

Critical Color: The Use of Color in Nature for Energy Performance
and Its Application to Building Skins

Eric R. Brooks

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Committee:
Mehlika Inanici
Galen Minah
Judith Heerwagen

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Abstract

Critical Color: The Use of Color in Nature for Energy Performance
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Eric R. Brooks

Chair of the Supervisory Committee:
Associate Professor Mehlika Inanici
Architecture

This thesis investigates how color could be used as a tool for energy performance. Color in Nature is not used as decoration to be applied to form. It is indeed selected and varied in response to varying physical constraints in nature. Color in Nature is integral to the survival of plants and animals.

The objective of the thesis is to develop guidelines for selecting color to design energy efficient opaque building skins under different climatic conditions. The investigations in this thesis are organized under five topics: 1) the physics of solar energy, 2) how plants and animals use color to sustain life, 3) the atmospheric and diurnal effects on incident solar radiation, 4) how color is defined in computer simulation tools, and 5) how the reflected light from opaque colored surfaces change with incident light qualities in the physical world.

Utilizing simulation results and empirical data, recommendations have been made to select opaque facade color that is informed by climate and context to aid in energy performance.

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CRITICAL COLOR: THE USE OF COLOR IN NATURE FOR
ENERGY PERFORMANCE AND ITS
APPLICATION TO BUILDING SKINS

INTRODUCTION

Adaptations to universal features of our world are apt to escape our notice simply because we do not observe anything with which such adaptations stand in contrast.

Roger N. Shepard.

At the time of this study, a broad based body of knowledge related to color research exists but is largely inaccessible to the designer due to its technical nature and seemingly disparate subject matter--from neural pathways to plant photosynthesis to animal camouflage and signaling. The goal of this study will be to acquire a better understanding of the physical origins of natural color and Nature's use of color for performance reasons in order to provide another option for making informed and rational decisions with regard to the use of color in architecture. Although it is extremely challenging to neatly carve out the concepts needed for the understanding of the phenomenon to be discussed, every attempt has been made to do so.

Color in Nature

The use of color in Nature does not exist for the enjoyment and benefit of human perception and experience. Human perception is highly influenced by on Nature's use of color for "life-giving and life-sustaining processes that have had their influence since the beginning of time (Mahnke, 1996, p. 9)." Color in Nature is a result of "...inherited characteristics [intended] for the survival of vegetable and animal life" (Mahnke, 1996, p. 9). As with nearly all processes in Nature, function and efficiency is at the heart of

2

Natural color. In the case of the Grand Prismatic Spring in Yellowstone National Park, algae employs various pigments to absorb various spectral regions of sunlight that are both available and useful for energy production within its environment affected by water depth and temperature (figure 0.1-1).



0.1-1

The Human Desire for Color

Color is “an important part of human experience” (Van Wilgenburg, 2009, p. 2). In Sweden studies have shown that people are “critical of a lack of color” (Mahnke & Mahnke, 1987, p. 62). According to Frank and Rudolf Mahnke:

People are very conscious of color and texture in the built environment, and they do like variations. The capacity to find enjoyment in looking at or living in the purity and severity of colorless, unadorned, or raw concrete buildings is limited to those who have the same aesthetic values as the architects of those environments. The general public usually associates such buildings with prisons or bunkers, and finds them cold, lifeless, and boring. Studies point out that the presence of color on exteriors gives rise to positive evaluations, while the absence of color is generally considered negative.

(Mahnke & Mahnke, 1987, p. 62)

They go on to state:

Does all this mean that color can be applied at random, that, as long as it is strong and bright, all will suddenly be well? Of course not.

(Mahnke & Mahnke, 1987, p. 69)

FIGURE 0.1-1 - The Grand Prismatic Spring, Yellowstone National Park.

Algae employs various pigments to absorb various spectral regions of sunlight that are both available and useful for energy production within its environment affected by water depth and temperature.

The application of color in architecture is often considered as an afterthought in the United States, although in some parts of the world it is viewed as a critical component of design from the onset. A major reason for this is that our contemporary western culture views color as simply playing a cosmetic or decorative role which is reinforced by color education (Van Wilgenburg, 2009, p. 2). Could a color strategy based on efficiency, as in Nature, provide a positive emotional or biophilic response?

The Trend of Architecture as Net-Zero

Formal moves in architecture for the realization of low or net-zero energy use are well known and becoming more and more prevalent. Facade color has a consequential impact

on energy use in addition to climate and context. Could facade color choices aid in this quest for net-zero energy use? Like Nature, could color selection foster efficiencies not currently realized?

An Inter-Disciplinary Approach

There is a need for re-establishing the links between science, art, and the built environment in the Goethean tradition--a search “for patterns” and the “hidden lawfulness within the welter of colour phenomena” (Van Wilgenburg, 2009, pp. 3-4). This approach, however, requires the design community to “adopt a new attitude toward scientific research conducted in many different fields and covering many disciplines” (Mahnke & Mahnke, 1987). Such an approach links study efforts but requires the practitioner to become familiar with the language spoken by the various disciplines. For example, “we cannot do without the physicist’s viewpoint of color, and it must be explained in the language of the physicist if we are to understand what color is, scientifically, and where its origins lie” (Mahnke, 1996, p. 8). Such an approach recognizes the fact that, in Nature, everything is interconnected and integrated. Such an approach “deals with the dynamics of several levels of reality at once” and may lead to ideas that may not come from any one particular discipline (Van Wilgenburg, 2009, p. 1). Furthermore, a “interdisciplinary approach is the most effective one in dealing with and recognizing environmental problems and design solutions to them” (Mahnke, 1996, p. 3).

Investigations into the use of color in Nature for energy performance and its application to building skins will have the following objectives:

1. Investigate the physics of light and color.
2. Investigate the affects of atmospheric and diurnal conditions on light qualities and the spectral selective strategies and thermal performance aspects of color use in Nature.
3. Investigate how color is used in architecture.

4. Investigate how color in computer simulation is defined and its impacts on incident solar energy absorption.
5. Investigate how colored surfaces react to the full spectral richness of terrestrial light energy under seasonal and diurnal skies.
6. Provide guidelines for facade color based on climate and energy performance.
7. Research current color changing technologies and propose possible application.

SUMMARY

It was soon realized that primary investigations into the impact of opaque surface color on energy performance, the use of color as a critical tool for evaluation, and biomimicry (natural use of color for energy performance) would require secondary research into physiology, psychology, biology, physics, and atmospheric science while using methods of simulation and observation to draw connections between these disciplines. This thesis lies at the convergence of these topics (figure 0.1-2).

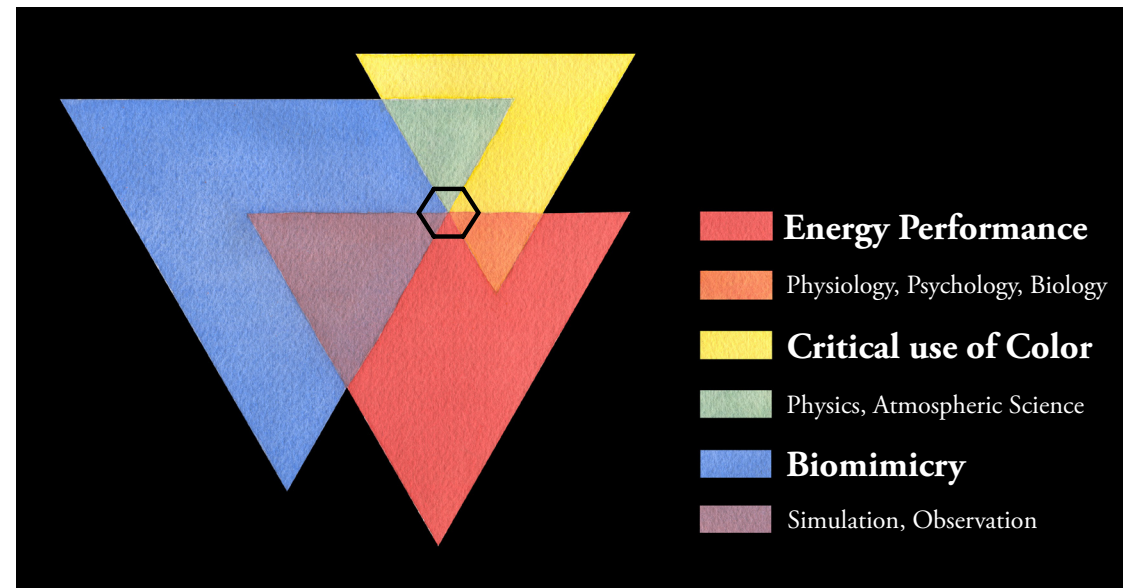


FIGURE 0.1-2 - Converging topics
Secondary research is necessary for establishing connections between primary interests: an inter-disciplinary approach

PART 1

PHYSICS OF ELECTROMAGNETIC RADIATION - "LIGHT ENERGY"

"Each encounter of light with bulk matter can be viewed as a cooperative event arising when a stream of photons sails through, and interacts with, an array of atoms suspended (via electromagnetic fields) in the void. The details of that journey determine why the sky is blue and blood is red, why your cornea is transparent and your hand opaque, why snow is white and rain is not"

(Hecht, 2002)

1.1. Electromagnetic Radiation - "Light Energy"

Electromagnetic (EM) radiation is energy emitted by objects (and their atomic structures) that are being excited by heat or other means and travels through space and matter within an electromagnetic field (Farrant, 1997, p. 2). The radiant energy is transported through the vacuum of space by quantifiable and indivisible packets known as photons that behave like particles when being emitted or absorbed, yet act as waves when traveling through space. In a vacuum all energy (EM radiation) travels at the same speed, regardless of the amount of energy transported by the photon, as one EM wave (Hecht, 2002, p. 36) (Farrant, 1997, p. 2). Different energy amounts, however, do travel at different wavelengths (distance between wave crests or troughs) or frequencies (number of waves in a given timeframe - usually seconds) (figure 1.1-1). These wavelengths can range anywhere from over 3000 miles down to much smaller than a single atom (Hecht, 2002, pp. 73-80). As the wavelength decreases, the amount of energy being transported increases (figure 1.1-2). All of these wavelengths combined yield an EM emission spectrum. Most are familiar with many types of EM radiation - FM radio waves, microwaves, ultraviolet (UV), and of course visible light.

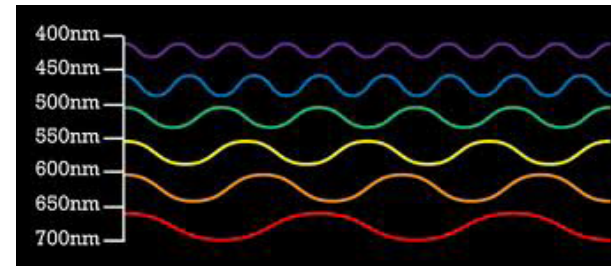
In the case of our Sun, a hot incandescent object driven by nuclear fusion, a spectrum (wavelength dependent spectral irradiance) is produced that is roughly half visible light (Baker & Steemers, 2002, p. 110). The other half is the familiar Ultraviolet (UV)

FIGURE 1.1-1 - Energy Dependent Wavelengths

Different photon energies travel at different wavelengths or frequencies

FIGURE 1.1-2 - Increasing Wavelength Yields Decreasing Energy

Photon Energy is the product of Planck's constant and the speed of light divided by the photon's wavelength



1.1-1

$$E = hc/\text{wavelength}$$

$h = 6.26 \times 10^{-34} \text{ J*s}$ (Planck's constant)

$c = 3.00 \times 10^8 \text{ m/s}$ (speed of light)

	wavelength (meters)	Energy (J)	fraction of Violet energy content
	3.8E-07	5.23E-19	100%
	4.3E-07	4.62E-19	88%
	5.5E-07	3.61E-19	69%
	6E-07	3.31E-19	63%
	6.25E-07	3.18E-19	61%
	6.5E-07	3.06E-19	58%
	7.5E-07	2.65E-19	51%

1.1-2

FIGURE 1.1-3 - Ultraviolet Irradiance

Roughly 4% of the Solar Energy striking the Earth lies in the Ultraviolet region

FIGURE 1.1-4 - Visible Irradiance

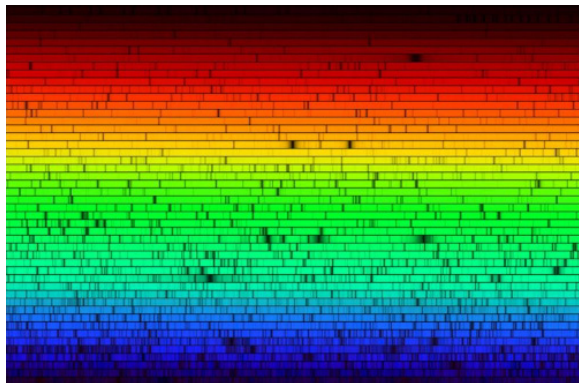
Roughly 53% of the Solar Energy striking the Earth lies in the Visible region

FIGURE 1.1-5 - Infrared Irradiance

Roughly 43% of the Solar Energy striking the Earth lies in the Infrared region

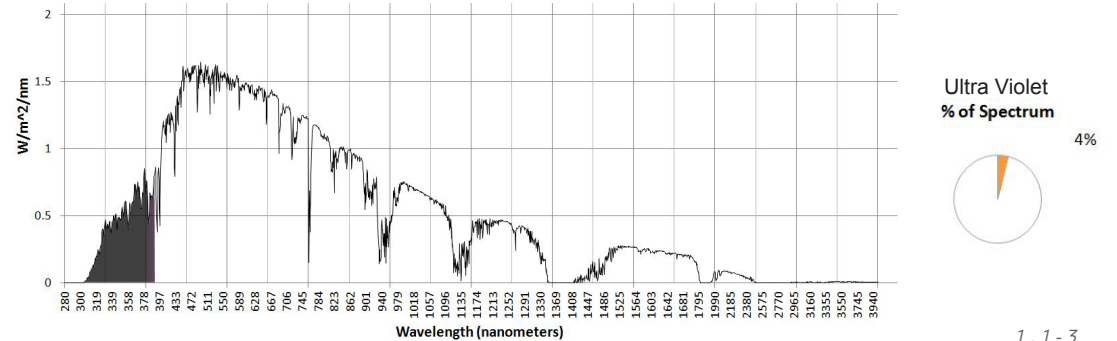
FIGURE 1.1-6 - Sun's Emission Spectrum

The Sun's emission spectrum is broken by Fraunhofer lines representing regions of spectrally selective absorption by elements present in the Sun's atmosphere

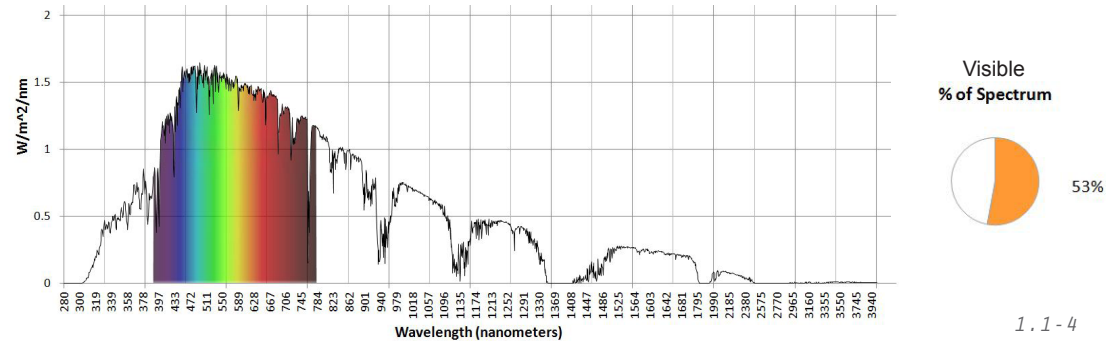


1.1-6

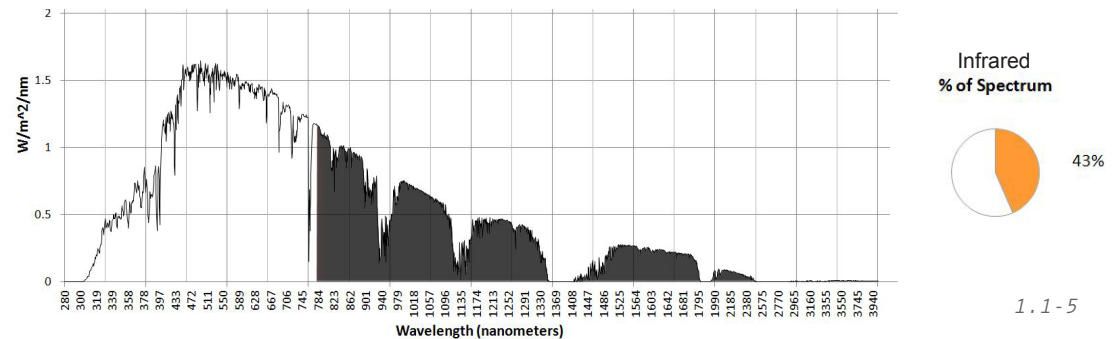
and Infrared (IR) with IR accounting for most of this (Levinson, Ronnen, 2011, p. 2). (figures 1.1-3 through 1.1-5). As seen from the emission spectrum (figure 1.1-6), the suns spectrum is not absolutely continuous and displays dark lines known as Fraunhofer lines. This is light energy's first encounter on its journey to the Earth's surface with the processes of selective absorption, in this case, of the Suns atmosphere by processes briefly discussed next (Farrant, 1997, p. 5).



1.1-3



1.1-4



1.1-5

1.2. Interaction of Photons, Atoms, and Molecules

Atomic Structure

All matter (macro and microscopic objects) around us is made of atoms or groups of atoms (molecules). Atoms are comprised of tiny negatively charged particles (electrons) orbiting a relatively huge positively charged nucleus (made up of protons and neutrons). How many electrons are present and how far from the nucleus they orbit partially determines the optical and chemical behavior of these atoms. Each discrete distance that the orbiting electrons are from the nucleus is referred to as a *shell* or *cloud* with the outer shell containing the *valence electrons*. It is the behavior of these valence electrons (orbiting in the outer shell furthest from the nucleus) resulting from a collision with a photon with a particular wavelength (and its associated energy) that is “ultimately the predominant source of light in the world” (Hecht, 2002, p. 64).

Atomic Ground State and Excited State

Without any outside influence, an atom exists indefinitely in a state of equilibrium or *ground-state* configuration. This stable configuration sees the nucleus-orbiting electrons in well defined shells located nearest to the nucleus. This configuration represents the atoms lowest energy state. There are other more energetic configurations known as *excited states* that represent electron orbits located farther away from the nucleus in well defined shells with discrete energy contents. Any outside influence (collision with other electrons, photons, or other atoms) that adds energy to the atomic system can cause an excited state. These configurations are “inherently unstable and temporary” as the atom prefers to exist in a ground state (Hecht, 2002, p. 64).

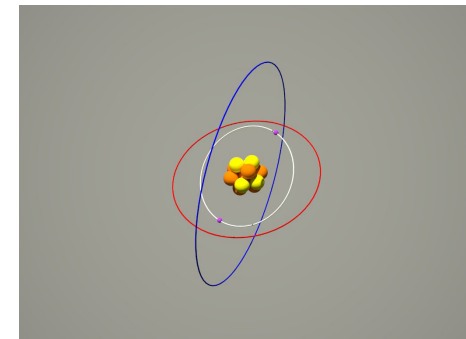
The Fate of Wavelength Dependent Spectral Irradiance - “Light Energy”

When a photon (light energy) strikes an atom or group of atoms (a molecule), one of two things can happen depending on the photons wavelength and its associated amount of energy. The first scenario involves a photon at a particular wavelength (with its particular

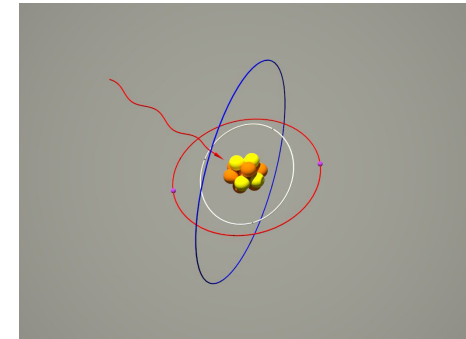
FIGURE 1.2-1 - Atomic Ground State

FIGURE 1.2-2 - Atomic Excited State

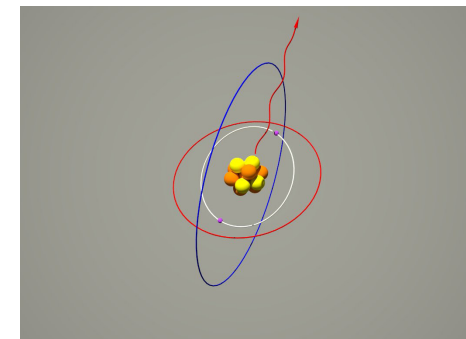
FIGURE 1.2-3 - Ground State with Photon re-emission



1.2-1



1.2-2

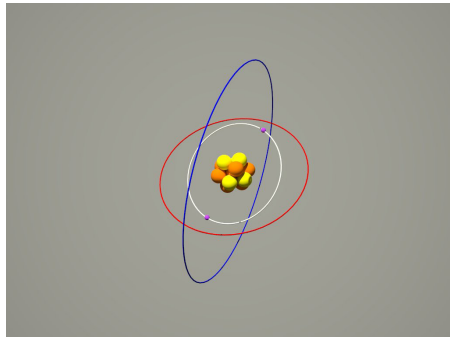


1.2-3

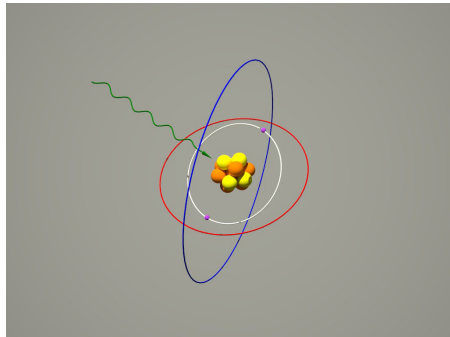
FIGURE 1.2-4 - Atomic Ground State

FIGURE 1.2-5 - Atomic Oscillation

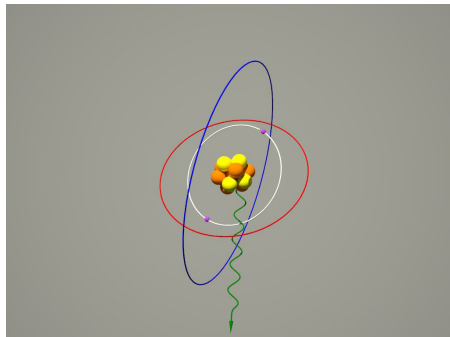
FIGURE 1.2-6 - Ground State with Photon reflection



1.2-4



1.2-5



1.2-6

energy amount) that corresponds with one of the atoms(s) well defined *excited states* or rungs on its “energy ladder” (Hecht, 2002, p. 64). One can think of this as physically climbing up a ladder, the higher one goes the more effort (energy) it takes and the chance of injury due to fall increases due to the increase in height and corresponding increase in potential energy. The photon and its energy is absorbed and the atom’s outer electrons jump to one of perhaps many well defined higher energy levels (Hecht, 2002, p. 67). This process is also known as *atomic or molecular resonance* (figures 1.2-1 through 1.2-3). The next step depends on the atom’s relationship to other atoms or molecules. If the atom or molecule is in isolation, the energy released in the process of returning to a *ground state* from the inherently unstable *excited state* is in the form of a photon of wavelength (and associated energy) equal to the original impacting photon. The “atomic landscape” of solids, liquids, and gases found in Nature is very dense when compared to a single atom or molecule in isolation. Most often the energy acquired from the impacting photon is absorbed or “taken up” and rapidly transferred to neighboring atoms through collisions causing “random atomic motion” or “thermal energy” and not re-emitted in a process known as *dissipative absorption*. An example would be a piece of steel in the sun absorbing photons and its atomic structure converting them to heat (Hecht, 2002, p. 67). Other times, in the case of photosynthesis, the energy is used for driving chemical processes. (Freeman, 2008, p. 203). “All material media partake in dissipative absorption to some extent, at one frequency [wavelength] or another” (Hecht, 2002, p. 67).

