Basic Design Principles for LED Lighting Systems

Dr. Kevin Garcia, CEO
Breault Research Organization

www.breault.com

Breault Research   Taking Light Further

Agenda

Introduction and General Comments

Illumination Design Principles and Common Optics

Efficiency Factors

Manufacturing Considerations (slides courtesy of Fraen Corp.)

LED Light Design Example

Introduction and General Comments

Breault Research Org. (BRO)

Provides optical software (ASAP®), training, and engineering services

Founded in 1979 by Dr. Robert P. Breault

Staff of 45, including 20+ engineers, based in Tucson, Arizona

ISO 9001:2000 Certified

General Comments

The purpose of illumination design is to provide the necessary amount and color of light into a specified area, angular distribution or both.

Illumination design is different from traditional optical (lens) design:

- There is no concern for the quality of image transfer in an illumination system.
- The performance merits for illumination systems vary significantly depending on the applications.
- Optimum or even minimally functional designs generally have complex surface shapes not well described by traditional optical surface functions.
- Detailed source descriptions are required for accurate system analysis.
- Accurate analysis requires large, long raytraces.
- Optimization is not easily implemented due to the high number of variables needed to describe illumination systems, the inherent stochastic nature of illumination system analysis, and the long analysis time required to evaluate those systems.

General Comments

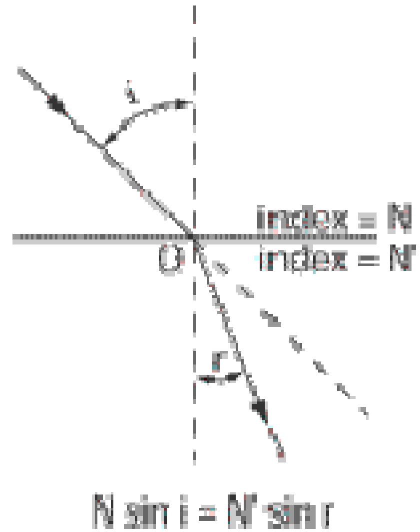
Illumination systems are different from traditional optical systems:

- Illumination systems generally are produced in high volume applications – this means low cost and ease of manufacture are of prime importance.
- Aesthetic qualities are a big concern for illumination systems. Systems have to "look good" in the lit and unlit state.
- Subjective measures are prevalent in illumination system design. The illumination pattern might be "too streaky" or "too much glare" which are difficult to quantify.
- The real laws of illumination engineering
  1) There is never enough light
  2) There is never enough time
  3) There is never enough money

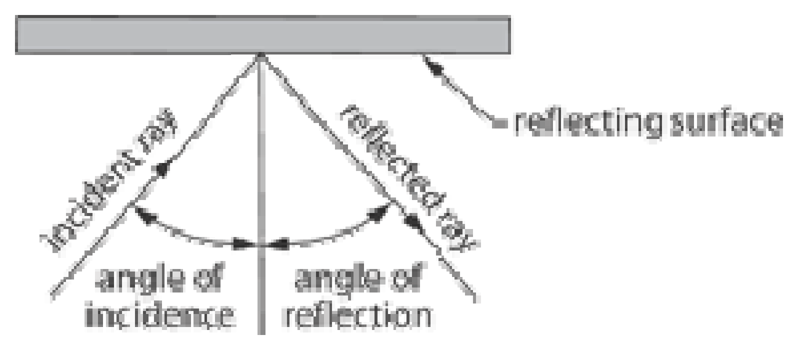
Illumination Design Principles and Techniques

Basic Optical Principles

Refraction: The bending of incident rays as they pass from a medium having one refractive index (N) into a medium with a different refractive index (N').



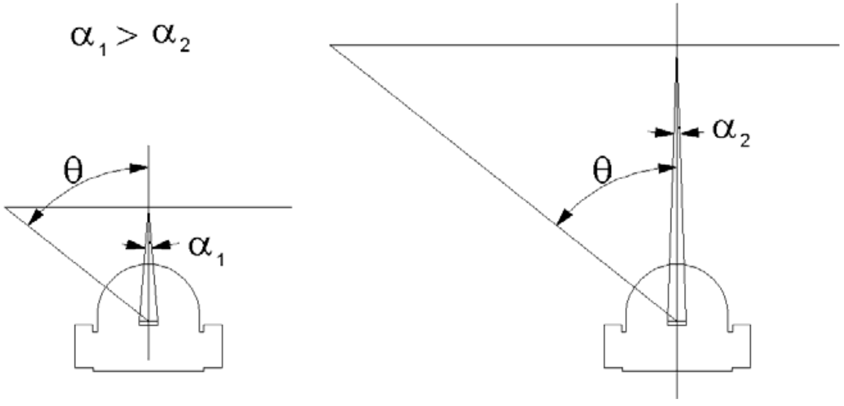
Reflection: Return of radiation by a surface, without change in wavelength. The reflection may be specular, from a smooth surface; diffuse, from a rough surface or from within the specimen; or mixed, a combination of the two.



Basic Optical Principles

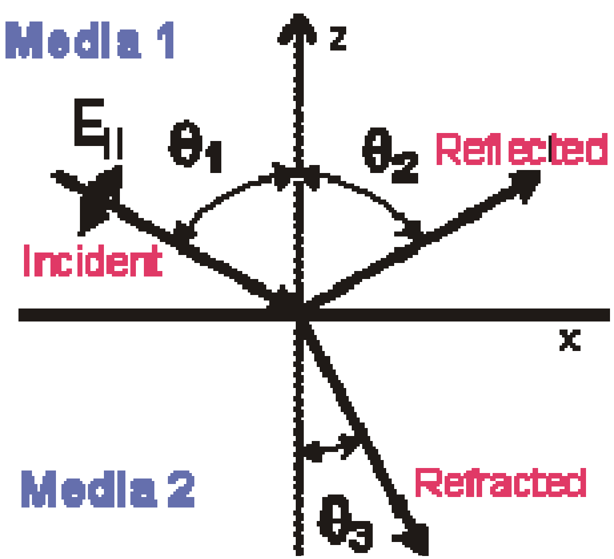
Total Internal Reflection (TIR): The reflection that occurs within a substance because the angle of incidence of light striking the boundary surface is in excess of the critical angle.

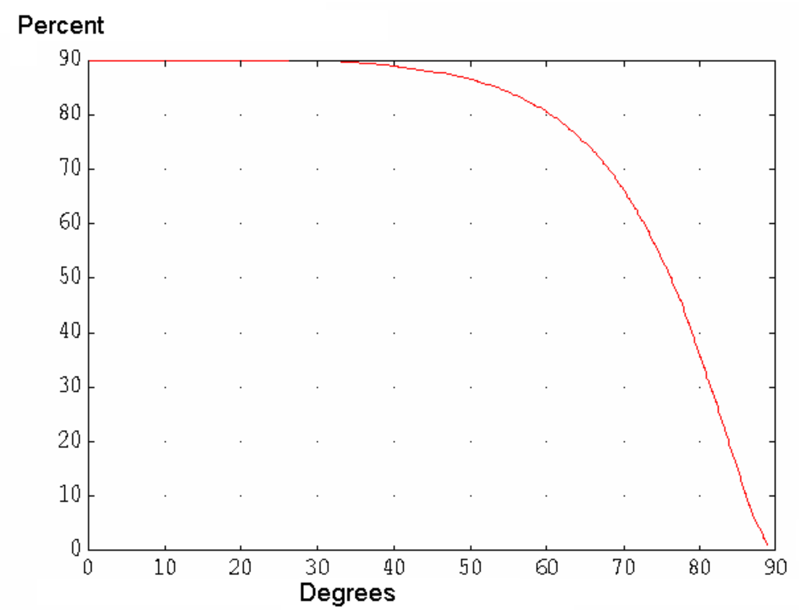
Etendue: A product of the area of a light beam (normal to its direction of propagation) and the solid angle that the beam includes. Etendue must be conserved; optical instrumentation cannot increase the etendue of a source; the etendue of an image cannot exceed that of the object. *More on this later!*



Basic Optical Principles

Fresnel Losses: Reflection losses incurred at input and output of optical elements because of the difference in refractive index between glass and the immersion medium.





