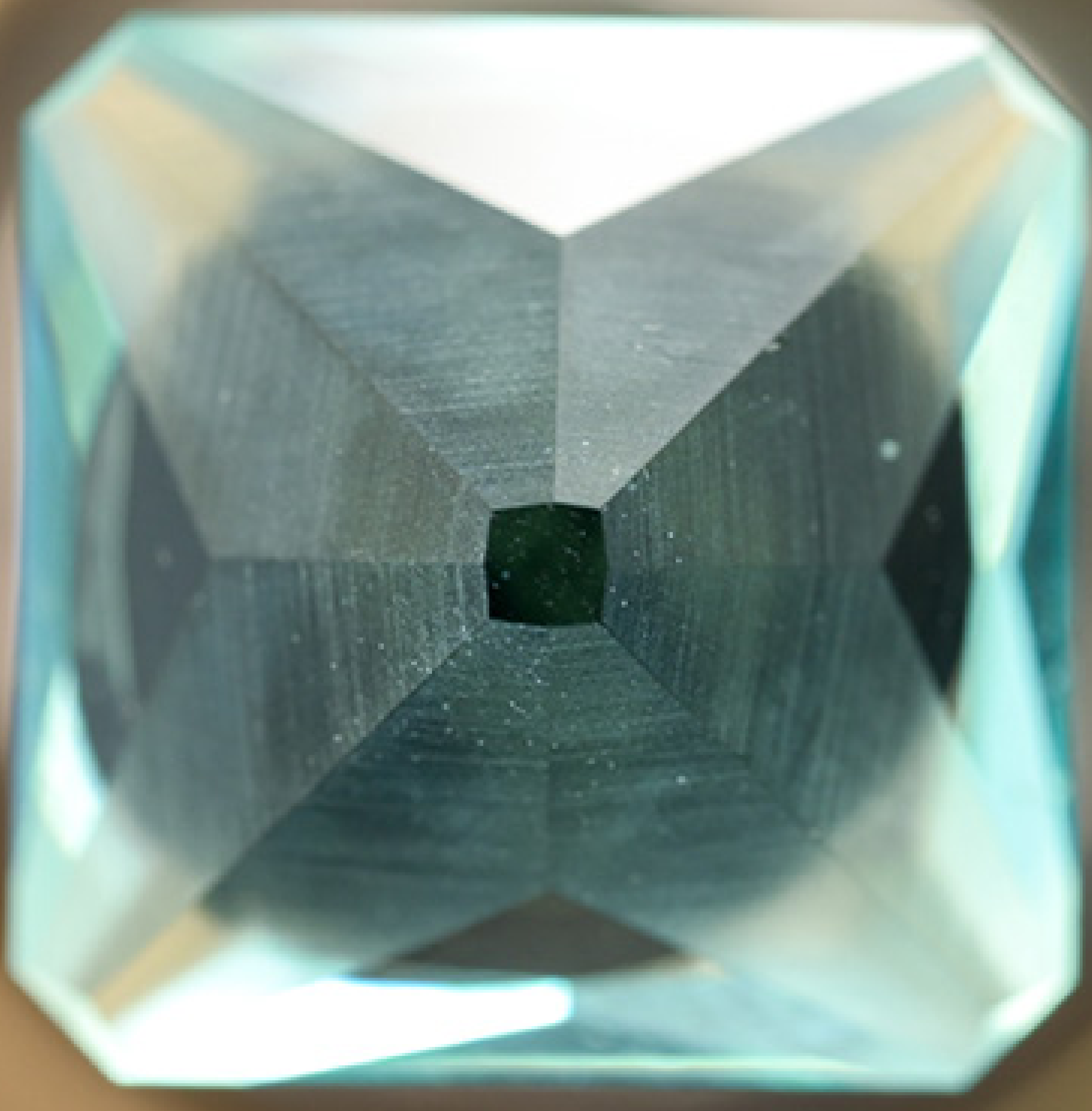
GEM faceting

Design Discoveries



Michael D. Cowing

Cover Photo: Justin Prim /World Gem Foundation

Figure 1a. Best/Ideal Round Brilliant Cut Diamond
Photo by Michael D. Cowing

Figure 1b. Best Round Brilliant Cut Purple Sapphire.
Faceting and photo by Gary Braun.

INTRODUCTION

Many discoveries await in this work written for the twin worlds of '**Diamond Cutting**' and '**Gemstone Faceting**'. Discover the attributes and properties of the most beautiful round brilliant diamond cut, the Ideal Round Brilliant, and the reasons it possesses the best optical light performance.

Discover that those properties also result in the best beauty and light performance in other round brilliant cut gems as well. Chief among these discoveries is that the best small range of pavilion angles of the Ideal Cut diamond is universally the best for all round brilliant cut gems. This work explains and demonstrates why. Also revealed is the all-important gem light performance connection with illumination contrast .

Find the reasons why the early Ideal Cut diamond, which is often mistaken for an Old European Cut, is seen as so fiery, even more so than the modern Ideal.

- Discover why diamond's Ideal crown and pavilion main angle combination near (34°, 41°) maximizes the potential in the round brilliant for all the gem's sought-after properties of brilliance, scintillation and fire.
- Discover the significance of the spectral reflection pattern, and its use in revealing a little-known feature of the gemstone interaction with illumination essential for fire to occur in diamonds and other gemstones.
- Discover the trade-off between fire and scintillation in the early Ideal and today's round brilliant cut, and the need for 'hearts and arrows' optical symmetry.
- Discover the advancement in gem faceting design by faceting design pioneer, Bruce Harding in 'Faceting Limits'.
- Discover through the 'eye of the round brilliant' why pavilion main angles any greater than 41° - 42° diminish the round brilliant's beauty/light performance, not only in diamond but colored gemstones as well.
- Discover how the table reflection percentage is used to accurately determine the pavilion main angle in round brilliant cut diamonds and other gemstones.
- Discover the essential role of illumination contrast in all three attributes of gemstone beauty.

Diamond and gemstone beauty, especially in colorless or light-colored gems, is judged in terms of the attributes of that beauty, which are:

- brilliance (aspects of brightness and contrast - bright-dark variation in reflections from the crown's facets);
- fire (rainbow colors from spectral dispersion); and
- scintillation (sparkle with movement).

It is important to recognize that there are several factors to bear in mind in diamond and colored stone cutting that often override cutting for maximum brilliance, fire and scintillation. We will see that chief among these is the necessity to cut the pavilion main angle a few degrees steeper than the gem's critical angle to avoid loss in brilliance due to 'windowing'. Other important considerations are 1. Cutting to obtain the best color. Of the colored gemstone's quality factors, it is often acknowledged that 'color is king'. 2. Cutting for best weight yield. With rare and expensive gem rough retaining every possible point of valuable weight may be an overriding goal. 3. Cutting to accommodate limitations in depth of facet rough. Cutting rough to obtain the largest face up size (called spread) often leaves insufficient depth necessitating a thinner crown or shallower than optimum pavilion. If the gem is purposefully cut with pavilion mains below the critical angle, with resulting windowing, for any of these reasons, the consequences are likely a lower appraised value and reduced salability. Appraisers valuing a cut gem take into consideration and report the percentage of windowing in a gemstone because of its mostly harmful effect on gem beauty.

The analysis tools and techniques used in this investigation, and in a series of four previous articles, are applicable to all gemstones, not only diamond. These tools and methods, reviewed below, are defined and their functions explained in the previous articles. They are:

- the spectral reflection pattern,
- reverse ray/beam tracing, and
- the 'eye of the round brilliant'.

REVIEW

Let us review these analysis tools and methods, and a few terms and concepts from the previous articles. This review can be skipped, especially by those who have read and are familiar with those articles.

