

# Sensitive Apertures

By Ben Ari McDonald

University of Arizona  
School of Architecture  
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## 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  $1 \text{ cd/m}^2$ ), 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.

## 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.

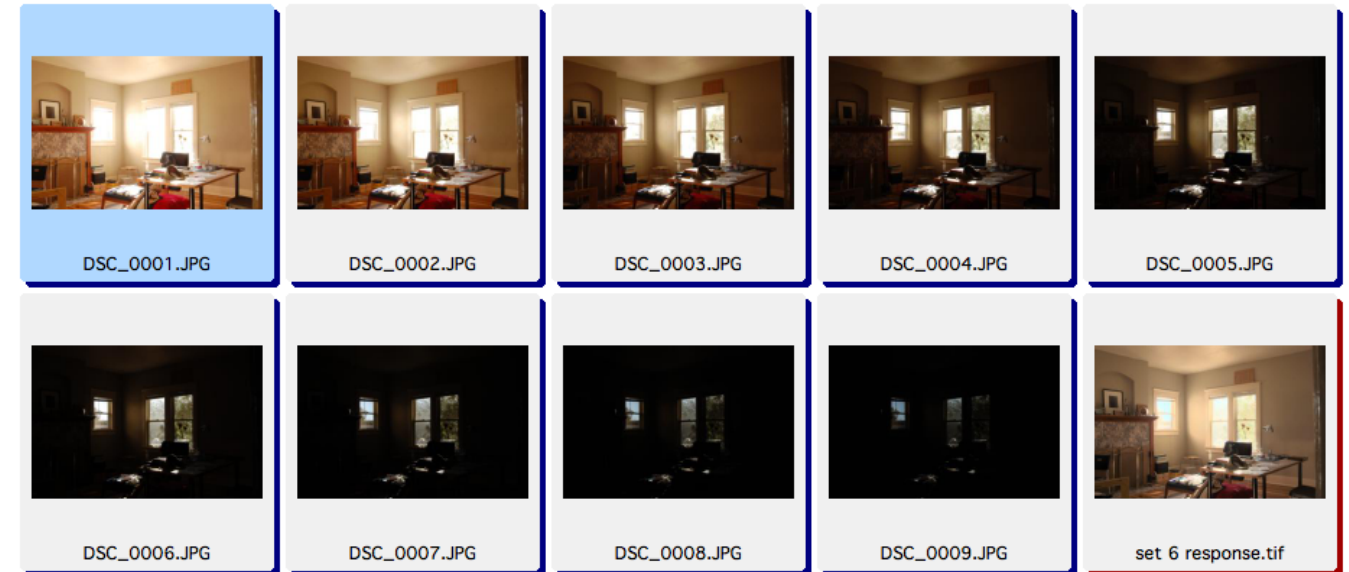
## Light Measurement

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<sup>2</sup>) 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 in.

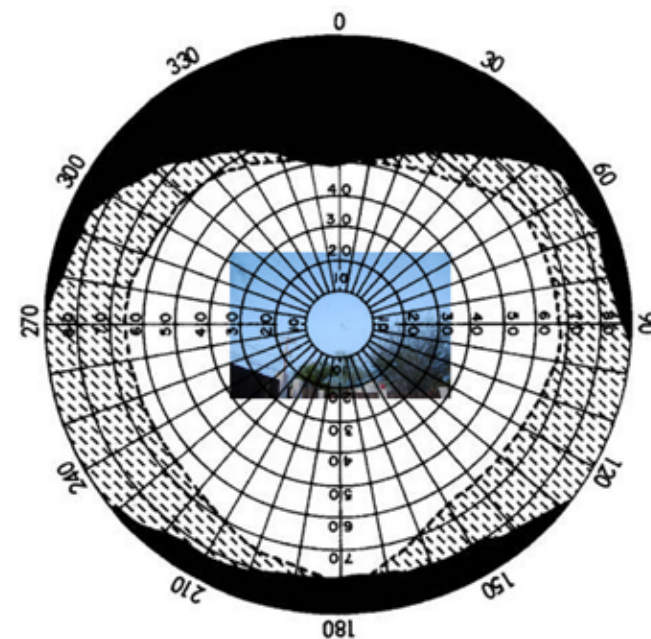
In the case of this thesis, the scene was an observed area of the sky. Using the imaging software, a reliable average luminance value was calculated over a selected area of the image. This value was then associated with the perceptual observations taken at the same time during twilight.



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 Anywhere 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/m <sup>2</sup>	quality
5:50	1170	
5:55	903	golden glow
6:00	717	
6:05	422	
6:10	312	
6:11		<b>sunset</b>
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		<b>end civil twilight</b>
6:40	.613	stars visible, very hard to read, colors difficult
6:45	.189	

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

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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
6:45	2.08	colors in eastern sky, planets visible landscape is black, very hard to read, stars visible, colors hard to distinguish
6:49		<b>end civil twilight</b>
6:50	.638	sky is dark

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

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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		<b>end civil twilight</b>

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

time	cd/m <sup>2</sup>	quality
5:50	1440	
5:55	901	
6:00	645	
6:05	437	
6:10	166	
6:12		<b>sunset</b>
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		<b>end civil twilight</b>
6:40	.542	stars visible
6:45	.186	

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

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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		<b>end civil twilight</b>

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

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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		<b>end civil twilight</b>
7:35	.240	stars visible

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

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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		<b>end civil twilight</b>
6:40	.451	

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

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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		<b>end civil twilight</b>

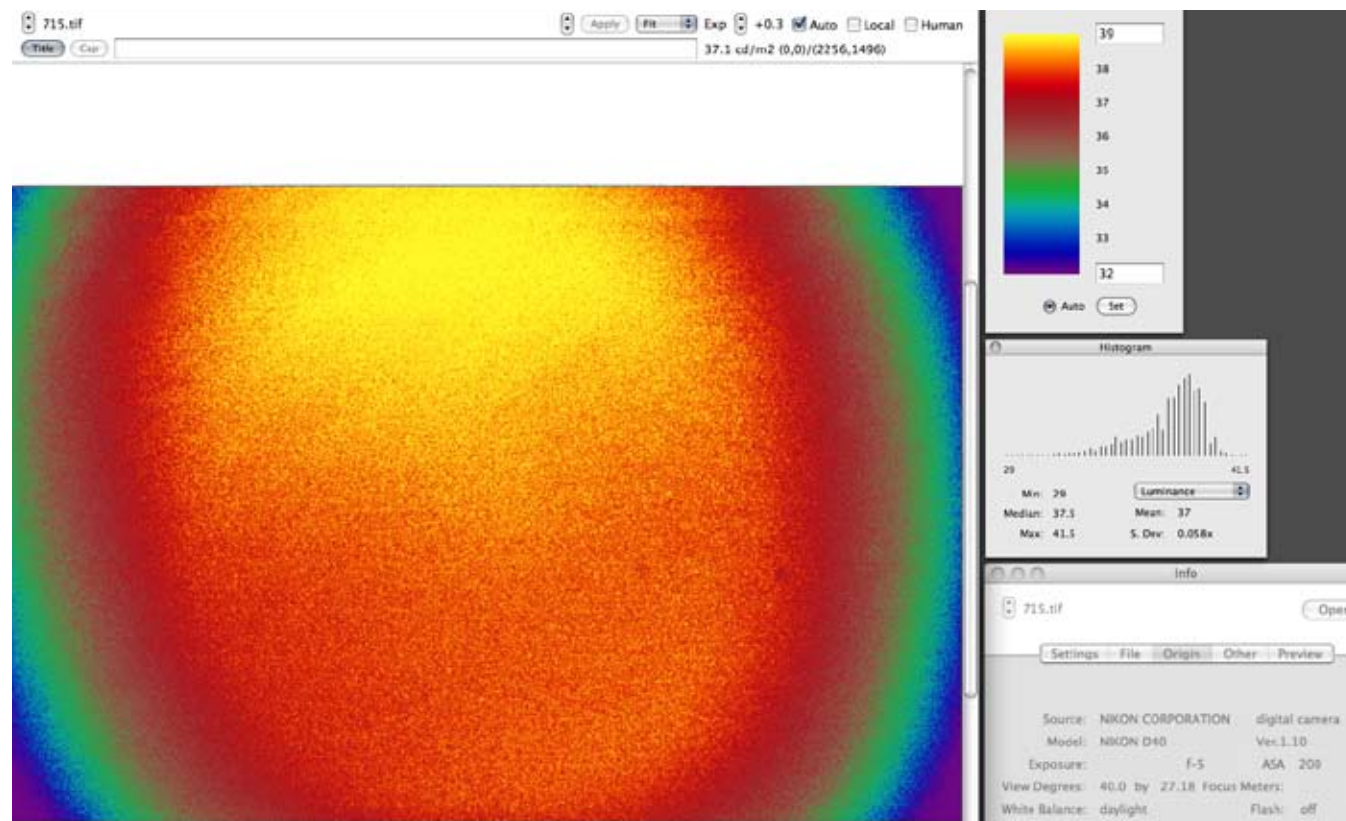
May 9, 2008, zenith, clear sky, no clouds  
f-stop: 5, zoom: , view degrees: 40

time	cd/m <sup>2</sup>	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		<b>sunset</b>
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	.197	sports difficult, hard to read
7:35	.536	too dark, sky lacks interest
7:37		<b>end civil twilight</b>
7:40	.196	blue color much more brilliant, rod sensitivity?