The second scenario involves a photon that is of a particular wavelength (and associated energy) that *does not* correspond to one of the atoms(s) well defined *excited states* or rungs on its “energy ladder.” In this case, upon impact with the atom(s), the photon is essentially reflected (with no change in energy or wavelength) in random directions causing to atom(s) to simply vibrate or oscillate at the same wavelength (frequency) as the impacting photon. This process is known as *non-resonant scattering* (figures 1.2-4 through 1.2-6) (Hecht, 2002, p. 67). This can be imagined as pebbles in a stream, each creating a wavelet, together streaming in a continuous wavefront.

The mechanisms of *atomic or molecular resonance* and *non-resonant scattering* result in

the spectrally selective absorption of light energy which is “responsible for most of the coloration in the world around us” (Hecht, 2002, p. 64).

1.3. Submicroscopic Effects and the Macroscopic View

When viewed at the macroscopic level, the submicroscopic processes discussed above can lead to many observable phenomena such as absorption, reflection, and transmission (as well as many variations and combinations thereof) when light strikes “various homogenous media” (Hecht, 2002, p. 86). The quantities of directional incident light energy that are either reflected (R), absorbed (a), or transmitted (T) have the following relationship with *conservation of energy* kept in mind: $1 = (R + a + T)$ where 1 represents 100% of the quantity of incident solar energy (Baker & Steemers, 2002, p. 89).

Absorption

As was discussed above, *absorption* is the process that results in the conversion of light in the form of photons to heat when they strike a material and that this process can be wavelength or spectrally dependent. This results in the material itself radiating photons at much longer wavelengths than that of the incoming one. An *ideally absorptive* material would “take-up” all incoming light energy and convert it to heat. Most natural and man-made materials display spectrally *selective absorption* where only certain photons with particular wavelengths are absorbed (a) while reflecting (R) or transmitting (T) the remainder via the relationship: $a = (1 - R - T)$. When visible light energy is incident upon opaque materials, transmission drops to zero which leaves only the effects of absorption and reflection to account for 100% of the incident visible light energy.

Reflection

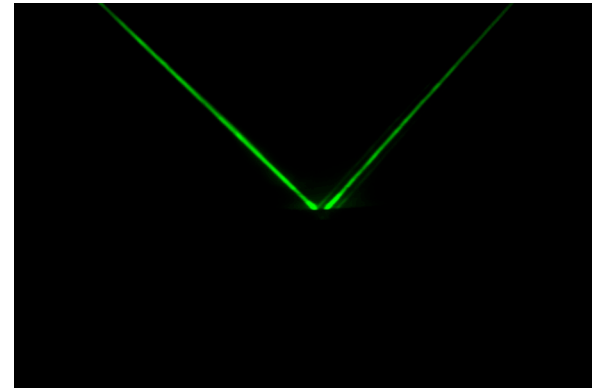
The process of *reflection* is a “wonderfully subtle affair usually involving the coordinated behavior of countless atoms” (Hecht, 2002, p. 86). Classically, it is the interaction of light with the boundary separating materials. Although it doesn’t exist in Nature, an *ideal specular* material will reflect absolutely all of the incoming directional light energy in

FIGURE 1.3-1 - Specular Reflection

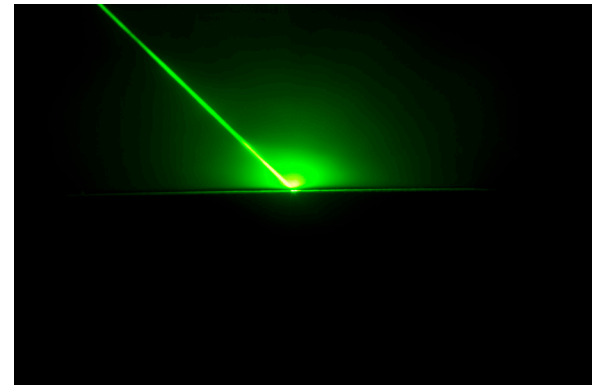
The reflection of a laser from a mirror displays a specular behavior with the angle of incidence matching the angle of reflection

FIGURE 1.3-2 - Diffuse Reflection

The reflection of a laser from sandpaper displays a diffuse behavior with light being reflected in all directions



1.3-1



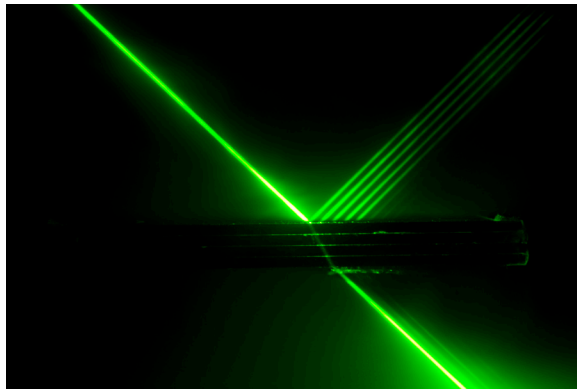
1.3-2

FIGURE 1.3-3 - Refraction

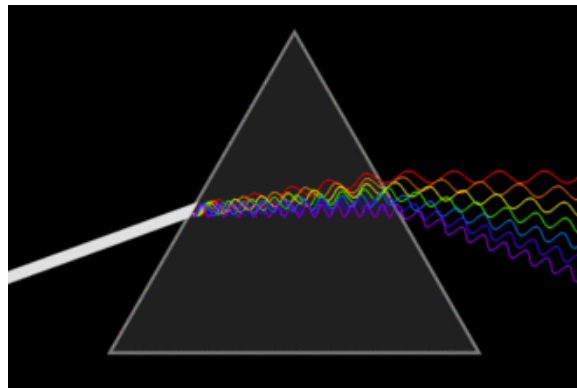
As the laser passes through several sheets of glass, the light beam is bent then emerges at the angle of incidence with portions being reflected by interface of the glass plates

FIGURE 1.3-4 - Wavelength Dependent Refraction

Shorter wavelengths are bent more than longer wavelengths



1.3-3



1.3-4

one direction per the *Law of Reflection* (figure 1.3-1). An *ideal diffuse* material will reflect absolutely all of the incoming directional light energy in all directions equally (figure 1.3-2). Most materials found in Nature (as well as most man-made materials) display a *directional diffuse* behavior which is a combination of *specular* and *diffuse* reflection. In this case the incoming directional light energy is diffused in all directions unequally, with a large portion following the *Law of Reflection*. The amount of reflected (R) energy equals the total incident energy less the amount absorbed (a) and the amount transmitted (T): $R = (1 - a - T)$ (Baker & Steemers, 2002, p. 89). With an opaque surface, the amount of *visible* light transmitted is zero leaving, again, only the effects of absorption and reflection to account for 100% of the incident visible light energy.

Two variations of reflection that occur at a micro and submicroscopic scale are known as *Mie Scattering* and *Rayleigh Scattering*. Both refer to the relationship of the incoming photon wavelength and size of the particle being impacted. No absorption is happening in either case. *Mie Scattering* occurs when the particle size is large in comparison to the incoming wavelength. The particle acts as an *ideal diffuser* and reflects all visible wavelengths equally in all directions. *Rayleigh Scattering* (non-resonant scattering) occurs when the particle size is a fraction of the incoming wavelength (Farrant, 1997, p. 11). Reflection in most Natural materials has a Mie or Rayleigh scattering component.

Transmission

Transmission refers to the interaction of light energy and the material it is passing through. Depending on the atomic or molecular makeup of the transmitting material and the angle of incidence, part or all of the wavelengths will pass through while the remainder are absorbed or reflected. The relationship of transmitted light energy to incident light energy (ratio) is known as *transmittance*. The quantities of incident light energy that is transmitted (T) is the total (1) less that absorbed (a) or reflected (R): $T = (1 - a - R)$ (Baker & Steemers, 2002, p. 89). One effect of directional visible light energy passing obliquely through transparent materials of different densities is *refraction* (figure 1.3-3). The speed of the photons change as they pass through the various media and

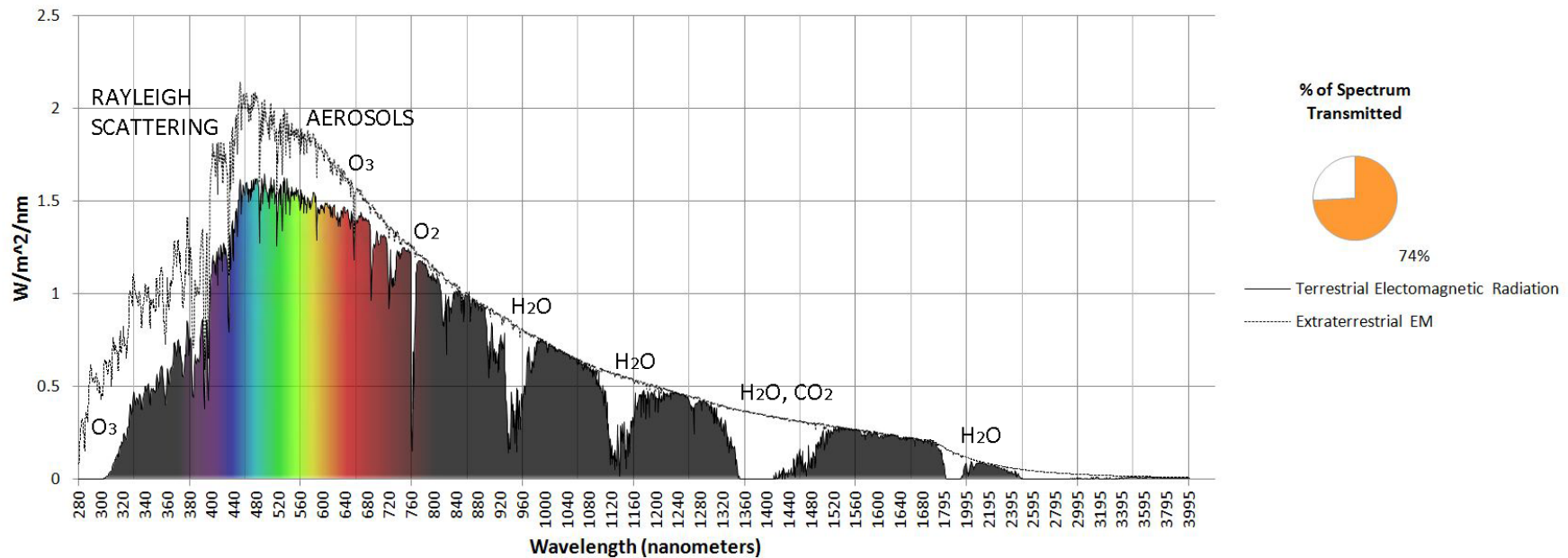
their paths are bent according to their wavelength and associated energies with long-wavelength low-energy photon paths being bent less than short-wavelength high-energy photon paths (figure 1.3-4) (Farrant, 1997, p. 10).

SUMMARY

Other phenomena including interference, diffraction, and iridescence are a result of various combinations of absorption, reflection, and transmission (Farrant, 1997, p. 11). All of the aforementioned phenomena have an impact to some degree on the spectral distribution of the light energy (visible and otherwise) which strike both the Earth's atmosphere and surface (figure 1.S-1). The Earth's outer atmosphere is impacted by about 1,353 watts of solar radiation per square meter. As much as 1,000 watts of solar radiation per square meter can strike the Earth's surface on a clear sunny summer day (Autodesk, 2012). Nature uses color to mediate this energy for benefit. Atmospheric and diurnal affects on the incident solar energy spectrum and how life on Earth has adapted to best harvest or reject portions of that spectrum are the subjects of Part 2.

FIGURE 1.S-1 - Incident Extra-terrestrial and Terrestrial Spectral Curves

Selective absorption and reflection by atoms and molecules in the Earth's atmosphere removes approximately 26% of the of the Sun's energy that strikes the top of the atmosphere



PART 2

LIGHT AND COLOR IN NATURE

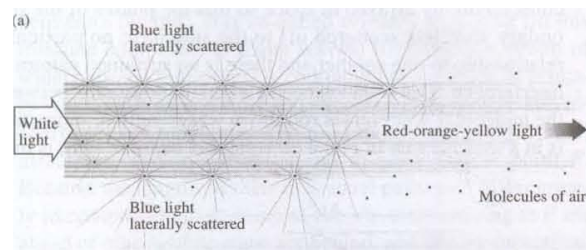
Part 1 served to show the relationship between wavelength, energy content, and the mechanisms including absorption and reflection that effect the light energy spectrum. The next investigation is how these relationships and mechanisms are “played out” in Nature.

2.1. Atmospheric and Diurnal Effects on the Incident Light Energy Spectrum

As light energy from the sun passes through the atmosphere, a complex mixture of molecule types, particle sizes, and varying densities thereof work together to affect the spectral characteristics of the light energy (ultraviolet, visible, and infrared) that reaches the earth’s surface. The atmosphere is chiefly made up of molecules of nitrogen and oxygen that have molecular resonances (therefore spectrally selective absorption) in the ultra violet (very short wavelength and high energy). The absorbed energy ionizes the atmosphere (creating ozone) and protects life from an “otherwise lethal stream of solar UV” (Hecht, 2002, p. 78). Not all UV wavelengths are absorbed, some are efficiently scattered which is why sunburns can happen during an overcast sky condition (Farrant, 1997, p. 11). The same atmospheric molecules *do not* have resonances or absorptive characteristics in the visible range, therefore the atmosphere is transparent (Hecht, 2002).

FIGURE 2.1-1 - Lateral Scattering

Particles in the atmosphere preferentially scatter short wavelength high-energy photons out of the sunlight leaving the beam with a greater percentage of red, orange, and yellow photons



2.1-1

As the photon wavelengths increase (and the associated energy decreases), the molecules (small in comparison to the wavelength) simply oscillate at the incoming photon wavelength (frequency) causing a scattering effect. The closer the photon’s energy is to the resonant frequency, the more it resonates and *laterally scatters* the incoming light energy--violet (of which there is little in the visible light spectrum) causes more vibration and lateral scattering than blue which causes more than green and so forth. The red end of the spectrum is scattered least resulting in light energy that has more red photons (figure 2.1-1). In the low-density environment of the upper atmosphere this phenomenon, known as *Raleigh Scattering*, is partly responsible for the blue sky. As the

density of the atmosphere increases, the effects of *Rayleigh Scattering* decrease, as “a dense uniform substance will not appreciably scatter laterally.” If this were not the case, distant mountains would have a reddish appearance rather than the familiar blue-violet hue (Hecht, 2002, p. 87).

Blue Variation

The density of the atmosphere is not absolutely uniform because of the unequal distribution of air molecules moving at various rates driven by meteorological phenomenon. The constantly varying density causes constantly varying degrees of scattering of the blue wavelengths. Large particles (water droplets, dust, pollution, ash, pollen, etc.), in comparison to the incoming light energy wavelength, present in the atmosphere in large amounts will tend to scatter all wavelengths, more or less, without any spectral preference. This is the phenomenon known as *Mie Scattering*, which results in more full spectrum white light being added below the *Rayleigh Scattered* blue light thereby making the blue less intense. The opposite occurs after a substantial rain has removed the dust from the air and the effects of *Mie Scattering* are reduced (Farrant, 1997, pp. 25-26) (Murphy & Doherty, 1996, p. 93).

Infrared and Red Absorption by Water

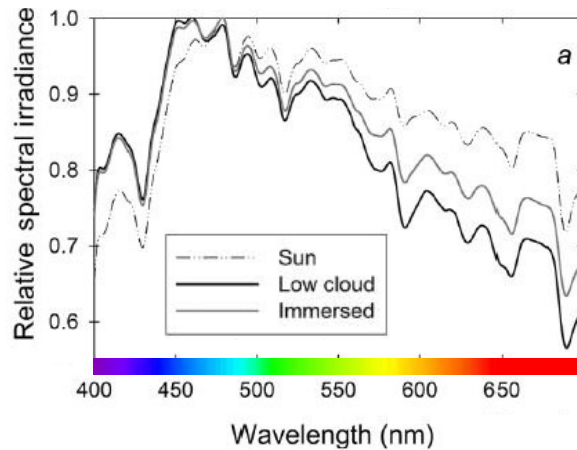
The appearance of clear water in full spectrum sunlight is due to the selective absorption (causing molecular resonance) of infrared and a portion of the nearby red light which is converted to heat. This removal of a portion of the red photons from the full spectrum white light results in water having a barely perceptible blue-green appearance. At a depth of around 100 feet, nearly all of the red wavelengths have been absorbed (Hecht, 2002, p. 134)(Marshall, 2009, p. 3). Water vapor in the atmosphere has a similar affect on the spectrum by decreasing the amount of red and infrared components.

Clear vs. Overcast

As was discussed earlier, a clear sky appears blue largely due to the upper atmospheres’

FIGURE 2.1-2 - Spectral Shift Affected by Sky Condition

Variations in Blue and Red end of the Light Energy Spectrum



2.1-2

Rayleigh Scattering of short wavelength, high energy blue photons. Clouds form as water vapor condenses around dust particles lower in the atmosphere. As the droplet size increases and the cloud becomes more dense, the degree of reflective *Mie Scattering* is lessened and the clouds darken (Baker & Steemers, 2002, p. 31) (Farrant, 1997, p. 31). The effect of clouds on the light energy spectrum is an overall reduction of irradiance (photons per unit area) across the spectrum—with a cloud immersed condition (fog) having only 15% of the cumulative total radiation (irradiance) of a clear sky. In all sky conditions the peak irradiance occurs in the blue-green wavelengths (while the intensity varies). However, as clouds cover the sky, there is a comparative increase in the blue high-energy portion of the spectrum, and a decrease in the red low-energy portion (figure 2.1-2) (Reinhardt, Smith, & Carter, 2010, p. 462).

Diurnal Effects

As the sun travels along its path (in relationship to a fixed point on the earth's surface), the column of atmosphere that the light energy has to penetrate steadily decreases from morning to mid-day and then steadily increases from mid-day to evening. When the sun is directly overhead, the effects of scattering are at their minimum because the column of atmosphere is at its shortest, thereby leaving less air molecules and particles to scatter the incoming light energy, and giving the sun a whitish-yellow appearance. The yellow tint is due to the fact that some of the blue light was *laterally* scattered out by the effects of *Rayleigh Scattering* (Farrant, 1997, pp. 25-26). As the column length of penetrated atmosphere increases, the amount of blue light scattering increases as well as scattering of increasingly shorter wavelengths such as green. This results in leaving the resulting spectrum biased toward the red at low solar altitudes (Hecht, 2002, p. 87) (Murphy & Doherty, 1996, p. 90). Despite the penetrated atmosphere column heights shared by the early morning and evening light energy, the spectral qualities may not be depending on the amount of water vapor present. The morning comes with the coolest temperatures and often the highest atmospheric water vapor burden. As was mentioned prior, water preferentially absorbs portions of the red wavelengths. This results in the spectrum having a shift toward green (Shepard, 1992, p. 511).

2.2. Physiological Effects of Light and Regularly Irregular Intensities and Spectral Qualities

“The mechanism of the color perception is complex, and to be able to specify the architectural use of color with a sound knowledge of the implications it is necessary to understand a little of the science behind color vision”

(Baker & Steemers, 2002, p. 92)

It is difficult to discuss color and the various wavelengths and energies that comprise them without injecting human physiology and perception to a certain degree while trying to steer away from the psychological and subjective implications. The functional aspects of vision are more objective and well understood and are an example of how Nature finds ways to stabilize (in the case of vision--the perception of) environmental effects. It is well known that human vision starts with the cooperative efforts of rods and cones on the retina contained within the eye structure. Light energy enters the iris, passes through the lens, and impacts the retina. The rods provide peripheral mono-chromatic night-time vision and contribute to daytime vision in the periphery. The cones are of three types, each having a particular sensitivity to either blue (short wavelength), green (medium wavelength), or red (long wavelength) and are active under relatively bright lighting conditions. These cones and their relative spectral absorption of light energy work together to provide information to the brain to create color vision (Farrant, 1997, p. 113).

A range of sensitivities a million fold (from starlight to bright sun) are available via the cooperation of the iris and brain on governing how much light energy is entering the eye and how the spectral intensities sensed by the cones and rods are interpreted and perceived. What is not as obvious, yet well understood, is that the sensitivity of the blue, red, and green receptors are automatically adjusted so that no one color predominates and, for example, a sheet of white paper appears white under many ambient lighting conditions -- an automatic “white balance” in photography terms (Baker & Steemers, 2002, p. 94) (Hecht, 2002, p. 77). The functional significance of this adaptive ability is believed to lie within our ancestors’ need for the ability to accurately identify edible foods

such as fruits and mushrooms in an ever-changing spectral distribution of light energy (Baker & Steemers, 2002, p. 94). Since “the light that reaches our eyes from an external surface is a product of both the spectral reflectance characteristics of a surface and the spectral energy distribution of the light that happens to fall on that surface”, the only way to achieve “perceptual constancy of colors” is for our visual system to “successfully infer the separate contributions--of the surfaces and of the lighting--that have jointly given rise to the retinal stimulus” (Shepard, 1992, p. 501). This adaptation prevents us from perceiving the constant spectral shifts of incident light energy that occur throughout the day and year unless the shifts are extreme as in the case of a sunset or other atmospheric condition such as pollution.

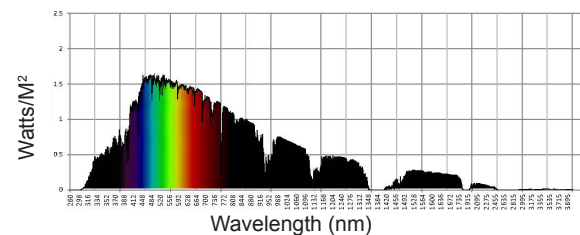
2.3. Vegetation and the Preponderance of Green

Upon looking at the spectral distribution of light energy from the sun filtered by the atmosphere it is realized that there is a peak in irradiance (photons per unit area per unit time) in the blue-green and green wavelengths. It seems that this region of the spectrum would be perfect for absorption for photosynthesis. Why wouldn't plants utilize these wavelengths? If they did they would not be reflecting it and we would not perceive them as green.

As recently as 1985 it was believed that the photosynthetic capacity of plants was largely static and that the only limit to the photosynthetic processes in vegetation was the availability of light energy. Since then there have been numerous discoveries of highly dynamic mechanisms that plants use to govern the absorption of incoming light energy including chloroplasts that stack to self shade, leaves that strategically move, and antenna complexes that can radiate up to half of the excess photons as heat. Plants are frequently forced to deal with excess light energy and the amount thereof depends on “instantaneous environmental conditions” including temperature and humidity (Ort, 2001, p. 29).

With the knowledge that plants often have to reject excess light energy, that they have sophisticated mechanisms to do so, and the fact that a large portion of the visible solar irradiance that strikes the earth's surface is in the blue-green and green wavelengths, the

FIGURE 2.3-1 - Spectral Irradiance
Peak spectral Irradiance occurs in the blue-green and green wavelengths



2.3-2

questions arise -- could the greenness of plants be a strategy to reject a large portion of light energy by *reflection*? Is green a performance based color? After all, if all of the incident light energy must be absorbed, reflected, or transmitted, reflection may be a good way to reduce the amount of energy absorbed.