Basic Optical Principles

Radiometry is the measurement of radiant energy and the geometrical characterization of that energy

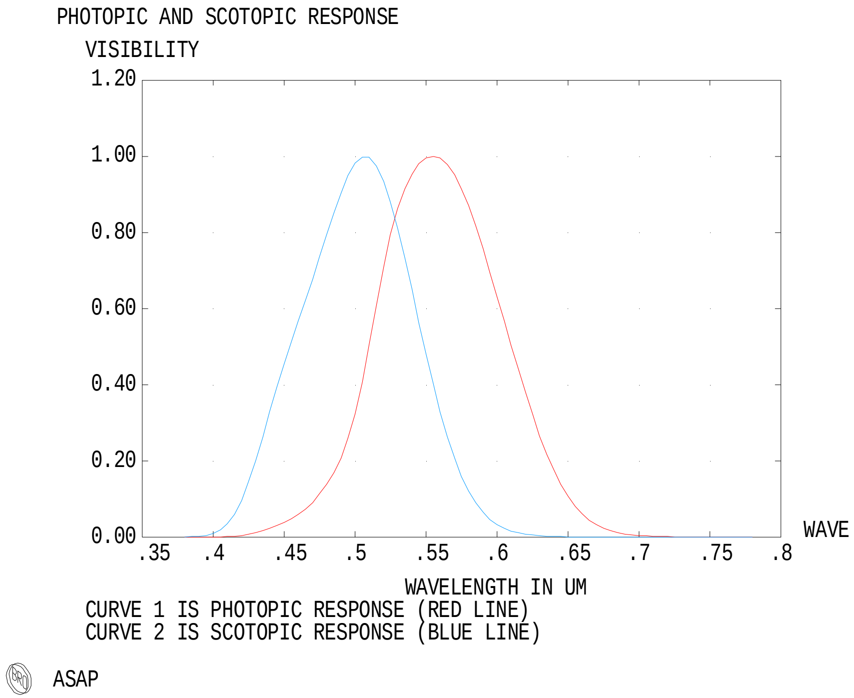
Radiometric units provide an absolute system based on fundamental physics ($E_{photon} = hv$)

Photometry is a normalized form of radiometry. Normalization is a process where a measurement or calculation is made to conform to a standard or established norm, in this case the response of the human eye

Photometric units provide a visual system based on the CIE standard observer

Radiometry to Photometry

Photopic units weight the real spectral power distribution by the eye's visual response in daylight.



$$\Phi_v = K_m \int \Phi_\lambda V(\lambda)\, d\lambda$$

K_m is the luminous efficacy and is equal to 683 lm/W at approximately 555 nm. Φ_λ is the source power spectral density and $V(\lambda)$ is the luminous efficiency function or visibility curve.

Photometric Units

Energy*	Q_n	–	talbot = lm-s
	(energy in visible spectrum)		
Energy Density*	U_ν	$\dfrac{dQ_\nu}{dV}$	lm-s/m^3
	(energy per unit volume in visible spectrum)		
Flux*	F_ν, P_ν	$\dfrac{dQ_\nu}{dt}$	lm
	(energy per unit time or power in visible spectrum)		
Exitance*	M_ν	$\dfrac{d\Phi_\nu}{dA_{source}}$	lm/m^2 = lx
	(power emitted per unit area of source in visible spectrum)		
Illuminance	E_ν	$\dfrac{d\Phi_\nu}{dA_{absorber}}$	lm/m^2 = lx
	(power falling on unit area of target in visible spectrum)		
Intensity*	I_ν	$\dfrac{d\Phi_\nu}{d\Omega}$	lm/sr = cd
	(source power radiated per unit solid angle in visible spectrum)		
Luminance	L_ν	$\dfrac{d^2\Phi_\nu}{dA_{source,proj}\, d\Omega}$	lm/m2-sr = nt
	(source power per unit projected area per unit solid angle in visible spectrum)		

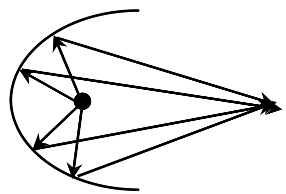
*should add the term "luminous" for each of these quantities

Optical Sources

The most fundamental part of an illumination system is the source!

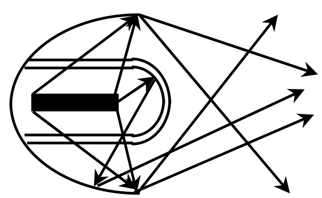
Wrong source model = wrong results!

GOOD



Ideal elliptical reflector
focuses onto small target

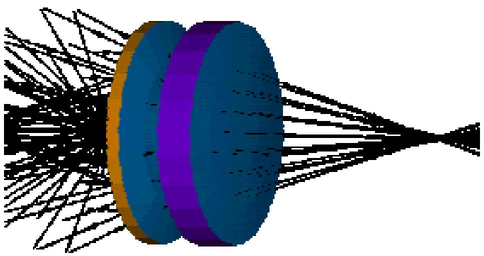
BAD



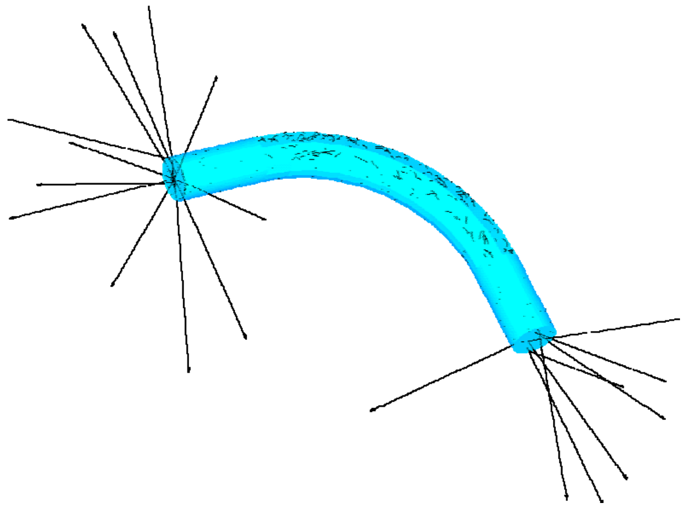
Light from large source
goes all over!

Rule of 10: “Assume” that source size matters if its size is greater than 1/10 of the distance to the nearest surface!

Common Illumination Optics

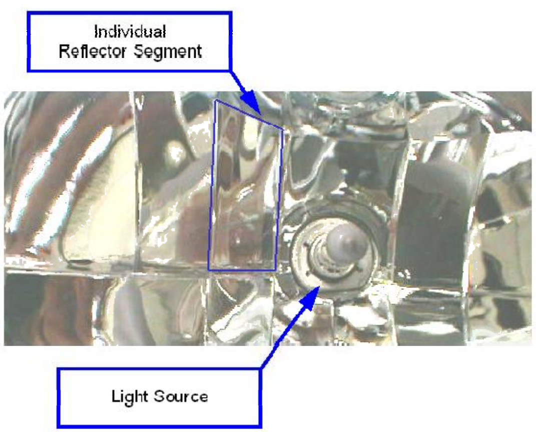


Lenses

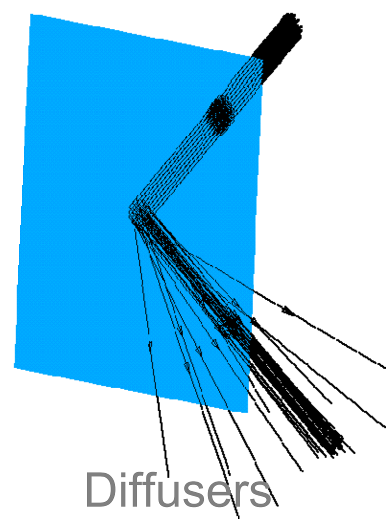


Lightpipes

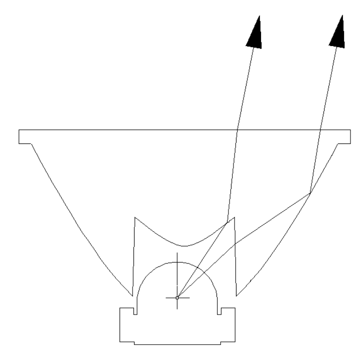
Fresnel Lens



Reflectors



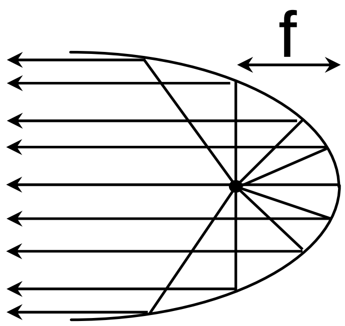
Diffusers



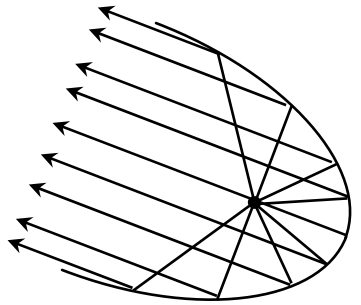
TIR Optics

Simple Shapes - Parabolas

A parabola collimates light from a single point focus



Collimation



Tilt to Control Angle

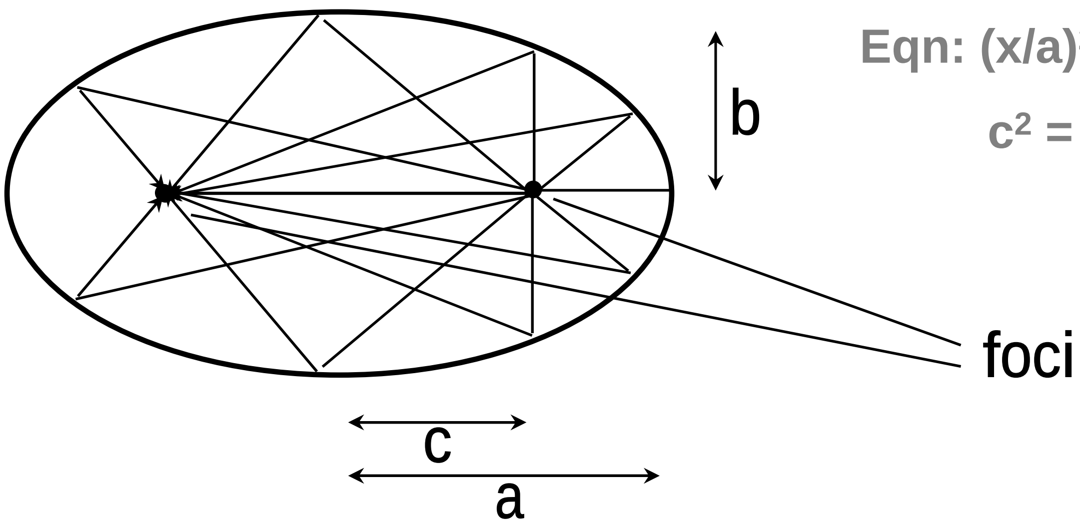
Eqn: $x = y^2/2f$ **(f is the vertex-focus distance)**

Parabolas work best with small sources

Parabolas produce non-uniform irradiance and intensity distributions when using real sources.