THE GEMSTONE'S SPECTRAL REFLECTION PATTERN

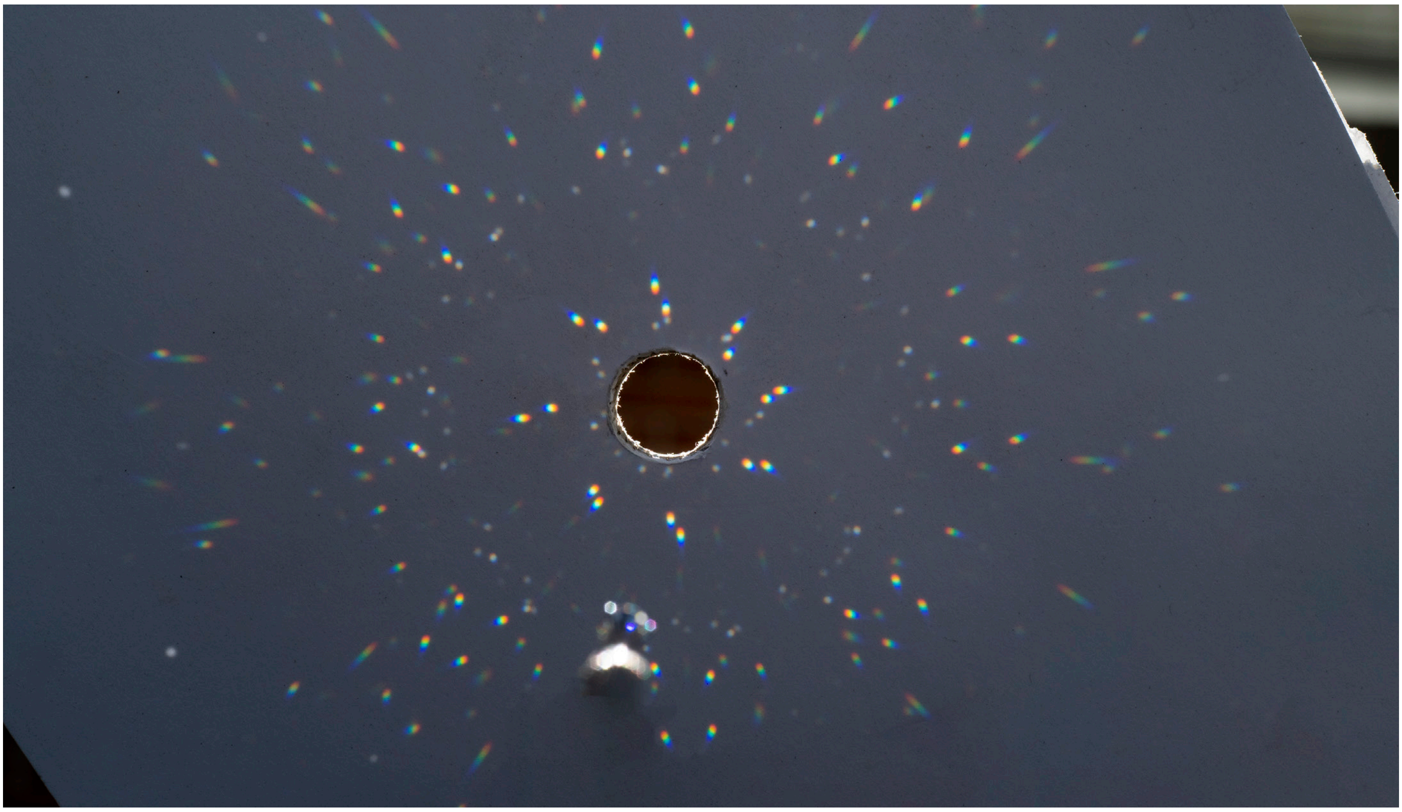


Figure 2. The spectral reflection pattern shown in this photo is generated by the narrow 0.53° beam of sunlight projected into the diamond (seen held below the hole), through the hole in the white board. Photo by Michael D. Cowing

A gemstone's spectral reflection pattern is produced by illuminating it with a narrow beam of light entering through a hole in a white card (or other flat screen). The Ideal cut diamond's spectral reflection pattern in Figure 2 utilized the narrow 0.53° beam of sunlight projected into the diamond through the hole in the white card. After two or more internal reflections the sunbeam emerged as a pattern of many tiny spectrums reflected and refracted back onto the white card.

The significance of the spectral reflection pattern is realized through understanding that it is identical to the reverse ray trace reflection pattern generated from the direction of an overhead viewer's eye.

REVERSE RAY TRACING

What is 'Reverse Ray Tracing'? Reverse ray or beam tracing is the analytical method used to discover and examine the properties of the 'virtual facets' that make up a gem's light performance. Unlike one dimensional mathematical rays, the rays in this work are three- dimensional bundles (beams) of parallel rays. The use of the word 'ray' in this article applies to both a ray and a beam.

The image in Figure 3 demonstrates the use of reverse ray/beam tracing to discover where in the diamond's surrounding, light is reflected to the overhead observer's eye from the 'virtual facets' that comprise the diamond's light performance. The reflection of the table seen inside the table (see Figure 4b & c) is composed of eight, small, pie-shaped 'virtual facets'. In the Figure 3 example, a beam the width of the diamond's table reflection is sent from the observer's eye position, entering within the table reflection. After two internal reflections from the 8 mains, the eight portions of the separated light beam emerge at 45° in eight directions. Those are the angular directions from where those 'virtual facets' reflect. There must be light in those directions for the eight 'virtual facets' in the table reflection to appear bright in the face up view.

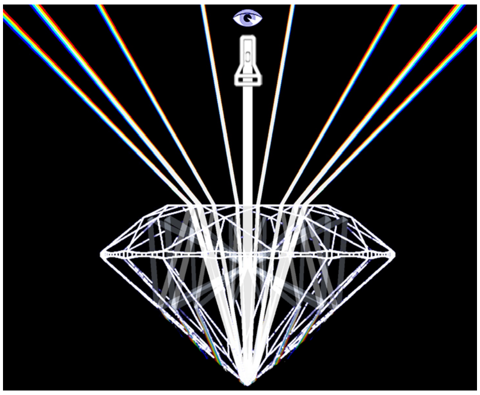


Figure 3. Example of reverse ray tracing the Ideal Cut (with Tolkowsky's 40.75° pavilion) using a light beam from the direction of the overhead viewer's eye, entering through the table reflection (TR) area. After two internal reflections from the 8 mains, the separated light emerges from the table at 45° in eight directions.
Image by Michael D. Cowing using DiamCalc

VIRTUAL FACETS

What do we mean by 'Virtual Facets'? We can see from Figure 4 b and 4 c that there are many more reflections than there are facets. This is due to the breakup and division of light reaching the observer after twice reflecting from the diamond's pavilion. Because they give the appearance of more facets than are actually present, they are called 'virtual facets'. Each is a potential location of light, sparkle or fire as seen in the photo Figure 4c. These 'virtual facet' reflections are the fundamental elements of diamond beauty and light performance. An assessment of a diamond's light performance can be made through an examination of the individual and combined properties of these 'virtual facets'. Two main properties of these fundamental facet reflections are their size and the direction around the diamond from which they reflect. These properties are unique to each virtual facet.

EQUIVALENCE OF SPECTRAL REFLECTION PATTERN GENERATION AND REVERSE RAY TRACING

The spectral reflection pattern is the same pattern produced by reverse ray tracing. In reverse ray tracing a ray/beam is sent in reverse of normal light travel, from the position of an overhead observer's eye, along the gem's axis, and entering perpendicular to its table. This results in the same spectral reflection pattern radiating from the gem onto a flat or hemispherical white surface.

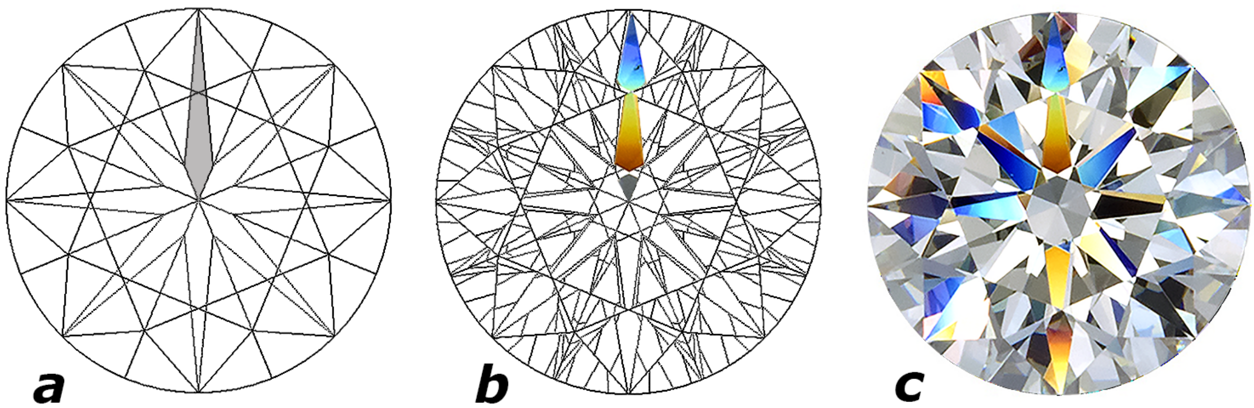


Figure 4. Face-up view of an 'Ideal' round brilliant. a. Wire frame outline of the diamonds 57 facets b. Outline of 'virtual facets' resulting from light interaction in doubly reflecting from the pavilion facets out through the crown. c. Photo of Ideal round brilliant displaying brilliance and fire emanating from these virtual facets.
Photo and images by Michael D. Cowing

We see that the spectral reflection pattern, and the reverse ray trace reflection pattern from an overhead viewer's eye are one and the same. As will be shown, this equivalence reveals the significance and usefulness of this pattern for gem facet design analysis.

IDEAL ROUND BRILLIANT CUT

Over the series of four previous articles, the analytical reasons were identified and demonstrated for the superior beauty and optical light performance of the Ideal round brilliant cut diamond. The proof of this best or ideal in round brilliant cutting is accomplished by demonstrating diminished beauty/light performance with deviations from the small range of angle combinations that historically are called Ideal. Today the facet angles of the sixteen pavilion and crown main facets, which have defined the Ideal in diamond cutting, are still the best, and are those that may attain both the top grades of Ideal 0 in the American Gem Society's (AGS) grading system, and Excellent in the Gemological Institute of America's (GIA) system. These articles reveal why the small range of Ideal round brilliant diamond design angles (of close to a 41° pavilion main angle and 34°-35° crown main angle), have not been surpassed in beauty and optical light performance, since they were first empirically found and cut over 150 years ago.

Figure 5. Early Ideal cut with its 16 dominant virtual facet reflections from the 8 large pavilion main facets.
Photo by Michael D. Cowing

These previous articles on the Ideal or best 57-58 facet round brilliant cut design focused on diamond. However, where the goal is to maximize the attributes of gemstone beauty, this article demonstrates why the principal design elements, angles and proportions of the Ideal brilliant cut diamond also apply (with adjustment in crown angle for differing refractive indexes (R.I.'s)to the best round brilliant cutting in other gemstones. Information, demonstrations and discoveries from the four previous articles are included throughout this work. These articles are available on line to be referenced for further detail. They can be accessed and downloaded as printable pdfs at https://acagemlab.com/category/diamonds/cut-beauty-light-performance/

THE IDEAL ROUND BRILLIANT CUT FROM THE EARLY 20TH CENTURY AND TODAY

In studying the Ideal round brilliant's evolution starting in the 1860's with Henry Morse, and a half century later the contributions of Marcel Tolkowsky, we observe that the face up appearance of the early brilliant was dominated by 16 large virtual facet reflections from the eight pavilion main facets (Figure 5). Their large size was due to the shortness of the 16 pavilion halves (also called lower girdle or break facets) that make up the remainder of the pavilion. At that time the halves were cut 2° steeper than the mains, and extended 60% from the girdle toward the culet. This dominant influence of the mains on the diamond's appearance contributed to the Ideal being defined first and foremost by the crown and pavilion main angles. The beauty and light performance of the early ideal cut is largely due to the properties of the pavilion's 8 mains and their 16 large virtual facets, and their optical interaction with the crown mains (bezel facets). Those properties include their size and cutting angles, and their resulting optical interaction with the gemstone's illumination.