The answer is no, although plants do use color to govern incident light energy in some surprising ways. As is well known, plants are predominately green because of the chlorophyll molecules contained within the vegetative tissues. What may not be as well known is why chlorophyll is green--why does it not absorb green wavelengths? The answer requires recollection of Part 1 and the energy states that an atom or molecule (group of atoms) can have as a result of a photon of particular wavelength and energy striking it: *ground state* or *excited state*. The molecule chlorophyll has resonances that can drive it to an *excited state* that correspond to energy carried by blue high-energy and red low-energy photons but not green mid-energy photons -- there are blue and red rungs on its "energy ladder" but not green. The green photons are re-emitted (reflected) and green is perceived -- they fall through the "ladder" while blue and red photons are absorbed to drive photosynthesis (Freeman, 2008, p. 205).

Although the color green is not used as a light energy rejection strategy, red sometimes is. The red pigment anthocyanin (as well as other red pigments) is used as a visible light screen--a photoprotective sunscreen of sorts that accumulates in response to light stress on a cellular dependent basis. The amount of this pigment can be sensitively modulated in response to local light energy conditions (figures 2.3-2 and 2.3-3). These transient red pigments reflect most of the red wavelengths, lower the absorption of blue, and selectively absorb green and ultraviolet wavelengths (Steyn, Wand, Holcroft, & G.Jacobs, 2002, pp. 350-353).

Accessory Pigments

Since chlorophyll is inefficient at utilizing green wavelengths, plants utilize other molecules in the form of *accessory pigments* to broaden the spectral range they can absorb (figures 2.3-4 and 2.3-5). Beta carotene and other carotenoids are pigments that reflect

FIGURE 2.3-2 AND 2.3-3 - Color for Photo-protection

Color can be used as a visible light screen in leaves under light stress. This can be employed on a cellular dependent basis as seen on a leaf that was previously shaded by another.



2.3-2



2.3-3

FIGURE 2.3-4 AND 2.3-5 -
Accessory Pigments for Absorption

Color is used by plants to absorb wavelengths of light that chlorophyll cannot absorb in a complementary relationship between pigment color and light wavelength.

FIGURE 2.3-6 - **Accessory Pigments Visible in Fall**

Accessory pigments become visible in the Fall as chlorophyll degrades.

Accessory Pigments:

Beta-Carotene – **ORANGE** absorbs **BLUE**

Lutein – **YELLOW** absorbs **VIOLET**

Phycocerythrin – **RED** absorbs **GREEN**

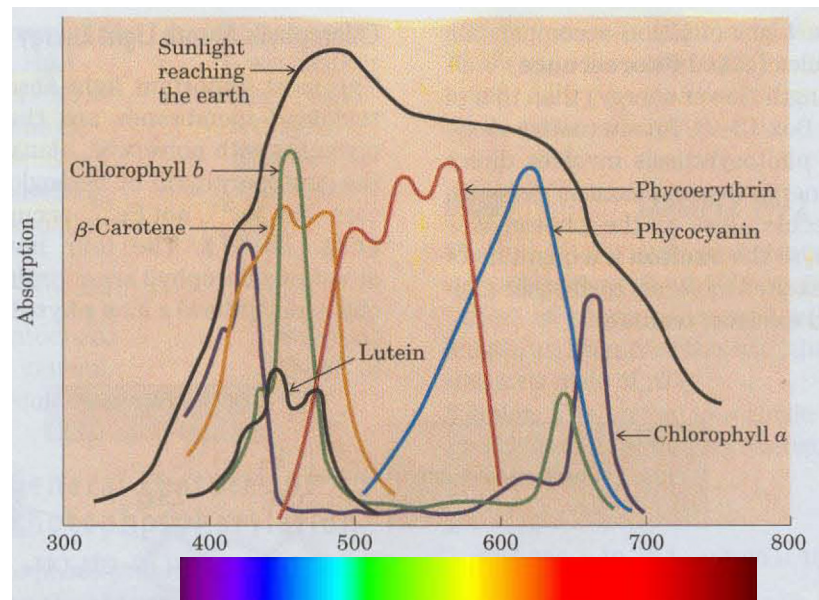
Phycocyanin – **BLUE** absorbs **ORANGE**

yellow, orange and red photons and absorb blue and green photons in a complementary color relationship. In this case the blue and green photons drive the pigment molecules into an *excited state* and instead of the energy being converted to heat, it is transferred to the chlorophyll photocenter (where the chemical reaction occurs turning light energy to sugars) in a type of “electron hot potato” for use in photosynthesis.

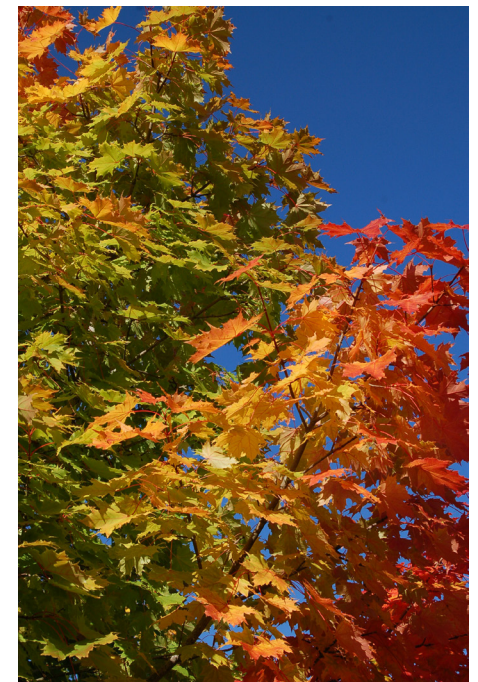
In autumn, as the length of night increases, the photosynthetic process in deciduous trees slows and the chlorophyll degrades and disappears allowing the *accessory pigments* to come into view and bring fall colors. The yellows, oranges, and browns we see are, for the most part, present in the foliage all summer but are masked by the chlorophyll. The reds are a result of the production of photoprotective anthocyanin that is produced in response to light stress caused by the imbalance of available light and lack of photosynthetic capacity as well as the accumulation of sugars in the leaves (figure 2.3-6)(Steyn, Wand, Holcroft, & G.Jacobs, 2002) (Tackett, 2011).



2.3-4



2.3-5



2.3-6

2.4. Color in Animals and Insects

The performance aspects of color in animals and insects are not always obvious. The bright colors of the parrot are certainly for signal, but the pigments that create some of the colors also provide an antibacterial effect that slows the degradation of the plumage (Friederici). The black wingtips of the seagull are colored by melanin that provides a structural strength benefit for feathers under the stresses of high fluid dynamic forces (Marshall, 2009, p. 1).

Color in Animals for Thermoregulation

Selective absorption and reflection utilizing color plays a role in animals as well as plants. As with plants, color is used to selectively absorb or reflect light energy based on the particular needs of the animal - signal, camouflage, or biological function. Some species of the Kenyan Chameleon, which are cold-blooded like all other reptiles, can vary the amount of incident solar energy that is absorbed by up to 37% (figure 2.4-1 through 2.4-6). The animal changes its reflectance and absorptance characteristics by changing its color thereby changing the rate of heat gain for thermoregulation. This ability provides for exceptional camouflage, but thermoregulation may be the primary role. While the animals are basking in the sun in the morning, they are often very dark on the side that faces the sun (for absorption) while remaining much lighter on the shaded side (for camouflage). This strategy may cause them to be highly visible to predators leading to the thought that heat gain is prioritized over crypsis (Walton & Bennet, 1993).

FIGURE 2.4-1 THROUGH 2.4-6 - Color for Thermoregulation

The Kenyan Chameleon can vary its color to regulate the amount of incident solar radiation that is absorbed or reflected



2.4-1



2.4-2



2.4-3



2.4-4



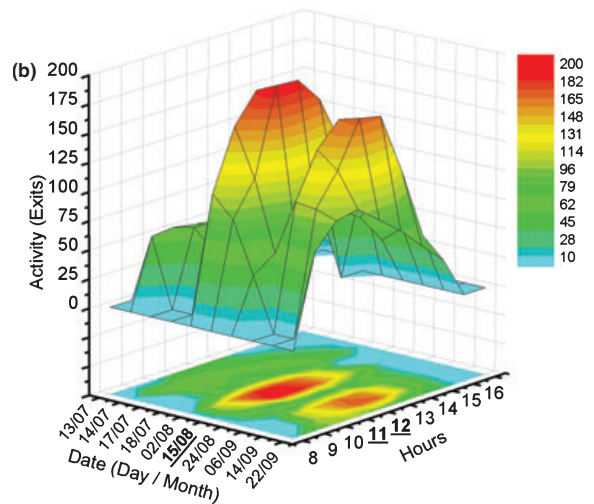
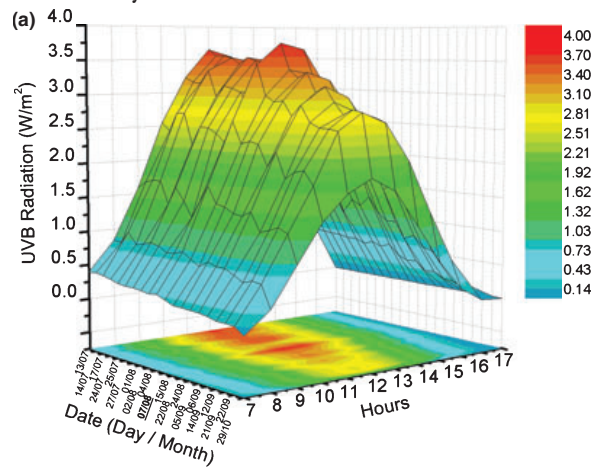
2.4-5



2.4-6

FIGURE 2.4-7 THROUGH 2.4-9 -
Color for Energy Harvesting

The Oriental Hornet uses yellow pigment to harvest Ultra-violet light in a complementary fashion as evidenced by the fact that their activity increases with increase in UV light availability



2.4-7

Color in Insects

As with animals, insects often employ color for signaling other members of the species and camouflage from those of different species (Hutchings, 1986, p. 115). The method for creating color is often through a *structural color* strategy. With the exception of blue (which is generally caused by nanoscale structures causing Rayleigh Scattering), most color in plants and animals are a result of pigment molecules. (Hecht, 2002, p. 87) (Farrant, 1997, p. 90) (Hutchings, 1986, p. 113). Although pigments are used as absorbers of light energy, color is generally the result of reflections caused by the effects of microscopic structures (ridges, layers, and crystalline structures) on the incoming light energy (Seago, Brady, Vigneron, & Schultz, 2008, p. 166) (Vukusic & Stavenga, 2009, p. S141). Preferential absorption and reflection of wavelengths through various mechanisms allows for particular wavelengths to be harvested or reflected. The Oriental hornet (figure 2.4-8v) is believed to employ a combination of yellow pigment (xanthopterin) and microscopic structural ridges and bumps to harvest ultraviolet (UV) light energy for conversion to electricity and use in flight while reflecting longer wavelengths (Plotkin, et al., 2010, p. 1075). This is evidenced by the fact that, unlike most insects and animals who curtail their activities mid-day, the Oriental hornet increases its activity when the light energy available in the UV wavelengths is at its highest (figure 2.4-7)(Volynchik, Plotkin, Bergman, & Ishay, 2008, pp. 81,84). The yellow wasp pigment xanthopterin has been used in the development of solar cells, although further investigation of the nanoscale surface structures may hold the key to the structural aspect of light harvesting (Plotkin, et al., 2010, p. 1075).



2.4-8



2.4-9

The Blue Morpho butterfly, as well as others, of course use color for communication and courtship--this is not surprising (figure 2.4-10). What may be surprising is that the color we see (the result of particular reflected wavelengths) “significantly influences thermoregulation” (Brunton & Majerus, 1995, p. 199). Perhaps the most surprising statement made by scientists may be that - “controlled absorption of incident solar radiation is the principal method of temperature regulation in most insects” (Vukusic, Sambles, & Lawrence, 2004, p. S237).

SUMMARY

This Part serves to build a base of understanding as to factors that contribute to the temporal nature of light energy in Nature and the mechanisms and strategies that life forms have evolved to use that light energy to their best long-term survival advantage. The next Part discusses how color is used in Architecture.

FIGURE 2.4-10 - **Color for Thermoregulation**

The Morpho Butterfly uses a combination of structural color and pigments to control the absorption of incident solar radiation.



2.4-10

PART 3

ARCHITECTURAL APPLICATION

Most often color is applied to architecture as decoration which is unlike color application as used in Nature. Humans like color and they generally have positive reactions to it. This alone provides a benefit, but what if color could be used as both an aesthetic and functional element? This is the focus of Part 3.

3.1. Color Application in the U.S.A.

Generally, there seems to be a lack of interest in the rational use of color in the visual design of buildings in the U.S., not to mention how color could be used as a tool to aid in energy performance. According to the Department of Architecture's Color and Light Professor, Galen Minah, there exists a deficit of color interest and knowledge among American architects¹. Architectural color application is more of an aesthetic treatment with little consideration of theory or use as "a critical tool for evaluation" (Minah, p. 11).

3.2. Color Application Abroad

There is, however, a tradition of the systematic use of color in the design world elsewhere with more rigorous and objective underpinnings. Although their methods have some major differences, colorists such as Jean Philippe Lenclos of France, Greta Smedal of Norway, and Shigenobu Kobayashi of Japan have developed systems for evaluation and application of color that strive to provide greater formal, perceptual, and psychological meaning. Lenclos' method of architectural color application starts with an analysis of local environmental color. Then a methodology involving black and white value studies is used for pattern formation to which environmental color is applied². Kobayashi's method is based on word association whereby descriptive terms are paired with particular

...the dominant theory of colour in western contemporary culture is still based on surface appearances and colour education reflects this view, rather than incorporating the latest interdisciplinary research...

-- Catherine Van Wilgenburg

(Van Wilgenburg, 2009, p. 3)

1 Statement in "Color and Light" course lecture

2 From authors personal communication with Professor Galen Minah and "Color and Light" course notes

colors to be applied mostly to products and for marketing purposes, although his methods could be applied to architecture (Kobayashi, 1998). Smedal uses Lenclos' environmental color analysis method, but her design and application of those colors is heavily influenced by the Natural Color System (NCS) which was developed by the Scandinavian Colour Institute³. In particular, Smedal proposed colors for the buildings in the town of Longyearbyen, which lies north of the Arctic Circle, that would provide "a varied and exciting experience" throughout the year (Smedal, 2001). The colors are informed by the natural palettes of the seasonal landscape and the highly variable qualities of the seasonal light. Colors were selected that would celebrate the architecture throughout the seasons. The buildings contrast the white snow-covered background in the winter as well as the dark rock-covered hillsides in the summer. The colors perform perceptually as well in the twenty-four hour winter darkness as they do in the twenty-four hour summer sunshine, and every lighting condition in between (Smedal, 2001) (figures 3.2-1 through 3.2-4). Although the use of color in this case certainly has performance aspects such as form perception, the colors are not necessarily thought of or applied in the same way Nature utilizes them.

3 From authors personal communication with Professor Galen Minah and "Color and Light" course notes

FIGURE 3.2-1 THROUGH 3.2-4 -
Critical use of Color Informed by Light and Context

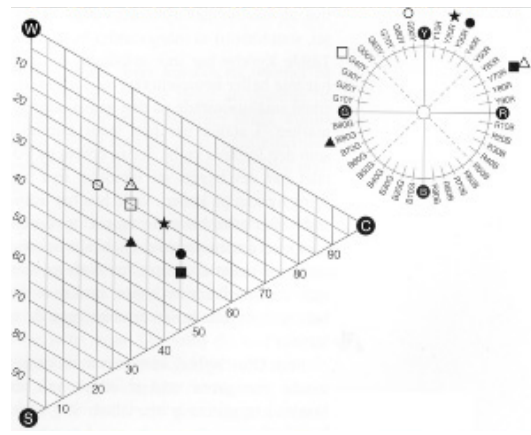
Greta Smedal used a highly developed methods for selecting color informed by Natural palettes, seasonal background color and variable lighting conditions.



3.2-3



3.2-1



3.2-2



3.2-4

FIGURE 3.3-1 AND 3.3-2 -
Functional Benefits of Color beyond Human Perception

A German glass company developed glazing that appears clear to humans yet appears as a barrier to birds by realizing that birds perceive ultraviolet light. This discovery was inspired by the Orb Weaver spider web which reflects UV light to help keep birds from flying through them and destroying the spider's work



3.3-1



3.3-2

3.3. Performative Application

Although the building sciences have not fully investigated the performance aspects of color, some industries have recognized the importance of understanding how Nature utilizes color for spectral selection and how it is perceived by organisms other than humans in some cases. It is well known that glazing manufacturers have developed glasses that selectively absorb, reflect, or transmit light energy in order to seek a balance between the need for natural light and the need to limit the heating effects of ultraviolet, (human)visible, and infrared light energy (Baker & Steemers, 2002, p. 117). A German glass company has gone beyond the human perception and comfort concerns related to glazing used in architecture (figure 3.3-1). Recognizing that birds can see ultraviolet light energy (unlike us) (Brunton & Majerus, 1995, p. 199), this manufacturer has developed a product that is transparent to humans yet appears as a barrier to birds. The product was inspired by the reflective properties of the Orb Weaver spider silk whose web reflects UV in an effort to keep birds from flying in to them and destroying their hard work (figure 3.3-2) (Arnold Glas, 2011). Tests have shown a 75% reduction of bird strikes on glazing which often lead to the death of between 4 million and 976 million animals each year (Quick, 2010) (Kellert, 2005, p. 101). Although this innovation is not necessarily affect energy performance, it is an example of how biomimicry can lead to functional benefits beyond human perception.

Present use of Color for Energy Performance

In recognition of the effects of color on surface temperature and thermal comfort, Secretary of Energy Steven Chu announced in 2010 plans to put in place a *Cool Roof* strategy for many Federal Government buildings for the purpose of energy use reduction. A cool roof is defined as a roof “whose surface is minimally heated by the sun, such as a bright white roof” in contrast to a “hot” roof “with a standard black surface” which can get very hot (Levinson, Ronnen; Lawrence Berkeley National Laboratory, Cool Roof Q & A (draft), 2011, p. 1). Another aspect of a cool roof material is its ability to emit the heat absorbed in the form of long wave radiation in an effort to

reduce surface temperature and slow heat flow through the roof structure into the building. As noted earlier, roughly half of the light energy reaching the Earth's surface is invisible infrared (IR). A white surface will reflect a large portion of the both the visible and IR spectral wavelengths (along with their associated energies) whereas dark surfaces reflect considerably less in both spectral regions therefore absorbing a large portion of the associated energy which is "taken up" and converted to heat (Levinson, Ronnen; Lawrence Berkeley National Laboratory, Cool Roof Q & A (draft), 2011, p. 2). Choosing a light colored roof over a dark roof can reduce the surface temperature by more than 50° F which substantially reduces heat flow into the occupied spaces of a building. In turn, this reduces the need for building cooling, reduces the required power for air conditioning generated by power plants which reduces greenhouse gas emissions, reduces local air temperatures which improves air quality, and slows climate change by reducing the amount of heat trapped by the atmosphere (Urban & Roth, 2010, p. 3). With this in mind, "cool roofing" has been developed that reflects large portions of the light energy (visible and invisible to humans) that are available in numerous colors other than white each with its own reflectance.

This strategy is a general recommendation that seeks to reject as much of the incident solar energy as possible. While a *Cool Roof* strategy may be effective at reducing surface temperatures, in certain latitudes and climates this strategy may actually *increase* the heating energy demand of the building by lowering the surface temperature and causing heat to flow from inside the building to outside. The Department of Energy recommends energy modeling prior to implementation (U.S. Department of Energy, 2011).

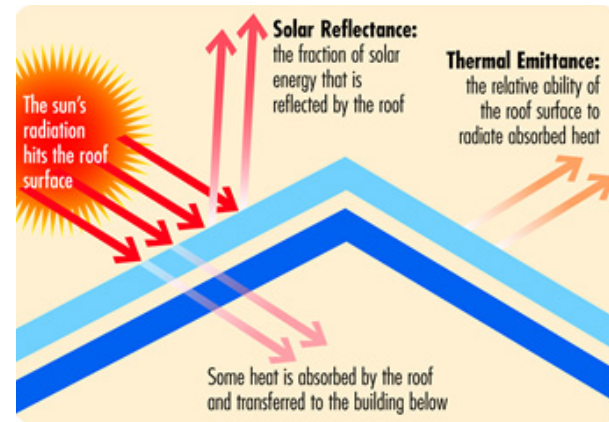
R=0.41	R=0.44	R=0.44	R=0.48	R=0.46	R=0.41
black	blue	gray	terracotta	green	chocolate
R=0.04	R=0.18	R=0.21	R=0.33	R=0.17	R=0.12

Cool-colored tiles (top row) look just like conventionally colored tiles but have higher solar reflectance (R). *Image Source: American Rooftile Coatings and Lawrence Berkeley National Laboratory*

3.3-4

FIGURE 3.3-3 THROUGH 3.3-5 - U.S. Department of Energy's Cool Roofs Strategy

The combination of highly reflective colors and materials with highly emissive materials are employed to reduce cooling loads.



3.3-3



3.3-5

FIGURE 3.3-6 AND 3.3-7 - The Bedouin Tents of the Sinai

The black tent fabric absorbs incident solar energy, increases surface temperatures, and induces convective currents creating a cooling breeze.



3.3-6



3.3-7

Past Use of Color for Thermal Comfort

The performance aspects of color are not a modern day discovery. The tents of the nomadic Bedouin tribes of the Middle East have a counter intuitive performance aspect to their color. Where shade nor breeze exists, the temperature on the Sinai plain can reach more than 120°F yet the interior of the *black* tent is comfortable (figure 3.3-7). The compostable black wool of the Bedouins goat herd is coarsely woven into fabric that allows air and diffused light to penetrate it when dry (figure 3.3-8). The black fabric absorbs the suns energy across a broad spectrum creating a “deep shade” while “creating a beautifully illuminated interior” (McDonough & Braungart, 2002). As the tent surface temperature increases, convective currents rise over the tent pulling air through the fabric from the inside out, “in effect creating a cooling breeze” increasing thermal comfort (McDonough & Braungart, 2002). This is an example of color used for aesthetic and function. What’s more is that when the fabric gets wet with rain, the fibers swell and the tent becomes water proof (McDonough & Braungart, 2002). Although similar strategies have been applied to solar chimneys in modern buildings for increasing natural ventilation rates, perhaps these lessons could be applied to other aspects of architecture in the desert metropolises of today.

This ingenious design, locally relevant and culturally rich, makes the desert skyscraper’s stark separation from local material and energy flows look downright primitive

*--William McDonough
(McDonough & Braungart, 2002)*

3.4. Energy Use in Buildings

According to the U.S. Department of Energy, 40% of energy use and 35% of the associated greenhouse gas emissions are attributable to buildings (Chu, 2010). Many advances in glazing have been realized in regard to controlling heat transfer by selectively transmitting, absorbing, or reflecting incident light energy while striking a balance between thermal and visual comfort (Baker & Steemers, 2002, p. 107). In the case of opaque wall surfaces, advances have been generally restricted to improvements in insulation materials and construction practices that reduce air infiltration. One is hard pressed to find instances where color is used to spectrally select wavelengths from the incident solar radiation (insolation) that are either reflected or absorbed let alone how such colors could affect heat transfer through the opaque wall assembly.