Simple Shapes - Ellipses

Ellipses reflect light from one focus (a point) to the other.



Eqn: $(x/a)^2+(y/b)^2 = 1$

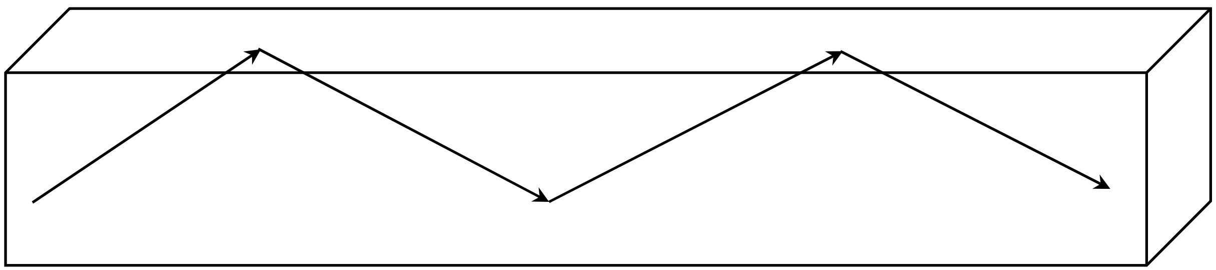
$c^2 = a^2 - b^2$

The spot size produced by an elliptical reflector is NOT equal to the source spot size.

Ellipses work best for small sources.

Lightpipes

Lightpipes use TIR to carry light from source location to remote target



Examples of Lightpipes:

- Uniformity Bars
- Fiber Optic Bundles
- Plastic Injection Molded Parts
- LCD Backlights

Advanced Shapes

For most practical illumination design problems – a simple shape will either not produce the desired result, or will be inefficient

Free form optics, TIR lenses, segmented reflectors/refractors have more degrees of freedom to manipulate the light

Analytical solutions are sometimes available for specific problems, however most require trial and error methods

Optical design and CAD packages allow easy generation of segmentation and freedom to alter the segments

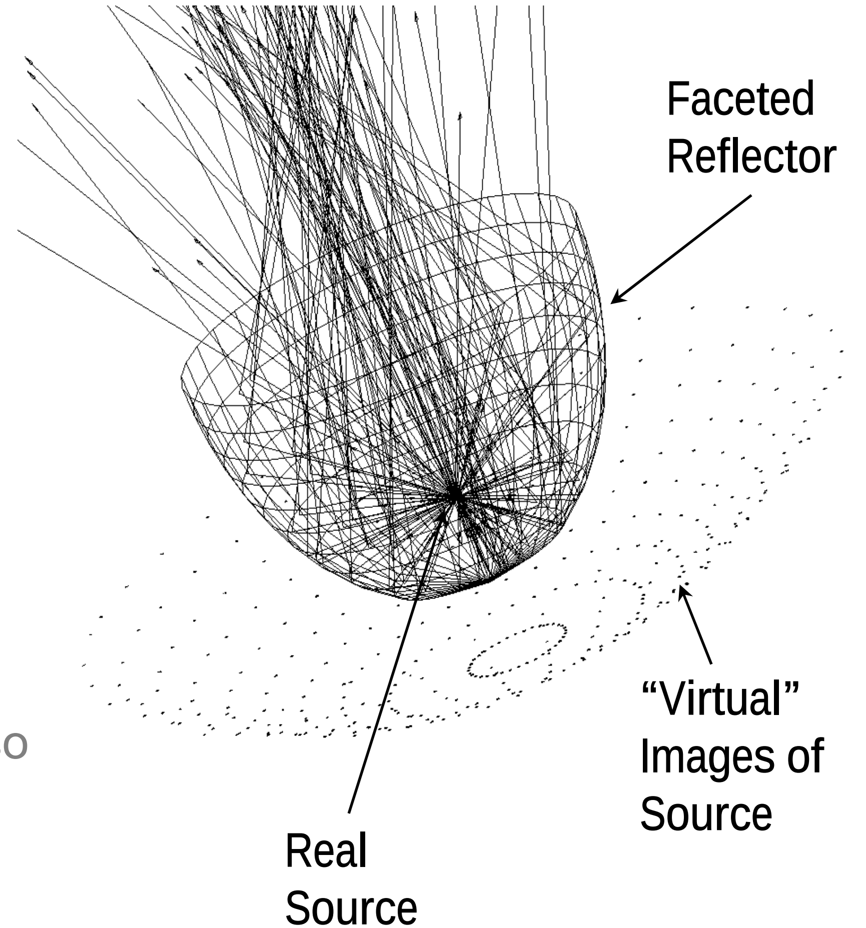
Faceted Reflectors

Placing flat facets on a base surface (usually an ellipse) is quite common.

The use of facets blurs out the image of a source, producing a more uniform irradiance pattern at the focus.

When looking back into the reflector, multiple "virtual" images of the source are apparent.

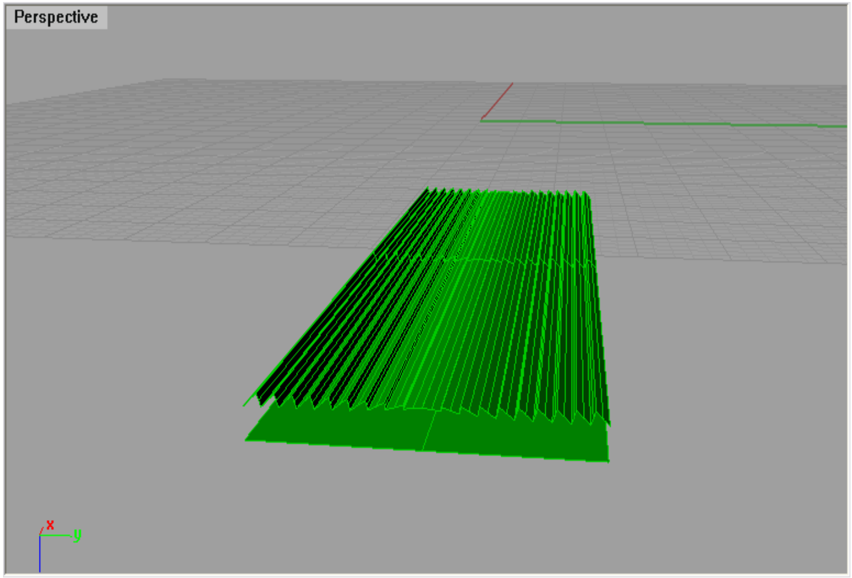
Each "virtual" image can be focused, so care must be taken in the design of imaging systems that work with this type of reflector.