TRADE OFF BETWEEN FIRE AND SCINTILLATION DUE TO THE LENGTH OF THE 16 HALVES (LOWER GIRDLE FACETS)

During the 20th century the sixteen pavilion halves that constitute the remainder of the pavilion were gradually increased in length from 60% to 77% - 80% or more, with resultant increase in their area and influence on the diamond's beauty.

The appeal of this increase in the length of the halves was the increased amount of sparkle that larger/longer halves contribute to diamond beauty. However, a consequence of the increase in the halves was the resulting decrease in the size of the mains, and their desirable properties of larger flashes of sparkle and

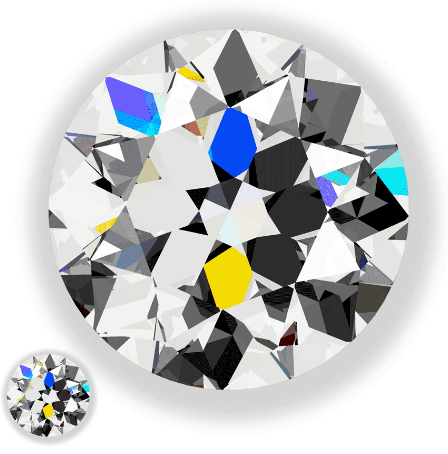


Figure 6. Computer image of the Ideal Cut diamond with 60% length of the lower halves.
Image by Michael D. Cowing using DiamCalc.

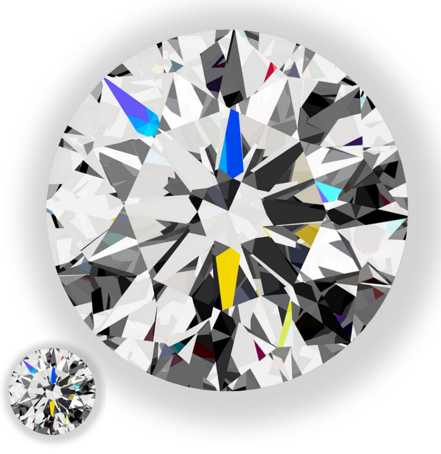


Figure 7. Computer image of the same Ideal Cut diamond of Figure 6, but with today's typical 77% lower halves. Image by Michael D. Cowing using DiamCalc.

fire. This large flash fire and sparkle seen in the Figure 5 photo and the Figure 6 computer generated image was an important aspect of the appeal of the early round brilliant from the eras of Morse and Tolkowsky. A comparison of the diamond images of Figures 6 and 7 show the diminishment of fire, when only the lower half length is changed from the 60% of Morse and Tolkowsky to the 77% or more popular today. This is more apparent in the small inset images that are closer to typical sizes.

Notice that the early Ideal has the greater fire even though it has the same amount of dispersion and identical crown and pavilion main angles. Perception of greater fire in the early Ideal cut is due to the larger reflections from the sixteen main virtual facets. Retaining as much as possible the large flash fire and sparkle from the mains, despite their reduction in size, is accomplished in the modern Ideal cut by exact alignment of opposing mains. This optical symmetry results in what is today called 'hearts and arrows' symmetry. Viewed face-up, as in the Figure 8 example, the eight rayed arrows pattern of exactly aligned reflections from the pavilion main facets is evidence of exceptional optical symmetry.

The diminishment of the mains necessitates their optical alignment, so that the resulting facet reflections in the face-up view are not further reduced or broken up by misalignment. Fire occurs in the virtual facets from the halves, but it is smaller and less noticeable, coming from the halves' more numerous, but smaller facet reflections.

Tilting of the gemstone from face up changes the pattern of reflections. The article 'Round Brilliant Cut Beauty and Light Performance Part 2' makes the case that: 'Because diamonds are evaluated for beauty in the face-up viewing position, this normal viewing angle is of greatest importance. This most important viewpoint, looking at the diamond face-up, perpendicular to the table, is sufficient for analysis, as it is indicative of the quality of light performance as the gem is tilted and moved under examination by the viewer'. The superior brilliance of the 'Ideal Cut' is retained at typical tilts from the perpendicular, as seen in the Figure 9 photo.

Retention of superior brilliance at angles off the perpendicular is called superior 'tilt brilliance'. It is a property of the Ideal Cut owing to the Ideal's optimum combination of crown and pavilion main angles. Lesser quality round brilliants that face up with less than the Ideal's beauty fall off in light performance with tilting, remaining below the Ideal in beauty.

Figure 8. Ideal Cut diamond exhibiting exceptional optical symmetry, referred to as 'hearts and arrows', seen face up as the eight rayed arrows pattern of exactly aligned reflections from the pavilion main facets. Photo by Michael D. Cowing

Figure 9. Ideal Cut's retention of superior brilliance when tilted. Photo by Michael D. Cowing

Figure 10. Example of 'windowing' in an oval, pink sapphire gemstone, where the background, not brilliance, is seen through the table area. Photo by Michael D. Cowing

INNOVATIONS IN GEM FACET DESIGN

Early understanding of the best gemstone faceting angles centered around avoiding pavilion angles less than the gem's critical angle. Cutting below that angle results in light that enters the crown refracting out of the pavilion rather than doubly internally reflecting off the pavilion and back out of the crown to the overhead observer. Those pavilion facets cut below the gem's critical angle are darker areas of little or no brilliance. The observer sees a 'window' to under the stone rather than reflections of light from above, as the photo of an oval, pink sapphire with windowing in Figure 10 illustrates.

This occurrence is best called windowing, but it is also referred to as light leakage. Avoidance of windowing was state of the art in faceting optics before 1975. An early exposition in the 1997 publication 'Color Encyclopedia of Gemstones' by Joel E. Arem explains the relationship between refractive index, critical angle, and pavilion main angle with the graph, Figure 11. He explains that to avoid windowing the pavilion angle must be a few degrees steeper than the critical angle. The critical angle (CA) is obtained from the gem's refractive index (R.I.) by the relationship, sin(CA) = 1/R.I., shown in the graph.

In conclusion, it is necessary to cut pavilion main angles a few degrees above the gemstones critical angle in order to avoid the loss in brilliance due to windowing. But this is not sufficient for maximum beauty (maximum brilliance, fire, and scintillation). Further apparent limits on pavilion angle are discovered by studying the angles empirically found to be best through 'cut and try'. Since its publication in 1962 the 'Table of Facet Angles' in 'Facet Cutters Handbook by Edward J Soukup has been a primary source of the empirically found best angles for gemstones of various R.I.'s. Another source of these empirically found best angles for cutting the round brilliant is found in 'Faceting Made Easy' by Trevor Hannam. While substantially in agreement with Soukup's table there are differences that prove revealing about the underlying gemstone optics.

For ease of analysis both tables are combined and arranged by increasing R.I. in the table Figure 12.

