Evidence of this is seen as these stones always contain multitudes of minute exsolved particles, with the color concentrated around them. In Chapter 6, the mechanisms involved in treated corundums are taken up in greater detail.

**Black-star sapphire**

Black-star sapphire differs from other corundums, in that its color is not due to impurity ions in solid solution or color centers. Instead, it results from the color of inclusions of exsolved hematite-ilmenite silk (Weibel & Wessicken, 1981). Similar to the Cr-green mica plates in aventurine quartz, this silk imparts a deep brown-black color to an otherwise blue, green or yellow sapphire. This is termed *mechanical coloration*—color by inclusions.

Not only is the hematite-ilmenite silk responsible for color, but these platelike inclusions also produce a six-rayed star effect. When it occurs in an otherwise blue or green sapphire, the rays of the star appear white. Rarely however, the hematite unmixes in a yellow sapphire, and the star takes on a golden-yellow color. Such *golden-star* black-star sapphires are mined at Bang Kha Cha and Khao Ploi Waen in Chanthaburi Province, Thailand, and are highly prized. This is evidenced by their high prices, which may command up to $100 per carat in the local (Thai) market.

**Other sapphire colors (see Table 4.1)**

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**Luminescence**

Corundum, particularly ruby, displays several forms of luminescence. These include:

- **Fluorescence**: Emission of visible light when exposed to higher energy radiation
- **Phosphorescence**: Continued emission after the stimulating source is removed
- **Thermoluminescence**: Emission of visible light when the specimen is heated
- **Triboluminescence**: Emission of visible light when the specimen is rubbed

The most important of these from the gemological standpoint is *fluorescence*. Fluorescence results when a stone absorbs higher energy (visible light, ultraviolet light or x-rays), and then re-emits it as lower energy in the visible region.

Ultraviolet (UV) light is most often used to stimulate fluorescence. Two different wavelengths are typically used—366 nm (long wave) and 253.7 nm (short wave). The viewing cabinets used in conjunction with these light sources provide a dark background and isolate the reaction from stray room light. It is best to grasp the stone with tweezers rather than holding it in the hand, again so that the reaction is seen against a perfectly black background. The gem should be grasped table-to-culet and held as close as possible to the light, for fluorescence diminishes in direct proportion to the distance the stone lies from the light. Examine the gem across the girdle, where it is thickest, to see the strongest
Figure 4.7 Sri Lankan yellow/orange sapphires owe part or all of their color to color centers, which may occur naturally or via human-induced irradiation. Some of these color centers are unstable and even sunlight may cause bleaching. *Left:* Simultaneous creation of hole and electron centers. Irradiation ejects an electron from an atom, ion, molecule, impurity or other defect (A). This is received by the electron precursor (B), which may also be an atom, ion, molecule, impurity or other defect. Now both hole and electron centers possess unpaired electrons. Either or both may absorb visible light when excited. *Right:* Formation of color centers in gemstones. 

a. Irradiation causes excitation and subsequent relaxation may trap the electron.  
b. Once trapped, daylight may cause more excitation, resulting in absorption of visible light (the precise wavelengths absorbed depend on the size of the step). Subsequent decay occurs in steps and generally releases heat. If one of the steps falls into the visible region, fluorescence (visible emission) results.  
c. Heating the gem may cause the electron to return to its original location, thus bleaching color and producing thermoluminescence.  
d. In some stones, energy produced by sunlight alone may cause fading. (Modified from Nassau, 1983)

There is no better technique of observing fluorescence in ruby than B.W. Anderson's crossed filters method. It requires two complementary filters—a blue filter to absorb all red, orange and yellow light, and a red filter to absorb all green, blue and violet light. When "crossed," the entire visible spectrum is absorbed, from violet to red, permitting no light to pass. Plastic or glass filters of the above colors usually work well, as does a strong solution of copper sulfate (for a blue filter).

In the test, a fiber-optic light (or another focused light) is directed through the blue filter onto several rubies. Now observe the gems through the red filter. An amazing sight awaits, with the rubies appearing as glowing red coals on a jet-black background. Because of the blue filter, only blue light falls onto the stones. They convert this blue light into a slightly lower form of energy—red light, emitted from the gem at the fluorescent doublet of 692.8 and 694.2 nm. This can be confirmed by examining the stones through the crossed filters with the spectroscope. A bright fluorescent doublet will be seen at the end of the red, silhouetted on a black background. It is a magnificent method of demonstrating exactly the principles of fluorescence, in this case, fluorescence to visible light. While long-wave UV is the most efficient stimulating energy, visible light also produces substantial fluorescence, as shown in Figure 4.11.

