discussions with Sasaki Associates in Cambridge, Massachusetts, U.S., and C.Mpelkas at GTE, Sylvania, Danvers, Massachusetts, U.S. Plant tendency to grow towards the light can be avoided, if artificial lighting is applied in a criss- cross fashion, illuminating the plants from all sides. Reflective material, such as whitish crossed marble, can be introduced underneath plant canopies to redirect light to the underside of the leaves, opening the stomates for more efficient photosynthesis, while avoiding plant elongation.

Passive techniques can advantageously be utilized in atriums, by exploiting the natural storage capacity of surrouding surfaces, which is dependent on the density, thermal conductivity, and specific heat properties of the used material. The more mass, the better heat capacity and subsequently less fluctuating diurnal temperature swings, which generally influence climatic comfort and energy costs in a positive direction. The most common and inexpensive way of storing heat is utilizing the dual functions of heavy masonry and concrete constructions as load bearing elements and finishing material. The optimal performance of the mass thickness is influenced by ambient climatic conditions as well as mode of radiation, but generally "the diurnal heat capacity for cementious materials peaks around 11 inches". (Johnson T., Vol IV, BOOK 2, chapter 2, not yet published.) The optimal thickness of materials radiated with diffused light is redused to half.

The surface color has little impact on the storage capacity, as long as the light is diffused and the mass evenly spread out. (Johnson, T., The Direct Gain Approach, p.103.) Dark colors can be utilized to obtain the maximal effect of direct sunlight on a small area. However, an atrium with large exposed surfaces will store heat sufficiently, even if the materials are of light nuances. Besides, the experienced light quality in an airy light atrium will create good conditions for plant growth.

CHAPTER 6

GUIDELINES FOR SKY LIGHT ILLUMINATION IN ATRIUMS - A REPORT ON A STUDY CONDUCTED AT MIT THE SPRING OF 198

Discussion

An atrium is not a quality space unless there is an adequate light level for vegetation. It is a personal remark, which might not pass uncontested. However, the intent of thesis is to supply design methods which can alleviate solutions aiming at a healthy plant growth.

Recommended light intensities

It has been shown in previous chapters that plants are dependent on certain minimum light intensities in order to survive. Any increase in light levels is generally enhancing plant growth. The optimal light level is determined by the origin of the plant species, but also by an individual acclimatization to prevailing conditions. Available sources on plantscaping give slightly varying information regarding optimal hourly light levels for certain plants. This is partly due to discrepancies in calculating duration of required light intensities. However, it is it is customary to divide plants into different groups according to their light requirements. The following recomendations are interpretations of data from Interior Plantscaping by R.Gaines. Plants are divided into four different groups depending on an increasing scale of recommended light intensities to grow well, minimum intensities to keep a healthy green color, and maintenance light levels to sustain over a limited time without growth.

LIGHT LEVELS(Fc) (for 12 hours)	RECOMMENDED	MINIMUM	MAINTENANCE
LOW	75-100	50	30-50
MEDIUM	200	75-100	75
HIGH	500	200	100-150
VERY HIGH	1000	500	500

There is a need for useful calculation methods early in the design process in order to determine average illumination levels and possible growth zones for plants in top-lit atriums. Various calculation methods for average illumination levels have also been presented in chapter 3.

Hopkinson suggests (H.p.202) that illumination levels for extended roof lights roughly can be calculated as proportional to rooflight area to total floor area and that total illumination suitably can be obtained through the B.R.S protractor method or simplified calculation methods (H.p.102). However, no information is given regarding the limits of the method indicating only that detailed illumination calculations for rooflights is not necessary beyond a certain height of the investigated space, presuming that only even light levels are desired. Other methods consider the impact of height, but in the form of a room index, and the prerequisite of an even light distribution. The influence of different reflectances on light distribution is also neglected in many cases. These factors are of significant importance for a thorough understanding of light distribution.

Objective

The purpose of this study is to increase the knowledge of the existing relationship between hight and light levels in top-lit atriums and the influence of different skylight configurations, and reflectances on light distribution. The result could supply the designer with a tool for suggesting pertinent growth zones for plants.

Limitations

It was decided to contain the study to toplighting under overcast conditions, as low light intensities are of critical importance for plant survival and any additional light will increase the possibilities for a healthy plant growth anyway . This implies that the diagrams only portray distribution of light affected by horisontal openings during overcast conditions and/or situations where the distribution of blue sky radiation is approximate to the distribution of global sky radiation on cloudy days. However, low light conditions due to overcast skies are often prevailing more than 50% of the time, and plants need approximately two days of sunshine to make up for a cloudy day. Thus, the required minimum light intensities have to be correlated to overcast conditions, making the use of the diagrams rather extensive. It is obvious that direct sunlight as well as combined vertical and horisontal openings increase illumination levels and change isolux contours depending on orientation and design of openings.

Experimental method

The influence of different configurations on light distribution in a top-lit atrium was to be investigated. The configurations should vary in shape, relative aperture, and reflectance, while the surrounding surfaces should vary in reflectance. Existing software programs for daylighting were scanned in the beginning of the investigation, in order to possible utilize fast micro computers for the investigation process. However, it was impossible to find any suitable and reliable programs, so it was decided to employ emperical methods. MIT owns a "light-box", approximatelly 3ft by 4ft in plan and 3ft high, which could be rebuilt to fit the special purpose. The light-box simulates overcast conditions by utilizing a bright artificially lit horizontal ceiling made of translucent sheeting with mirror-cladded walls. A hatch covers a 19 inches square hole in the bottom part of box to enable an eye's view of the daylight tested rooms. The hatch was simply demounted and replaced with a three feet deep light well sticking down from the belly of the light-box. The light well was equipped with a movable floor, to enable readings of light levels at different distances from the light-box hole, or in this case preferably called the skylight level. Nine evenly spaced photosensors were fixed to the floor and connected to a data acquisition control unit, number 3421A, from Hewlett Packard. (See fig. of light-box.) The different configurations were cut out of opaque foamcore, and pasted with paper of different colors; white, beige, and flat black. The light well was cladded with similar colored paper. However, the runs for medium reflectances were conducted with naturally colored wafer board. (See pictures of configurations at the end of this chapter.)

Configurations

Shape

The different shapes were cut out symmetrically to simplify the interpretation of the findings. However, some configurations allowed for assymmetrical spacing in order to determine the impact of assymmetry on light distribution.

Aperture size

It was decided to test the influence of the aperture size on light distribution, in order to verify or reject proposed approximazations for light levels, which generally assume that illumination levels proportionally follow the size of the opening. Four sizes were chosen expressed as a percentage of the maximum opening.

100=100%

75=75%,

50=50%,

25=25%

Reflectances

Every configuration was also tested with different wall and ceiling reflectances. Four shades ranging from black to white were introduced as the controlling parameters. Three of them will be presented in this thesis:

Black(S)=15% reflectance, but also glass surfaces
Medium(M)=40% reflectance, usually the average value for many surfaces.
White(H)=85% reflectance, possible only on surfaces without glass.

Codes
The coding of the different configurations is a combination of all affecting variables, for instance A50H, indicating shape=A, aperture=50%, and high=H reflectance.

Light well

Photosensors
It was possible to utilize eight photosensors spaced in an even symmertical pattern on the light well floor. It should have been nine, but the equipment did not allow for more connections. This had no actual impact as the symmetry of the square floor plan and the configurations, only required three positions, center, edge, and corner. (See fig. of photosensor positions) The extra positions were merely a safety marginal.

H/D : The proportional ratio of hight to depth
The impact of various distances between increments was tested at the beginning of the experiment, and it was found necessary to record light levels only at five different heights, or distances to the top, in order to obtain a sufficiently even curve. The five different heights(H) were chosen in accordance with their proportional ratio to the width, or depth(D), of the light well. These ratios were subsequently called H/D and indicated the proportional relationship between height and depth.

Note: Comparative data of average light level at different heights, apertures, and reflectances indicated a direct proportional correlation between size of aperture and illumination levels, as long as the light was evenly distributed and the reflectance medium (M). Surfaces with high reflectances showed proportionally increased illuminatior levels of more than 30% at shallow hights, (H/D = 0.25), and a total aperture of 25% (See graphs in the appendix section.)

H/D=0.25,

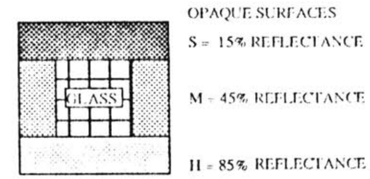
H/D=0.5

H/D=1.0

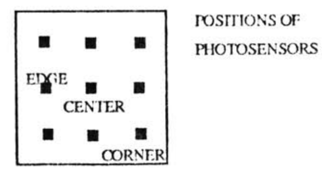
H/D=1.5

H/D= 2.0.

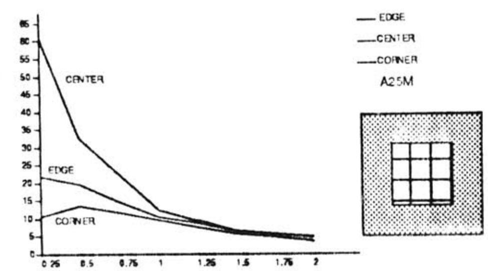
Note: The large majority of atriums have an H/D ratio between 1.0 and 2.0. This ratio is sometimes referred to as S.A.R. (Bednar, Michael J., The New Atrium, p.66.)



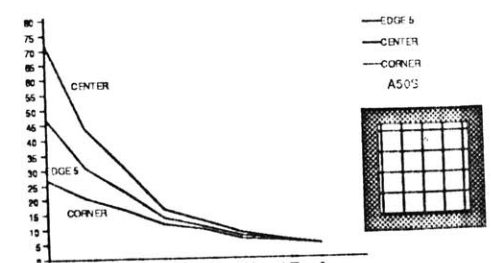
Recordings



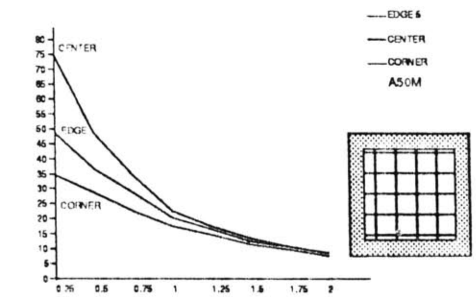
Several configurations of various shapes and mentioned apertures were tested during the experiment, with the purpose to eventually track the H/D, where light levels tend to even out independent of the different shapes. The recorded light intensities were transferred to a Macintosh Multiplan spread sheet with ability to graphically present three different curves. The horizontal axis represents H/D, while the vertical axis depicts the daylight factor(DF). it is possible to determine light levels, in footcandles or lux, for any hight by reading off the daylight factor from the diagram and multiply by the ambient light level and divide the sum by 100. Usually it was decided to plot the recorded data of the center, the edge , and the corner, but also other interelated comparisons were plotted. This thesis will only describe some data from a few different configurations. (See fig. for explonation of different surfaces)



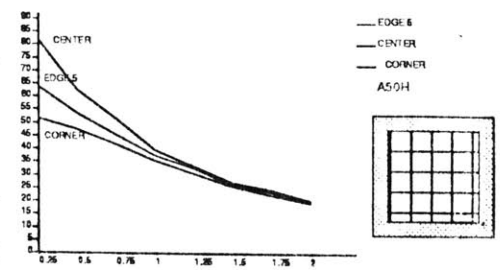
Findings

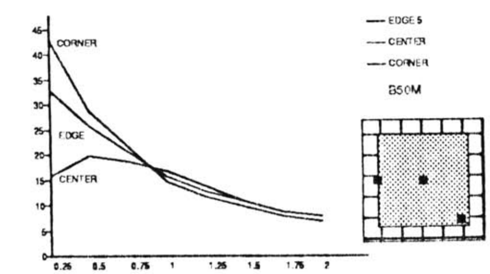


It was soon realized that the height and H/D ratio had a strong impact on the measured light intensity, which was to be expected. The influence of different reflectances was also directly related to light levels, as well as the aperture. (see fig A25M, A50M, and A50H) However, the configurations modified the tendency, and could even reverse the general trend of increasing light levels. (See fig B50M. center) However, more astonishing was the general tendency of light levels to be independent of photosensor positions once H/D was higher than 1 to 1.5. The levels were hardly influenced by configurations, size of the aperture, or reflectances, though a slight shift could be recognized at H/D greater than 1. High reflectances and large apertures tended to close the gap between the different light levels a little sooner. (Compare fig B25M with B50M. and A50S with A50H.)



Other observations indicated that the total illumination level was not proportional to the relative aperture, until H/D was close to 2.0. (See fig A25M, A50M, and A75M.) However, this could be explained by the impact of the various configurations on light distribution at shallow heights. Comparative data of average light levels at different heights, apertures, and reflectances indicated a direct proportional correlation between size of aperture and illumination levels, as long as the light was evenly distributed. Other interesting observations indicated that illumination levels for medium reflectances (M) were not drastically higher than the light level for flat black reflectances. (S= black, and glass surfaces). It was also possible to graphically present the absolute maximum and minimum light intensities that can be possible to obtain in a top-lit atrium, given a certain configuration. (See fig. A25S,M,H.) See note on p. 114for more details.



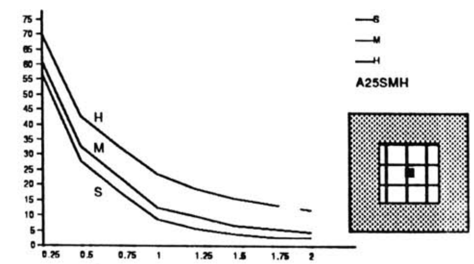


Test of findings in outdoor conditions

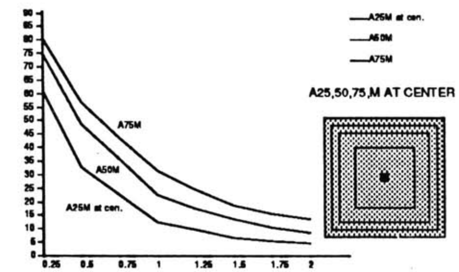
Light-box recordings were tested under natural conditions, to verify the different findings observed during the investigation. The impact of natural conditions on illumination levels followed astonishingly well the investigated method. (See fig.A50M-Lightbox-Out)

Conclusions

It has been shown that different configurations have a drastic effect on light distribution, at shallow heights. That is, when the height over depth ratio(H/D) is less than 1.0. The influnce is gradually decreasing and the light distribution has evened out at a ratio of approximately H/D=1.5. This seems to hold true for any aperture size and various reflectances, though some small shifts are observed. Configurations with openings emphasized towards the center seem to have a slightly higher illumination level, probably due to a wider view of the brighter sky zenith. However, the average illumination levels for configurations with the same aperture size seem to be directly proportional to the relative ratio of the aperture to the floor area. This corresponds to earlier mentioned approximate design methods for determining average light levels.



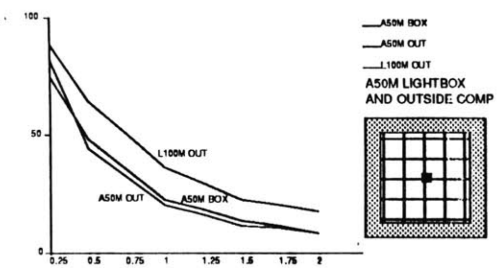
The relation could be expressed as $D.F._{avg} = U \times Ag/Af$, where U is a utilization factor dependent on reflectance and the H/D ratio. A future development of an existing table in indicating the close relationship between a well index and the efficiency of the well=U, might prove to be a good solution to the problem of determining average light levels. (See figure, developed from Dalighting A Resourcebook by Bryan.H., et al p.7-42, in the right column of this page)= see page 119.