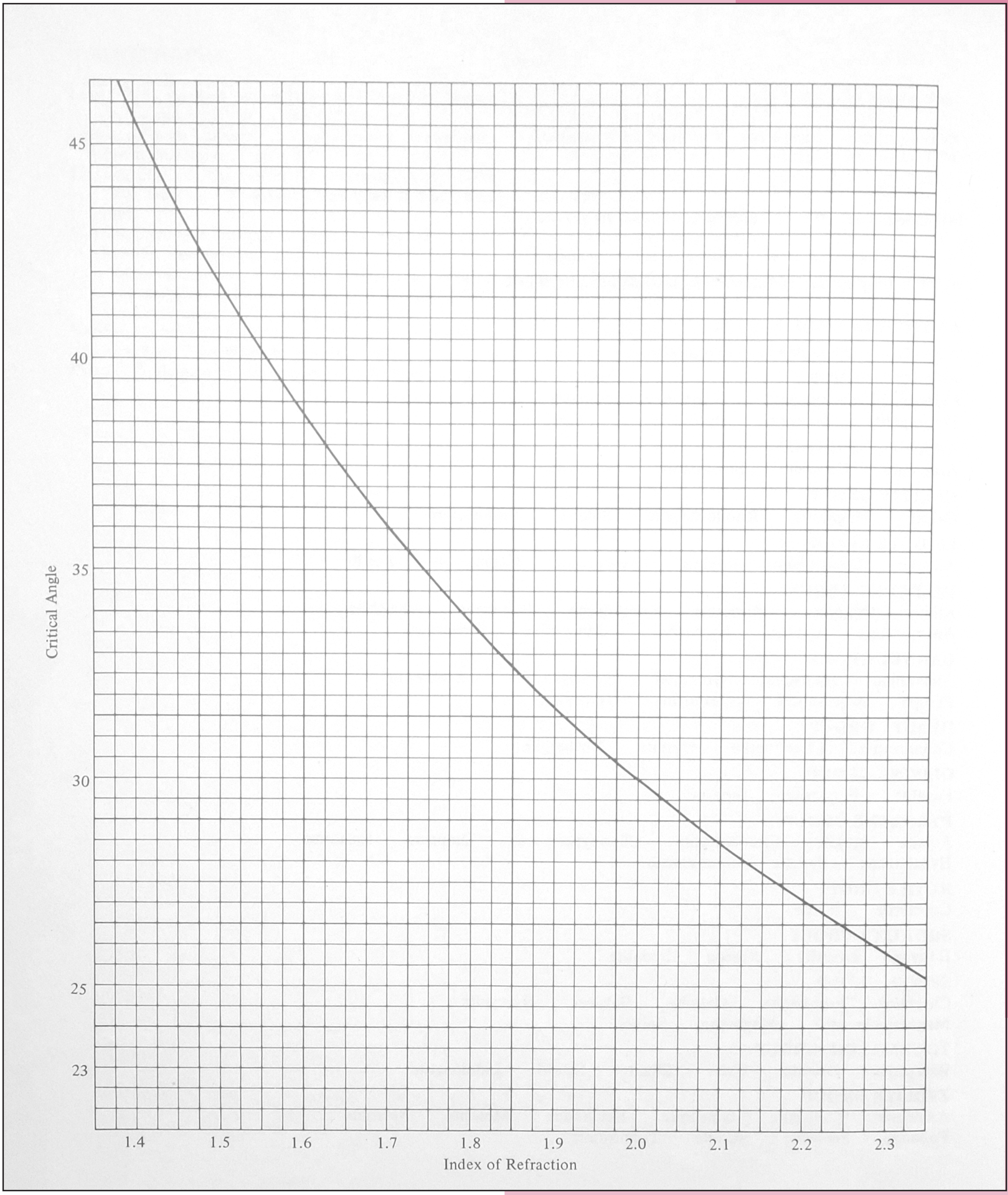


Figure 11. "Graph of index of refraction plotted against critical angle. ... This graph is most useful to the gem cutter for determining main pavilion angles. Maximum brilliance is achieved [by avoiding windowing] when the pavilion main angle is slightly greater [about 3 degrees] than the critical angle. This can be determined for any given gem material with a quick refractive index measurement on a polished surface prior to cutting the pavilion."

Graph and explanation by Joel Arem from 'Color Encyclopedia of Gemstones'

Table of Facet Angles, Empirically Found Best by 'Cut and Try'

Gemstone	R.I.	Critical Angle	Bezel Main	Star	Upper Girdle	Pavilion Main	Lower Girdle	Source
Fluorite	1.43	**44**	43	28	48	45	47	Hannam
Opal	1.44/1.47	**43**	41	26	46	45	47	Hannam
Opal	1.45	43.5	41	26	45-47	45	47	Soukop
Glass	1.45 +	41	42	27	37	43	45	Hannam
Obsidian	1.48	**42.5**	42	27	46-48	43	45	Soukop
Feldspar	1.52	41	42	27	46-48	43	45	Soukop
Iolite	1.53/1.54	**40.4**	42	27	47	43	45	Hannam
Iolite	1.54	40.5	42	27	46-48	43	45	Soukop
Quartz	1.54/1.553	**40**	41	26	46	42	44	Hannam
Feldspars	1.56/1.57	**40**	42	27	47	43	45	Hannam
Amethyst	1.56	40	42	27	46-49	43	45	Soukop
Quartz	1.56	40	45	30	47-49	41	43	Soukop
Scapolite	1.56	40	42	27	46-48	43	45	Soukop
Beryl	1.56	**40**	42	27	47	43	45	Hannam
Beryl	1.57	39.5	42	27	46-48	43	45	Soukop
Lazulite	1.61	**38**	39	24	42	41	43	Hannam
Topaz	1.61/1.62	**38**	39	24	44	41	43	Hannam
Topaz	1.62	38	43	28	47-49	39	41	Soukop
Prehnite	1.62	38	43	28	47-49	39	41	Soukup
Tourmaline	1.63/1.65	**38**	39	24	44	42	44	Hannam
Apatite	1.63	**37**	39	24	44	42	44	Hannam
Tourmaline	1.64	37.5	43	28	47-49	39	41	Soukop
Andalusite	1.64	37.5	43	28	47-49	39	41	Soukop
Apatite	1.64	37.5	43	28	47-49	39	41	Soukop
Euclase	1.65	37.3	43	28	47-49	39	41	Soukop
Spodumene	1.65	37.31	43	28	47-49	39	41	Soukop
Peridot	1.65/1.69	**37**	39	24	44	42	44	Hannam
Peridot	1.65	37	43	28	47-49	39	41	Soukop
Phenakite	1.65	37	43	28	47-49	39	41	Soukop
Spodumene	1.66	**37**	39	24	44	41	43	Hannam
Spodumene	1.66	37	43	28	47-49	39	41	Soukop
Kornerupine	1.67	37	43	28	47-49	39	41	Soukop
Spinel	1.71/1.736	**36**	40	25	45	41	43	Hannam
Spinel	1.72	35.5	37	22	41-43	42	44	Soukop
Epidote	1.73	35	37	22	41-43	42	44	Soukop
Chrysoberyl	1.74	35	37	22	41-43	42	44	Soukop
Chrysoberyl	1.74	**34.5**	39	24	44	42	44	Hannam
Pyrope	1.74/1.75	**35**	38	23	43	41	43	Hannam
Grossular Garnet	1.742/1.748	**35.5**	38	23	43	41	43	Hannam
Garnet (Violet-Red)	1.75/1.76	**34.8**	35	20	40	39	41	Hannam
Corundum	1.76	34.5	38	23	43	42	44	Hannam
Corundum	1.76	34.5	37	22	41-43	42	44	Soukop

Gemstone	R.I.	Critical Angle	Bezel Main	Star	Upper Girdle	Pavilion Main	Lower Girdle	Source
Almandine Garnet	1.76/1.83	**33.5**	38	23	43	41	43	Hannam
Garnet	1.77	34.5	37	22	41-43	42	44	Soukop
Zircon (Low)	1.78-1.84	33	37	22	41 -43	42	44	Soukop
YAG	1.83	**33**	37	22	42	40	42	Hannam
Demantoid Garnet	1.88	32.13	43	28	45-49	40	42	Soukop
Zircon (High)	1.93-1.98	31	35	20	39-41	41	43	Soukop
Zircon (High)	1.99	**30.2**	35	20	40	41	43	Hannam
Cassiterite	1.99	30.2	35	20	39-41	41		Soukop
Cubic Zirconia	2.16	**27.4**	35	20	40	41	43	Hannam
Sphalerite	2.37	**25**	35	20	39-41	41	43	Soukop
Strontium Titanate	2.41	**24.5**	35	24	40	41	43	Hannam
Diamond	2.42	24.4	35	20	39-41	41	43	Soukop
Titania (Synthetic)	2.9	**20.2**	32	15	34-36	41	41.5	Soukop

Figure 12. Table of Round Brilliant Facet Angles for different RI gemstones empirically found best by 'cut and try'.

The graph Figure 13 from the angle data in Figure 12 makes this analysis much clearer. The graph shows the critical angle, in orange, of the Figure 12 gems as their R.I. increases, as in Arem's graph in Figure 11. The best pavilion main angles for each gem are graphed in blue.

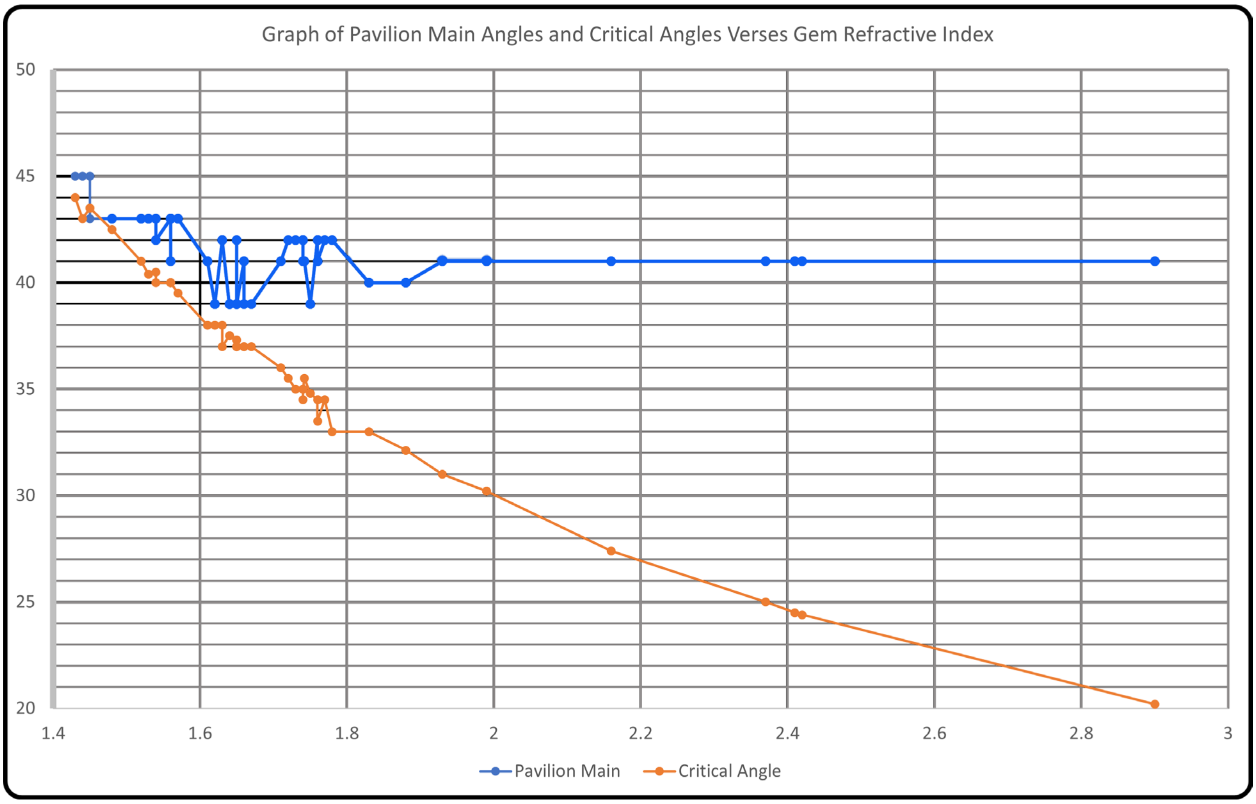


Figure 13. Graph of empirically found best pavilion main angles for gems of different R.I.'s.

