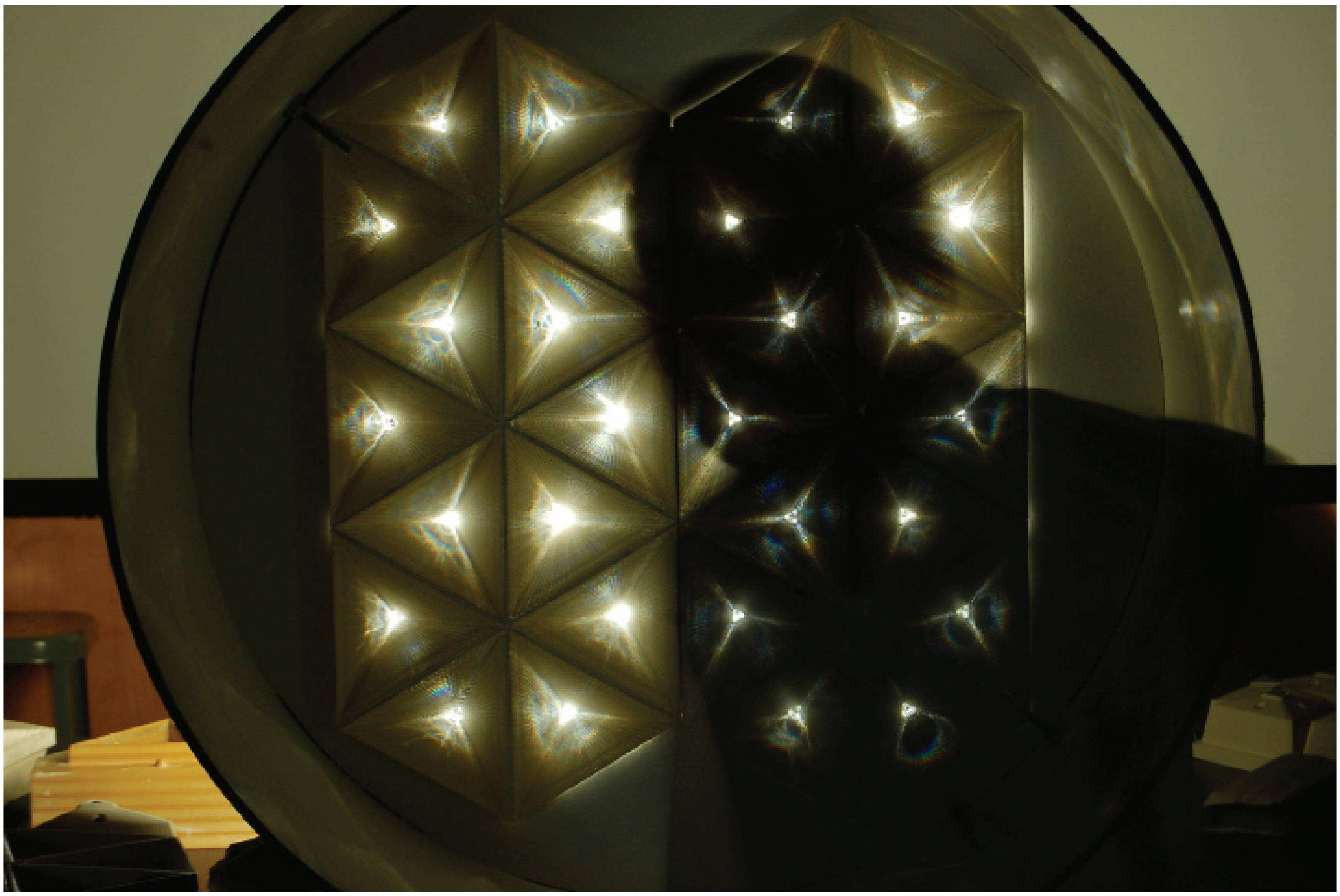
Sensitive Apertures

By Ben Ari McDonald

A Master's Report Submitted to the Faculty of the Department of Architecture
In Partial Fulfillment of the Requirements For the Degree of Master of Architecture
in the Graduate College of The University of Arizona.



University of Arizona
School of Architecture
Spring 2008

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Approval by Master's Report Thesis Committee Members:

Alvaro Malo

Alvaro Malo, Chair — Date
Professor of Architecture

Dr. Joseph Simmons — Date
Department Head and Professor of Material Science

Dr. William Bickel — Date
Professor Emeritus of Physics

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"Light reveals architecture and, in the best instances, architecture reveals light."

Marietta Millet, Light Revealing Architecture

Preamble

Light, vision, and perception have been dominant themes in architecture for ages. This project is one in a pile of many to use these phenomena as inspiration for building space.

The focus of this work comes from asking myself the question, 'what is the *right* kind of light?' Certainly, this is a big question with many variables that make a definitive answer hard to find. But I ask this only of myself and so the answer lies within me.

'... the right kind of light *for doing what*?'

For being still and aware. For thinking and contemplating. It is not about working on a particular task; I'm talking about the kind of light that you can project your mind into. Like firelight or twilight.

Hypothesis

Twice a day, at dawn and dusk, photoreceptive cells in our eyes reach a ‘crossover’ point of equal efficiency in response to ambient daylight. At these low light levels (around 1 cd/m^2), color and detail sensing cone cells share responsiveness with shape and contrast sensing rod cells. This perceptual phenomenon within the ‘mesopic vision range’ marks a potentially unique moment of visual awareness and the starting point a possible search for the ‘right’ kind of light.

This project proposes to discover a desirable light quality through observations at twilight and then set that condition up in the design of an architectural enclosure system. Most attention will be given to how the light is transmitted and presented within this enclosure. Rather than dimming daylight using large expanses of darkened translucent materials such as plastic or glass, this project aims for a solution using opaque material pierced with small, solar-oriented, refractive apertures to admit and redirect a limited amount of light onto the interior surfaces of the material. When the direction of the sun and the geometry of the light containers align, light will fill the aperture spaces uniformly. At all other times, the enclosure will admit light in a dynamic way that will, by the nature of the small apertures, reveal changing light and the passage of time.

Structurally, this idea is imagined to be a cellular network of ceramic light containers shaped to receive light from the apertures. Together, these cells will form a field of roof or wall enclosure within an otherwise dark space. As vision in mesopic range primarily affects our ability to distinguish detailed shapes and color, the scale of the light containers and the presence of refracted color will be tuned to highlight this change in our perceptual capacity.

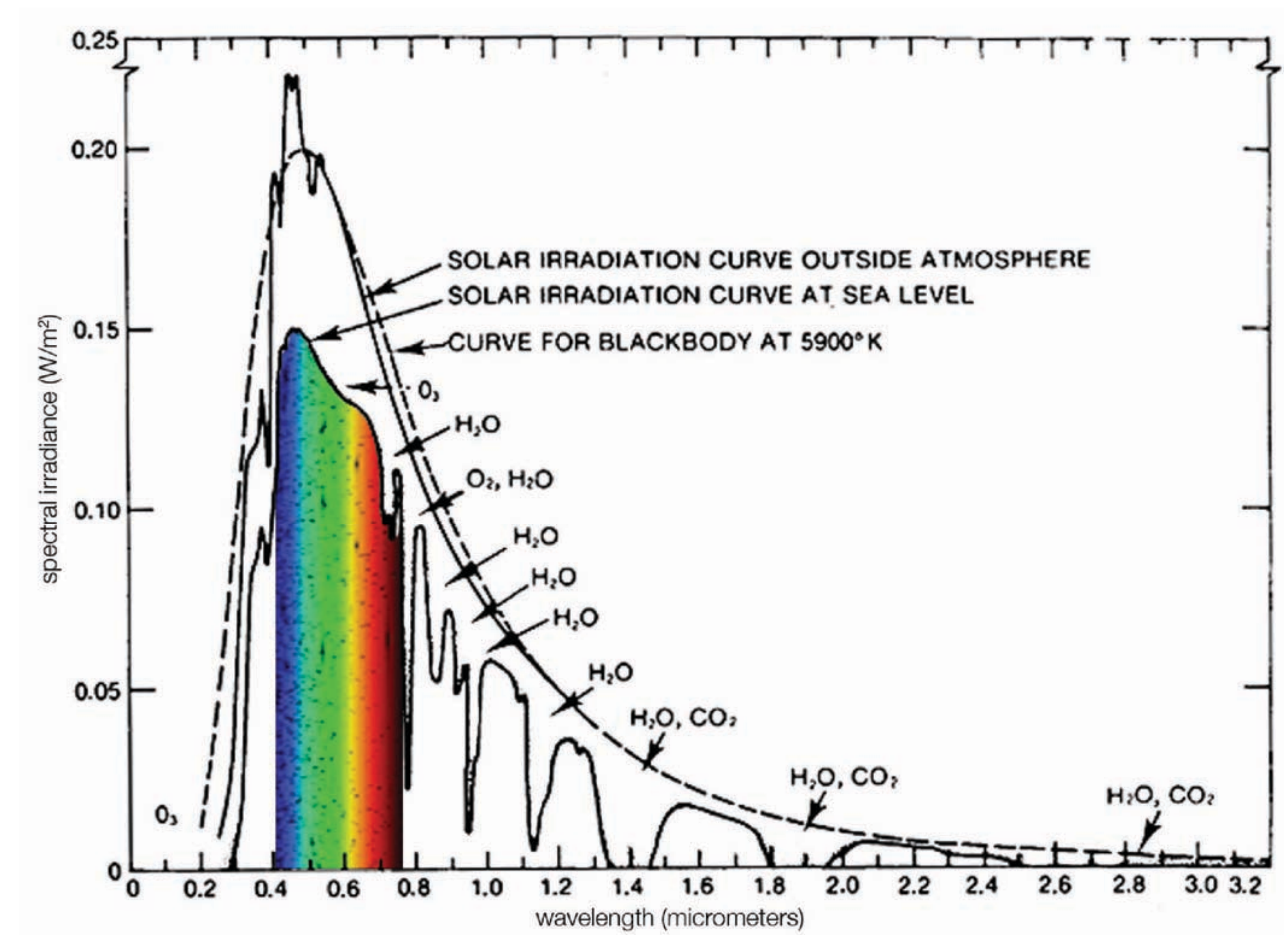
light and perception

Solar Origin

It seems all life forms have evolved directly or indirectly as a response to the radiative power emitted by the sun. It comes as no surprise then that our visual perception is closely linked to the sun's spectral properties.

An overlay (Figure 1) of the spectral distribution of power from the sun and our range of vision demonstrates the evolutionary target of human visual sensitivity to light matches the range of most abundant wavelengths of the sun.

Radiative absorption by molecules in our atmosphere significantly impacts energy received at sea level. Note the drastic valleys of irradiance caused by absorption, especially in the longer wavelengths. Radiation within the visible range, however, remains relatively smooth.

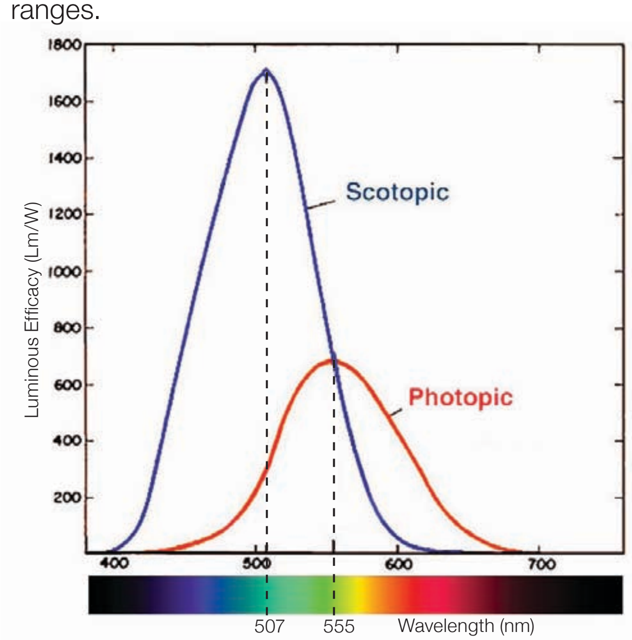


1. Solar Irradiation (Source: Handbook of Geophysics and Space Environments, S. Valley. 1965)

Within the range of detectable wavelengths (380nm - 780nm), so closely tied to the sun's energy, our vision has varying sensitivity. Generally speaking, sensation peaks in the middle of this range (around 555nm) and is very week toward the ultraviolet and infrared boundaries.

Spectral Sensitivity

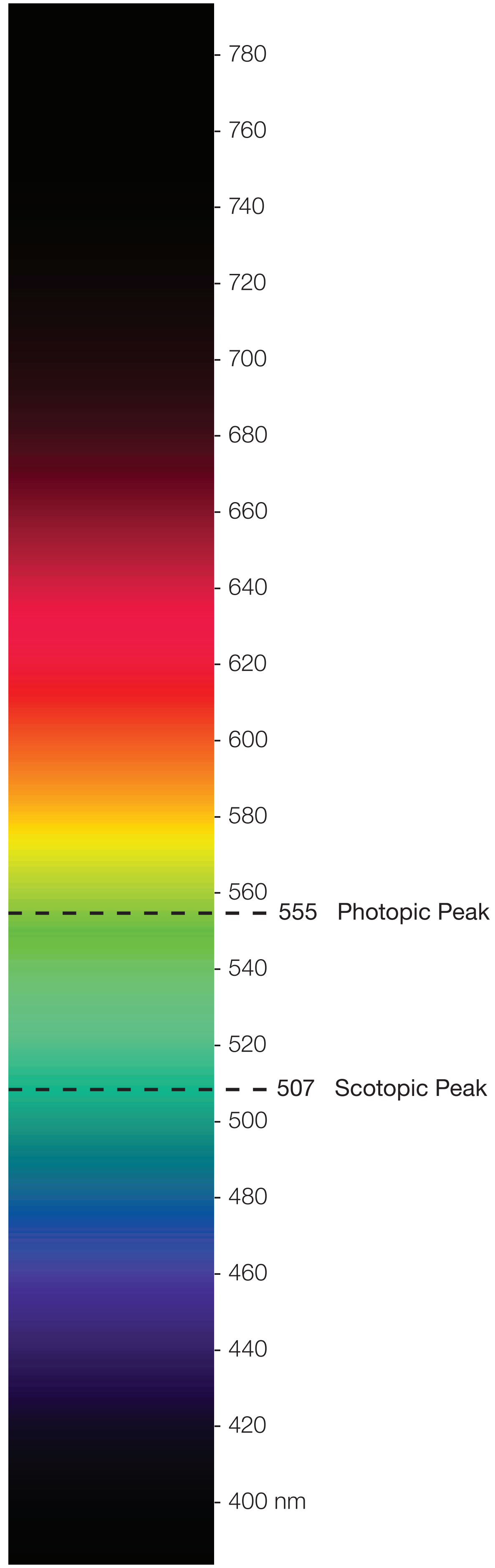
A more subtle fact is that this spectral sensitivity curve changes relative to the amount of light present in our visual field. Our vision goes through three major wavelength sensitivity changes. These are called the photopic, scotopic, and mesopic visual ranges.



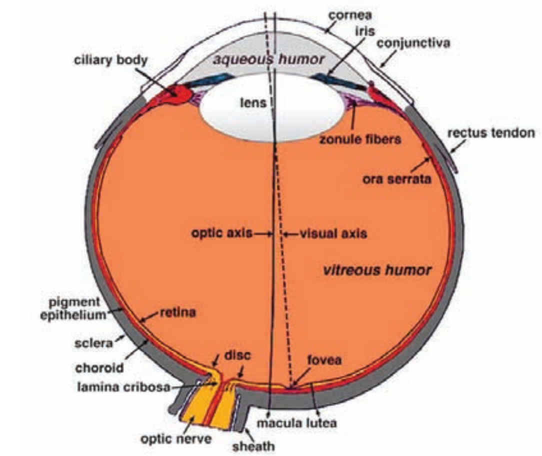
2. Luminous Efficacy Functions (Source: http://webvision.med.utah.edu/)

Most of our daily visual experience occurs within the photopic range (> 3 cd/m^2). This is our light-adapted vision. At these levels, cone cells are the most active. Strong signals from the three types of cone receptors allow us to maximize our color and detail sensing ability. The great majority of cone cells are packed in the fovea of the eye (Figures 6,7) which corresponds to the center of our vision.

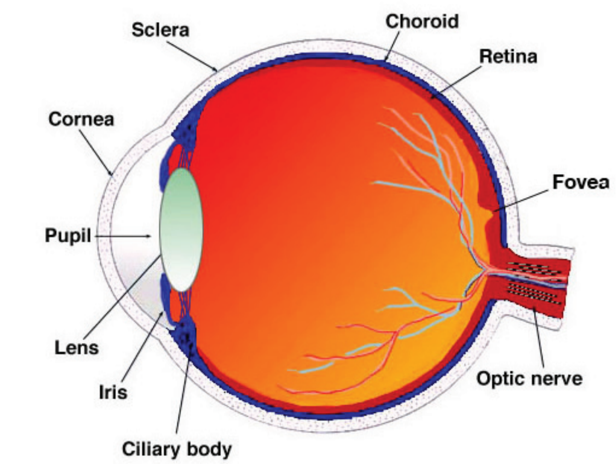
Vision in the scotopic (< .001 cd/m^2) range requires dark adaptation. At these light levels, rod cells are the dominant receptors and cone response is nearly non-existent. Because there is only one type of rod cell, scotopic vision is color blind. What rods lack in color detection, however, is made up for by an increased ability to sense peripheral vision, detect movement, and detect subtle changes in shape and contrast. A classic example of this is from stargazing when an object in the sky is invisible to the center of vision but is revealed when we avert our eyes slightly to allow more rod cells to pick up a response.



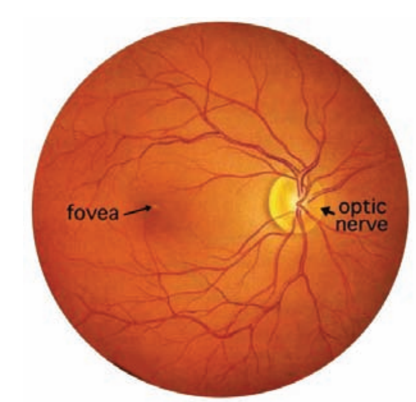
3. visible spectrum



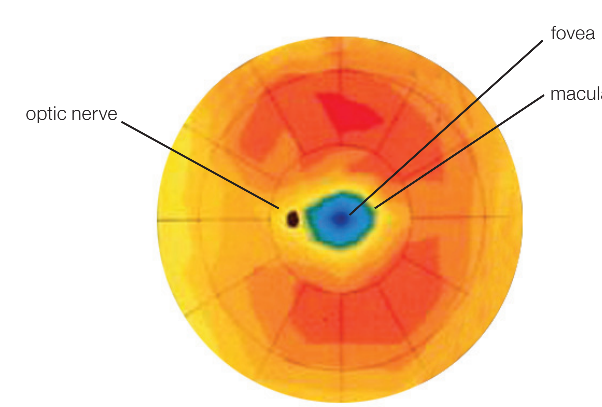
4. horizontal section of eye



5. vertical section of eye



6. ophthalmoscope view of human retina



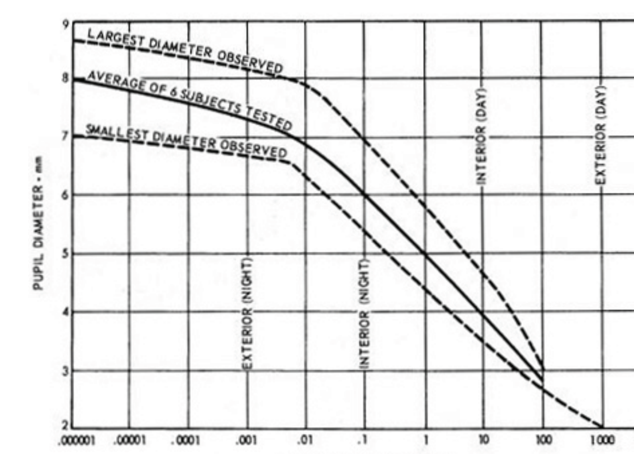
7. retina rod/cone distribution

Finally, mesopic vision range (.001cd/m^2 - 3 cd/m^2) occurs in between light and dark. Within this range, rod and cone response is shared. As of yet, there is no standard luminous efficacy function for mesopic vision. It appears that vision in this range undergoes rapid changes that are a result of a complex set of factors including illumination level, spectral content of the image, and adaptation time. Owing to a lack of scientific knowledge relating to the mesopic range, it might be best described experientially as a combination of photopic and scotopic vision. Color and detail are simultaneously detectable with peripheral vision, motion detection, and light sensitivity.

This thesis sets out to explore the perceptual intrigue of the mesopic range through observational studies which are then intended to be used as inspiration for creating an architectural enclosure.

Pupil Aperture

Adaptive pupil size helps the eye to accommodate the broad range of light levels spanning photopic and scotopic vision. Beyond the basic principle of letting more or less light into the eye, the size of the pupil (Figure 8) also determines the region of the retina that receives light and helps to explain the perceptual changes of dark versus bright environments. In bright light, the pupil contracts and limits incoming light to falling in the center of vision containing most of the cone cells. In the absence of light, muscles in the iris relax, resulting in an enlarged pupil that admits light to a much larger portion of the retina, thus allowing rod cells more opportunity for response.



8. Pupil Luminance Response (Source: IESNA Lighting Handbook)


9. Pupil dilation (actual size)

architectural precedents

Pantheon: Oculus

The domed space of the Pantheon has many things going for it to make it a powerful spatial experience: proportions, acoustics, materials, and construction methods. Of particular interest to this thesis is the way light interacts with the coffered interior of the structural concrete. There are more practical functions for the coffers than how they respond to light; structurally they lessen the outward thrust of the dome by making it lighter; acoustically they allow for sound absorption and tune reverberation times. But the way they temper the blinding beam of oculus light is inspirational. This surface texture allows the light to be partially absorbed by the coffered hollows around the perimeter of the projected light. They help to soften the sun this way and break down the light into tactile components of direct light, sharp shadows, soft shade and gentle glow.


Pantheon, Rome, 125 AD

Mosque Al-Rifai: Uniformity

Another formally basic dome space, this mosque shows a great sensitivity to the way light is introduced. In contrast to the single oculus of the Pantheon, light enters this space through a full ring of clerestory windows. The result is a more even light that sets up the potential for a uniformly glowing space. It is the scooping surface texture in the pendentive, however, that makes the glow work. This texture out-performs the Pantheon coffering by subdividing the light to the extent that lines of direct light and shadow become blurred.


Mosque al-Rifai, Cairo, 1869-1912

Alhambra: Density

The Alhambra provides a more extreme example of how spatial texture can modify the sensation of light. The small scale and tightly packed density of the decorative interior geometry creates the impression of a vast vibrating field of light.

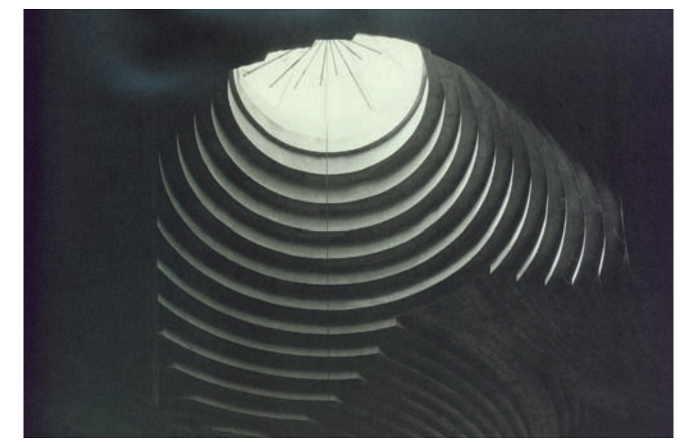

Alhambra, Grenada, 1360

Armand Bartos: Absorption
Textural quality in this project takes the discrete coffers of the Pantheon and Maqarnas of the Alhambra and transforms them into linear contours that are inseparable from the form of the space. These stepping constructions allow the light to transition gradually from bright to dark in regular intervals. In this way, light absorption becomes a dominant visual effect.

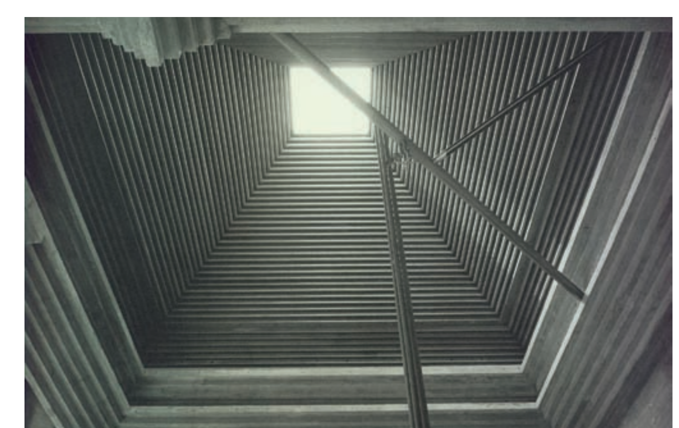
Paolo Portughesi: Coagulation
Material performs like a light sponge as a way to temper the extreme contrasts between exposed sunlight and interior darkness. Bright light, constantly flooding into space requires material in it's path to coagulate its energy by absorbing and redirecting it in a controlled manner.

Carlo Scarpa: Scale
Stepping depths, setbacks, and edge profiles determine the nuanced behavior of light within the space. These variables are integral with the structure and are suggestive of a clear construction methodology. Neither the subtractive Pantheon coffers nor the additive Alhambra muqarnas achieve this kind of clarity. The integrated textural display within the larger spatial geometry influenced later studies.

Armand Bartos, Shrine of the Book and the Sanctuary of the Dead Sea Scrolls, Jerusalem, Israel, 1959-65



Paolo Portughesi: Chiesa della Sacra Famiglia, Salerno, Italy, 1969-74



Carlo Scarpa, Cemetery Brion-Vega, San Vito d'Altovole, Italy, 1970-72

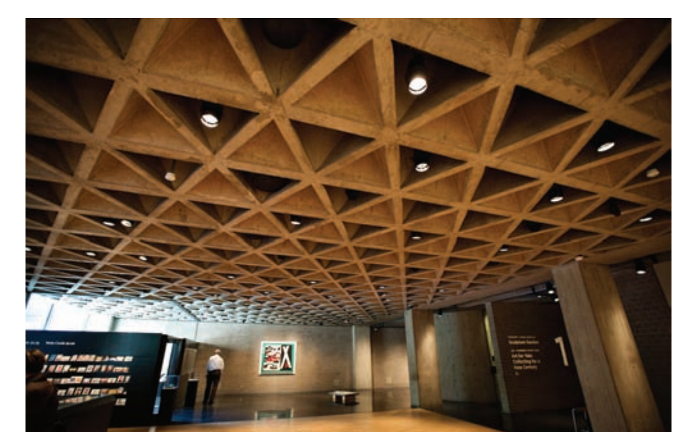
Alvaro Aalto: Scattering
Many of Aalto's library spaces introduce natural light through a series of deep skylight wells. Direct sunlight is 'caught' within this depth and is scattered many times within the white lining. The result is a very uniform, omni-directional light that eliminates distracting shadows.