Well Index= Well height x (Well width + well length) divided by

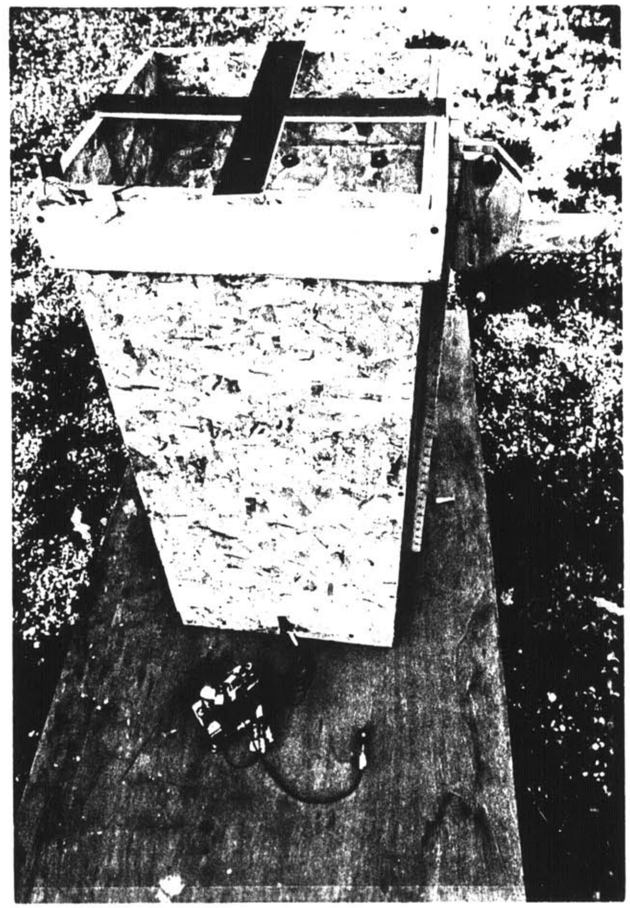
(2 xWell width x well length)

Different reflectances can play a major role in affecting illumination levels. However, the practical use of high reflectance walls have limitations because bright surfaces require scrupulous maintenance and they also create glare problems and limit the use of interior glass walls which act as light sinks.

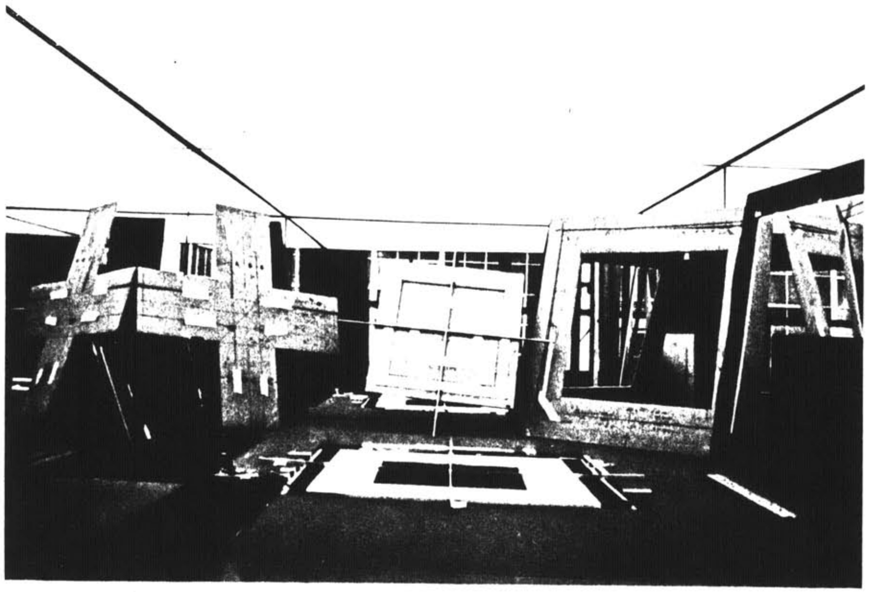


Not surprisingly the test indicates that the deeper the atrium the greater the influence of surface brightnesses as the internal reflective component IRC increases proportionally. However,interesting to note is that flat black surfaces still reflect reasonably enough to enable illumination levels to closely follow those of medium high reflectance.

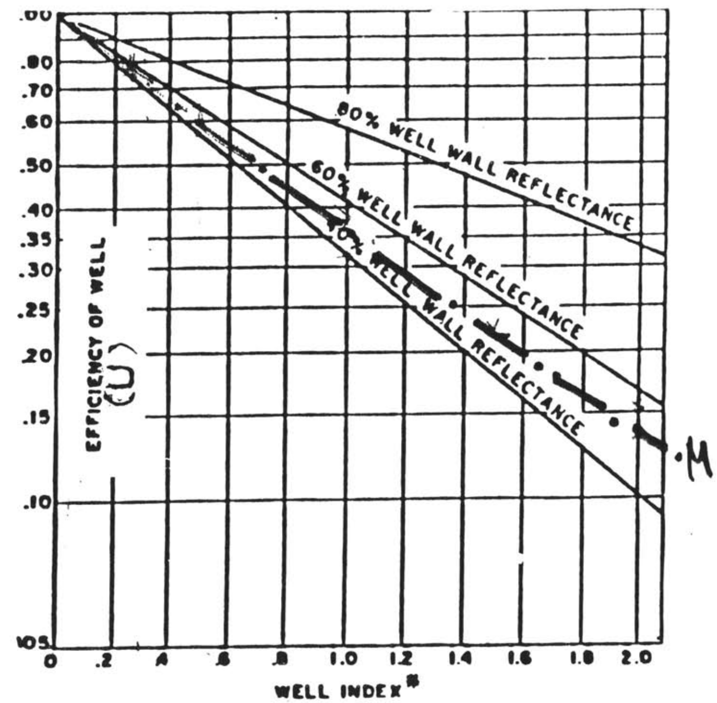
LIGHT-BOX

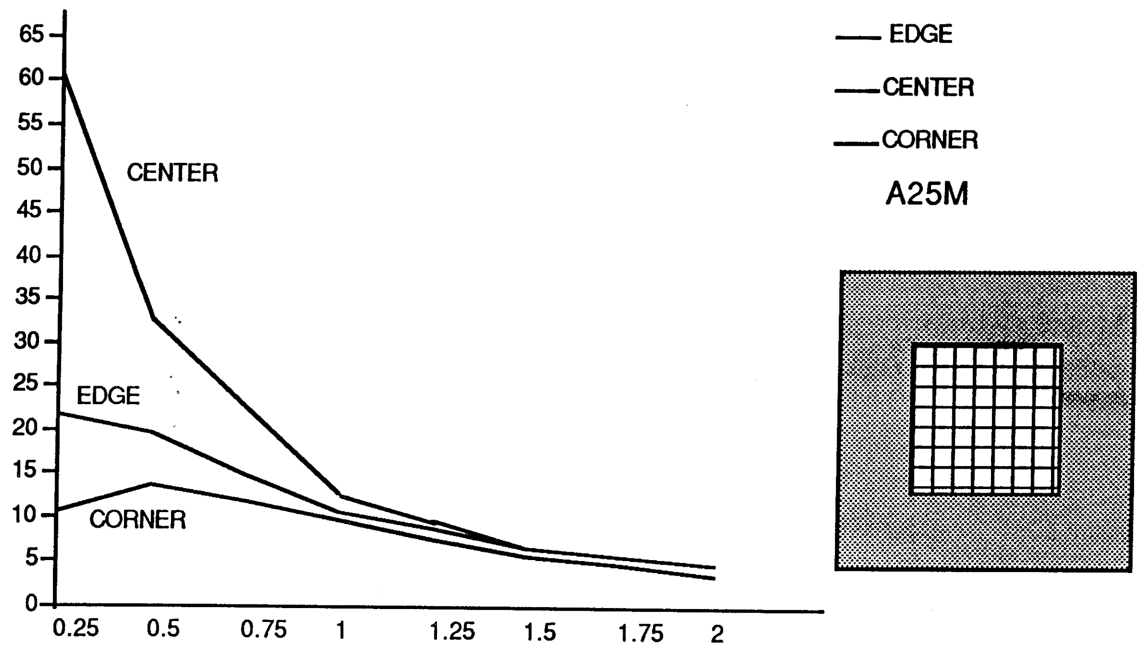


LIGHT - WELL



CONFIGURATIONS

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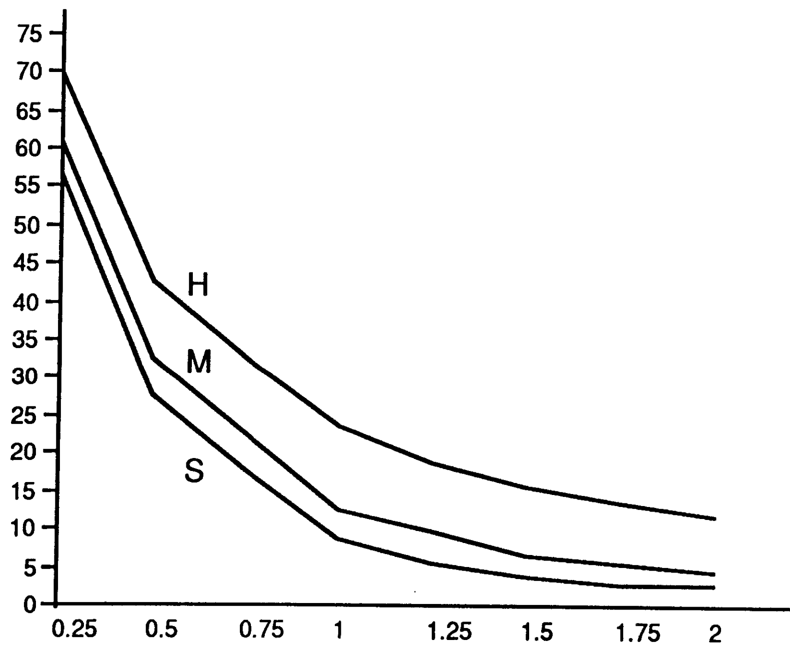
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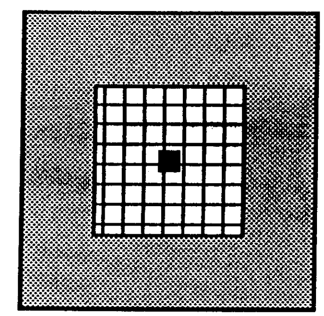

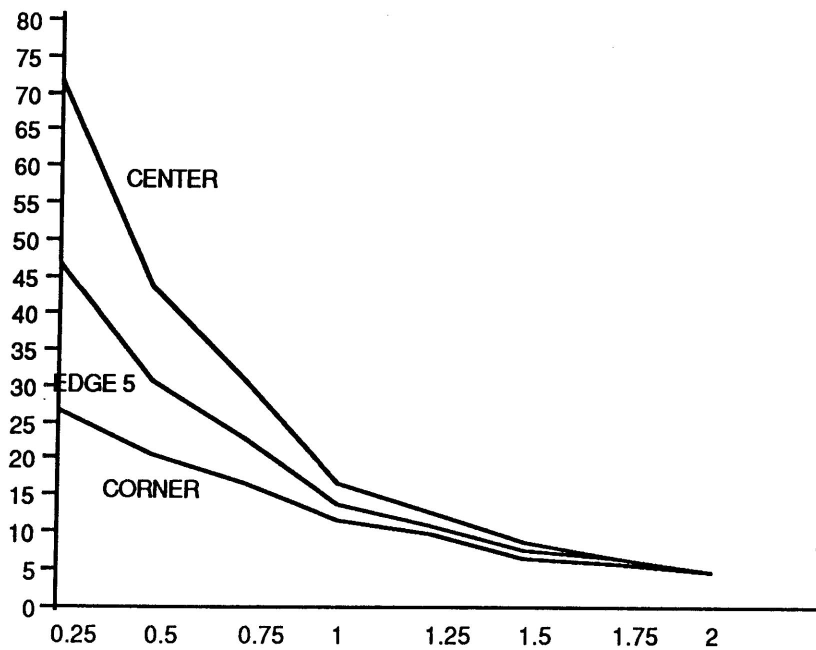
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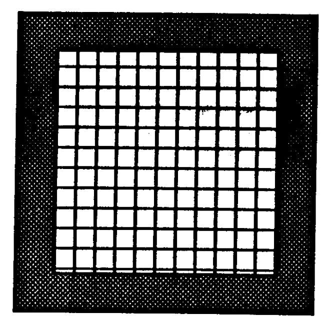

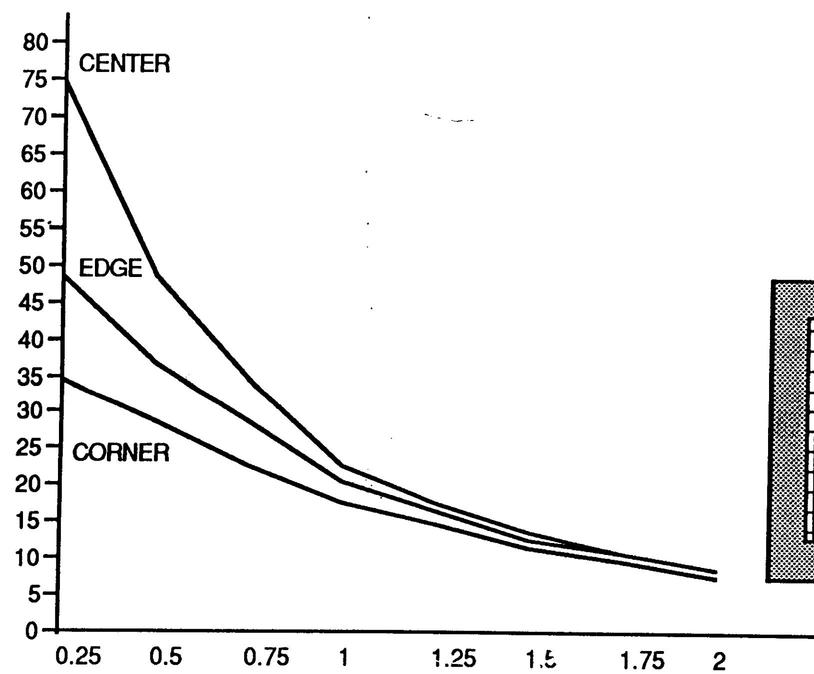
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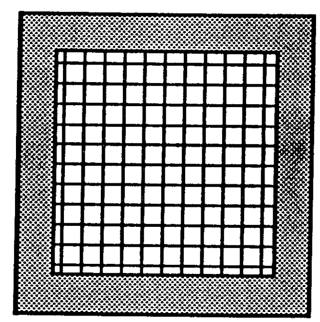