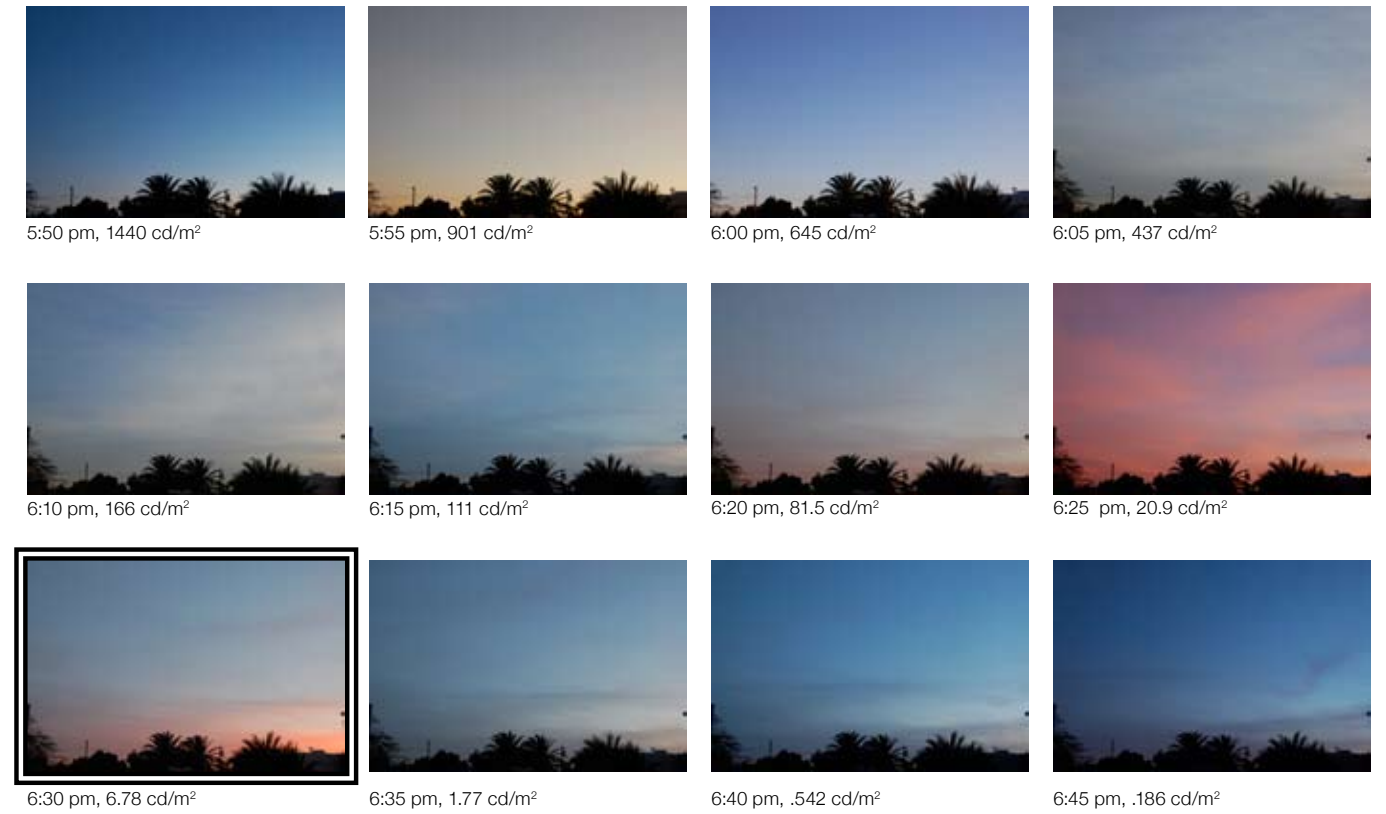
## Typical Image Luminance Analysis

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<sup>2</sup>), the luminance value recorded for this time is an average of the entire image.

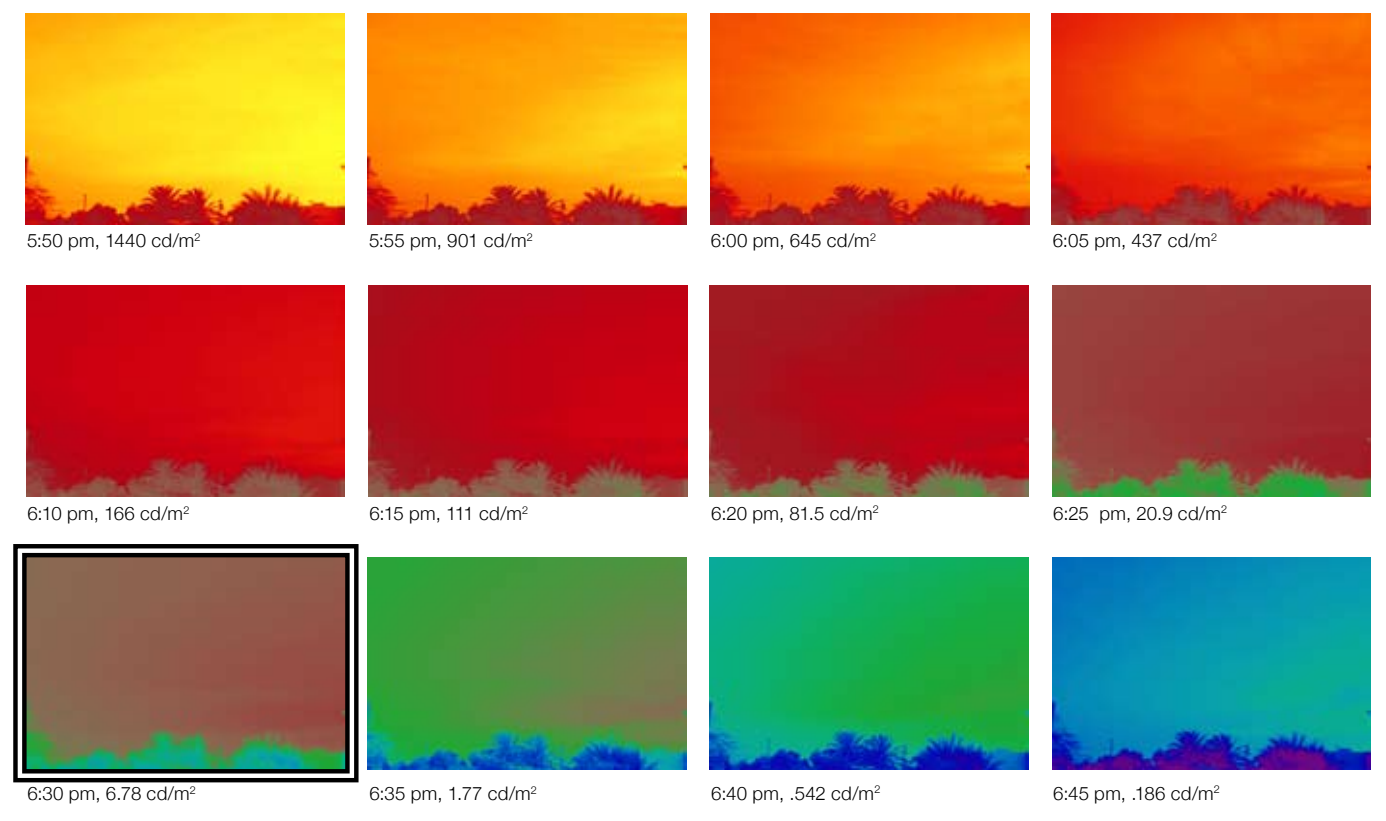
Proceeding this way, average luminance values corresponding to observed areas of sky were recorded for each image. Figure 6 shows another way to visualize luminance values across an entire twilight session by setting a custom range for the false color map based on the brightest values from the early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

### Floater

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.