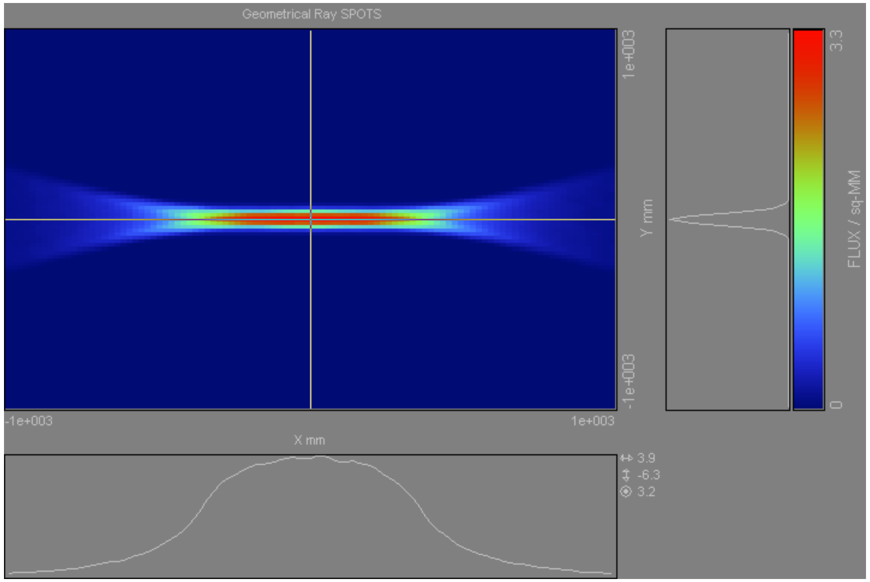


Fresnel Lens

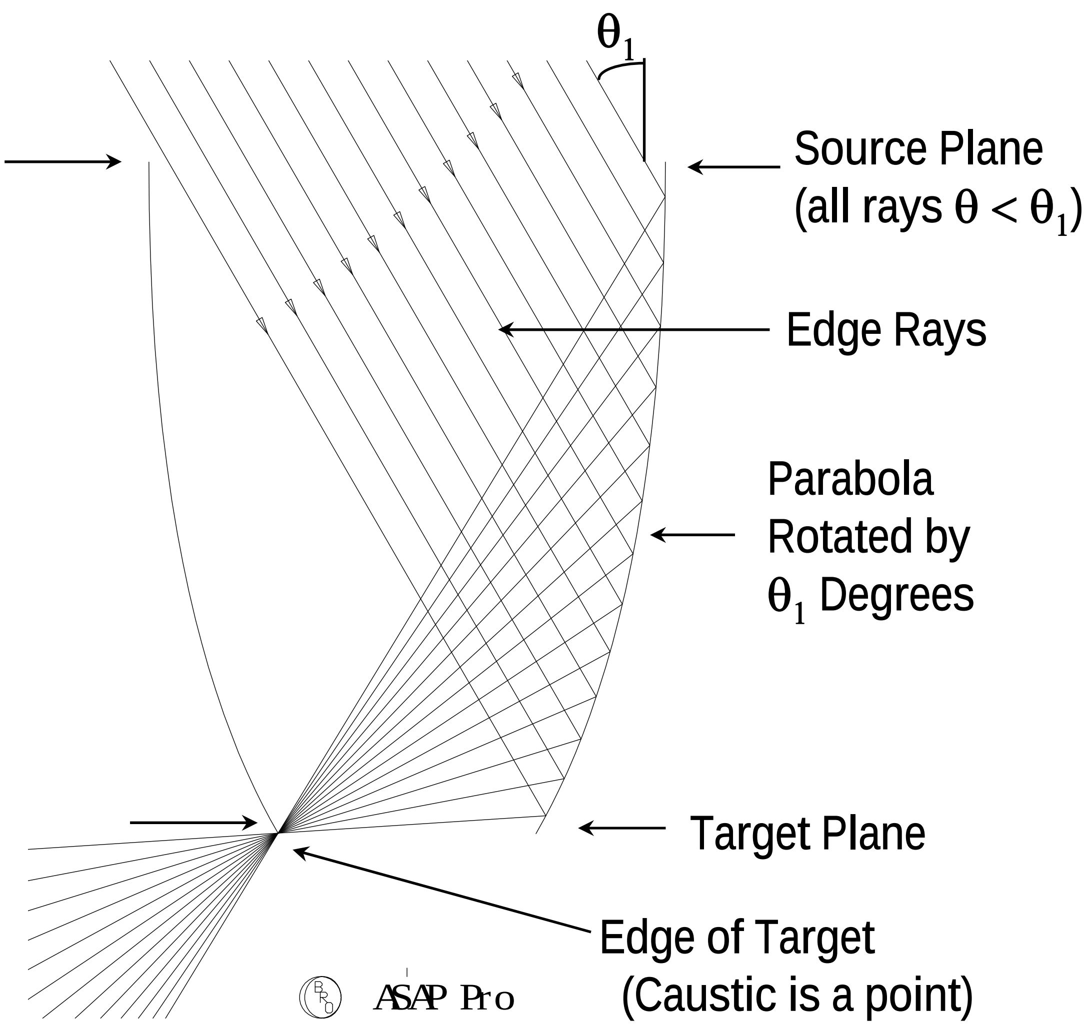
Fresnel lenses offer a shallow profile and good collimation ability.

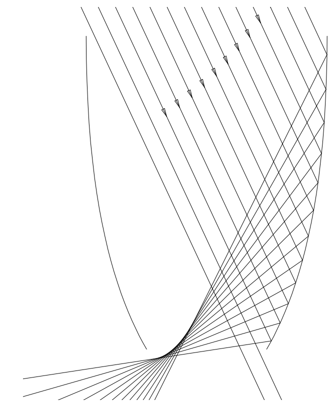
Fresnel lenses use dioptric (refractive) and/or catadioptric (TIR) elements to redirect light.

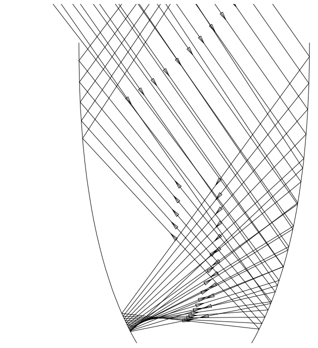




Compound Parabolic Concentrator (CPC)

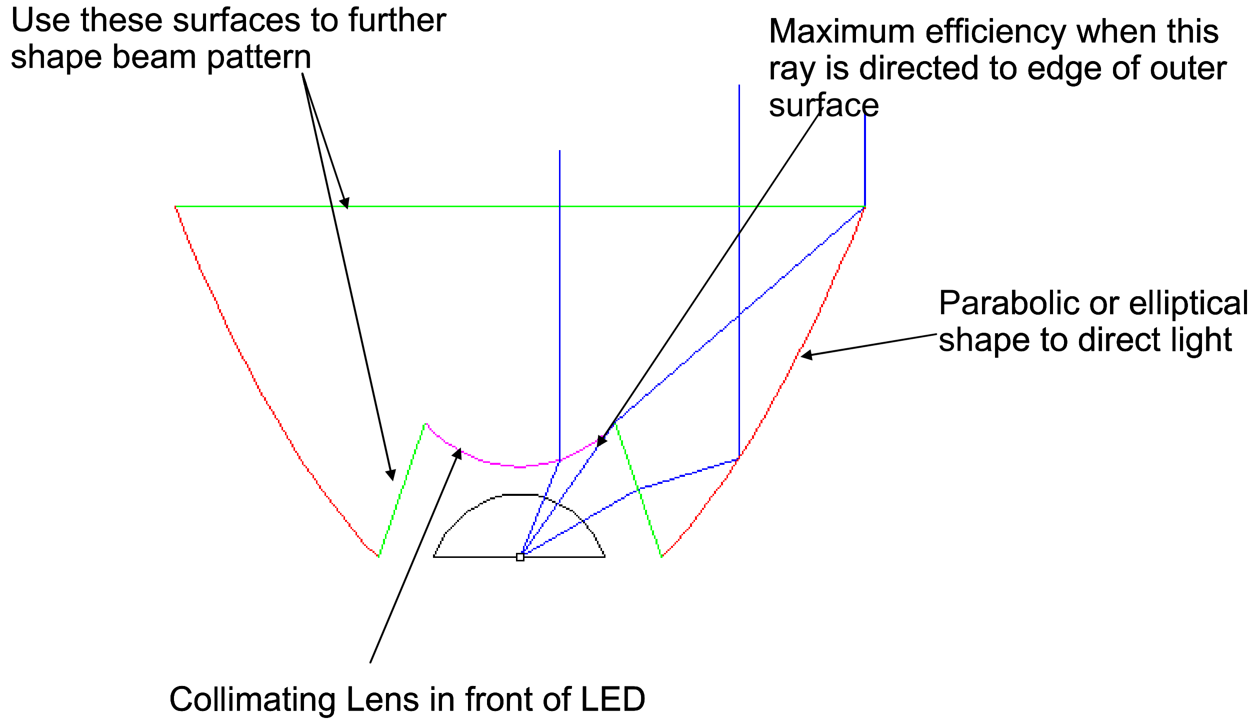






TIR Lens

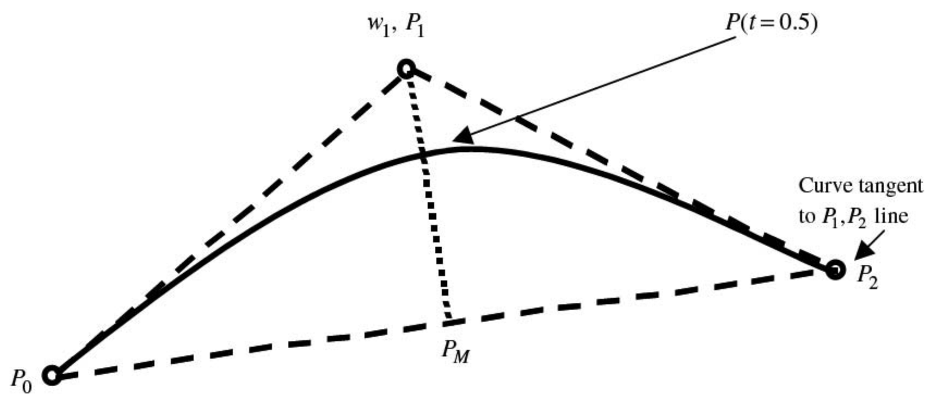
TIR lenses use a combination of total internal reflection and refraction to collimate light and maximize collection efficiency and throughput.