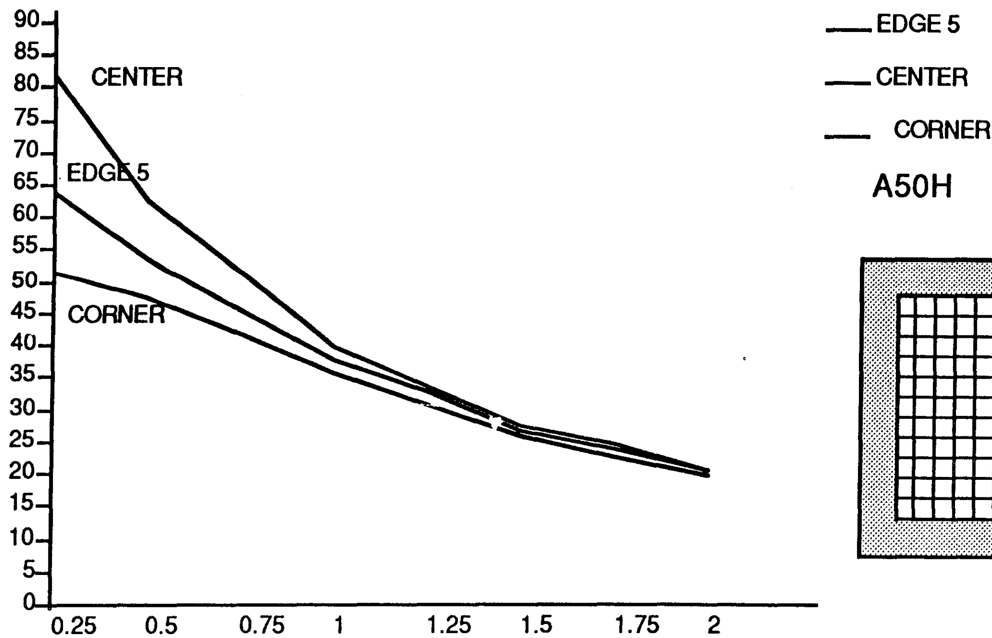
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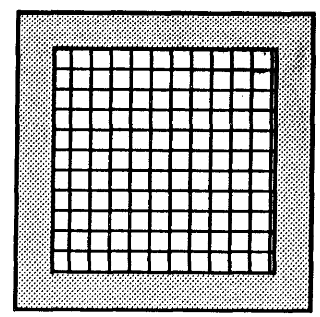

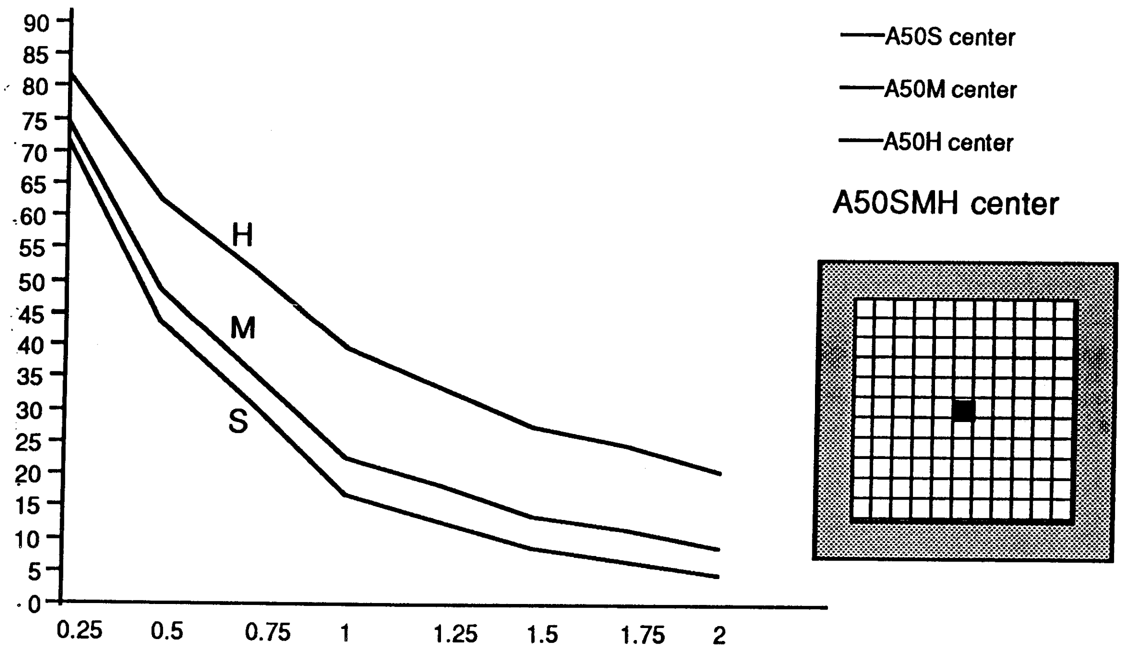
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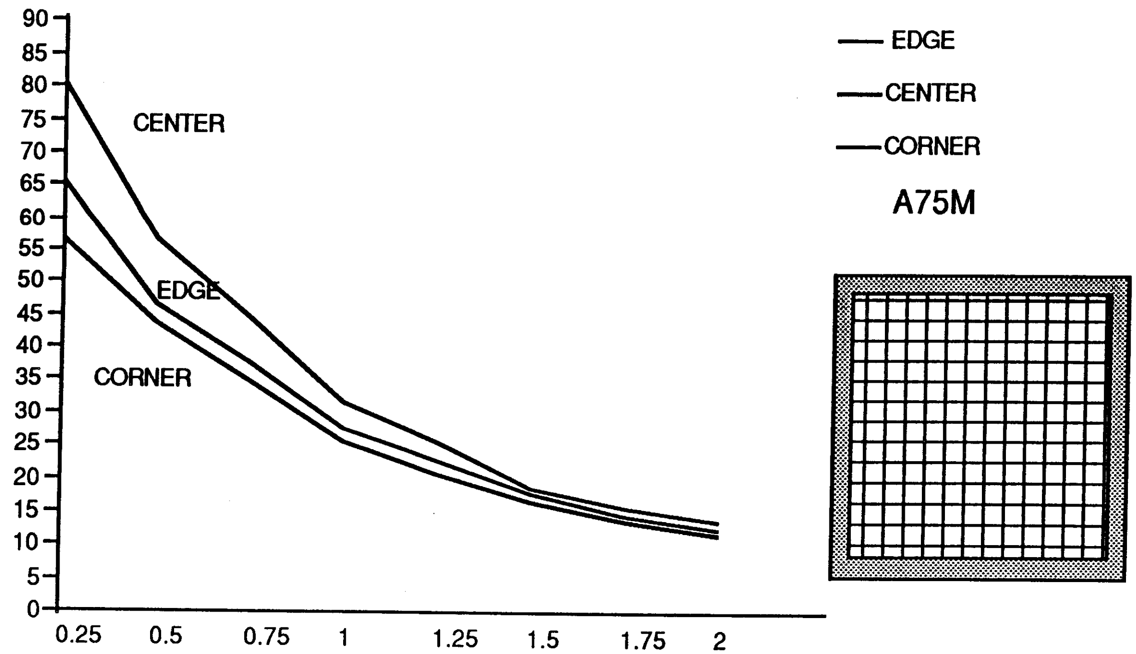
A50SMH center



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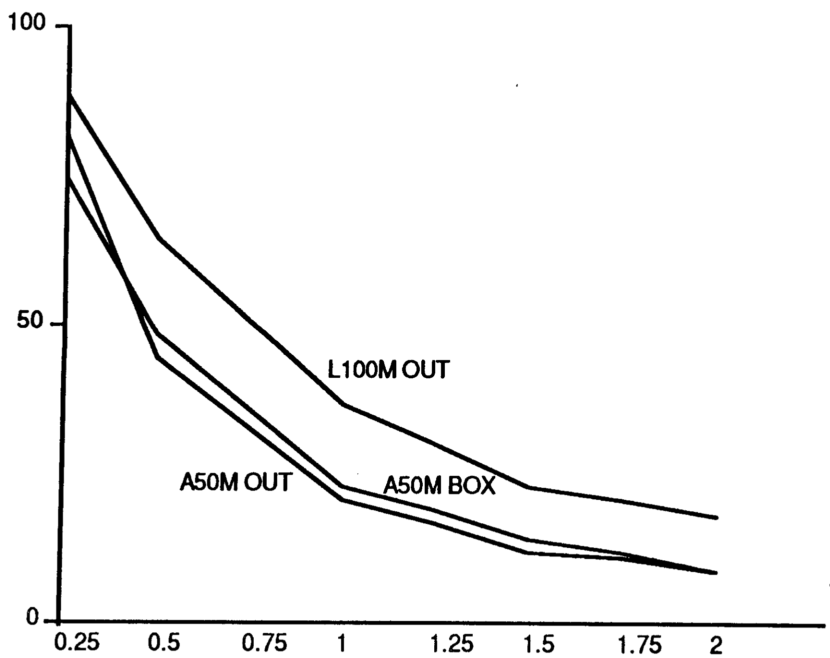
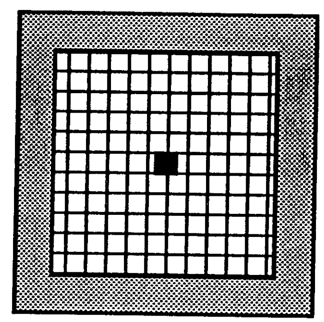
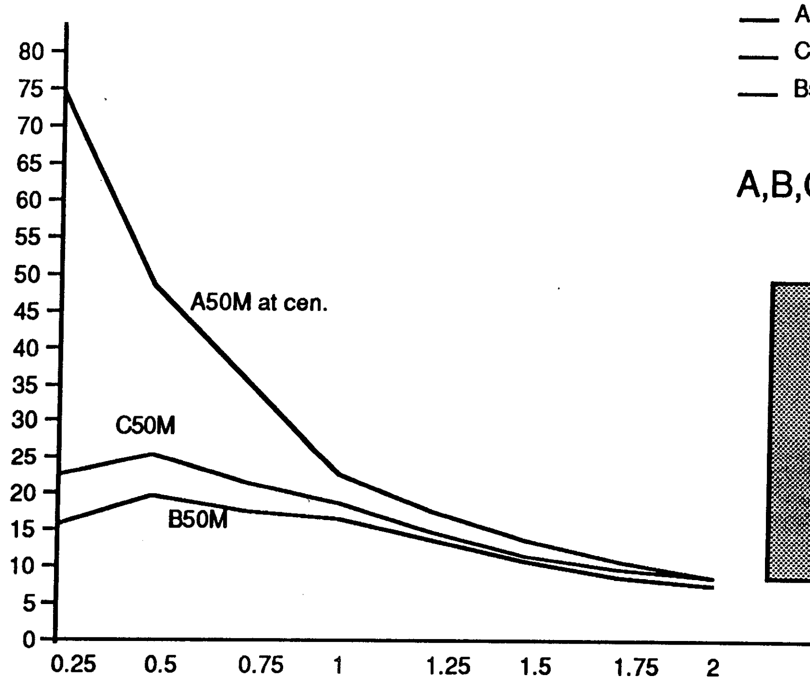
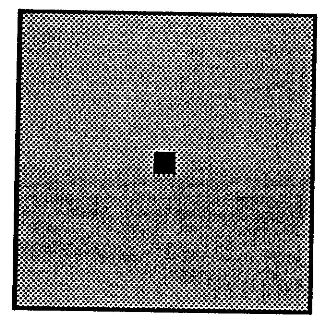


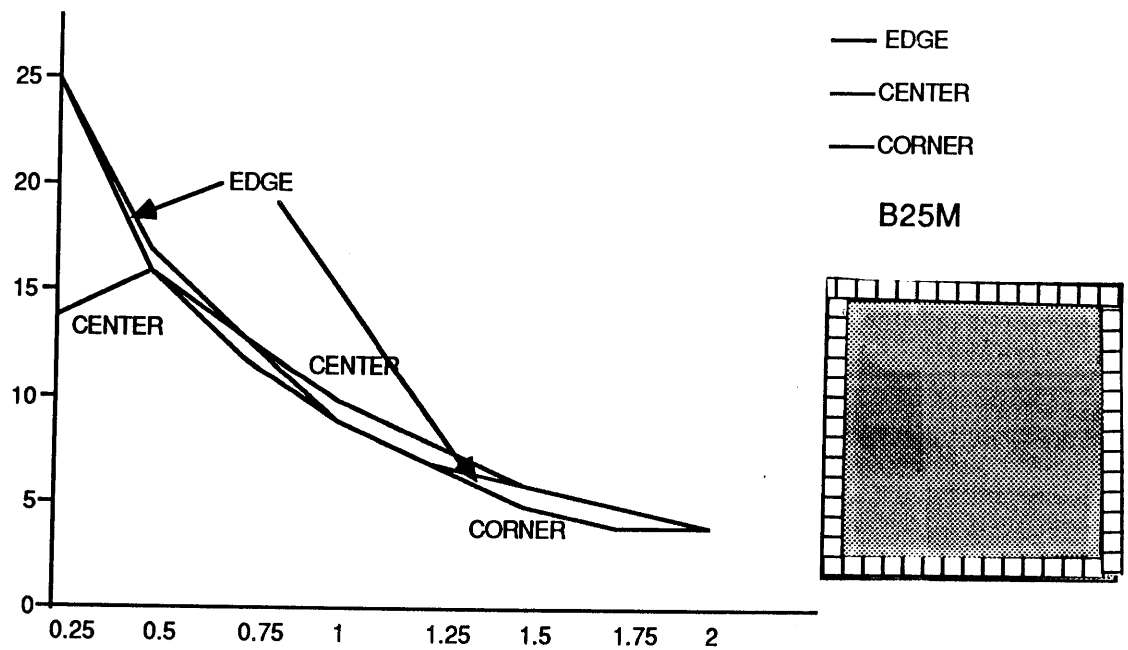
A50M LIGHTBOX
AND OUTSIDE COMP





A,B,C 50M At Center

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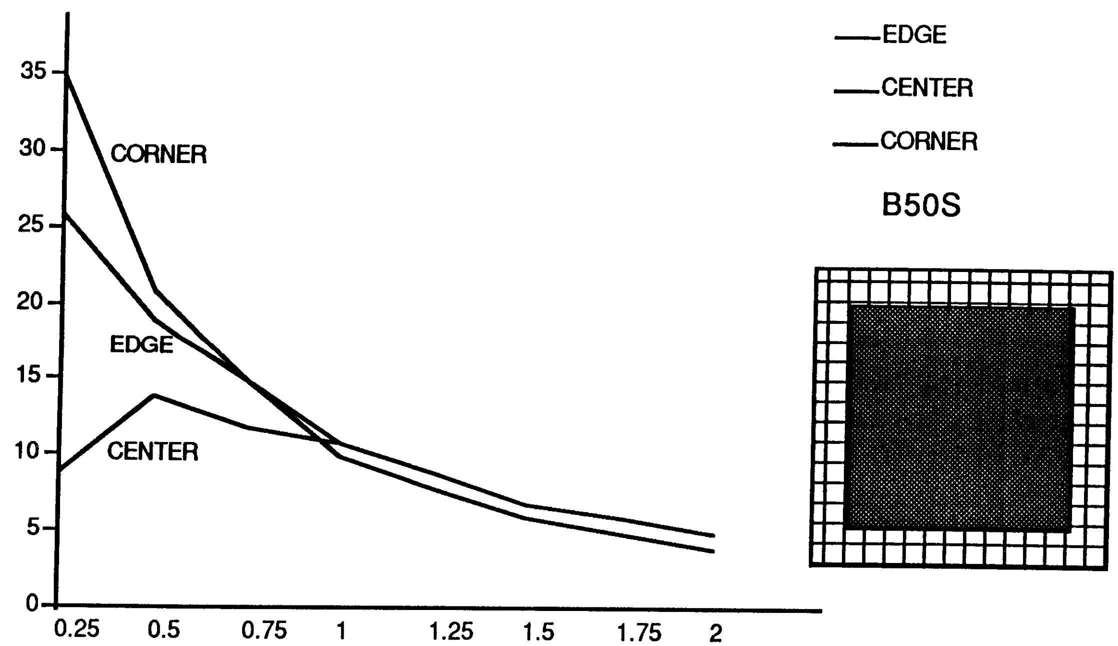

