CHAPTER 5

Forensic Analysis of Glass

OBJECTIVES

In this chapter, you should gain an understanding of:

- The composition of different types of glass
- The optical and nonoptical properties of glass
- Techniques to determine the way in which glass has fractured
- Techniques to match glass fragments
- The use of scanning electron microscopy and X-ray fluorescence to determine the elemental composition of glass

FEATURES

- On the Crime Scene—Glass Fragments Solve Hit-and-Run
- On the Crime Scene—Forensic Analysis of Glass Windshield Fragments
- Back at the Crime Lab

WRAP UP

- Chapter Spotlight
- Key Terms
- Putting It All Together
- Further Reading

YOU ARE THE FORENSIC SCIENTIST

When a pane of glass shatters, small, sharp pieces called shards are thrown over a wide area. Larger pieces travel in the direction of the blow and are usually found close to the original location of the glass pane. Smaller shards can be propelled up to 10 ft. from the pane, also in the direction of the blow. If a pane of glass is shattered by a violent blow, hundreds of tiny backscattered shards will inevitably become caught in the hair or clothing of the person who broke the pane. Because these shards are so small (less than 1 mm long), they are easily dislodged. The speed at which they fall off the perpetrator depends on the type of clothing worn by the individual and his or her subsequent activities. Most shards are lost in the first hour after the event, and the probability of finding glass evidence on a suspect decreases over time. Investigators collect these tiny shards from a suspect by combing the suspect's hair and shaking his or her clothing over a clean piece of paper. If two or more glass shards from a suspect's hair or clothes are found to be indistinguishable from a control sample of glass from the scene, they can be considered significant associative evidence.

1. A car has its driver's window smashed during an attempted robbery. A suspect who is running down the street is stopped by police. He claims to have nothing to do with the car. What should the officers' next step be?
2. The lab finds glass shards on the suspect's sweatshirt. Which tests should now be done on the glass fragments?

Introduction

Glass has been shown to be very useful evidence because it is often encountered in criminal investigations. For example, when a burglar breaks a window pane, small fragments of glass are often showered onto his or her hair, clothing, or shoes, and these fragments can later be found on the suspect as transfer evidence. This chapter describes the many different types of glass commonly found at crime scenes and explains how glass fragments can be placed in specific classes through the use of optical and nonoptical analysis methods. In addition, the chapter describes how to individualize a glass fragment by making a **fracture match**.

Types of Glass

Glass is a solid that is not crystalline but rather has an amorphous structure. The atoms of an amorphous solid have a random, disordered arrangement, unlike the regular, orderly arrangement that is characteristic of **crystalline solids**. Another characteristic property of glass is that it softens over a wide temperature range rather than melting sharply at a well-defined temperature.

Soda-lime glass is commonly used in windows and bottles. It consists of 70% silicon dioxide (SiO_2), 15% sodium oxide (Na_2O), 10% calcium oxide (CaO), and 5% of other oxides. This type of glass is made by heating together sodium carbonate (baking powder), calcium oxide (lime) or calcium carbonate (limestone), and silicon dioxide (sand). Soda-lime glass has a green to yellow tint, which is most easily seen by looking at the edge of the pane. This color is caused by an iron impurity that is present in the sand. Soda-lime glass starts to soften when it is heated to a temperature of more than 650°C, a fact that can prove useful when investigating fires. For example, if the windows of a burned building are found to be deformed (melted), the temperature of the fire must have exceeded 650°C. Common window glass fractures when its surfaces or edges are placed under tension, and an edge fissure may propagate into visible cracks.

A variety of metal oxides can be added to this basic recipe to give glass a special appearance. For example, the addition of lead oxide (PbO) to the glass will give it a high brilliance because of its greater internal reflection of light; for this reason, lead glass is used for expensive crystal dinnerware. The addition of cobalt oxides will make the glass blue, manganese oxide will make it purple, chromium oxide will make it green, and copper oxide will make it red or blue-green.

In 1912, the Corning Glass Company found that the addition of 10% to 15% boron oxide (B_2O_3) to glass made the resulting product more shock and heat resistant. This borosilicate glass was given the trade name Pyrex® and was subsequently found to resist attack from virtually all chemicals except hydrofluoric acid (HF), which etches its surface.

Tempered Glass

Tempered glass (also known as safety glass) is more than four times stronger than window glass. During its manufacture, the sand, lime, and sodium carbonate are heated together, and the hot glass that is formed is rolled into sheets. Its upper and lower surfaces are then cooled rapidly with jets of air. This process leaves

ON THE CRIME SCENE—GLASS FRAGMENTS SOLVE HIT-AND-RUN

On June 24, 1995, on the island of Providenciales in the Turks and Caicos Islands, a passerby reported to police that a woman's body was lying on the side of the Leeward Highway. The police found the body of a 42-year-old woman lying face down. Upon investigation, police concluded that the victim had been struck by a car some time after midnight while walking home from her job as a waitress.

The local constable carefully documented the area surrounding the body. His report of items scattered around the body included earrings, a watch, a pendant and chain, eyeglasses, debris from the undercoating of a vehicle, and nine large glass fragments. The constable photographed the items in their original positions, measured distances from the body to the found objects, and collected soil samples from the surrounding area. These items were packaged and sent to the Miami-Dade Police Crime Laboratory in Florida for analysis.