We see through analysis of this Figure 13 graph from the Soukup and Hannam tabulated data that: After you get above the 1.62 R.I. of Topaz, with critical angle 38°, you find that the most often best pavilion main angle is 41°, and the next most often is 42°, with no angles above 42°. Below 1.62 R.I. the critical angle is within 3° of 41°, and avoiding major windowing becomes the overriding factor pushing the chosen pavilion main angle to 43°, and for fluorite and opal to 45°. Pavilion main angles 43 and above prove harmful to gemstone beauty. These non-optimal angles are an attempt to reduce the detrimental effect of windowing.

THE WHY BEHIND THE BEST PAVILION MAIN ANGLES FOR MAXIMUM GEM BEAUTY

We have seen that 'the empirically found best gem design angles have close to the same 41° - 42° pavilion main angle despite the various gemstone's differing refractive indices (RI's).'

Why is close to a 41° pavilion main angle best for both diamond and other gems?

To understand why a close to 41° pavilion angle is best requires the concept of the 'round brilliant's eye'. Originally formulated for diamond and called the 'diamond's eye', this concept holds true for all gems, because it is independent of a gem's refractive index (R.I.).

We observe from Figure 14 that the pattern of virtual facet reflections seen in the face-up view of the round brilliant cut naturally separates into three concentric rings with properties that resemble an eye, 'the eye of the round brilliant'. These eye-like rings are most easily observed in gems with excellent optical symmetry (each pair of main facets perfectly mirror each other, See photos Figure 14 and Figure 15 (Row a/Column 1)). With a little practice they usually become evident in the face-up view of the gem. (The table edge separating the iris from the whites is easily located. The sometimes difficult to identify border edge of the table's reflection can often be located by centering it in the table, and finding the butterfly shaped pairs of star facet reflections that surround and mark the table reflection boundary.)

The Eye of the Round Brilliant

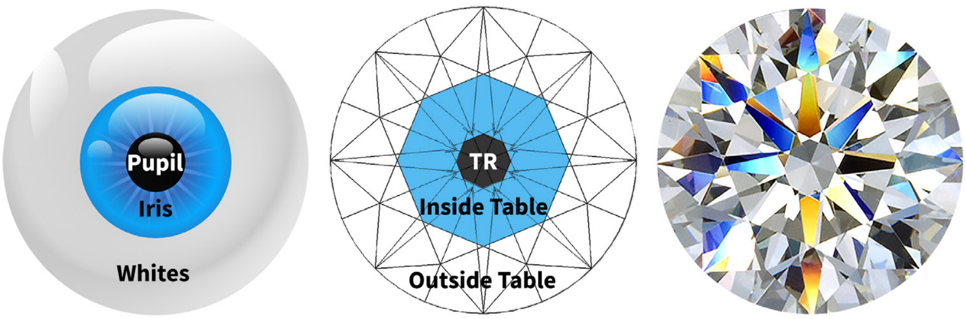


Figure 14: From the center to its girdle, the round brilliant reflection pattern has three identifiable rings of light reflection that have properties resembling an eye. In the center of the brilliant cut is an octagonal, grouping of 8 pie-shaped reflections (colored black.) This octagonal grouping is a reflection from the pavilion main facets of the octagonal table. This center table reflection (TR) is the pupil of the brilliant's eye. The remainder of the reflection pattern that is seen inside the table's edge is the middle ring and is colored blue. It corresponds to the iris. The third or outer ring is all the facet reflections seen outside the table. This corresponds to the 'white of the eye'. Photo and images by Michael D. Cowing

THE ROUND BRILLIANT'S EYE

The significance of the analogy to an eye is that the center ring, which is the table's reflection (TR), dilates like the human eye's pupil when the round brilliant is cut with a pavilion that is steeper than 41°. When a brilliant cut's pavilion main angle is cut close to 41°, the gem's pupil (the table reflection), will be small, about a third the size of the table (ranging from about 29% to 35%). A steeper pavilion results in a dilation of the table reflection. The table reflection expands and begins to dominate the table area diminishing the important iris (blue ring) area. The properties of light return from the table reflection are inferior to those of the middle ring (iris).

Consequently, as the table reflection dilates with greater than 41° - 42° pavilion main angles, the brilliant cut's beauty/light performance diminishes.

ANALYSIS OF THE ROUND BRILLIANT'S LIGHT PERFORMANCE IN THE TABLE REFLECTION

Analysis of the table reflection (TR), the pupil of the brilliant's eye, is fundamental to an understanding of brilliant cut light performance, especially in regard to why 41° - 42° pavilion main angles are the best for diamond and other gemstones.

Figure 15 summarizes the analysis of effects on gem light performance due to the increasing table reflection (TR) when a pavilion is cut steeper than 41° - 42°. The reverse ray tracing in Figure 15 (Row c) analyzes the dilating table reflection area.

Dilation of the table reflection is seen in Figure 15 - row a and b, as the pavilion angle increases from 40.75° to 42.75° and 44.75°. By the time the pavilion angle reaches 44.75°, Figure 15 (Column 3), the table reflection has dilated to fill the table, which has turned dark due to reflecting from the observer's head. The important middle ring iris is gone.

THE NAILHEAD ROUND BRILLIANT GEMSTONE

Gems with a dark table due to a deep pavilion are called nailheads. This same table reflection dilation occurs in gems of R.I. different from diamond, because this dilation occurs independent of a gems R.I. Examples are the colorless chrysoberyl, Figure 15 (Row a/Column 3), which was cut with a pavilion angle near 45°, and the peridot, Figure 16, cut with 45° pavilion main angle.

As the table reflection fills the table, instead of the light seen in it reflecting from the 45° direction, as in the Ideal, Figure 15 (Row c/Column 1), it instead reflects from high angles approaching 90° and the viewer's head, as in Figure 15 (Row c/Column 3). The viewer's head obstructs illumination from high angles resulting in a darkening of the whole table.

It is important to note that as the gem is tilted sufficiently, the nailhead effect goes away. The lower the R.I. the sooner it goes away. Also, in round brilliants cut with tables under 50%, as was the norm in the 1800's, the relative darkness of the small table is less apparent and goes away with less tilt than that of today's round brilliants with 53% - 59% and larger tables.

Well before a pavilion angle of 45°, and above 41.75°, the table reflection has dilated to a degree that reduces the important iris-like middle ring, diminishing its contribution to diamond beauty. By 42.75°, less than 2° steeper than Ideal, the table reflection has dilated to fill two-thirds of the table diameter. An example of the consequent reduced light performance can be observed in the diamond in Figure 15 (Row A/Column 2), which has roughly a 2/3 table reflection. The expanding table reflection with its poorer light return properties and the resulting reduction in iris area is a principal reason a diamond with pavilion angle greater than 41.75° is not graded an AGS 0 Ideal or a GIA Excellent.

This analysis of the 'eye of the round brilliant' has demonstrated why close to 41° and not over 42° is the small range for best round brilliant beauty/optical light performance for gemstones of all refractive indices.

The gemstone's eye analogy has shown why 41° - 42° pavilion main angles were found best by empirical, 'cut and try'. This optical effect is the same for gems of all R.I.'s, because table reflection dilation is independent of the gemstone's R.I.

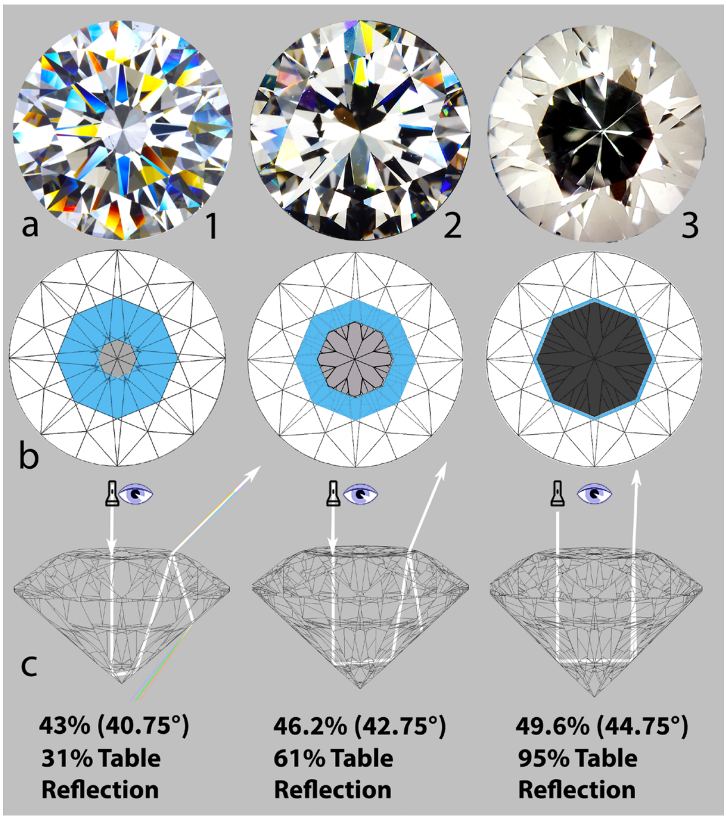


Figure 15. Analysis with photographs of effects on gem light performance due to a pavilion that is cut steeper than the narrow 41° - 42° range. Although shown with diamond, the TR dilation is the same for other gems, because this optical effect is independent of the gem's R.I. An example is the colorless chrysoberyl, (Row a/Column 3), which was cut with a pavilion angle near 45°.
Row a diamond and gem photography by Michael D. Cowing. Rows b and c are images created by Michael D. Cowing using DiamCalc.