Although fluorescence is a useful gemological test, some caution must be used in interpreting the reactions. Fluorescence usually is caused by impurities within the stone, with

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2: The inverse square law. Halving the distance increases illuminance by a factor of four.
Luminous rubies of lore

Ruby long had the reputation of being self-luminous. Witness the following selection from G.F. Kunz (1913):

The luminous "ruby" of the King of Ceylon is noted by Chau K'o-kua, a Chinese writer of about the middle of the thirteenth century and hence a contemporary of the Arab Yelafish. He says: "The king holds in his hand a jewel five inches in diameter, which cannot be burned by fire, and which shines in the night like a torch. This gigantic, luminous gem was also believed to possess the virtues of an elder of youth, for we are told that the king rubbed his face with it daily and by this means would retain his youthful looks even should he live more than ninety years.

Kunz annotations
* See the English translation of his "Chu-fan-chi," by Friedrich Hirth and W.W. Rockhill, St. Petersburg, 1911, p. 72.

G.F. Kunz, 1913. The Curious Lore of Precious Stones

The famous Portuguese physician, Garcia da Orta, who lived in Goa from 1534–64, published a classic work on the medicinal products of India. In this volume, which was said to be the third book ever printed in India, da Orta discussed self-luminous rubies (Orta, 1913):

...it is true that a lapidary told me that he counted on a table a few very fine rubies from Ceylon, very small, such as we call stone rubies, because they are sold at twenty the ditto. One got between the folds of a table, and at night, in the dark, the table seemed to have a spark of fire, so that it was like a candle. A very small ruby was found, and when it was taken upon the spark no longer appeared on the table. I do not know whether this is the truth or a lie. But I know that the lapidary who told me this professionally told lies sometimes, as he found them profitable in his trade, and he got so used to it that he occasionally related marvels of his own accord.

Garcia da Orta, 1563
Coloquios dos simples e drogas he cousas medicinais da India (Colloquies on the Simples and Drugs of India)

only tiny fractions of one percent being necessary in many cases. Since the impurity content can vary a great deal from stone to stone, the fluorescent reactions may also vary. Thus, fluorescence should never, never be solely relied upon to establish the identity of a gem. Instead, it provides only a rough indication, even under the best of circumstances. Far too many rubies and sapphires have been misidentified by gemologists who put too much faith in the colorful glows seen under ultraviolet light.

Table 4.3 is an admittedly weak attempt at setting out the typical fluorescent reactions for the different varieties of corundum. It should by no means be considered the last word on the subject. Variations in the trace element content can produce entirely different reactions; thus, this can be considered only as a general guide. For individual reactions, see the tables for each type in Chapter 7 (synthetic) and Chapter 12 (natural).

**Corundum Spectra**

![Corundum Spectra](image)

**Figure 4.9** Visible absorption spectra of corundum. Depending on the coloring agents present, these three spectra may occur in various combinations.

**UV phosphorescence.** Phosphorescence refers to a continuing of fluorescence after the stimulating radiation source has been switched off. A common example is the green glow exhibited by many light switches after the light is turned off.

According to Webster (1939), both natural and synthetic (Verneuil) rubies display a weak phosphorescence to UV light. But because this after glow lasts just a fraction of a second, it is of limited diagnostic use. Cr-rich Burmese and synthetic rubies tend to show a slightly longer phosphorescence than Thai/Cambodian rubies, where Fe quenches the effect.

**Absorption spectra**

**Visible region**

Among B.W. Anderson's many contributions to gemology, that which will be remembered longest is his work in the field of spectroscopy. Beset with a degree of color blindness, Anderson was forced to avail himself of other means identifying gems, rather than relying on characteristic colors. One of his greatest innovations was introducing gemologists to an instrument which had long been used in analytical chemistry—the hand spectroscope. In a series of 40 ground-breaking articles in The Gemmologist, Anderson and C.J. Payne laid down the absorption spectra for virtually every major gem material. So comprehensive were these articles that, even today, they remain the most important source of data on visible-region spectra (Anderson & Payne, 1953–1957).