Eleven days later, a suspect was identified when neighbors reported that his car was missing a headlight. The suspect denied being involved in the accident and requested that his attorney be present for any further questioning. Upon gaining access to the suspect's car, the police found considerable damage to the driver-side front fender as well as a missing headlight on that side of the vehicle. Because this was an older car, each side had two headlights, each of which contained glass lenses. Because the car had been washed, a careful examination of the vehicle did not reveal any biological material. However, glass fragments were found lodged in the bumper and inside the lamp assembly of the missing light. The constable collected these fragments and samples of debris from the undercarriage of the car for further analysis.

The Miami-Dade Police Crime Laboratory analyzed the glass fragments in particular to determine whether an association existed between the glass fragments found on the crime scene and the glass fragments found in the suspect's vehicle. At the lab, investigators visually inspected the fragments for fracture matches but did not find any. Later, glass fragments stamped with the markings "e-a-l-e-d" found at the crime scene were matched to those taken from the suspect's car. Equipped with a GRIM2 refractive index measurement apparatus (which is discussed in this chapter), the police lab found that nine of the crime scene fragments had similar qualities to those of the suspected car—enough to be statistically significant. Furthermore, the lab established that all the fragments came from a common source by using elemental analysis with an inductively coupled plasma-optical emission spectrometer (ICP-OES).

the center of the glass relatively hot compared with the surfaces and forces the surfaces and edges to compress. Tempered glass is stronger because wind pressure or impact must first overcome this compression before there is any possibility of fracture.

When tempered glass breaks, it does not shatter into pieces with sharp edges, but rather breaks into "dices" (i.e., small pieces without sharp edges). Tempered glass is used in the side and rear windows of automobiles, in large commercial windows, in doors, and even in shower doors and home windows where the window is less than 1 ft from the floor.

Windshield Glass

Automobile windshields are made from **laminated glass** (**FIGURE 5-1**). Today, windshields are made with two layers of glass, with a high-strength vinyl plastic film, such as polyvinyl butyral (PVB), being sandwiched in between the layers. The three pieces are laminated together by applying heat and pressure in a special oven called an autoclave.

This type of glass is ideal for automobile windshields because of its strength and shatter resistance.

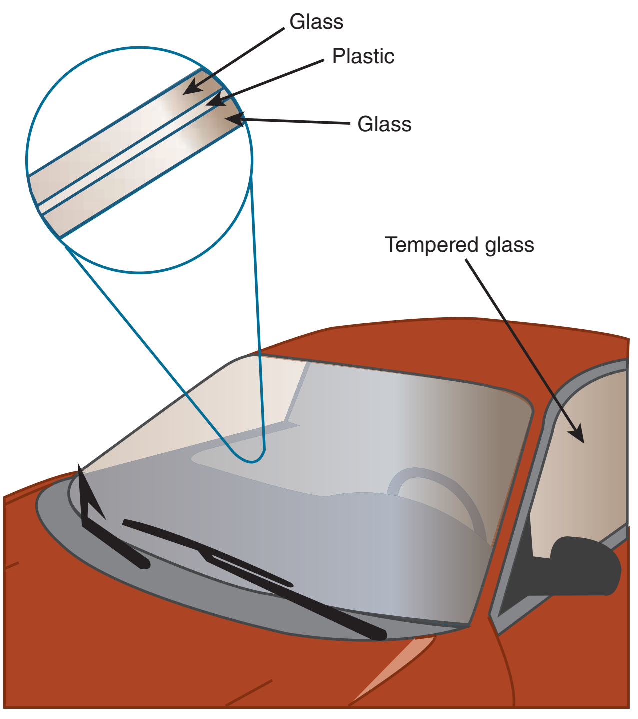

FIGURE 5-1 Automobile windshields are made from laminated glass whereas the side and rear windows consist of tempered glass.

The plastic film holds the glass in place when the glass breaks, helping to reduce injuries from flying glass. The film can also stretch, yet the glass still sticks to it. Laminated safety glass is very difficult to penetrate compared with normal window-pane glass. The glass sandwich construction allows the windshield to expand in an accident without tearing, which helps hold the occupants inside the vehicle. Banks use a similar bullet-proof glass that has multiple layers of laminated glass.

Forensic Examination of Glass Evidence: An Overview

For the forensic scientist, the goals in examining glass evidence are twofold:

- To determine the broader class to which the glass belongs, thereby linking one piece of glass to another.
- To individualize the glass to one source—a particularly difficult challenge given that glass is so ubiquitous in modern society.

To pinpoint the source of the glass evidence, the forensic examiner needs the two usual samples: glass fragments collected from the crime scene and glass fragments taken from some item belonging to the suspect. The examiner must then compare these samples (often side-by-side via a stereomicroscope) by identifying their characteristics—for example, their color, fracture pattern, scratches and **striations** (irregularities) from manufacturing, unevenness of thickness, surface wear (outside versus inside surfaces), surface film or dirt, and weathering patterns. In particular, the examiner tries to fit the "pieces of the puzzle" together by matching the irregular edges of the broken glass samples and finding any corresponding irregularities between the two fragments (**FIGURE 5-2**). Finding a perfect match is tantamount to individualizing the glass to a single source with complete certainty.