Figure 16. Nailhead round brilliant peridot cut with 45° pavilion main angle.
Photo by Michael D Cowing

DISCOVERY OF THE OBSERVER'S INFLUENCE ON GEM BEAUTY AND OPTICAL LIGHT PERFORMANCE

A major contribution to the understanding of gemstone optics and best facet design angles was made by faceter, mathematician, and engineer, Bruce Harding, with the publication of his article 'Faceting Limits' in the fall 1975 edition of GIA's 'Gems and Gemology'.

Harding was the first to point out to the faceting world the important effect on gemstone beauty/optical light performance of the obstruction to gem illumination caused by the viewer's head. Harding set out with the design goal expressed in 'Faceting Limits' to avoid combinations of pavilion and crown main angles that result in facets that reflect from the relative darkness of the observer's head.

Harding said "rays which are reflected to the viewer's eye must come from directions which missed his head. Figure 17 shows that at a viewing distance of one foot, as when examining a stone prior to purchase, the angle (or divergence) between incident and reflected directions of the same ray must be at least 10°; otherwise, the viewer will see reflections of himself."

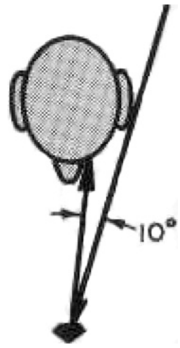


Figure 17. The angle (or divergence) between incident and reflected directions of the same ray must be at least 10°. Image by Bruce Harding

Harding derived the optical mathematics for the equations of lines on his basic faceting chart, Figure 18, between which lie combinations of crown and pavilion main angles shaded dark, which reflect from within the 10° minimum divergence imposed by the viewer's head.

Dark shading of areas of the charts, which violate the 10° minimum divergence, separate the chart into three unshaded areas which are labeled Zones A, B and C. Harding notes "Most recommended designs (those of Soukup and Tolkowsky) lie in Zone A."

Harding's faceting charts are shown in Figure 19 for gems of different refractive indexes representative of common faceting materials. (Understanding the additional complexity of the lighter grey areas is unnecessary.)

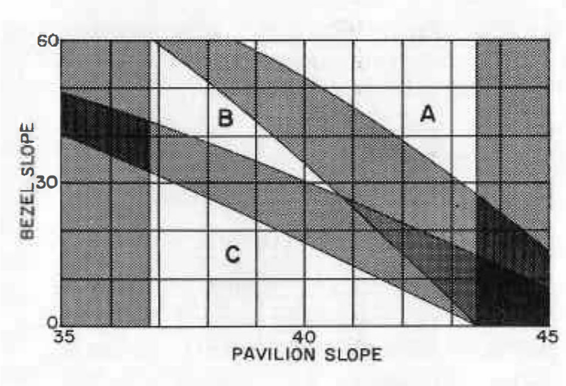


Figure 18. Harding's basic faceting chart

A remarkable discovery is made, when we observe the locations of the solid black marks on these charts that represent the best, time honored designs for gems of different RI's, as recommended by Soukup, E.J. (1962) Facet Cutters Handbook, and Tolkowsky, Marcel (1919) Diamond Design.

The discovery is that, rather than avoid observer obstruction, those best main angle combinations, for not only diamond, but for each different RI gem, are all reflecting from the border or just outside Harding's 10° divergence line at the Zone A boundary (This is the line of the upper boundary of the upper diagonal shaded area in the charts of Figure 19).

Verification of this discovery is observed in the gem's spectral reflection pattern, Figure 20. Generated by reverse ray tracing, the inner portion of the Ideal cut diamond's spectral reflection pattern is displayed. Here are seen the spectrum reflection locations of the 16 virtual facets from the 8 mains.

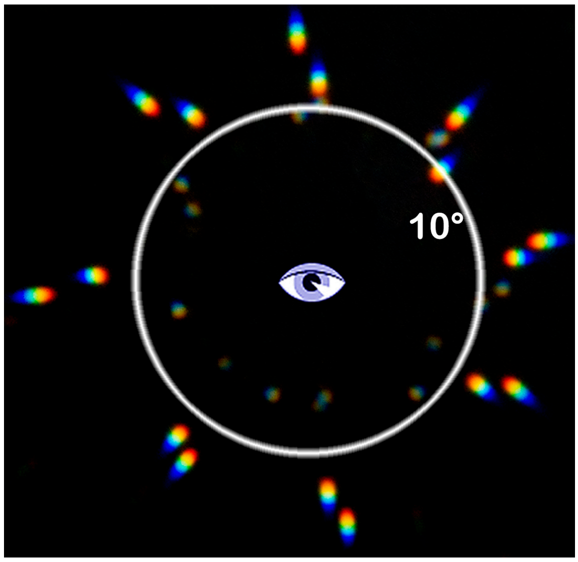


Figure 20. Spectral reflection pattern of the sixteen main virtual facets. The white circle indicates 10° divergence from the observer's eye. Photo by Michael D. Cowing

Just as Harding's charts show, the location of these spectrums reveal that the 16 main virtual facets of the Ideal cut diamond are reflecting from the area of illumination contrast just outside 10° divergence from the observer's eye.

Most importantly, Harding's charts reveal the same is true of other gemstones with different RI's. These empirically found best main angle combinations of diamond and the other gems in Figure 19 all reflect from just outside the line of 10° divergence.

The two large virtual facets from each of the eight mains from each gem reflect from high, but not too high angles (around 10° to 15° away from the viewer's eye), and just outside of Harding's 10° minimum divergence required to avoid complete head obstruction. This important discovery explains why the small range of angles around the central ideal main angle combination of (34°,41°) is the best for diamond. That small range is graded by the major labs of GIA as Excellent, and AGS as Ideal. As Harding's charts reveal, the same is true for gems of other RI's as well. The empirically found best main angle combinations for diamond and other gems result in the main's virtual facets reflecting from the high angle just outside 10° minimum divergence. This is where illumination contrast due to observer obstruction is encountered. Overhead spotlights like those in jewelry store ceilings are also important contributors to high contrast in the diamond's illumination at high angles, from where the best cut gem's sixteen main virtual facets reflect.

As seen in his Figure 19 charts, the historically best angle combinations for each gem species have mains reflecting from angular locations just outside the contrast edge of the 10° minimum divergence. This is the minimum divergence to avoid eye-to-near-ear obstruction in close viewing, as illustrated in Figure 17. All head obstruction is not avoided. For instance, there

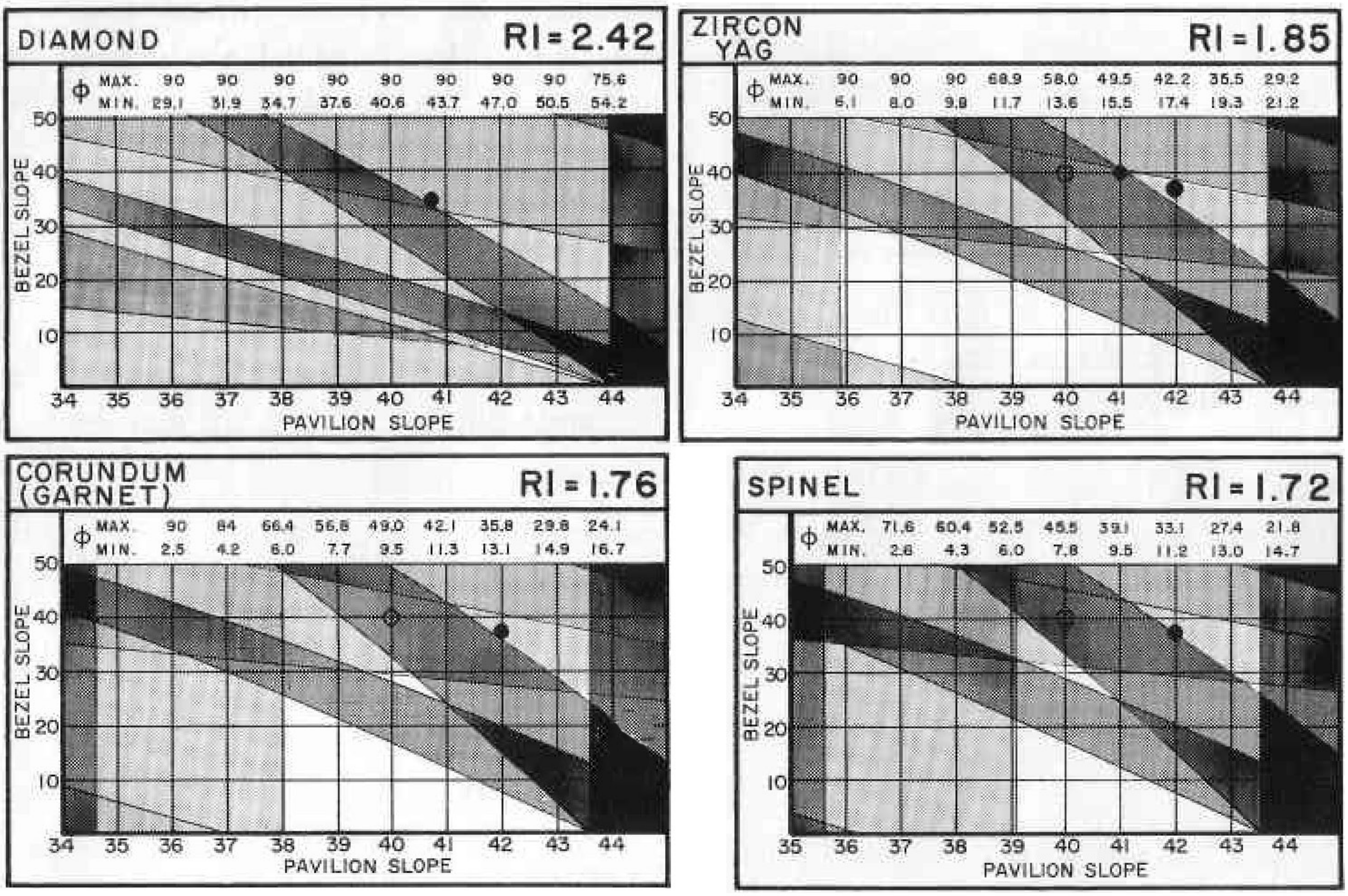


Figure 19. Faceting charts with lighter areas indicating least head obstruction. Charts by Bruce Harding

is greater obstruction from each eye to the far ear. However, with binocular vision our brain simultaneously combines a double exposure of reflections, one from each eye. Thus, the combined scintillation and fire from both eyes may be seen despite the eye to far ear obstruction so long as there is 10° or greater divergence.