A spectroscope gives a direct display of the visible spectrum from 400–700 nm. It does this by splitting light, either with prisms or by diffraction grating, and laying this out so as to be viewed with the eye. White light is first passed through the stone and then into the instrument. Certain wavelengths

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3 Are you reading these footnotes? Good.
may be absorbed, and others freely transmitted, creating an absorption spectrum consisting of bright colors and dark absorption bands and lines. The position of these bands of broad absorption and lines of narrow absorption have diagnostic value. Their position can be roughly measured by means of a wavelength scale, or estimation by reference to the colors or known lines of a sample filter or stone. Even using a spectroscope with a built-in wavelength scale, however, yields only approximate measurements.

There exist three basic spectra in natural corundum, due to the elements chromium, iron, and vanadium. Those of chromium and iron spectra are extremely common, while that of vanadium is rare. They are shown in Figure 4.9.

The absorption spectrum of ruby is derived principally from the element chromium, with iron occasionally playing a small part. Chromium produces a distinctive spectrum which will easily separate ruby from all other minerals; however, synthetic ruby is also colored by chromium and so shows an identical spectrum.

**Using the hand spectroscope**

The direct-vision spectroscope is one of the most difficult instruments to master. But in the hands of an experienced observer, the information gained can be of great value. Thus, it is vital that anyone aspiring to the title of gemologist be well versed in this instrument’s use. While it is beyond this book’s scope to describe the use of this instrument, a few brief tips are called for.4

Successful use of the spectroscope is largely a question of path length. Longer light paths allow more absorption, thus strengthening faint lines; shorter paths produce less absorption and so allow distinction of individual lines within areas of heavy absorption. Path length is determined by the following:

- **Position of the stone:** Stones must be carefully positioned so that only light passing through them reaches the spectroscope. Due to the arrangement of facets or inclusions, light may exit the stone in several different directions; the stone should be positioned so that the maximum amount of light passes out towards the spectroscope. Placing one’s hand around the stone in different positions allows one to determine exactly where the light is headed. Oval stones should be positioned so that the broad side faces the spectroscope. The stone’s position must also take into account color zoning. Absorption lines normally result from color, so the stone should be positioned so that light passes through deeply-colored areas, to maximize absorption.

- **The light source and its position:** The light source itself is of tremendous importance. It must be intense, and focussable to a narrow spot. Fiber optic illuminators of 150 watts or more work well for spectroscopy. The light may be positioned to allow transmission directly through the stone from below, or reflected from above. In most cases, the reflection method is superior, for it allows a longer path through the stone and, thus, more absorption. If too much absorption is seen, the path should be shortened by moving the light and/or the stone to lessen the absorption. For example, shortening the path in Fe-rich Thai/Cambodian rubies may allow one to pick out the iron lines at 451.5, 460, and 470 nm, in addition to the Cr spectrum. Lengthening the path intensifies faint lines, which

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4 An excellent description of the use of the spectroscope can be found in Anderson’s *Gem Testing* (1990).
allows one to see the 451.5 nm complex in heat-treated Sri Lankan sapphires, where it is normally weak.

- **Spectroscope adjustment and position:** First the instrument is centered on the spectrum by rocking it up and down with the slit only slightly open. Once the slit is located, the slit is adjusted just enough to allow the spectrum to appear (not too much!). Adjust the drawtube focus for each individual area, as different colors come into focus at different points. In locating faint lines, much skill is needed. Like a pinball machine, one learns through practice how to finesse the instrument. Try not to look directly at a faint line, but instead peer out of the corner of the eye. Open and close the slit rapidly and rock the instrument up and down at the same time. This will help to resolve the faint lines which are so often encountered.

Once one understands the implications of path length, it is simply a question of positioning the instrument in the proper position to catch the light. When both light and stone are correctly positioned, the instrument itself still needs to be correctly placed. This involves moving the spectrope into the light path exiting the stone. Always make sure the instrument is firmly anchored with the holder supplied on table models, or with modeling clay or plasticine. Although the instrument is called the hand spectrope, the fact is that it just cannot be used effectively in the hand alone. A holder to anchor the instrument is absolutely essential.