FIGURE 5-2 Matching broken pieces of glass. Finding a perfect match is tantamount to individualizing the glass to a single source with complete certainty.

Courtesy of Jon Girard.

Nonoptical Physical Properties of Glass

Many nonoptical physical properties can be used to compare a questioned specimen of glass to a known sample. These nonoptical physical properties include surface curvature, texture, and special treatments. Clearly, frosted glass cannot be a match to a clear window glass. Similarly, a curved piece (such as a fragment from a bottle) cannot come from the same source as a flat piece (such as from a window). And finally, laminated glass would not compare to wire-reinforced glass. Thus, these sorts of comparisons are most useful in proving that the two pieces cannot be associated.

Surface Striations and Markings

When sheet glass is rolled, the rollers leave parallel striation marks, called ream marks, on the surface. Even polishing does not completely remove these marks, and their presence can be enhanced by low-angle illumination and photography. These ream marks may hint at how various pieces should be oriented in the case of an indirect physical match where an intervening piece may be missing. The relative spacing might also be useful as a means of individualization. Surface scratches, etchings, and other markings might be employed in a similar way as the forensic examiner tries to piece together the puzzle.

Surface Contaminants

The presence of such impurities as paint and putty is useful in two ways. First, the patterns of the adhering materials might suggest how the pieces fit together. Second, chemical analysis of the adhering materials might further individualize the pieces and prove their association.

Thickness

Thickness can be measured to a high degree of accuracy with a micrometer. One must be careful, however, in assuming that the thickness is constant—it is not, particularly in curved pieces of glass. For this reason, the forensic examiner must take several representative measurements of both the known and the questioned samples. Determination of curvature can distinguish flat glass from container, decorative, or ophthalmic glass. Thickness is a very useful way of proving that two pieces of glass, which are otherwise extremely similar, are not actually from the same source.

Hardness

A number of scales are used to describe the hardness of substances. Geologists and mineralogists often employ the **Mohs scale**, which indicates a substance's hardness relative to other substances. On the Mohs scale, the softest common mineral—talc—is assigned a relative value of 1, and the hardest common mineral—diamond—is assigned a relative value of 10. Each of the remaining values is assigned to another appropriate common mineral. For example, quartz is assigned the Mohs value 7 and topaz is assigned the Mohs value 8.

The relative positions of the minerals on the Mohs scale reflect their scratching power: A harder substance will scratch a softer one. Thus, diamond will scratch everything else on the list; topaz will scratch quartz and everything lower on the Mohs scale, down to talc. Talc, by contrast, will not scratch anything else on the list. For an unknown mineral or substance, its relative hardness is determined by using it to try to scratch the benchmark minerals. Its position on the scale is between the benchmark mineral, which it scratches, and the next mineral on the list, which scratches it. For instance, an unknown mineral that scratched talc and quartz, but was itself scratched by topaz, would be assigned a relative position between 7 and 8. In this same fashion, all other materials can be ordered appropriately.

The Mohs scale is not very useful for glass samples, however, because all glasses tend to fall in the same range, between 5 and 6. Thus, the Mohs scale is too insensitive for forensic work, as are all of the other standard hardness scales. Generally, the forensic lab establishes relative hardness by referring to glass samples in its collection. The relative scratching power of the known and questioned samples is established by trying to scratch these samples with glass in the lab's collection. Either the scratching powers of the known or unknown samples are similar or they are not.

Glass Fractures

Elasticity is the ability of a material to return to its previous shape after a force is exerted on it. For example, when a force is exerted on a pane of glass, it stretches (this bending may not be visible to the naked eye). If the force is not too high, the glass will then return to its original state and no damage occurs. However, if the force exceeds the glass's elasticity, the glass fractures.

The forensic examiner may be able to analyze fractured window panes and determine the direction of an impact and the amount of force applied to them, suggesting what actually happened at the scene. For example, it is often important to establish whether a window was broken from the inside or the outside. At the scene of a homicide, a broken window near the door latch may be an attempt to disguise the crime as a burglary. In the case of a burglary, the window would have been broken from the outside. However, if the homicide was deliberate, the perpetrator may have broken the window from the inside in an attempt to mislead investigators into thinking burglary was the intruder's primary goal.

Characteristics of Glass Fractures

Glass may be subjected to three types of forces (strains):

- **Compressive force** squeezes the material.
- **Tensile force** expands the material.
- **Shear force** slides one part of the material in one direction and another part in a different direction.

Each of these forces causes a deformation, which is resisted by the internal cohesion (stress) of the material. Glass breaks when a tensile strain that is sufficient to overcome the natural tensile stress limit of the material is applied.

If a person places a weight on a horizontal sheet of glass, the pane will experience compressive strain where the load meets the pane. The side holding the weight is called the loaded side, designated as side L, and the unloaded side is designated as side U. The deformation induced by the load will cause side U to expand, so side U will experience a tensile strain. If the tensile strain is sufficient to overcome the tensile strength of the pane, the pane will develop cracks on the unloaded side. Several of these cracks may appear, and they will grow or travel in two directions simultaneously. First, they will grow from the unloaded to the loaded side. Second, they will radiate outward, away from the load point; they are, therefore, called **radial cracks**. The radial cracks form several pie-shaped (or triangular) sectors radiating from the point of loading. If the load is suddenly removed, these sectors will stay in place because the third side of each of the triangular sections is still solid glass.