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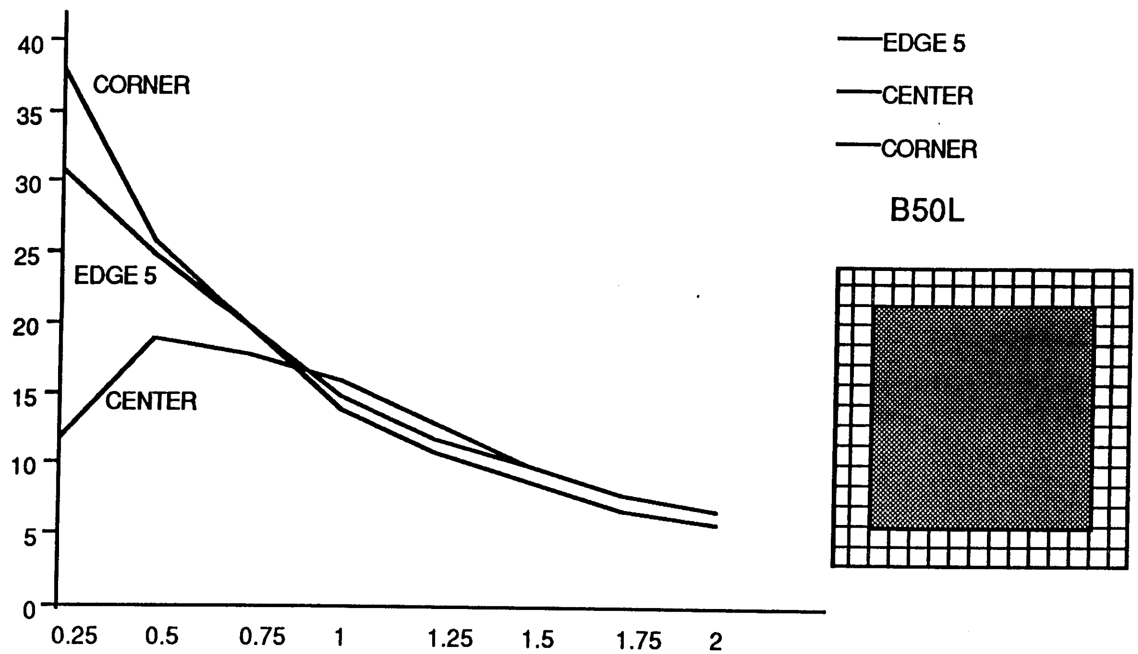
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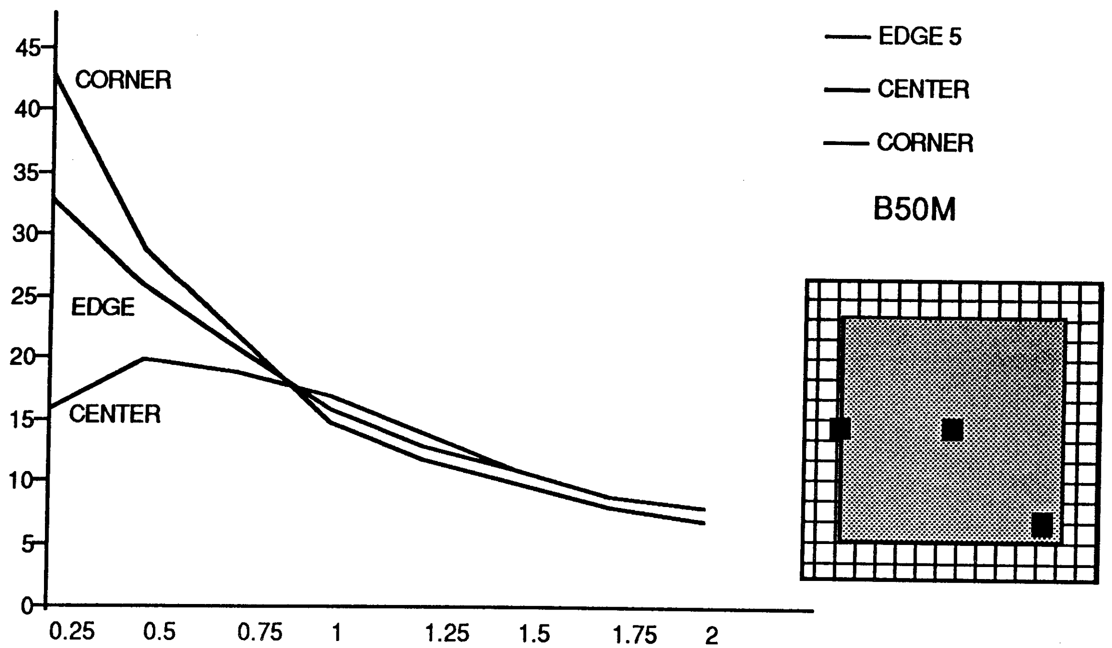
132.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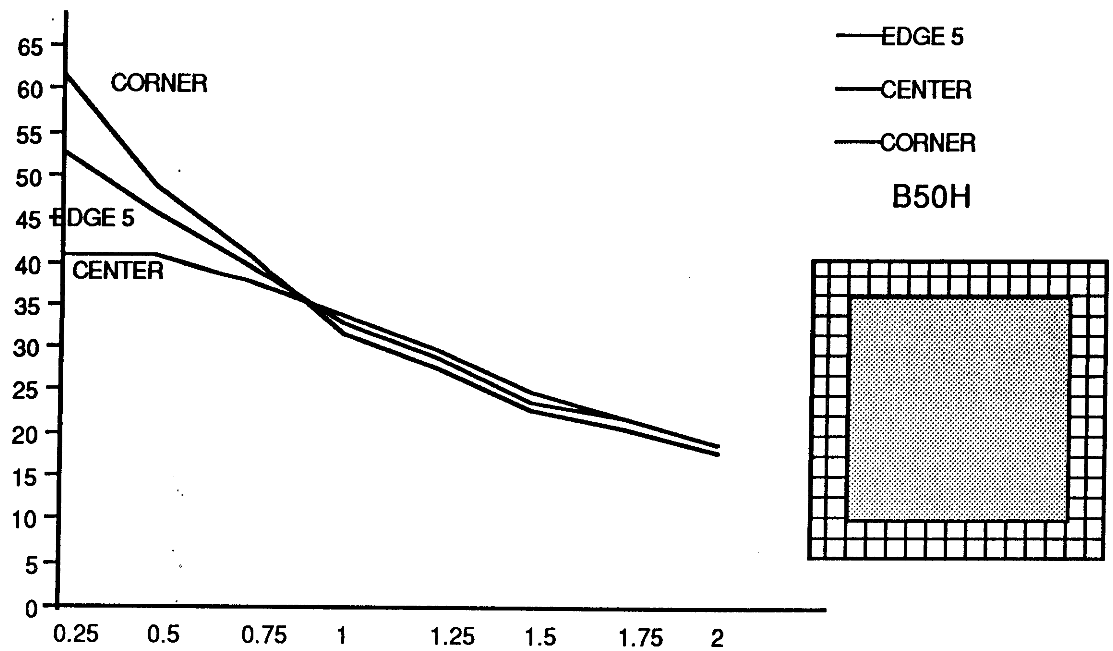
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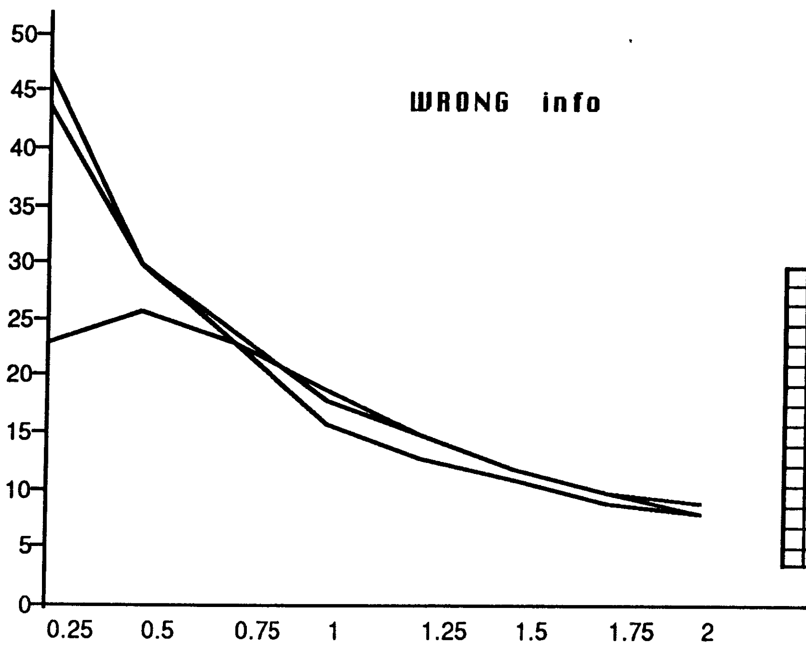
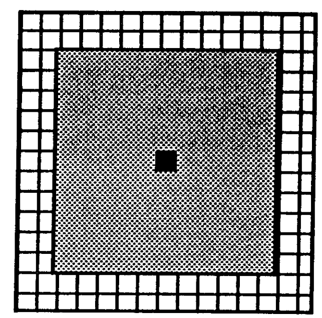
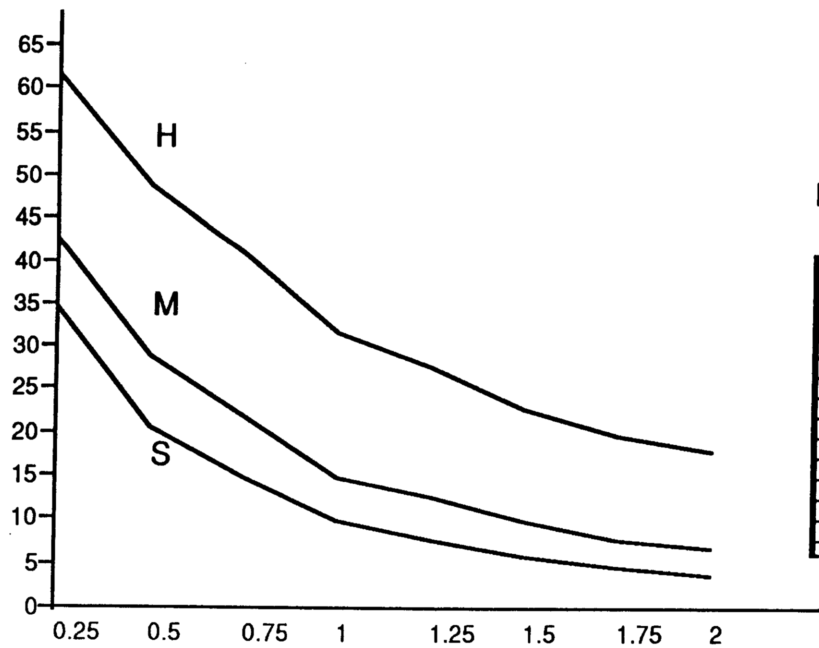
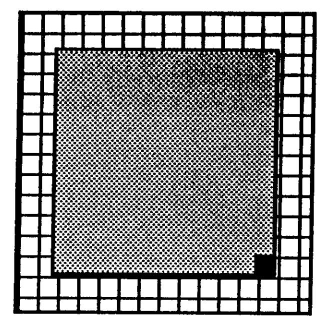