Gordon Bunshaft: Translucency
Thin marble slabs temper exterior light levels to protect the rare book collection housed inside. The same overall luminance levels could have been achieved in a more clinical way using traditional glass panels with reflective coatings; however, the visual texture and preferential light scattering inherent in the natural stone make the light quality in this space particularly interesting.

Louis Kahn: Cellular Structure
The triangular structural grid in Kahn's art gallery suggests a method for tiling a uniform shape while creating structural continuity through the intersecting ribs. This framework then allows the interior of individual cells the freedom to take on other functions such as lighting, acoustic performance, and building services.


Alvar Aalto, National Pensions Institute, Helsinki, Finland, 1952

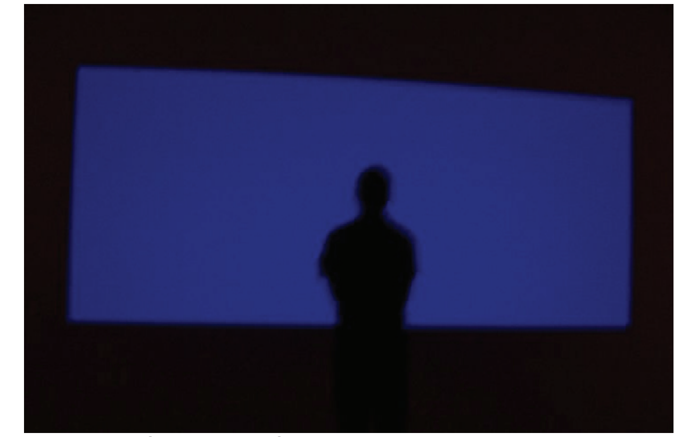

Gordon Bunshaft, Beincke Rare Book and Manuscript Library, New Haven, Connecticut, 1963


Louis Kahn, Yale University Art Gallery, New Haven, Connecticut, 1951-53

James Turrell: Solidification
Spatial volume and light frequency are combined to produce a visual perception devoid of material, leaving only light to be experienced. Turrell says, "There is a volume of best fit. When you do this it seems as though it fogs up. It tends, just like a volume of smoke, to seem to become quite solid."

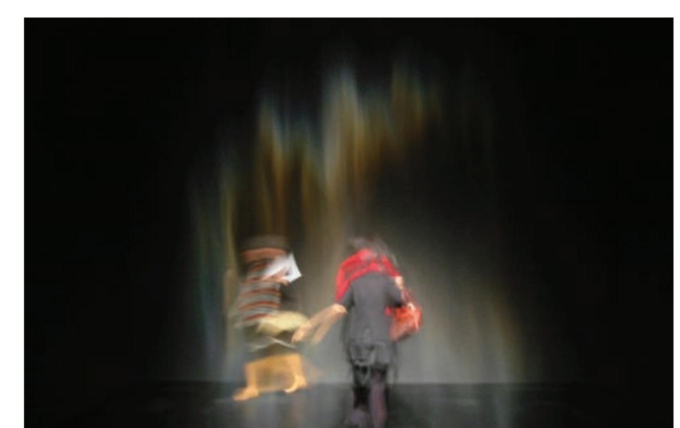
James Turrell: Contemplation
Turrell's work is rarely experienced immediately. The quality of his spaces require time to for our senses to accommodate to the particular environment. During this adaptation period, people may sit or lay down in silence for a half and hour or more. One's mental state develops during this 'opening of the senses'. Turrell calls this ..." not not-thinking, but it's not thinking in words." This condition of mental awareness is a primary motivation for this project.

Olafur Eliasson: Spontaneity
Unique phenomena occur and particular moments in time in Eliasson's work. There is movement and transformation that is dependent on the interaction of the viewers and the work.



James Turrell, Space Division Construction, 1976

James Turrell, Skyspace observers



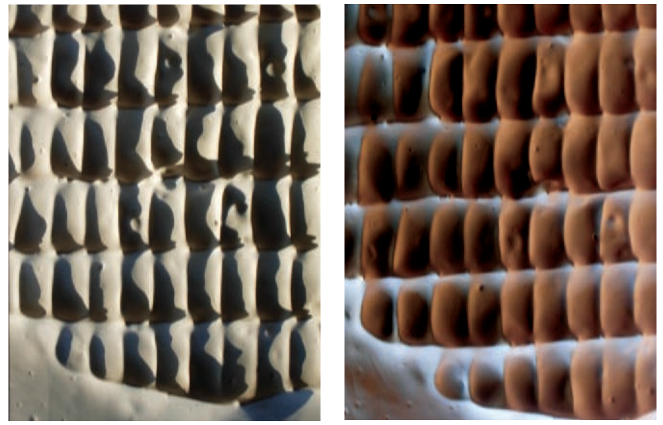
Olafur Eliasson, Beauty, 1993

preliminary empirical studies

Surface Texture Studies:

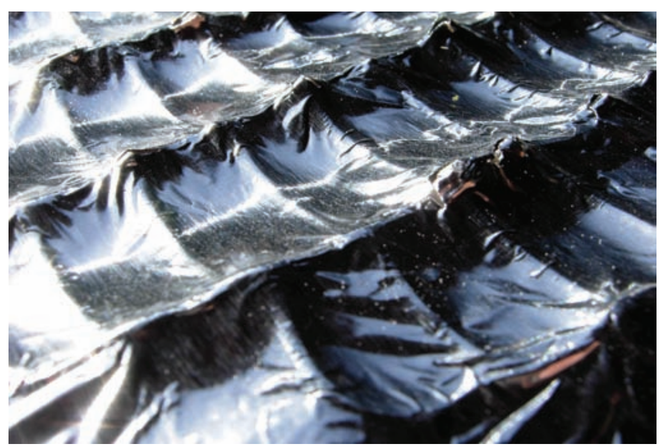
Light behavior was tested in a series of gypsum plaster textures. Laser-cut screens were placed on top of the plaster and then pulled off moments before cure. This process resulted in a continuous series of peaks and depressions. Depending on the incidence of sunlight, the individual texture cells were observed to ‘pool’ light by the ability of the directly-lit surfaces to scatter light back onto the shadowed surfaces. It was also observed that it was sometimes perceptually difficult to distinguish peak from valley. This phenomenon showed the potential for the behavior of light to affect material perception.

Also explored was the reflectivity of the plaster surface by adding glass micro-spheres. Each glass sphere behaves as a retro-reflector that sends light back in the direction of the source. When viewed from near the source, the glass reflection had the visual effect of flattening the surface.



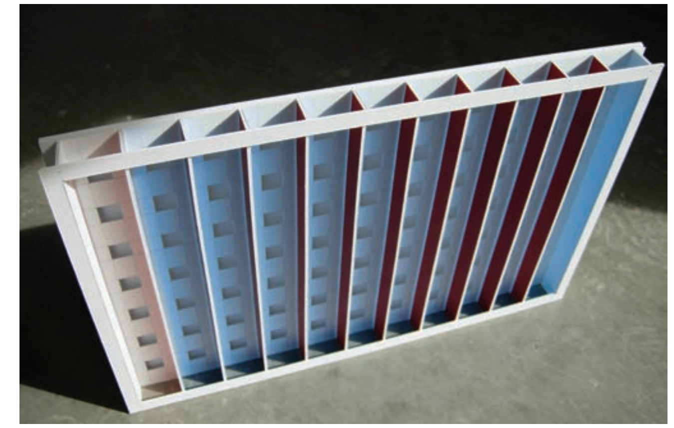
1. Wet-formed plaster texture models

2. Plaster texture detail

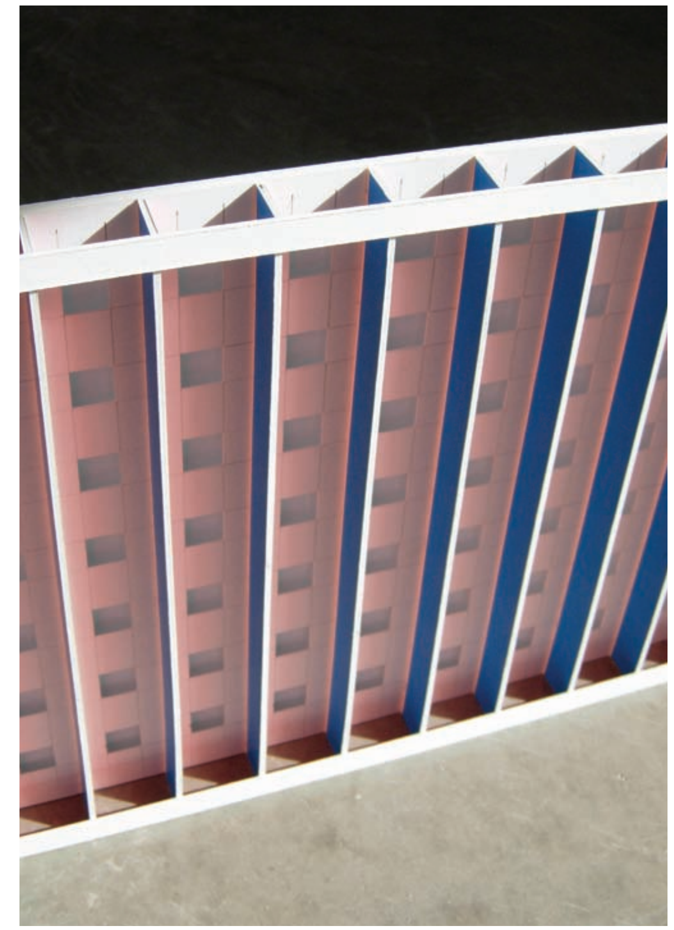


3. Foil-coated surface

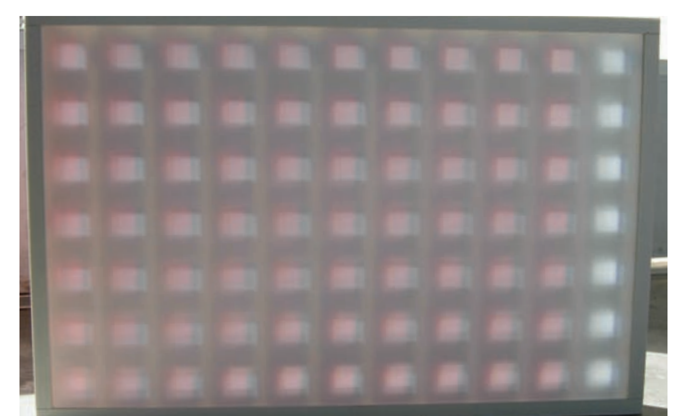
4,5. Glass bead surface



6. Light wall exterior: light incident on blue side of fins



7. Light wall exterior: light incident on red side of fins



8. Light wall interior

Layered Light Wall Study:

Exterior vertical louvres reflect different colors of light as the sun changes position. The colored light then passes through a matrix of perforations that create a uniform field, disguising the vertical nature of the outer fins. Finally, an inner layer of translucent screen receives light from the holes and diffuses it to the interior space.

The abstracted light effect produced by this model became more provocative than the blunt methods used to create it. A study of this light quality triggered subsequent motivations to make an enclosure that performed in a similar fashion - but without using applied color or translucent material.

Light Observation Box:

Light Tight

Subtle nuance in the behavior of light is drowned out by over abundance of daylight. Building an inhabitable dark box provided a way to begin experimenting with natural light in a more controlled manner. Measuring 5'-8" cubic, this size allowed for direct observation from the inside space. Wood frame assemblies hold interchangeable wall panels to perform a series of light experiments. (Figures 1-4)

Light leaking

None of the many attempts to achieve a completely light-tight construction succeeded. Somehow, light always found a way in. (Figure 5) However, further study of these light 'leaks' revealed an intriguing quality of the resultant light. Since the leaks always occurred within very small gaps at the intersections of materials, the penetrating light was forced immediately onto a material surface. It was realized that this method of introducing glancing light had the advantage of revealing the textural qualities of the materials. In this case, normal cardboard was visually transformed into a material looking more like stone than fiber. (Figure 6,7)

Developing this kind of light, the box was reassembled using clear acrylic spacers at all wall panel connections. These provided a more consistent reveal for light's entrance. (Figures 8,9)

Camera Obscura

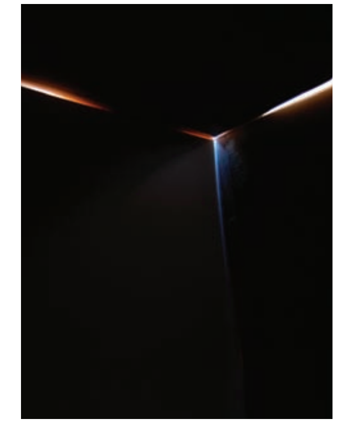
An 1/8" diameter 'pinhole' in one of the wall panels projected a large image of the outside environment into the cube. The effect of this one small puncture highlighted the potential darkness has to reveal subtle optical behaviors. (Figures 10,11)

1. Frame detail

2. Box fabrication

3. Transportable panels

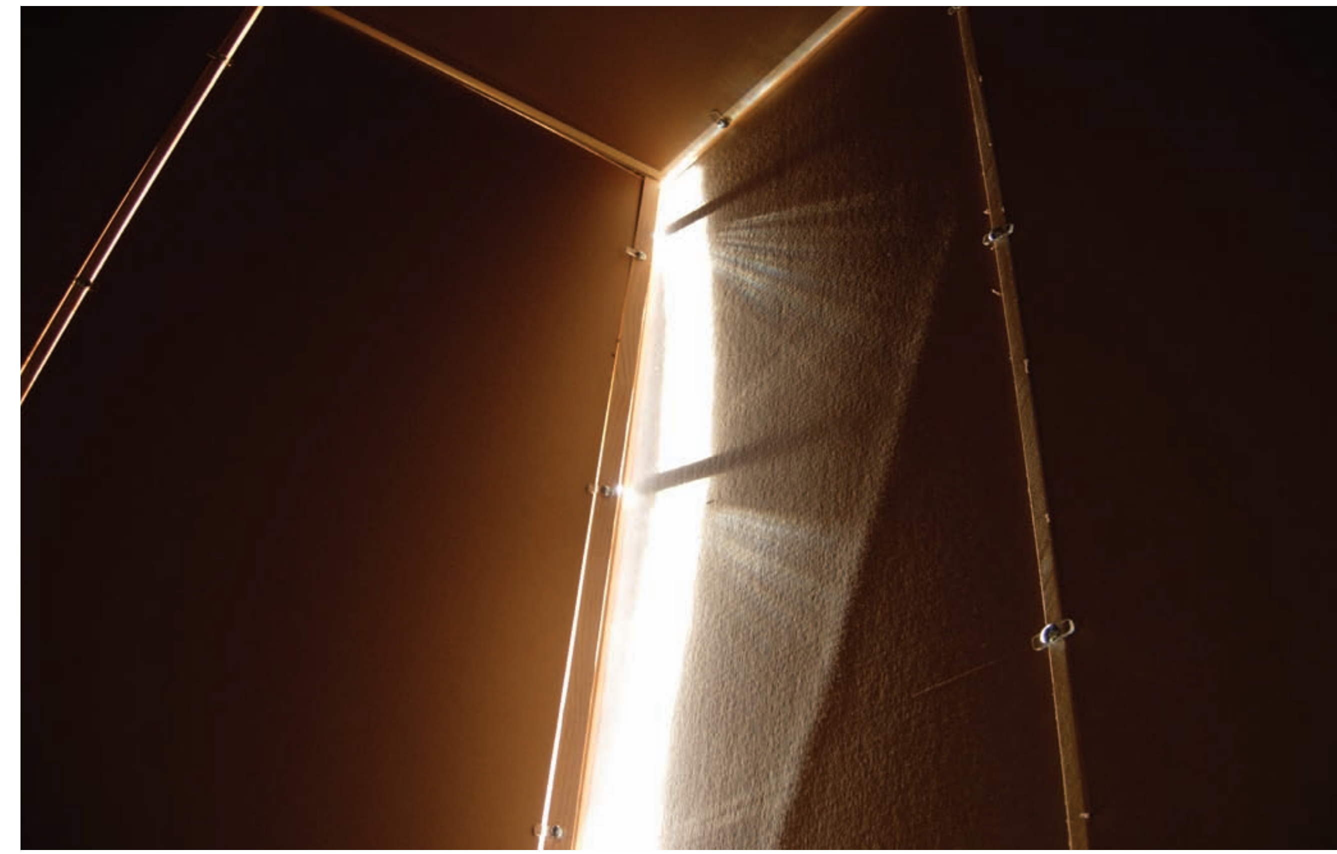
4. Park installation



5. Light gap

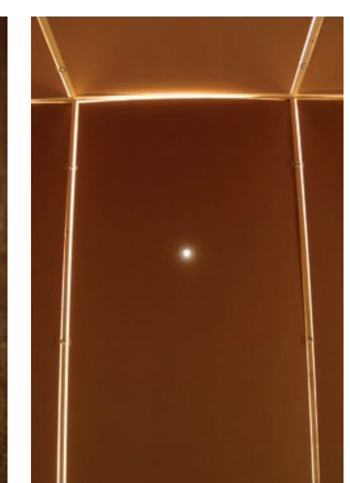
6. Cardboard texture

7. Cardboard texture detail



8. Leaking light

9. Wall panel capture detail



10. Camera obscura pinhole

11. Camera obscura projected image

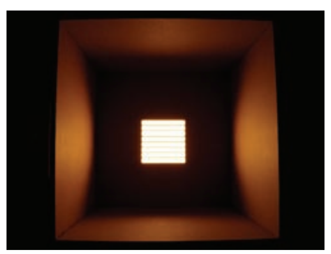
Investigation: Light + Aperture

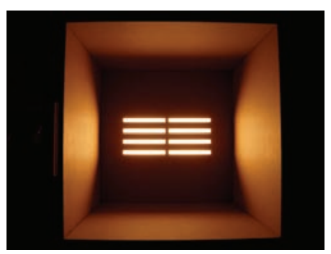
This study measured the changing light intensity inside a space relative to the configuration of light apertures.

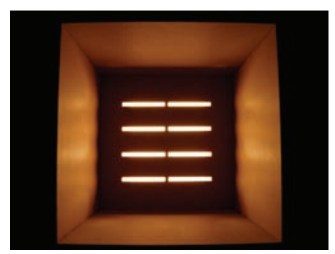
The initial motivation was inspired by the observations of James Turrell that light in a space can reach a quality of ‘solidification’. The idea was to see if it would be possible to find this light resonance phenomena by studying the variables that contribute to the total light environment and hoping to find a measurable moment when the amount of light inside the test space did not obey the predicted values for light intensity. Four factors were identified that could potentially contribute to this effect:

1. aperture
2. volume of best fit
3. texture - large
4. texture - micro

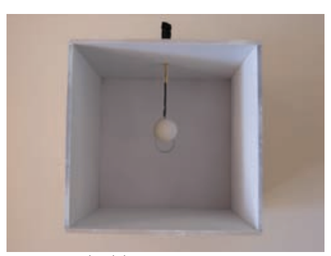
This study focused on the first factor, aperture. The design of the experiment was to measure the light intensity inside a box of a fixed volume that entered through one of four aperture panels (Figures 1-4). As a control, each wall panel had eight identical apertures to make the open area consistent. The only variable among the panels was isolated to the distribution of those eight apertures. The theory was that perhaps for a given volume of space there is a particularly efficient configuration of apertures that would produce more light intensity than others. The prediction was that of the four panels, (ranging from center-concentrated to perimeter-dispersed) the one with the apertures at the perimeter would produce more light inside the box because it would allow the adjacent walls inside the space immediate access to the light and thus more light would be internally reflected.


1. Aperture 1

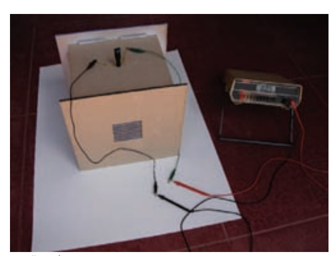

2. Aperture 2

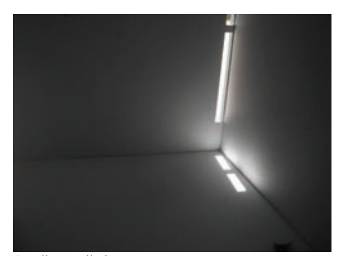

3. Aperture 3


4. Aperture 4

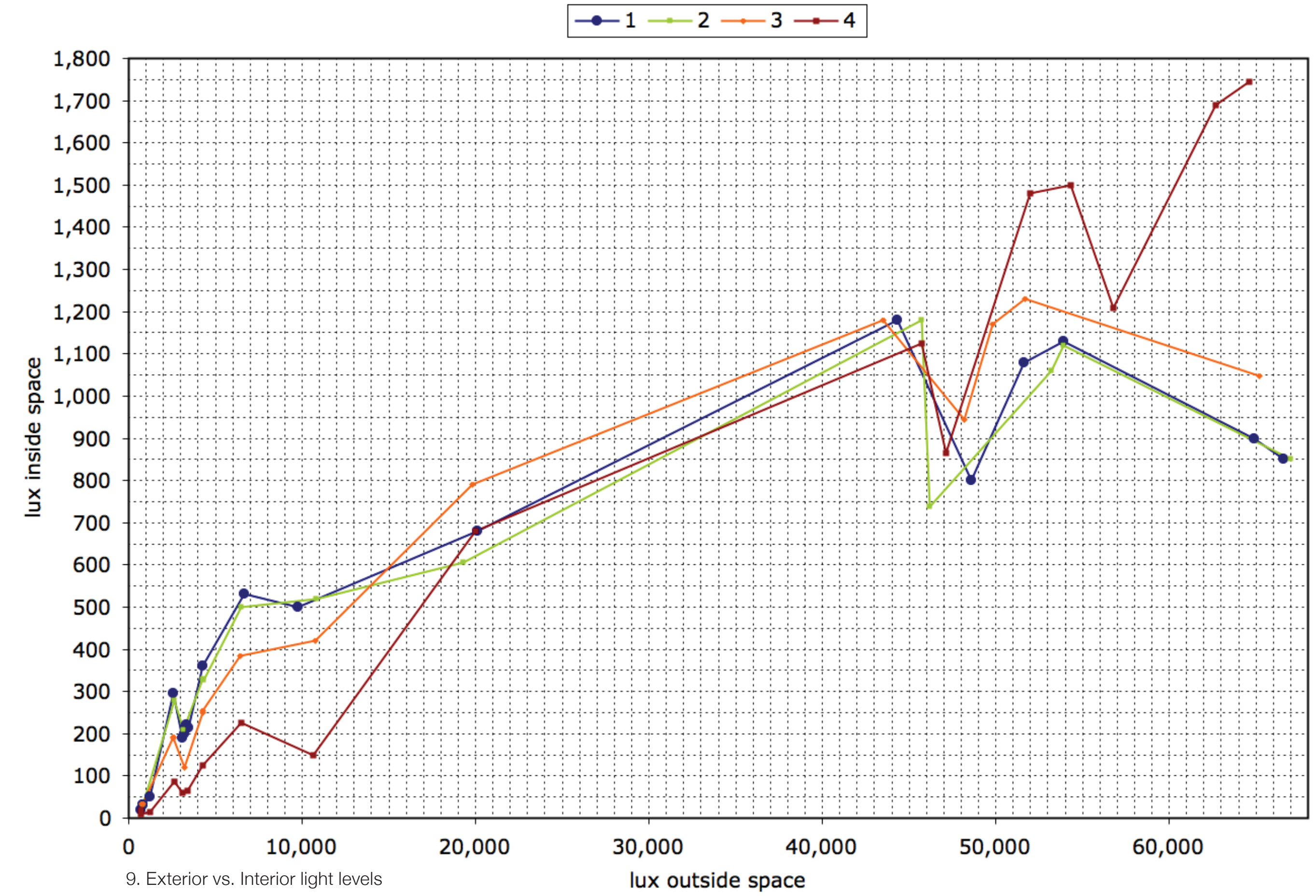

5. sensor inside space


6. calibration


7. final set up


8. direct light

Professor Dr. Bickel helped to make a custom light sensor inside of a diffuse sphere (ping pong ball) that could be suspended in the center of the light box to approximate the head height of a person inside such a volume (Figure 5). Because the sensor measured resistance only, it was necessary to calibrate the data with true light intensity measurements using a trusted light meter (Figure 6). With this accomplished, resistance data could be translated into lux.

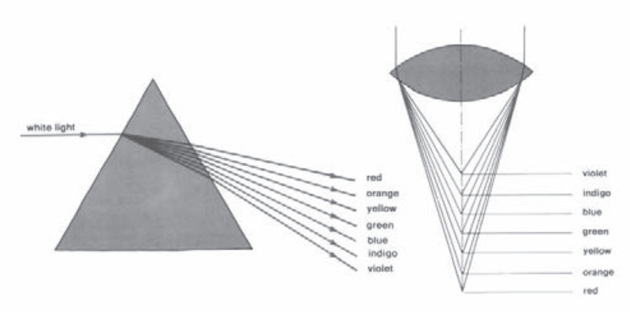


9. Exterior vs. Interior light levels

After laser-cutting the aperture panels, data could be collected. Measurements were taken in a variety of natural light conditions ranging from low indirect light from the sky to bright direct light from the sun. The final comprehensive graph (Figure 9) was intriguing. From 0 to 45,000 lux, the general trend was that panel 1 by and large produced the most light inside the volume. This contradicts the original prediction. However, beyond 45,000 lux, there was a near reversal in the trend with the panel 4 producing more light. The presence of direct light in the light box (Figure 8) at these high intensities could explain this phenomena. More data would need to be collected to determine if panel 1 is most efficient in indirect lighting conditions and panel 4 is most efficient in direct light.