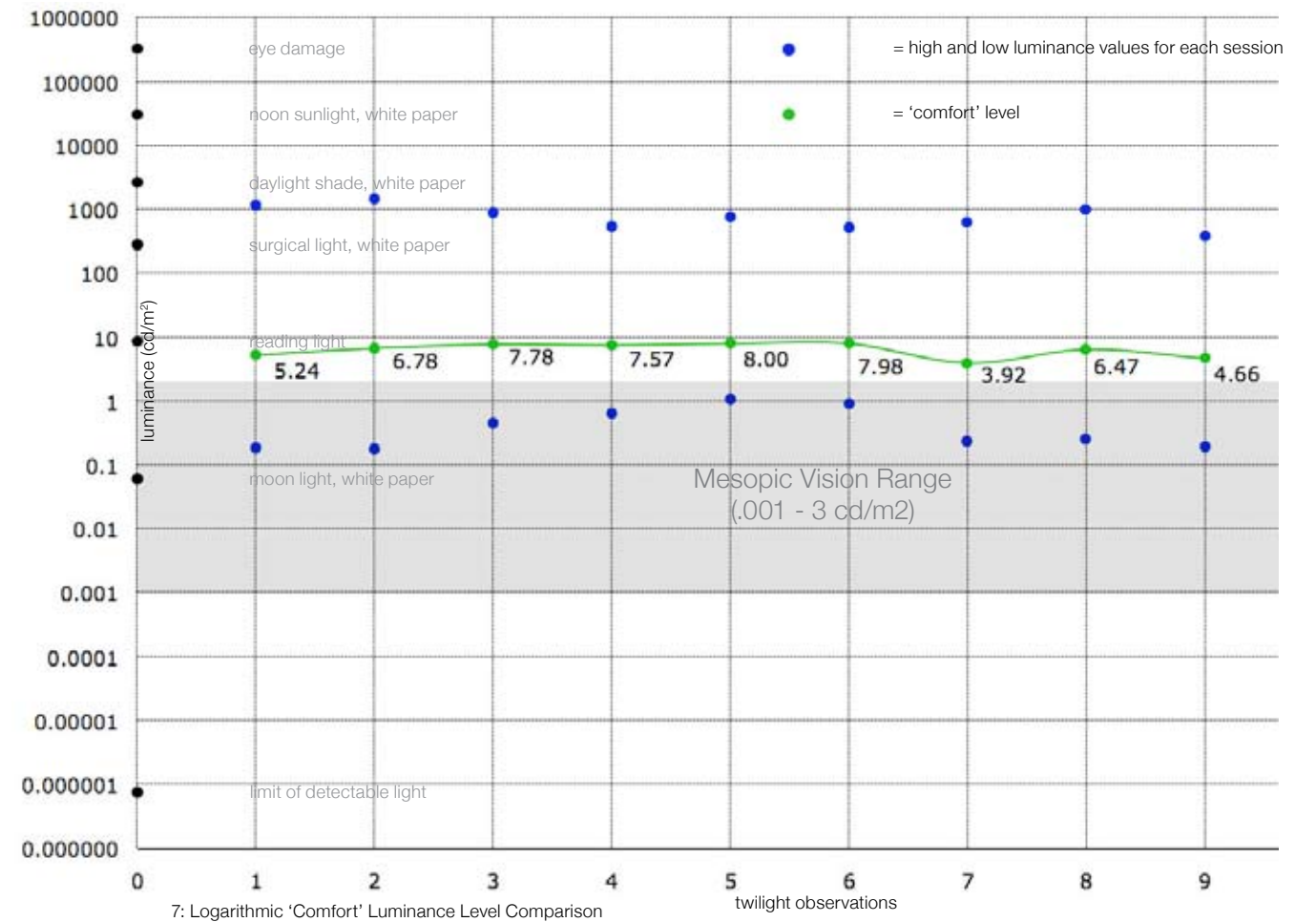
### Sound

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 more clearly.

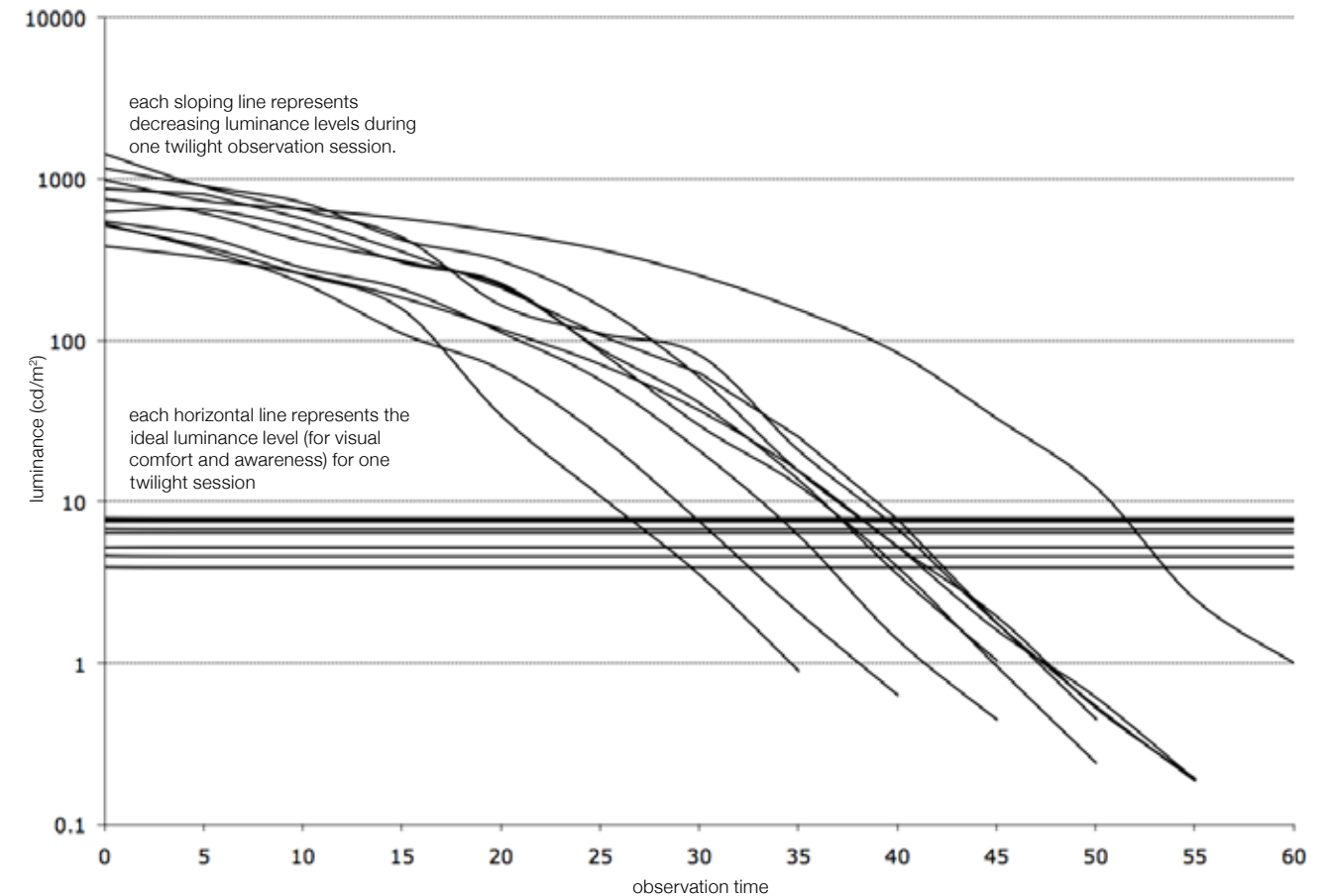
### Observation Analysis

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  $\text{cd}/\text{m}^2$ . 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 leaves a window open for future investigation.



7: Logarithmic 'Comfort' Luminance Level Comparison



8: Logarithmic 'Comfort' Luminance Level Graph

sensitive apertures

fabrication

### 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.

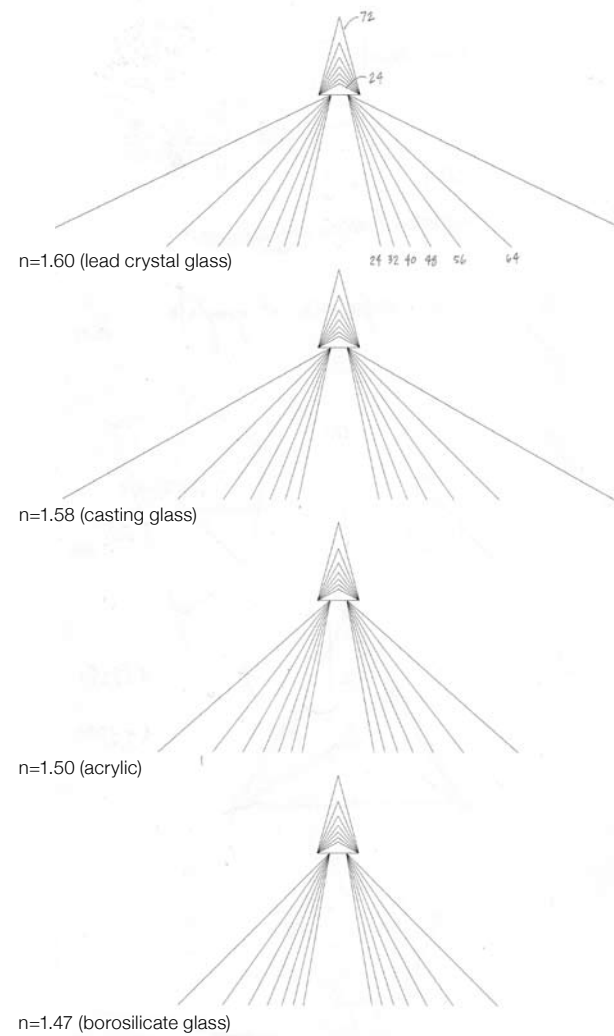
Secondly, the light that was allowed to enter through the enclosure needed to be as uniform as possible. This requirement sparked the idea to use refraction at the aperture and spatial depth within the enclosure in order to spread the light on the inside surface of the enclosure. Using packing geometry 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'.