Although reductions in building energy use can be realized by improvements in insulation and glazing, even more can be saved by the form the building takes and integration of efficient mechanical systems. Additional energy savings could be realized if “the building and its environmental systems” harvested “constantly replenished ambient energies” (Buchanan, 2005, p. 30). A substantial portion of building energy use is for electric lighting and cooling (Buchanan, 2005, p. 30). In order to reduce the energy required for these needs, modern buildings are beginning to take the form of buildings from a century ago, although driven by somewhat different necessities. Access to daylight and natural ventilation was key to a habitable building a century ago because technology used for mechanical means was limited. Today many of the same lessons are being applied to reduce building energy consumption while improving the environment of the occupant by providing views and individual environmental controls (New Buildings Institute, 2011) (Buchanan, 2005, p. 30).

Thinner floor plates that allow for natural light and ventilation are often achieved by introducing courtyards and other building geometries to the floor plan. As a rule of thumb, a 2:1 ratio exists between the amount of daylight penetration and the top of window elevation (figure 3.3-8). Higher ceilings (therefore higher window heads) are often employed to increase the depth of usable daylight levels that reach into the floor

FIGURE 3.3-8 - Rule of Thumb for Daylight Zone

The depth of daylight penetration is related to the head height of the window by a 2:1 ratio.

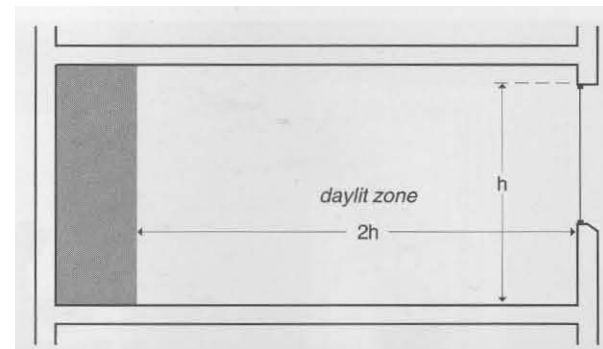
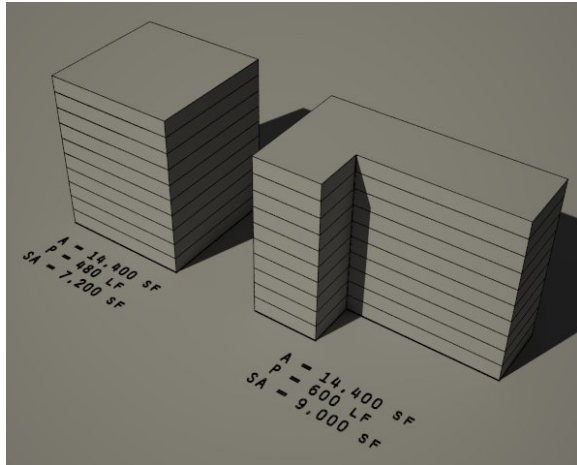


FIGURE 3.3-9 - The Impact of Thin Floor Plates on Skin Area

Thin floor plates and high ceilings can substantially increase the building skin area as compared to more compact plans.



3.3-9

plate (Baker & Steemers, 2002, p. 64). The combination of these strategies can add “substantially to the perimeter area [skin area] of a building” (New Buildings Institute, 2011)--as much as 30% (figure 3.3-9)⁴.

Energy use intensity (EUI) is defined as the quotient of the annual building energy use and the building area (Peterson & Crowther, 2010, p. 40). Low EUI’s are key to achieving zero-energy buildings and are influenced by floor area, floor to floor height, ventilation rates, air infiltration rates, conduction through glazing and opaque surfaces, and climatic conditions. To achieve acceptable EUI’s, glazing is generally limited to around 30% of total building skin area leaving around 70% of the building skin as opaque surfaces.⁵ The resulting increase of opaque building skin could be viewed as a detriment or perhaps as an opportunity for color application as in Nature to aid in energy use reduction.

SUMMARY

Armed with the knowledge gained by the investigation of the spectral qualities of solar energy, the affect of atmospheric conditions and diurnal cycle on that spectrum, how Nature uses color for performance reasons, and the need to control the conduction of heat through the building skin, the next investigation will look into how color could be used for energy performance benefits in architecture.

⁴ According to authors personal communications with Mike Hatten of SOLARC Architecture and Engineering

⁵ As instructed in studio by Joel Loveland of the University of Washington Integrated Design Lab

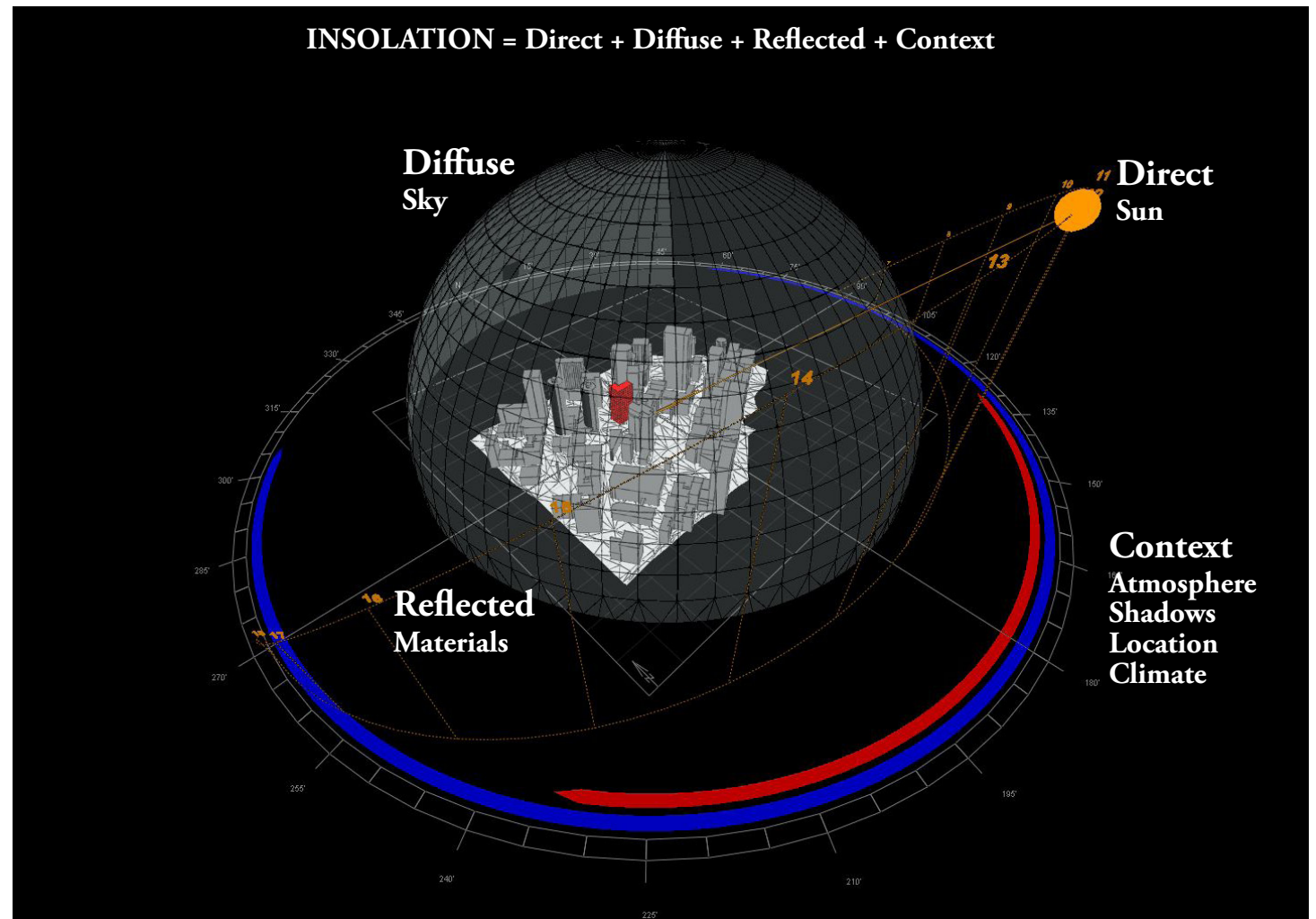
PART 4

SIMULATION STUDIES: THE EFFECT OF CLIMATE, CONTEXT, AND COLOR ON THE ABSORPTION OF INCIDENT LIGHT ENERGY BY OPAQUE SURFACES

Part 3 focused on some of the architectural applications of color for aesthetic and performance purposes as well as some of the constraints posed by the trend of zero energy buildings. Intuition, experience, or the earlier discussion on Cool Roofs tells us that a white surface exposed to the sun remains much cooler than a black surface exposed to the same spectral irradiance. Using light or dark colors is a straightforward evaluation of the impact of a higher or lower surface reflectances on surface temperatures. White and black are the most obvious cases. The combination of red, green, and blue values determine the overall reflectivity of a colored opaque surface in simulation. In order to study how various colors would affect the amount of insolation absorbed or reflected by an opaque surface over a period of time in different climatic regions, simulations using Ecotect were performed, which is the subject of Part 4.

4.1. Insolation

Insolation is a term that refers to the solar radiation falling on a surface across the full spectrum received from the Sun. Insolation is made up of three components. The first is the radiation received directly from the Sun. The second is the diffuse radiation received from the sky visible by the surface. The third is the radiation reflected by the surrounding material surfaces. All have the units of watts per square meter (W/m^2). The amount of insolation falling on a surface is affected by the angle incidence (which changes as the sun moves through the sky), the shadows cast from surrounding geometry, the amount of diffuse sky light visible from a surface, and the reflectivity of the surrounding geometry (figure 4.1-1) (Autodesk, 2012) .



4.1-1

FIGURE 4.1-1 - The Components of Insolation

Insolation is the sum of direct radiation from the Sun, diffuse radiation from the sky, and reflected radiation from materials. All of which are affected by climate and context.

4.2. Study Building Model

A theoretical building was modeled and configured in a way that represents an architectural form that is influenced by the need for daylighting and natural ventilation located in an urban setting (figure 4.2-1 and 4.2-2). Locations for the simulations were selected with reference to some of the various geographical and climatic regions as defined by the U.S. Department of Energy (figure 4.2-3).

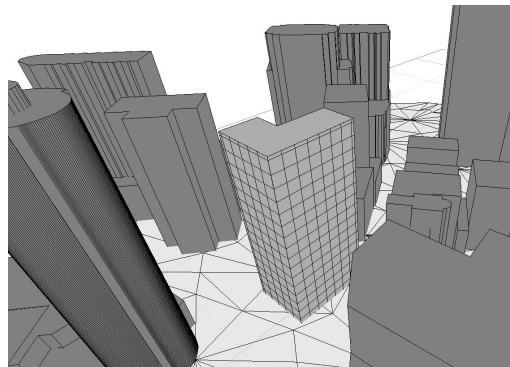
To simulate the impact of neighboring buildings on the amount of insolation experienced by the subject building and realizing that most American cities have similar urban center configurations, a GIS model of a portion of downtown Seattle was used to contain the theoretical building model. This same urban and building model was used for each of the four simulation locations--Seattle, Chicago, Phoenix, and Houston.

FIGURES 4.2-1 AND 4.2-2 Building Model in Urban Setting

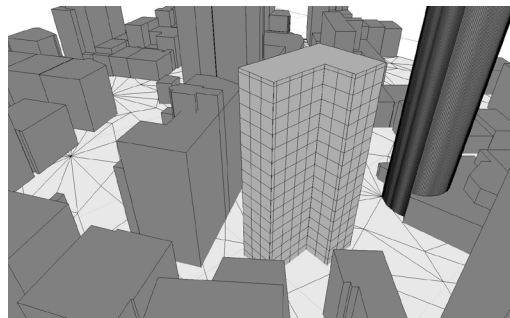
View from Southwest (figure 4.2-1).
View from Northeast (figure 4.2-2)

FIGURE 4.2-3 - U.S. Climate Zones

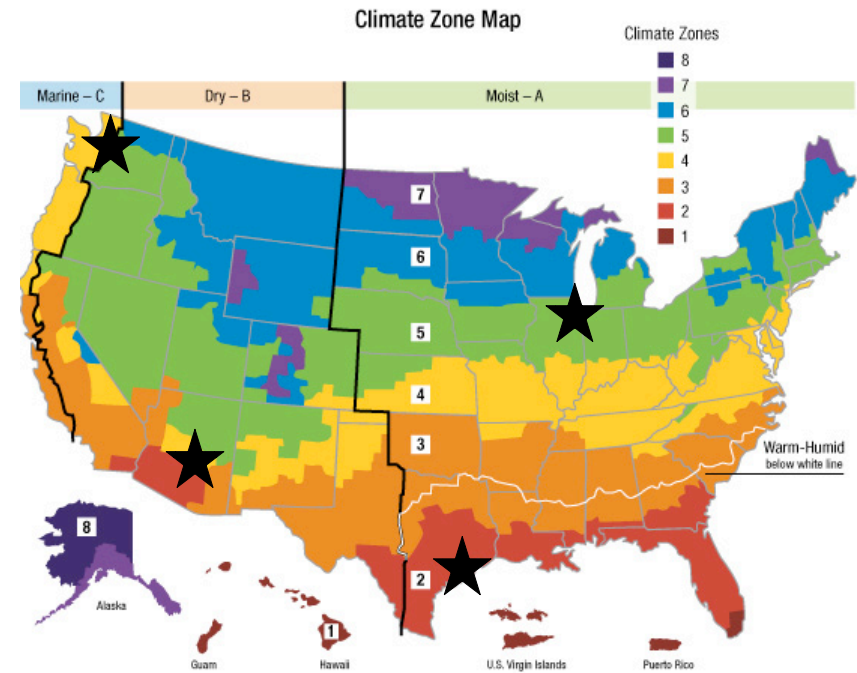
Cities studied include Seattle, Chicago, Phoenix, and Houston which represent a wide range of climates



4.2-1



4.2-2



4.2-3

4.3. Simulations

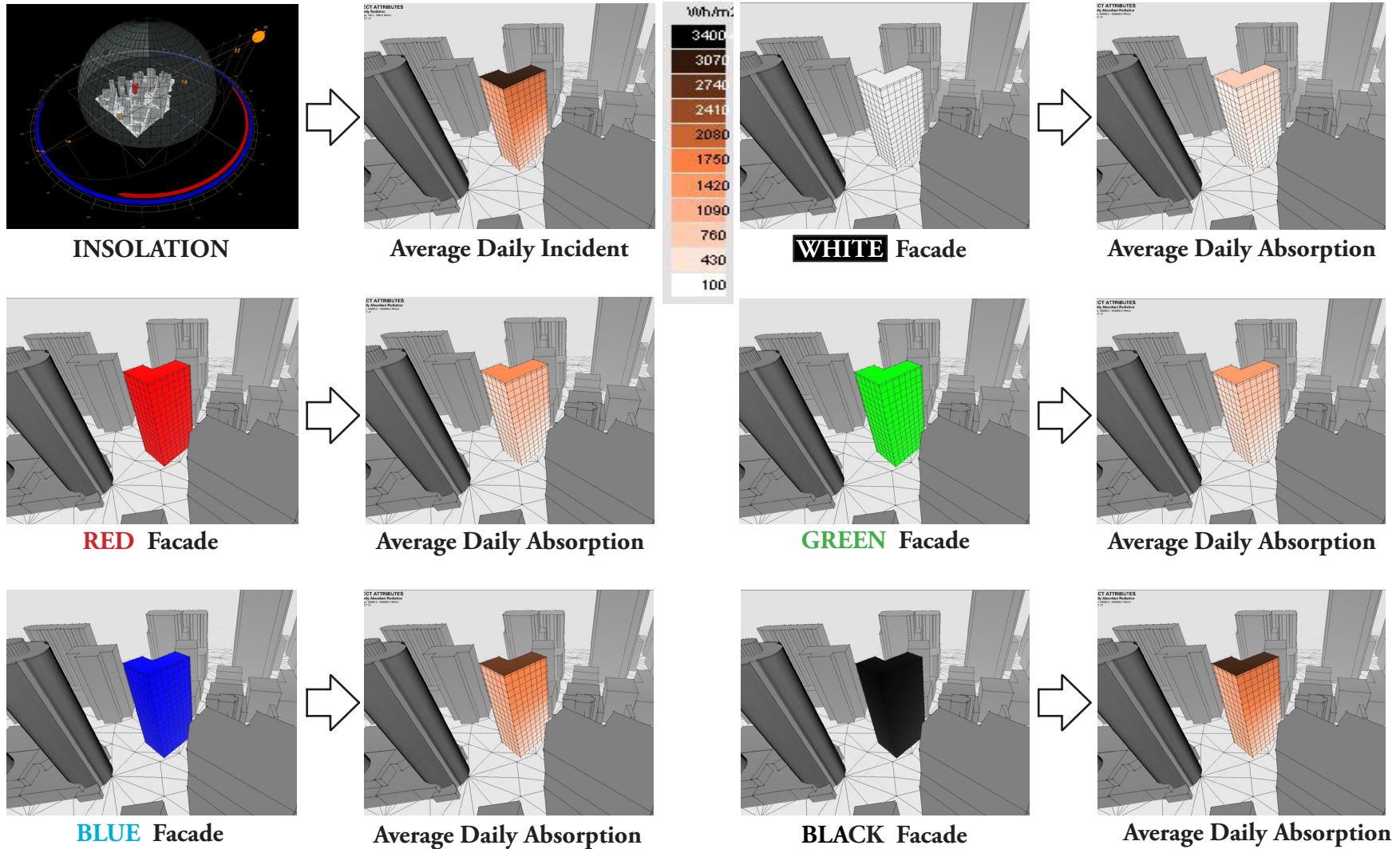
Ecotect was then used in conjunction with Typical Meteorological Year (TMY) files that represent average long term climatic conditions such as cloud cover and temperature at weather stations located near the simulation sites. Seasonal solar angles were accounted for in the simulations based on latitude and longitude. Simulations were performed for each city location on an annual basis for the period of time between 7am and 9pm.

The building facade surfaces were subdivided into twenty by twenty-foot square analysis grids to be used for illustrating the fine grain nature of the impact of climate, context, and location. For each location, the same building was simulated six times. The first simulation was a calculation of how much incident solar radiation (insolation) the building would be subject to on a daily average throughout the year. The next five simulations calculated the amount of that insolation that would be absorbed by the same building skin if it were colored white, red, green, blue, or black. In all cases, false color was used to graphically represent quantities, with black indicating areas of high insolation or absorption, white indicating areas of low insolation or absorption, and shades of orange representing intermediate values (figure 4.3-1 through 4.3-4).

Seattle

FIGURE 4.3-1 - Simulation Results for Seattle

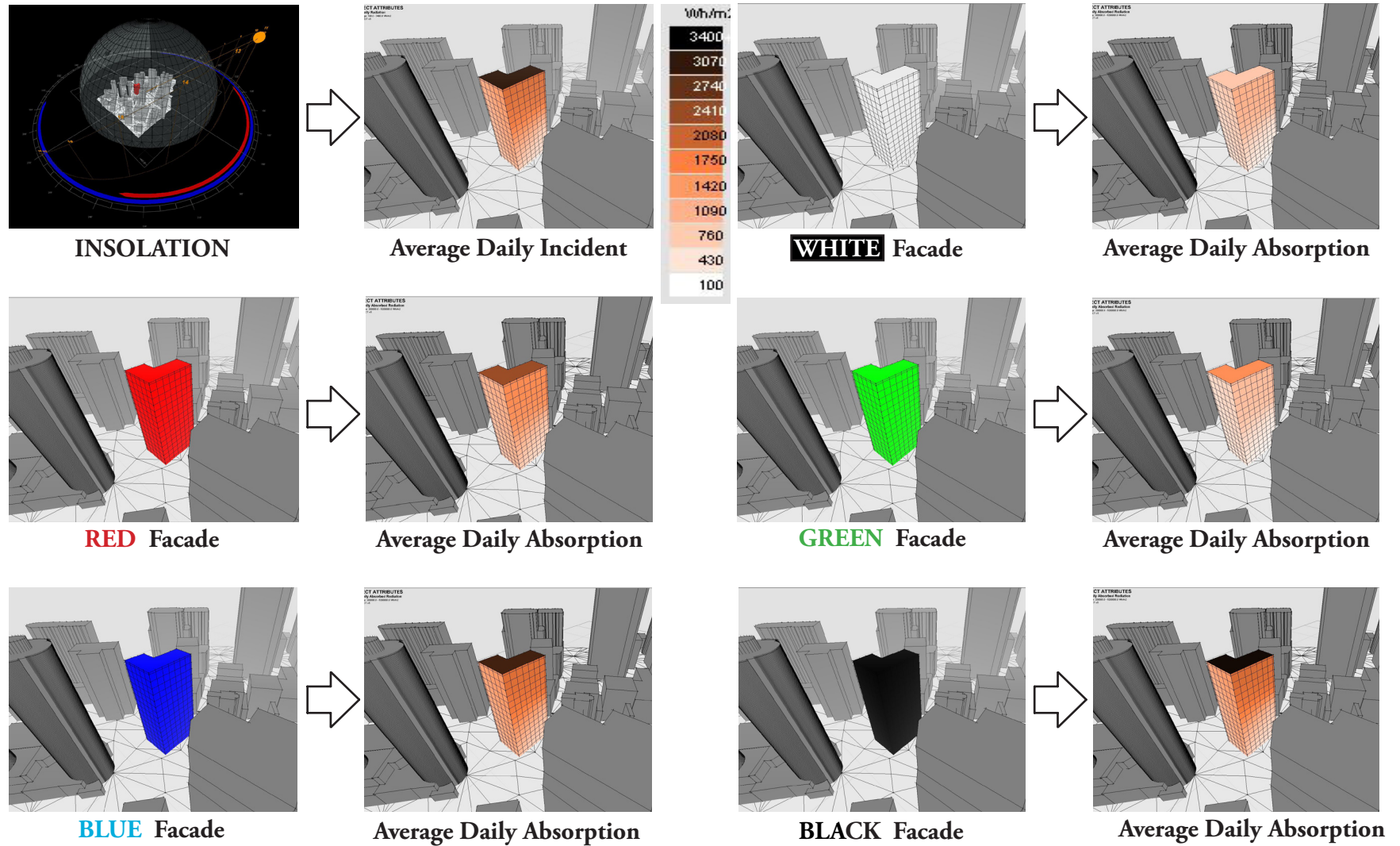
False color images illustrate amount of incident solar radiation available and amount absorbed by each color