Cone of Vision
Glass Lenses and Conical Columns

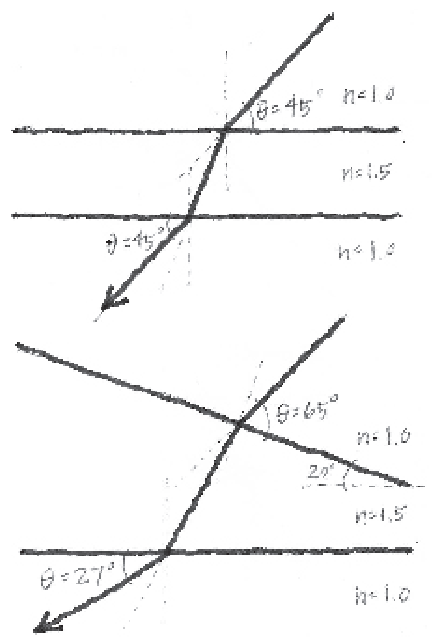
This study examined a direct method for merging natural light and structure based on the property of light refraction. A ring of glass, with properties similar to a fresnel lens, focuses light (Figure 4), suggesting the form for a column that follows the light's conical geometry. When sunlight is overhead, the column surface that would otherwise be in shadow is uniformly illuminated by direct light focused from the glass lens. This kind of interaction is an example of light-based architecture designed in concert with natural phenomena.



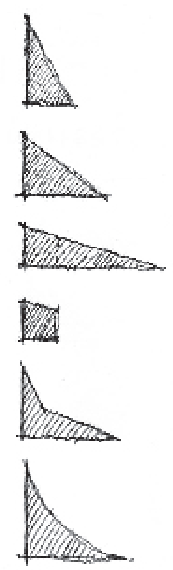
1. Prismatic and lens refraction.

Method

Refraction: a simple diagram (Figure 1), but also amazing to bend light by changing its speed. Consider refracted light that passes through a convex lens; the convergence of rays pass through the glass and take the form of a cone. This paper takes this fact and imagines the cone as a suggestive architectural column where the shape of the column is determined by the empirically demonstrated path of light. A logic is created that couples light and architectural form where changing the geometry of one forces the other to respond. A process of refining and checking outcomes emerges where the formal result can be tuned based on other constraints such as structural force distribution. Before being able to empirically test the light path in order to know the precise form of the column, a glass lens was fabricated.



2. Application of Snell's Law: n1(sine)1 = n2(sine)2.

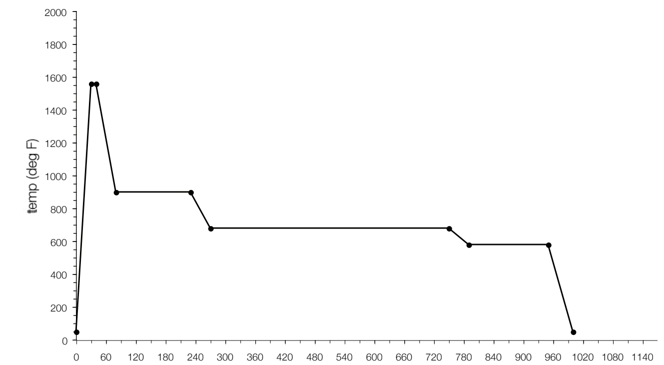

3. Possible lens sections.

Lens Geometry

For efficiency, this study is most interested in the the surface geometry of our cone-like shape. Thus, there is no use for the center of the glass lens - only the outer ring (Figure 4). (The resulting lens becomes something similar to a Fresnel lens which flattens the geometry of a solid lens by breaking it up into a series of smaller sections.) The main characteristic of the lens is its focal length. This determines the overall height of the cone element. Within the focal length, there are many options for shape geometry that affect the form of the cone. A curving slope (like a true convex lens) will have a different column form and light quality than a straight slope. The limiting factor of the lens geometry is determined by Snell's Law (Figure 2); at certain slopes and at specific incident angles, total internal reflection will occur where no light will pass through the bottom of the lens.


4. Fresnel lens behavior of prism torus.

For the purposes of this experiment, the elements were scaled down to a manageable model-size. A 12" diameter lens was fabricated with a simple sloping section having a focal distance of approximately 10". At this small scale, it was feasible to make this solid lens. However, enlarging this experiment to the scale of a room would likely require making a custom Fresnel lens film that could be integrated into a typical insulated glass unit for fabrication.



5. Glass annealing schedule.


6. MDF CNC-formed.

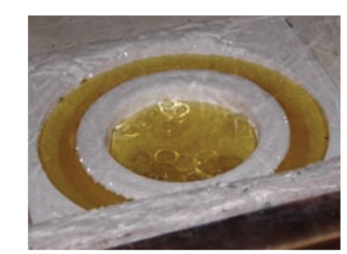

7. Plaster mold.

Lens Making Process

The lens making process began with a computer model of the 3D geometry. The digital file was then input into a CNC router that shaped a MDF block into the positive shape. Once the MDF was completely sealed with polyurethane, a plaster (50% Hydro Cal, 50% Silica Flour) waste-mold designed to withstand the high temperature of the glass oven was poured into the shape. This plaster will disintegrate with water after the baking, thus allowing the easy removal of the glass. After the plaster dried, glass frit was filled into the negative form and the piece was ready for heat.


8. Glass frit prior to heating.

The oven temperature was programmed (Figure 5) to rise rapidly to the melting point of glass and then to slowly cool down until the glass can be removed. The controlled cooling (annealing) is a crucial step which allows the glass resolve internal stresses. Once the oven was sufficiently cool, the glass was pulled out and washed to remove any remaining plaster. Finally, the glass required polishing to remove a cloudy texture that was left where it was in contact with the mold.


9. Molten glass during annealing process.


10. The waste mold is pulled away from the glass.

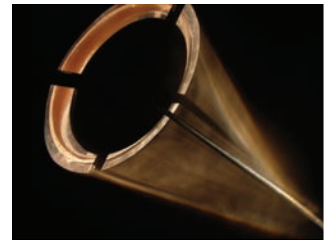
The final glass torus came out reasonably well. However, quite a few air bubbles were trapped in the glass. This could be a result of moisture in the plaster releasing during the heating process. Also, polishing the glass to a specular finish requires a lot of effort. It would be good to find a mold material that produces a smoother texture than the plaster formula used here.


11. Final glass lens.

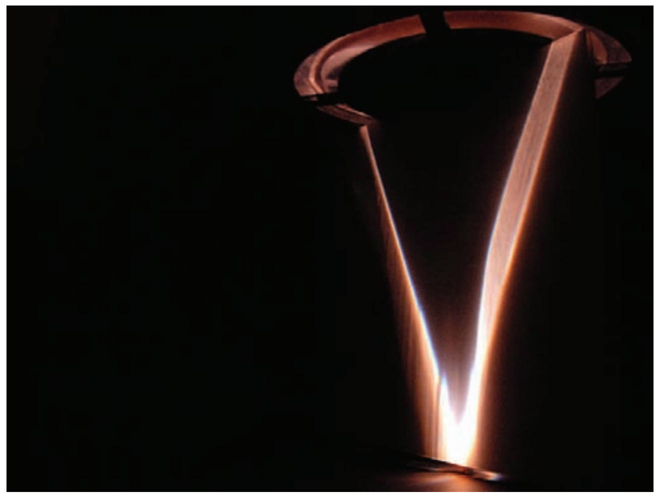
Light Cone

With the final cast glass lens, testing the refracted light's behavior was finally possible. A dark box was constructed to isolate the light coming in through the lens above. What was visible at first was only the spot of focused light on the ground plane. To make the path of light more visible, the space was filled with carbon dioxide vapor from dry ice. At last, the figure of the cone appeared. (Figures 12, 14, 15)

13. Cone interior with flooded light



14. Cone interior with light only coming from lens.



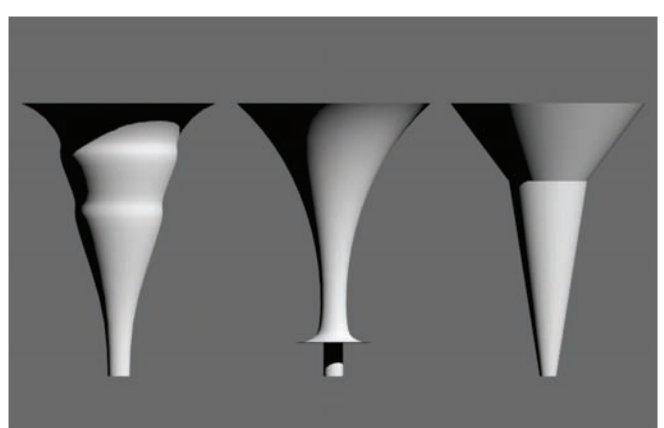
12. Cone interior with flooded light

15. Empirical demonstration of light path.

At this stage, the precise shape and color dispersion of the cone could be documented. Colors were faintly visible within the mist from prismatic refraction. A more solid light-reflecting material than vapor was necessary to display the color more vividly. In this setup, the asymmetrical geometry of the cone was pronounced and can be attributed to deformations in the lens.

A telling test was to place a white board in the middle of the cone. (Figure 12). This revealed the true sectional attributes of the shape. It was immediately obvious how thick the band of light entering the top was. The exposed aperture of the lens can be varied to make the cone 'thick' or 'thin'. The ample thickness shown here adds some welcome tolerance to material cone in the next stage.

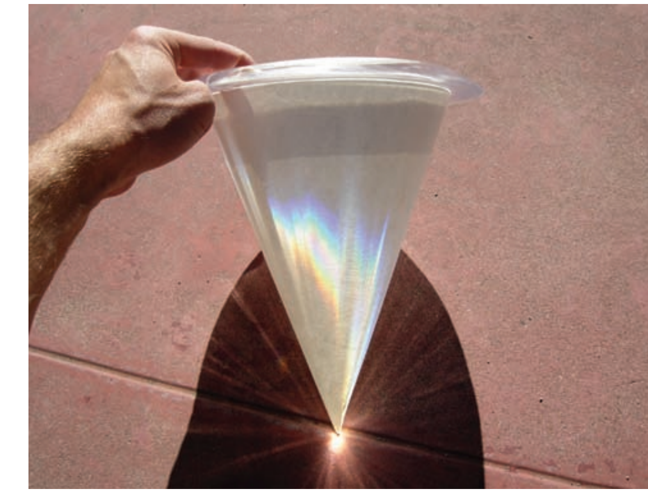
A critical look at the geometry of the cone will inform future lens geometries that are beyond the scope of this experiment. One might try to elongate the shape and vary the curvature in order to achieve a form that is more responsive to potential structural conditions. A variety of desired column shapes would then determine the lens geometries needed to make those happen. (Figure 16)



16. Theoretical conical geometries depending on lens geometry.

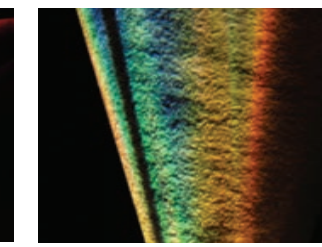
Material Cone

The introduction of a material cone into the detail affects the kind of light we see along the convergence path. The material cone captures only a sectional instance of the light. Even minor variations in the geometry of the cone produced significantly different results. Different wavelengths of light (Figures 18, 19) were made visible depending on the location of the material surface there to expose it. When placed under the sun using white paper for the cone, some very interesting prismatic effects occurred (Figure 20). The revealing of the textural quality of the paper is striking. This condition of light delicately grazing a material surface is a rare moment in architecture and often reveals a new dimension to the material. In this project, the material cone is intentionally designed to receive light in this way and thus requires a new level of attention to textural and chromatic qualities that future iterations are intended to address.



17. Paper cone outdoors. (note the focal length)

18. Color on flat plane placed in light path.

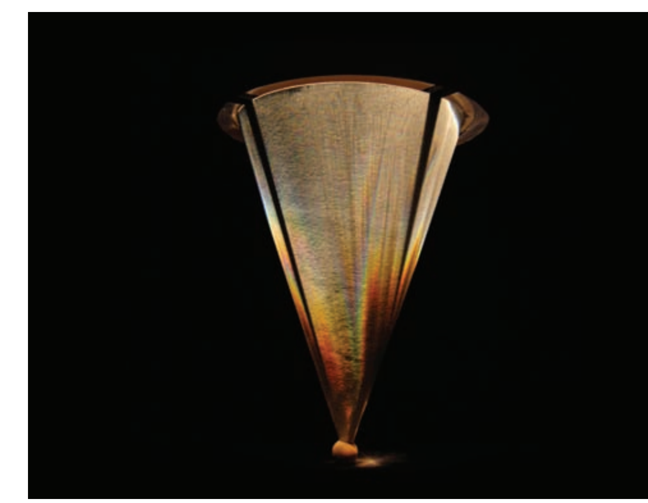


19. Revealing of paper cone texture.

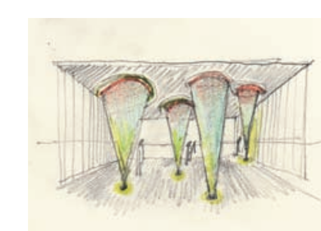
Architecture

Beyond simply experimenting with the physics of light, this project suggested the potential for architecture to exhibit a sensitivity to light and time. In future studies it will be necessary to consider how the lens will orient to the sun at a particular time of day or day of year - and then to consider what effect is desired for other times of day. The fact that the duration of this unique light quality is limited also suggests the potential to tell time. It is possible that in a space with multiple columns, each cone could be designed to illuminate at different times of day, forming a spatial light clock. (Figure 21)

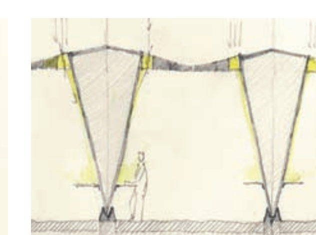
It should also be noted that in order to heighten the effects I am working with, a relatively low ambient light level is required. It would be hard to imagine a space with one of these installations offering enough light quantities for work tasks. Instead, this idea lends itself to uses where low light levels are preferred, i.e. relaxation spaces, religious spaces, etc.



20. Paper cone from interior space.



21. Multiple column space.



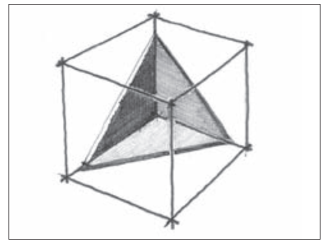
22. Potential scale/application.

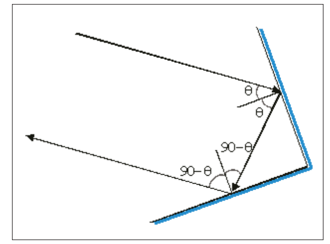
Light Matter Interaction
Variations on the Cube Corner

Electromagnetic energy from the sun speeds, pulses, and oscillates toward the earth. Just before impact, it asks its imminent material mate, 'how will you direct and organize me?' This study explores a method for answering that question by organizing light using optical principles inspired by geometry of the cube corner.

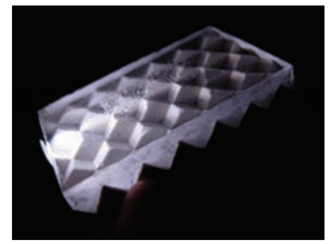
Light is an unbiased medium made evident to our perception by the bias of material it is allowed to interact with. The natural material world around us effortlessly creates light reactions visible to us as color, pattern, reflections, transparency, etc. Man-made materials, however, require thought and effort to build in a light-organizing bias

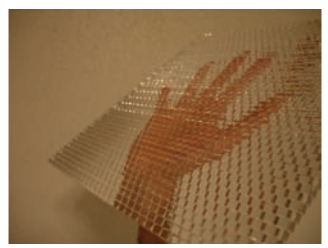
A traditional cube corner (Figure 1) made with an even, specular surface is an efficient retroreflector which reflects rays of light back along their incident direction (Figure 2). However, even in non-specular conditions this structural geometry produces unique effects which are a result of light bouncing evenly among the three surfaces. In daylight, a scattering cube corner can seem to 'glow' (Figures 9) because of this interaction. The following process of experimentation seeks to find an ideal material and scale for the cube corner geometry as it organizes incoming light.

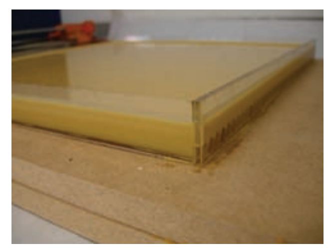

1. cube corner: three mutually perpendicular, intersecting flat surfaces

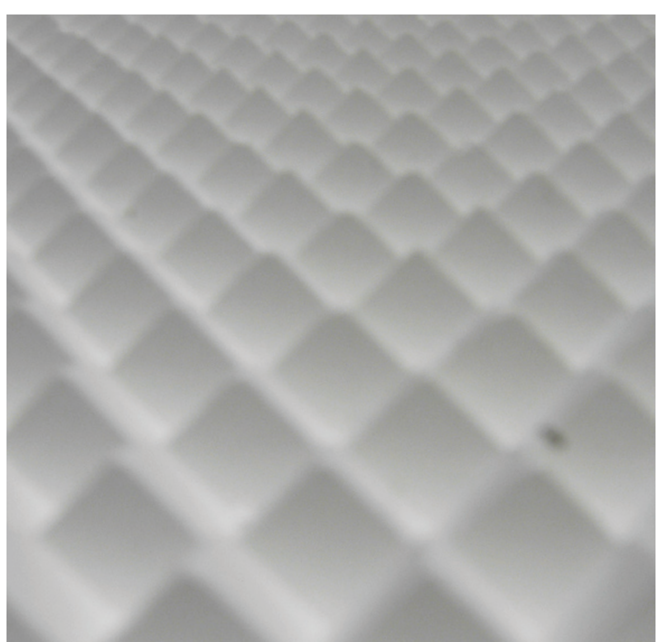

2. light path diagram

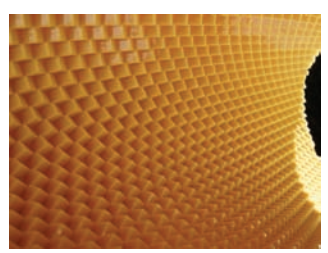

3. initial texture model

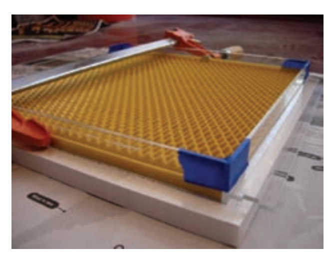

4. internal light through cast resin

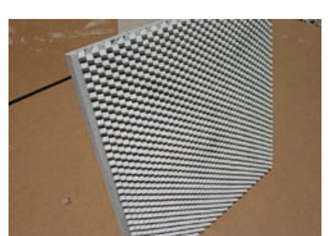

5. laser-cut acrylic strips bonded to form sheet

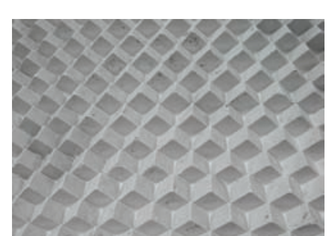

6. liquid rubber over acrylic sheet


9. cube corner glow (plaster)


7. rubber mold


8. rubber mold ready for plaster


10. plaster cast (w/ graphite)

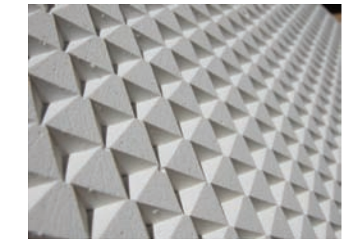

11. plaster cast detail

Plaster Casting

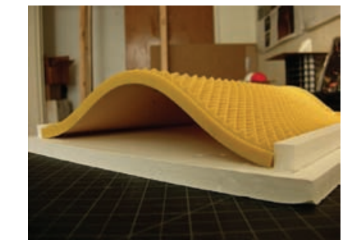
To begin, it was necessary to fabricate a cube corner texture. In the first attempt, a handful of sawn plastic cubes were glued together and used as a form to make a small plaster cast (Figure 3). Despite the crude methodology, the end product held some promise in the way the texture changed its nature drastically based on the incident light and location of the viewer. Resin was then poured into this sample and studied in various lighting conditions. With light entering from the side, the layer of resin seemed to encapsulate the light (Figure 4).

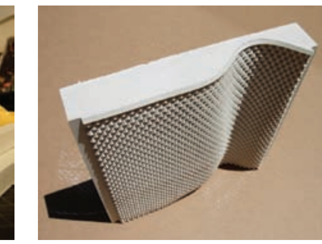
In order to begin more precise studies of larger samples a new method of fabrication became necessary. By laser-cutting a series of 1/4" acrylic strips and bonding them together a 12" sq. field of 1/4" sq. cube corners (Figure 5) was fabricated. From this, a rubber negative (Figures 6-8) was poured which was then used to make a number of positives casts out of other materials such as plaster (Figures 9-11) and polyester resin (Figures 20,21).

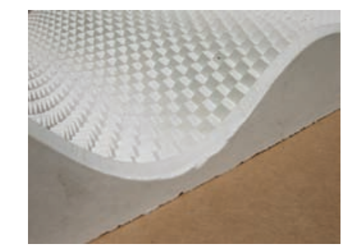
The first series of castings were white plaster. This material scatters light very well and clearly produced concentrated pooling of light within the texture (Figure 9). A plaster mix with added graphite was also tested to see how the texture would respond to more absorptive colors (Figures 10,11). The end result, however, was still quite light and the search remains for a way to make medium and deep black tiles. It may be that plaster is not the appropriate material for this and that another process using a thinner black material, like paper making, would be more suitable.

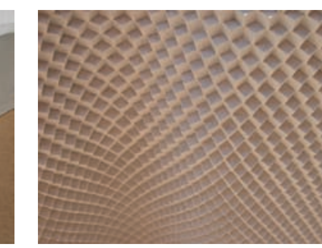

12. plaster cast sanded to isolate triangular facets

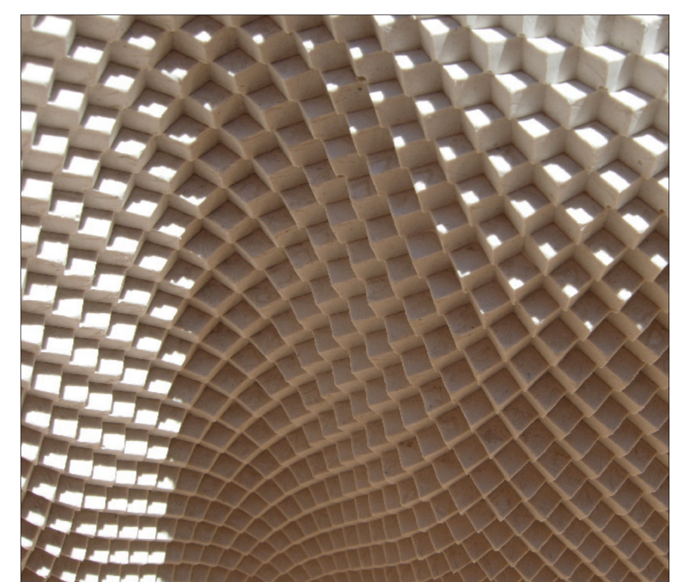

13. inherent triangular geometry

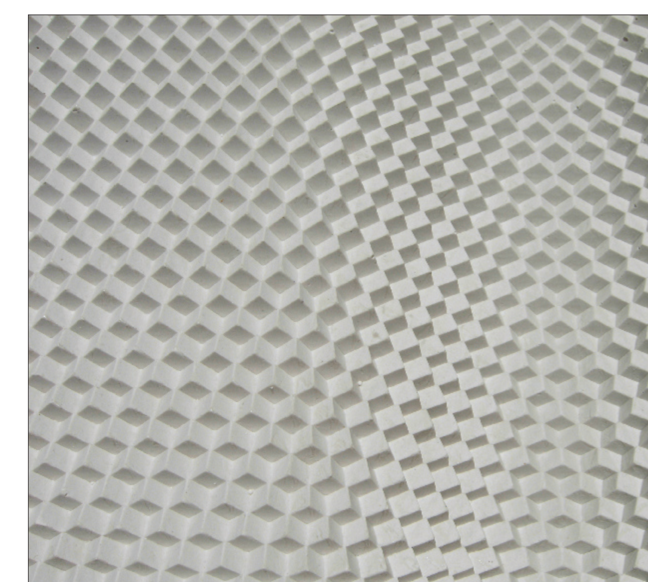

14. preparation for curved surface casting


15. curved plaster cast


16. apparent concentration of light in the valley


17. curved geometry


18. shade / shadow on curved surface


19. changing orientation to light

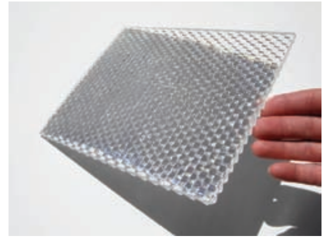
A final manipulation of the tiles was to sand the surface texture down half way (Figures 12,13). This process revealed an underlying triangular geometry that isolates each individual cell within a matrix. Imagining being able to give each triangle a pocket would become the inspiration for folded paper models and a larger casting later on.

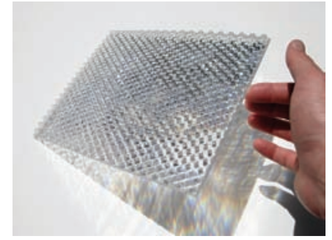
After working with flat tiles, a curved surface was cast (Figures 15-19) by confining the rubber form to give a natural curvature (Figure 14). In the final curved tile, there was an immediate recognition of how the changing orientation of the small texture produces very different light effects. With the flat tiles, either the viewer or the sun needed to move in order to see what is always evident in the curved tile. It is also interesting to speculate how the precise curvature of the parabola in future models might create larger-scale light concentrations.

Resin Cast

In contrast to the plaster tiles which were limited to scattering light, a tile of polyester resin was cast from the same rubber mold. The resin retained the smoothness of the rubber in a way the plaster could not and this allowed for observation of how the light behaved in near specular conditions. One interesting phenomenon was how each resin cube corner cell reflected or transmitted light depending on the orientation. With the flat side of the tile toward the light source, the entire tile reflected all light and cast a shadow as if it were opaque (Figure 20). With the textured surface toward the light, the tile acted as an array of prisms (Figure 21).

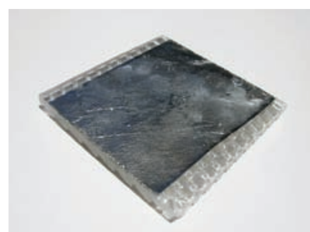
To see how this texture acted as a true retroreflector, two smalls samples (Figures 24,25) were aluminized with the help of Dr. Bickel and the Physics Laboratory. After pumping out the air in the glass chamber (Figure 22) to create a vacuum, heating filaments melted aluminum wire which had been looped over the filament. The liquid aluminum then turned into a gas and coated the sample. The most interesting sample was the one we coated on the textured side. Though not specular enough to produce images, the surface became 90% reflective and created brilliant spots of light (Figure 22).