## Refraction Studies

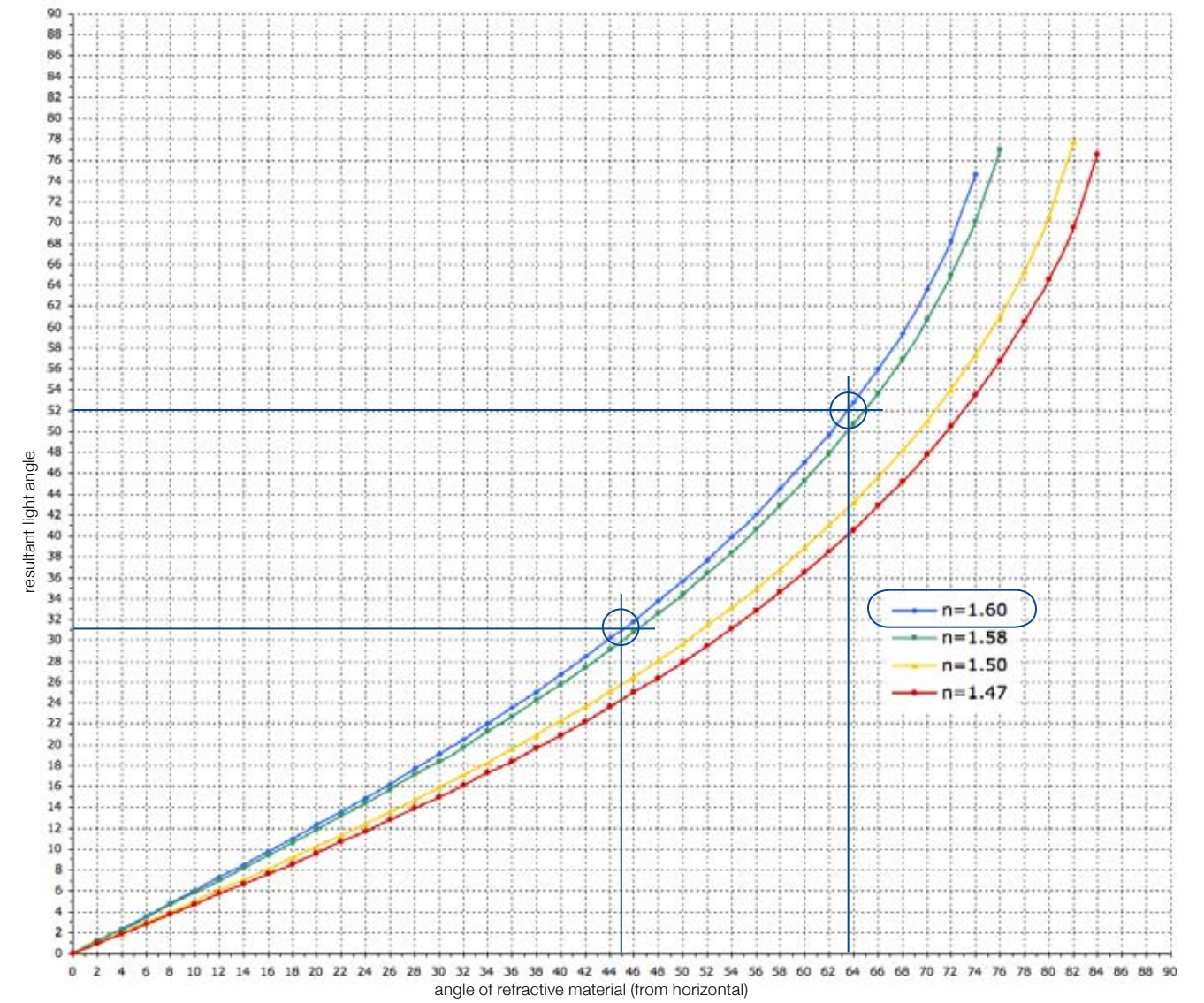
A series of diagrams and graphs show the range of possible refraction angles using available materials such as acrylic and glass. These clearly show how the more refractive materials are able to more effectively bend the light.

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).

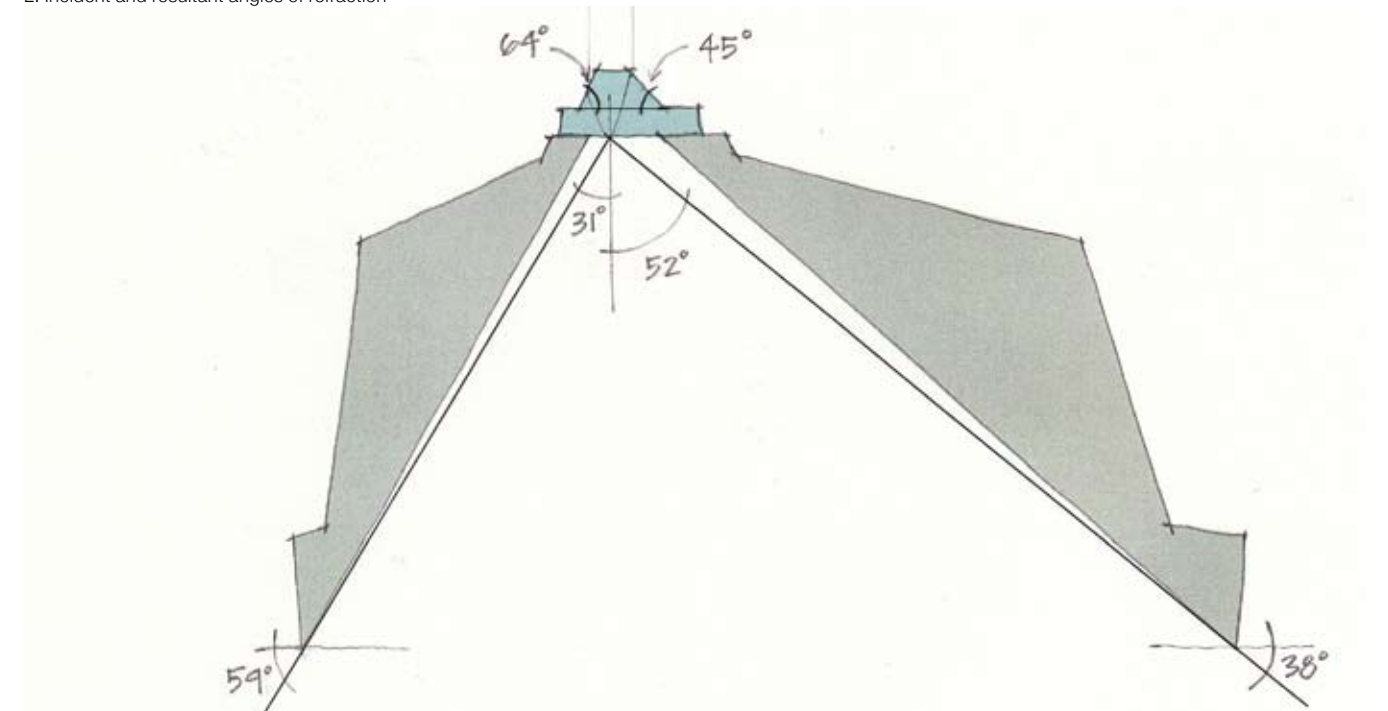
Lead crystal glass, with an index of refraction ( $n$ ) of 1.60 was chosen for the final form. To ensure the material of the light container captured the refracted light, the form was made slightly steeper.