If the load persists, however, each sector will continue to be forced outward. This movement causes compressive strains on side U and concurrent tensile strains on side L. These strains will cause new cracks to develop on the loaded side. As before, these cracks grow in two ways: first from the loaded to the unloaded side, and second, until they connect two

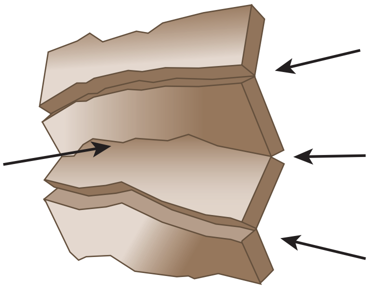

FIGURE 5-3 Radial cracks grow from the loaded point outward and from the unloaded side to the loaded side. Tangential (also known as concentric) cracks grow from one radial crack to another and from the loaded side to the unloaded side.

radial cracks. These new cracks are called **tangential cracks** or **concentric cracks**, and the resulting pattern has a spider web appearance (**FIGURE 5-3**).

Note that radial cracks grow from the load point outward and from the unloaded side to the loaded side. In contrast, tangential cracks grow from one radial crack to another and from the loaded side to the unloaded side. This is the case if the weight was placed statically on a pane of glass.

By contrast, when a bullet is shot at the pane of glass, the load is a **projectile**. The load side is known as the **entrance side**, and the unloaded side is known as the **exit side**. The same cracking occurs, and the same hole formation happens, when a static load is applied. However, as the initial velocity of the projectile increases, the central hole becomes smaller, the cracking patterns become simpler, and the central hole develops a pattern wherein the exit hole is invariably wider than the entrance hole (**FIGURE 5-4**).

Examination of the edges of broken pieces of glass will reveal a set of curved lines known as **rib marks**

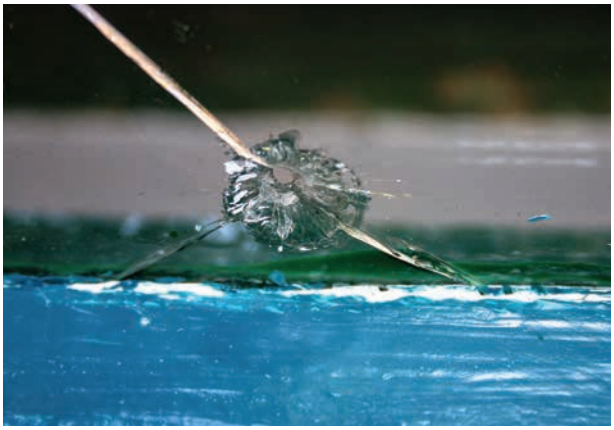

FIGURE 5-4 The bullet entered from the backside (entrance side), making a smaller hole, and passed through the glass pane, leaving a wider hole at the front surface (exit side).
Courtesy of Jon Girard.

(or "stress" marks). These arcs are always nearly perpendicular to the surface at the side on which the break started, and they curve until they are nearly parallel to the surface on the opposite side (e.g., the side to which the break grew). In a radial crack, the rib marks will be nearly perpendicular to the unloaded (or exit) side and nearly parallel to the loaded (or entrance) side. Things will be exactly reversed for a tangential crack, which grows in the opposite way. The 3R rule helps in remembering this pattern:

- Radial cracks give rib marks, which make
- Right angles on the
- Reverse side from where the force was applied.

The direction of lateral propagation of the crack is always from the concave sides of the rib marks toward their convex sides. Thus, in a radial fracture, the rib marks will be oriented with their concave sides "cupped" toward the load (or entrance) point.

Forensic Examination of Glass Fractures

If all of the glass pieces are present, the first thing to check for is the hole made by the load or projectile (e.g., bullet, hammer), which will be wider on the exit side. As can be seen in **FIGURE 5-5**, the angle at which a bullet pierces a pane of glass can help identify the position of the shooter. If the bullet came at an acute angle from the left, glass fragments will be sprayed to the right and the exit hole will be an irregular oval. If the bullet came from an acute angle from the right, glass fragments will be sprayed to the left and the exit hole will be an irregular oval. This test works best when the hole is made by a high-speed projectile. In the event that the hole was made by a low-speed projectile (such as a hammer), this test will not be very meaningful. Therefore, for low-speed projectiles, it is usually best to examine the rib marks. Of course, to make this examination meaningful, each edge must be determined to be either a radial or a tangential crack (which is why it is so important that all pieces be collected), and interior and exterior sides of the pieces must be identified (which is why it is so important that the investigators mark the proper orientation of each piece directly on the item, as well as documenting all orientations in their notes and photos).

Therefore, if a forensic scientist is examining the edge of a radial fracture, whichever side shows nearly perpendicular rib marks will be the unloaded (or exit) side, that is, the side away from the force that caused the break. Alternatively, if the forensic scientist is examining a tangential fracture, the side showing the nearly perpendicular rib marks will be the loaded (or entrance) side, that is, the side from which the original breaking force was applied.