20. resin cast
flat side up blocks light

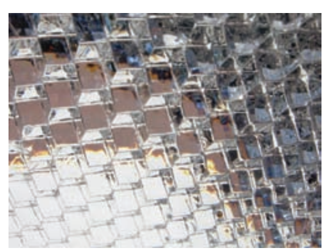

21. resin cast
flat side down admits light

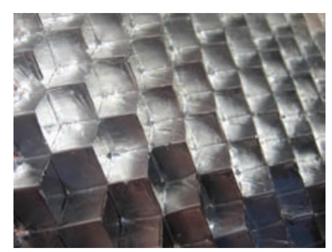

22. vacuum chamber for aluminzing resin samples


23. heating filiment with melted aluminum globules during aluminization


24. aluminized resin - flat side


25. aluminized resin - texture side


26. texture: uncoated resin


27. texture: aluminized resin


28. larger scale paper model


29. folded paper geometry

Paper Geometry

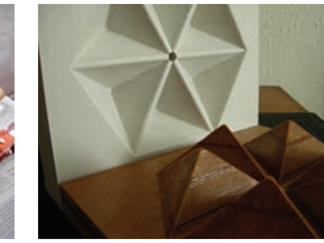
Increasing the scale of the tiles, a blanket of folded paper recreated the texture similar to the earlier sanded plaster model (Figures 12,13). This scale (2-1/2" sides) made the light-pooling phenomena easier to see and inspired an even larger texture for the final plaster model.

Light Transmitting Structural Tile

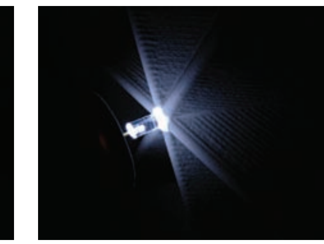
This larger scale model used a light conduit to distribute light incident to the back of the tile through the material and then back onto the inside surfaces - a hex cell formation of cube corners. Because the facets reflect light efficiently within each cell, only a minimal light intensity was needed to illuminate the entire area. The effect of this arrangement is that an otherwise opaque material takes on a sense of becoming translucent.

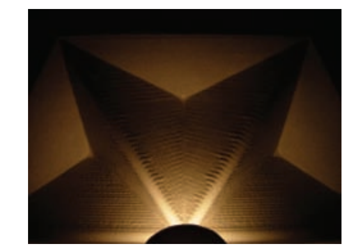
The attempt to cover multiple cells with one point of illumination (acrylic tube, 3/8" dia.) was for efficiency. An alternative method would be to direct light into each cell with a dedicated source. Factors such as the length of the the acrylic conduit and the thickness of the structural tile heavily influence the inner light quality. Further studies aim to experiment with tuning both ends of the light conduit to achieve maximum responsiveness to particular orientations of incident light. A field of these tiles could be linked together through compression to form a roof structure that acts as a light instrument constantly responding to the time of day.

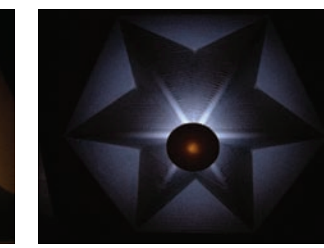

30. CNC-milled MDF negative ready for casting

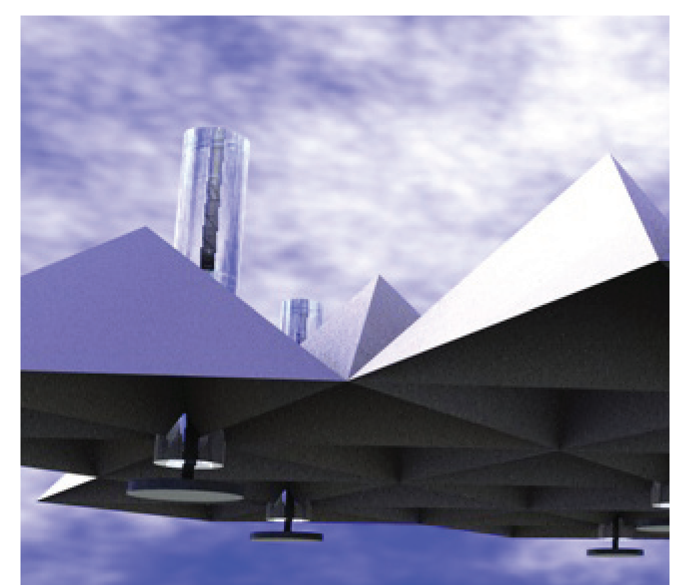

31. plaster cast pulled from form

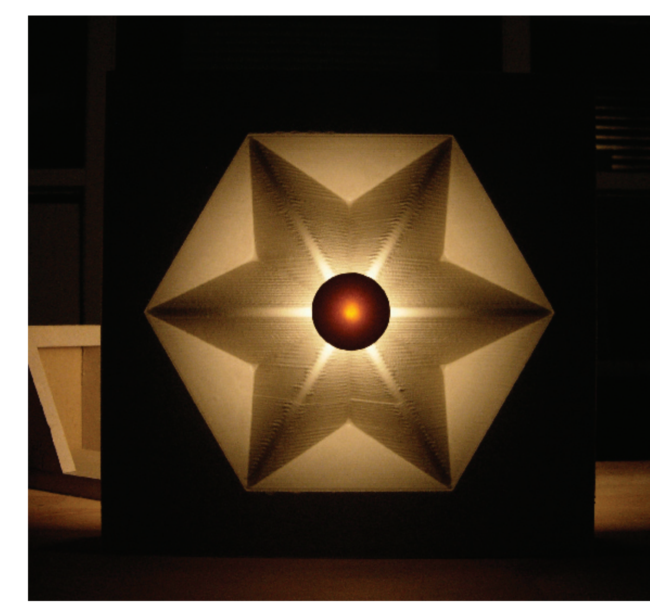

32. acrylic tube through center of module


33. acrylic tube with circular reflector


34. back-lit plaster (incandescent source)


35. back-lit plaster (blue LED source)


36. Computer model


36. reflected light fills cells

ideal light study

Light and Awareness

The study of light, particularly since the invention of the electric variety, has had a strong connection with production. For good reason; we need light to do most things. We need light to bath, cook, read, work, play, etc. A lot of effort has been put into finding the most appropriate light levels to facilitate productive efficiency. Organizations like the IESNA (Illuminating Engineering Society of North America) have published recommended light values for tasks ranging from grooming to ironing to casual reading in bed.

This thesis is set apart from the production-based tradition of light investigation. After initial, unbiased probes into various light phenomena trended toward the creation of spaces with very low light levels, it was clear this work was not setting out to make use of light for conventional tasks like reading or playing sports. Instead, what emerged was a desire to study the kind of light that is most conducive to the act of thinking.

While it is obviously possible to think in the dark (or with closed eyes) this thesis makes the argument that our mind is merged with our senses and that an environment which is tuned to widening these perceptual senses is also one which opens our mind to more creative thinking.

The first major study of this thesis investigates the proposed relationship between ambient light level and perceptual awareness.

Light Measurement

To test the relationship between perceptual response and ambient light levels, a method was needed for objectively recording light along a smooth gradient from bright to dark. The transitioning sky during twilight emerged as the ideal environment for doing this. The sky offers a uniform field of light which eliminates potentially distracting detail.

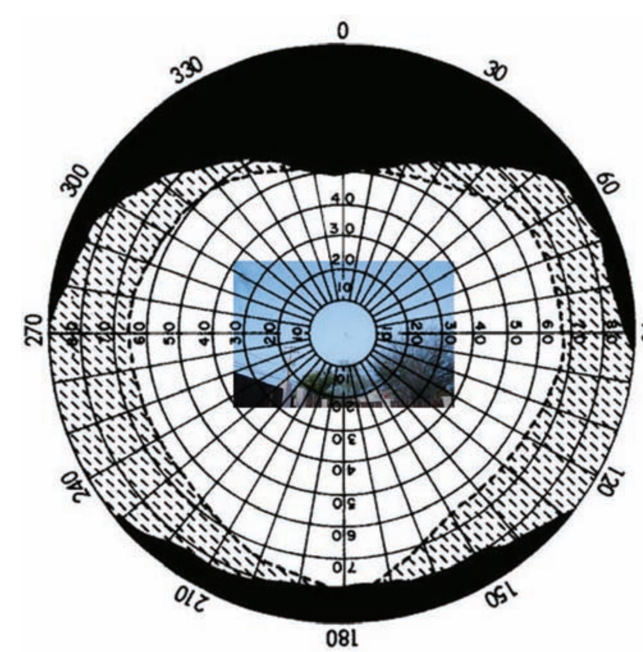
Light level recording is a complicated task. Until recently, without spending lots of money on sensitive luminance meters, it has been difficult to find an affordable, accurate device that is adjusted to the unique sensitivities of human vision. Traditionally, architects have used basic light photometers that measure the illuminance (total incident light falling on a given area, measured in units of lux) of an environment. These photometers have proven useful for particular studies but they do not account for human visual sensitivity and provide only a very generic record of light intensity because they receive light from such a wide angle (usually around 180 degrees).

Recently, however, it has become possible to affordably measure much more accurate light data using an average digital camera. This means that any picture taken with a calibrated digital camera can be interpreted by a software program to measure accurate luminance (visual power per unit area, measured in candelas/m^2) values for each pixel of the image. The advantage of this is that the record of the light is closely matched to the scene an observer is interested it.

In the case of this thesis, the scene was an observed area of the sky. Using the imaging software, a reliable average luminance value was calculated over a selected area of the image. This value was then associated with the perceptual observations taken at the same time during twilight.

1. Camera calibration photo series

2. Observation laboratory



3. Typical photo field of view (66 degrees) overlay with total visual field

Experimental Method

Photosphere, software written by Greg Ward of Anyhere Software, was used to measure luminance values. The first step of the process involved calibrating the user camera to the software. A series of 9 bracketed photographs (Figure 1) were taken of an interior scene with a large range of light values. These photographs were then merged in Photosphere to create a single HDR (High Dynamic Range) image that was stored as the calibration data.

With the calibration complete, luminance values could be measured from any HDR creation that was a compilation of at least three bracketed (one image underexposed, one accurately exposed, one overexposed) photographs of a scene.

Once this method was established, the light observation experiment began. For a series of nine twilight sessions spread throughout the spring, luminance images and perceptual observations were made every 5 minutes over the course of an hour. (Figure 2 shows one of the locations chosen for observing the eastern sky.)

Assuming a particular luminance level exists that has the biggest impact on widening the senses, a major focus of each session was to pin point a particular time and light level that had this effect. It turned out it was possible to discriminate among the light levels and, as written in the observation data that follows, this moment was recorded as ‘favorite light’.

February 17 2008, southern horizon, clear sky
f-stop: 10, zoom: , view degrees:34.1

time	cd/m²	quality
5:50	1170	
5:55	903	golden glow
6:00	717	
6:05	422	
6:10	312	
6:11		sunset
6:15	164	nice sky glow
6:20	59.1	getting hard to read, moon very visible
6:25	15.5	
6:30	5.24	favorite time, planets visible
6:35	1.60	
6:36		end civil twilight
6:40	.613	stars visible, very hard to read, colors difficult
6:45	.189	

February 18 2008, southern horizon, thin haze, some blue sky visible
f-stop: 10, zoom: , view degrees:40

time	cd/m²	quality
5:50	1440	
5:55	901	
6:00	645	
6:05	437	
6:10	166	
6:12		sunset
6:15	111	sunset colors at best, eastern sky glow, earth turns reddish
6:20	81.5	glowing sky colors
6:25	20.9	south sky glow, car headlights necessary, hard to read
6:30	6.78	favorite time, sky colors turn grey, shimmering quality
6:35	1.77	very hard to read
6:37		end civil twilight
6:40	.542	stars visible
6:45	.186	

February 19 2008, southern horizon, mostly clear sky, high clouds
f-stop: 10, zoom: 18mm, view degrees: 65.8

time	cd/m²	quality
5:50	874	
5:55	811	dark floaties from eye distracting, wispy clouds more visible
6:00	570	reading is very pleasant
6:05	355	sun still visible, high clouds appear much lower, flattened sky, blue deepens
6:10	214	eye floaties less visible,
6:13		sunset
6:15	108	nice soft light
6:20	62.7	car headlights necessary
6:25	25.1	sudden pink color on clouds, planets visible, sky deepens, red over blue
6:30	7.78	favorite light, earth too dark, sky just right
6:35	1.78	eye floaties totally gone, stars just visible, blue over red
6:38		end civil twilight
6:40	.451	

March 4, 2008, southern horizon, clear sky, no clouds
f-stop: 10, zoom: 18mm, view degrees: 65.8

time	cd/m²	quality
6:10	531	floaties very visible, no sunset colors yet
6:15	367	last light on landscape
6:20	227	sun just below mountains, calmer blue sky
6:24		sunset
6:25	111	some pink in eastern horizon
6:30	65.9	car headlights necessary, sky seems to have patches of blue and grey
6:35	25.6	floaties going away, hard to read
6:40	7.57	favorite light, active sky, no more pink colors in eastern sky, planets visible
6:45	2.08	landscape is black, very hard to read, stars visible, colors hard to distinguish
6:49		end civil twilight
6:50	.638	sky is dark

March 30 2008, eastern horizon, clear sky
f-stop: 10, zoom: 18mm, view degrees: 65.8

time	cd/m²	quality
6:20	757	squinting
6:25	618	blue and gray patterning at particular focal length dense white shooting stars (like the kind when i am dizzy) frenetic pattern some slow, some fast - but evenly distributed
6:30	416	nice smooth light, some floaties in focus, some out
6:35	314	landscape becomes very interesting and detailed when sky darkens and the two are close in contrast. (easy to jump from one to the other)
6:40	220	‘fireflies’ still visible, floaties present, horizon getting pinkish
6:43		sunset
6:45	89.2	horizon is layered (blue, pink, blue) floaties almost gone, nice light, sky looks very grey
6:50	41.2	very hard to see fireflies, floaties barely visible
6:55	13.8	is the sky flattening in this light? so even-looking
6:57	~8	favorite light
7:00	3.57	sky got much more blue/purple, difficult to read, sky is too dark then sky goes back to grey
7:05	1.05	too dark
7:07		end civil twilight

April 20 2008, eastern horizon, clear sky
f-stop: 10, zoom: 18mm, view degrees: 65.8

time	cd/m²	quality
6:40	518	greyish sky
6:45	384	sun still visible in landscape. great vision for sports.
6:50	257	fireflies firing
6:55	157	floaties still visible, fireflies, more color in sky, good light, car headlights
6:57		sunset
7:05	34.4	good balance of sky/land
7:10	10.9	shimmering sky. fireflies not visible. totally even, soft light. like under water. even, but not still. landscape too dark
7:12	7.96	favorite light
7:15	3.55	sky color back to grey. too dark. stars visible. hard to read or distinguish color
7:20	.9	too dark
7:23		end civil twilight

April 23, 2008, eastern horizon, clear sky, no clouds
f-stop: 10, zoom: 18mm, view degrees: 65.8

time	cd/m²	quality
6:40	550	sun in trees, heavy squinting
6:45	443	‘stars’ easy to see, firing all over, blue sky
6:50	284	last direct sunlight on trees, ‘stars’ easier to see with fast eye movements
6:55	209	floaters less visible
6:59		sunset
7:00	113	sky loses color, horizon gains (chalky salmon) gnats about 1m away interfere with vision!
7:05	57.2	nice light
7:10	20.9	horizon dark, car headlights
7:15	6.24	‘stars’ have gone away
7:16	5.27	favorite light, nice match with landscape
7:20	1.41	hard to read, real stars visible
7:25	.454	hard to see color
7:25		end civil twilight

May 3, 2008, eastern horizon, mostly clear sky, wispy clouds
f-stop: 10, zoom: 18mm, view degrees: 65.8

time	cd/m²	quality
6:45	629	closed eyes: starts black and grow brilliant red
6:50	651	landscape dull looking, sky very bright, making eyes water, fireflies very visible
6:55	492	fireflies activated by quick eye movements, green leaves colorless, direct sunlight still visible
7:00	306	sun just gone, landscape picks up nice glow
7:05	226	gnats, floaties, fireflies, nice balance between sky and land, good for sports
7:06		sunset
7:10	85.2	nice even sky, fireflies hard to see
7:15	29.7	floaties muted, no fireflies, sky loses color
7:20	12.6	landscape too dark, getting hard to read
7:25	3.92	favorite light, high clouds distracting, reading strained
7:30	.952	too dark, planets visible
7:33		end civil twilight
7:35	.240	stars visible

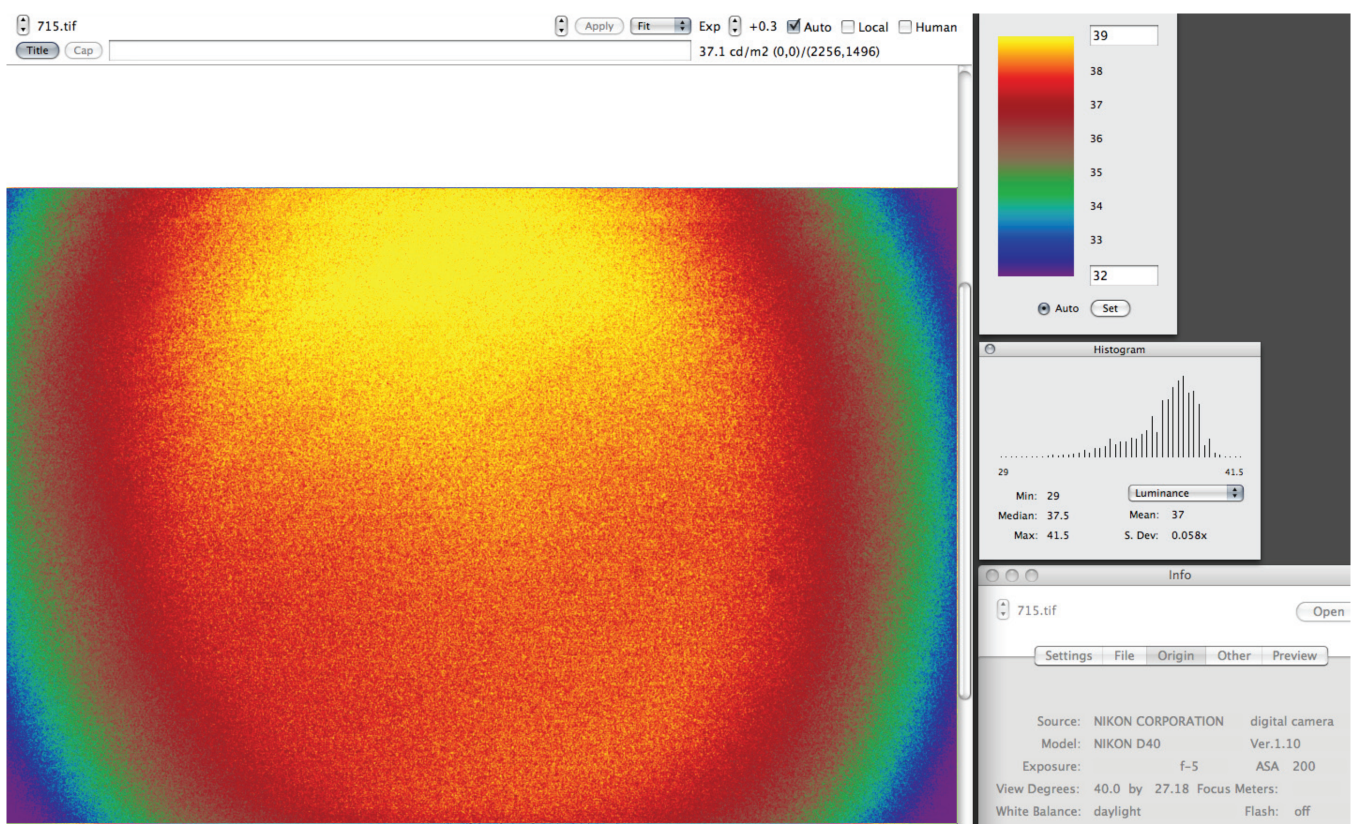
May 9, 2008, zenith, clear sky, no clouds
f-stop: 5, zoom: , view degrees: 40

time	cd/m²	quality
6:45	387	heavy squinting
6:50	328	‘stars’ easy to see
6:55	260	floaties more visible after 30 seconds
7:00	185	nice blue color, much deeper than horizon
7:05	118	fireflies, floaties
7:11		sunset
7:10	71.5	nice light, ‘stars’ seem much faster
7:15	37.1	landscape nicely balanced with sky
7:20	15.7	calmness, hearing sensitivity increases
7:25	5.34	floaties very hard to see
7:26	4.66	favorite light, immersing, calm awareness
7:30	.1.97	sports difficult, hard to read
7:35	.536	too dark, sky lacks interest
7:37		end civil twilight
7:40	.196	blue color much more brilliant, rod sensitivity?

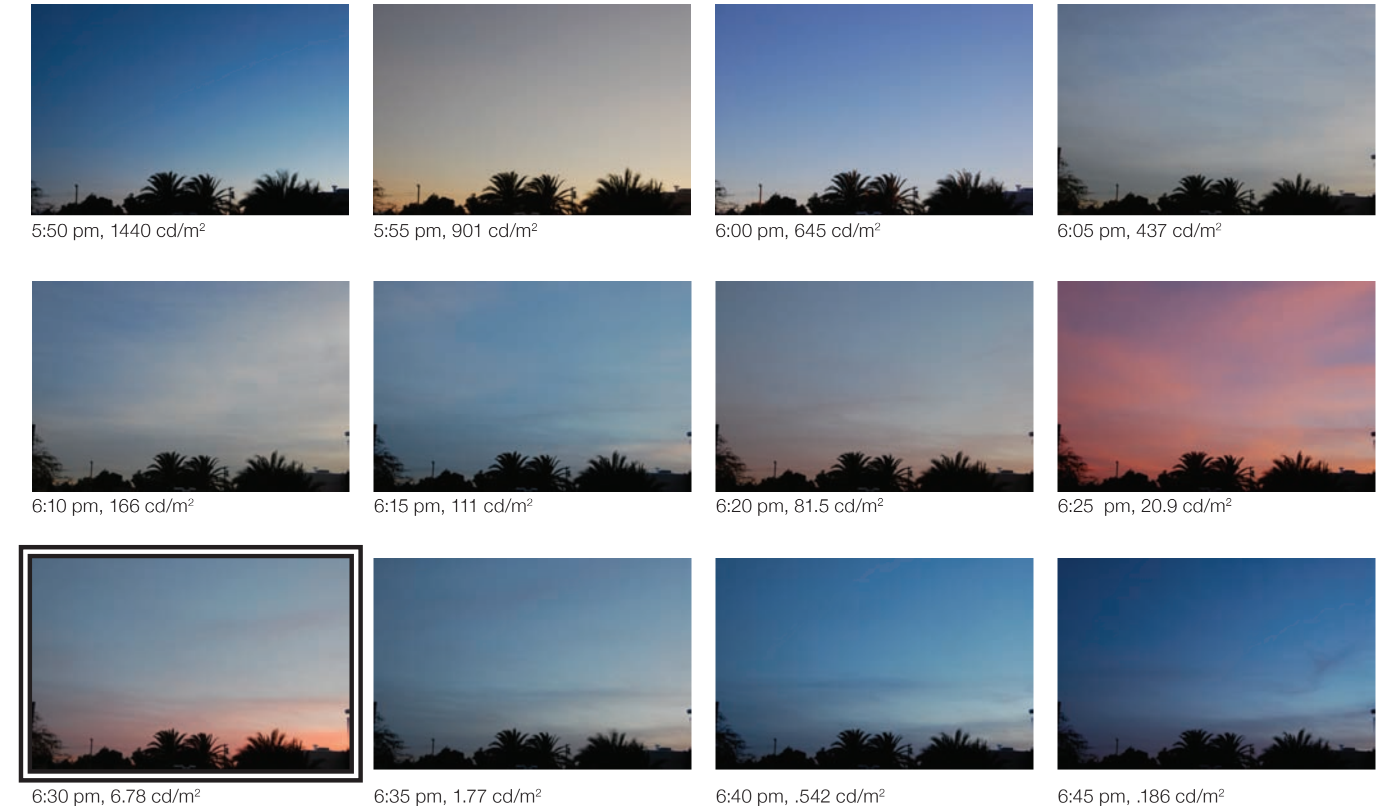
Typical Image Luminance Analysis

Figure 4 shows a typical example of an HDR image displayed in Photosphere as a false color luminance map. This particular image is from the overhead sky at 7:35 on May 9th (West is up). Even though the brightness of the sky was relatively consistent across the image to the naked eye, the luminance map clearly shows more brightness, as it should, toward the western-setting sun. Because the range of luminance values is so narrow (32-39 cd/m^2), the luminance value recorded for this time is an average of the entire image.