1. Possible light paths for various aperture angles



2. Incident and resultant angles of refraction



3. Typical light container refraction analysis



13. Material Science laboratory furnaces



14. Casting tools



20. Unfinished glass castings



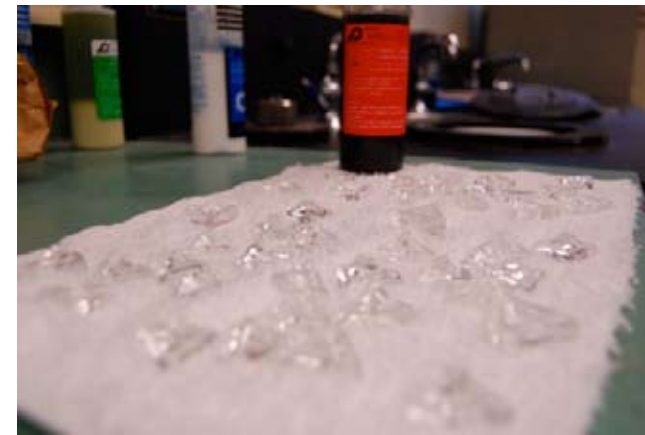
21. Polishing wheel



15. 1000° C furnace



16. Casting



22. Final polish with 9 micrometer polycrystalline diamond lubricant



23. Finished apertures



17. Graphite mold



18. Glass placed in oven for annealing



24. Finished apertures

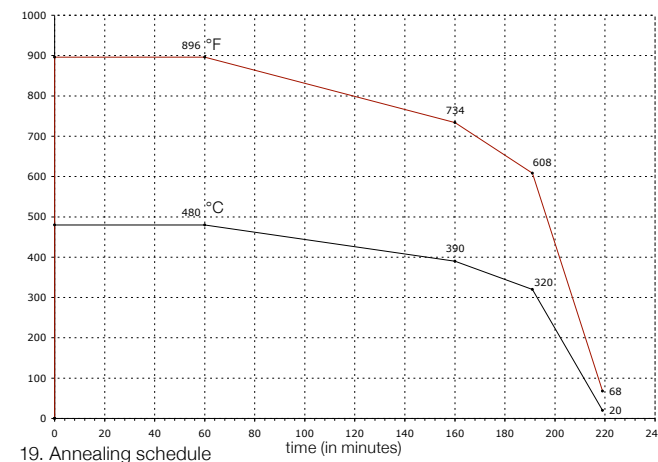


25. Annealing oven

## Aperture Fabrication

### 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.



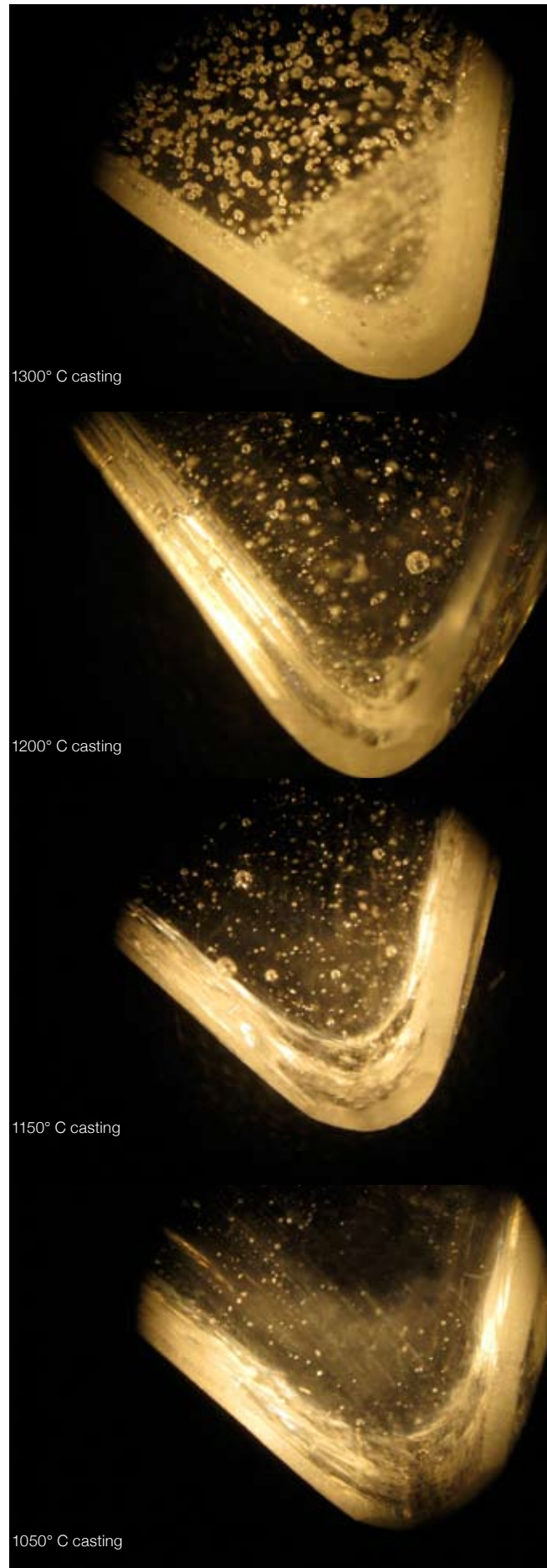
19. Annealing schedule

### 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.

### 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 gaseous bubbles. The size and density of these bubbles altered the optical behavior of the glass by diffusing the light.



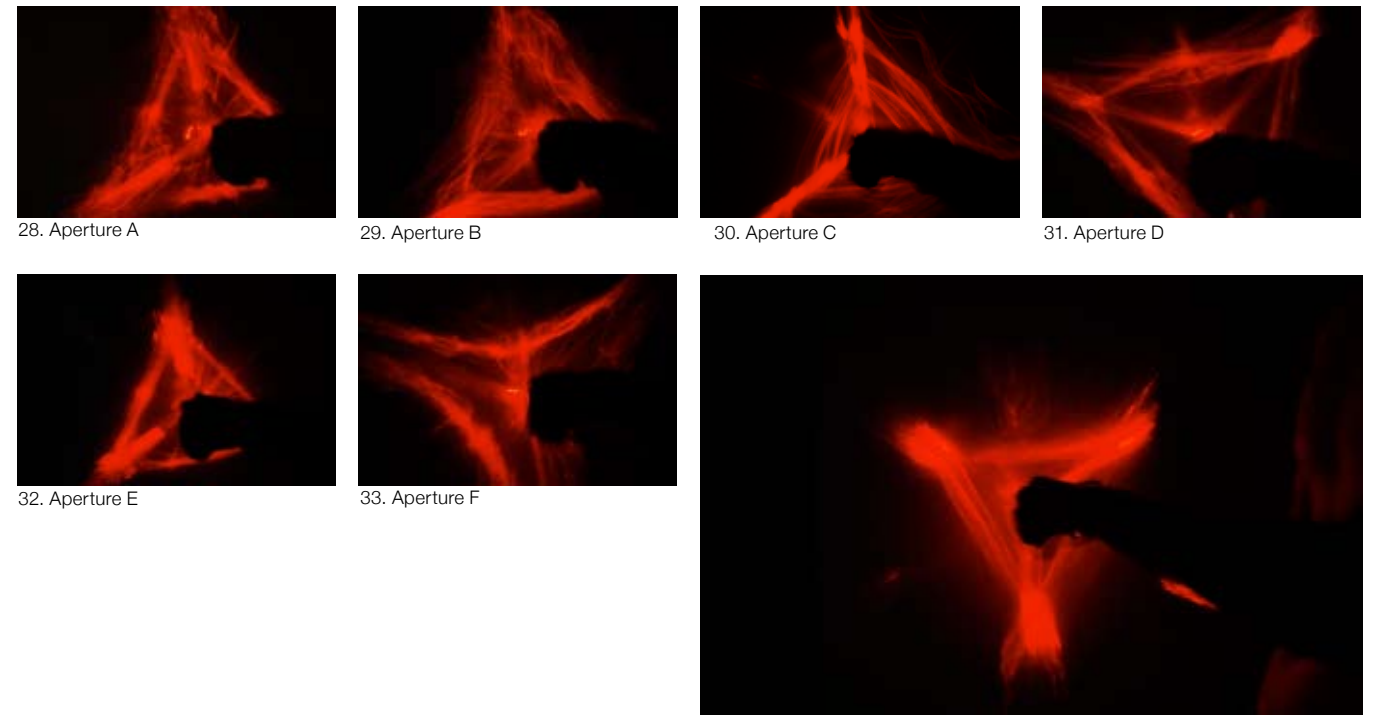
1300° C casting

1200° C casting

1150° C casting

1050° C casting

27. Microscopic analysis of clarity



28. Aperture A

29. Aperture B

30. Aperture C

31. Aperture D

32. Aperture E

33. Aperture F

34. Aperture Glass



A

B

C

D

E

F

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)