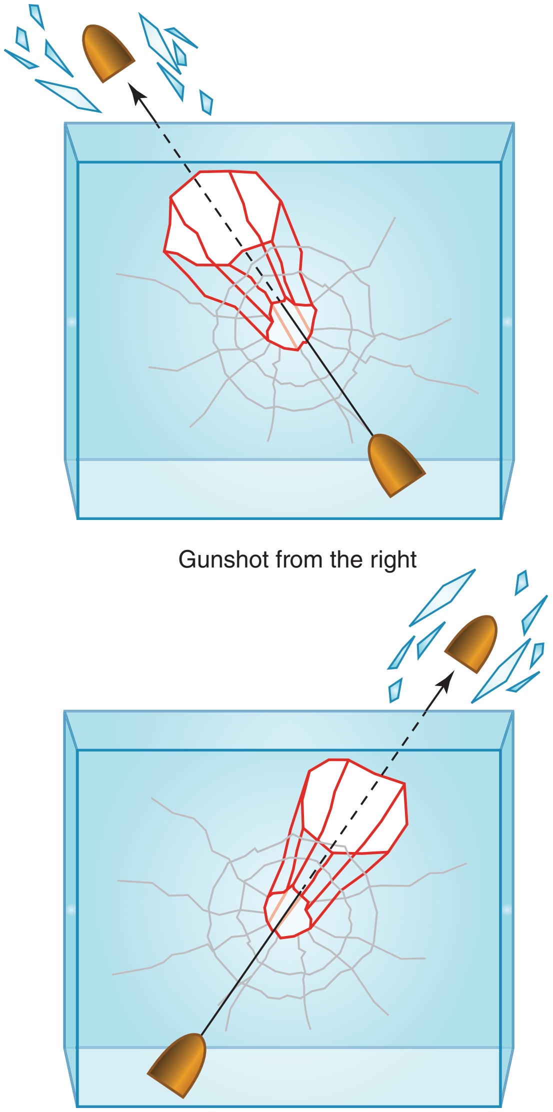

FIGURE 5-5 The angle at which a bullet pierces a pane of glass can help identify the position of the shooter.

In the event that the investigator or evidence technician neglected to mark which side of the glass was inside and which side was outside, it is sometimes possible to figure out this information in the lab. Traces of window putty, for example, would indicate an exterior side, and paint traces of different colors might also be used to distinguish between the two sides.

Of course, the preceding discussion assumes that the glass is not tempered. When tempered glass breaks, it produces small pieces; the fractures cannot be categorized as radial or tangential, so the kind of analysis mentioned previously is not applicable.

When there are several bullet holes, analysis can determine the sequence of the impacts. The first shot will cause fractures that simply "run out" (terminate) wherever the original strains have been sufficiently relieved in the material. The radial fractures associated with a second shot will run out when they meet a fracture from the first shot, and so on for all subsequent shots (**FIGURE 5-6**).

The majority of fragments recovered from a suspect's clothing or hair will likely be very small (0.25 to 1 mm). Most glass evidence adhering to a suspect is lost fairly rapidly, depending on the suspect's subsequent activities and the texture of his or her clothing. For example, wool sweaters will retain glass fragments longer than a leather jacket. The size of a fragment may be so small that individual characteristics cannot be found. In such cases, the forensic examiner turns to measurements of density and refractive index to characterize glass evidence.

Glass Density Tests

Density tests are often performed on glass fragments. When a forensic scientist measures the density of a glass fragment, he or she is measuring one of its physical properties. Density is a class characteristic, so it cannot serve as the sole criterion used for individualizing the glass evidence to a single source. Such measurements can, however, give the forensic scientist enough data to warrant further testing of other evidence or to provide enough evidence to exclude the glass fragments as having originated somewhere other than the crime scene. In addition, if a sufficient amount of separate class characteristic evidence can be gathered against a suspect, the evidence collectively may make a strong circumstantial case, which may result in conviction.

To see how this works, consider decorative glass. This type of glass is made by adding different minerals to the glass recipe as the basic ingredients—sand, lime, and sodium carbonate—are being heated. The density of the resulting glass will vary with the type and amount of minerals added. If a recovered glass fragment is placed in a liquid that has higher density than the glass, the glass fragment will float. If the liquid is less dense than the glass fragment, the glass will sink. When the density gradient column method is used to determine the density of glass, the forensic scientist uses a **density gradient tube** filled with a liquid that has been specially prepared to have a density gradient.

The gradient is prepared such that the density at any level is less than that of any level lower in the tube and greater than that of any level higher in the tube. The gradient is prepared by mixing bromoform and bromobenzene, two dense organic liquids, in different proportions. When glass fragments are poured in the top of the column, they fall through the liquid until they become suspended in the liquid at the level that is the same density as the particular glass fragment. Fragments of different