Free Form Design

Use Bezier math to describe shapes

***NOTE** The curve is tangent to the line between the end point and the nearest control point.*



Equation of curve:

$$P(t)=\left((1-t)^2 P_0+2t(1-t)w_1P_1+t^2P_2\right)/\left((1-t)^2+2t(1-t)w_1+t^2\right)\ t>0,\ t<1$$

The weight w_i deforms the curve along the bisector between the control point P_1 and the midpoint of the two endpoints [$P_M=(P_0+P_2)/2$]. As the weight increases, the middle of the curve P(t=0.5) moves towards the control point according to the formula below.

$$w_1\left[P_1-P(0.5)\right]=P(0.5)-P_M$$

With Bezier representations of data, free form shapes are easily parameterized with a few variables to allow for iterative geometry manipulations for free form surface development

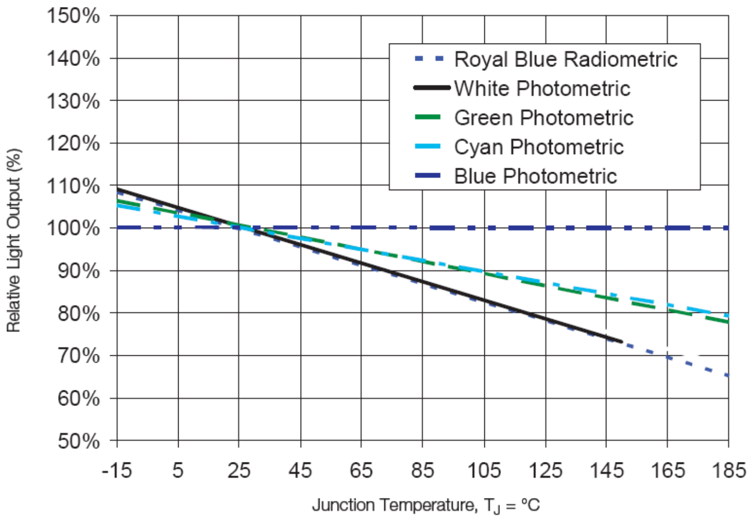
Efficiency Factors

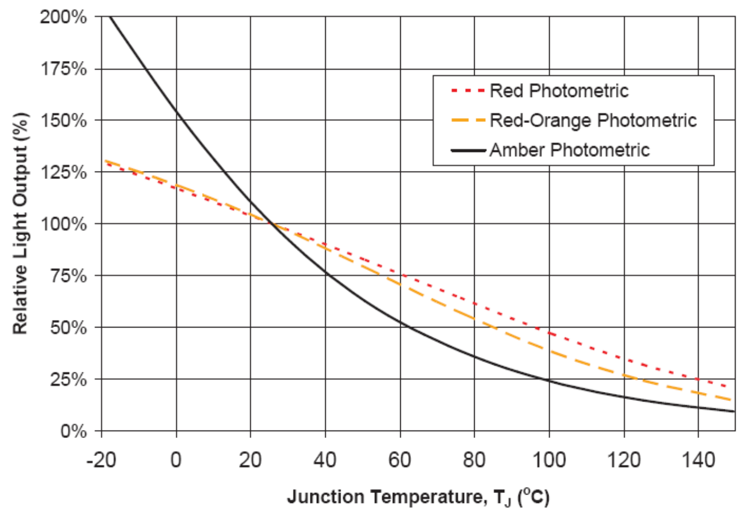
Thermal Derating

As Junction Temperature increases, light output decreases

Some LEDs are more sensitive to Junction Temperature

Junction Temperature is required to model LED output

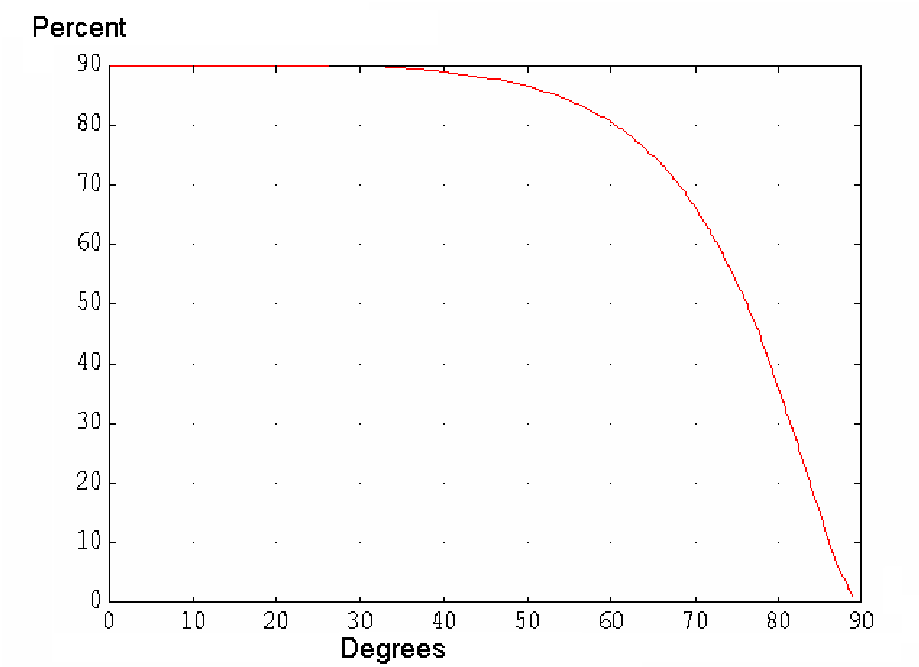