### Non-visible spectra

Spectrophotometers are able to detect spectral features outside the visible region. Those areas studied for gemology include the ultraviolet and infrared regions. While studies have indicated this area warrants further research, the expense of the instrumentation involved means that only the most well-heeled gemologists have access to such tools. The result has been a paucity of studies in these regions. Too often, when such studies have been published, they involve but a handful of stones. Until more comprehensive studies involving large numbers of stones from a variety of sources are published, the following data must be viewed as work-in-progress.

#### Table 4.2: Krüss UVS 2000 spectra

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural corundum (Type I)</td>
<td></td>
</tr>
<tr>
<td>Ruby</td>
<td>&gt;98% (121 stones)</td>
</tr>
<tr>
<td>Lines 1 and 2 stronger than line 8</td>
<td></td>
</tr>
<tr>
<td>Blue sapphire</td>
<td>&gt;92% (109 stones)</td>
</tr>
<tr>
<td>Lines 1 and 2 stronger than line 8 (without line 10)</td>
<td></td>
</tr>
<tr>
<td>Synthetic corundum (Type II, except some blue sapphires)</td>
<td></td>
</tr>
<tr>
<td>Ruby</td>
<td>&gt;74% (118 stones)</td>
</tr>
<tr>
<td>Line 8 equal or stronger than lines 1 and 2</td>
<td></td>
</tr>
<tr>
<td>Blue sapphire</td>
<td>&gt;86% (28 stones)</td>
</tr>
<tr>
<td>Lines 1 and 2 stronger than line 8 (with line 10) or line 6 stronger than lines 1 and 2</td>
<td></td>
</tr>
</tbody>
</table>

#### Ultraviolet (UV) spectra

Blue sapphires also display absorption lines in the UV region and these can be useful in separation from Verneuil synthetics. As this region is invisible, however, special instruments or techniques are required to observe these lines. Absorption lines are present in natural blue sapphires at 379 and 364 nm and are said to be due to ferric iron. These can...
Table 4.3: Fluorescent reactions of untreated corundums

<table>
<thead>
<tr>
<th>Variety</th>
<th>Long wave UV (366 nm)</th>
<th>Short wave UV (253.7 nm)</th>
<th>X-rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruby (including pink)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Burma, Sri Lanka, Vietnam, Afghanistan, Kenya, Tanzania</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Thailand/Cambodia</td>
<td>Moderate to extremely strong red to orange red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weak to moderate red to orangy red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moderate to strong red to orangy red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to moderate red to orangy red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moderate to strong red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to moderate red</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue sapphire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Sri Lanka, Kashmir (India)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Australia, China, Colombia, Nigeria, Thailand, Cambodia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong red to orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong red to orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dull red or yellowish orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purple &amp; violet sapphire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Burma, Sri Lanka, Vietnam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong red to orange red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong red to orange red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong red</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow &amp; orange sapphire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Australia, Thailand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Sri Lanka</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Vietnam</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not reported</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to weak red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not reported</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weak to strong orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not reported</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green sapphire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Australia, Thailand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Generally inert; rarely weak red to orange</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colorless sapphire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Sri Lanka</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to strong orange to red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to moderate orange to orange red</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert to moderate red or orange red</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Heat treated gems often display a chalky blue-green fluorescence under SW. Generally it is the colorless areas of the gem which show this fluorescence. Dyed gems may display a fluorescence concentrated in the cracks (where the dye is located). This fluorescence may differ from that of the stone itself.

be found even in Sri Lankan sapphires where the 451.5 nm line is not present (Anderson & Payne, 1948). These UV lines are absent in Verneuil synthetics. Nautiyal & Mukherjee (1958) reported lines at 388 and 375 nm for natural sapphires. As they used more sophisticated measuring apparatus, their wavelength measurements are probably more accurate than Anderson’s.

UV spectra have proven useful in separating natural corundums from a variety of synthetics. Unfortunately, the cost of UV spectrophotometers is out of reach of most labs. However, Krüss of Germany has manufactured a cheaper UV spectroscopy that will allow many separations to be made. The Krüss UVS 2000 makes use of a mercury emission lamp which has a total of 17 emission lines ranging from about 260 nm in the UV to 580 nm in the visible region. Krüss has numbered these lines, and those numbers are used in Table 4.2, which is based on Montgomery (1991b).

By use of a fluorescent screen, the UVS 2000 allows one to see whether a gem transmits light in the region from 260–580 nm. Any lines not visible indicate absorption of that area by the gem in question.