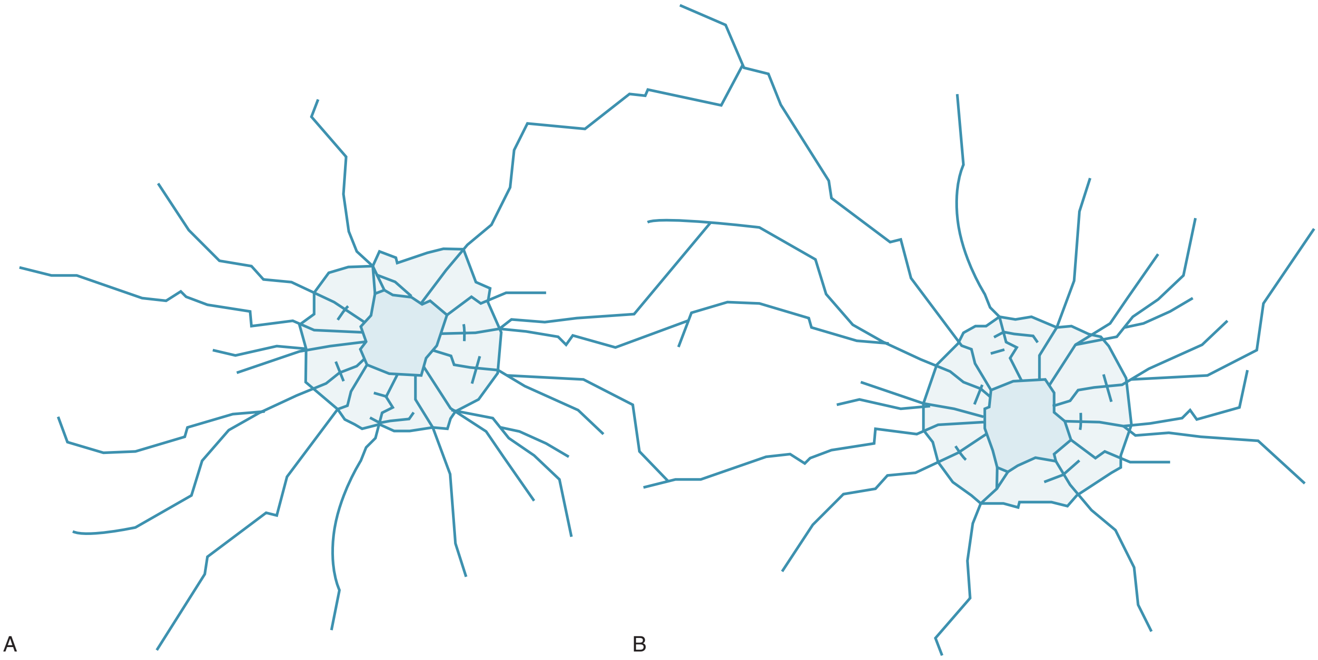

FIGURE 5-6 In these two bullet holes in one piece of glass, the formation of **(B)** preceded the formation of **(A)**.

densities will, therefore, settle at different levels in the column. The questioned glass fragment's density may then be compared with a glass sample from the crime scene to prove (or disprove) that it is a match.

Density measurements should not be performed on fragments of glass that are cracked or contain an inclusion, because these flaws will make the glass seem less dense than it really is. (An inclusion is a defect that forms when a particle or bubble becomes embedded in the main body of the glass.) Window glass, in particular, does not have a uniform density. For this reason, the variation in density of the known sample should be determined with samples taken from different locations in the window, or door, whenever possible. Likewise, because the surface or edge of tempered glass is denser than at its interior, care must be taken with tempered glass to measure several known samples. Density comparisons between known and questioned specimens should be made using fragments of approximately equal size.

The Federal Bureau of Investigation (FBI) has reported density results for 1,400 glass samples. From this information, it is known that the range of densities for flat glass, container glass, and tableware glass all overlap.

When the density tests are concluded, any evidence that does not match the known specimen can be excluded. However, if questioned and known samples are found to have comparable densities, further testing is required. A refractive index test is usually performed to support the comparison. If the density measurement indicates that the specimen from the crime scene matches the reference material, a refractive index test that also indicates a match will improve the discrimination capability by approximately twofold.

Optical Physical Properties of Glass

Color

Comparing the color of a suspect piece of glass with the color of a reference sample can distinguish whether the two samples share a common source. As a consequence, significant color differences between glass fragments can be used as the basis for exclusion of a suspect.

Given that sample size may affect the apparent color, side-by-side comparisons should be made with fragments of approximately the same size. These fragments should be visually compared by placing them on edge over a white surface using natural light. Viewing the glass in this way allows for the optimal observation of color. It also allows the examiner to distinguish between the true color of the glass and any coatings or films that might be present on the glass's surface. In addition, observing the glass using both fluorescent and incandescent light is often helpful in distinguishing colors.

Refractive Index

Light has wave properties. That is, a beam of light traveling from a gas (such as air) into a solid (such as glass) undergoes a decrease in its velocity, such that the beam bends downward as it passes from the air into the glass. The application of this phenomenon allows the determination of the glass's refractive index, a measure of how much the light is bent (refracted) as it enters the glass.

The bending of a light beam as it passes from one medium to another is known as refraction. The refractive index, η, is the ratio of the velocity of light in the air to the velocity of light in the glass being measured. The velocities of light in both media are related to the angles that the incident and refracted beams make with a theoretical line drawn vertically to the glass surface (**FIGURE 5-7**).

$$\eta_D^x = \frac{V_{air}}{V_{glass}} = \sin\theta_{air} / \sin\theta'_{glass}$$

where:

V_{air} = Velocity of light in air
V_{glass} = Velocity of light in glass
θ = Angle of light in air
θ' = Angle of light in glass
x = Temperature
D = Light from sodium D line (589 nm)

The velocity of light in a liquid sample is always less than that of light in air, so refractive index values for solids are always greater than 1.