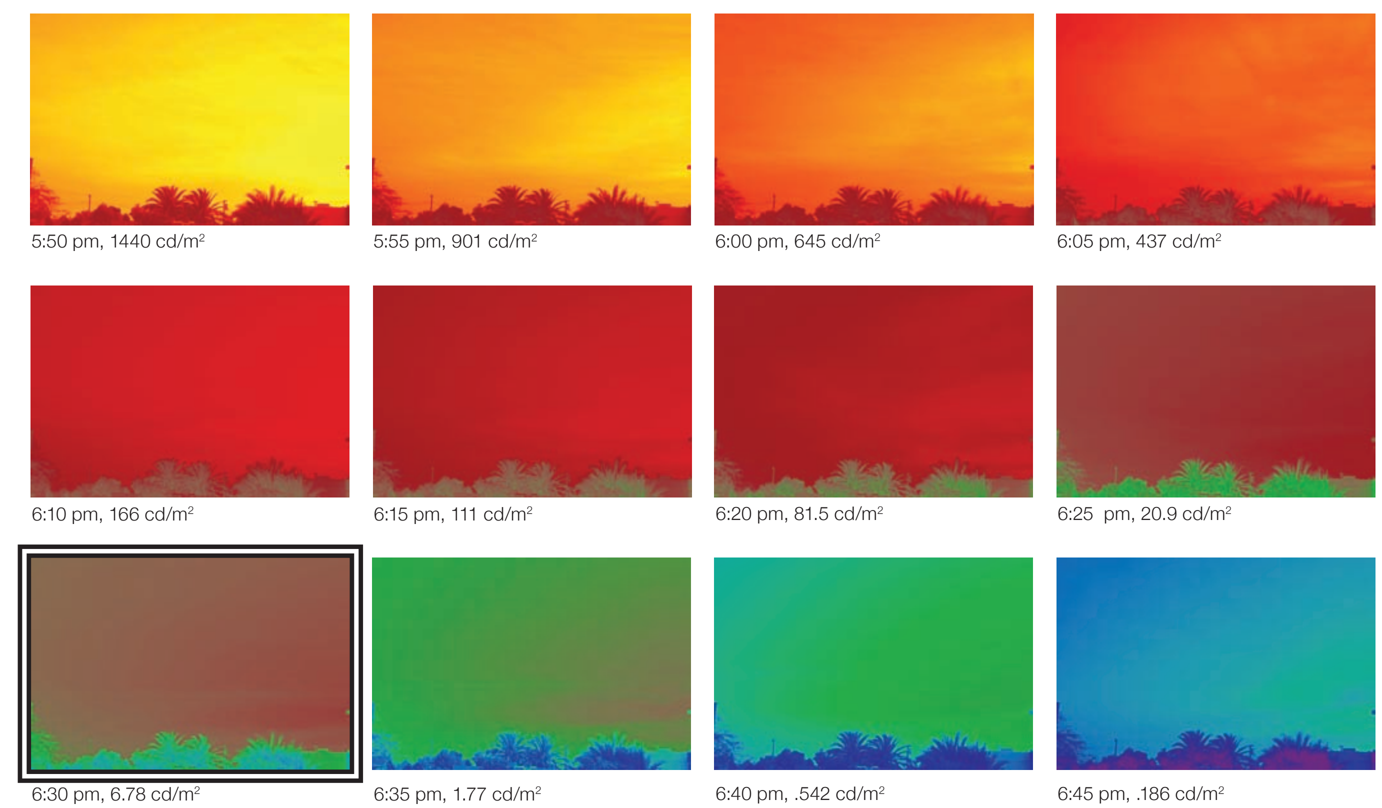
Proceeding this way, average luminance values corresponding to observed areas of sky were recorded for each image. Figure 6 shows another way to visualize luminance values across an entire twilight session by setting a custom range for the false color map based on the brightest values from the early photo and darkest values from the latest photo.



4. Photosphere false color luminance map of zenithal sky at twilight



5. HDR twilight image sequence



6. False color HDR twilight image sequence

"What causes this sense of infinite calm emanating from these [twilight] light phenomena? Compare them with the rainbow, arousing feelings of cheerfulness and joy."

Marcel Minnaert, Light and Color in the Outdoors

Perceptual Findings

The twilight observation sessions provided a good deal of insight into how light levels affect perception. After the first few evenings a series of indicators emerged which became useful to record and track within and between evenings.

Floaters

One of the first, readily perceived phenomena was the visual presence of 'floaters'. These are microscopic fibers within the vitreous that have gelled together. These clumps of debris float around within the vitreous cavity, and they can cast tiny shadows on the retina. The degree of distraction these floaters cause varies widely among subjects but what was interesting to note was how they disappeared when there was no longer sufficient light to cast their shadows - and how at that moment seeing became more pleasurable.

Stars

A more subtle phenomena was the occurrence of a field of 'shooting stars'. These random-appearing, uniformly distributed flashes were most visible during the early part of twilight. Slowly as the sky darkened, however, they became less and less visible until a certain time when they would vanish completely. Again, this phenomena is highly variable from person to person. If extreme, they can be a sign of a number of eye diseases - but normally the explanation is that the vitreous is tugging on the retina, causing the sparks and shooting stars. That fact that this phenomena disappeared beyond a particular light level suggests the over abundance of light contributes to the friction between the vitreous and retina. Because it was also observed that the most comfortable light level was consistently experienced within minutes of the absence of visual stars, there is reason to think visual comfort is directly related to the light level that causes the least physiological tension within the eye.

Periphery

Peripheral vision is another factor relevant to the degree of perceptual awareness and comfort level. As the sky gradually darkened, it was possible to experience the increasing awareness of visual periphery. In bright light, most of our visual attention is given to the center of vision where cones provide the dominant response. This limits our visual awareness because we do not get much feedback about our fuller spatial environment. Of course, the opposite is true in darkness when peripheral vision is good but we struggle to see color and detail. During the twilight studies, it was observed that there is a middle ground where both rod and cone vision is enabled without sacrificing too much of one or the other. This condition was found to heighten the state of perceptual awareness.

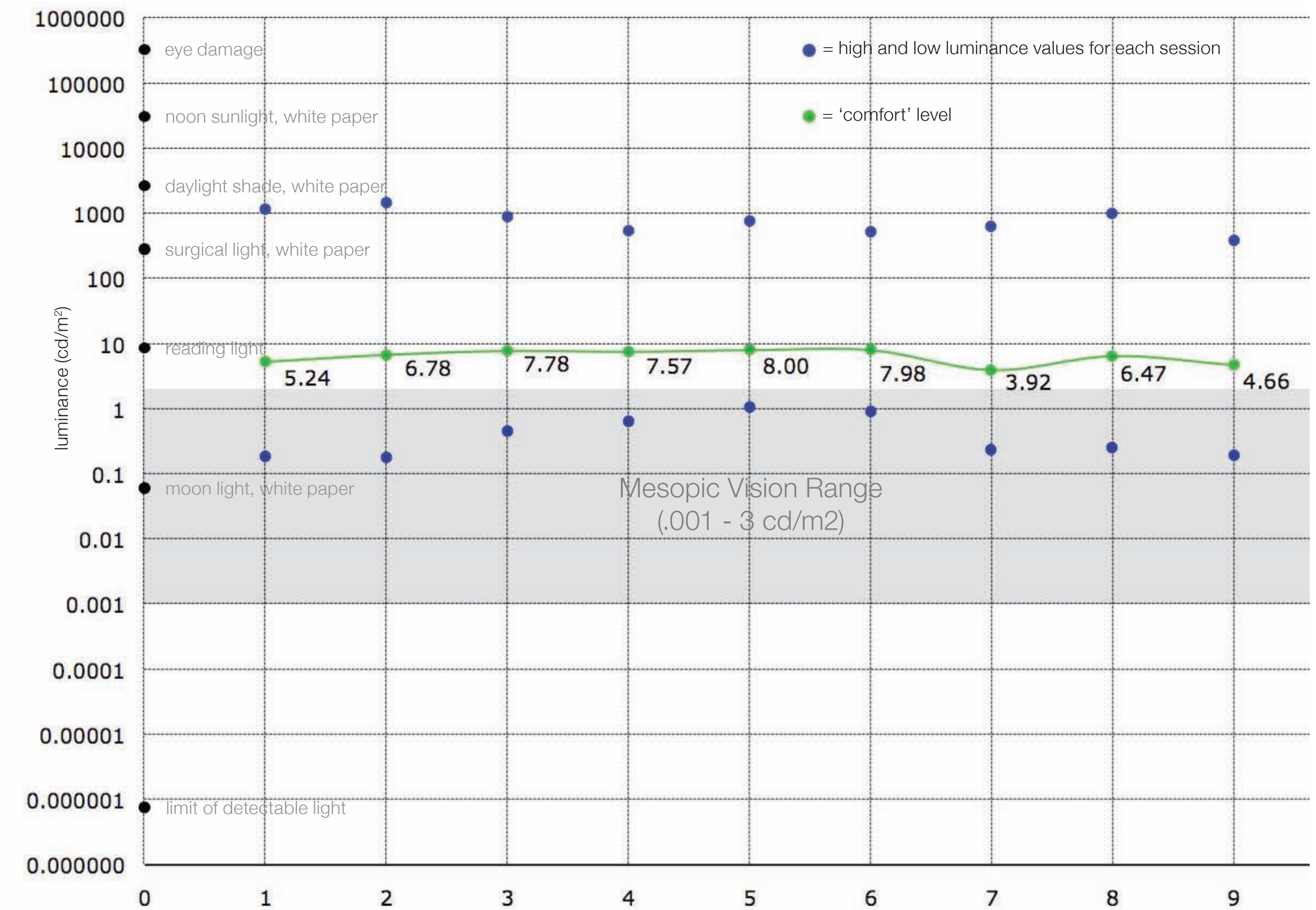
Sound

Though most attention during the observation sessions was given to visual perception, an emergence of a heightened acoustic sense was also noticed. Offering a reason for this goes beyond the intent of this study but the experience was straightforward; it was sensed that during twilight a general white noise gradually receded, creating an acoustic calm in which the range of hearing increased, allowing wildlife or human chatter or distant cars to stand out and be heard much more clearly.

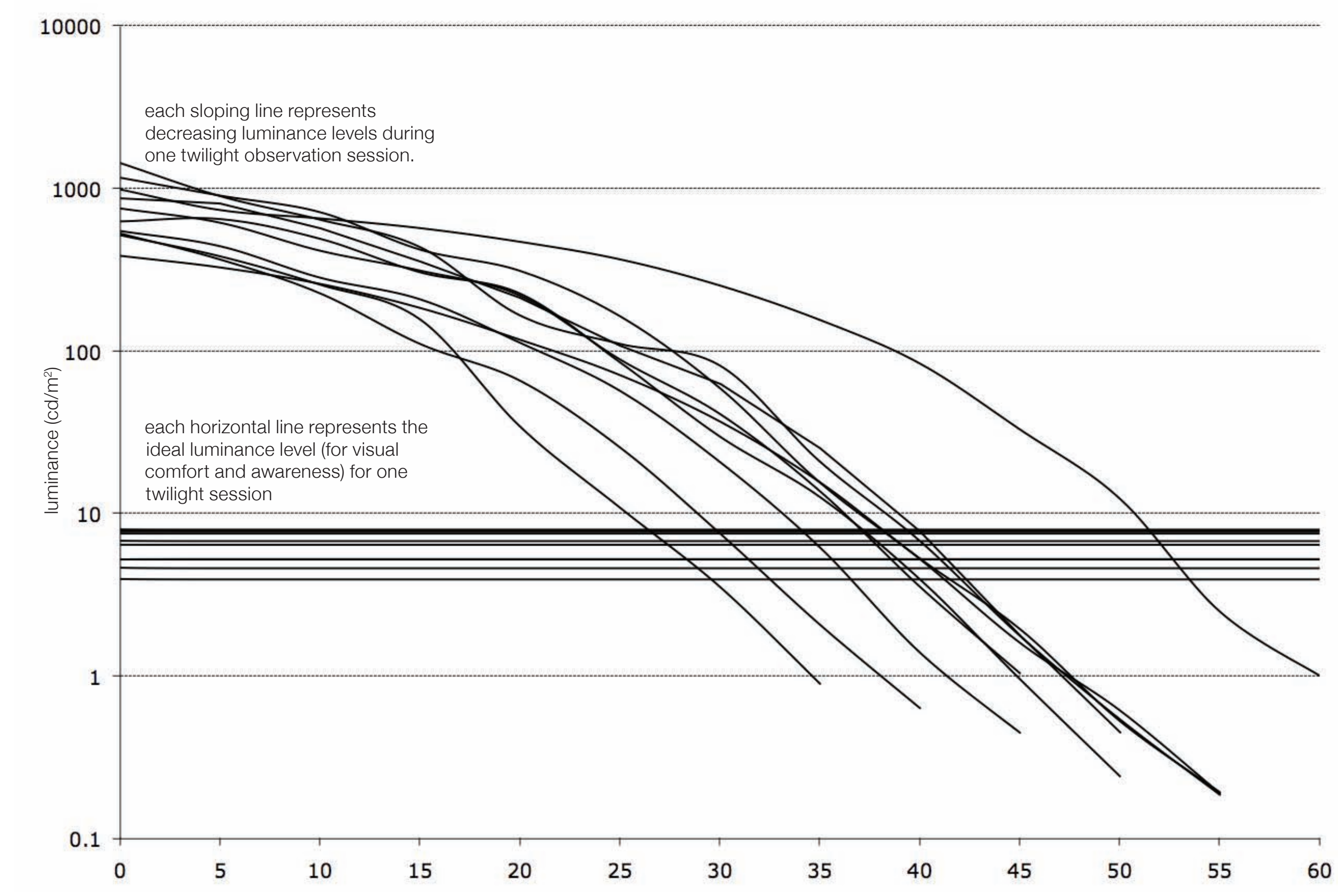
Observation Analysis

Once the perceptual valued could be matched with numerical luminance data, it was possible to graph the outcome and look for trends. The series of light observations is recorded in Figures 7 and 8.

Across all observations, the ideal comfort luminance level ranged between 3.92 and 8.00 cd/m². This consistency within a much larger range of observed light levels was not expected. It suggests that an ideal luminance level for perceptual awareness may exist and leaved a window open for future investigations.



7: Logarithmic 'Comfort' Luminance Level Comparison



8: Logarithmic 'Comfort' Luminance Level Graph

sensitive apertures

Light Containers

To set up a space conducive to perceptual awareness and thinking, the final stage of this thesis was to create an architectural enclosure system that could function as an analog to the desired luminance level of the twilight sky.

The first major constraint of this system was that the light levels needed to be drastically reduced from outside to inside. To accomplish this using predominantly opaque material, a field of apertures was proposed to evenly distribute small quantities of light.

Secondly, the light that was allowed to enter through the enclosure needed to be as uniform as possible. This requirement sparked the idea to use refraction at the aperture and spatial depth within the enclosure in order to spread the light on the inside surface of the enclosure. Using packing geometry from the previous cube corner studies to create a uniform field, it made sense to place the aperture at the apex of the tetrahedral geometry - the light ‘container’.

The following pages document the development of this enclosure system through stages:

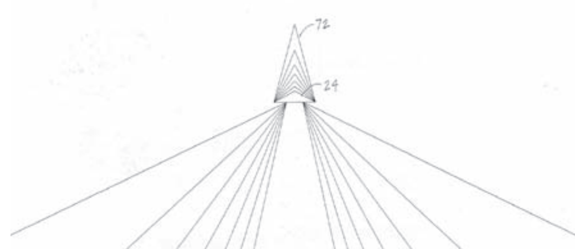
basic refraction studies
aperture fabrication
light container fabrication
assembly

Refraction Studies

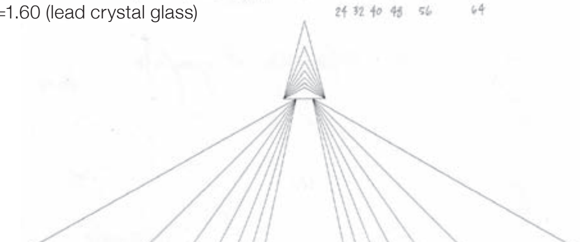
A series of diagrams and graphs show the range of possible refraction angles using available materials such as acrylic and glass. These clearly show how the more refractive materials are able to more effectively bend the light.

These angles were then used to create the specific geometry a typical light container needed in order to contain the refracted light. Figures 1 and 2 show the relationship between the angle of the transparent aperture and the angle of the resultant light path (assuming incident light is vertical).

Lead crystal glass, with an index of refraction (n) of 1.60 was chosen for the final form. To ensure the material of the light container captured the refracted light, the form was made slightly steeper. (Figure 3)



n=1.60 (lead crystal glass)

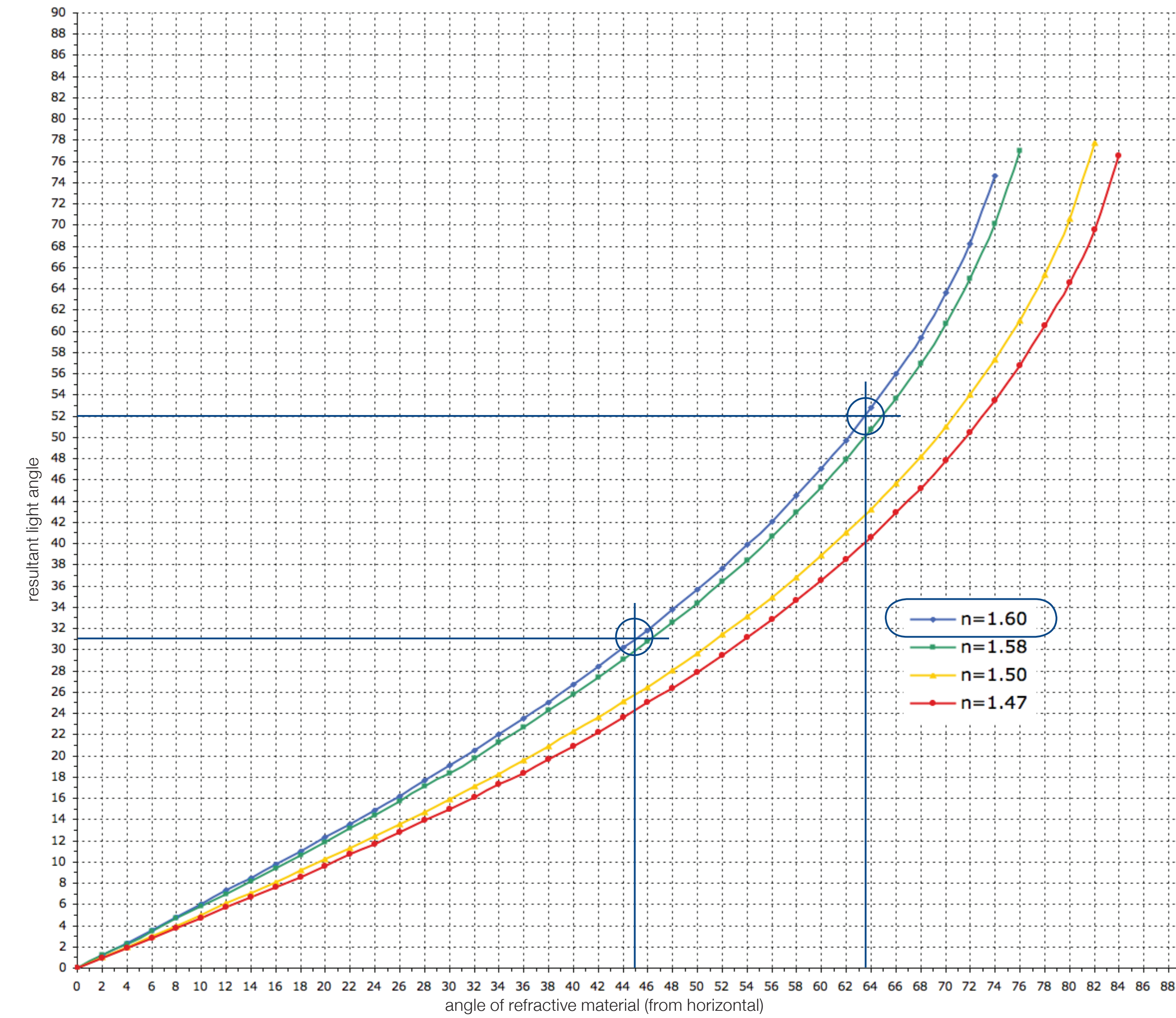


n=1.58 (casting glass)

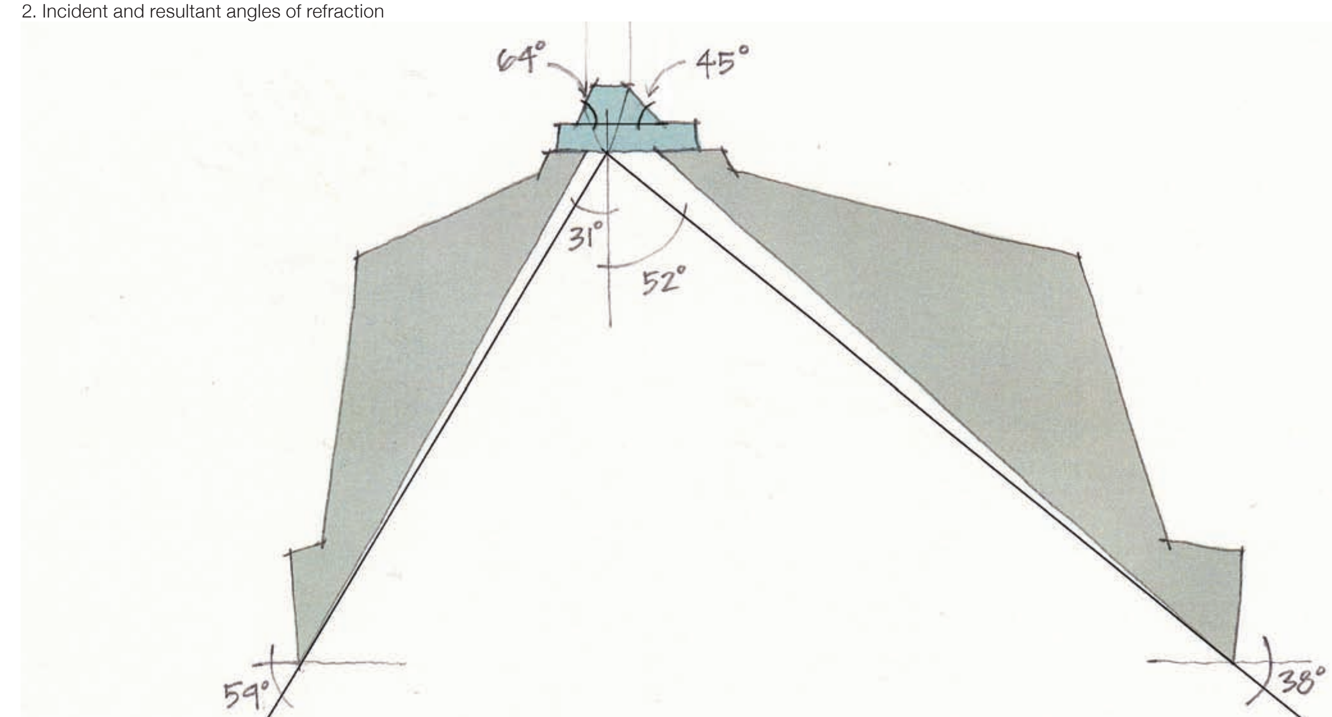
n=1.50 (acrylic)

n=1.47 (borosilicate glass)

1. Possible light paths for various aperture angles



2. Incident and resultant angles of refraction

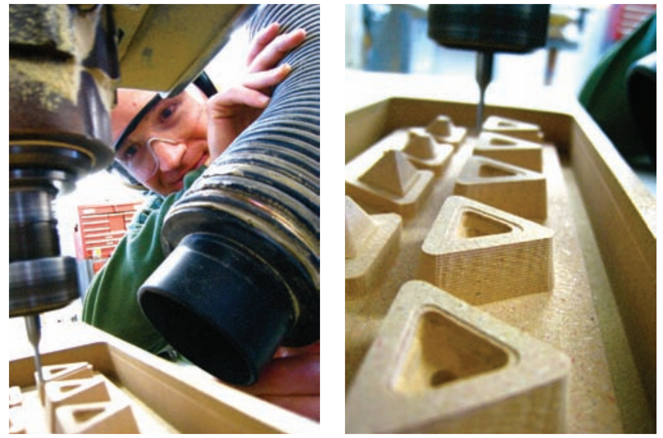


3. Typical light container refraction analysis

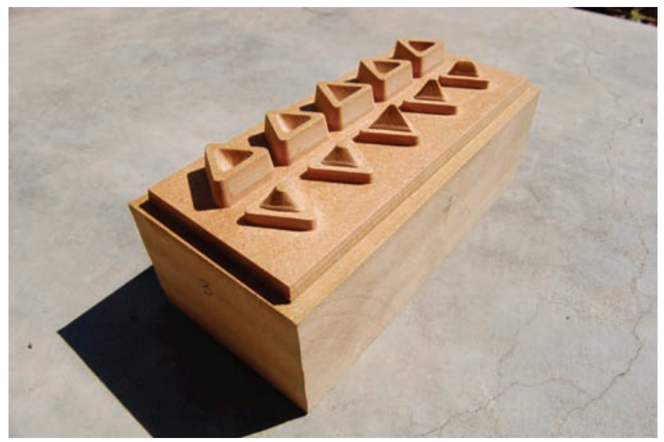
Aperture Fabrication: Acrylic

Glass was chosen as the ideal material because of its durability and high index of refraction. However because the glass fabrication process took a long to time to begin, cast acrylic was also explored.

A series of ‘best guess’ aperture geometries were digitally designed so each could be tested empirically for best performance. At first, the CNC router was used to machine the geometries out of MDF (Figures 4-6). Liquid silicone was then cast into these as a final step before being able to cast acrylic. Because the apertures were so small, it was a challenge to get enough machining resolution to make the apertures as smooth and clear as possible. 3d printing was tested for precision but it too had more texture than desired. Finally, Dupont’s Corian countertop material was tested for its machinability with the router and the results were far better than the MDF or 3D print. (Figure 7)



4. CNC routing of MDF



5. Typical light container refraction analysis

6. Typical light container refraction analysis

7. Typical light container refraction analysis

Aperture Fabrication: Glass

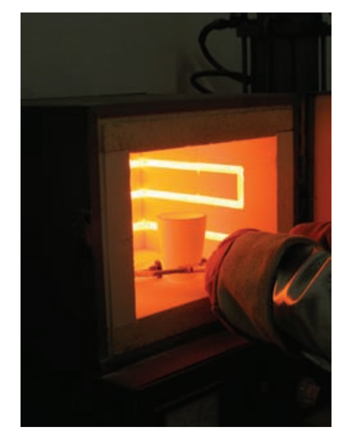
Casting the small glass apertures required a thorough process of seeking advice on and off campus, asking for material donations, and being able use lab space and furnaces in the Material Science Department.

A strict requirement of the apertures was that they had to be optically clear - the surface of the glass had to be smooth and specular. Any light scattering at the surface would have defeated the refractive intentions for the glass. After talking with glass fabricator Charly Amling, in the Chemistry Department, it became clear that graphite might be a perfect mold material for casting glass. Thankfully, a few blocks of graphite were generously donated for this research by Leon Good of Weaver Industries. The graphite block was then carefully machined using the CNC router (Figure 8). Special care needed to be taken for this machining because graphite, though relatively soft and easy to machine, also produces dangerous shavings which are both abrasive and conductive.