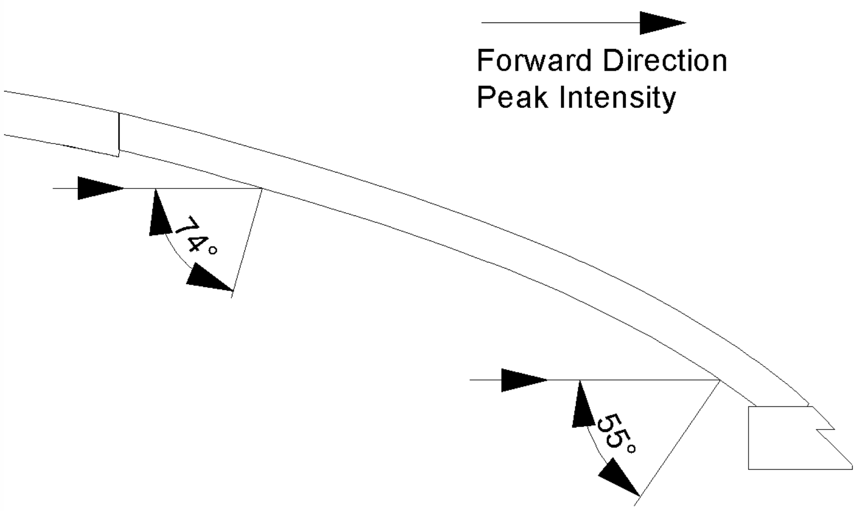


Fresnel Losses

Fresnel losses vary with incidence angle and refractive index

Steep cover lens slope causes substantial Fresnel losses



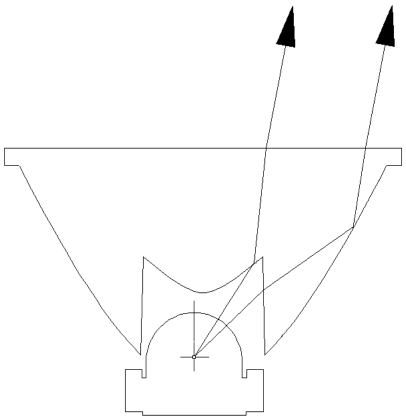


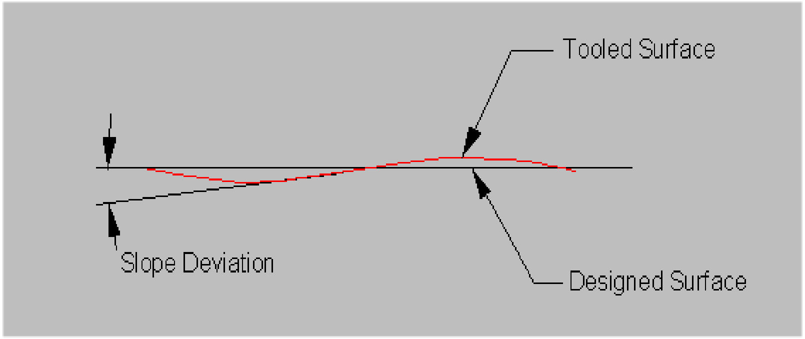
Tolerance Error

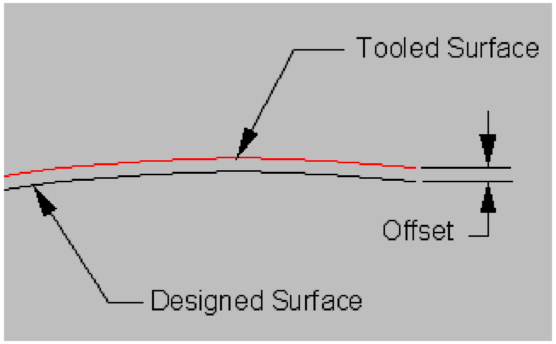
LED-to-optic positioning errors exist

Manufactured optic shape can deviate from specs

Roughness, absorption and haze can be present in/on the optic

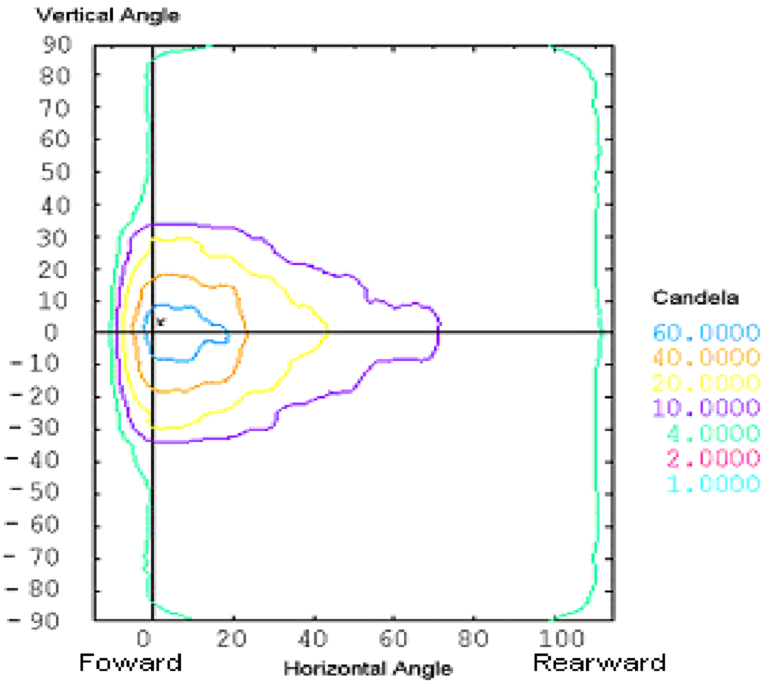


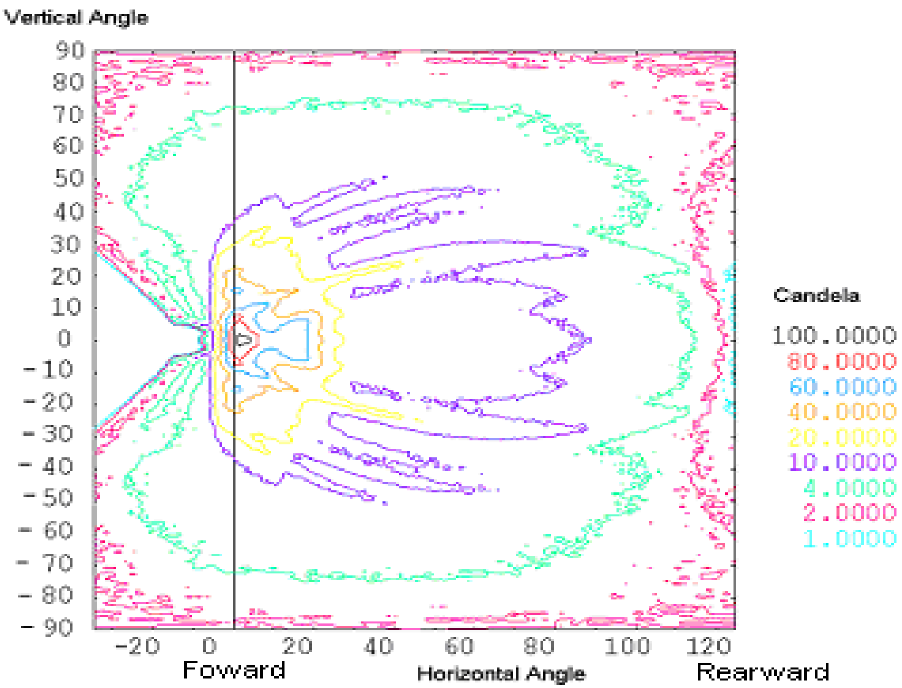




Distribution Pattern Mismatch

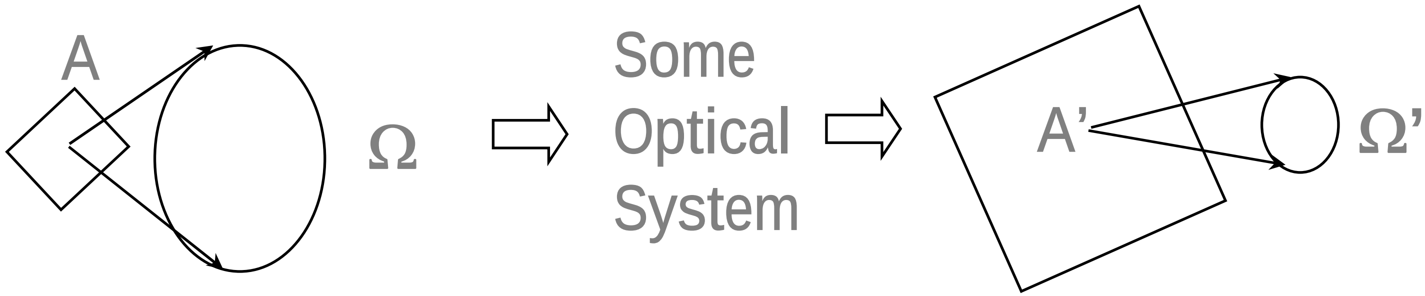
Mismatch between ideal and actual photometric distribution reduces system efficiency





Etendue

Also known as the Lagrange Invariant, Conservation of Brightness and the AΩ Law



$$A\Omega = A'\Omega'$$

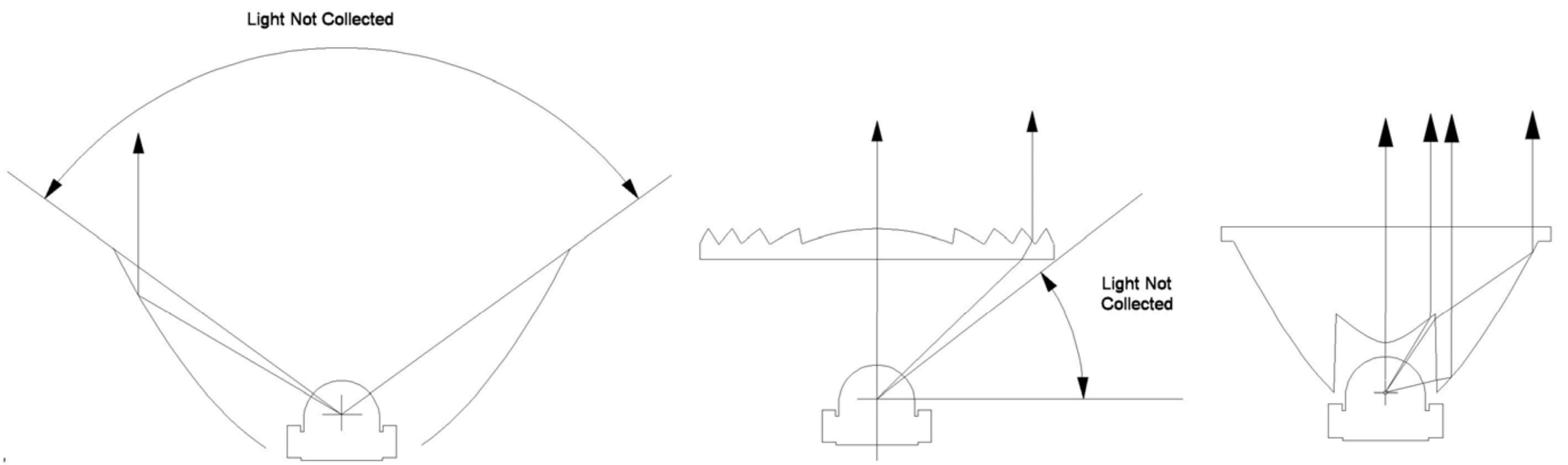
Lowering the area increases angular spread!

Increasing the area decreases angular spread!

Collection Efficiency

Max throughput achieved by maximizing collection efficiency.

Note collection efficiency and angular distribution trade-off.