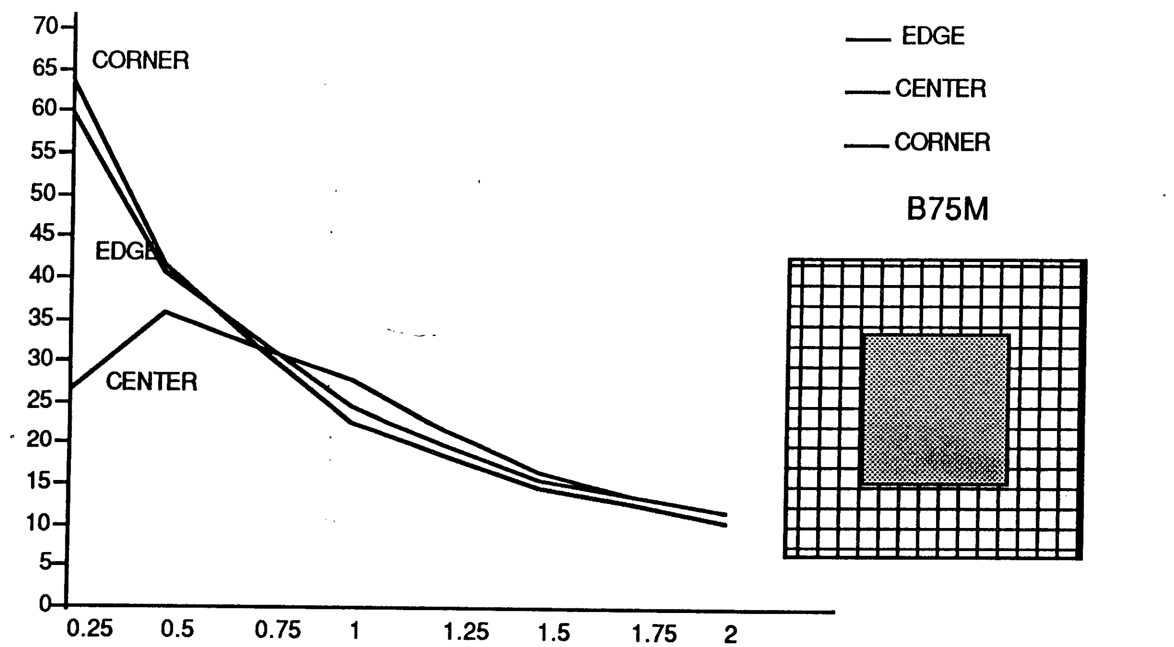
B50SMH center





B50SMH CORNER

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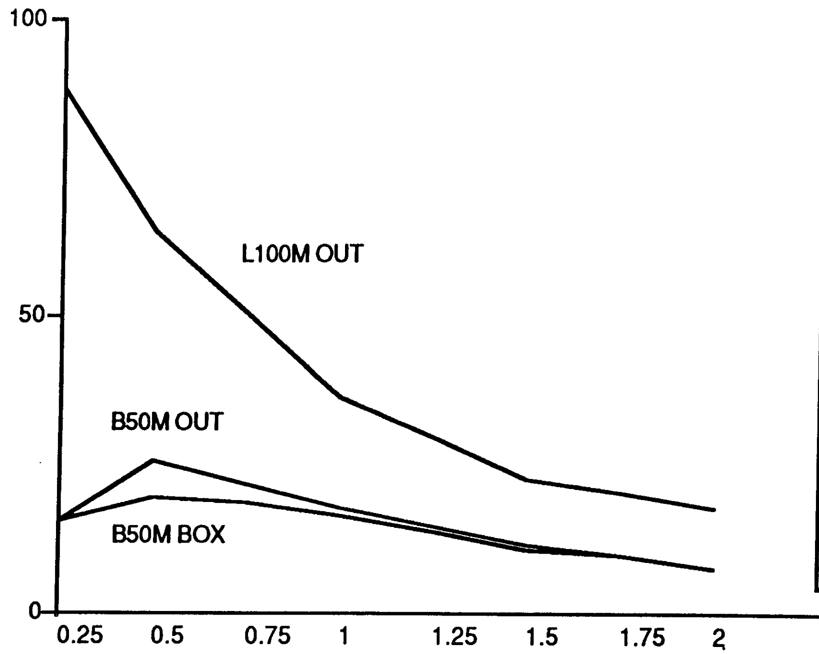
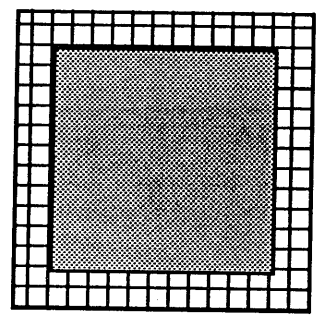
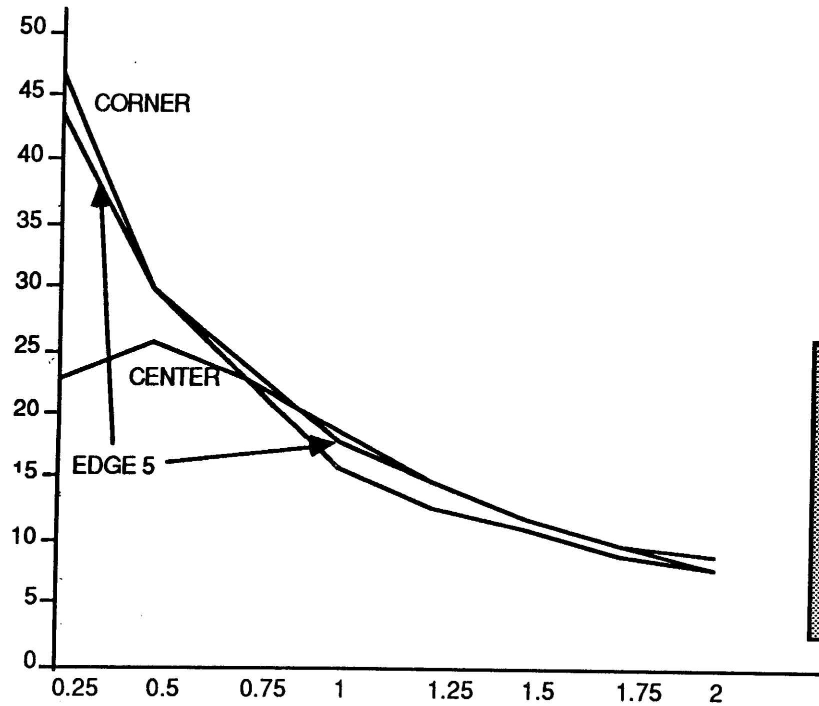


B50M Comparison
Light box to outside

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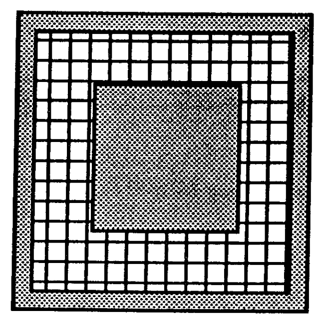

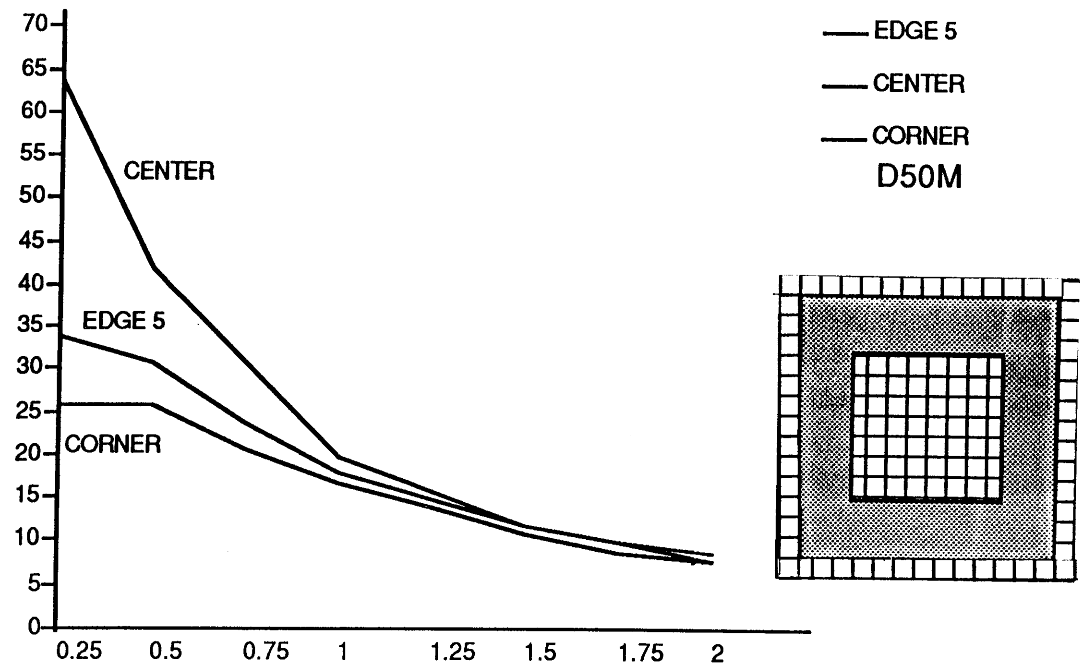
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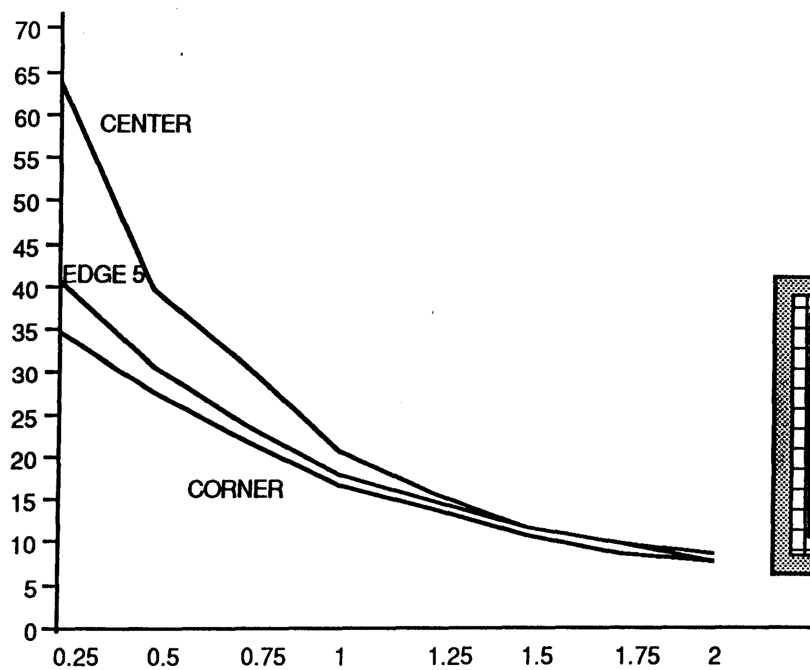
140



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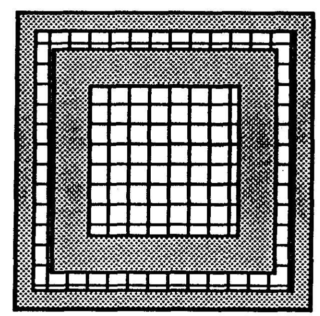

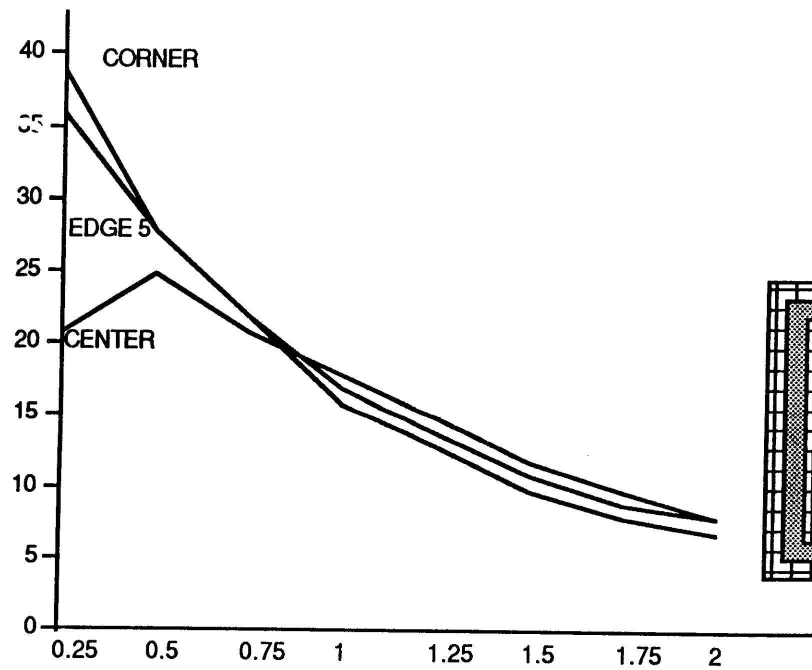
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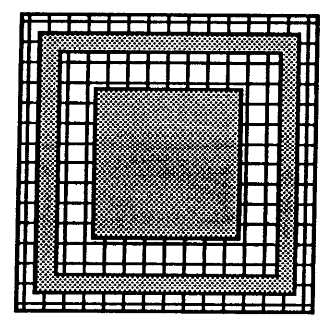

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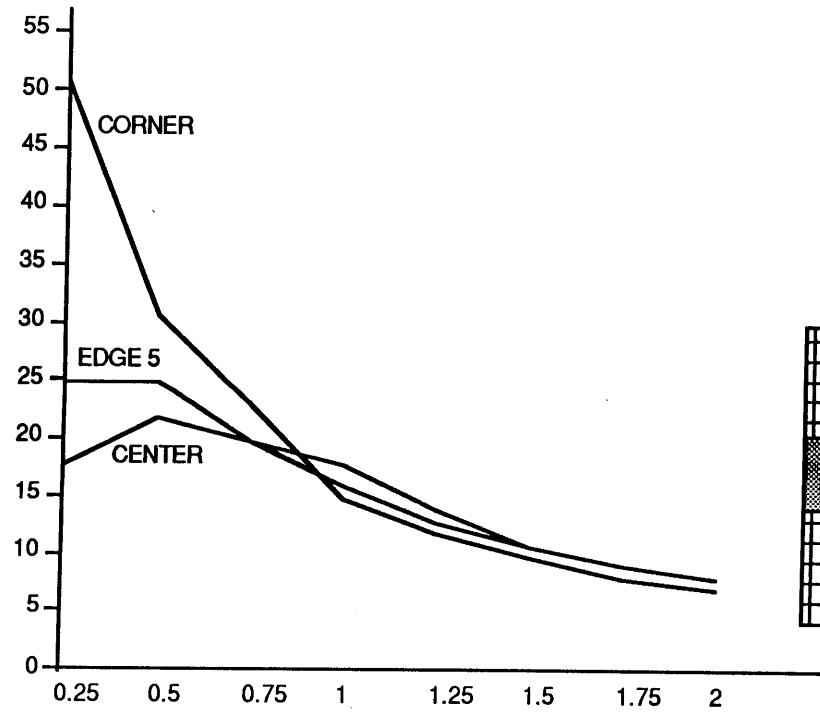

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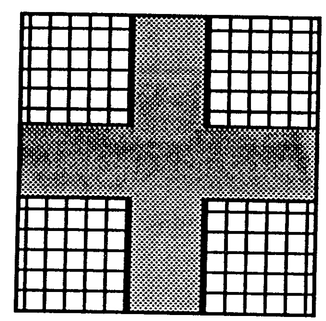
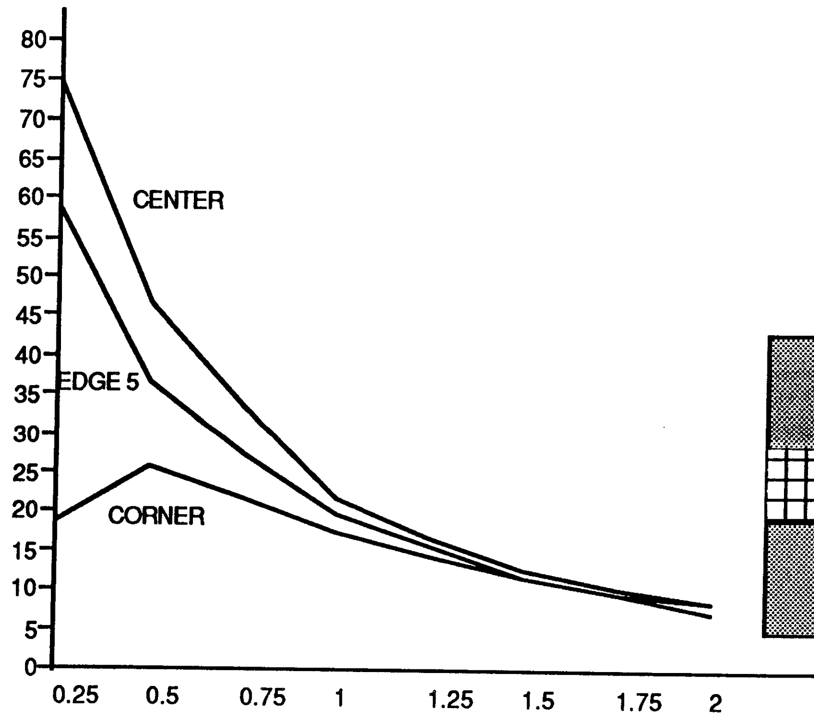
G50M

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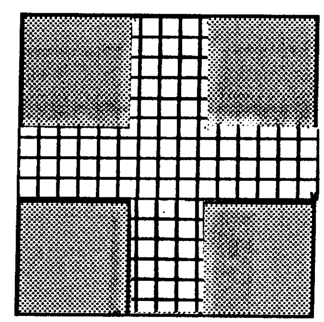