Infrared (IR) spectra

Peretti & Smith (1993) reported that Russian hydrothermal synthetic rubies show a number of sharp lines between 3000 and 3800 wavenumbers, in addition to the normal infrared spectrum of corundum. Smith & Surdez (1994) found a number of sharp lines between 3100 and 3400 wavenumbers in Burmese rubies from Mong Hsu.

Pleochroism

Corundum crystallizes in the trigonal division of the hexagonal system. Lattice points are equally spaced along the horizontal plane, but differently spaced in the vertical plane. This type of symmetry in the distribution of electron clouds means that light will behave differently, depending on its direction of travel.

In corundum and other uniaxial gems, light entering in any direction except parallel to the c axis is split into two rays. Because of differences of atomic symmetry, and subsequently, vibration direction, each ray may be absorbed differently. Thus, one ray takes on one color, while the other takes a different color. This difference in color with direction is termed pleochroism ('multicolored'). Uniaxial materials possess two vibration directions (ω and ε), and so, potentially, two different colors, one corresponding to each vibration direction. As a result, uniaxial gemstones, such as corundum, are dichroic. Because pleochroism results from the difference in vibration directions, it varies in a manner similar to the refractive indices. The color corresponding to the ordinary ray (o-ray) is constant throughout the crystal, while that corresponding to the extraordinary ray (e-ray) is variable. Parallel to the c axis (optic axis), the e-ray color matches that of the o-ray. Thus no pleochroism is seen in this

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5. Surprisingly, Denning & Mandarino (1955) found in a study of synthetic ruby, that while the pleochroic pattern was similar to the RI variation, it did not match exactly. In fact, for light of 486 nm, there was noticeable pleochroism even parallel to the c axis. But the above model is close enough for our purposes.
Although iron is not normally used to color Verneuil synthetic yellow and orange sapphires, a weak, ill-defined line at 455 nm has also been reported on rare occasions (Anderson, 1980). In the deeper yellow and orangy yellow synthetic, a complete cutoff from about 450 nm, to the end of the violet, may be seen. This is also present with some natural sapphires and so is of no diagnostic value.

On occasion, the 451.5 nm complex has been detected in iron-rich purplish red rubies, particularly those from Thailand/Cambodia. Such stones will also show the normal Cr spectrum, but since the iron lines have yet to be found in synthetic rubies, their presence is proof of natural origin.

Vanadium spectra. The final instance in which the spectroscope is diagnostic is for the Verneuil color-change sapphire. Here vanadium is utilized as the coloring agent and it shows up in features that somewhat resemble those of ruby (natural and synthetic), with a fluorescent line close to 690 nm and a broad absorption band centered at about 580 nm. But instead of three lines in the blue, as shown by ruby, the synthetic color-change sapphire shows a single prominent line at 475 nm. The author has witnessed this vanadium line in only two natural corundums from Mogok, Burma, although it has also been seen in Tanzanian sapphires. Thus it is quite rare in natural corundums, and so, if seen, would strongly suggest (but not prove) a Verneuil synthetic.

Verneuil UV spectra
For a listing of Verneuil UV spectra, see Table 7.2.

Verneuil UV fluorescence
Had Karl Marx been a gemologist instead of writer, he no doubt would have labeled UV fluorescence “the opiate of gemology.” No test is easier to perform, and none comes within hair’s breadth of approaching the sense of security one gets basking in the warm red glow of a suspect ruby. The hand is withdrawn from the box, and the mind soars, serene in the knowledge that another synthetic ruby has met its match. But just as with opium and Marxism, the honey-moon is brief. It’s a crazy little thing called reality—with the exception of Thai/Cambodian stones, most natural rubies fluoresce just as strongly as their synthetic brethren.

Use of UV fluorescence for the separation of natural and Verneuil synthetic corundum is fraught with danger. Due to the overlap in reactions of natural and flame-fusion synthetics, under no circumstances should it be considered anything other than a weak indication of a stone’s identity. That said, in experienced hands, the test can still prove useful. Table 7.2 on page 157 includes a summary of the UV fluorescence of Verneuil synthetic corundum.

Synthetic star corundum
The Verneuil process is also used to grow star rubies and sapphires. Production of asteriated corundum was first achieved in 1947 by Union Carbide’s Linde Division. Linde patented the process in 1949 (Pough, 1966).