Manufacturing Considerations

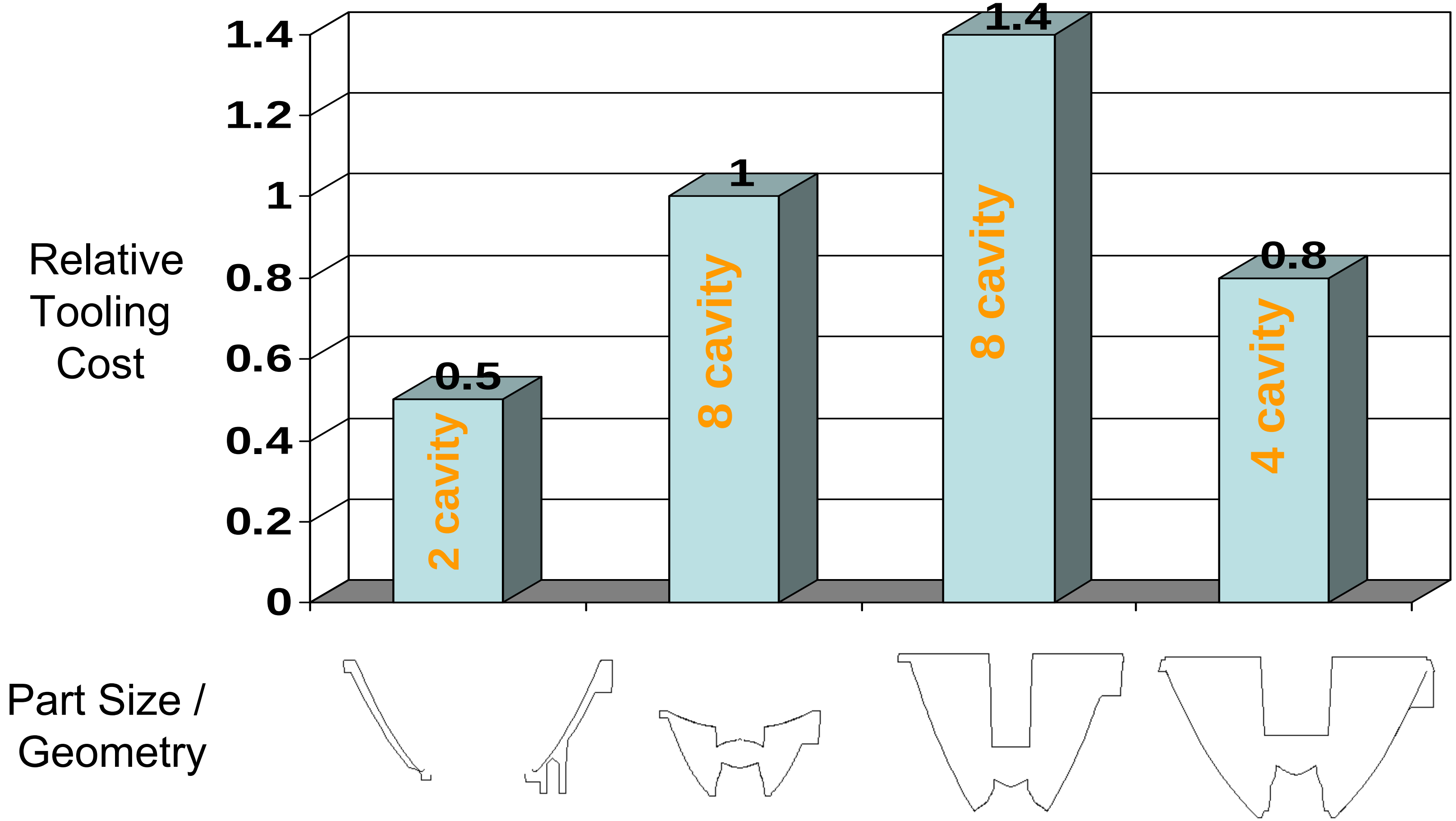
Design Form Trade-Off's

Form	Cost	Performance	Light Control
TIR	$$	▲ ▲	▲ ▲
Reflector	$	▲	▲
Hybrid	$$	▲ ▲ ▲	▲ ▲ ▲
Multi-element	$$$	▲ ▲ ▲ ▲	▲ ▲ ▲ ▲

Manufacturing Trade-Off's

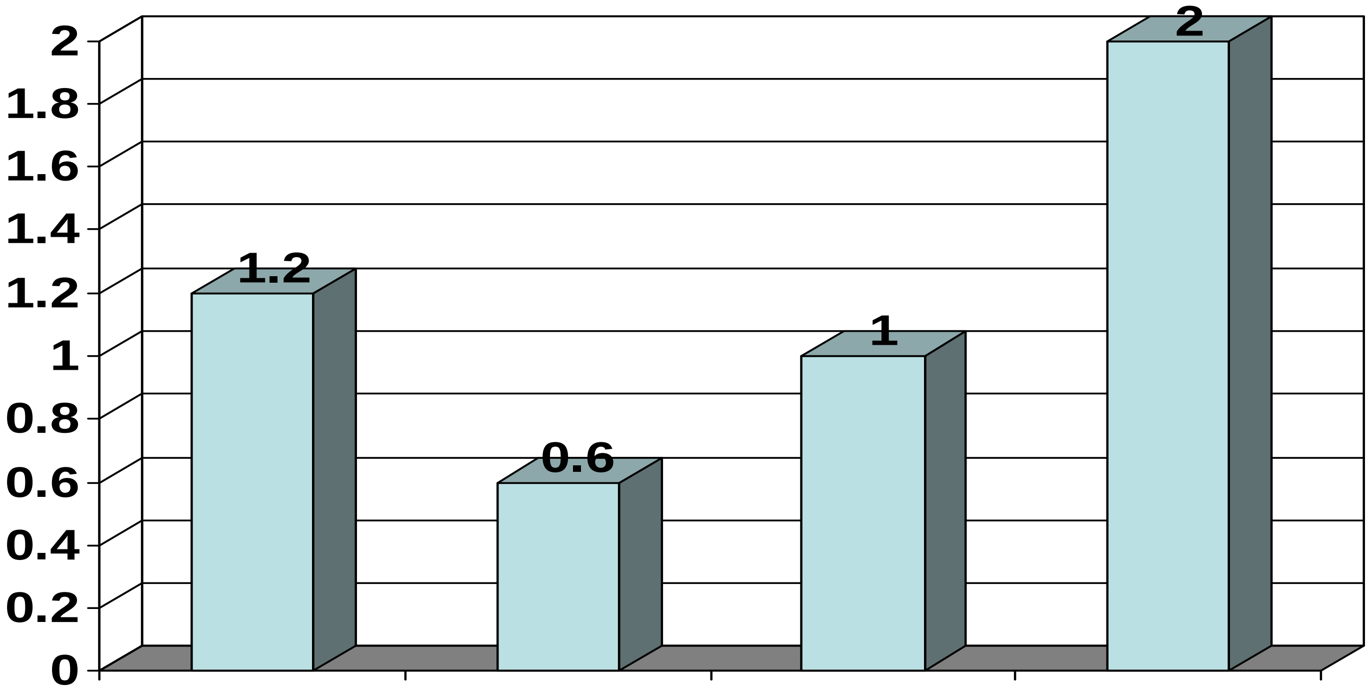
Form	Mold Complexity	Relative Cycle Time
TIR	▲ ▲ ▲	1
Reflector	▲ or (▲ ▲)	0.15
Hybrid: lens + reflector	▲ ▲ ▲	0.5 + 0.15
Multi-element	▲ ▲ ▲ ▲	# elem * 0.8

Typical Tooling Costs

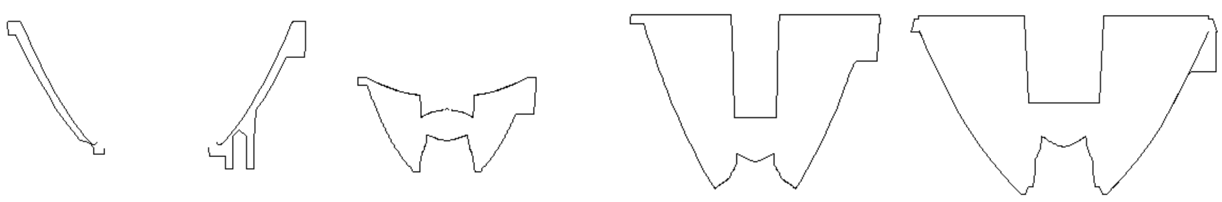


Relative Part Costs

Relative Part Cost ($)



Part Size / Geometry



LED Light Optical Design Example

Design Requirements

Round spot light beam for interior automotive illumination application

Illumination pattern defined for use on a task plane at 1.0 Meters from optical system exit face

Radius	Lux Min	Lux Max
0.00 - 0.23	**100**	**200**
0.23 - 0.27	**10**	**65**
0.27- 0.30	**5**	**35**
0.30 - 0.35	**0**	**8**

Circular Pattern with Cross Section Values as Shown

Design Requirements

Lumileds K2 White LED:

- Electrical and thermal design for 50 lumen minimum optical output

Package Constraints:

- 19 mm opening for optical system
- Overall depth of optical system with LED < 50 mm

Appearance Requirements:

- Flat or nearly flat outer lens is an aesthetic requirement
- Beam pattern smoothness as uniform as possible
- Outer beam pattern cutoff to be well-defined but not too sharp

First Order Analysis

Minimum Flux Required In Test Pattern:

Radial Position (Meters)	Min Lux	Region Area (M^2)	Flux (Lumens)
0.00-0.23	100	0.17	17
0.23-0.27	10	0.06	0.6
0.27-0.30	5	0.05	0.25
0.30-0.35	0		0
		Total Flux	**17.85**

Total Flux from Source is 50 Lumens:

Assume Optical System Efficiency >75%

Assume 25% margin desired on test points

Total Flux Available from System is approximately:

50 * 0.75 (efficiency) * 0.75 (margin allowance) = 28 lumens

Sufficient light is available from source to illuminate target with desired illuminance: 28 > 17.85