Chicago

FIGURE 4.3-2 - Simulation Results for Chicago

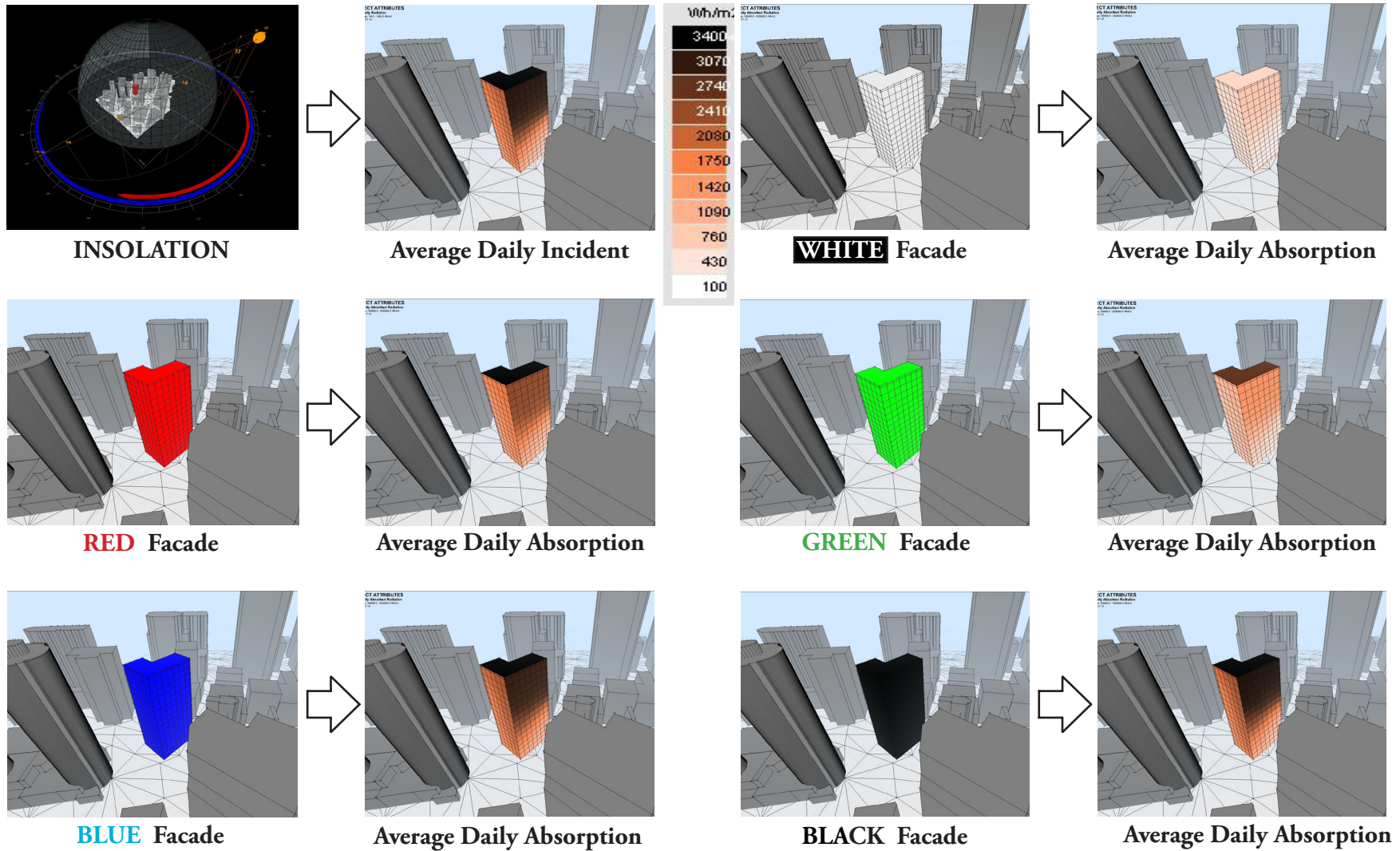
False color images illustrate amount of incident solar radiation available and amount absorbed by each color



Phoenix

FIGURE 4.3-3 - Simulation Results for Phoenix

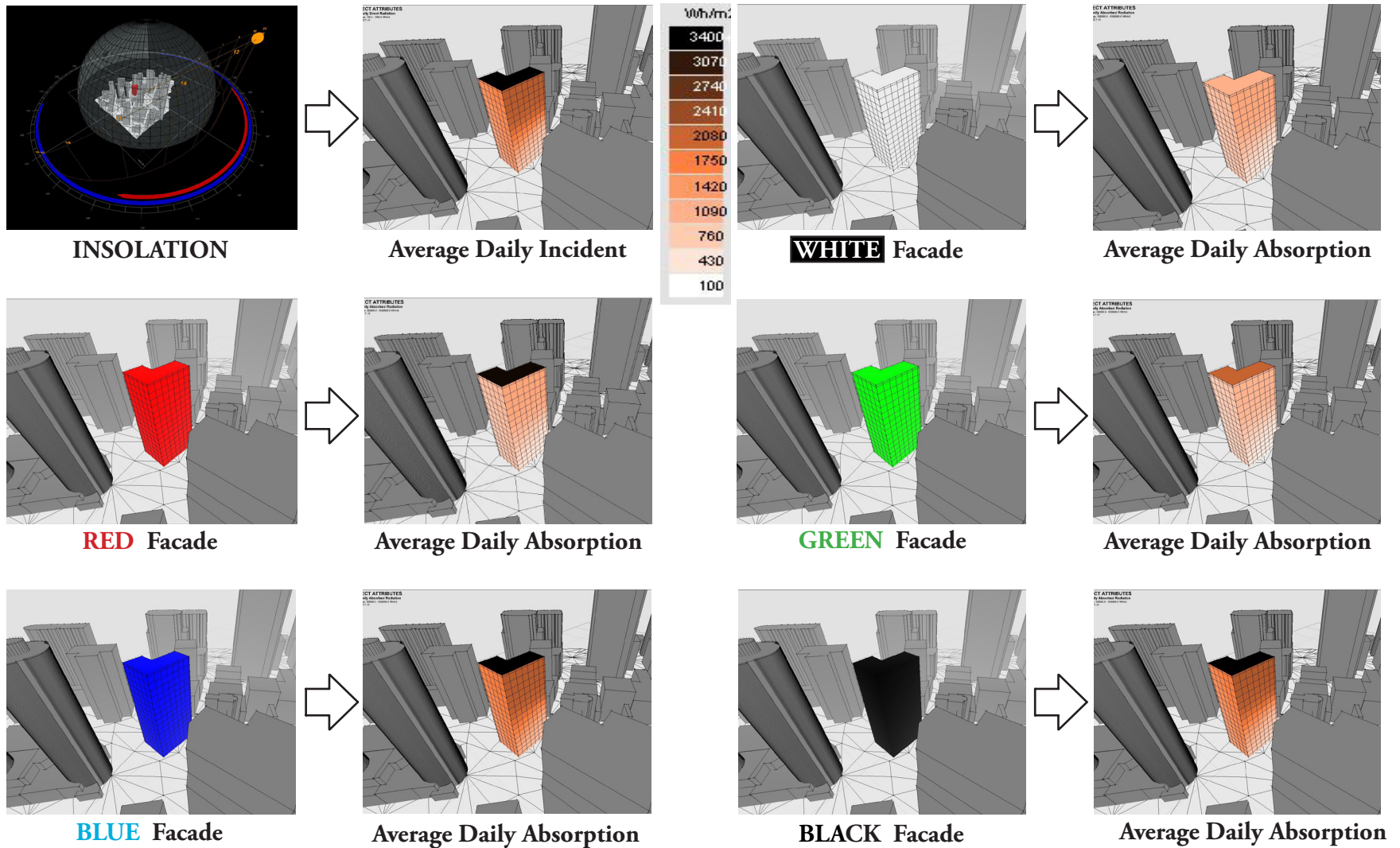
False color images illustrate amount of incident solar radiation available and amount absorbed by each color



Houston

FIGURE 4.3-4 - Simulation Results for Houston

False color images illustrate amount of incident solar radiation available and amount absorbed by each color



4.4. Color Definitions in Simulations

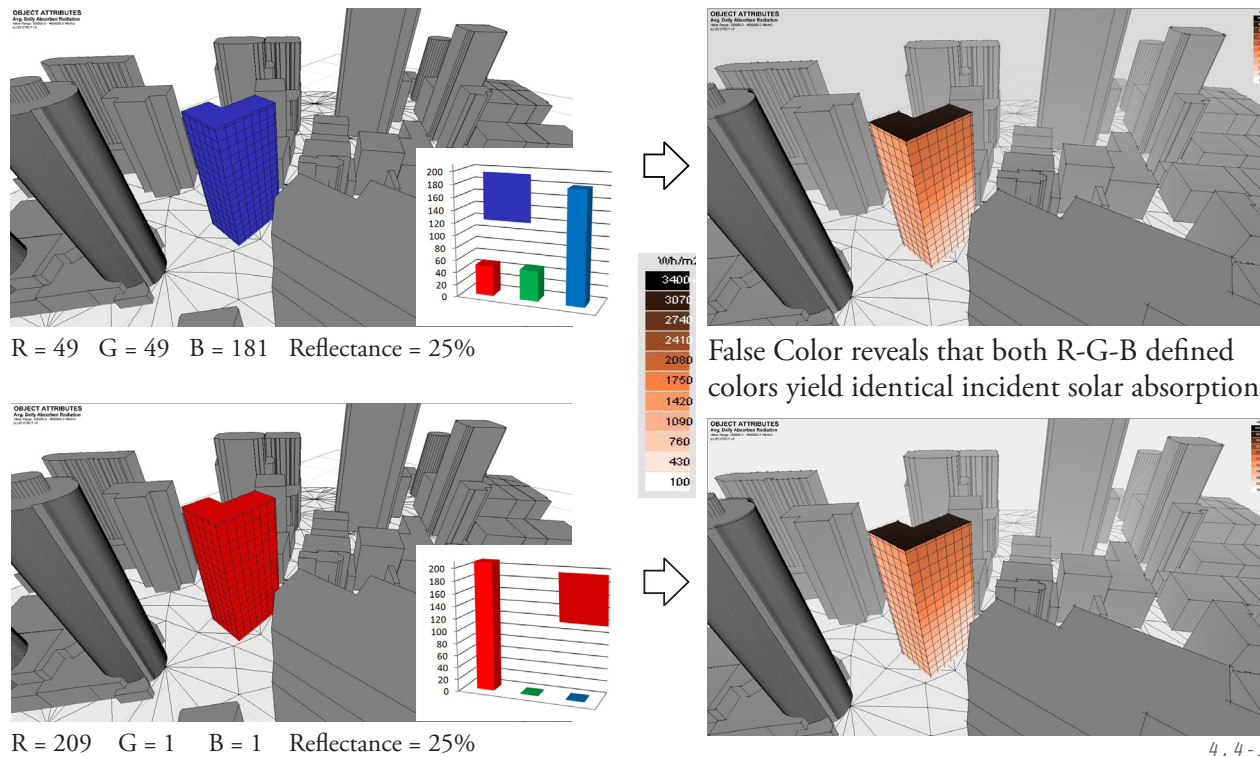
It is important to note that color in simulations is defined by the levels of red, green, and blue (RGB) that are combined to give a certain colored appearance by an opaque surface. The RGB levels are used by the software to compute a reflectance factor -- the percentage of the incident light energy that will be reflected. The amount absorbed by the opaque surface is simply the portion not reflected. It is also important to note that this method of color representation can be subject to metamerism whereby two different color appearances can have the same reflectance factor (figure 4.4-1). For the purposes of the simulations, white had a reflectance of 83.5%, red had a reflectance of 30%, green had a reflectance of 59%, blue had a reflectance of 11%, and black had a reflectance of 0% (figure 4.4-2).

FIGURE 4.4-1 - Method of Color Definition in Simulations

Color in simulations are defined by levels of Red, Green, and Blue that are used to calculate a reflectance factor. This method can result in different appearances having the same reflectance.

FIGURE 4.4-2 - Color Definitions in Study Simulations

For the purposes of this study, facade colors and reflectances were defined as shown.



WHITE:	R=213 G=213 B=212
	Reflectance = 83.5%
RED:	R=255, G=0, B=0
	Reflectance = 30%
GREEN:	R=0, G=255, B=0
	Reflectance = 59%
BLUE:	R=0, G=0, B=255
	Reflectance = 11%
BLACK:	R=0, G=0, B=0
	Reflectance = 0%

4.4-2

4.4-1

4.5. Results

The results highlight the impact that climate, context, location, and orientation have on the amount of solar insolation available for absorption or reflection with the most dramatic difference seen between Seattle (with its predominate cloudy skies and northern latitude) and Phoenix (with its predominate clear skies and southern latitude). Furthermore, the simulations show some major differences in how much of that insolation is absorbed based on color and its associated singular reflectance factor (figures 4.3-1 through 4.3-4).

SUMMARY

Simulations show how different colors might perform differently when subject to different variables and demonstrate how certain facade colors may hold benefits over others for mediating absorption of incident light energy depending on climate and context. This information, coupled with the monthly diurnal temperatures for a particular climatic region, might be used for determining the best opaque facade color selection that could aid in the reduction of energy use by influencing the surface temperature which in turn influences conductive heat flow through that opaque surface. Part 5 includes an empirical study of how the surface temperature of a range of colors react to incident light energy under various atmospheric, diurnal, and seasonal conditions.

PART 5

EMPIRICAL STUDIES: MEASUREMENT OF SPECTRAL PROPERTIES OF DAYLIGHT AND COLORED SURFACES AND THE EFFECT ON SURFACE TEMPERATURE AND CONDUCTIVE HEAT FLOW

Part 4 investigated the effect of color (as represented by simulation) on the quantities of incident light energy that is absorbed or reflected based on climate and location. Part 5 will serve to build an understanding of the relationship of color to surface temperature and the relationship of surface temperature to the conductive heat flow through the opaque surfaces of architectural constructs. The empirical studies took place over a six month period under various seasonal and sky conditions in the Seattle area with the exception of the initial observations in July which were done in Southeastern Wyoming.

5.1. Empirical Study Apparatus

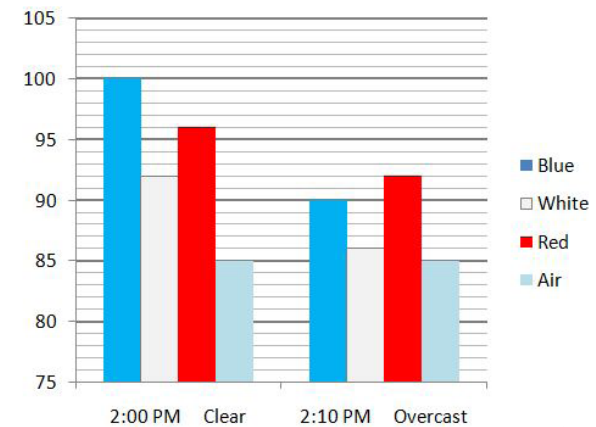
The initial observation of how color can influence surface temperature occurred while painting a sign for a fireworks stand which was of course red, white, and blue (figure 5.1-1). After painting, the sign was laid in the sun to dry. After some time had passed it was noticed that there were significant differences in surface temperature depending on the color that could be sensed by touch. Digital thermometers were then placed on each color (red, white, and blue) and the readings indicated that the blue was the hottest, the white was the coolest (as might be expected), and the red temperature fell in between. A short time later some clouds blocked the direct sun and it was noticed that, although the white remained the coolest, the red area of the sign became the hottest and the blue fell in between (figure 5.1-2).

FIGURES 5.1-1 AND 5.1-2- Fireworks Sign and Variable Surface Temperatures

Initial observations of the relationship between color, surface temperature, and sky condition happened while painting a sign



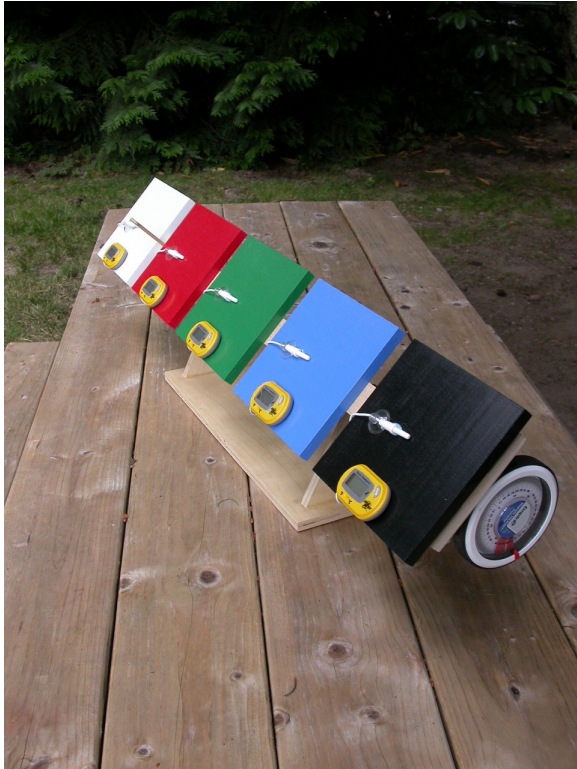
5.1-1



5.1-2

FIGURE 5.1-3- Empirical Study Apparatus

Painted plywood squares and digital thermometers were used to observe surface temperatures.



5.1-3

A physical apparatus was designed and assembled to perform empirical studies on the relationship between color and surface temperature. The apparatus was designed so that it could be adjusted to maintain a normal angle to the sun as it moved through the sky. Initially the apparatus had a red, green, and blue painted 18mm Baltic Birch plywood squares measuring six inches by six inches. Next came the introduction of a white and black square of the same size and material as the original three along with an angle gauge that could be used in conjunction with a compass and sun location information obtained from the Naval Observatory website (adjusted for daylight savings if applicable and magnetic declination) in order to orient the apparatus normal to the sun even when it was obscured by clouds (figure 5.1-3). In addition to the five larger plywood squares, the final form of the apparatus saw the introduction of a white, red, green, blue, and black painted three inch square of 0.02 inch thick aluminum mounted on 18mm Baltic Birch plywood with foam tape. All ten squares were fitted with digital thermometers to obtain their respective surface temperatures.

5.2. Effect of Color on Surface Temperatures Observed under Various Sky Conditions

Observations were made approximately every two weeks throughout the day under various sky conditions from July through December. Sky conditions were documented with a Nikon Coolpix 4500 fitted with a fisheye lens. While maintaining a normal orientation to the sun, the surface temperatures of each of the ten colored squares, the air temperature in the shade, and the relative humidity was recorded. After each day's set of observations were complete, atmospheric pressure was attained from the NOAA Satellite and Information Service. The pressure along with the observed *relative humidity* was used to calculate the *specific* or *absolute humidity* which is a measure of the percentage of the

atmosphere that is represented by water vapor at a particular time⁶. This was done in an attempt to correlate the effect of water vapor on the spectral distribution of the incident light energy.

Data was analyzed and plotted to illustrate the fluctuations in the surface temperatures of the colored squares, the air temperature in shade, and specific humidity as the atmospheric and diurnal conditions changed (figure 5.2-1).

A major characteristic of the recorded surface temperatures (observed under numerous sky conditions and times of day over a six month period) was the apparent dependency of the individual colors' temperature on these Natural variables. Research undertaken in Part 2 showed that the incoming light spectrum was significantly affected by such variables and this data seemed to support those findings. With the understanding that light energy is either reflected or absorbed (in the case of an opaque surface) and in an attempt to further understand the variable temperature differentials that existed between the white, red, green, blue, and black plywood and aluminum squares, the diffuse reflectance of each colored square was estimated using the *macbethcal* routine resident in the LBNL developed Radiance synthetic imaging system software.

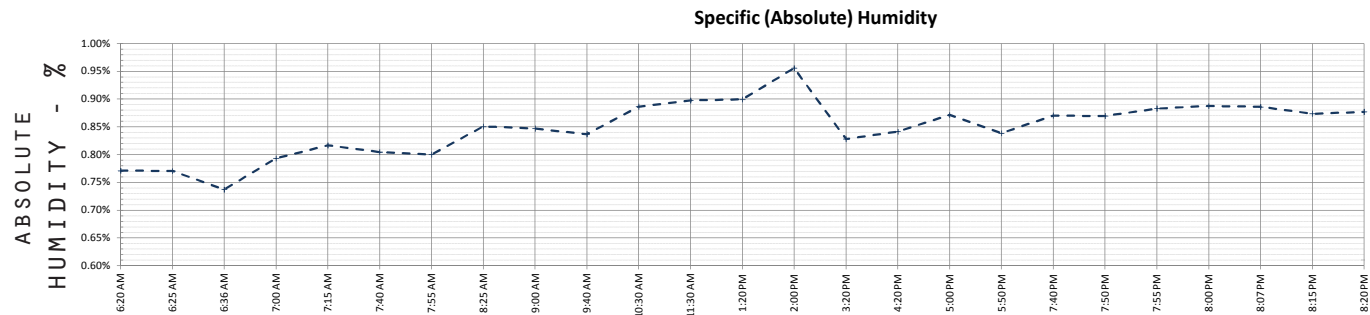
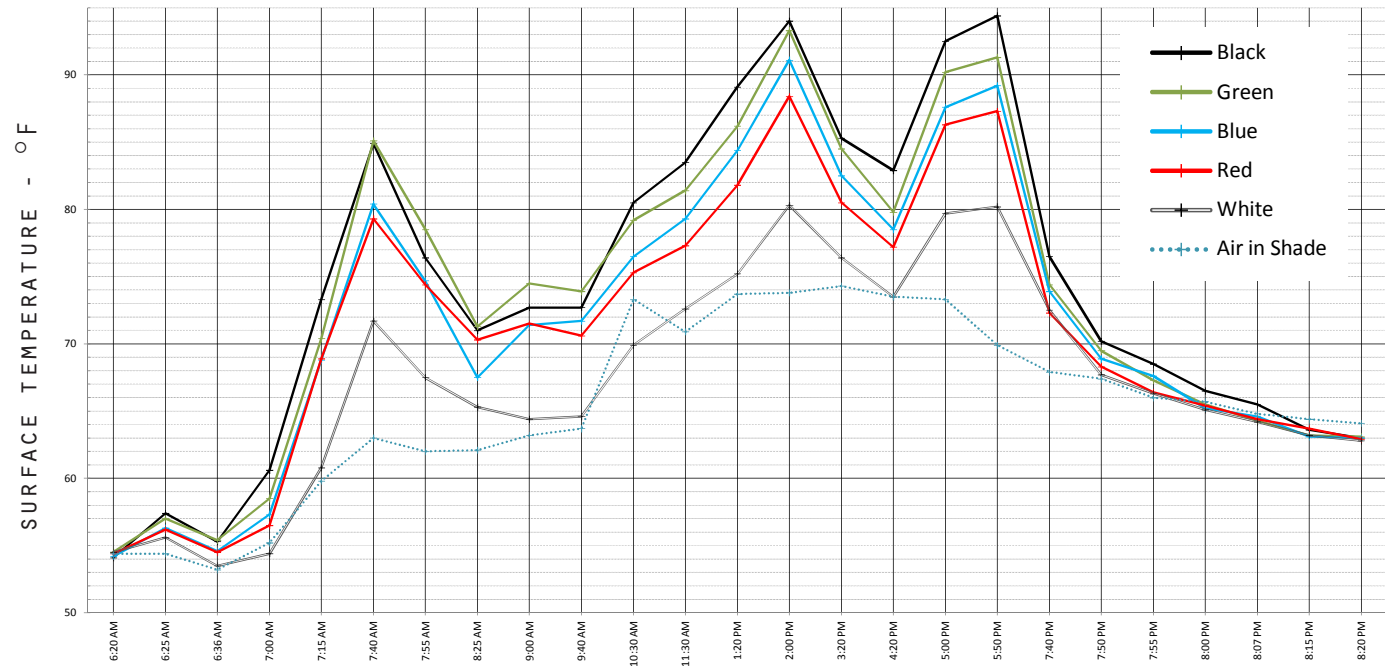
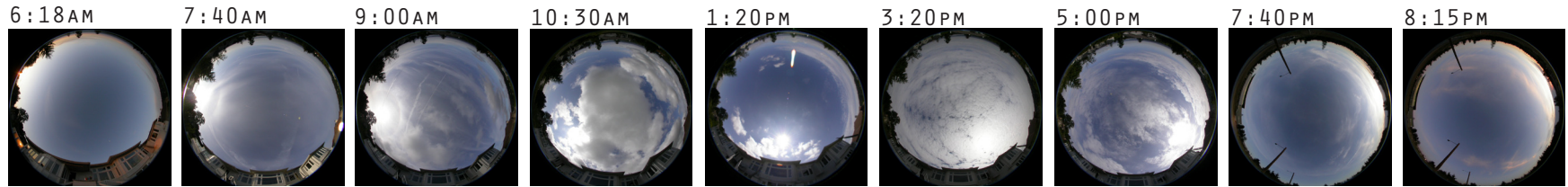
Digital photographs were taken with a Nikon Coolpix 4500 camera on a tripod oriented at right angles (vertically and horizontally) to the apparatus and a Gretag Macbeth[®] ColorChecker[™] Color Rendition Chart under an overcast sky to better insure constant lighting conditions for all photos (the chart is used in photography and cinema for color rendition). A calibration file was then created using the HDR version of the aforementioned chart photo in concert with the Radiance *macbethcal* routine and known red, green, and blue (RGB) values for each of the colored patches on the chart. This

FIGURE 5.2-1 - Effect of Color on Surface Temperatures Observed under Various Sky Conditions

A major characteristic of the recorded surface temperatures observed under numerous sky conditions was the apparent dependency of the individual colors' temperature on Natural variables.