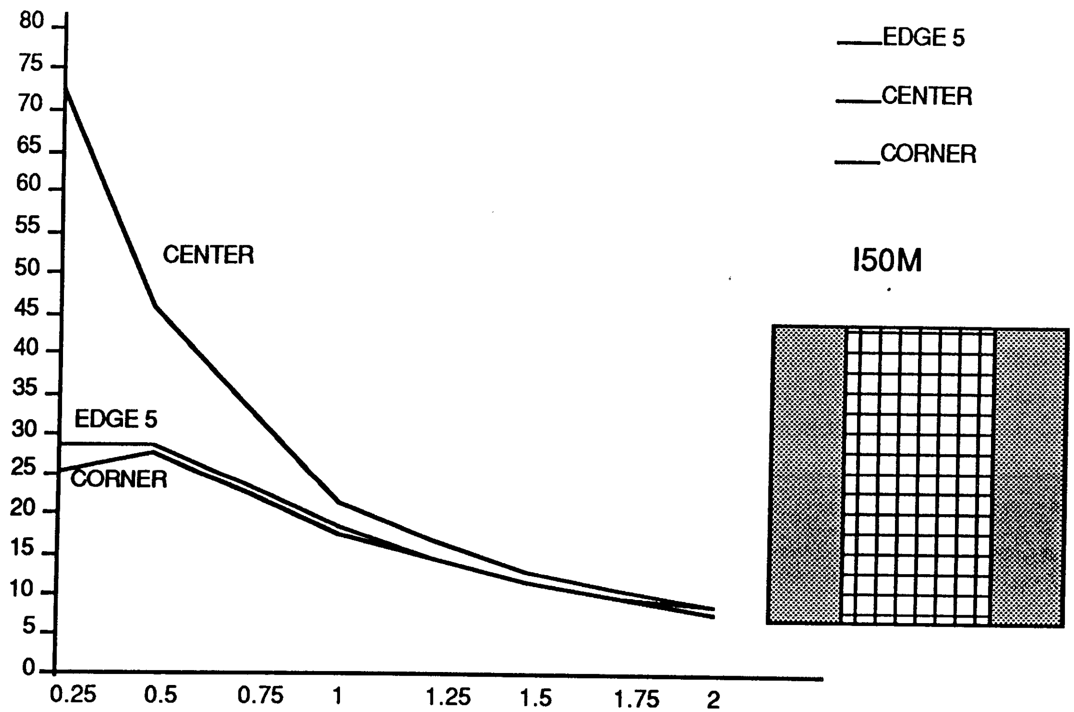

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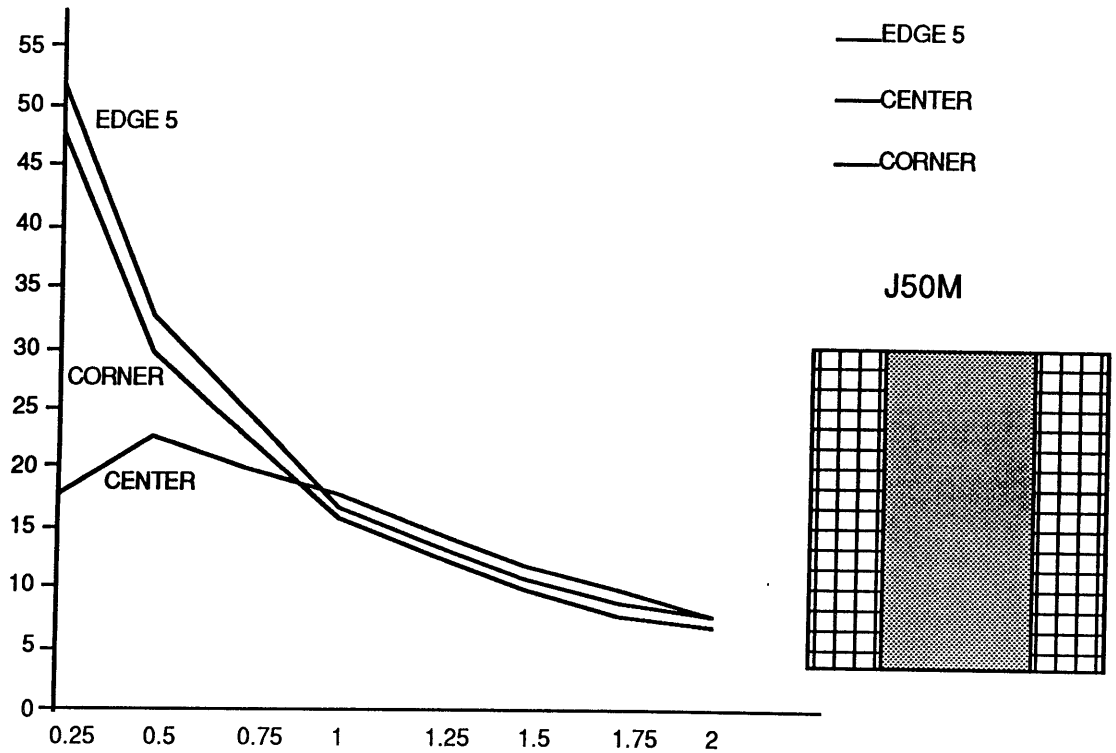
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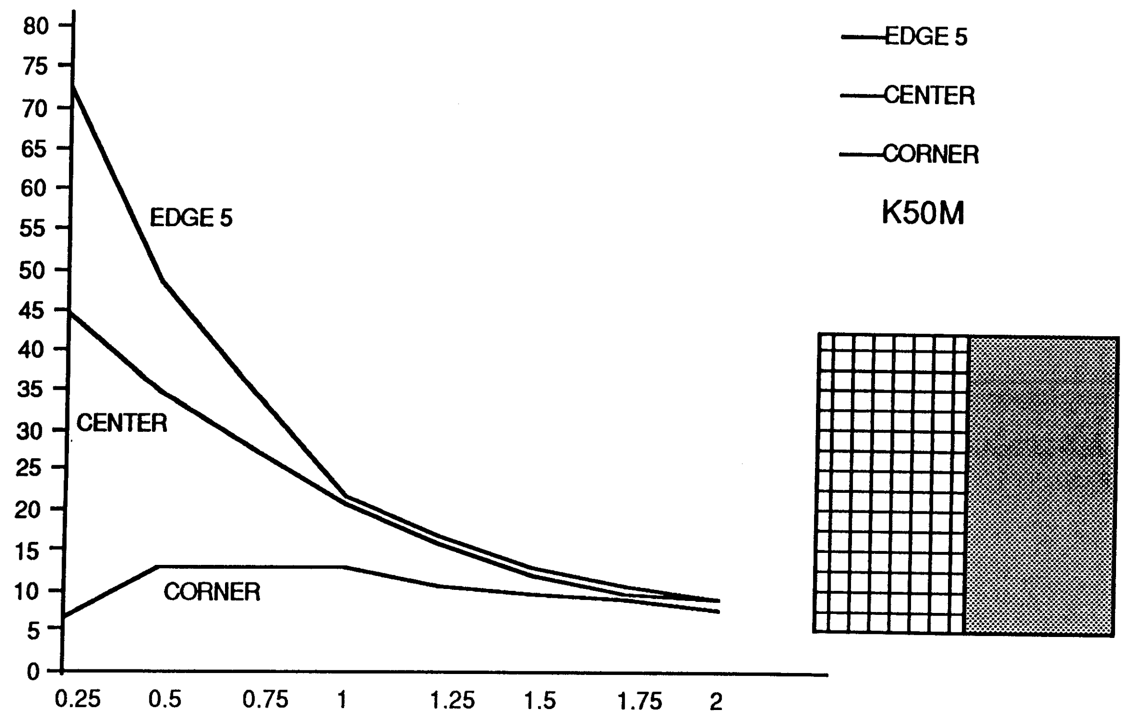

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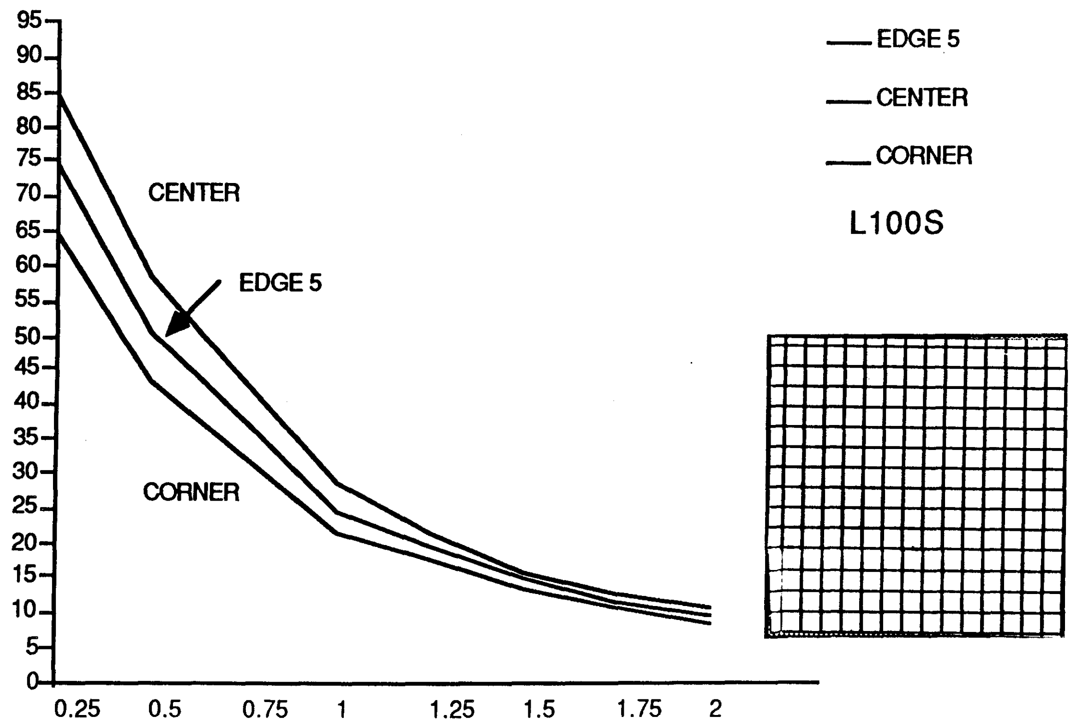
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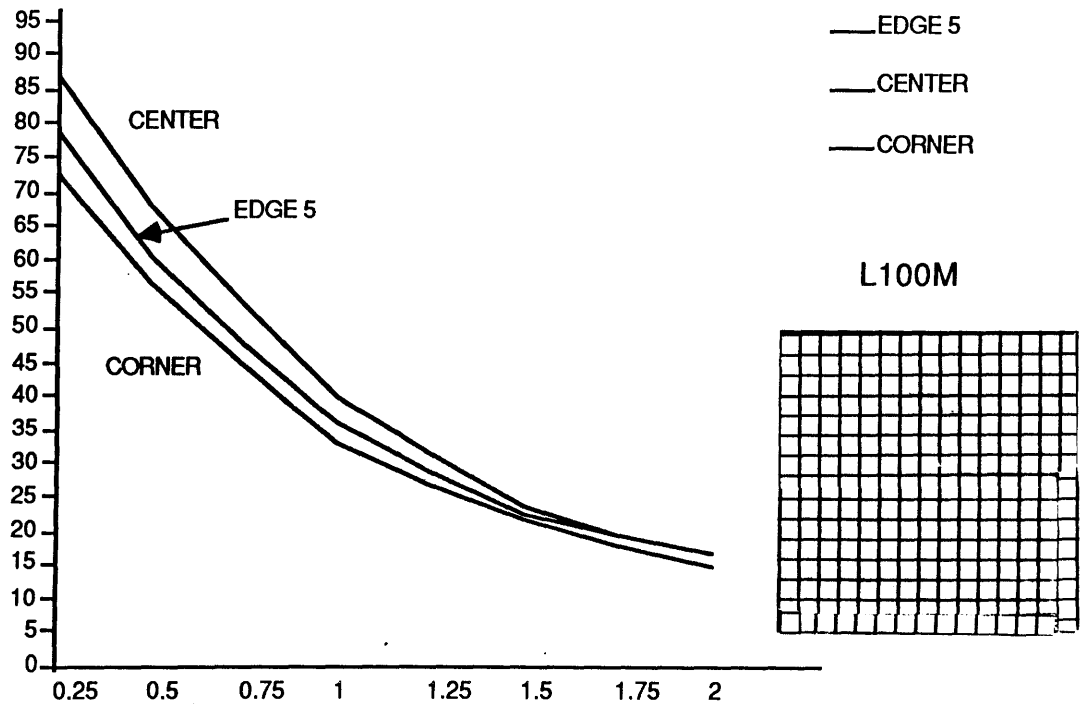
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55
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20
15
10
5
0
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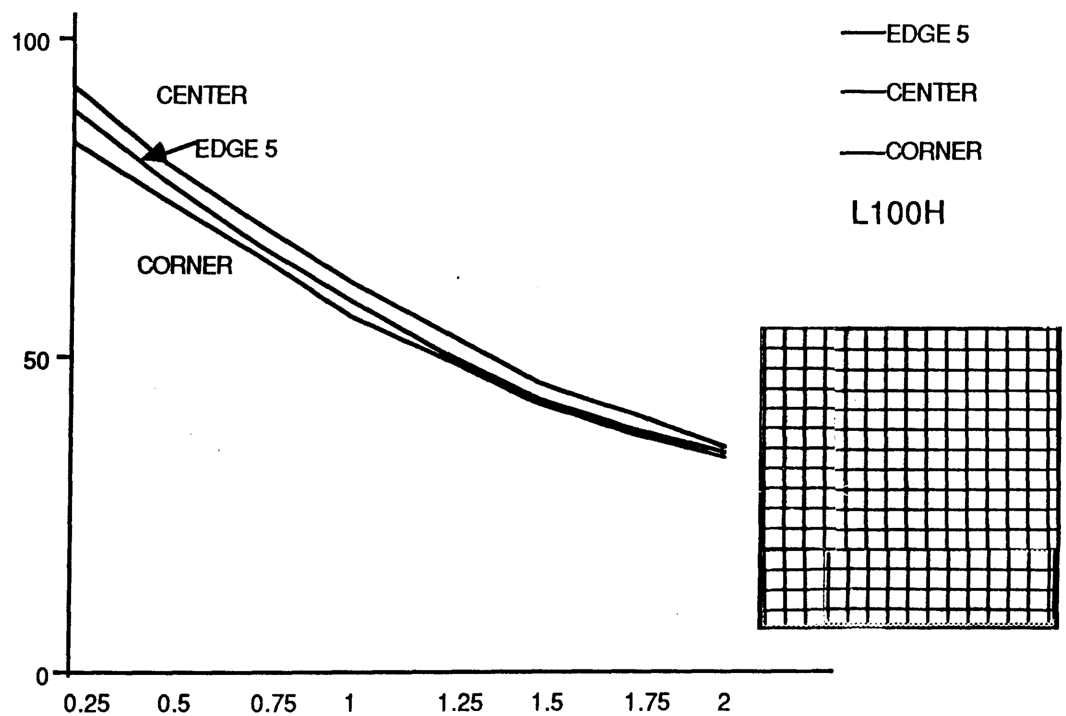
CENTER
EDGE 5
CORNER
EDGE 5
CENTER
CORNER
L100M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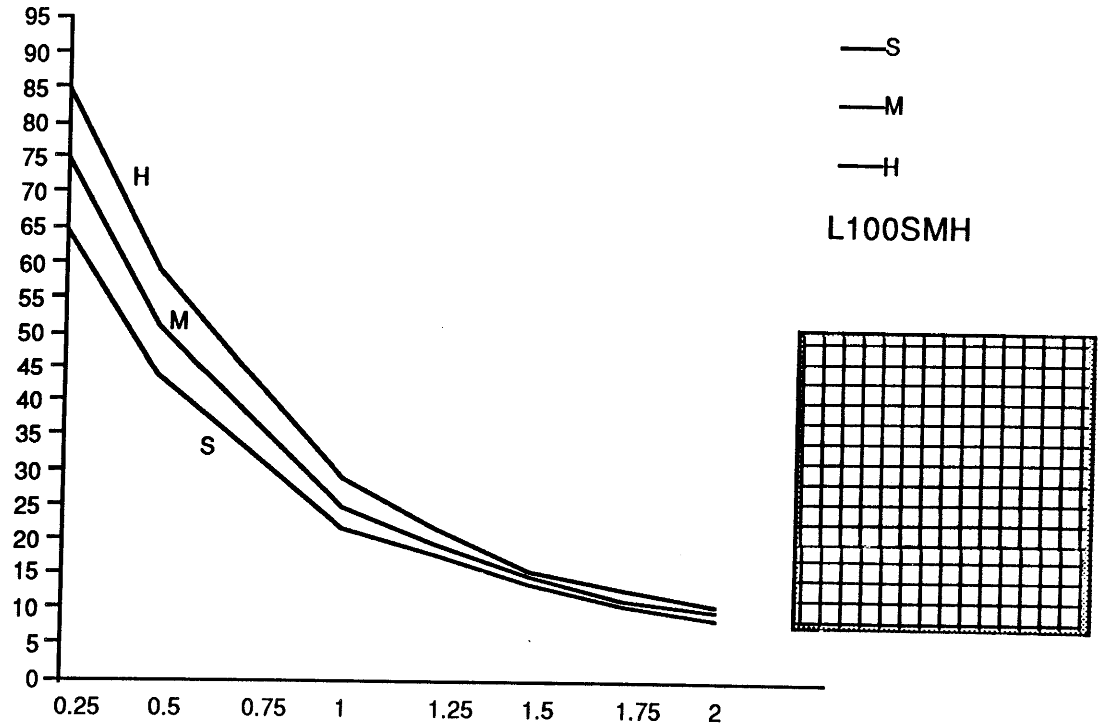
CORNER
L100H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1.25
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L100SMH

CONCLUSION

This is a thesis that wished it were a book.