Etendue Analysis

Perform Etendue Check:

Output Optic Etendue is 20.38 Ω mm^{2}

62% of 50 Lumens has Etendue of 6.2 Ω mm^{2}

- Since 6.2 < 20.38 all of this light will be usable so 31 Lumens is available from this portion of the LED

38% of 50 Lumens has Etendue of 74.6 Ω mm^{2}

- Since 74.6 > 20.38 only a portion of this light will be transferred into the desired angle.
- Approximate transfer efficiency of this light is (20.38/74.6) = 27%
- Lumens available from this portion of the LED is 0.27 * 19 = 5.1 Lumens

Actual Lumens available through given output diameter due to Etendue limits is 31+5.1 = 36.1 Lumens

From previous assumptions total flux available for meeting pattern is now 36.1*0.75*0.75 = 20.3 Lumens

Required flux previously calculated to be 18 Lumens therefore system is feasible but marginal

First Order Analysis Summary

System requirements have been checked and found to be feasible but marginal within given assumptions

Due to marginal flux availability, this is the appropriate time to explore changing parameters:

- Output diameter increase to improve etendue transfer
- Source output increase
- Different source with more favorable etendue characteristics
- Specification relief

Parameter changes not necessary but can have the following benefits:

- Lower cost / lower component count optical system
- Optical system tolerance is increased
- Assembly and fabrication costs may be lowered
- Commonality with existing components

Design Approach Selection

System requirements have been checked and found to be feasible but marginal within given assumptions

To meet optical performance requirements and provide relief from tight tolerance molding, a multi – element optic system was developed.

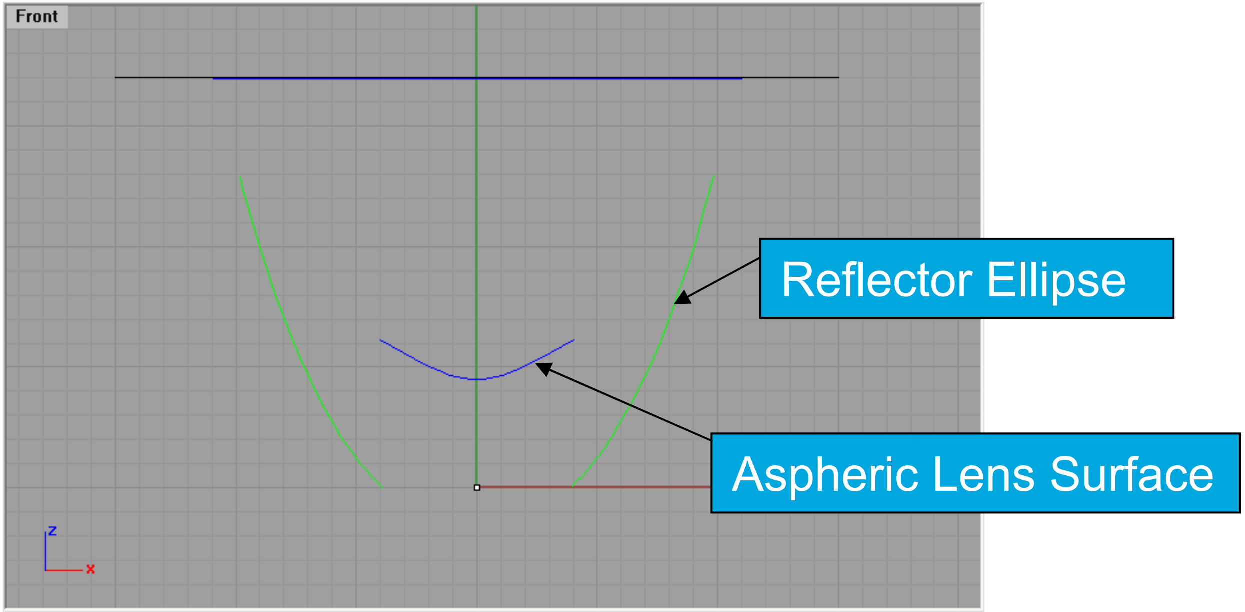
Form	**Cost**	**Performance**	**Light Control**
TIR	$$	★ ★	☀☀
Reflector	$	★	☀
Hybrid	$$	★ ★ ★	☀☀☀
Multi-element	$$$	★ ★ ★ ★	☀☀☀☀

In this case, the marginal amount of flux available coupled with the expected complexity and potential expense of molding a TIR only optic justified seeking a multi-element system solution.

Initial Multi-Element Layout

An aspheric lens profile will be used to direct the center emission into the center of the test pattern.

To gain more control of the edge of the pattern near the 0.23M test point, a reflector optic will be used to define the edge of the pattern.



Final Design Optimization

After completing the initial design concept as shown previously, the geometry is now parameterized mathematically and a computer algorithm is used to automatically optimize the design.

Optimization of illumination system designs is a difficult task.

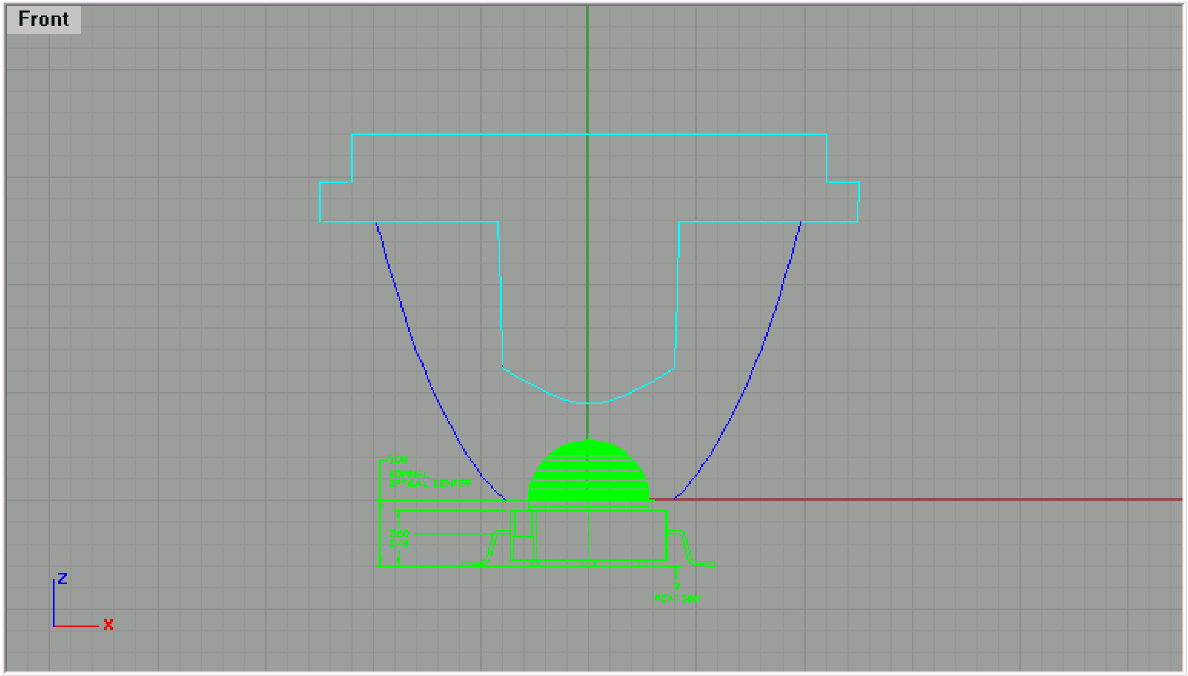
A problem usually requires several input and output variables to define the solution space.

Merit functions are not easily determined:

- Developing a good merit function is essential for getting convergence.
- Penalty terms are often needed to restrict the solution search to only designs that meet all criteria.

Illumination optimization generally should be limited to small searches in solution spaces that have been well bounded by initial designs.

Final Design Configuration



Lens – Clear Polycarbonate

Nominal Slope Error ± 0.5°

Reflector - Polycarbonate

Metallized for 85% Reflectivity

Nominal Slope Error ±0.5°

Lumileds K2 White LED at 50 Lumens Output

Results and Comparison

Test Points show compliance to specification and improved uniformity with multi-element system

Final Multi-Element Design:

<u>TASK LIGHT SPEC COMPARISON</u>

CENTER VALUE	=	165	(100 - 200 LUX)
0.11 M RADIUS	=	165	(100 - 200 LUX)
0.23 M RADIUS	=	112	(100 - 200 LUX)
0.27M RADIUS	=	54	(10 - 65 LUX)
0.30 M RADIUS	=	13	(5 - 35 LUX)
0.34 M RADIUS	=	6	(0 - 8 LUX)

Conclusion

Conclusion

Illumination system design is more complex than illumination systems may appear.

Many factors need to be considered concurrently during the design process (concurrent engineering):

- Optical
- Mechanical
- Thermal
- Electrical
- Manufacturing Costs

Trial and error is a part of the design process but can be reduced through the use of optical design software and optimization routines. Designer expertise and experience is still irreplaceable.

Questions?

Contact Information

Breault Research Organization
Suite 350
6400 East Grant Road
Tucson, AZ 85750 USA
1.520.721.0500
www.breault.com