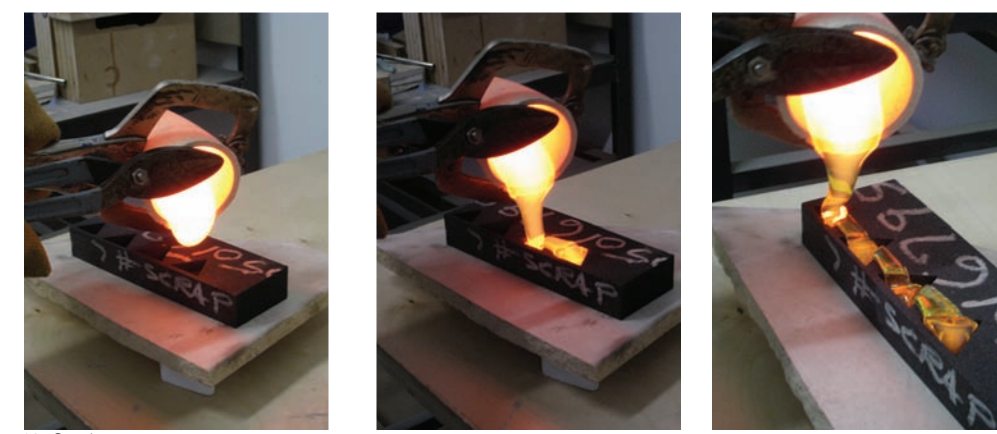
Even though graphite is an ideal material for casting glass into, it is prone to oxidation when exposed at temperatures above 480°C. This required glass to be melted in a crucible first which could then be poured into the graphite which could then be placed in a separate oven for annealing. (Thankfully, graphite’s oxidation threshold was also the annealing temperature of the lead crystal glass used for the casting)

The first casting experiment with graphite was done using two ovens in the Architecture materials laboratory. The glass product of this cumbersome procedure (Figures 9-12) was beautifully clear - but also deformed because the glass did not reach a high enough temperature to become liquid enough to fill the small shapes in the graphite.

8. Machined graphite mold block

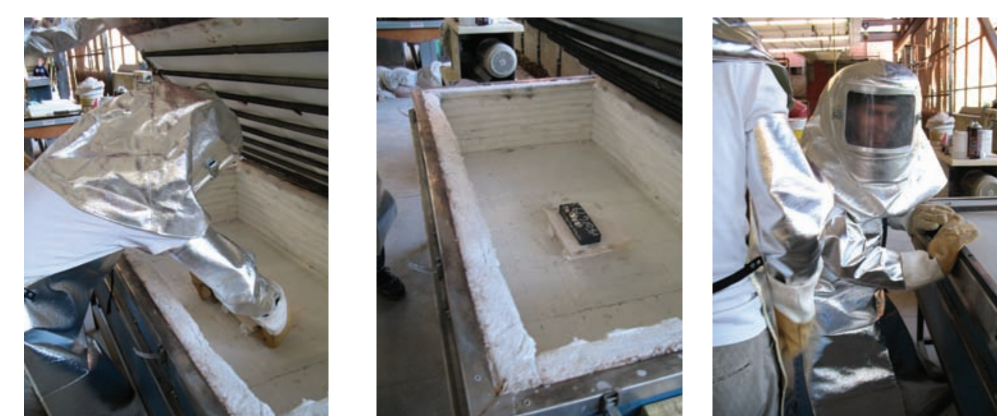


9. 850°C furnace



10. Casting sequence

11. Heat reflective armor



12. Annealing oven

13. Material Science laboratory furnaces

14. Casting tools

15. 1000° C furnace

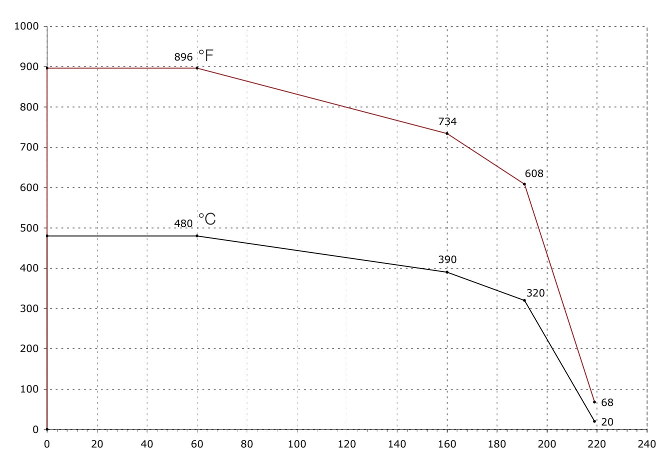
16. Casting

17. Graphite mold

18. Glass placed in oven for annealing

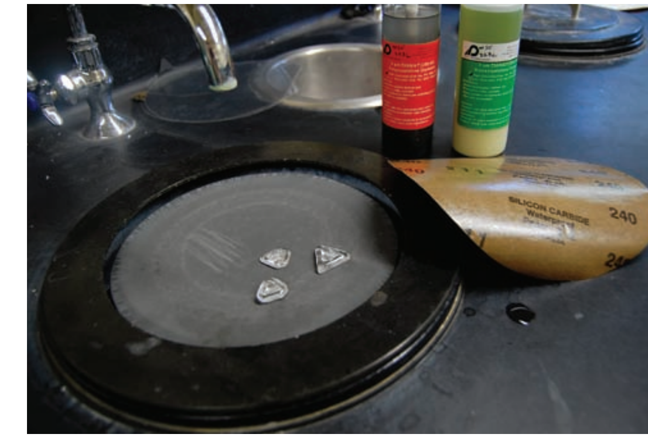
Glass: Casting

The second casting series was done using a pair of small furnaces in the Material Science laboratory. These furnaces were able to reach 1300° C, the true melting point of the glass. Once the glass castings were sufficiently cool in the graphite mold, they were removed and placed in the other oven for annealing (Figures 17-19). This process allowed new castings to be made back to back which greatly increased production efficiency.

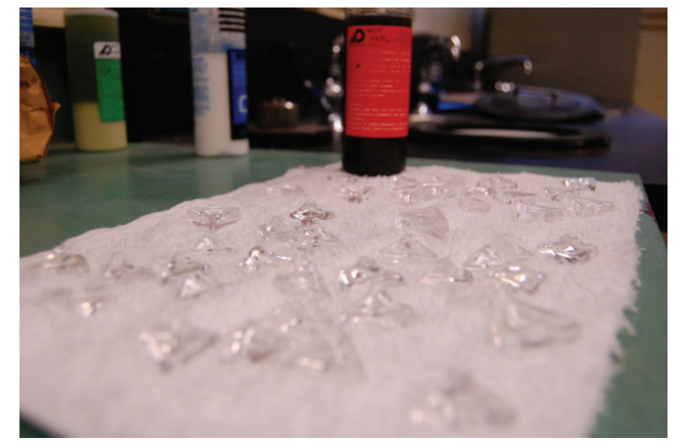


19. Annealing schedule

20. Unfinished glass castings



21. Polishing wheel



22. Final polish with 9 micrometer polycrystalline diamond lubricant

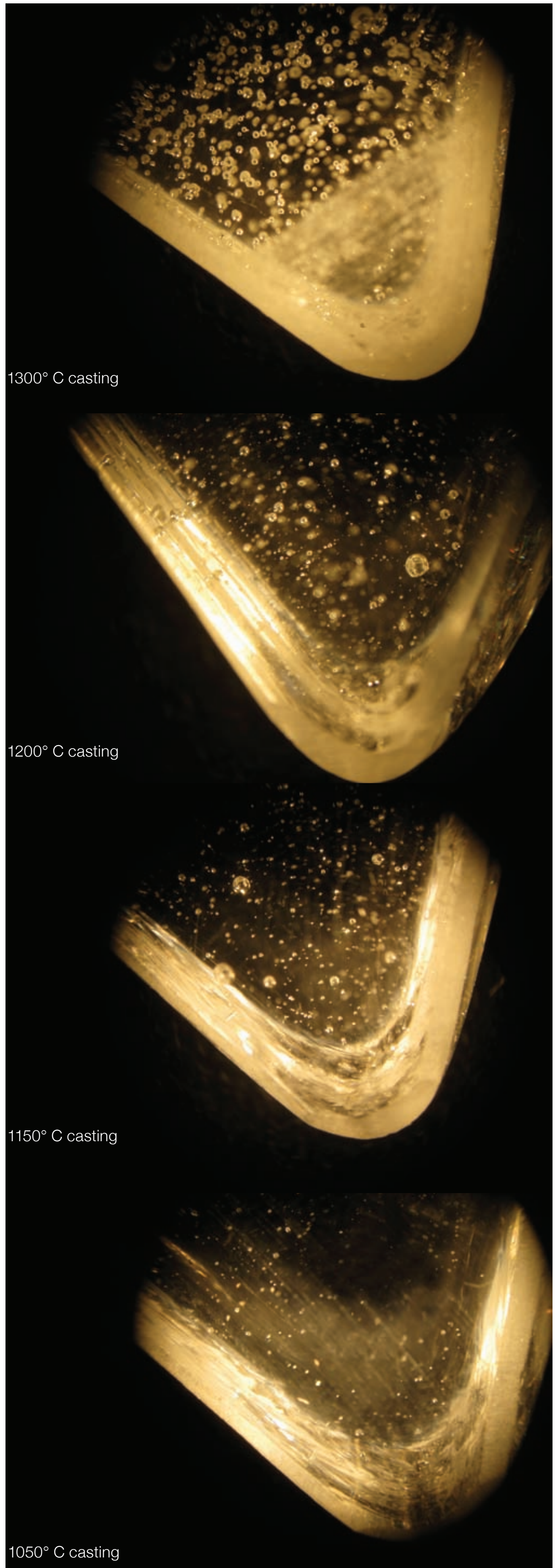
23. Finished apertures

24. Finished apertures

25. Annealing oven

Glass: Finishing

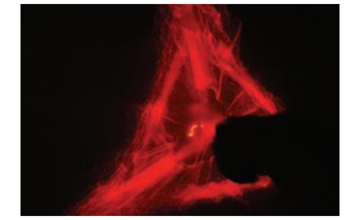
After annealing, the glass apertures required grinding to remove the upper half. This was followed by wheel polishing (Figure 21) using water-lubricating abrasive pads decreasing in grit size from 240 to 400 to 800 to 1200. A final polish was made using a 9 micrometer polycrystalline diamond lubricant.

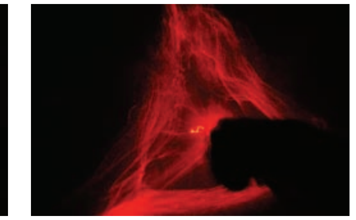


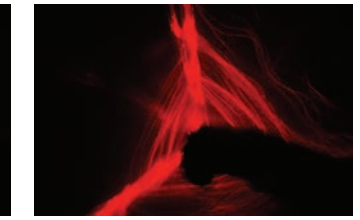
27. Microscopic analysis of clarity

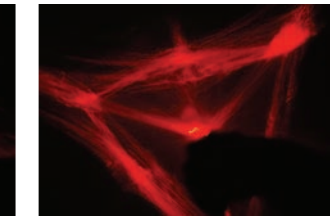
Glass: Optical Clarity Analysis

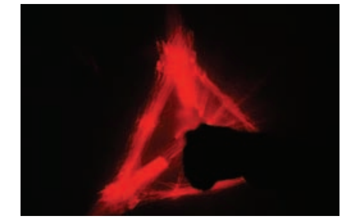
The glass apertures were cast at temperatures ranging from 1050°C to 1300°C. At the lower temperatures, the glass remained very viscous which made casting difficult and prevented the glass from completely filling in the graphite cavity. Though some detail resolution was lost in these casts, the optical character was very clear and bubble free. Castings made at the higher temperatures significantly decreased the viscosity of the glass and made pouring much easier. These temperatures, however, caused certain compounds in the glass composition to react, producing many small entrapped gasous bubbles. The size and density of these bubbles altered the optical behavior of the glass by diffusing the light.

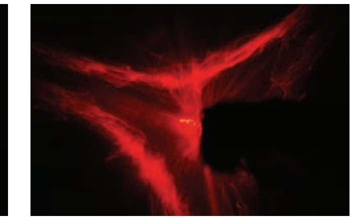

28. Aperture A

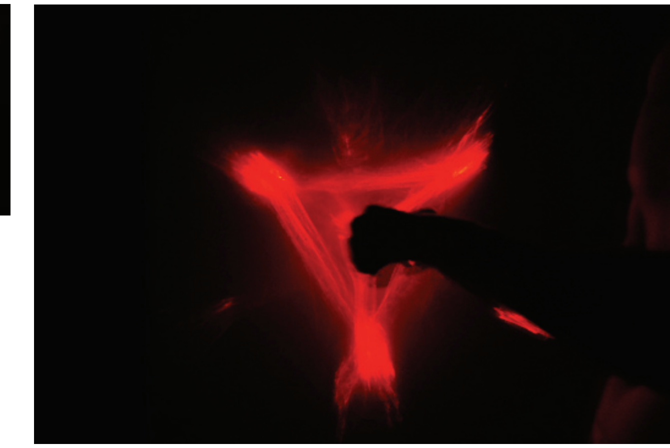

29. Aperture B


30. Aperture C


31. Aperture D


32. Aperture E

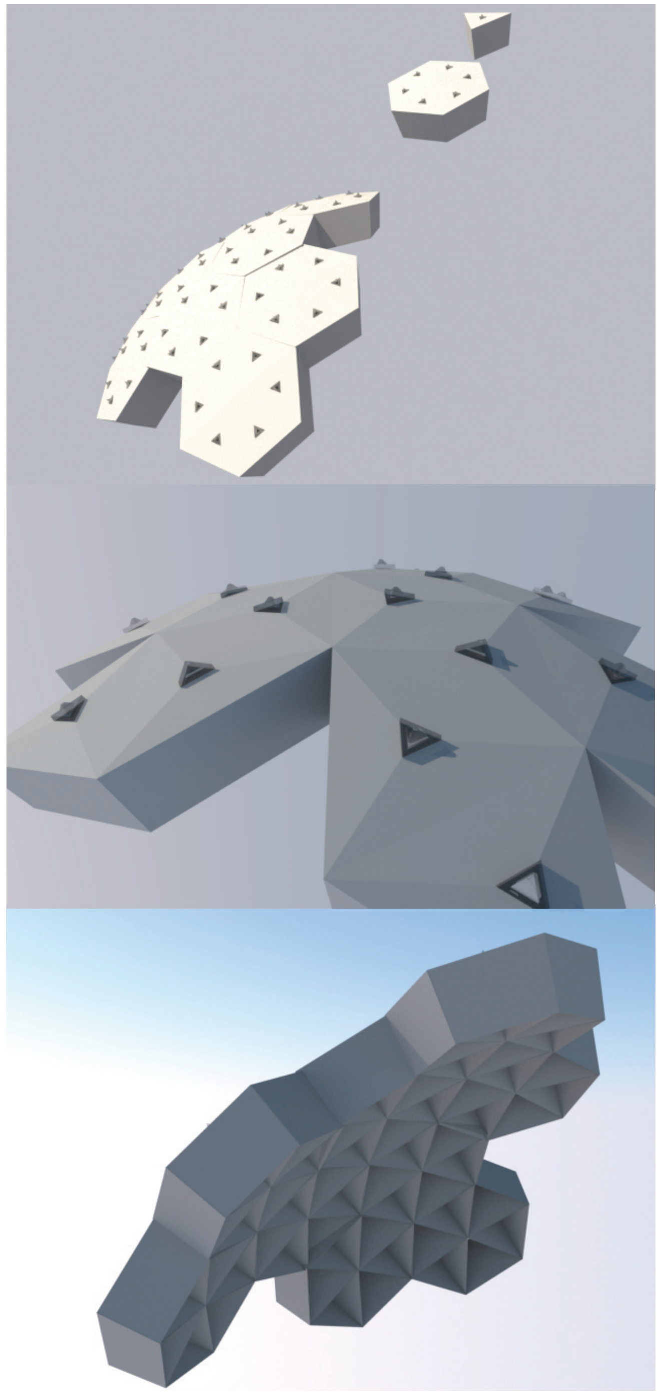

33. Aperture F


34. Aperture Glass

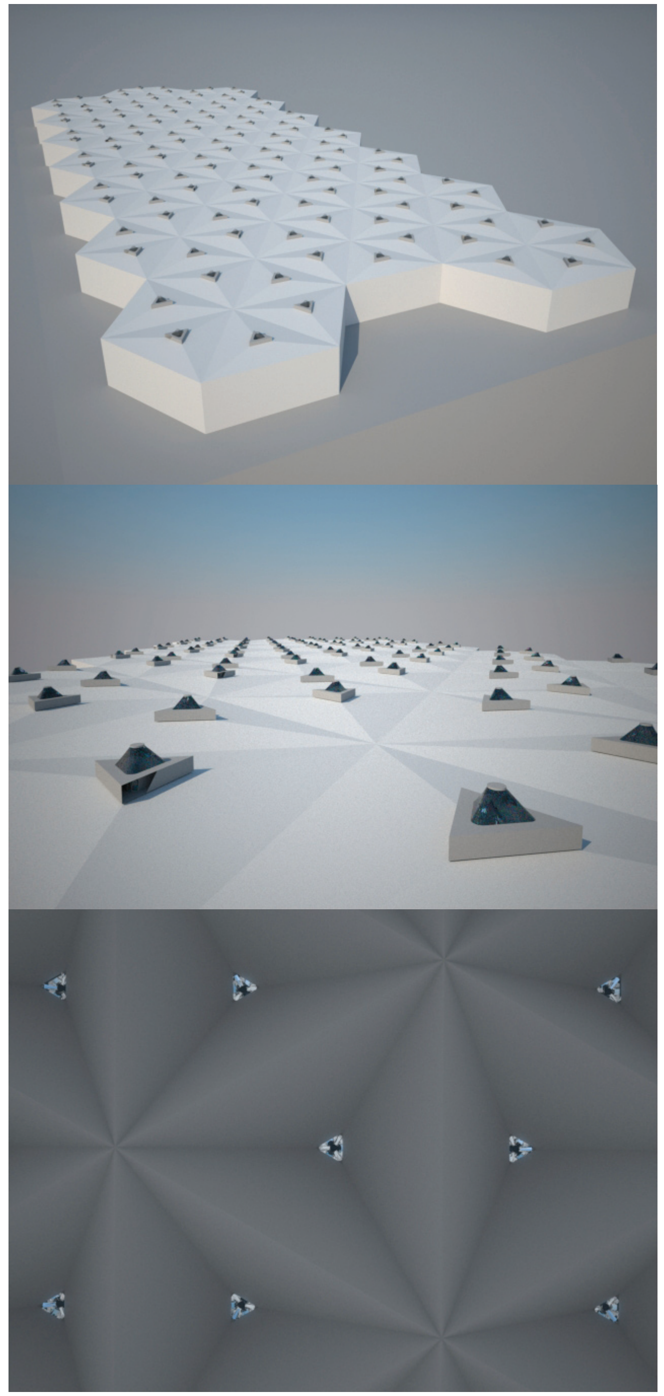
35. Microscopic analysis of clarity

Aperture Optical Behavior Testing

A series of aperture geometries in acrylic and glass were tested using a laser pointer and long exposure photography. The light patterns captured in these images show the refractive signature for each object and provides a method for judging the performance of the objects. In this project, only one geometry was produced in glass (Figure 34). It is evident from the image how more light is present at the points of the triangle than along the edges. This phenomena is also apparent in the final light demonstration (Page 67)



36. Curved tiling geometry

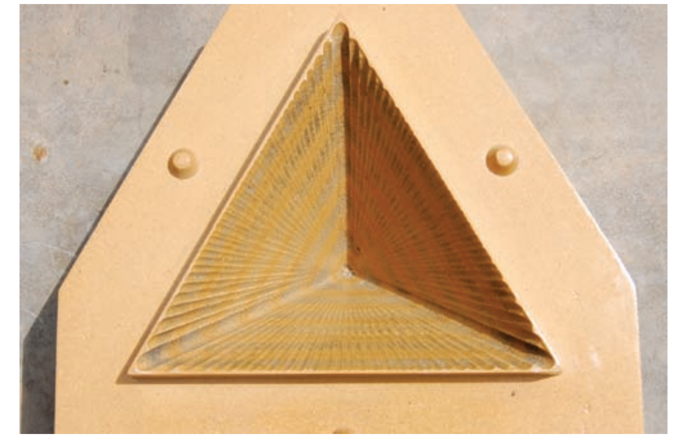


37. Planar tiling geometry

Light Container Fabrication

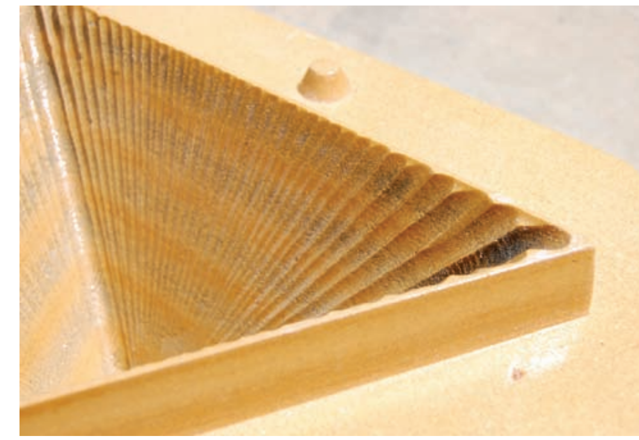
Digital Fabrication

Curved and planar geometries were studied digitally. The initial set of light containers were envisioned to be able to tile together to form a double-curved enclosure (Figure 36). This form was abondoned, however, when it was realize that significant tolerance at the joints were needed to get the cells to take this shape. For the second and final iteration, a planar geometry was chosen (Figure 37) which allowed the cells to be minimally and consistently spaced. The light effect of the planar geometry was also more closely aligned with the initial light intention to create an enclosure that would uniformly glow at a particular time of day.

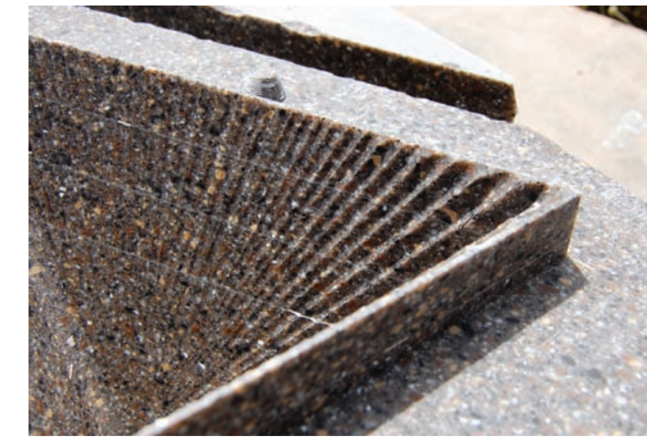


38. MDF master mold

40. Corian master mold



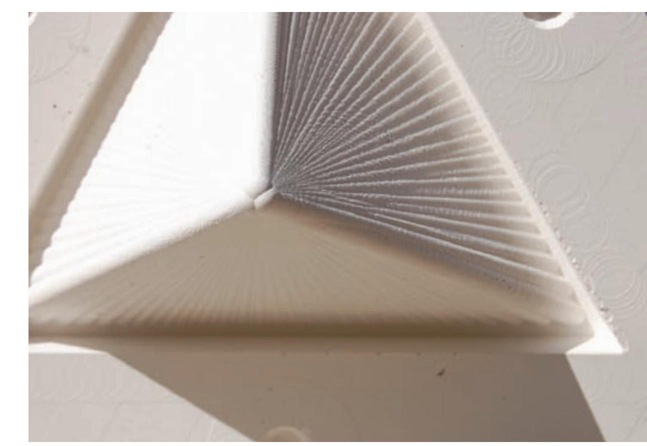
39. MDF master mold detail



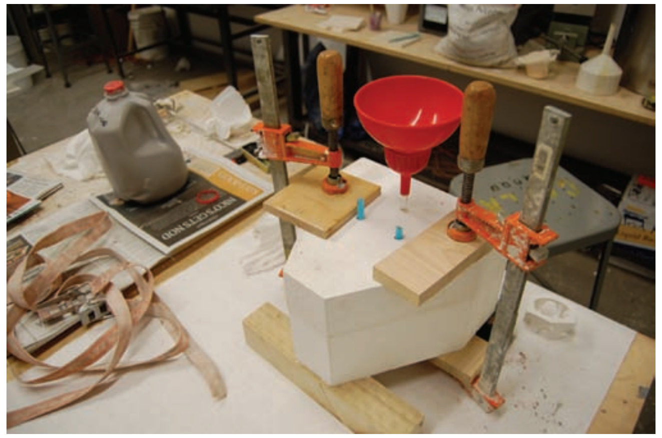
41. Corian master mold detail

Material Fabrication

Slip-cast ceramic was chosen as the material for the light containers for its white firing color, structural integrity, and ability to provide insulation as a hollow form. Mold making became the critical process for producing the slip cast containers. Once the digital model was refined, it was machined from MDF using the CNC router (Figures 38,39). In the sealing process, however, resolution of the tool path texture was lost. In response to this, Corian countertop material was tested for its machining ability and was eventually chosen as the ideal material to cast molds with because it did not require any sealing treatment beyond spray mold release (Figures 40,41). Figure 42 shows the detailed clarity of the pottery plaster cast from the Corian form.