⁶ Calculations done with the guidance of Laura Hinkelman and Thomas Ackerman of the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean.

AUGUST 18, 2011



calibration file was then compared, again using the Radiance software, to the HDR version of the photos of the colored squares on the apparatus. The output of the software yielded a final HDR photo file that had been adjusted to take into account the lighting condition under which the original photos were taken. These RGB values were used to calculate the reflectance of each colored square (figure 5.2-2).

Aside from some minor differences between the 18mm Baltic Birch and 0.02 inch aluminum, the reflectance values of the white squares were found to be around 77%, the black approximately 2%, the red approximately 15%, the green approximately 12%, and the blue approximately 9%. These results suggested that there would be a proportionately consistent relationship between the surface temperatures of the five colors. Interestingly this relationship was not found to be consistent under variable atmospheric and diurnal conditions. It was observed that under certain conditions, although the white was generally the coolest and black the warmest, that the green was nearly as warm as the black despite the large difference (10%) in calculated reflectance. Furthermore, there were conditions where the red and blue squares alternated being the warmest of the two and were both almost always cooler than the green despite having a calculated reflectance higher and lower than the green respectively (figure 5.2-3).

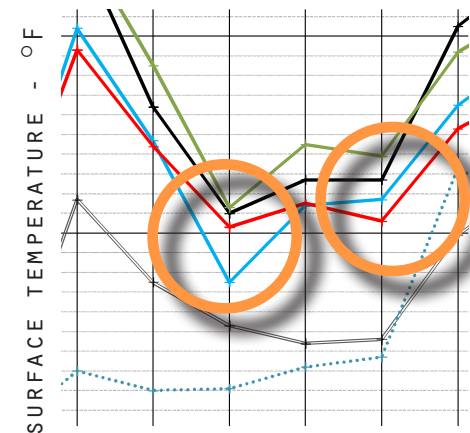
Recognizing that reflectance is a surface characteristic that is not variable, the only explanation for this lack of a proportionately consistent relationship was that the spectral distribution of the incident light energy was not constant and that this had an impact on surface temperatures that cannot be explained using a singular reflectance value derived from an RGB definition. Color in simulation software is geared toward photometry which is the measurement of how humans respond to that part of electromagnetic radiation detectable by the human eye--visible light (Inanici, 2004). These software packages incorporate how humans might perceive the luminous environment and not the physical richness of the full spectral distribution let alone the temporal nature of light

FIGURE 5.2-2 AND 5.2-3 -
Calculated Colored Surface Reflectances of Painted Plywood Squares

The painted plywood square surface reflectances were calculated using Radiance software with the thought that they would predict differential surface temperature behaviors. It was observed that the relationships of the colored surface temperatures varied with sky condition.

WHITE:	Reflectance = 77%
RED:	Reflectance = 15%
GREEN:	Reflectance = 12%
BLUE:	Reflectance = 9%
BLACK:	Reflectance = 2%

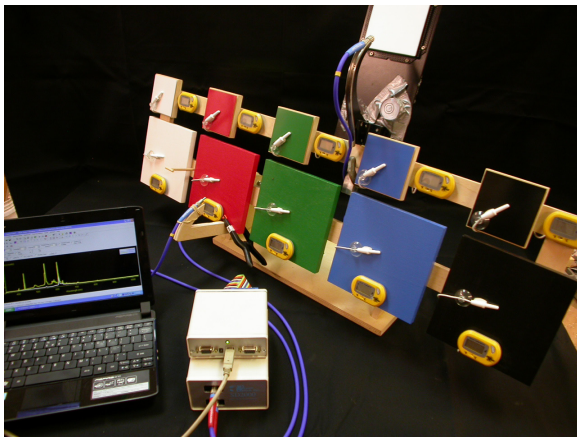
5.2-2



5.2-3

FIGURE 5.2-4 - Gear Set-up for Recording Incident Light and Reflected Light Qualities of Colored Squares

The spectral qualities of both the incident light and light reflected from each colored square was recorded in an attempt to explain the inconsistent surface temperature relationships.



5.2-4

energy with its spectral variation. This method was chosen for computational efficiency which was of major concern when these software packages were developed. The richness of the physical spectrum is “filtered” through the lens of the three chromatic human visual system and represented by the amount of red, green, and blue (RGB) content. Both the incident light intensity and the reflectivity of materials are based on an RGB definition. By simply varying the amounts of red, green, and blue, the user can represent the incident light intensity and material color (as the reflected portion of the incident light) as humans would perceive it but not necessarily how it is represented in the physical world which is subject to constantly varying spectral intensities *and* wavelength dependent distributions (Inanici, 2004). Empirical investigations illustrated this point by highlighting the dependency between the temporal qualities of Natural incident light energy and the amount of that energy that is either absorbed or reflected by various colors which impacted surface temperatures.

In order to better understand the relationships between atmospheric conditions, the spectral characteristics of the incident light energy, and the observed colored surface temperatures, data was collected throughout three different days in late November and early December using an SD 2000 Ocean Optics Spectrophotometer with two light inputs -- master and slave -- sensitive to wavelengths between 340 and 1028 nm (figure 5.2-4). Spectral data was collected using two fiber optic cables connected to the instrument--one cable targeting each of the colored plywood squares (of the experimental apparatus described above) in succession, and the second targeting a piece of Spectralon that reflects 99% of the incident light energy across the region detectable by the equipment. Data was captured in a text file on a host computer via a script file⁷.

⁷ Script written by Bonnie Light of the UW Applied Physics Laboratory

Since the optical purity of the two fiber optic cables (master and slave) were not identical, fifteen sets of wavelength dependent measurements were recorded with each cable targeting the Spectralon under reasonably constant lighting conditions. After rejecting the high and low values, the remaining values of each wavelength were averaged, and a baseline spectral distribution curve was created for each cable. Finally, using the baseline spectral distribution curves for each cable, a fiber optic *cable differential constant* was calculated. This constant was then applied to the cable with the least optical purity in order to relate the curves and allow for direct comparison of the data collected via each cable--master and slave.

To better highlight the spectral shift that can happen with varying atmospheric conditions, data collected from two different observations during one day was normalized to directly compare their spectral distributions. The comparison of these spectral curves showed a significant shift toward the red end of the spectrum under clear skies as compared to overcast, despite the sun having the same altitude (figure 5.2-5).

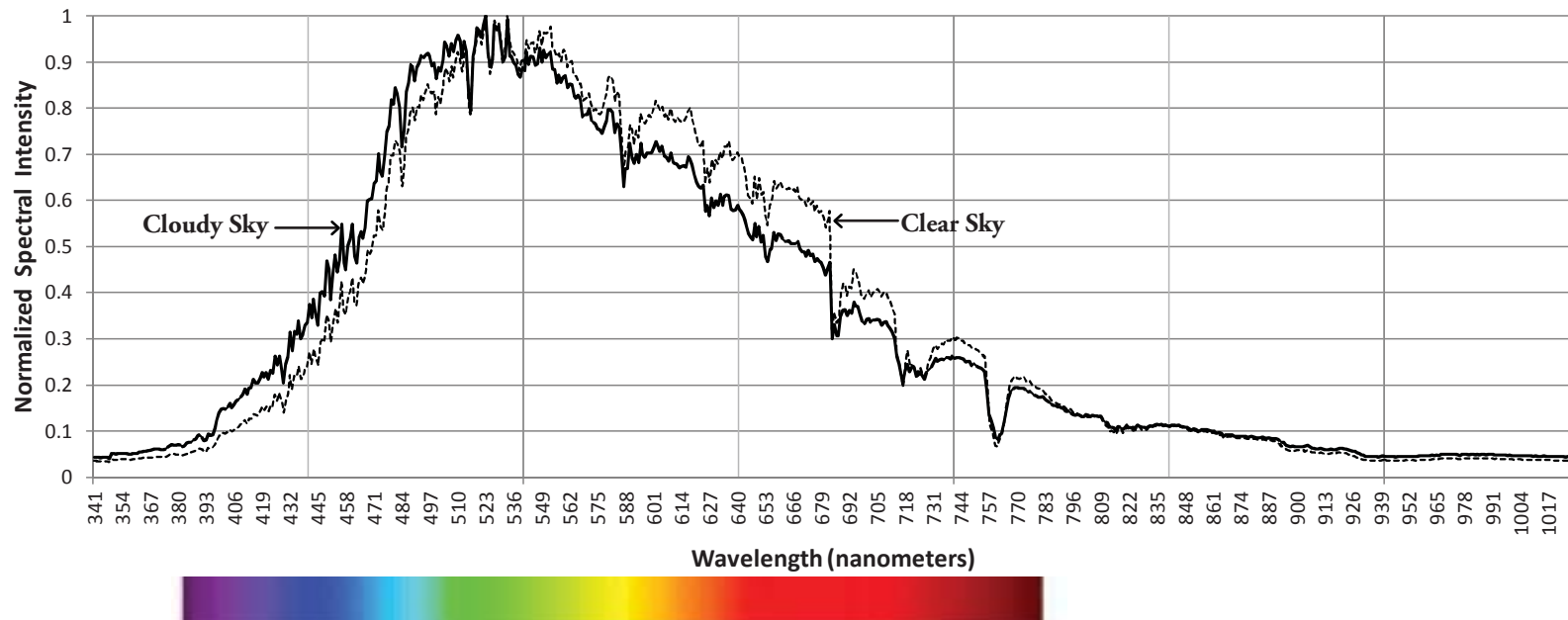
FIGURE 5.2-5 - Incident Light Qualities vary with Sky Condition

The spectral qualities of the incident spectrum experiences a Blue shift under cloudy skies and a Red shift under clear skies

Incident Light Energy Spectral Qualities vary with Diurnal and Sky Conditions



Normalized Spectral Distributions

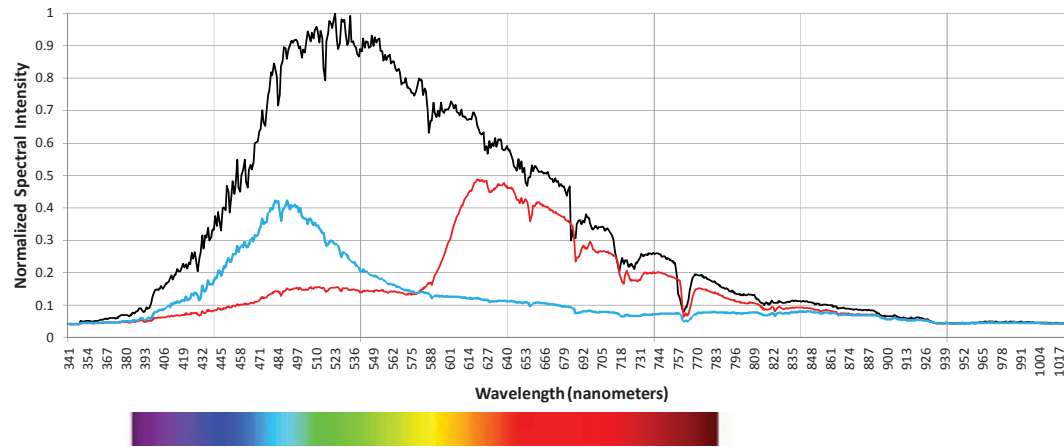


With the ability to directly compare the reflected spectral data obtained by the master and slave cables, five sets of reflected spectral data were collected at various times and under various sky conditions for each of the five colored plywood squares. The data for each color was averaged and plotted in comparison to the spectrum reflected by the Spectralon which represented spectral qualities of the incident light. The differential between the spectra was calculated to determine the portion of measured incident light energy that was either absorbed or reflected by each of the colored squares during each of the observed times. This data revealed that the portion of the measured incident light energy that was reflected by any one of the five colors varied with environmental conditions--resulting in nearly a ten point change in reflectance for blue for example (figure 5.2-6).

FIGURE 5.2-6 - Colored Surface Absorptance Varies with Incident Light Qualities

The blue shift under cloudy skies means that there is more blue light for the Blue square to reflect which results in less of the incident spectrum being absorbed leading to lower surface temperatures. The red shift under clear skies means that there is less blue light for reflection which results in more of the incident spectrum being absorbed and higher surface temperatures.

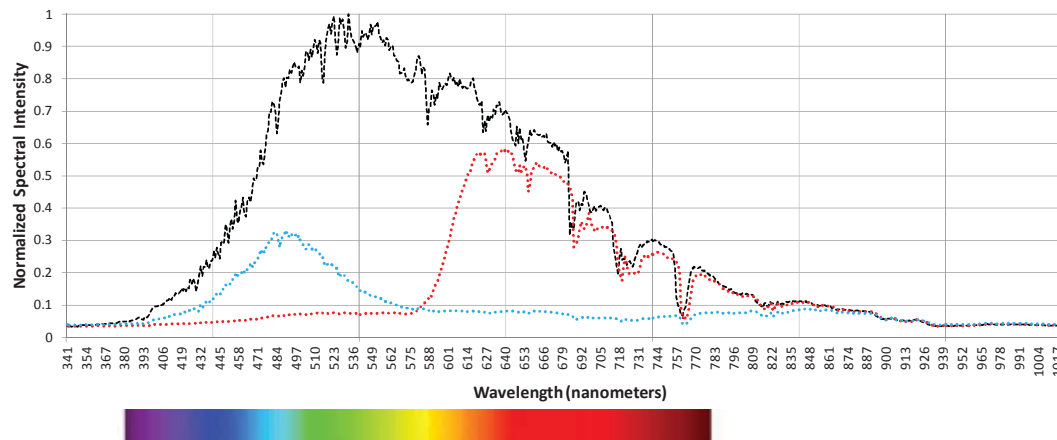
Normalized Spectral Distributions - Overcast



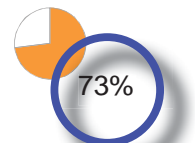
% of Measured Incident Spectrum Absorbed by BLUE



Normalized Spectral Distributions - Mostly Clear



% of Measured Incident Spectrum Absorbed by BLUE

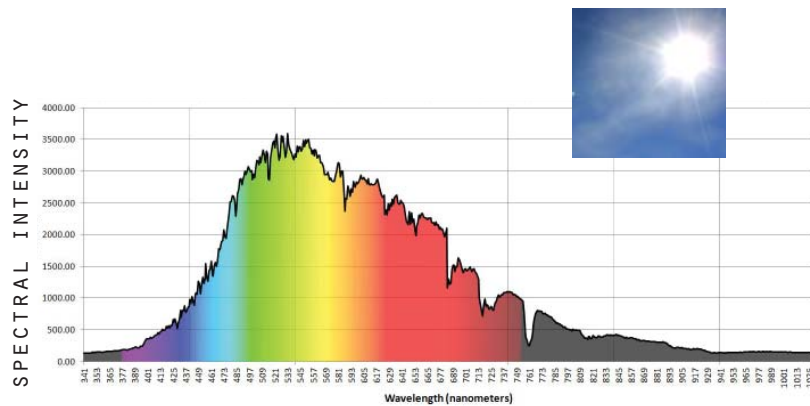


The interdependence between reflected light and incident light spectral qualities can explain the variable relationships between the individual color surface temperatures observed and recorded under variable diurnal and atmospheric conditions. The variable reflected light qualities are a product of the variable incident light qualities and the constant and unchanging wavelength dependent reflectance qualities of the material. A constant and unchanging reflectance factor, as color is simulated, does not represent reality (figure 5.2-7).

FIGURE 5.2-7 - Reflected Light Qualities vary with Incident Light Qualities

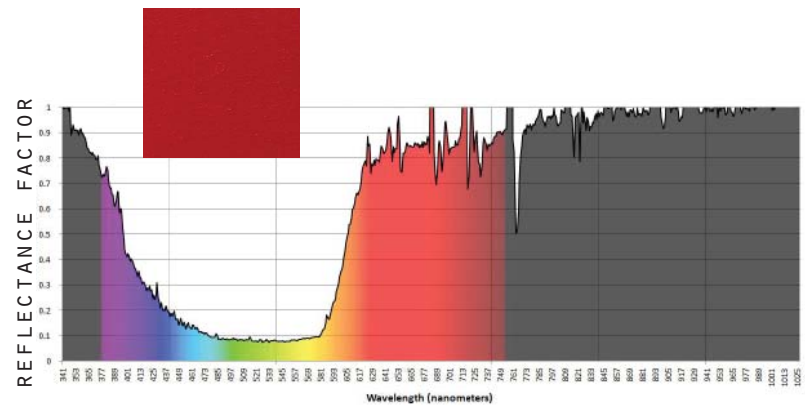
In reality, the portions of the incident light energy that are either reflected or absorbed vary with the qualities of the incident light energy -

$$\text{INCIDENT} \times \text{MATERIAL} = \text{REFLECTED}$$

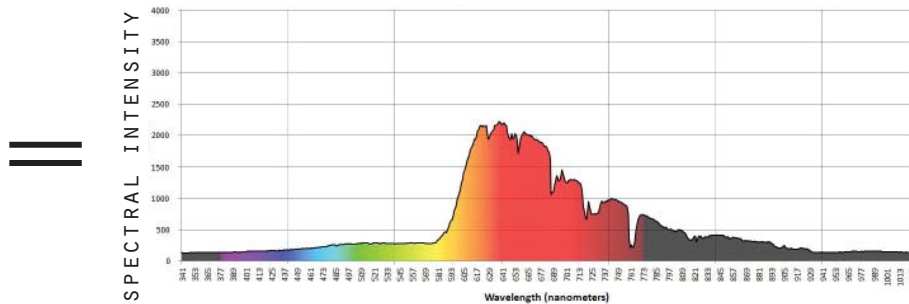


VARIABLE INCIDENT LIGHT ENERGY SPECTRUM

X

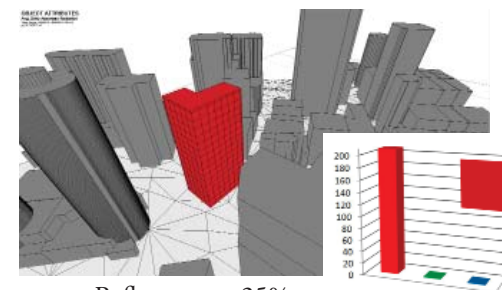


CONSTANT MATERIAL REFLECTANCE SPECTRUM



VARIABLE REFLECTED LIGHT SPECTRUM

≠



Reflectance = 25%

SIMULATED

5.3. Effect of Surface Temperature on Conductive Heat Flow through Opaque Assemblies

FIGURE 5.3-1 AND 5.3-2 - Relationship of Temperature Differential and Conductive Heat Flow

Heat flow through an opaque assembly with a constant U value varies linearly with the differential in surface temperature between the inside and outside.

A reduction in surface temperature differential by as little as 2°F can result in a 20% reduction in the rate of conductive heat flow.

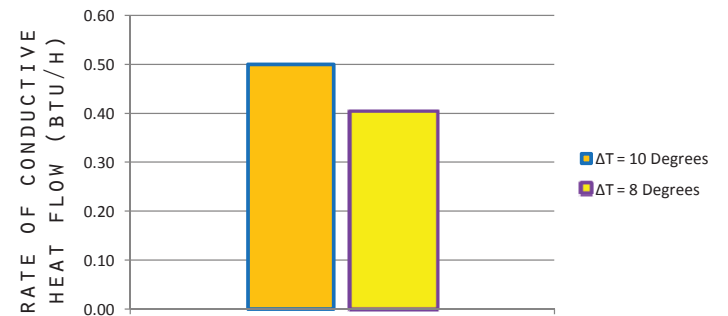
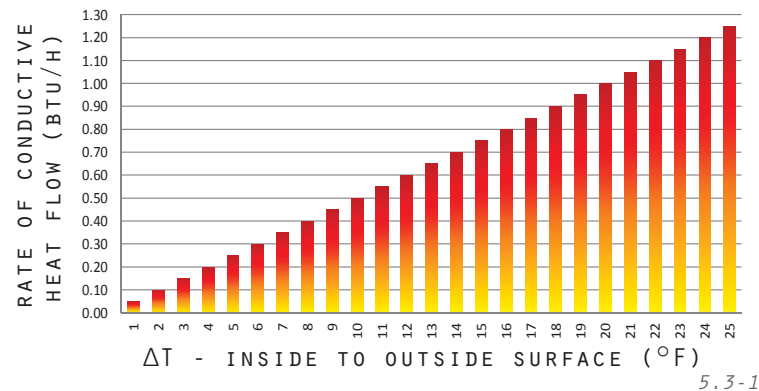
Conductive Heat flow (q) through an opaque surface is defined as the product of the heat transfer coefficient of the assembly (U-value), the area through which the heat is flowing (A), and the differential between the inside and outside surface temperature (ΔT), or as an equation: $q = U \times A \times \Delta T$. The rate of conductive heat flow varies linearly with the differential in surface temperature (figure 5.3-1). By reducing the differential in surface temperature by as little as 2 degrees, the rate of conductive heat flow could be reduced by twenty percent which could result in less energy use to overcome its affects (figure 5.3-2).

$$q = U * A * \Delta T$$

Heat flow via conduction through 1 square foot of opaque building skin

$$q = U * A * \Delta T = \text{Heat Flow via Conduction (Btu/h)}$$

- 20 R value of opaque building skin (hr sqft °F/Btu)
- 0.05 U value of opaque building skin (Btu/hr-sq ft °F)
- 70 inside surface temperature (°F)



SUMMARY

Observations show that colored surface temperatures react differently under different atmospheric and diurnal conditions. Data analysis reveals that the spectral qualities of the incident light energy are constantly shifting in both intensity *and* spectral distribution.

This Part demonstrates that specific colors have specific wavelength dependent reflectance characteristics that do not vary with the incident light spectrum and that a color can only reflect or absorb those wavelengths that are present in the incident light spectrum. It also shows that color represented by a singular RGB reflectance factor cannot be accurate under a variable incident light spectrum. As those spectral qualities vary, the proportion of incident light energy reflected or absorbed by the colored surface change. The only method to insure a constant reflectance factor under a variable light energy spectral distribution would be to provide a variable reflectance spectrum which could be employed to provide a constant colored surface reflected light spectrum and a constant surface temperature. Part 6 proposes some facade color application that could be employed based on climate and the dominate need for cooling or heating.

PART 6

FACADE COLOR INFORMED BY CLIMATE AND CONTEXT

Part 4 illustrated the impact that climate and context have on the quantity of available incident solar energy as well as how facade color influences how much of that available light energy is absorbed or reflected by opaque surfaces. Part 5 showed how atmospheric and diurnal conditions affected the qualities of incoming light energy, how the qualities and quantities of reflected light by colored surfaces vary with incident light variability, how both affect surface temperature, and the impact of surface temperature on conductive heat flow through an opaque building facade. This part investigates opaque facade color application influenced by climate that could be beneficial in reducing building energy use for heating or cooling.

Guidance for facade color is based on information collected by government agencies over a long period of time from weather stations near the selected city over a period of several decades. Cloud cover, monthly diurnal average temperature, rainfall, humidity, and wind speed are a few of the data points collected. These files are known as typical meteorological year files (TMY)--the same files used in the simulations. The Ecotect weather tool and the Climate Consultant interface were used to translate the TMY files into graphic formats. Heating or cooling dominance was determined by analyzing the number of months of the year in which the diurnal average temperature fell below or above the comfort zone as represented by the horizontal green bar shown in the graphic format thereof. For the purposes of this study, the internal building loads are neglected in determining heating or cooling dominance as this is beyond the scope. Additional guidance for facade color is provided by research conducted in Part 2 as well as the empirical studies from Part 5.