Asterism in natural corundum is due to reflection of light from sets of microscopic silk, which intersect in three directions at 120° within the basal plane (0001). Most silk consists of rutile (TiO₂), although hematite (Fe₂O₃), ilmenite (FeTiO₃), and magnetite (Fe₃O₄) have also been identified. It forms parallel to the prism faces of the host corundum via exsolution (see page 94).

A Linde star is born. While rutile inclusions were identified in asteriated corundum in the nineteenth century and the principles of exsolution were also understood at an early date, it took a chance observation before star rubies and sapphires were synthesized. In 1947, while experimenting with titanium as a coloring agent in synthetic corundum, Linde’s J.N. Burdick noticed a trace of silk in one of the boules. Appreciating its significance, he then began experiments which succeeded in developing enough silk to produce a star.

The process involves addition of 0.1 to 0.3% of titanium oxide (TiO₂) to the feed powder, over and above the normal percentages of coloring agents. Then, the boule is grown in the usual fashion, with the titanium entering into solid solution with the alumina. After cooling, it is annealed at between 1100–1500°C for between to 72 hours to 2 weeks, or more. By maintaining this temperature over a lengthy period of time, the titanium unmixes in the form of needles within the synthetic corundum host and a star is born.

Linde’s early production suffered from titanium’s tendency to move to the outside surface of the growing boule, creating a star in which rays stretched only halfway down the cabochon sides, fading away near the girdle. Other stones showed incomplete stars and transparent areas, due to the uneven silk distribution. The problem was solved by intermittently altering the flame temperature as the boule grows, thus allowing one layer to solidify before the next is deposited. The result is a boule containing layers of uniform titanium distribution, alternating with layers with uneven distribution. As layers are only 0.10 mm thick, the star appears continuous to the eye and the stone can even be recut without problem.

A disadvantage of the torch temperature modification is that boules must be kept smaller in size. The largest cut stone Linde ever produced was a 109-ct star ruby, which was donated to New York’s American Museum of Natural History.

Synthetic star rubies went on sale in September 1947 at $30/ct, and several years later Linde introduced synthetic blue star sapphires. Only cut stones were sold, with cutting performed automatically by Linde. In addition to star rubies and blue sapphires, small quantities of white, gray, purple, green, pink, yellow, brown and black stars were made.
Linde enjoyed an early monopoly, but this was short-lived. Sometime before 1957, the Wiedes Carbidwerke of Freyung, [West] Germany, began selling synthetic star corundums ('Stars of Freyung') produced by a slight variation on the Linde method. The German stars were more transparent and natural appearing than Linde's. Synthetic star corundum has also been produced in Israel, Japan, Switzerland, and Russia. Currently, synthetic star corundum is produced solely by the Verneuil process. Linde did receive a patent for manufacture of synthetic star corundum by the Czochralski process, but these stones were never marketed.

Reports on the exact identity of the needles in synthetic star corundum differ. Some suggest that they consist of rutile (TiO₂), while others (Nassau, 1968) state that aluminum titanate (Al₂TiO₅) theoretically might also be formed. Today it is understood that they are rutile (Kurt Nassau, pers. comm., 3 April, 1995).

Researchers in Japan during the late 1970s grew Ti-doped ruby by the flux process in an attempt to study and replicate the relatively large exsolved rutile needles found in natural corundums (Takubo & Kitamura et al., 1980). According to this study, rutile typically formed parallel to the first-order...
Table 7.2: Properties of Verneuil synthetic corundum