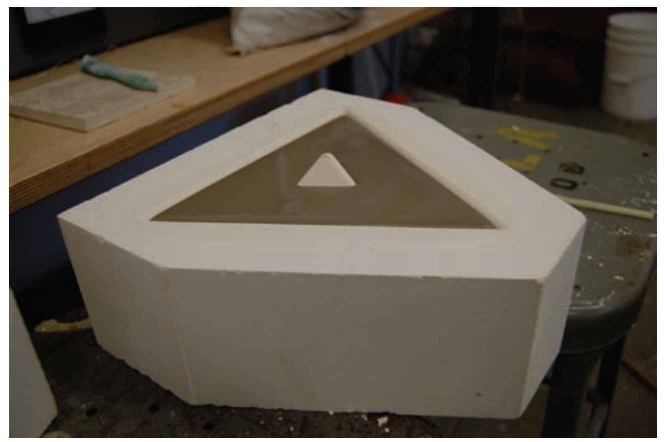


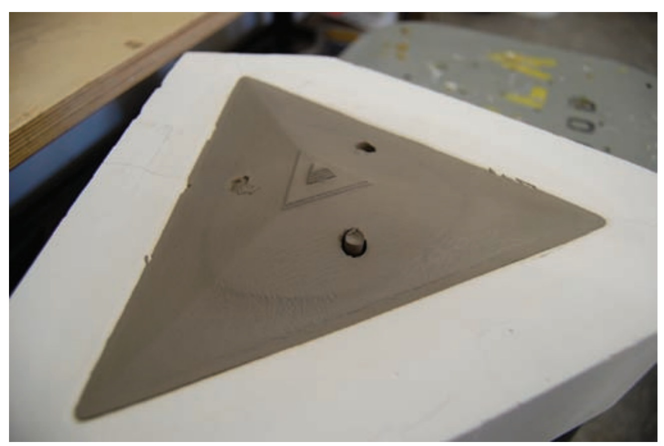
42. Pottery plaster cast from Corian master


43. Slip casting setup


44. Slip casting production line

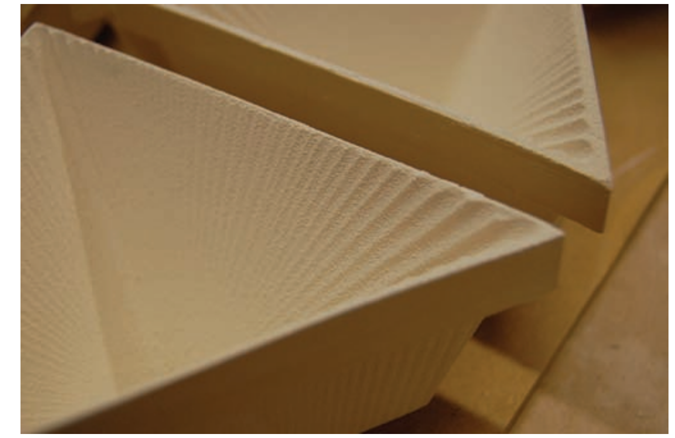

45. Pottery plaster molds for slip casting

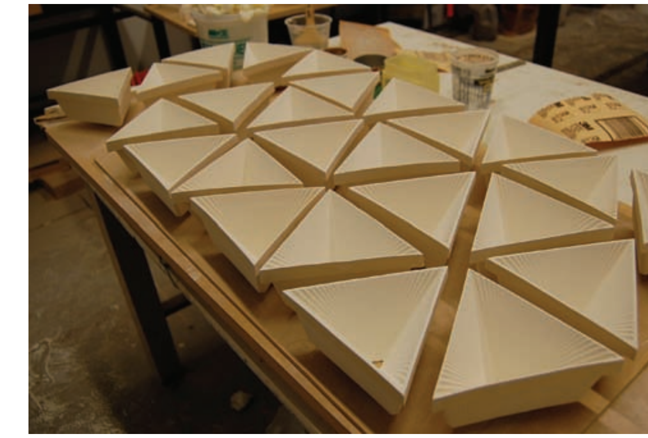

46. Slip


47. Greenware

Slip Casting

Two-part pottery plaster casts made from the machined Corian molds enclosed a cavity which was then be filled with the liquid slip. (Figures 45,46) The pottery plaster is highly absorbent and pulls moisture from the slip at all interfaces, causing the slip to harden. After a period of about 15 minutes, the thickness of the hardened slip was optimal and the remaining liquid was poured out, producing the hollow cavity for insulation as see in Figure 55. The clay body then remained undisturbed in the plaster for a period of at least 8 hours which gave them time to harden enough to be released from the molds to air dry. To increase production capacity, four sets of the plaster sets were made so that up to 12 pieces could be made daily. (Figure 44)


48. Glaze coating detail

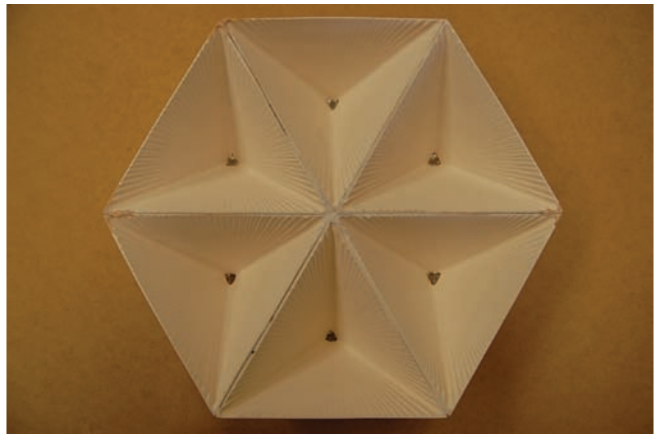

49. Glazing production


50. Ceramic kiln

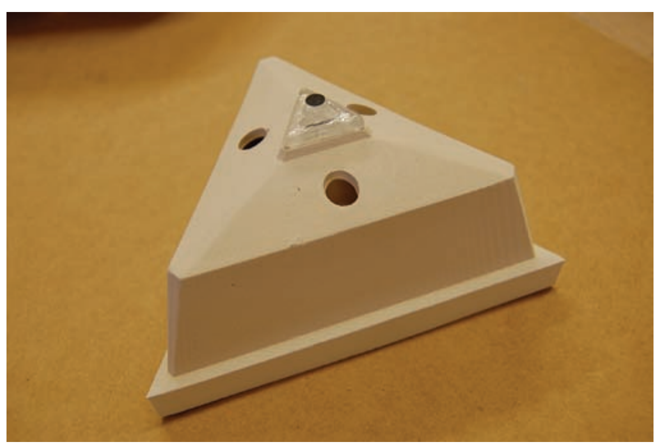

51. Glazing application

Glazing

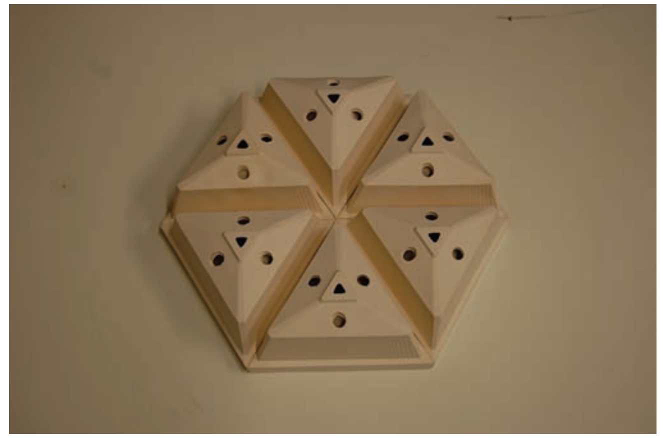
The finish surface of the light containers greatly affected the quality of light. To reinforce the intention of an evenly scattered interior light, a matte white glaze was chosen to minimize any specular behavior. After an initial bisque fire (Figure 50), the light containers were glazed using a spray applicator. (Figure 51)

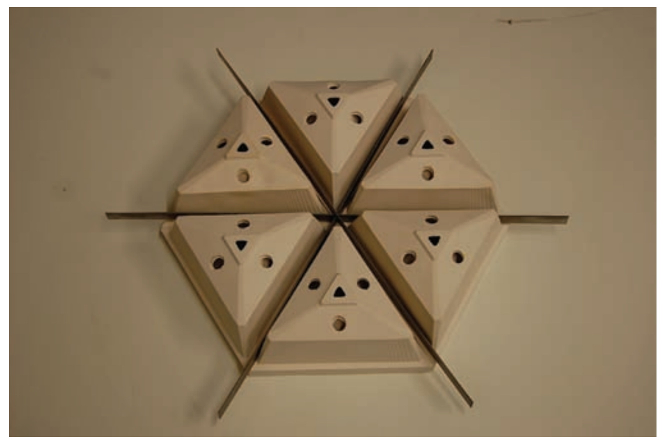

52. Hexagonal unit interior


53. Interior detail


54. Typical light container


55. Section through typical cell

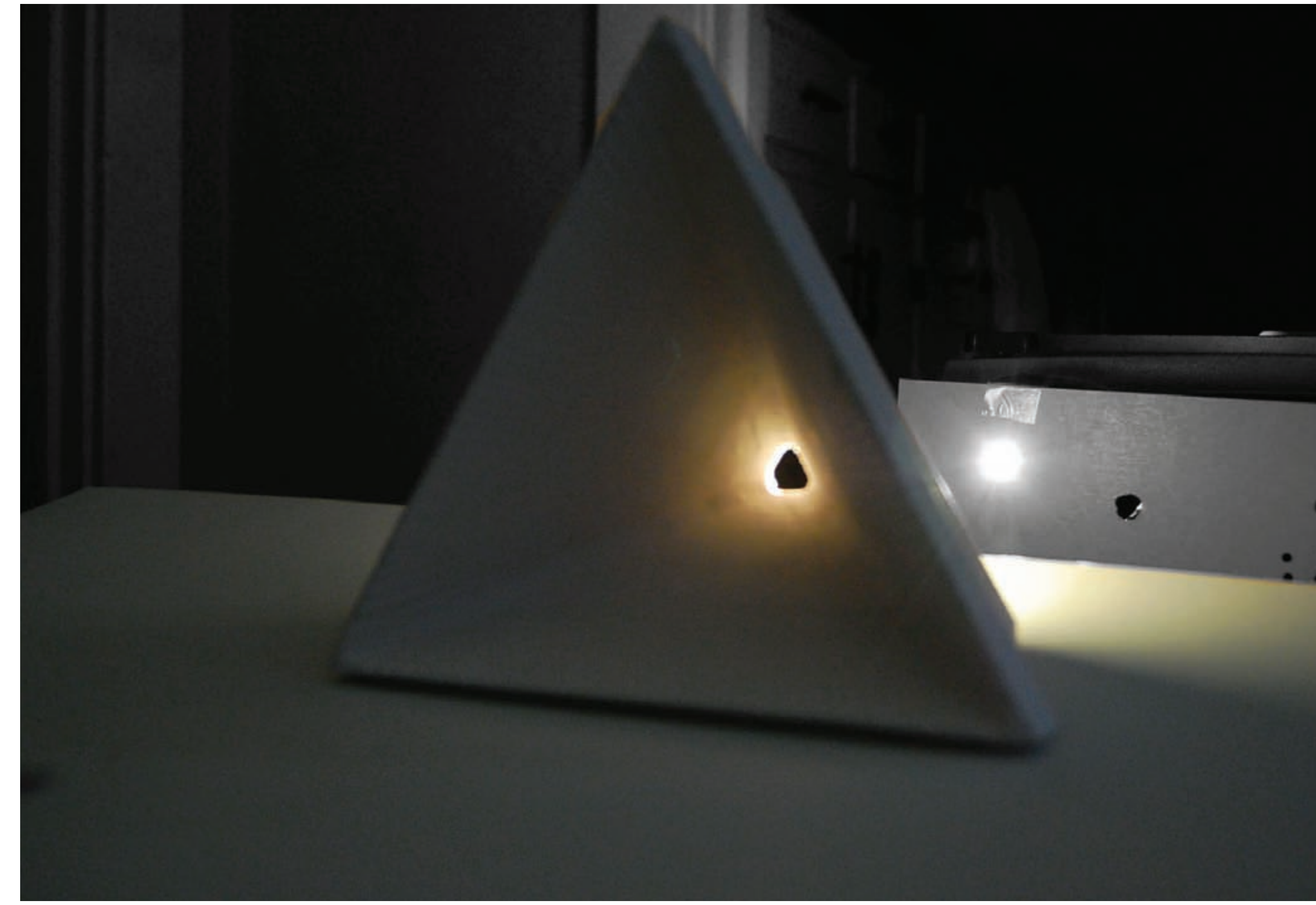

56. Hexagonal unit exterior

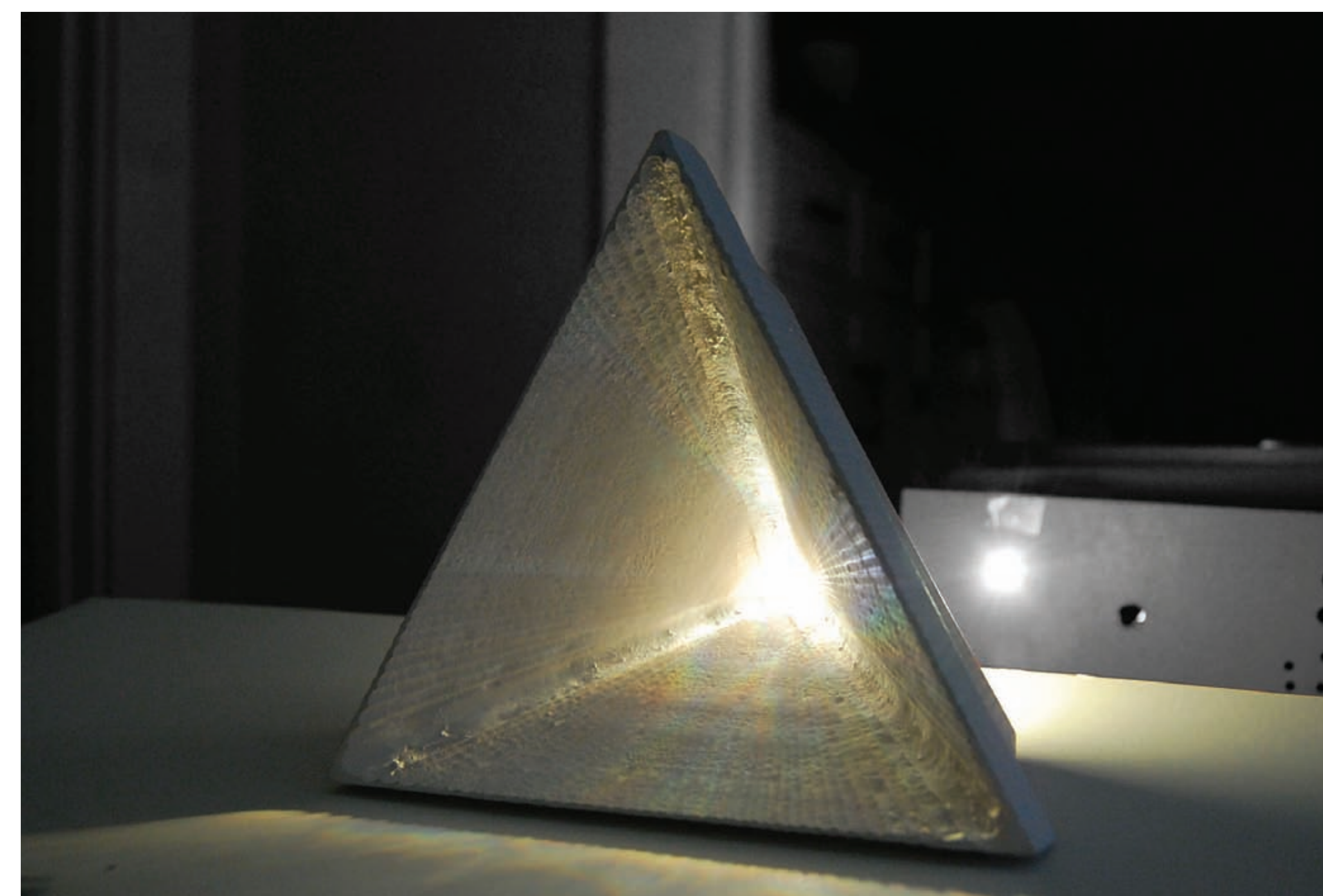

57. Potential reinforcement

Assembly

Individual light containers were bonded into larger cells using fiberglass and epoxy resin. The space between cells on the outside of the enclosure provided opportunity for reinforcement, weather sealing, and additional insulation.

Prior to the assembly of a large number of cells, a quick light study looked at the refractive performance of one container. Figures 58 and 59 demonstrated the performative difference between aperture and no aperture and provided some assurance that the cells were going to function as designed.

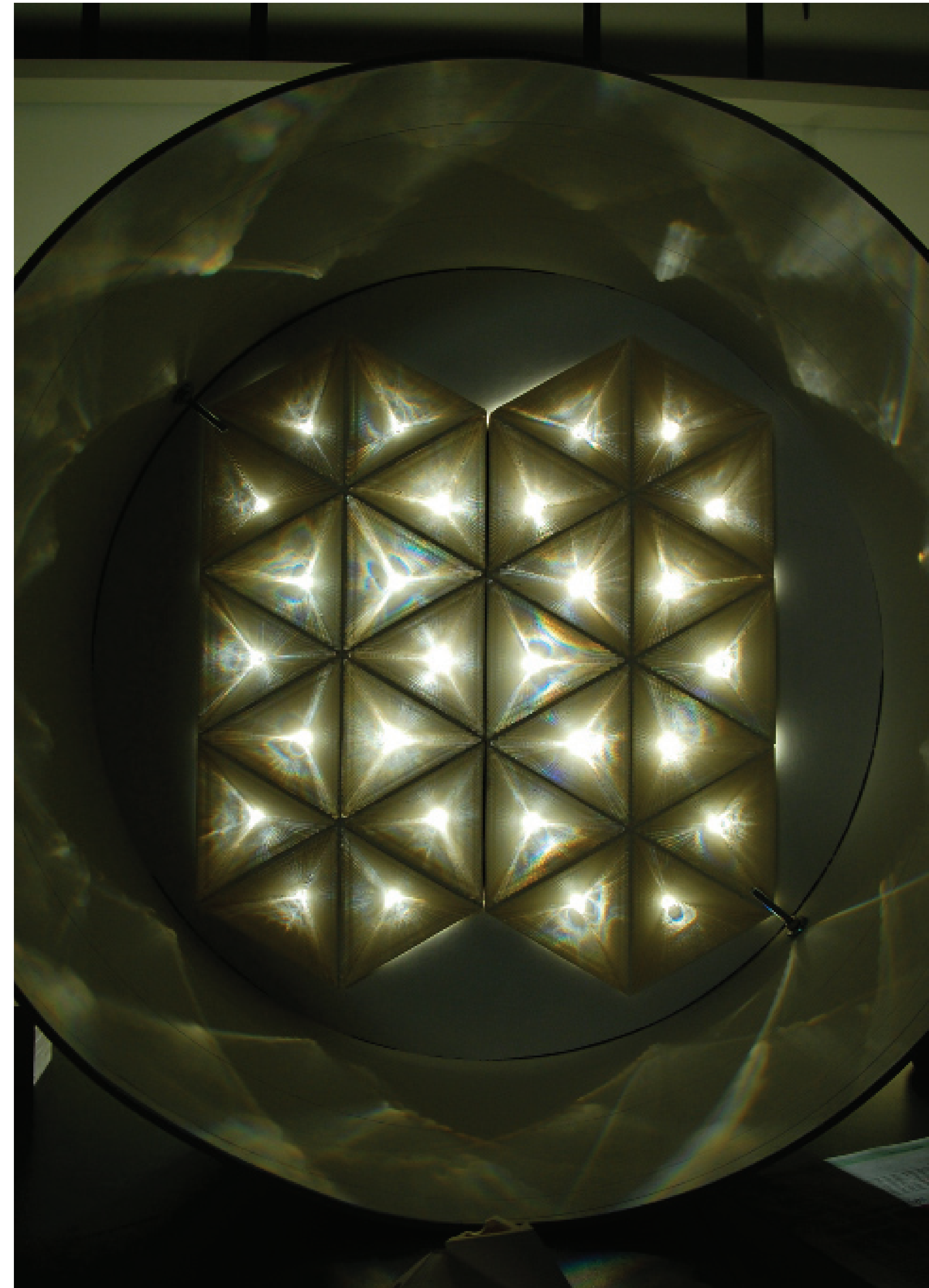

58. Light test - no aperture


59. Light test - with aperture

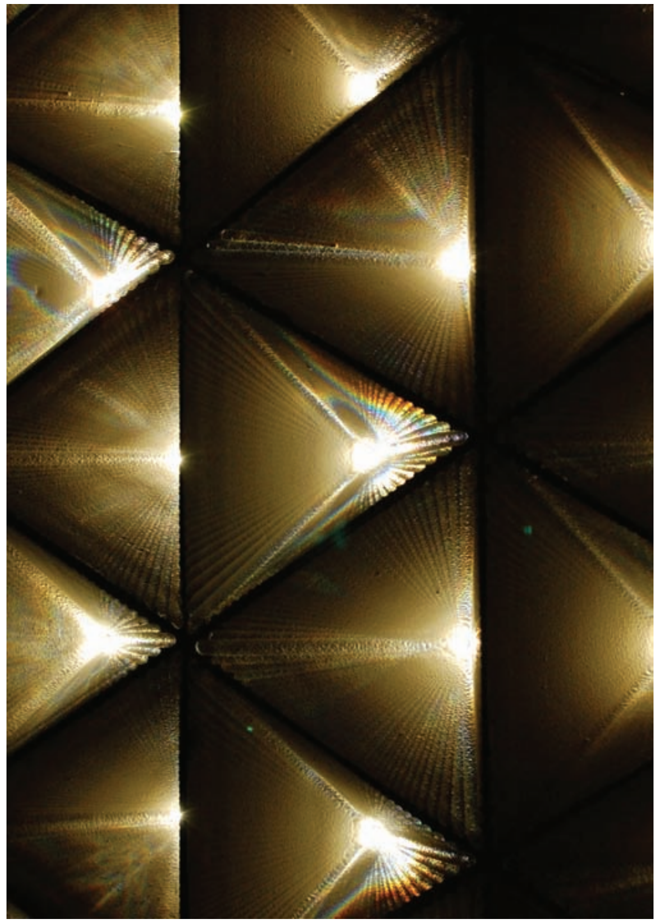
60. Large scale light test

Light Study

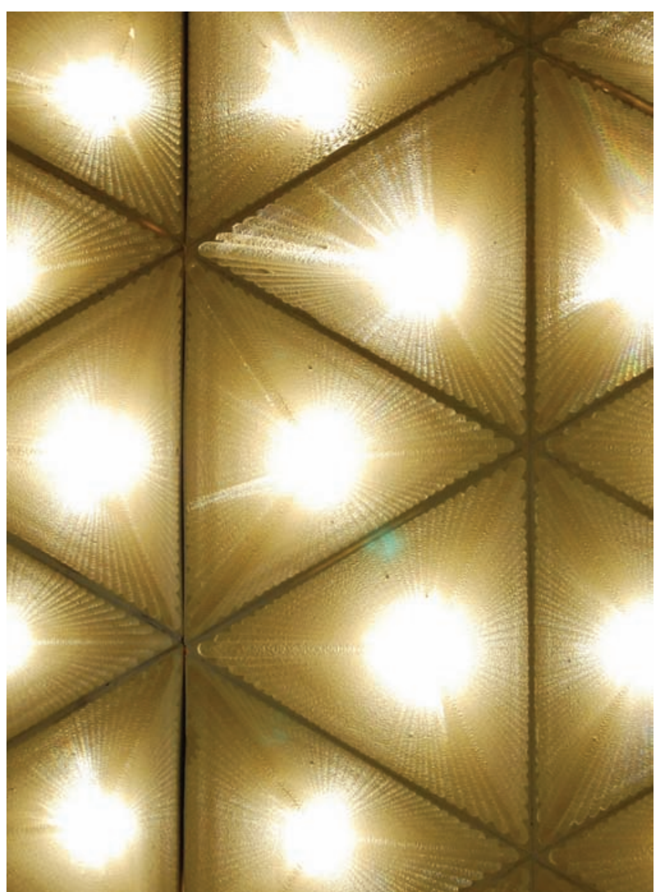
A larger demonstration of the system was set up using projector light as a sunlight substitute. Refractive colors were very visible in most of the cells and described how the light was being redirected. Irregularities in the geometry of the light path provided insight into how the aperture geometries might be able to be improved in future iterations. In addition, light clearly spilled past the boundary of individual cells, as seen projected onto the walls of the drum in Figure 61. This effect was not intentional but hold promise as a phenomenon to further integrate.