6.1. Seattle

Analysis of the graphic format of the TMY files from the Seattle-Tacoma International Airport show that the monthly diurnal average temperatures impose a heating dominated climate (figure 6.1-1). Analysis of the average cloud cover reveal a sky condition dominated by clouds with cloud cover ranging between sixty percent and greater than eighty percent for seventy-seven percent of the year (figure 6.1-2).

In this case, it makes sense to absorb as much incident solar energy as possible for passive solar heating. Empirical studies conducted in Part 5 demonstrated that cloudy skies cause a blue shift in the solar energy spectrum. Investigations of color in Nature showed a complimentary relationship between color and absorption. Therefore, a red-orange or dark colored opaque facade would absorb a greater quantity of insolation which could increase outside surface temperatures by absorbing the blue-green insolation shift. This increase in outside surface temperature would reduce the rate of conductive heat flow out of the building which could reduce average yearly heating loads (figures 6.1-3 through 6.1-5).

FIGURE 6.1-1 - Seattle Monthly Diurnal Average Temperature

The Seattle TMY file reveals a heating dominated climate with the average diurnal temperatures falling below the comfort zone for ten months and within the comfort zone for two.

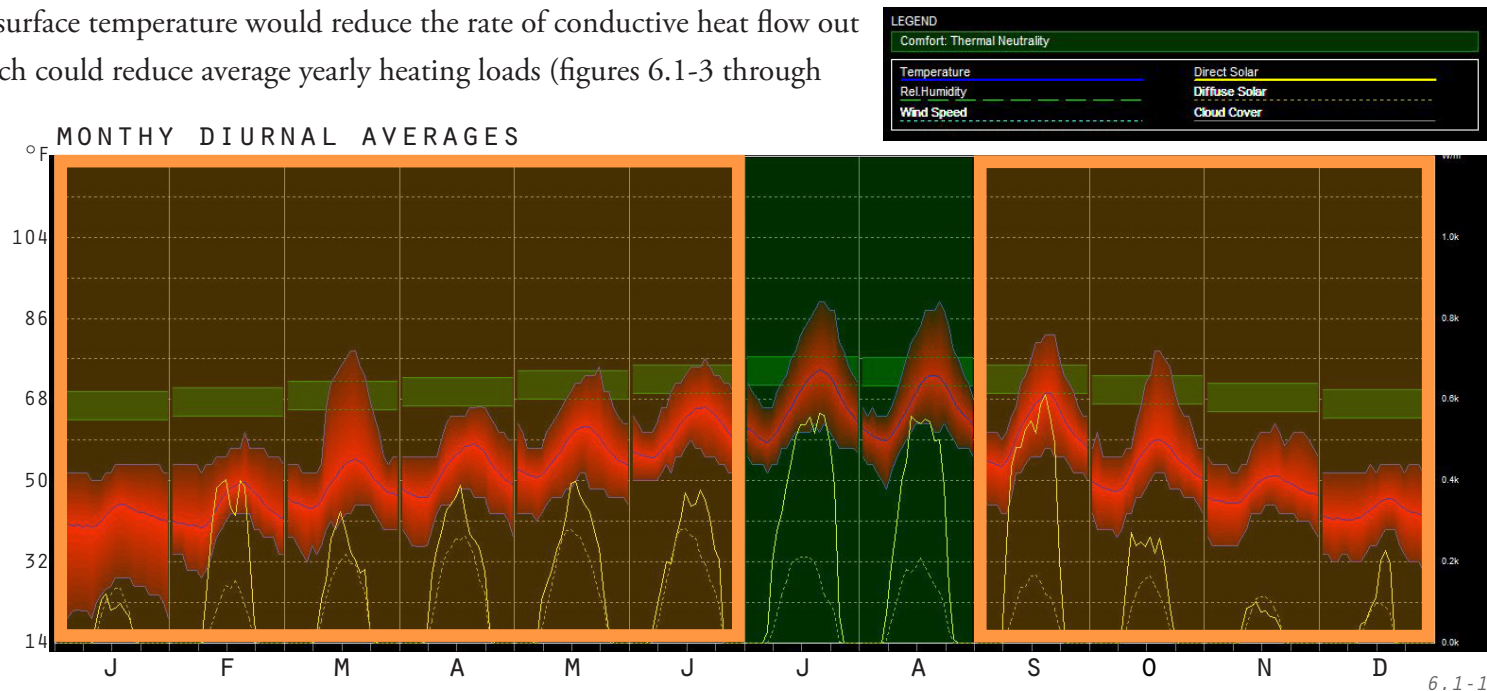
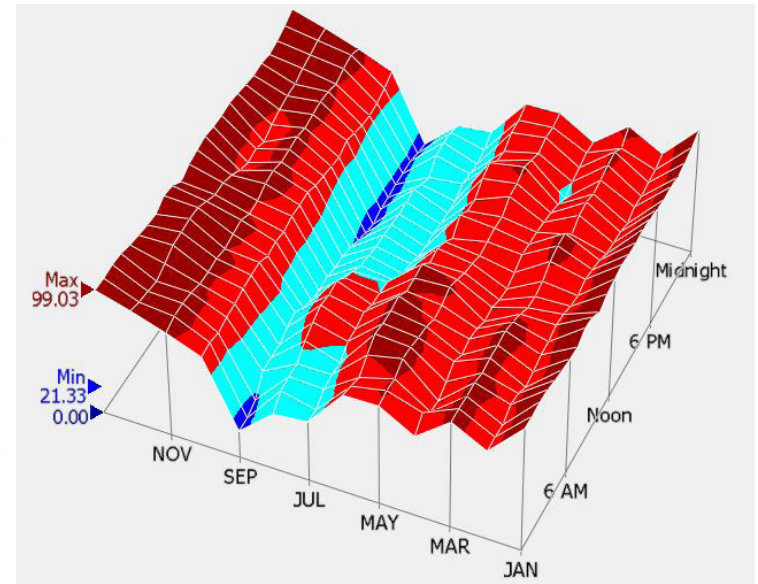
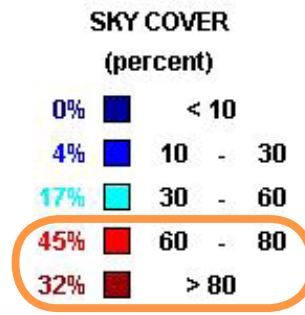


FIGURE 6.1-2 - Seattle Average Cloud Cover

Sky condition dominated by clouds with cloud cover ranging between 60% and greater than 80% for 77% of the year.

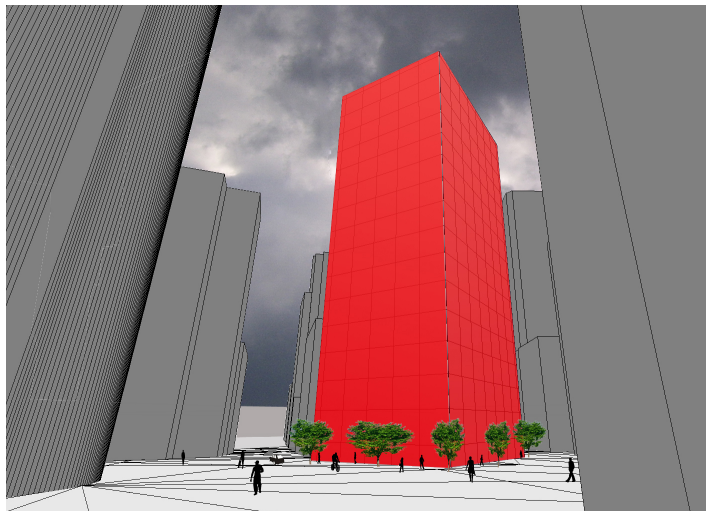
Seattle - Heating Dominated, Cloudy Sky Dominated



6.1-2

FIGURES 6.1-3 THROUGH 6.1-5 Facade Color Informed by Seattle Climate

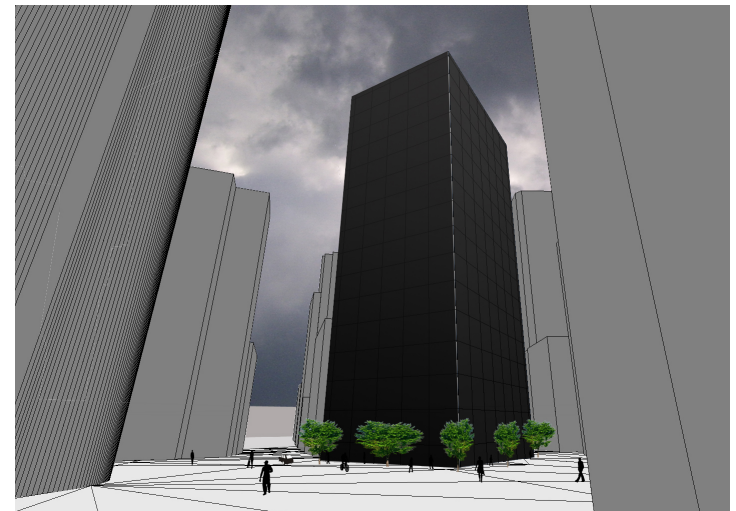
A Red-orange or dark colored facade would absorb the Blue/Green shift in insolation spectrum in a complementary fashion to increase outside surface temperature for passive solar heating.



6.1-4



6.1-3



6.1-5

6.2. Phoenix

Analysis of the graphic format of the TMY files from the Phoenix Sky Harbor International Airport show that the monthly diurnal average temperatures impose a cooling dominated climate (figure 6.2-1). Analysis of the average cloud cover reveal a predominately clear sky condition with cloud cover ranging between ten and sixty percent for nearly the entire year (figure 6.2-2).

In this case, it makes sense to reflect as much incident solar energy as possible. Empirical studies conducted in Part 5 demonstrated that clear skies cause a red shift in the insolation spectrum. Investigations of color in Nature showed that color is used to reject similarly colored spectral regions of insolation. Therefore, a red-orange or light colored opaque facade would reflect a greater quantity of insolation which could decrease outside surface temperatures by reflecting the red-orange insolation shift. This decrease in outside surface temperature would reduce the rate of conductive heat flow into the building which could reduce average yearly cooling loads (figures 6.2-3 through 6.2-5).

FIGURE 6.2-1 - Phoenix Monthly Diurnal Average Temperature

The Phoenix TMY file reveals a cooling dominated climate with the average diurnal temperatures falling above the comfort zone for seven months, within the comfort zone for three, and below for two.

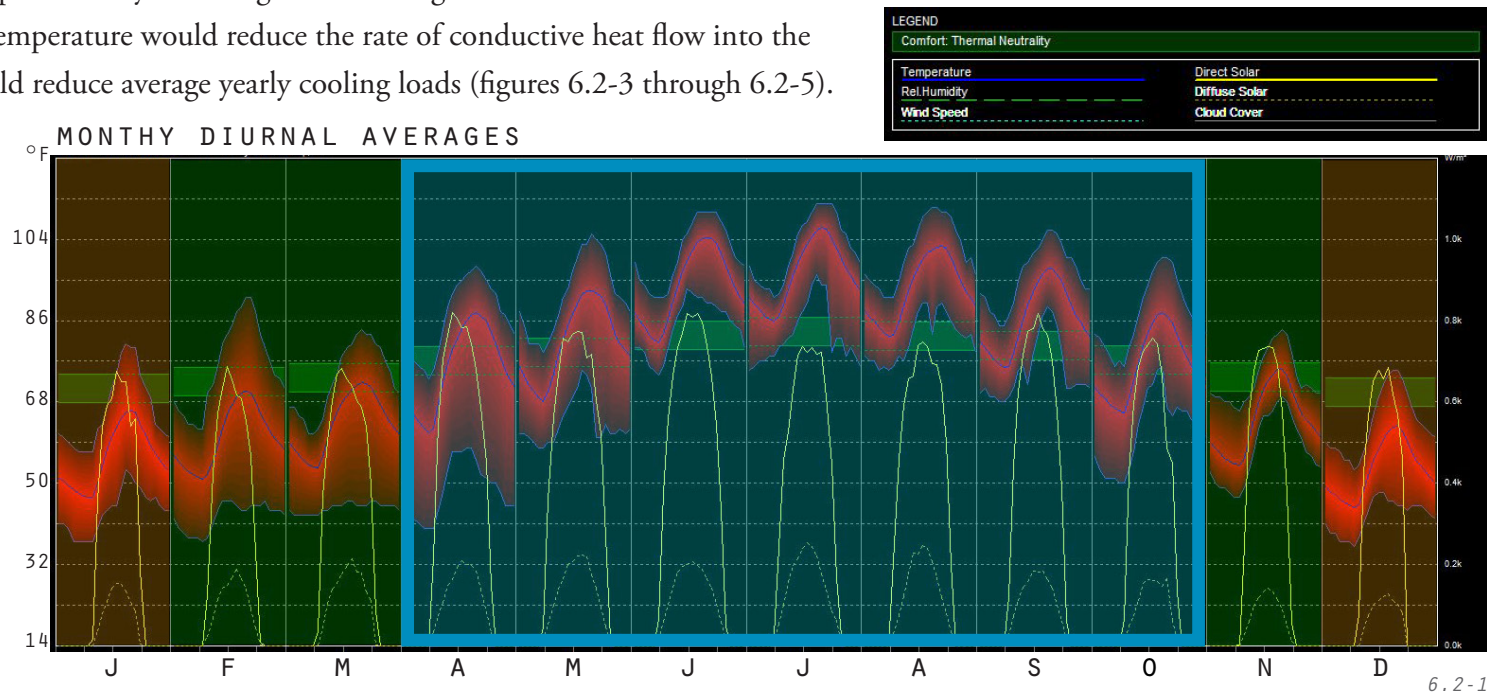
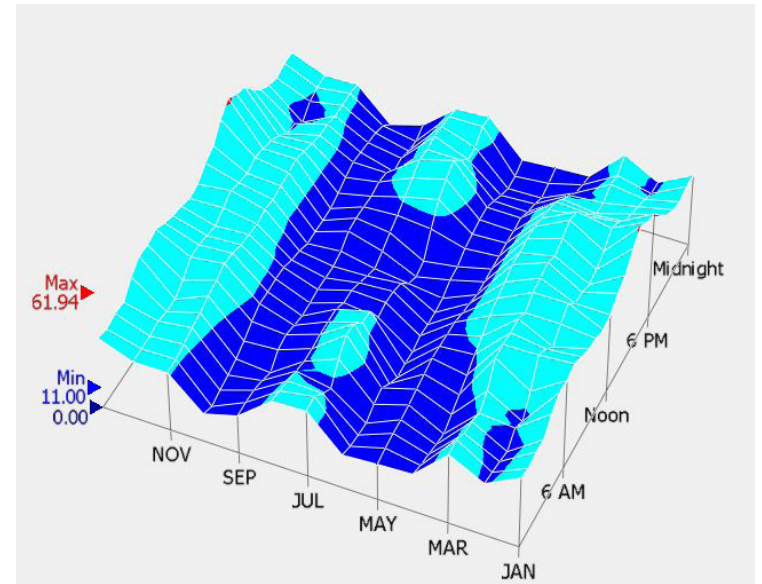
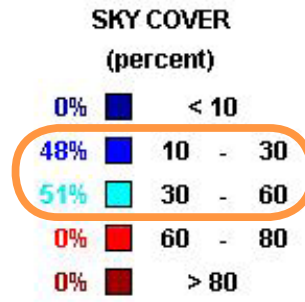


FIGURE 6.2-2 - Phoenix Average Cloud Cover

Sky condition dominated by clear skies with cloud cover ranging between 10% and 60% for 99% of the year.

Phoenix - Cooling Dominated, Clear Sky Dominated



FIGURES 6.2-3 THROUGH 6.2-5 Facade Color Informed by Phoenix Climate

A Red-orange or light colored facade would reflect the Red shift in the insolation spectrum to decrease outside surface temperatures and decrease cooling loads.



6.2-4



6.2-3



6.2-5

6.2-2

6.3. Houston

Analysis of the graphic format of the TMY files from the Houston Bush Intercontinental Airport show that the monthly diurnal average temperatures impose a cooling dominated climate (figure 6.3-1). Analysis of the average cloud cover reveal that sky conditions are often cloudy with cloud cover ranging between thirty and eighty percent for nearly the entire year (figure 6.3-2).

In this case, it makes sense to reflect as much incident solar energy as possible. Empirical studies conducted in Part 5 demonstrated that cloudy skies cause a blue shift in the insolation spectrum. Investigations of color in Nature showed that color is used to reject similarly colored spectral regions of insolation. Therefore, a blue or light colored opaque facade would reflect a greater quantity of insolation which could decrease outside surface temperatures by reflecting the blue insolation shift. This decrease in outside surface temperature would reduce the rate of conductive heat flow into the building which could reduce average yearly cooling loads (figures 6.3-3 through 6.3-5).

FIGURE 6.3-1 - Houston Monthly Diurnal Average Temperature

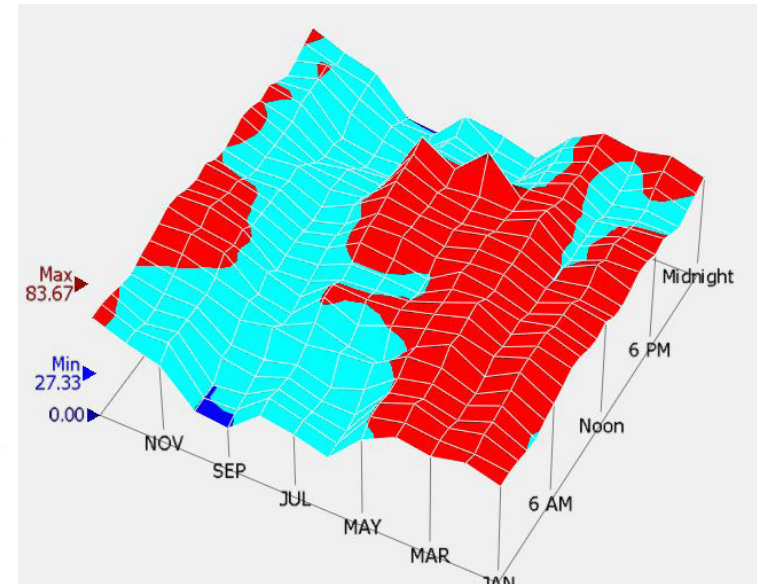
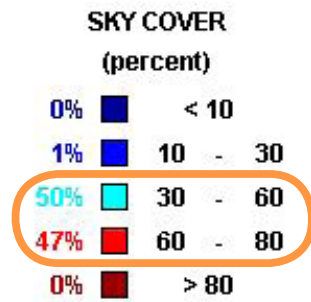
The Houston TMY file reveals a cooling dominated climate with the average diurnal temperatures falling above the comfort zone for six months, within the comfort zone for two, and below for four.



FIGURE 6.3-2 - Houston Average Cloud Cover

Sky condition dominated by clouds with cloud cover ranging between 30% and 80% for 97% of the year.

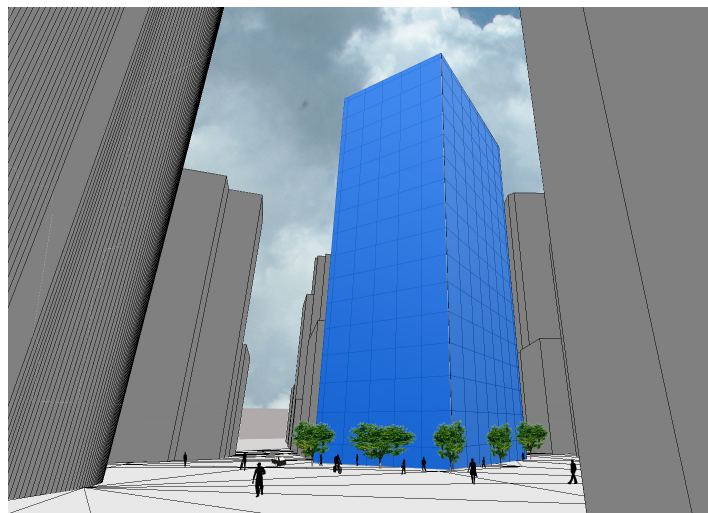
Houston - Cooling Dominated, Cloudy Sky Dominated



6.3-2

FIGURES 6.3-3 THROUGH 6.3-5 Facade Color Informed by Houston Climate

A Blue-green or light colored facade would reflect the Blue/Green shift in the insolation spectrum which would decrease the outside surface temperature and reduce cooling loads.



6.3-4



6.3-3



6.3-5

SUMMARY

While these colored facade guidelines are fairly simplistic, further development of simulation software to account for actual spectral qualities of insolation under various atmospheric and diurnal conditions could be developed that would allow for a more fine grained evaluation. Colors could be selected based on facade orientation and the desire to absorb or reflect insolation based on specific needs such as morning warm-up. Variations of color value could be used depending on the vertical location of the facade segment and the impact of neighboring building shadows.

PART 7

EVALUATION OF INVESTIGATIONS

Investigations taken on by this thesis provide guidance and new ways of thinking about color other than use as a decorative element and how using current simulation technology may not accurately predict absorption and reflection by materials. In summary:

- Nature uses color for many reasons but performance efficiencies are the chief driver.
Plants and animals use color as a tool to aid in survival of the particular species influenced by the environment in which they evolved.
- Color definitions in simulations do not accurately represent the reflective characteristics of materials under variable incident solar energy spectra.
Simulations treat color in the way that humans perceive it and not in the way it physically behaves as influenced by atmospheric and diurnal variables.
- Context, climate, and diurnal effects have a significant impact on colored opaque surface temperatures.
The amount of insolation absorbed or reflected by a colored opaque surface can be significantly influenced by the qualities of the insolation spectrum which is in turn affected by many variables.
- Colored opaque surface temperatures can significantly impact conductive heat flow and energy use.
Architectural application of color informed by critical analysis could be used as a tool for influencing exterior surface temperatures which could serve to mediate conductive heat flow and reduce the energy used to overcome that heat flow.