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
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| **Color range/phenomena** | Red (including pink): Light pink to dark red or purplish red  
Blue: Light to dark blue or violetish blue  
Yellow: Light to deep yellow to orange-yellow  
Orange: Light to deep orange to red-orange  
Violet/Purple: Light to deep purple to violet to violet-blue  
Green: Bright lime green  
Colorless  
Color-change (due to V; do not confuse with blue-violet gems): Daylight—light grayish green to deep bluish green  
Incandescent light—purplish red  
Stones (6 rays): All colors |
| **Synthetic process Location** | Verneuil (flame fusion)  
Various manufacturers worldwide |
| **Crystal habit** | Round to elongated boules which are split lengthwise in the plane of the optic axis. Such rough may be broken, tumbled, burned, stained, etc., to resemble natural rough.  
Cut gems are generally under 20 ct.; cut gems of up to 120 ct. have been reported  
Prices of cut gems in Bangkok range from US$0.35 to 3.00/ct for transparent material. Reds and yellows are cheaper, blues are up to twice as expensive as reds, and the green material, which is in little demand, may sell for ten times that of the red.  
**Syn. Star Corundum**:  
Star material generally wholesales for $1.00–2.00/ct cut |
| **Stone sizes Prices** | |
| **Spectra** | Visible:  
Both natural and Verneuil syn. corundum may show a Cr spectrum, which is of no diagnostic value  
A complete Fe spectrum, consisting of a strong line at 451.5, a slightly weaker line at 470 nm, has yet to be found in any syn. corundum made by any process. In rare instances, a weak 451 line has been found in the blue variety of Verneuil syn. corundum. Thus the presence of the complete 451.5, 460, 470 Fe spectrum strongly suggests a natural corundum (unheated or heated).  
In the color-change variety of Verneuil syn. corundum, a vanadium spectrum is seen, consisting of a single distinct line at 475, a broad band centered at 580 (which gives the stone its color change), and a fluoresce line near 690 nm. While this V spectrum strongly suggests synthetic origin, it has also been encountered rarely in certain natural corundums, particularly those from Mogok, Burma.  
**Ultraviolet spectra**:  
Syn. red to pink—UV transmission (315 nm) generally stronger than visible-region (approx. 550 nm) transmission. 80% show Type II spectra (see Table 4.2 on page 79 for description)  
Syn. blue—Lines 1 & 2 stronger than line 8 (with line 10) or line 8 stronger than lines 1 & 2 (see Table 4.2 for description). |
| **Fluorescence** | Red (including pink):  
LW: Moderate to very strong red to orange-red; usually quite strong, except in dark-toned stones  
SW: Same as long wave, except sometimes slightly weaker. Light-toned stones may show chalky reactions; examination of fluorescence under magnification may help reveal curved growth lines (make sure eyes are properly shielded).  
Blue:  
LW: Generally inert; stones containing Cr may show weak to strong red to orange-red  
SW: Inert to strong chalky blue to green (the colorless portions of the stone fluoresce; blue areas are inert). Examination of fluorescence under magnification may help to reveal curved banding (make sure that eyes are properly shielded). Stones containing Cr may show weak to strong red to orange-red.  
Green:  
LW: Weak to moderate orange-red, orange or red  
SW: Weak to moderate dull orange to brownish red  
Orange:  
LW: Inert to strong red, orange-red or orange  
SW: Inert to strong red, orange-red or orange  
Yellow:  
LW: Inert to moderate red to orange-red  
SW: Inert to moderate red to orange-red  
Colorless:  
LW: Inert to weak chalkly blue to green  
SW: Weak to strong white or chalky pale blue; examination under magnification may reveal curved growth lines (make sure eyes are properly shielded)  
Violet/purple:  
LW: Weak to strong red to orange-red  
SW: Weak to strong red to orange-red  
Color-change:  
LW: Weak to strong orange  
SW: Weak to strong orange, chalky blue to green  
Stones (6 rays): Various reactions |
| **Other features** | Verneuil corundum boules tend to be elongated pieces of slightly oval cross-section, split lengthwise to relieve strain. The c axis lies in the plane of the split, but does not always follow the boule length. Since the Verneuil product is sold by weight and the price is unaffected by c axis orientation, the lapidary concentrates on weight retention. Given a split boule segment which is flat on one side and round on the other, maximum weight retention is gained by placing the table along the split. Since the c axis always lies in the plane of this split, this means the c axis would lie parallel to the table. In contrast, natural corundums are oriented for best color in addition to maximum weight retention, because the quality of color does impact the price. For most natural and treated corundums, the best color and the greatest weight retention is gained by positioning the c axis at 90° to the table. These differences in orientation between the natural and Verneuil synthetics create subtle differences in the face-up color, due to pleochroism.  
The location of the c axis in corundum can be determined by reference to a variety of factors, including RI readings, an interference figure, pleochroism, lack of doubling, the position of the V axis, the color in the face-up view, and the color in the face-down view.  
To summarize, certain cutting factors tend to differ between the natural/treated product and the Verneuil synthetic. Just like the fluorescent reactions, if taken by themselves, cutting factors are not reliably diagnostic, because cutting decisions are totally made by humans. But in combination with other features they can represent additional pieces of the puzzle. |