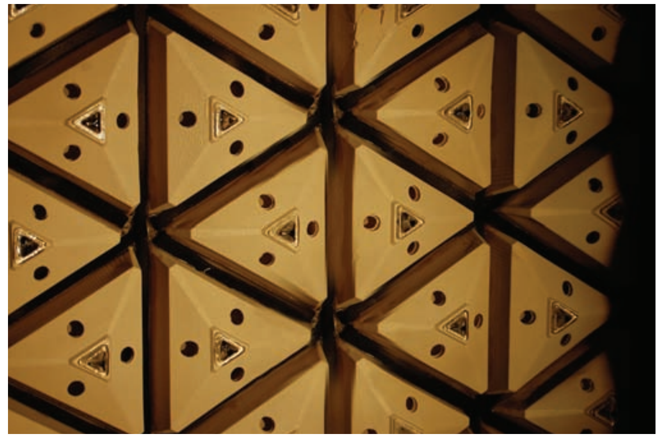
61. Light containers



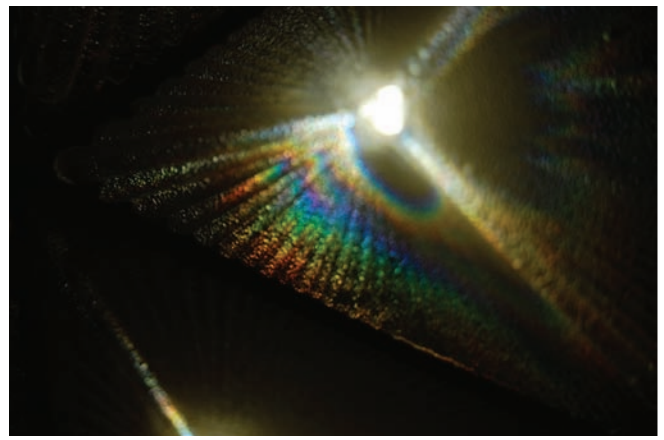
62. Planar tiling



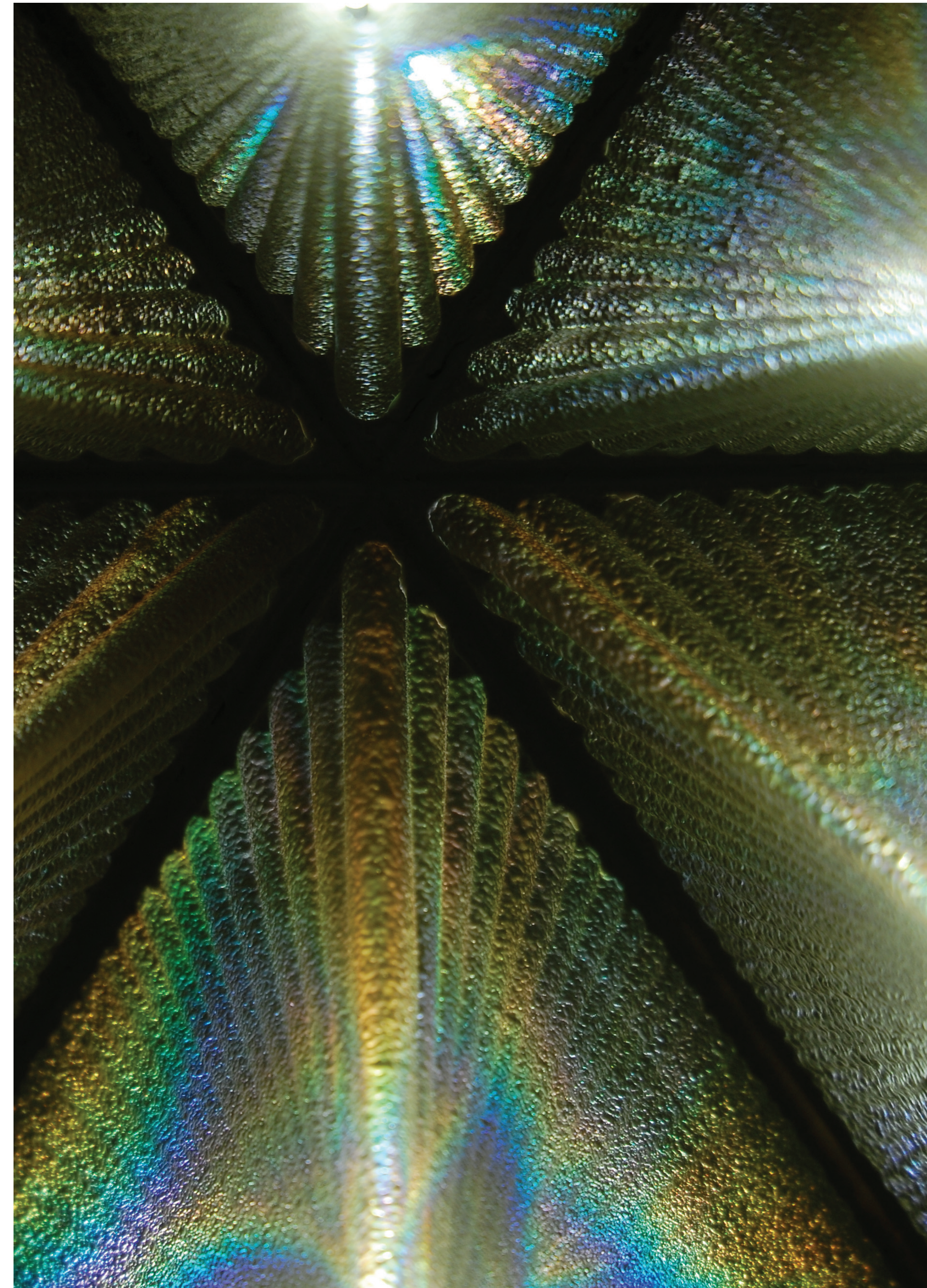
63. Planar Tiling



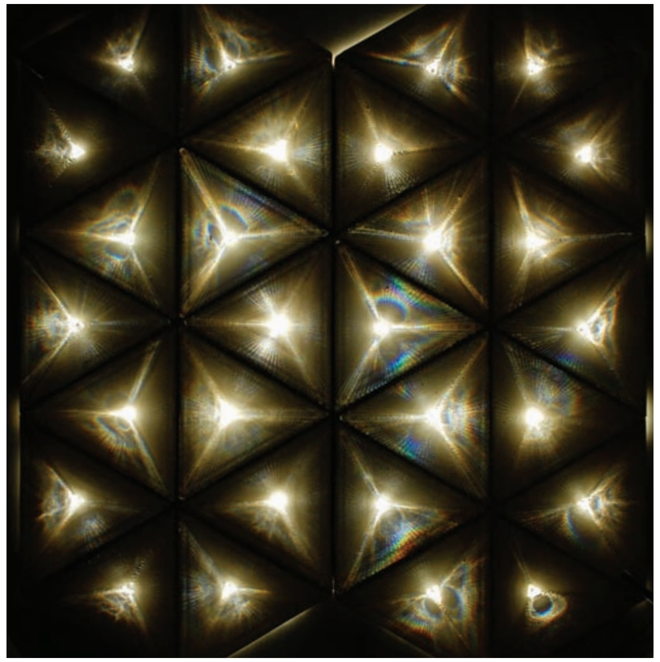
64. Exterior



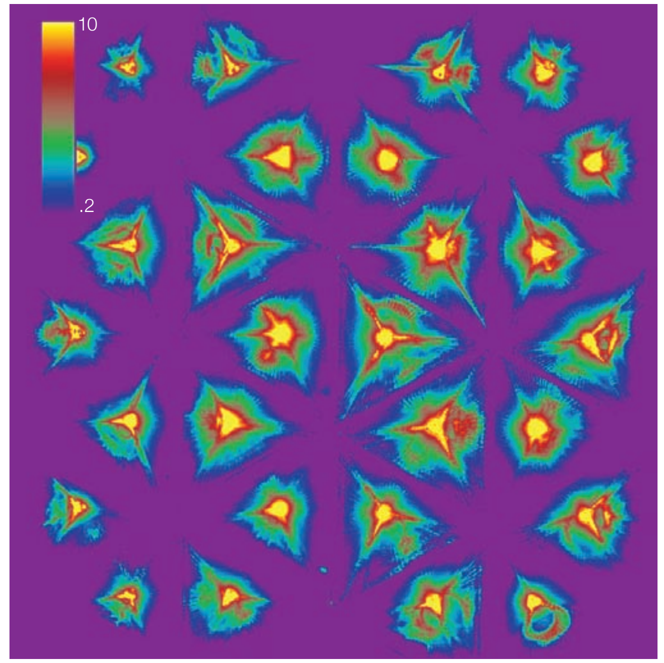
65. Interior detail



66. Light Container intersection

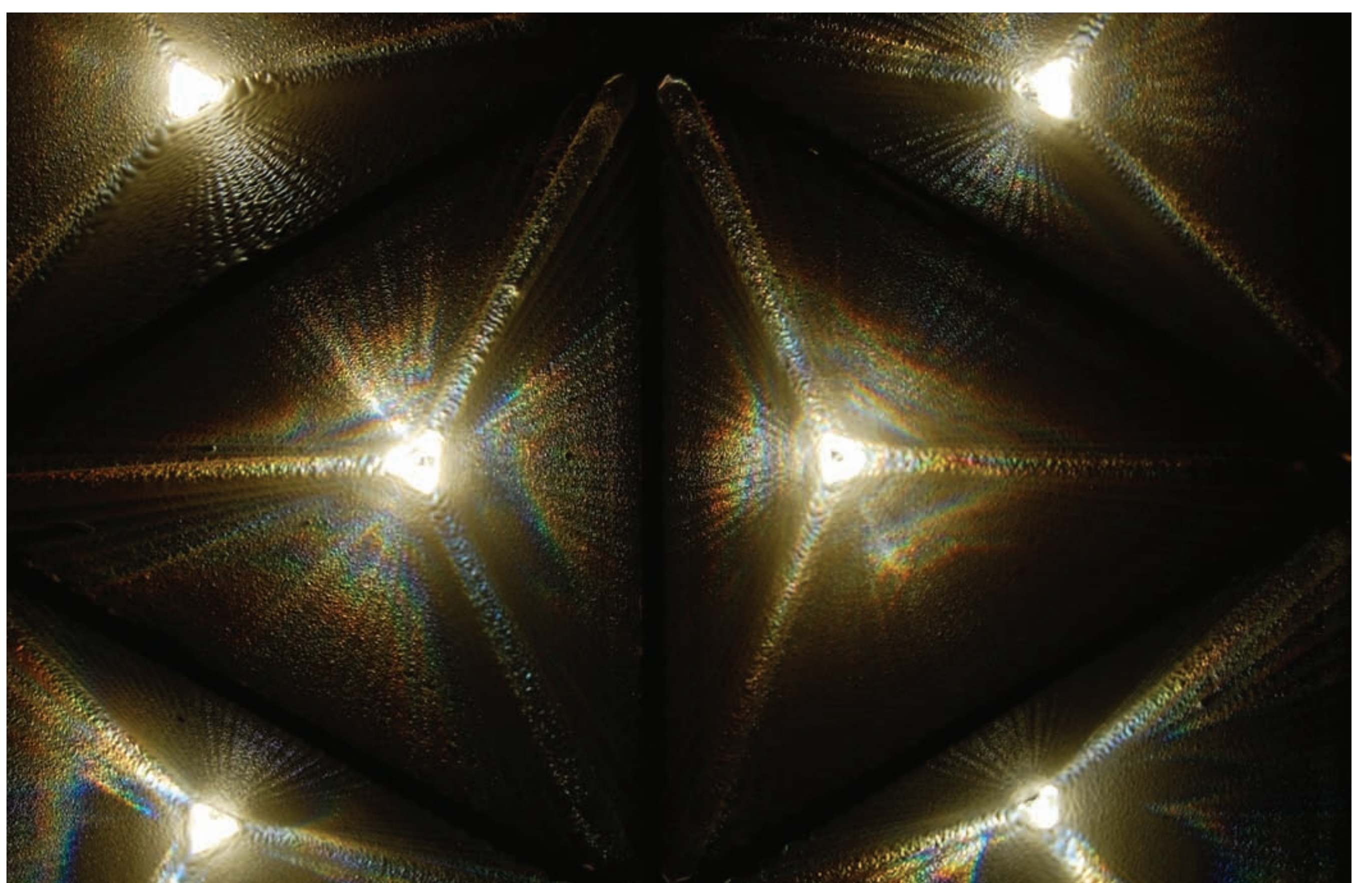


69. HDR composite photograph



70. False color luminance image for values between 10 and .2 cd/m^2)

Finally, an HDR image of the enclosure was made to demonstrate the proposed method for analyzing the resultant luminance values. Despite the arbitrary luminous intensity of the projected light source, Figure 70 shows significant presence of light levels falling near the target luminance values at the upper boundary of the mesopic vision range.



71. Light containers

potential applications

This study proposes the existence of a particular quality of light that provokes a heightened sense of perceptual awareness. Perhaps because light is such a dominant stimulus in our experience of the world, we are less familiar with its subtleties. Visual signals tend not to stimulate immediate comfort reactions the way our skin quickly judges thermal or tactile comfort. Yet based on observational experience, this thesis speculates that our visual perception does trigger these similar value judgements; it is just that they are too often ignored.

After several sessions of twilight observation, my personal experience was that I began to sense my eyes feeling light the way we feel with our touch. This new sense then produced a stimulated awareness of and focus to my mental state. I don't want to get carried away here or sound mystical; I did not have any epiphanies or revelations. I was simply in a kind of light rapture.

Historically, perceptual awareness has probably been most revered in religion. It is interesting to note that the great majority of worship spaces have a similar light levels as the ones discovered here. There is probably little coincidence this is the case; a refined knowledge of perceptual awareness is in our evolutionary blood. It may be that only in recent years, with the advent of electric lighting, we have been able to live without it - but not without experiential sacrifice.

If true, the recovered knowledge of visual perception can be used in architecture to tune the behavior of light in space to take best advantage of this phenomenon. The intent of Sensitive Apertures, as an architectural enclosure system, is to provide an environment that allows this kind of awareness to take place. There can be use for this in our everyday home, office, and community environments. It suggests the importance of the role of gazing space as a key component of spatial comfort and mental stimulation.

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http://www.lon-capa.org/~mmp/kap25/Snell/app.htm

Radiometry and Photometry. http://www.optics.arizona.edu/Palmer/rpfaq/rpfaq.htm

Color and Vision: http://webvision.med.utah.edu/, http://www.handprint.com/HP/WCL/wcolor.html

glossary

Photometry

CANDELA
Unit of luminous intensity, describing the intensity of a light source in a specific direction.

COLOR TEMPERATURE
The color temperature is a specification of the color appearance of a light source, relating the color to a reference source heated to a particular temperature, measured by the thermal unit Kelvin. The measurement can also be described as the “warmth” or “coolness” of a light source. Generally, sources below 3200K are considered “warm;” while those above 4000K are considered “cool” sources.

FOOTCANDLE (FC)
The English unit of measurement of the illuminance (or light level) on a surface. One footcandle is equal to one lumen per square foot. 1 footcandle = 10.8 lux.

FOOTLAMBERT
English unit of luminance. One footlambert is equal to 1/p candelas per square foot.

ILLUMINANCE
A photometric term that quantifies light incident on a surface or plane. Illuminance is commonly called light level. It is expressed as lumens per square foot (footcandles), or lumens per square meter (lux).

LUMEN
A unit of light flow, or luminous flux. The lumen rating of a lamp is a measure of the total light output of the lamp.
The lumen is an SI derived unit for luminous flux. The abbreviation is lm and the symbol is Fv. The lumen is derived from the candela and is the luminous flux emitted into unit solid angle (1 sr) by an isotropic point source having a luminous intensity of 1 candela. The lumen is the product of luminous intensity and solid angle, cd-sr. It is analogous to the unit of radiant flux (watt), differing only in the eye response weighting. If a light source is isotropic, the relationship between lumens and candelas is 1 cd = 4p lm. In other words, an isotropic source having a luminous intensity of 1 candela emits 4p lumens into space, which just happens to be 4p steradians. We can also state that 1 cd = 1 lm/sr, analogous to the equivalent radiometric definition. Lumens are what we get from the hardware store when we purchase a light bulb. We want a high number of lumens with a minimum of power consumption and a reasonable lifetime. Projection devices are also characterized by lumens to indicate how much luminous flux they can deliver to a screen. (from J. Palmer (U of A)

LUMINANCE
A photometric term that quantifies brightness of a light source or of an illuminated surface that reflects light. It is expressed as footlamberts or candelas per square meter. The luminous flux spreading outward per steradian in a given direction per square meter of perceived surface area. Its radiometric counterpart is Radiance.

LUX (LX)
The metric unit of measure for illuminance of a surface. One lux is equal to one lumen per square meter. One lux equals 0.093 footcandles.

PHOTOMETRY
The science dealing with the measurement of light as opposed to radiant power.

Quantity	Radiometric	Photometric
Power	watt	lumen
power per unit area	W/m2	lm/m2 = lux
power per unit solid angle	W/sr	lm/sr = candela
power per area per solid angle	W/m2-sr	lm/m2-sr = cd/m2 = nit

Vision and Perception

ACCOMODATION:
when there is no stimulus, as in complete darkness, or uniform luminance, the [visual] system accommodates (focuses) to distance of approximately one meter.

CONES
-most sensitive to green/yellow (long wavelength light)
-located in retina periphery

CREPUSCULAR
1. of, pertaining to, or resembling twilight; dim; indistinct.
2. appearing or active in the twilight

FLICKER FUSION
The image refresh rate at which individual images are undetectable and the sequence appears to be continuous.
(30 fps for humans, 200 fps for fruit flies)

FLOATERS
fragments of condensed coliagen in the jelly inside the eyeball.

MESOPIC
between 001 cd/m^2 and 3 cd/m^2
“low mesopic vision desaturates hue, shifts the white point toward blue, and constricts the perceptible differences in a reflectance gray scale toward white. The appearance of white surfaces changes from an almost luminous brightness to a veiled, shimmering gray; foveal detail disappears and the world dissolves into a quilt of large, low contrast shapes.” www.handprint.com

PHOTOPIC
> 3 cd/m^2
luminous efficacy function peaks at 555nm

RODS
-sensitive to blue/green (short wavelength light) (see luminosity response curve graph p.42 Linvingstone. “the relationship between the response and the number of photons varies with the wavelength of the light.”)
-send signals to luminance ganglion cells (same cells that receive sum of response from cone cells)
-located in retina center (fovea (2 degrees of visual field))

SCOTOPIC
< .001 cd/m^2
luminous efficacy function peaks at 507nm

‘STARS’
A blow to the head can cause the vitreous fluid that fills the back two-thirds of the eyeball to rub against the retina. In fact, as we age, the vitreous fluid becomes thicker and can push or pull on the retina even with more modest movements of the head. “The retina does not feel pain – it only responds by sending some form of light signal,” says Dr. David Granet, professor of ophthalmology at UCSD. “So certain types of exertion stimulate the retina and cause the “stars.”
http://physicalsciences.ucsd.edu/outreach/QA/qa_072104.htm

TWILIGHT
The period between sunset and total darkness or between total darkness and sunrise. Total darkness does not occur immediately when the sun sinks below the horizon because light from the sun that strikes the atmosphere is scattered (both by the air itself and by suspended matter, e.g., dust and smoke). Civil twilight ends when the center of the sun is 6° below the horizon. Although it is still not very dark, it is necessary to use artificial light to carry out most activities. Nautical twilight ends when the sun’s center is 12° below the horizon; at about this time the light is too dim for the user of a sextant to see a sharp horizon. Astronomical twilight ends when the sun’s center is 18° below the horizon; by this time even the faintest stars overhead can be seen. (Similar definitions apply to morning twilight.) During twilight, Venus or Mercury is often seen as the evening star or morning star. The length of twilight depends on latitude and the time of year. Twilight is generally shorter at the equator, where the sun’s path toward the horizon is more nearly vertical than at higher latitudes; typically, astronomical twilight may last for 1 hr at the equator and 1 1/2 hr in New York City.

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for creating the beautiful program, Photosphere, which allowed me to capture luminance data with ease

Tim Eliassen, TriPyramid Structures, Inc.
for suggesting the University of Arizona

appendix

Indices of Refraction

material	N
vacuum	1.00
air	1.00
water (ice)	1.30
water	1.33
eye, aqueous humor	1.33
eye, vitreous humor	1.34
milk	1.35
alcohol, ethyl	1.36
eye, cornea	1.38
eye, lens	1.41
glass, fused silica 1.45	
glass, borosilicate	1.47
oil, vegetable	1.47
plexiglas	1.48
glass,crown,soda-lime	1.51
salt	1.51
quartz, crystalline 1.54	
amber	1.54
glass, flint (29% lead)	1.56
Reichenbach C1500	1.57
Reichenbach 100RW	1.60
Gaffer G210	1.62
glass, flint (55% lead)	1.66
sapphire	1.76
glass, flint (71% lead)	1.80
zircon, high	1.96
zirconia, cubic	2.17
diamond	2.41
iodine crystal	3.34
silicon	4.24

Luminance Benchmarks

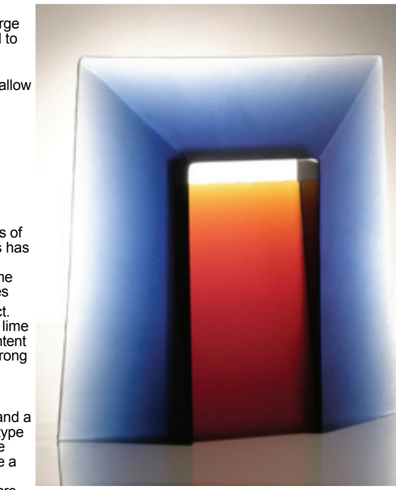
cd/m^2	source
7.0×10^{10}	lightning flash
3.2×10^{9}	sun (zenith)
1.0×10^{8}	photoflash
4.0×10^{6}	eye damage after brief exposure
4.3×10^{5}	sun (horizon)
3.2×10^{5}	eye damage after long exposure
3.2×10^{5}	upper photopic limit
1.2×10^{5}	60W incandescent light
3.0×10^{4}	white paper in noon sunlight
1.3×10^{4}	clear sky (horizon)
1.1×10^{4}	T8 fluorescent light
7.0×10^{3}	low beam car headlights
4.2×10^{3}	full moon (zenith)
2.6×10^{3}	white paper in daylight shade
2.5×10^{3}	clear sky (zenith)
2.0×10^{3}	cloudy sky (zenith)
2.0×10^{3}	white paper in dark cloudy day
5.6×10^{2}	full moon (horizon)
3.2×10^{2}	upper mesopic limit
2.8×10^{2}	white paper in surgical light
1.3×10^{2}	overcast sky (zenith)
1.3×10^{2}	white paper in office light
100	wax candle flame
84	white paper under reading light
1	clear sky, twilight (zenith)
.1	lower mesopic limit
.06	white paper in full moon
3.2×10^{-4}	white paper in starlight
4.0×10^{-4}	starless night sky
7.5×10^{-7}	absolute threshold (steady light)

source: Wyszecki & Stiles (1982), Packer & Williams (2003), Makous (1998), Handbook of Space Astronomy & Astrophysics (1982), Hunt (2004)

Casting Glass

This range of transparent coloured glass was designed to withstand the special demands of both large and small lost-wax and investment plaster casting applications. Properties that Gaffer® considered to be valuable for an all round casting glass included the following:

- An ability to achieve the **entire colour spectrum** with the same base glass. This would allow firing and casting characteristics to be the same across the range. Colour could then be mixed.
- Extreme resistance to devitrification.
- Low viscosity at casting temperatures.
- Low annealing and strain point temperatures.
- High surface definition.
- A high refractive index, high dispersion and good optical clarity.
- Excellent cold working properties.



Red Wedge 550mm tall
www.richardwhiteley.com

The challenge involved in meeting some of these goals is constrained by the temperature limitations of Plaster of Paris, or gypsum, the main ingredient of common glass casting moulds. Plaster of Paris has an upper temperature limitation of around 900°C. (1650°F). It begins to decompose at around 880-900°C. (1616-1650°F), both physically breaking down and losing strength, while at the same time giving off SO_3 gas, which introduces surface blisters into the glass object. This makes the use of typical soda lime glasses, and even medium lead content glasses unwise, because of their strong tendency to devitrify at around 800-900°C. (1470-1650°F), owing principally to their relatively high viscosities at these temperatures, and a propensity for faster devitrification type crystal growth. In addition soda lime glasses, in particular, generally have a considerably higher annealing point, which means longer cooling cycles are required, especially in the case of massive pieces.Gaffer® casting glass, however, has virtually no tendency to devitrify at all at top casting temperatures, nor on its descent in temperature down to the annealing range. Furthermore, its very low viscosity, and low surface tension at 780-900°C. (1426-1650°F), leads to very good surface definition. This makes it especially suitable for jewelry scale pieces, as well as large work. Low annealing temperatures, and superior cold working characteristics, lead to lower costs overall. The chemical formulation closely approximates glasses used by the Czech casting artists.Careful control of time/temperature melting parameters, along with special conditioning techniques ensures that all colours are homogenous and compatible with each other.

Billets.

SPECIFICATIONS:

Linear expansion coefficient (a): 92×10^{-7} (20-300°C.)
Density: 3.6g/cc. (Or 2.08 ounces/cu.in. or 3.73 ounces/US fluid ounce).
Casting temperature (Recommended): 780-850°C. (1426-1562°F.)
Annealing temperature (tg): 440°C. (824°F)
Strain point: 400°C. (752°F)

Frit.

Casting Crystal Lead Emissions.

Several customers over the years have asked us whether kiln firing our casting crystal at top melting temperatures gives off harmful lead emissions.

In order to give an accurate scientific answer to that question we commissioned in 2001 a laboratory report from Watercare Services Ltd in Auckland, a company employed by the City Council to monitor water and air pollution. The purpose of the study was to assess compliance with Occupational Safety and Health (OSH) Workplace Exposure Standards (WES) and Biological Exposure Indices for New Zealand (2001)

In order to give worst case results the lead monitoring was carried out in the studio of local artist Anne Robinson, melting 2 x 25kgs of casting crystal at 870°C (1600°F) in a deliberately unventilated room. All doors and windows were shut. The methodology for determining the lead in the kiln room was as follows:

Methodology

A sample of ambient workplace air (next to the kiln vent) was drawn through an SKC IOM Inhalable Dust Sampler (plastic) to capture particulate lead. The IOM sampler is designed to capture dust, which is fine enough to be inhaled by employees. The sample gas stream was then passed through a dilute solution of nitric acid and hydrogen peroxide. This solution captures any lead fumes, which may pass through the filter. An SKC Personal Sampling Pump calibrated to a flow rate of 2.00 ± 0.01 litres/min was used to draw sample through the sampling system.

Results and Discussion

The results of the lead monitoring are presented in the Table below:

Gaffer® Casting Crystal Annealing Schedules. Semi-Open and Open Forms *

Thickness (inches) (mm)	Anneal Soak at 824°F at 440°C	Initial Cooling Rate (°F/Hr) (°C/Hr)	Initial Cooling Range (°F) (°C)	Second Cooling Rate (°F/Hr) (°C/Hr)	Second Cooling Range (°F) (°C)	Final Cooling Rate** (°F/Hr) (°C/Hr)	Final Cooling Range (°F) (°C)	Total Elapsed Time
.5 in 12 mm	1.0 hr	120 67	824 - 694 440 - 368	240 133	694 - 604 368 - 318	1200 670	604 - 75 318 - 24	2hrs 53mins
.75 in 19 mm	1.5 hr	52 29	824 - 679 440 - 360	104 58	679 - 589 360 - 310	520 290	589 - 75 310 - 24	6hrs 6mins
1.0 in 25 mm	2.0 hr	29 16	824 - 664 440 - 353	58 32	664 - 574 353 - 303	290 160	574 - 75 303 - 24	10hrs 44mins
1.5 in 38 mm	3.0 hr	13 7.2	824 - 626 440 - 330	26 14.4	626 - 536 330 - 280	130 72	536 - 75 280 - 24	25hrs 30mins
2.0 in 50 mm	4.0 hr	7.8 4.3	824 - 594 440 - 312	15.6 8.6	594 - 504 312 - 262	78 43	504 - 75 262 - 24	45hrs
2.5 in 60 mm	5.0 hr	5.2 2.9	824 - 566 440 - 296	10.4 5.8	566 - 476 296 - 246	52 29	476 - 75 246 - 24	2 days 23hrs
3.0 in 75 mm	6.0 hr	3.3 1.8	824 - 524 440 - 273	6.6 3.6	524 - 434 273 - 223	33 18	434 - 75 223 - 24	5 days 4hrs
3.5 in 88 mm	7.0 hr	2.5 1.4	824 - 486 440 - 253	5.0 2.8	486 - 396 253 - 203	25 14	396 - 75 203 - 24	7 days
4.0 in 100 mm	8.0 hr	1.8 1.0	824 - 454 440 - 234	3.6 2.0	454 - 364 234 - 184	18 10	364 - 75 184 - 24	10 days 15hrs
4.5 in 113 mm	9.0 hr	1.6 0.9	824 - 417 440 - 214	3.2 1.8	417 - 327 214 - 164	16 9	327 - 75 164 - 24	12 days 14hrs
5.0 in 125 mm	10.0 hr	1.3 0.7	824 - 383 440 - 195	2.6 1.4	383 - 293 195 - 145	13 7	293 - 75 145 - 24	17 days 4hrs
5.5 in 138 mm	11.0 hr	1.1 0.6	824 - 347 440 - 175	2.2 1.2	347 - 257 175 - 125	11 6	257 - 75 125 - 24	21 days 6hrs
6.0 in 150 mm	12.0 hr	0.9 0.5	824 - 312 440 - 156	1.8 1.0	312 - 222 156 - 106	9 5	222 - 75 106 - 24	27 days
8.0 in 200 mm	16.0 hr	0.47 0.26	824 - 172 440 - 78	0.94 0.52	172 - 82 78 - 24	- -	- -	62 days

* Based on: Schedules for commercial annealing of ordinary ware. Corning Glassworks. Corning N.Y. 1950. For forms that are able to cool reasonably equally on all sides.
** Obviously cooling rates of thinner pieces are faster than ordinary kilns would lose heat. In those cases the kiln can be allowed to cool at its normal rate.