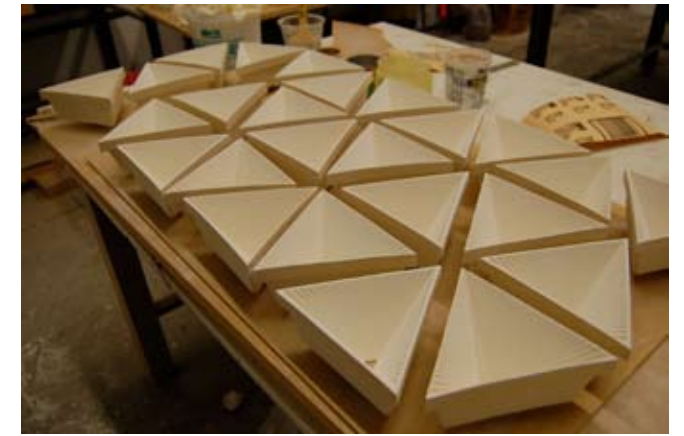
43. Slip casting setup



44. Slip casting production line



48. Glaze coating detail



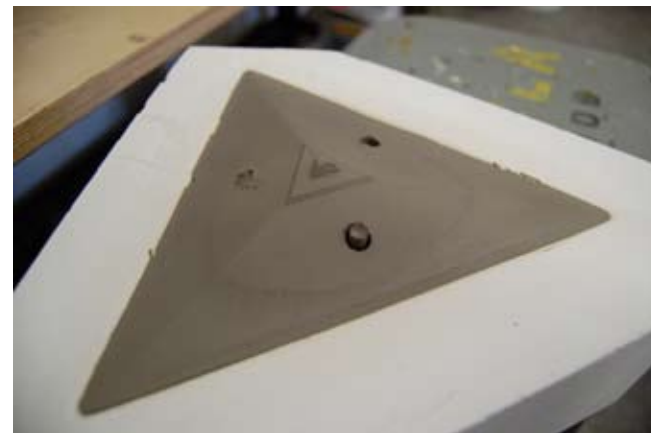
49. Glazing production



45. Pottery plaster molds for slip casting



46. Slip



47. Greenware



50. Ceramic kiln



51. Glazing application

## Light Container Fabrication: Ceramic

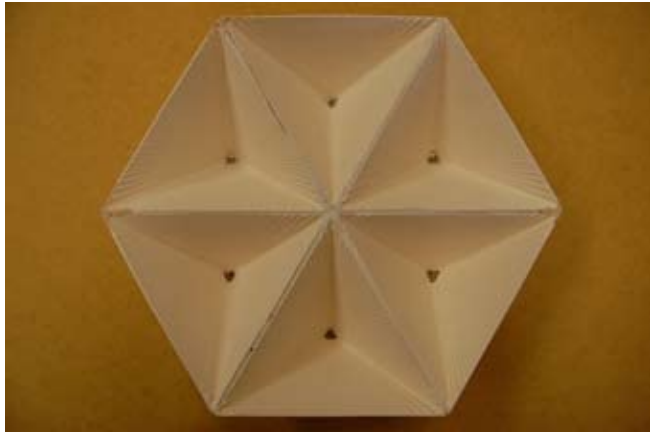
### Slip Casting

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,

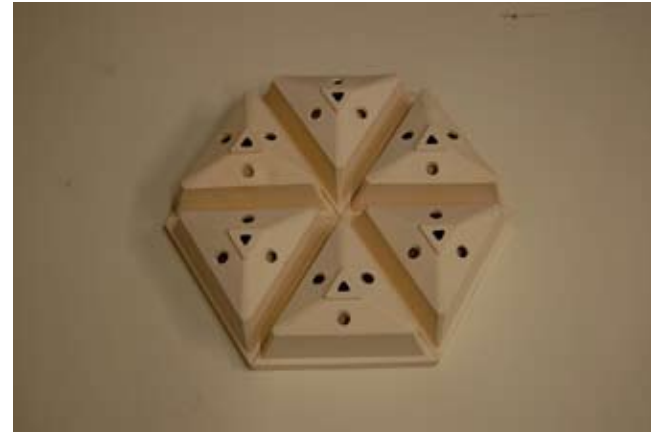
the thickness of the hardened slip was optimal and the remaining liquid was poured out, producing the hollow cavity for insulation as see in Figure 55. The clay body then remained undisturbed in the plaster for a period of at least 8 hours which gave them time to harden enough to be released from the 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)

### Glazing

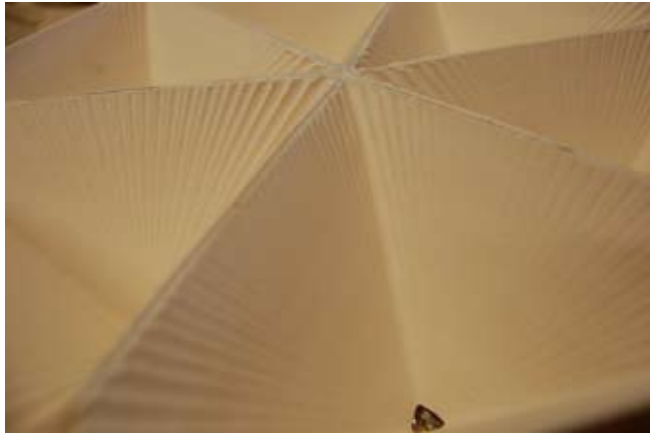
The finish surface of the light containers greatly affected the quality of light. To reinforce the intention of an evenly scattered interior light, a matte white glaze was chosen to minimize any specular behavior. After an initial bisque fire (Figure 50), the light containers were glazed using a spray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