PART 8

FURTHER DIRECTION

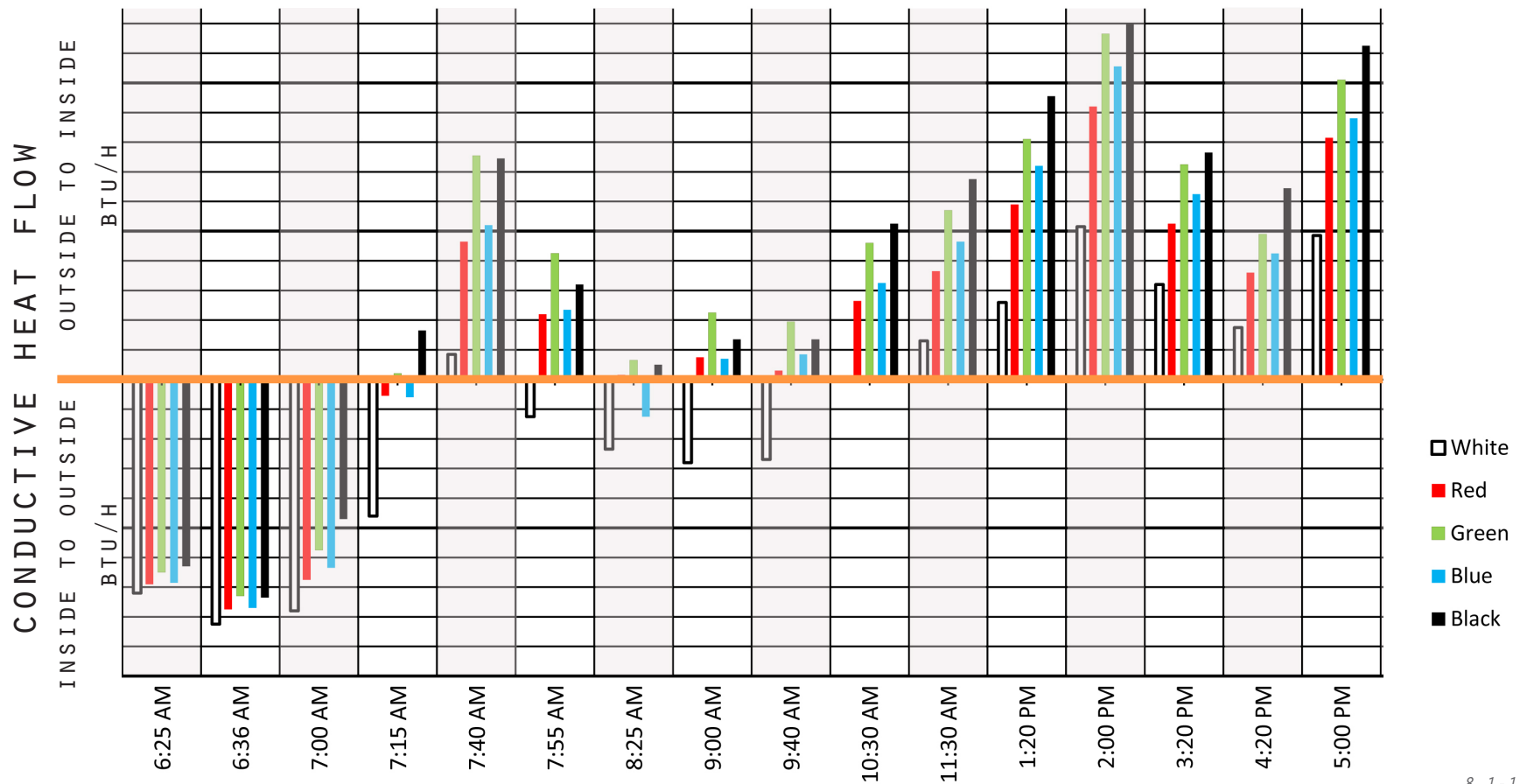
Unlike Nature, the Cool Roofs initiative strives to reject as much of the incident solar energy as possible. In the case of the Chameleon, Nature seeks to harvest this energy in various quantities--sometimes absorbing a large portion, sometimes reflecting a large portion, and many steps in between. How could this lesson be applied to building skins?

8.1. Influence of Color on Rate and Direction of Conductive Heat Flow

In this study, the rate and direction of conductive heat flow through a theoretical one-square-foot opaque surface having a U value of 0.05 BTU/hour °F ft² (corresponding to an R-value of 20) was estimated. To calculate the surface temperature differential, the interior surface temperature was assumed to be 70°F with the exterior surface temperature corresponding to the observed surface temperatures of each of the five colored squares. When one looks at how the rate and direction of conductive heat flow through an opaque surface is influenced by the empirically studied colored surface temperatures from Part 5 (which are impacted by diurnal and atmospheric conditions), some interesting results are apparent (figure 8.1-1). The colored bars correspond to each of the five colors observed. The magnitude and direction of the bars represent the rate and direction of conductive heat flow with bars above the orange line representing heat flowing *into* the building and bars below the orange line representing heat flowing *out of* the building. This suggests that certain colors may be more beneficial depending on sky condition, time of year, and the need to absorb or reflect light energy based on building heating or cooling loads.

FIGURE 8.1-1 - Influence of Color on Rate and Direction of Conductive Heat Flow

The magnitude and direction of the bars represent the rate and direction of conductive heat flow with bars above the orange line representing heat flowing *into* the building and bars below the orange line representing heat flowing *out of* the building.



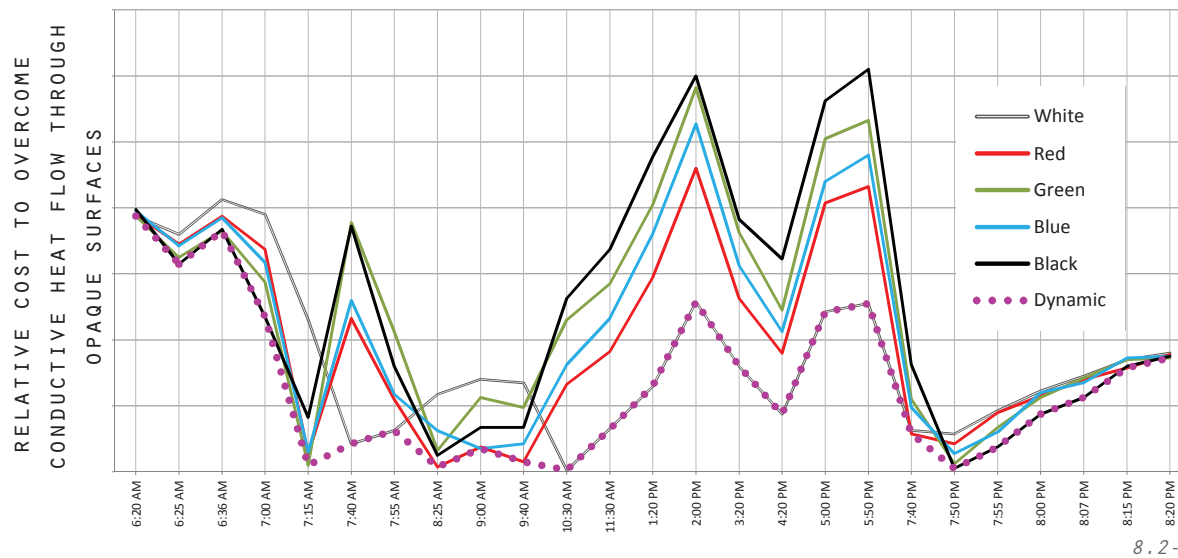
8.2. Impact of a Dynamic Colored Facade on Energy Use

A simplistic cost analysis of the expenditure required to maintain an interior opaque surface temperature of seventy degrees while the exterior surface temperature fluctuates based on one days' empirical observations was performed. The line graph reveals how some colors may be more economically beneficial than others depending on time of day and atmospheric and diurnal conditions. The purple dotted line traces a path that shows what color would be the most economically beneficial at different times of this particular day (figure 8.2-1). The bar graph illustrates the possible savings offered by a dynamic color strategy as compared to other static colors (figure 8.2-2). This suggests that a variable or dynamic color strategy may be beneficial.

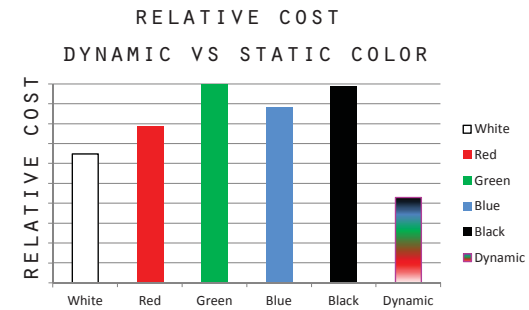
FIGURES 8.2-1 AND 8.2-2- Impact of a Dynamic Colored Facade on Energy Use

The line graph illustrates the relative costs required to overcome conductive heat flow as impacted by colored surface temperatures. The purple dotted line illustrates the benefits of a dynamic color strategy.

The bar graph illustrates the cost savings offered by a dynamic color strategy.



8.2-1



8.2-2

Dynamic color provides a	34% reduction over Static White
Dynamic color provides a	45% reduction over Static Red
Dynamic color provides a	57% reduction over Static Green
Dynamic color provides a	51% reduction over Static Blue
Dynamic color provides a	57% reduction over Static Black

8.3. Variable Structural Color

As with the methods in which color appearance is accomplished with butterflies, a tunable facade color could be employed using structural color. By varying the refractive index of the facade material, the portions of incident solar energy reflected or absorbed could be varied. By linking the interior and exterior surface temperatures, the rate and direction of beneficial conductive heat flow could be influenced depending on the particular room occupant comfort requirements within the building.



FIGURE 8.3-1 - The Blue Morpho Butterfly

Color in insects is often a result of nano-scale structures that are tuned to particular wavelengths of light to create colored appearance.

8.4. Current Temperature Activated Color Technologies

Currently there are several temperature activated color change technologies available. While some may be considered novelties, in the case of the beer bottle label (figure 8.4-1), they do show the possibilities of the technology. Technologies developed by Liquid Crystal Resources LLC (LCR Hallcrest)⁸ include inks and dyes that are either heat or cold activated and color changing liquid crystal films (figure 8.4-2). Moving Color, Inc.⁹ has developed glass tiles that change color with temperature (figure 8.4-3). Graduate students at M.I.T. have developed a roof tile that changes from black to white as temperature increases (figure 8.4-4) in order to take advantage of incident solar radiation on a seasonal basis by absorbing heat in the winter and reflecting it in the summer.¹⁰

FIGURES 8.4-1 THROUGH 8.4-4 - Current Temperature Activated Color Change Technologies

Numerous temperature activated color changing products are available today.

Dyes - LCR Hallcrest



8.4-1

8 <http://www.hallcrest.com/>

9 <http://www.movingcolor.net/>

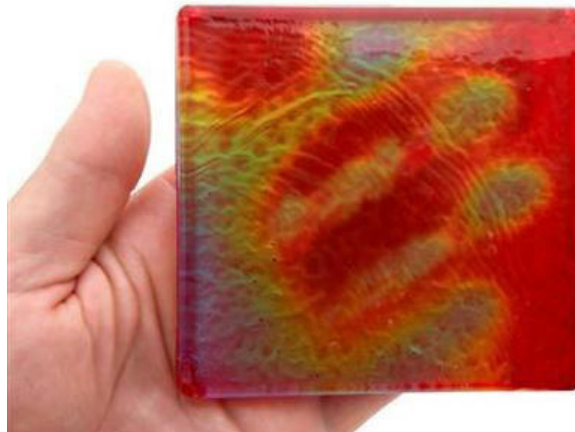
10 <http://www.physorg.com/news174209373.html>

Liquid crystals - LCR Hallcrest



8.4-2

Tiles - Moving Color



8.4-3

Roof tiles - M.I.T.



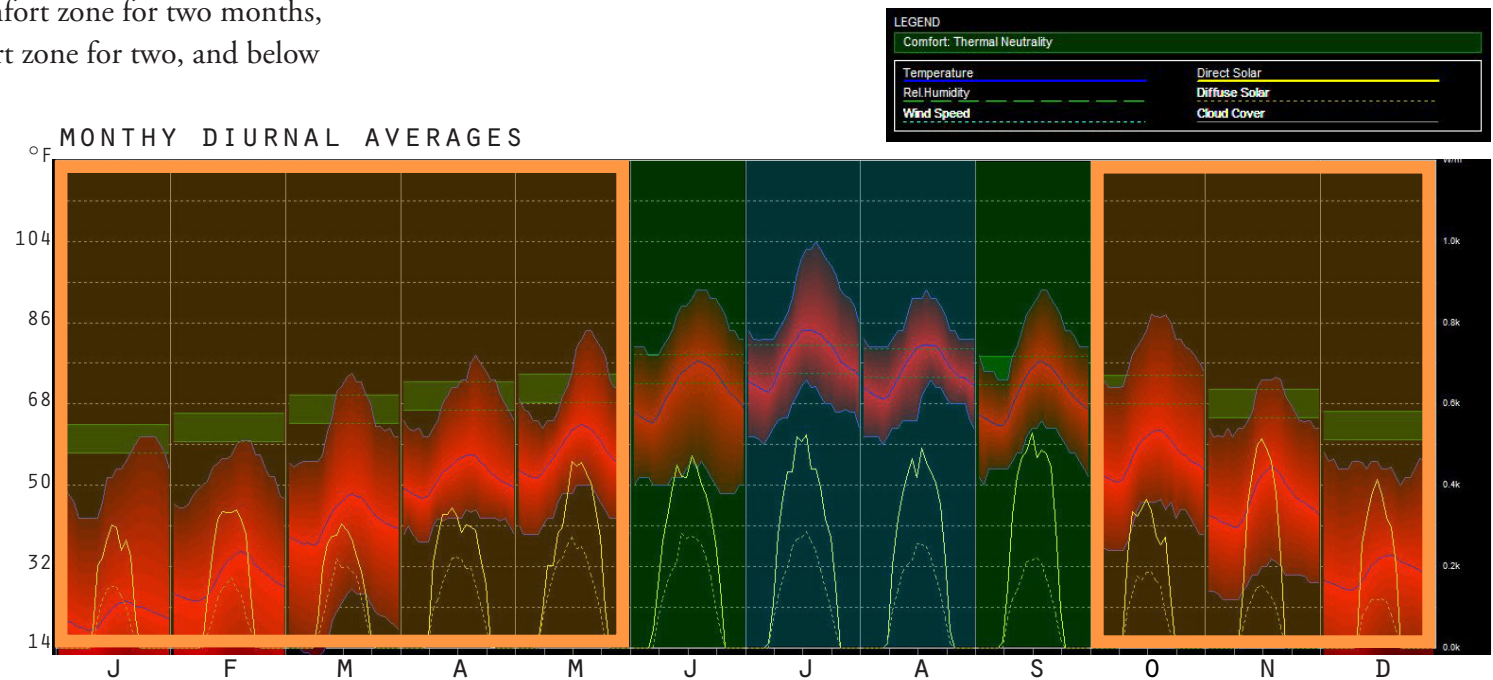
8.4-4

8.5. Dynamic Colored Facade for a Building in Chicago

Inspired by the method in which chameleons vary their color for thermal benefit, a dynamic colored facade is explored. As with the methods used in Part 6, analysis of the graphic format of the TMY files from the Chicago Midway airport show that the monthly diurnal average temperatures impose a heating dominated climate (neglecting internal loads) with as much as a sixty degree seasonal temperature change (figure 8.5-1). In this case, it makes sense to vary the amount of incident solar energy either reflected or absorbed depending on sky condition and season. Empirical studies conducted in Part 5 demonstrated that clear skies cause a red shift in the insolation spectrum while cloudy skies induce a blue shift. Nature uses color to either absorb or reflect spectral regions of insolation depending on need.

FIGURE 8.5-1 - Chicago Monthly Diurnal Average Temperature

The Chicago TMY file reveals a heating dominated climate with a 60 degree seasonal temperature change. Average temperatures fall above the comfort zone for two months, within the comfort zone for two, and below for eight.



On a sunny summer day a red-orange or light colored opaque facade would reflect a greater quantity of insolation which could decrease outside surface temperatures by reflecting the red-orange insolation shift thereby reducing cooling loads. This decrease in outside surface temperature would reduce the rate of conductive heat flow into the building which could reduce cooling loads (figure 8.5-2).

On a *cloudy* summer day a blue-green or light colored facade would reflect the blue shift in insolation similarly reducing the exterior surface temperature and reducing the rate of conductive heat flow into the building reducing cooling costs (figure 8.5-3).

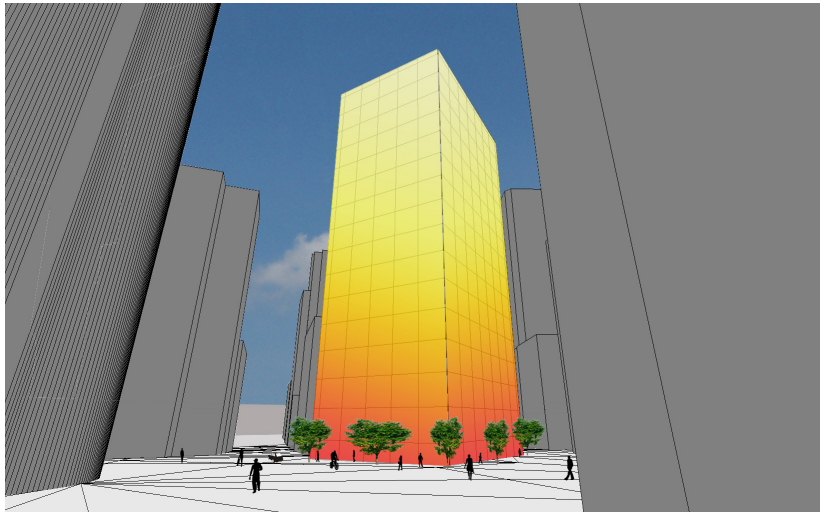
Conversely, on a sunny *winter* day, a blue-green or dark colored facade would *absorb* the red shift in insolation in a complementary fashion to *increase* the exterior surface temperature which would serve to decrease the rate of conductive heat flow *out of* the building and may induce some passive heating that would help to reduce *heating* loads (figure 8.5-4).

Finally, on a *cloudy* winter day, a red-orange or dark colored facade would absorb the *blue* shift in insolation in a complementary fashion to increase the exterior surface temperature of the building decreasing the rate of conductive heat flow out of the building to promote passive heating and reduction in heating expenditure (figure 8.5-5).

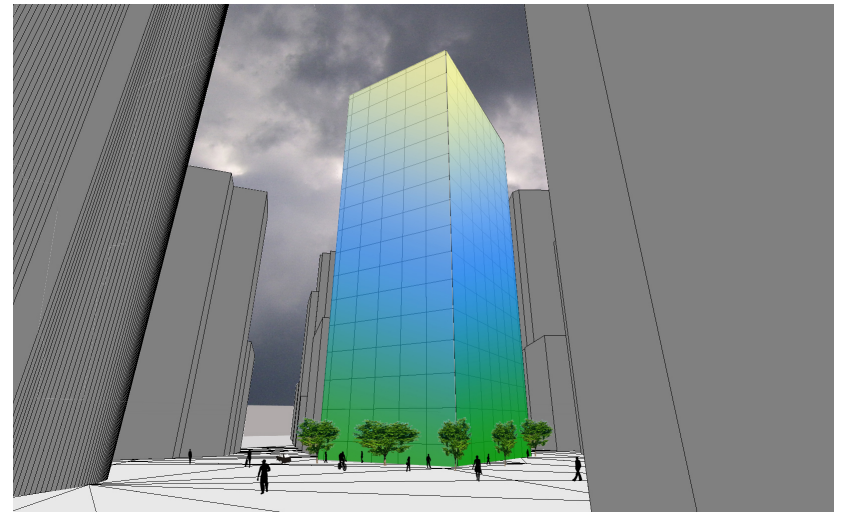
FIGURES 8.5-2 THROUGH 8.5-5 -
Dynamic Color Facade for Chicago

A dynamic color facade could selectively absorb or reflect spectral regions for benefit to aid in reduction of energy use for heating or cooling based on sky condition and season.

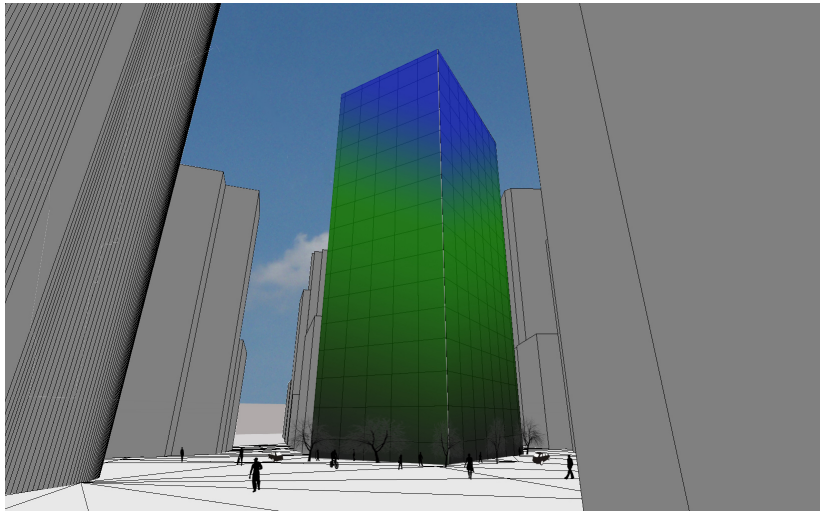
Sunny Summer Day



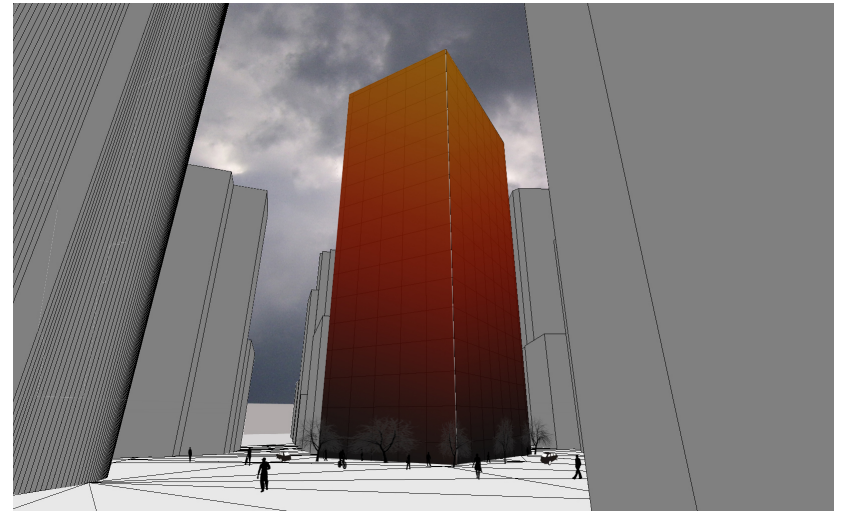
Cloudy Summer Day



Sunny Winter Day



Cloudy Winter Day



SUMMARY

While such a dynamic color strategy may be fantasy, current technologies may be able to be expanded upon to achieve these ideas. Development of other technologies could be developed with the idea that a building skin could harvest solar energy for benefit while realizing the temporal nature of the spectrum. With the ever increasing cost of energy, even a modest decrease in energy use resulting from such a strategy could provide a substantial savings over the life of a building. Perhaps such a color strategy, based on performance as in Nature, could offer a beneficial biophilic or emotional response to the built environment not currently available by providing “psychotherapeutic effects that can be utilized to meet the psychological needs of people living in unresponsive, crowded environments” (Mahnke & Mahnke, 1987, p. 69).

CONCLUSION

There was a time when insulation was not deemed important due to cheap energy. The negative affects of heat flow could be overcome by active mechanical systems. As worldwide energy demand increases and sources of cheap energy (fossil fuels) become more scarce, strategies involving super-insulated building shells and Cool Roofs have become more prominent. This study suggests that perhaps the minimization of heat flow and the outright rejection of incident solar energy may not be the only methods for reducing energy use. Perhaps color could be used as a tool harvest light energy and carefully influence the magnitude and direction of heat flow for benefit by working with, instead of against, Nature.

Although color strategies proposed herein could be referred to as *biomimicry*, efforts to steer away from this term were made in an attempt to reduce the mindset that humans are somehow set apart from Nature. We are a product of Nature and as so, we are subject to the same pressures brought about by environmental conditions that have impacted all other terrestrial beings. As discussed briefly in Part 2, color constancy is a performance driven process that is intended to maintain the appearance of colors under variable lighting conditions and diurnal cycles by the automatic adjustment of responses to red, green, and blue wavelengths. The same ideas could be applied in an attempt to maintain temperature constancy of the building interior by using exterior color to influence heat flow through opaque surfaces. The desired interior surface temperature could be coupled with the exterior surface temperature as affected by the instantaneous spectral qualities of the incident light energy. Then the exterior surface color could be tuned to mediate this energy for benefit. Perhaps a net-zero heat flow could be achieved by the selection of color alone. Like a plant, a building could reach homeostasis in part by utilizing color as Nature does.

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