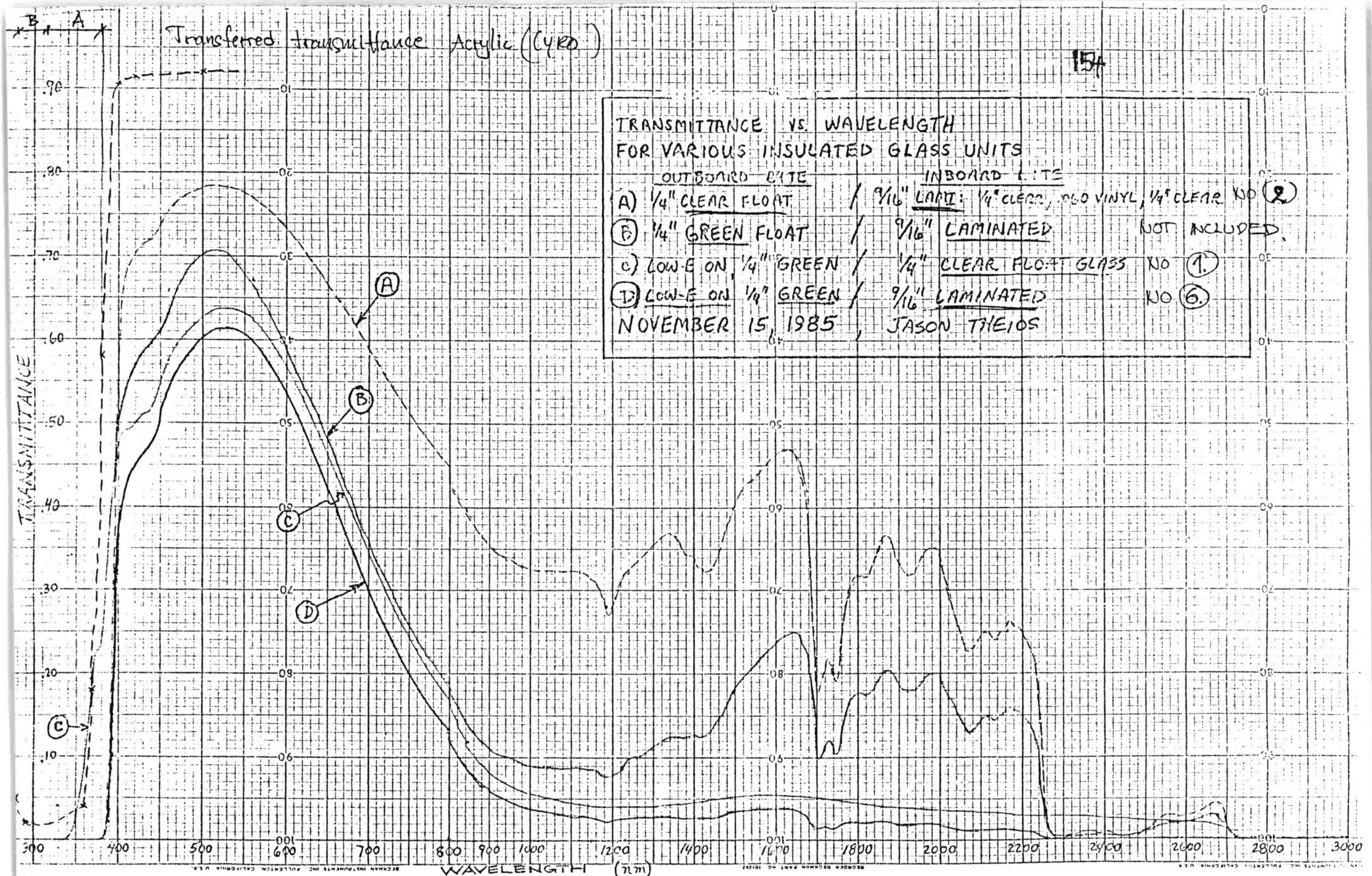
The specific features that distinguish a quality atrium are several and not necessarily to be found in technical solutions. On the contrary, many outstanding charachteristics are related to the quality of health, comfort and aesthetic pleasure, while serving functional needs.

All life is dependent on the energy radiating from the sun, and neither man nor plants can survive without sufficient amount of it. However, plants seem to stand in a closer relationship to light and is directly affected by its energy content. There are also other documented plant responses which are linked to the quality of light as well as the intensity level. For one thing, plants have aquired seasonal adjustment in order to survive when the climate is harsh, while man has built shelters to protect himself from severe impact. These fundamental differences between climatic preferences necessarily create problems when the optimal environments of man and plants are desired to merge. There are also new indications that man is more dependent on light, than previously envisioned. Changes in daylength can affect man's biological clock just as plants are known to respond to the diurnal circle. Different wavelengths and intensities might also be proven to influence the perfomance and health of plants as well as people. Still, buildings are errected whithout climatic considerations with consequences for both people and plants. For instance, windows with reflective or tinted glass take an increasing share of the market. However, this thesis has indicated a link between transmitted light and plant growth, showing that plants respond favorably to a spectrum close to natural daylight. It has also been shown that architecture which is sensitive to climatic considerations can develop a rich and aestheically pleasing expression, which otherwise would have been lost. It has also been the purpose of this thesis to alleviate achitectural decisions to enable a quality environment. Maybe an increased understanding of light distributions in atriums can lead to better solutions, where both people and plants can coexist in a healthy and comfortable environment.

APENDICES

•SPECTROGRAPHS OF VARIOUS GLASS TYPES AND ACRYLIC SHEETS USED FOR RESEARCH ON PLANT GROWTH RESPONSE TO LIGHT QUALITY AS DESCRIBED IN CHAPTER 3.

• GRAPHS FOR DETERMINING AVERAGE ILLUMINATION LEVELS IN TOP-LIT ATRIUMS AS DISCUSSEED IN CHAPTER 6.



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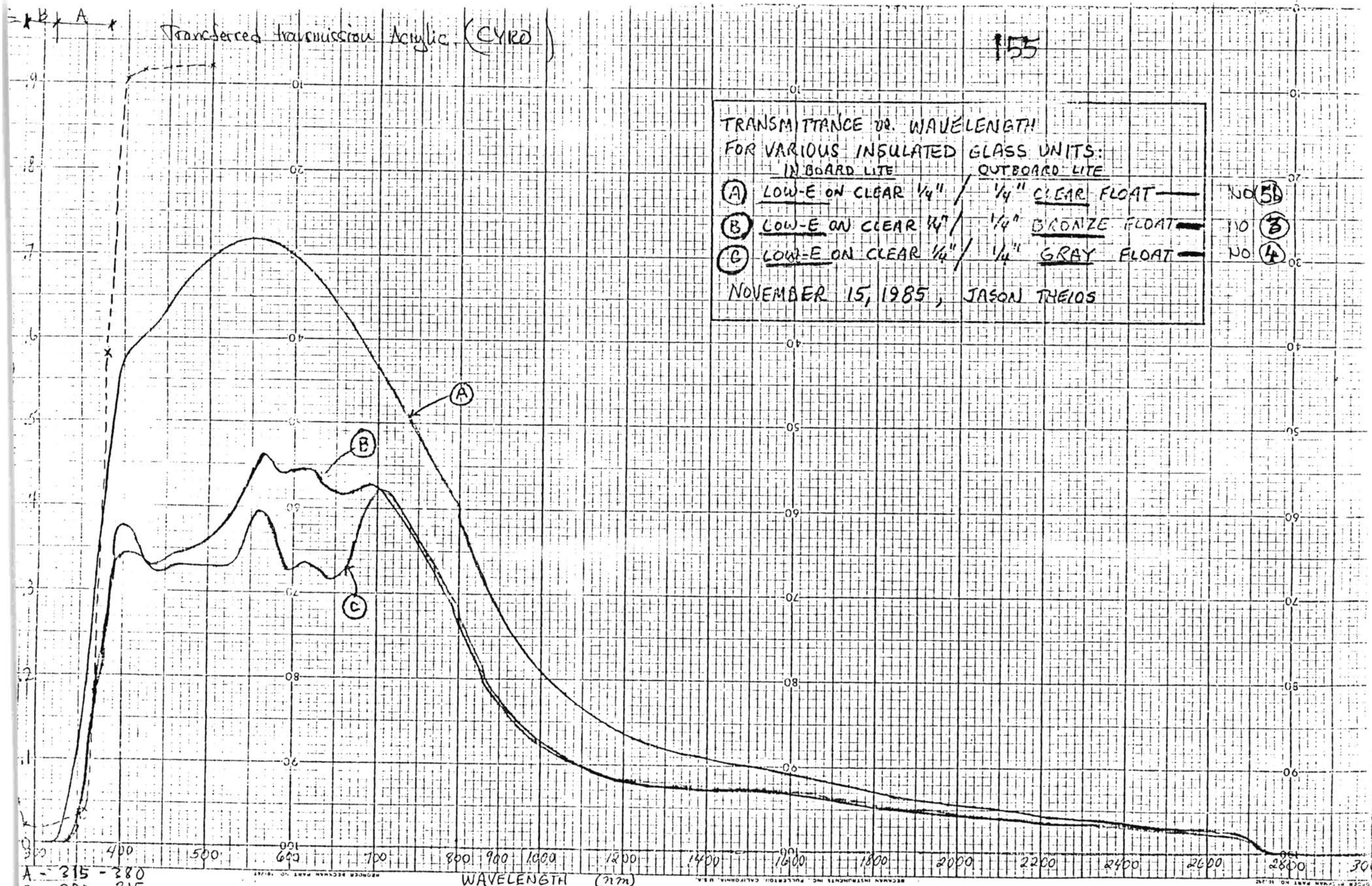
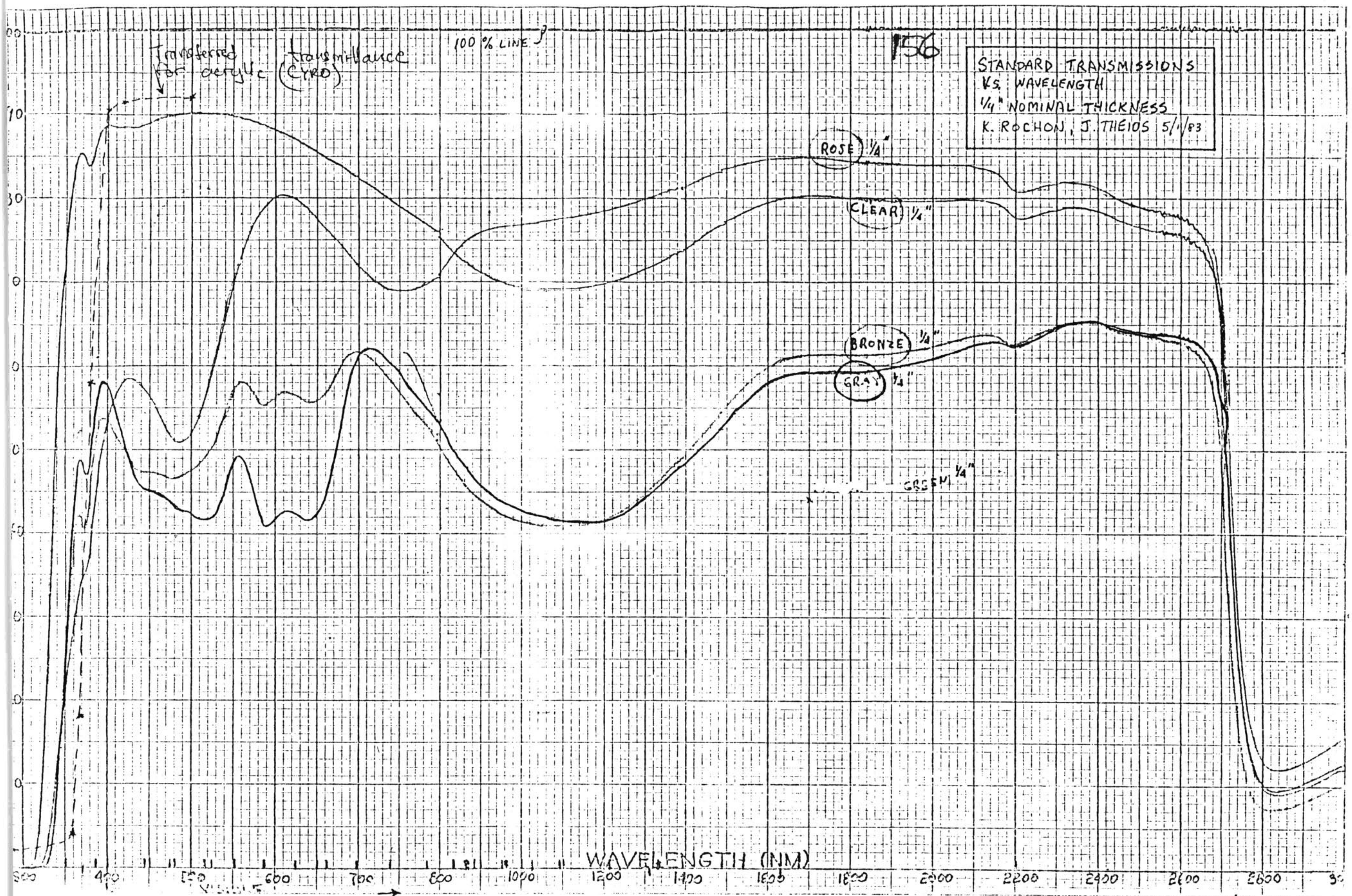
154
TRANSMITTANCE VS. WAVELENGTH
FOR VARIOUS INSULATED GLASS UNITS
OUTBOARD LITE / INBOARD LITE
A) 1/4" CLEAR FLOAT / 9/16" LAM: 1/4" CLEAR, .060 VINYL, 1/4" CLEAR NO 2
B) 1/4" GREEN FLOAT / 9/16" LAMINATED NOT INCLUDED.
C) LOW-E ON 1/4" GREEN / 1/4" CLEAR FLOAT GLASS NO 1.
D) LOW-E ON 1/4" GREEN / 9/16" LAMINATED NO 6.
NOVEMBER 15, 1985, JASON THEIOS
TRANSMITTANCE
.90
.80
.70
.60
.50
.40
.30
.20
.10
WAVELENGTH (nm)
300
400
500
600
700
800
900
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
A
B
C
D