As the gem is tilted from the face-up perpendicular, the divergence increases, so back and forth tilting in examination causes the reflection locations of the facets to move in and out of the contrast edge of head obstruction. As will be shown, this changing contrast results in scintillation and fire. The answer to why this circumstance is best for gemstone sparkle and fire was developed and demonstrated in the third article, 'Diamond's Spectral Constellation' summarized as follows:

OPTICAL LIGHT PERFORMANCE OF THE MAIN'S SIXTEEN LARGE VIRTUAL FACET REFLECTIONS AND THEIR NEXUS WITH ILLUMINATION CONTRAST

Rather than avoid dark reflections from the viewer, we have shown that the best angle combinations for diamond and other gems result in reflections that, with movement, are in and out of the contrast edge of head obstruction. The reason this is best for gem beauty and light performance was developed in the third article, 'Diamond's Spectral Constellation'. There it was demonstrated that all three aspects of gemstone beauty; fire, scintillation and the contrast aspect of brilliance, depend upon illumination contrast.

It is demonstrated by the Ideal diamond photograph in Figure 21 that, absent illumination contrast, at the points from which virtual facets reflect, there is no scintillation, no fire and no contrast aspect of brilliance. In Figure 22, that same diamond is now exhibiting high contrast brilliance when illuminated by high contrast lighting at high angles from a Philips Circle Line fluorescent light.

Obstruction caused by the observer, especially his/her head is a key ever-present feature introducing contrast in the gem's illumination. It has influenced the evolution of the most beautiful and highest performing round brilliant, the Ideal Cut. Observer obstruction most often introduces contrast in the gem's illumination at high angles that is favorable to light performance in gems whose facet design angle combinations take advantage of it.

In addition to the dependance of scintillation and contrast brilliance on contrast in illumination, this third article expanded long-established understanding of the optics of fire by demonstrating fire's dependence on contrast in the gemstone's

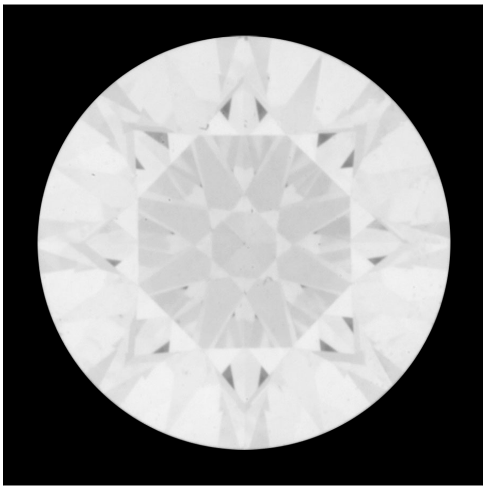


Figure 21. Photograph of an Ideal cut diamond in diffuse illumination with no observer obstruction. Without illumination contrast the diamond has no contrast brilliance, no scintillation, and no fire.
Photo by Michael D. Cowing

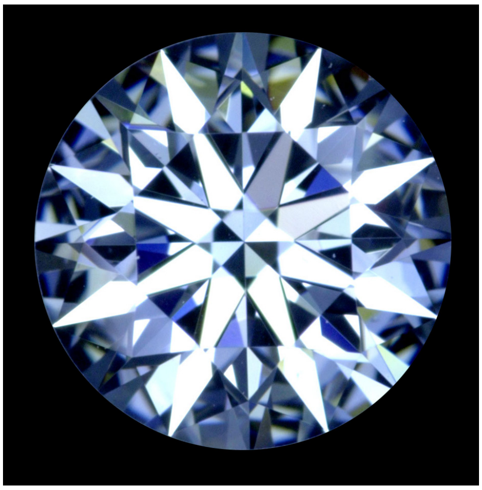


Figure 22. Photograph of same ideal cut diamond from Figure 21 exhibiting high contrast brilliance due to high contrast lighting at high angles from a Philips Circle Line fluorescent light.
Photo by Michael D. Cowing

Illumination. 'Fire' is enabled in gemstones due to dispersion of light into its spectral colors. The greater a gemstone's property of dispersion the greater is the spectral fanning of light rays into spectral colors. Dispersion of rays occurs upon their entry or exit of a gemstone at an angle to a facet's perpendicular. The greater the angle and the closer to parallel to a facet the greater is the spectral fanning, and the greater the potential for the observation of fire. A discovery demonstrated using the spectral reflection pattern is the essential role of 'illumination contrast' in the production of diamond's fire. The occurrence of fire in any particular 'virtual facet' is dependent upon bright-dark contrast in the illumination at the location in the surrounding being reflected. The greater the bright-dark contrast at that location the more vivid the fire. The spectral reflection pattern and reverse ray tracing were employed in that work to explain how and why fire occurs at contrast borders between light and dark, and the colors of that fire.

Bright spotlights produce the greatest illumination contrast, and consequently the most vivid fire. As we can see in Figure 21, if there is no contrast in a diamond's illumination it will not only exhibit no scintillation or contrast brilliance, but also no fire. This is because the optics that result in spectral colors of fire from any particular 'virtual facet' exist at light-dark contrast borders. When there is no contrast at the locations from which 'virtual facets' reflect there is no fire, as shown in the Figure 21 photograph of an Ideal cut diamond. In diffuse illumination with no contrast from observer obstruction there is no fire.

Without illumination contrast the diamond has no contrast brilliance, no scintillation, and no fire. The ever-present contrast from observer obstruction results in fire seen in the diamond, even under a low contrast, overcast sky such as existed in the Figure 23 photograph.

Figure 23 (Left) The lower 4 mains are black reflecting the observer's head, while the inner virtual facet at 1 o'clock reflects daylight. The two inner virtual facets at 10 & 2 o'clock reflect blue fire from the contrast edge of observer obstruction. The red-yellow wavelengths are obstructed and absent, leaving the blue fire from the blue-violet wavelengths. Figure 24 (Right). Vivid colors of fire emanate from virtual facets missing one end or the other of their spectrum due to the sharp contrast of many white LED spotlights located where most of the diamond's virtual facets reflect. Photos by Michael D Cowing

Spectacular fire, such as seen in Figure 24, occurs where there is high contrast from spotlighting at most of the diamond's virtual facet, spectral reflection locations. (See 'Diamond's Spectral Constellation' for a detailed explanation.) All three attributes of diamond beauty, fire, scintillation and the contrast aspect of brilliance have been shown to depend on contrast in the diamond's illumination.

In summary, for the best/ideal optical light performance, the reflections from the 16 virtual facets from the pavilion mains in gems of all RI's must not, in the face-up view, reflect from the dark areas within 10° of the observer's eyes. For the best fire and scintillation, they also should not come from constantly bright diffuse areas lacking essential contrast. Rather, the best/ideal design for each gem RI has the crown and pavilion main angle combination reflecting from locations close to the contrast border between the relatively dark head and the surrounding bright illumination. Under these circumstances, slight tilting or movement produces on-off flashes of scintillation and fire from the transitions in contrast between dark and bright

LIGHT PERFORMANCE DESIGN ANALYSIS OF THE SPINEL ROUND BRILLIANT USING ITS SPECTRAL REFLECTION PATTERN

The principal facet design discoveries, established here, are that the historical, empirically found best round brilliant cuts of gems of all RI's have similar 41° - 42° pavilion main angles, and the combination of their pavilion and crown main angles reflect from the area of illumination contrast just outside 10° divergence from the observer's eye. With these discoveries, we are equipped to optimize beauty and light performance in round brilliant designs of gems of all RI's. The compromises listed in the Introduction that may be required are kept in mind, especially the problem of windowing with gems of RI lower than the 1.62 of topaz.

Using spinel as our example, the following design analysis demonstrates utilization of the spectral reflection pattern generated through reverse ray tracing, along with Harding's charts to validate and even improve the historical, empirically arrived at, best main angle combinations as listed in Soukup's, 'Facet Cutter's Handbook'.

In order to observe a gem's face-up light performance, an illumination similar to jewelry store lighting is employed. That is a combination of diffuse lighting and high contrast spot lights, but with no light coming from within the 10° observer obstruction boundary. See Figure 25.

Figure 26 is the computer simulated face up light performance of the spinel, cut with the historically best angles (37°, 42°) listed in Soukup's, 'Facet Cutter's Handbook'. It is a photo realistic simulation of the spinel's appearance in the Figure 25 illumination. Notice the dark reflections from the dominant sixteen main virtual facets that are occurring under the illumination of Figure 25.

The 16 reflections from the spinel's mains are dark, because they reflect from just within the 10° boundary of observer obstruction, where there is no light. From the spectral reflection pattern to the right of Soukup's spinel image, repeated as the top-left gem in Figure 27, we observe that both the inner (I) and outer (O) virtual facet reflection locations are inside the 10° divergence circle, and reflecting darkness.

Raising the bezel/crown main angle of Soukup's round brilliant spinel 3° to (40°, 42°) is seen, in the middle-left spinel, to improve both brilliance and fire, by increasing the ray divergence of the 16 main virtual facets, from just inside the 10° observer obstruction to just outside. This is verified by the mains reflection pattern to the right of the improved middle spinel in Figure 27.