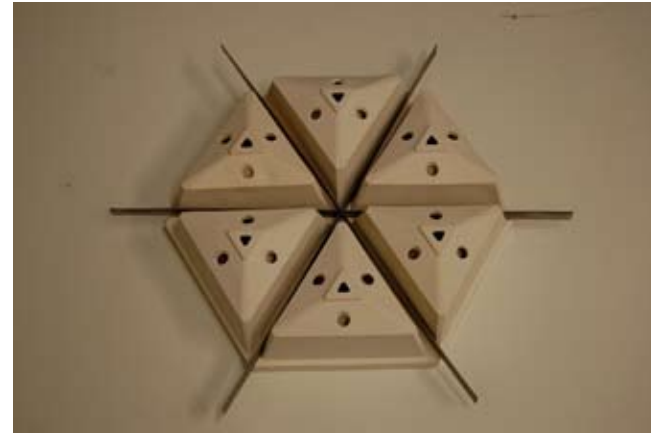
52. Hexagonal unit interior



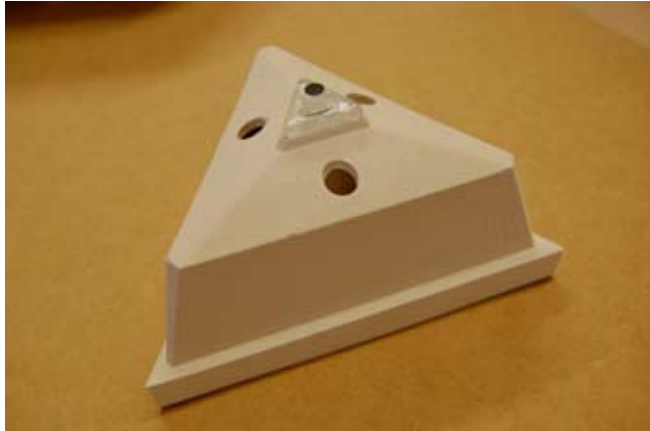
56. Hexagonal unit exterior



53. Interior detail



57. Potential reinforcement



54. Typical light container



55. Section through typical cell

### Tiling

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

sensitive apertures

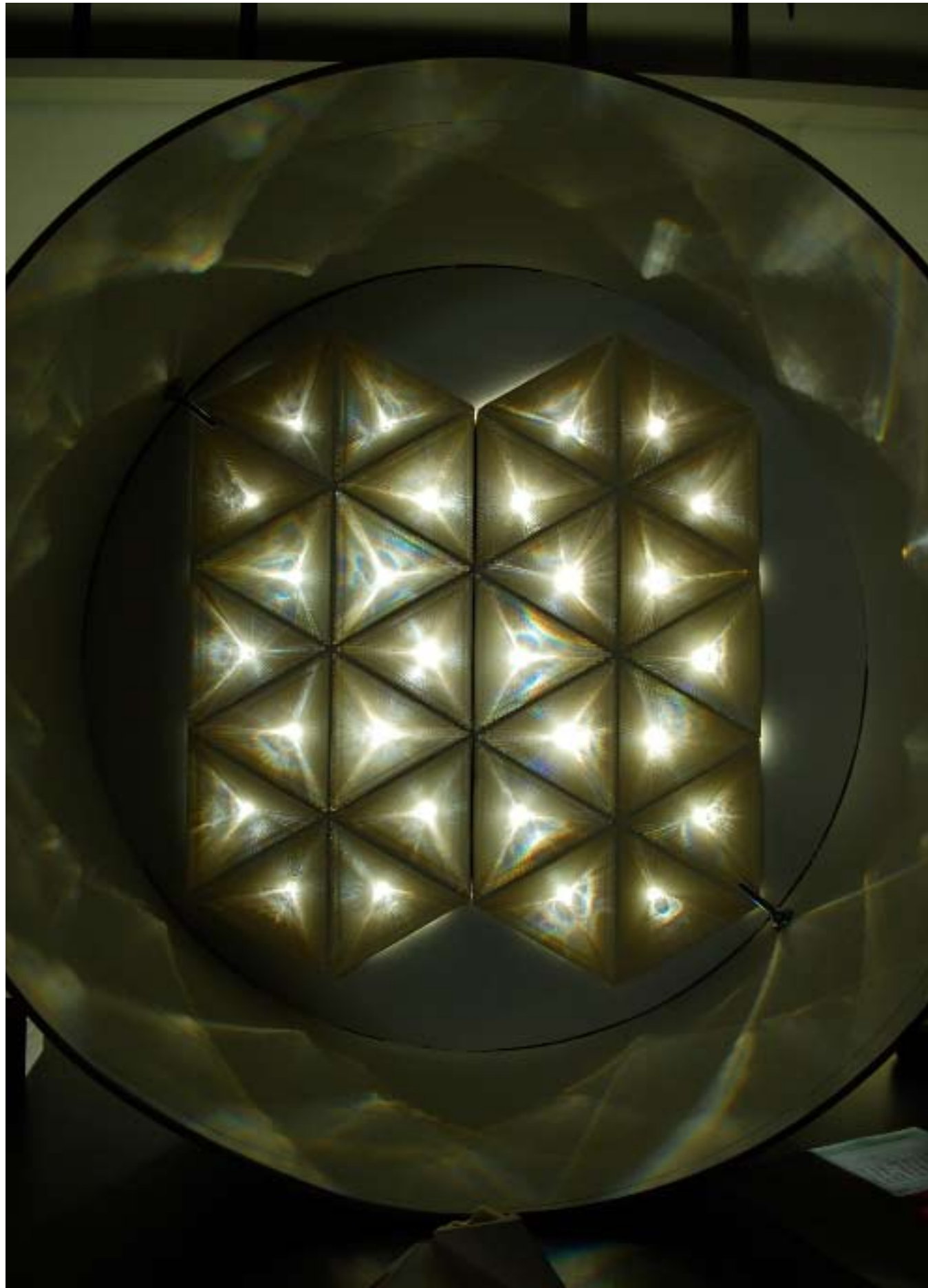
assembly



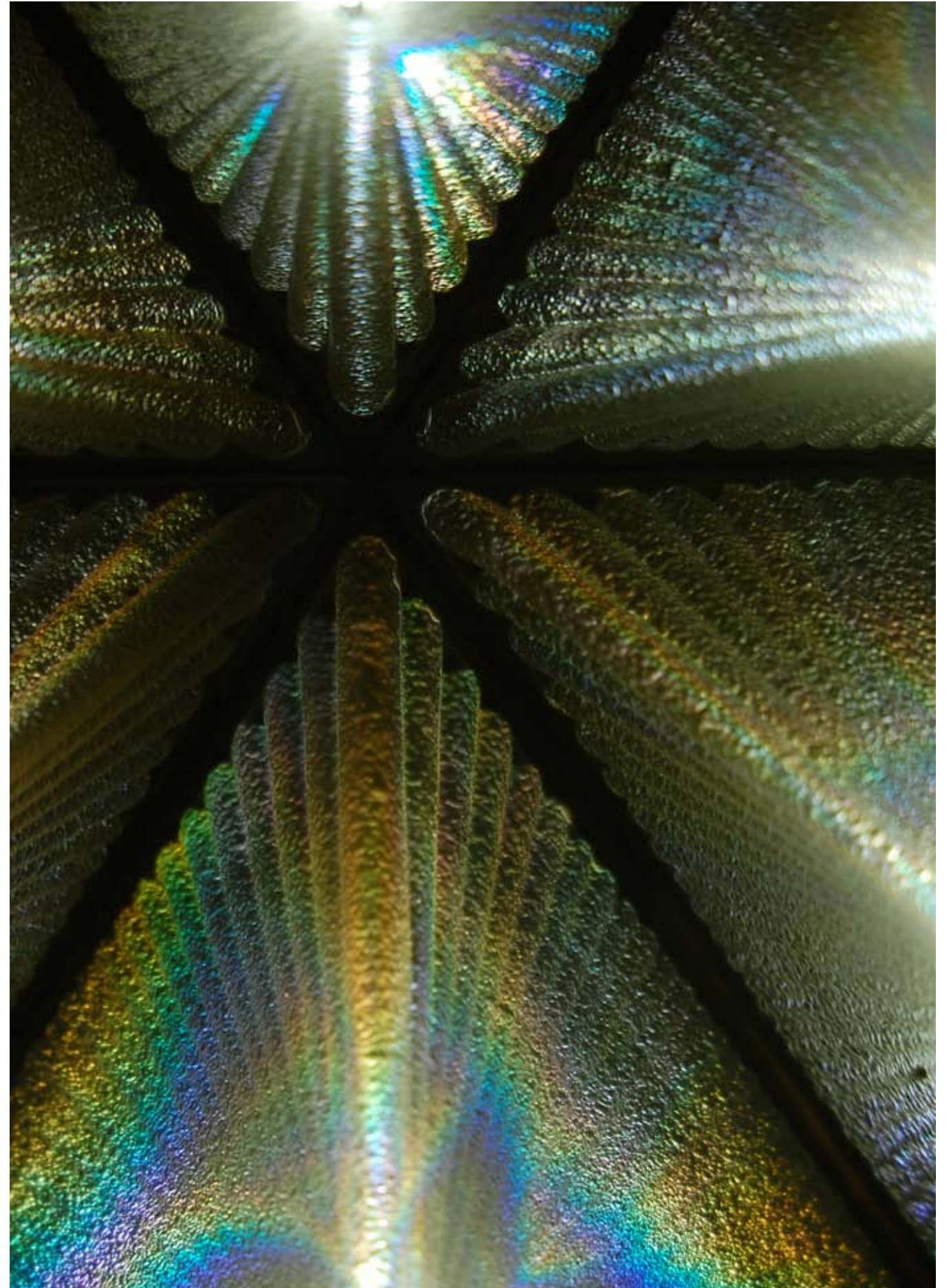
Large scale light test

### Assembly

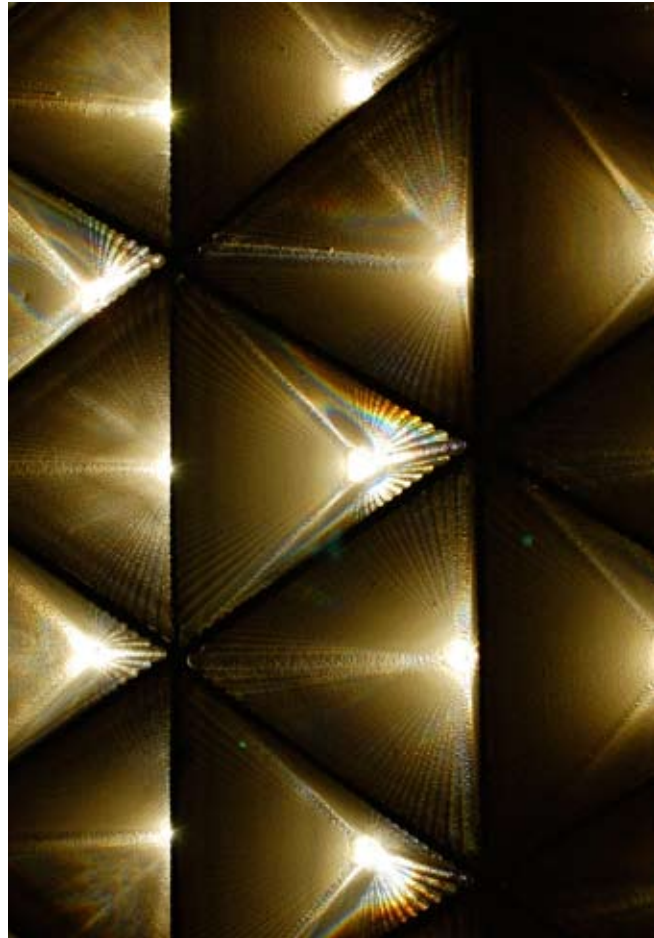
A larger demonstration of the system was set up using projector light as a sunlight substitute. Refractive colors were very visible in most of the cells and described how the light was being redirected. Irregularities in the geometry of the light path provided insight into how the aperture geometries 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