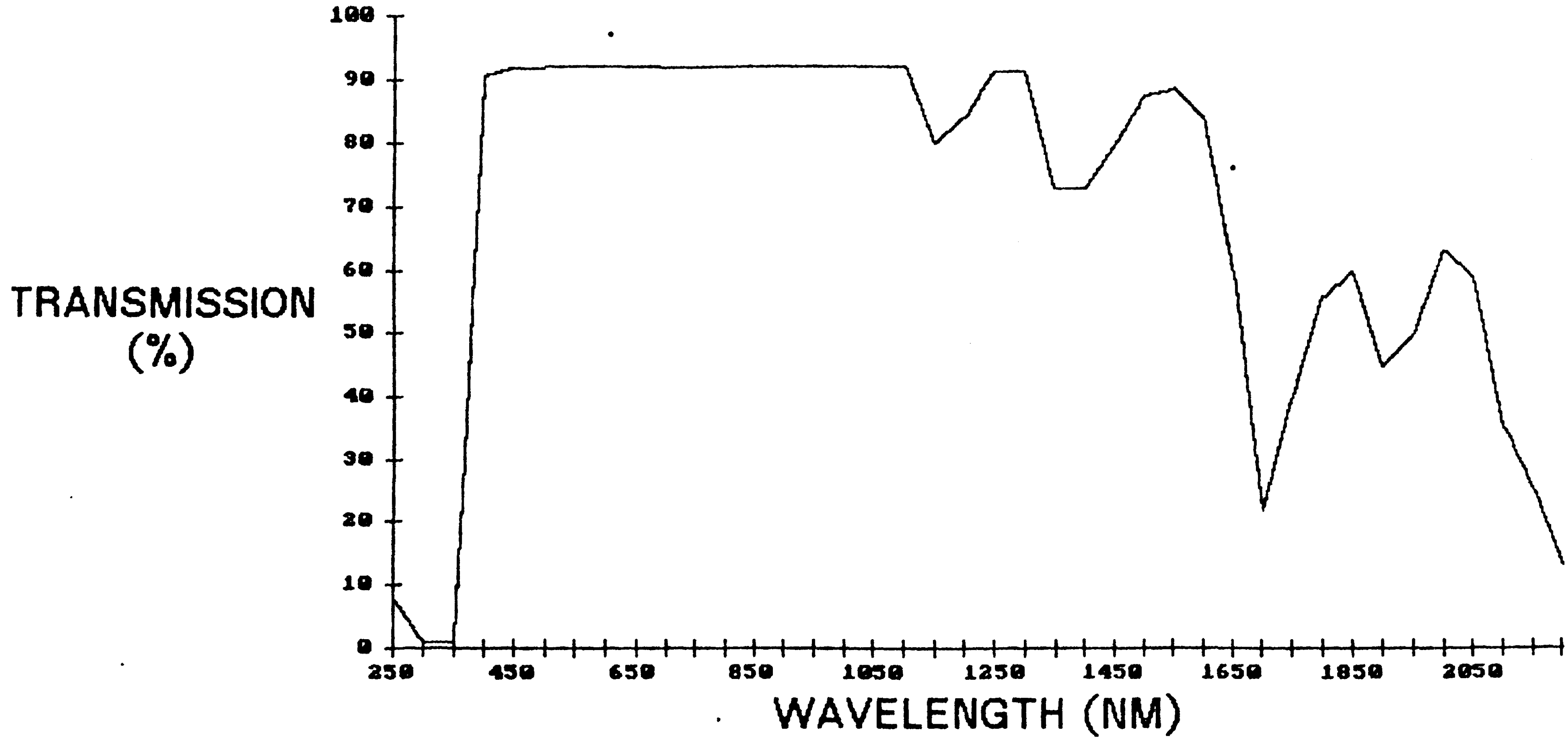
A - 315 - 380
B - 280 - 315
C - <280



156
STANDARD TRANSMISSIONS
VS. WAVELENGTH
1/4" NOMINAL THICKNESS
K. ROCHON, J. THEIOS 5/1/83
100 % LINE
Transferred for acrylic (CYRO) transmittance
ROSE 1/4"
CLEAR 1/4"
BRONZE 1/4"
GRAY 1/4"
GREEN 1/4"
WAVELENGTH (NM)
400
600
700
800
1000
1200
1400
1800
2000
2200
2400
2600
2800

157. 1-1-86

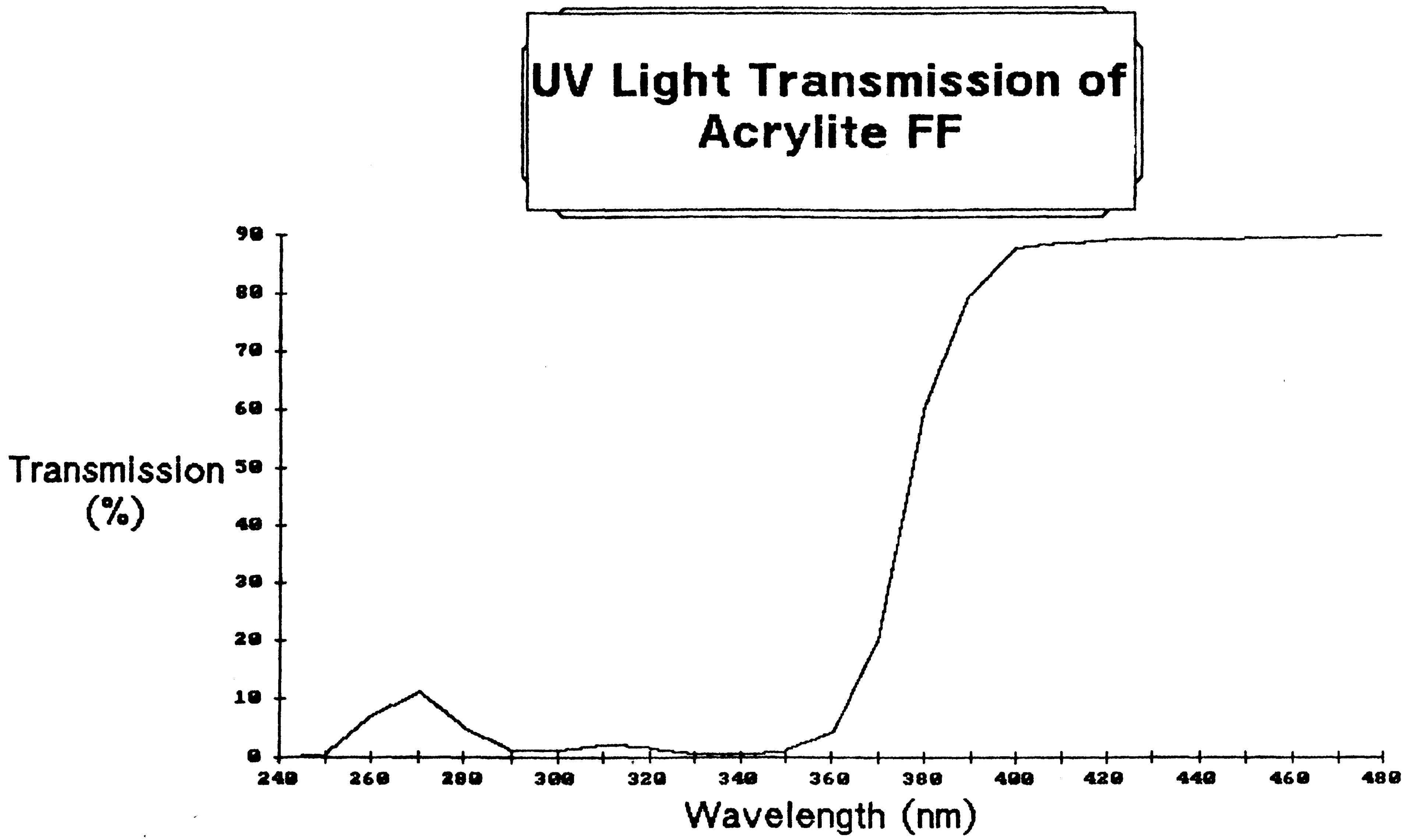
TRANSMITTANCE CHARACTERISTICS OF CLEAR ACRYLITE FF



Graph 2

158.

1-1-84



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Pages 159
160
161

REFE.'ENCES

REFERENCES REFERRED TO AS NUMBERS IN CHAPTER 1.
(other references inserted in the text.)

4 Treshow, Michael, Environment & Plant Response, p.104-105.
5 Lange, O. L., Nobel, P.S., Osmond, C.B., Ziegler, H., Physiological Plant Ecology I, p.42
6 Scrivens, S., Interior Planting in Large Buildings, p.31. See fig 5.3, p.30.
7 Thorington, L., The Medical and Biological Effects of Light, p.36. Fig p.37.
8 Wurtman, R., The Effects of light on the Human Body, p.69.
9 Neer, Robert M., The Medical and Biological Effects of Light, p.15.
10 Thorington, L., The Medical and Biological Effects of Light, p.34.
11 Thorington, L., The Medical and Biological Effects of Light, p.36.
12 Wurtman, R., The Effects of light on the Human Body, p.71.
13 Philips, Lighting Manual, p.16.1.
14 Wurtman, R., The Effects of light on the Human Body, p.71
16 Lange, O. L., Nobel, P.S., Osmond, C.B., Ziegler, H., Physiological Plant Ecology I, p.110.
17 Lange, O. L., Nobel, P.S., Osmond, C.B., Ziegler, H., Physiological Plant Ecology I, p.110.
18 Classification at Kew Garden, London.
19 Olgyay, V., Design with Climate, p.17, referring to C.E.P. Brooks.
102 Lange, O. L., Nobel, P.S., Osmond, C.B., Ziegler, H.Physiological Plant Ecology I, ,fig 6.3 p.176
105 Evans, M., Housing, Climate and Comfort, p.40. Also Bryan, H., class notes, MIT Energy in Buildings, 1984.

REFERENCES REFERRING TO PHOTOGRAPHS

Test house and test cells, photographs taken by the author.	Page 88-90
Gateway Two, Arup Associates, The Architects Journal, 3 August, 1983, p.33.	Page 102
Gateway Two, Arup Associates, The Architects Journal, 3 August, 1983, p.33.	Page 103
One Finsbury Avenue, Arup Associates, Arup Associates Booklet, 1985, p.17.	Page 104 above
Stained glass, Working with Light, Andrew Moor Associates, Cambridge House, 356 Camden Road , London N7 OLG, England.	Page104 below
Museum of Fine Arts, I.M. Pei, photograph taken by the author.	Page 105
Royal Garden Hotel, CFJK Arkitektgruppe, (P. Knudsen), Trondheim, Norway, Contract International 21, box 1083, S-26901, Båstad, Sweden, p.1-2.	Page 106 above and below
Light box and light well, photographs taken by the author.	Page 118-119

BIBLIOGRAHPY

•Andersson, Bruce, The Solar Home Book, Brick House Publishing Co., Inc., Andover, Mass., 1976.
•ASHRAE Handbook 1981 Fundamentals, Ammerican Society of Heating, Refrigerating and
•Air-Conditioning Engineers, Atlanta, GA, 1985.
•Austin, Richard L., Designing the Interior Landscape, Van Nostrand Reinhold Company, New
•York, 1985.
•Bainbridge, David, Village Homes' Solar House Designs, Rodale Press, Emmaus, Pennsylvania, 1979.
•Bednar, Michael J., The New Atrium, McGraw-Hill Book Company, New York, 1986.
•Bryan, Harvey J., Kroner, Walter M., Leslie, Russel P., Center for Architectural Research Rensselaer Polytechnic Institute, New York, July 1981.
•Building Redesign and Energy Challanges, Printed in Washington DC, Nov 1984.
•Caldwell, M.M., Plant Response to Solar Ultraviolet Radiation, 029642 - QK710-E5, Encycl. Plant Physiol New Ser. p 169-107, 1981 v 12.
•Cathey, HM, Cambell, LE, Plant Response to Light Quality and Quantity, 139833, Breed Plant Less Favor Environ. p 213-257 ill 1982.
•Conover, C.A./. Poole, R.T., Acclimatization of Indoor Folliage Plants, Horticultural Review v. 6 1984.
•Evans, Martin, Housing, Climate and Comfort, The Architectural Press Limited, London, 1980.
•Final Report on The Effects of Wavelength Selective Film on Greenhouse Energy and Plant Growth, Environmental Research Laboraty, The University of Arizona, 1985.
•Gaines, Richard, L., Interior Plantscaping, Building Design for Interior Foliage Plants, Architectural Record, New York, 1977.
•Helms, Ronald N., Illumination Engineering for Energy Efficient Luminous Environments, Prentice-Hall, Inc., Engelwood Cliffs, NJ, 1980.
•Hopkinson, R.G., Collins, J. B., The Ergonomics of Lighting, Mac Donald & Co. Ltd., London, 1970.
•Hopkinson, R. G., Petersbridge, P., Longmore, J., Daylighting, William Heinemann Ltd., London, Melbourne, Toronto, 1966.
•IES Lighting Handbook, Illuminating Engineering Society of North America, New York, 1981.
•Johnson, Timothy E., Solar Architecture, The Direct Gain Approach, McGraw-Hill Book Company, New York, 1981.

•Kreider, Jan F., Kreith, Frank, Solar Heating and Cooling, McGraw-Hill Book Company, New York, Hemisphere Publiching Corp., Washington, 1976.
•Küller, Richard, Ljusets Biologi (The Biology of Light), Tekniska Högskolan, Lund, Sweden, 1981.
•Lange, O. L., Nobel, P.S., Osmond, C.B., Ziegler, H., Physiological Plant Ecology I, Responses to the Physical Environment, Springer-Verlag, Berlin, Heidelberg, New York, 1981.
•Larson, Leslie, Hanson, Donald, Climate and Comfort, The Architectural Press Limited, London, 1980.
•Lee, Richard, Forest Microclimatology, Colombia University Press, New York, 1978.
•Manaker, George H., INterior Plantscapes, Prentice Hall Inc., Engelwood Cliffs, NJ, 1981.
•Olgyay, Victor, Design with Climate, Bioclimatic Approach to Architectural Regionalism, Princeton University Press, Princeton, JN, 1983.
•Passive Solar, Proceedings of the 2nd National Passive Conference, March 16-18 1978, University of Pennsylvania, Philadelphia, Pennsylvania ,1978.
•Philips, Lighting Manual N.V. Philips Gloeilampenfabriken, 1975.
•Phillips, Derek, Lighting in Architectural Design, McGraw-Hill Book Company, New York, Toronto, London, 1964.
•Rassmusen, Steen, Eiler, Experiencing Architecture, The M.I.T. Press, Cambridge, Mass., 1959.
•Saxon, Richard, Atrium Buildings - Development and Design, Van Nostrand Reinhold, New York, 1983.
•Scrivens, Stephen, Interior Planting in Large Buildings, The Architectural Press, London, Halsted Press Division, John Wiley & Sons, New York, 1980.
•Van der Veen, R., Light and Plant Growth, The MacMillan Company, New York, 1959
•Wurtman, Richard J., The Effects of Light on the Human Body, in Hormones and Reproductive Behavior, W.H. Freeman & Co, 1979.