A further improvement in light performance is seen in the third spinel image, Figure 27. It was obtained by dropping the pavilion mains a degree from 42° to 41° by cutting to (47.5°, 41°). Staying outside the 10° observer obstruction, while reducing the pavilion main angle by 1° to 41°, is accomplished by increasing the crown main angle along Harding's -7.5° inverse slope boundary of 10° observer obstruction. This reduces the table reflection, increasing the size of the 8 inner main virtual facets, while keeping the main's 16 virtual facets reflecting from just outside the 10° obstruction boundary.

The larger 8 main reflections inside the table exhibit more brilliance and fire, because of their greater area than the smaller corresponding 8 inner main reflections in the middle diamond with 42° pavilion mains. If there is sufficient depth to the rough, this is the way to go. However, greater depth is required with the shallower 41° pavilion, because of the required 47.5° higher crown. Such practical issues, as gem rough depth requirements, are considerations that often require compromise with the optimization of the gem's light performance. Harding's graphs can be used, as was done here, to show how to adjust the pavilion and crown main angles to improve the gems light performance, while keeping the mains reflecting from just outside the 10° obstruction boundary.

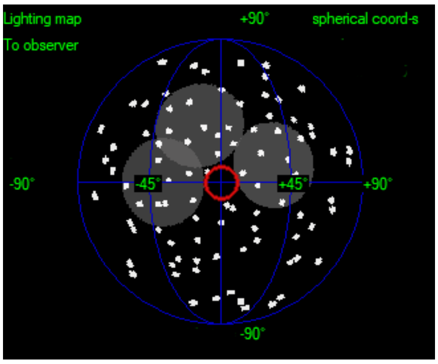


Figure 25. Experimental lighting including 10° observer obstruction (Area outlined in red)

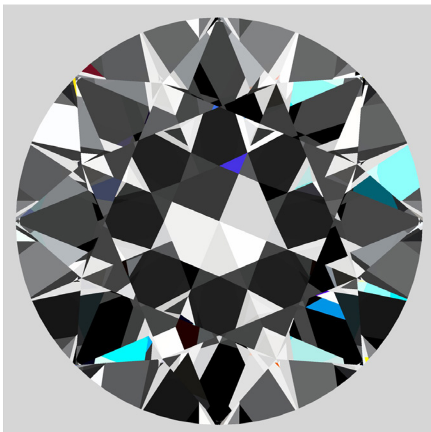
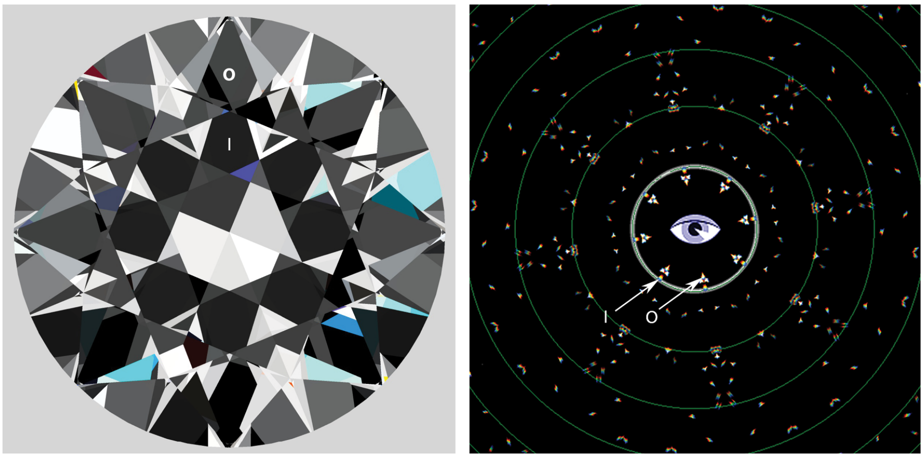


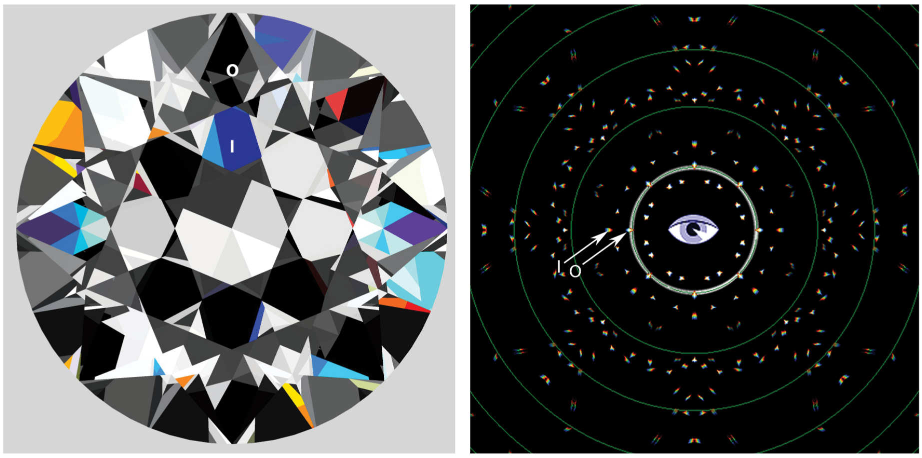
Figure 26. Computer simulation of spinel cut with angles (37°, 42°) from Soukup's 'Facet Cutter's Handbook', in the illumination of Figure 25.

In summary, the best empirically arrived at main angle combinations for gems with RI's different than diamond have, like diamond, close to 41° - 42° pavilion mains. This keeps the table reflection, with its poor reflection properties, small, and the 'iris' area large for best light performance. From Soukup's recommended best round brilliant main angle combination of gems with RI lower than diamond, it is found that they require a steeper crown angle than that of diamond. This is in order that they reflect from the same best high angle direction as diamond, just outside the contrast edge of 10° observer obstruction.

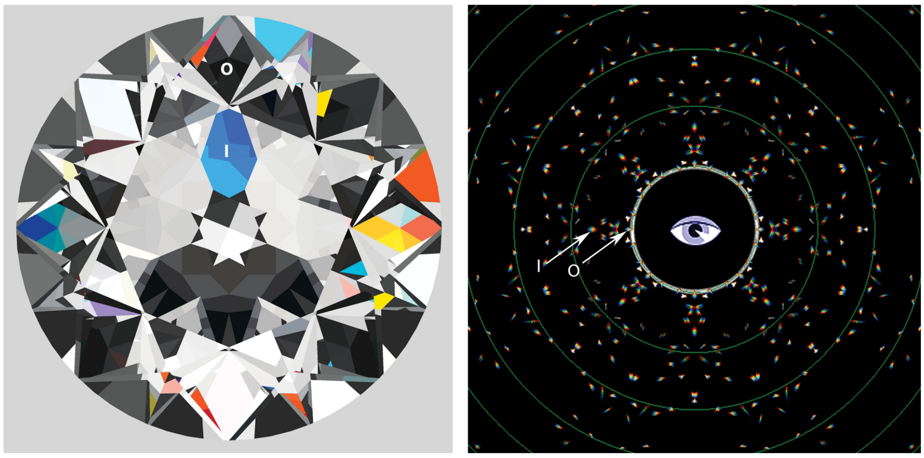


Best spinel (37°, 42°) bezel, pavilion main combination from Soukop's Handbook

Spectral reflection pattern of Soukop's spinel with (37°, 42°) main angles



Raising the bezel crown main angle 3° to (40°, 42°) improves both brilliance and fire, by increasing the ray divergence of the 16 main virtual facets from just inside the 10° observer obstruction to just outside



Cutting to (47.5°, 41°) is a small further improvement in light performance attained by reducing the pavilion main angle by 1° to 41° compensated by increasing the crown main along Harding's - 7.5° inverse slope boundary of 10° observer obstruction. This reduces the table reflection, increasing the size of the 8 inner main virtual facets, while keeping the main's 16 virtual facets reflecting from just outside the 10° obstruction boundary.

Figure 27. Spinel Round Brilliant Cut Light Performance Analysis

References

Arem, J. (1977), 'Color Encyclopedia of Gemstones', Van Nostrand Reinhold Company, p. xxiv

Cowing, M. (2018), 'Let There Be Light', Gems & Jewellery /Spring/ Volume 27 / No. 1, https://acagemlab.com/diamond-design-and-light-performance/

Cowing, M. (2020), 'Round Brilliant Cut Beauty and Light Performance Part 1', Gemmology Today, June 2020. https://acagemlab.com/round-brilliant-cut- beauty-and-light-performance-part-1/

Cowing, M. (2020), 'Round Brilliant Cut Beauty and Light Performance Part 2', GemmologyToday, September 2020. https://acagemlab.com/round- brilliant-cut-beauty-and-light-performance-part-2/

Cowing, M. (2021), 'Diamond's Spectral Constellation', Gemmology Today, June 2021.https://acagemlab.com/ideal-brilliant-cut-and-spectral-constellation/

Cowing, M. (2021), 'History and Utility of Gemstone Reflection Pattern Generation and Analysis', Gemmology Today, March 2022. https://acagemlab.com/

DiamCalc, Octonus Software, Http://www.octonus.com/oct/products/3dcalc/standard

Harding, B. (1975), 'Faceting Limits', Gems and Gemology, fall 1975, Gemological Institute of America, Los Angeles, CA.

Soukup, E.J. (1962) Facet Cutters Handbook, Gemac Corp, Mentone, California, 64 pages

Tolkowsky, M. (1919), 'Diamond Design', E. F. N. Spon, Ltd., London, PP. 6, 23-25, 94-95, 97-104.

Wade, F. (1916), 'Diamonds - A Study of the Factors that Govern their Value', G.P. Putnam's Sons, New York and The Knickerbocker Press, London.