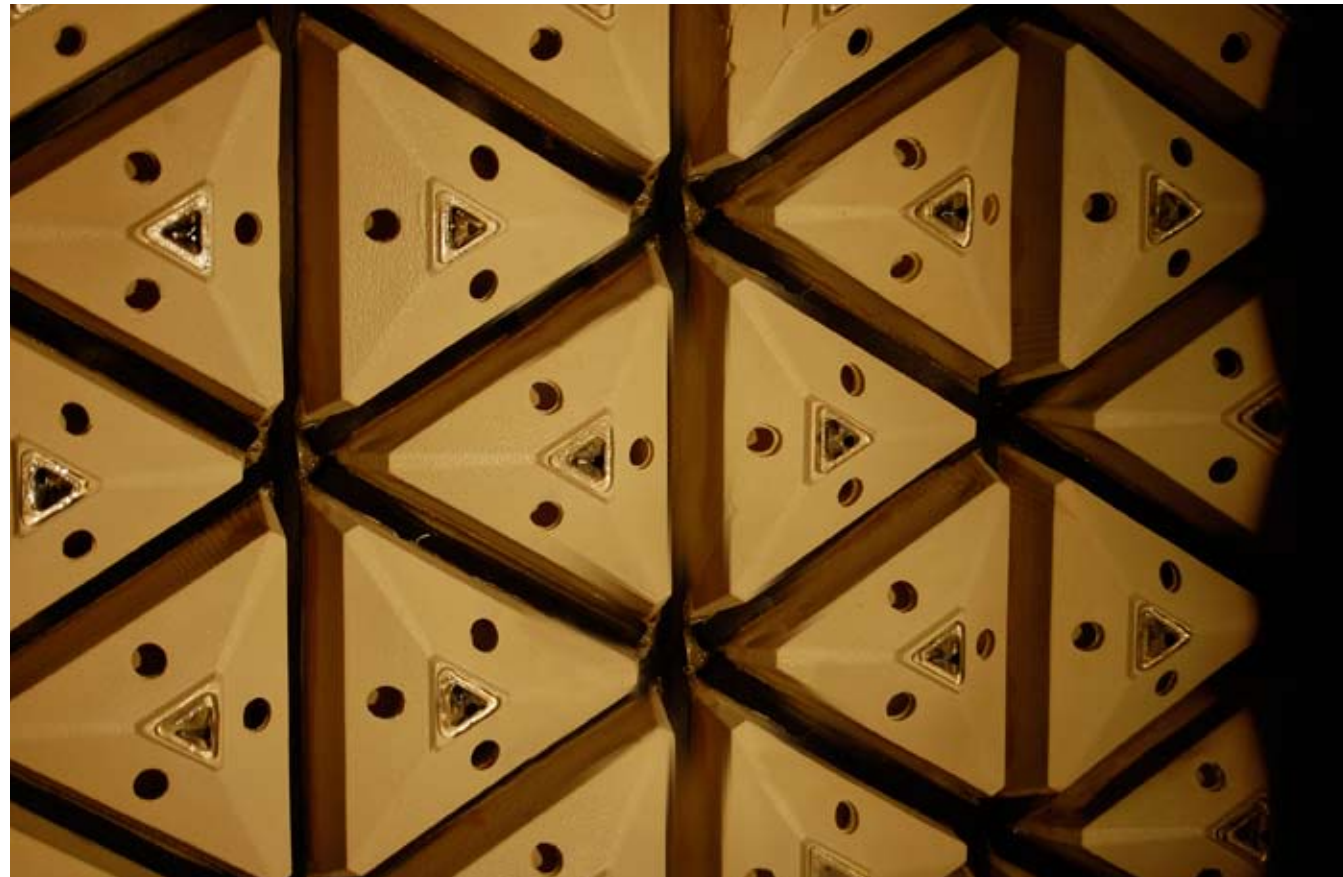
66. Light Container intersection



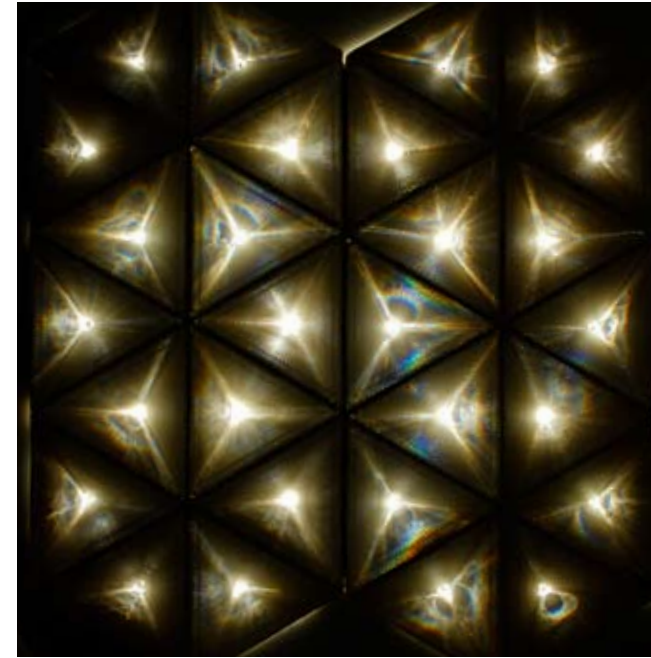
62. Interior tiling



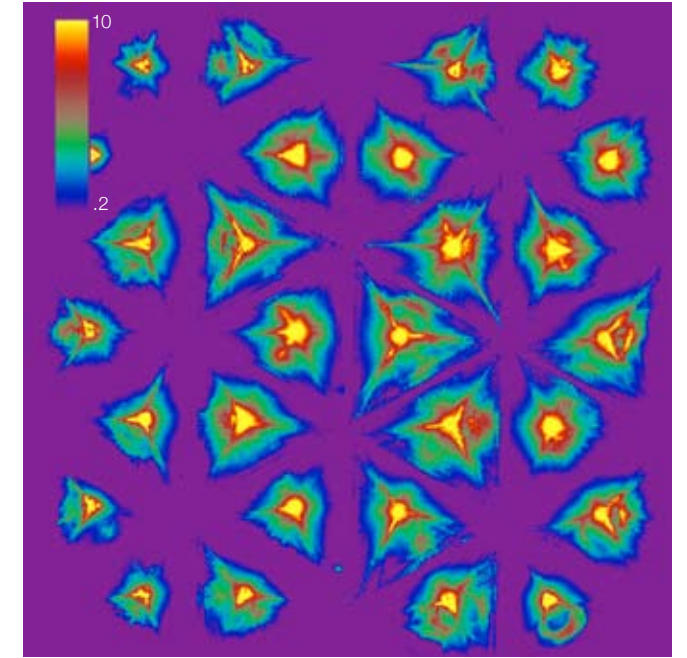
65. Interior tiling



63. Exterior detail

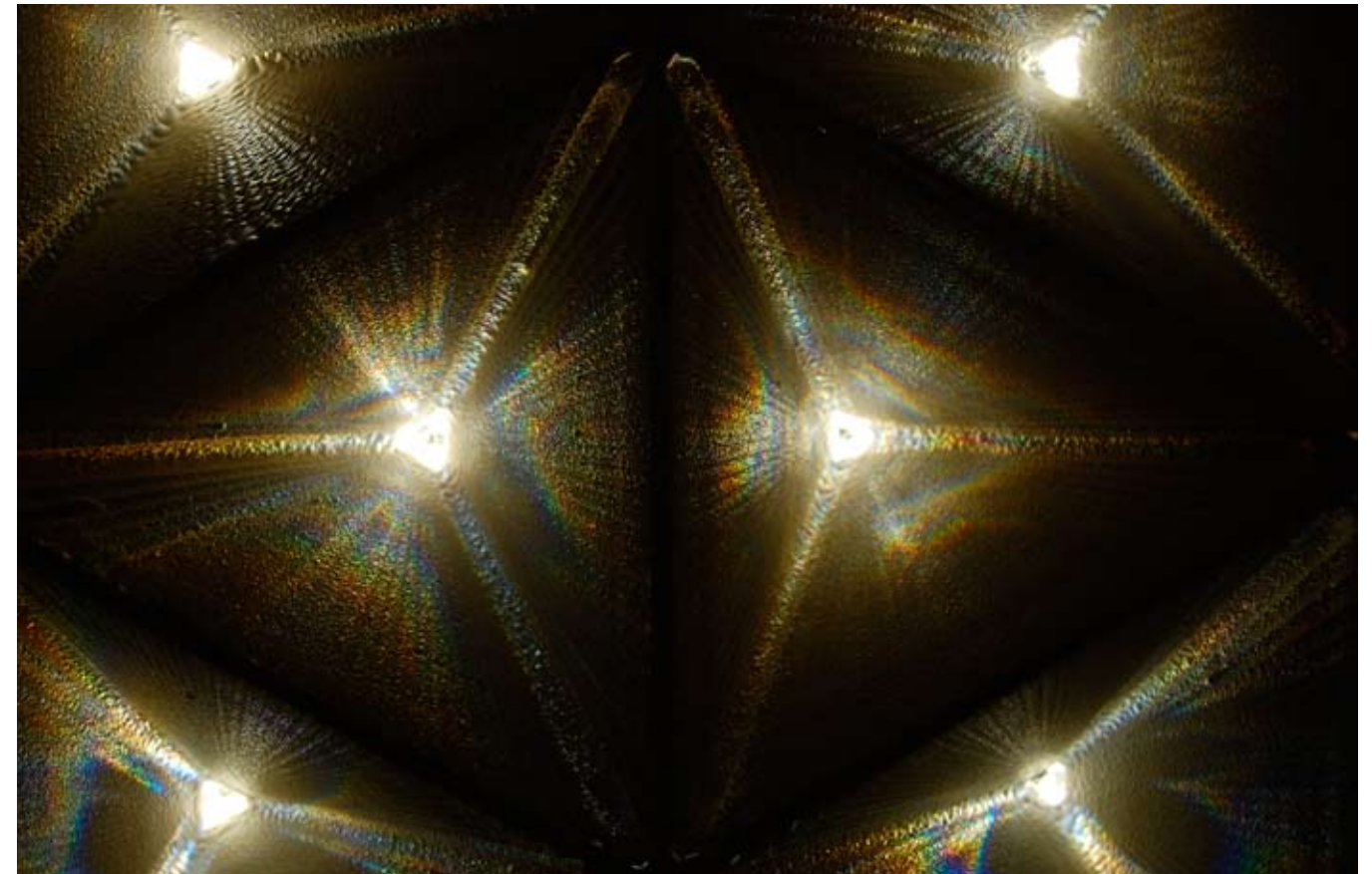


69. HDR composite photograph



70. False color luminance image for values between 10 and .2 cd/m²)

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