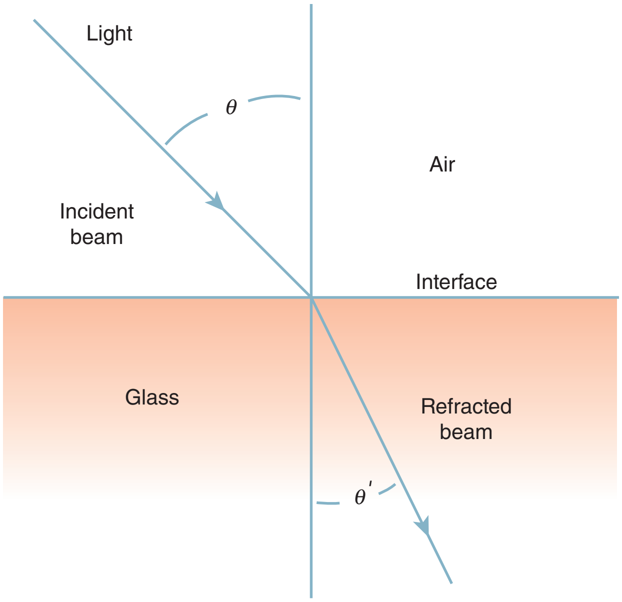

FIGURE 5-7 Refraction of light through glass. The refractive index—a measure of how much the light is bent (refracted) as it enters the glass—can be used as a basis of comparison for glass samples.

The temperature and wavelength of the light being refracted influence the refractive index for any substance. The temperature of the sample affects its density, and the density change affects the velocity of the light beam as it passes though the sample. Therefore, the temperature at which the refractive index is

ON THE CRIME SCENE—FORENSIC ANALYSIS OF GLASS WINDSHIELD FRAGMENTS

Danny Peterson, a 21-year-old student of Iowa State University, died on June 8, 2002, six days after being hit by a vehicle. Peterson and two friends were walking along the shoulder of a road when a vehicle veered off the pavement, fatally injuring Peterson, and sped away. After Peterson was transported to the hospital, Detective Jack Talbot of the South Lake Minnetonka Police Department investigated the scene of the accident. He recovered small glass slivers from a windshield on the road and fragments from a headlight in a nearby culvert. Fragments of windshield glass were also collected from Peterson's clothes.

There was no straightforward match for the windshield fragments, but the glass from the headlight matched a specific make and model of car—the 2001–2002 Mercury Cougar. Although the headlight glass seemed important, it was not probative. In fact, the headlight turned out to belong to a 2001–2002 Mercury Cougar that was in the repair shop on the day of the accident.

All investigative leads were followed but to no avail. However, three months after the accident, a young woman called the police with a promising lead. She suggested that her husband, Guido Vivar-Rivera, might have been involved in the accident. On the night of the accident, Rivera was drunk and upset, saying that someone broke his Pontiac's windshield with a rock. The windshield was repaired soon after the accident.

The police inspected the outside of Rivera's 1996 Pontiac Grand Am and saw stress fractures on the bumper, possibly caused from the impact of hitting Peterson. Detective Talbot questioned employees at the repair shop who replaced the windshield. The employees said it was unlikely the windshield damage was caused by a rock.

Detective Talbot and his team arrested Rivera and obtained a search warrant for the Pontiac Grand Am. In addition to the stress fractures on the bumper, they found a dent on the hood and pieces of broken window glass on the inside of the car. This glass was a match with the windshield fragments found at the scene of the accident and on Peterson's clothes.

Rivera was convicted of felony hit-and-run and served his time at the Hennepin County Adult Correctional Facility.

determined is always specified by a superscript in the notation of η. Likewise, the wavelength of the light used affects the refractive index because light of differing wavelengths bends at different angles. The bright yellow light from a lamp containing sodium, which produces a beam with a wavelength of 589 nm (refer Figure 5-6), is commonly called the sodium D line. This lamp provides the standard wavelength of light, denoted as η_D. Thus, the refractive index of a liquid measured at 20°C using a sodium lamp that gave a reading of 1.3850 would be reported as $\eta_D^{20} = 1.3850$.

Single sheets of plate glass, such as those commonly used for making windows, usually do not have a uniform refractive index value across the entire pane. Because the index of refraction can vary as much as 0.0002 from one side to another, the difference in the refractive indices of the questioned plate glass fragment and the reference sample must be smaller than 0.0002 if the forensic scientist is to be able to distinguish the normal variations in a pane of glass from variations that would rule out a match altogether.

The refractive index is one of the most commonly measured physical properties in the forensic laboratory, because it gives an indication of the composition and the thermal history of the glass. Two methods are used to measure the refractive index of glass: the oil immersion method and the Emmons procedure.

Oil Immersion Method

When using the oil immersion method, a forensic examiner places the questioned glass fragments in specialized silicone oils whose refractive indices have been well studied. The refractive index of the oil is temperature dependent: As its temperature increases, its refractive index decreases. Silicone oils are chosen for this task because they are resistant to decomposition at high temperatures. The refractive index of virtually all window glass and most bottles can be compared by using silicone oil as the comparison liquid and by varying its temperature between 35°C and 100°C.

An easy way to vary the refractive index of the immersion oil is to heat it. The suspected glass fragments and immersion oil are placed on a microscope slide, which is then inserted into a hot-stage microscope (**FIGURE 5-8**). The stage of such microscopes is fitted with a heater that can warm the sample slowly, while accurately reporting the temperature to ±2°C. A filter inserted between the lamp and the sample allows light with a constant 589-nm wavelength to reach the sample. Increasing the temperature has little effect on the refractive index of the glass but decreases the refractive index of the oil by about 0.004 per 1°C.

When the glass fragments are initially observed through the microscope, they will produce a bright halo around each fragment, known as the Becke line (**FIGURE 5-9**). As the temperature increases, the refractive index of the oil decreases until the Becke line and the glass fragments disappear from view. At this point (called the match point), the refractive indices of the oil and the glass fragment are the same, so the examiner is no longer able to see the glass fragments that are immersed in the oil. The examiner can compare suspect and known samples in this way to determine whether they have the same match point; alternatively, he or she can estimate the refractive index of the glass from graphs that report the refractive index of the oil as a function of temperature.

Automated systems are also available for making refractive index measurements using the immersion method. The Glass Refractive Index Measurement (GRIM) system, for example, combines a hot-stage

FIGURE 5-8 A hot-stage microscope is a key instrument in the forensic examination of glass. The temperature of the sample affects its density, and the density change affects the velocity of the light beam as it passes through the sample and hence its refractive index.

Courtesy of Foster & Freeman Ltd.

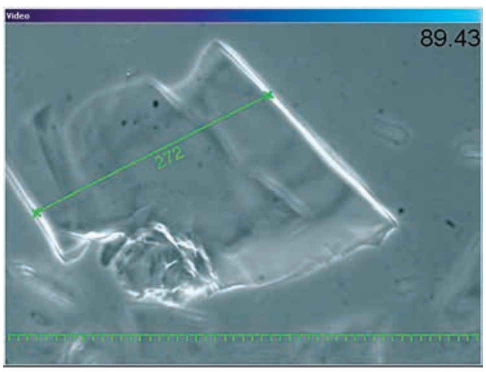

FIGURE 5-9 Oil immersion is one technique used to determine the refractive index of glass. The Becke line appears as a bright halo around the glass fragment.

Courtesy of Foster & Freeman Ltd.

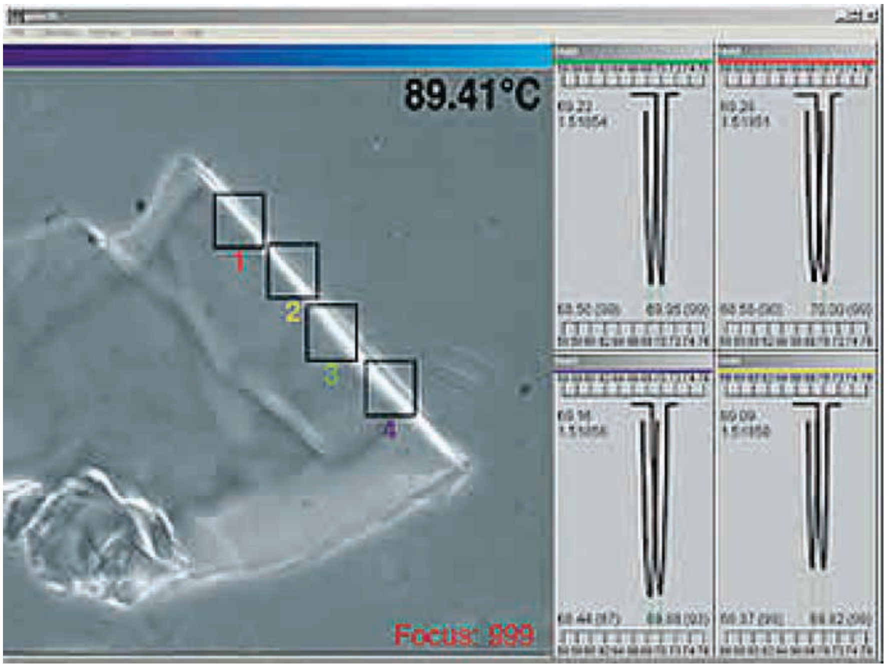

FIGURE 5-10 The GRIM 3 system is an automated technology to measure the refractive index of glass.
Courtesy of Foster & Freeman Ltd.

microscope with a video camera that records the behavior of the glass fragments as they are being heated (**FIGURE 5-10**). That is, the camera shows the contrast between the edge of the glass fragment and the immersion oil as the temperature increases, until it reaches the match point. The GRIM system's computer then converts this temperature to a refractive index using reference information stored in a database.

Emmons Procedure

The Emmons procedure, which was developed by the Association of Official Analytical Chemists, uses a hot-stage microscope in conjunction with different source lamps. It measures the index of refraction at a variety of wavelengths. Most often, the refractive index measurements are recorded by first taking a measurement with a sodium lamp (the sodium D line at 589 nm) and then by using a hydrogen lamp (which produces two lines, the C line at 656 nm and the F line at 486 nm). The microscope converts the difference in the refractive indices between the particle of glass and the silicone oil to a difference in brightness contrast, and it enhances the Becke line. This procedure increases the precision of the refractive index measurements taken on the glass particles.

The questioned glass is crushed and placed in the silicone oil on the hot stage. As the temperature of the hot stage increases, measurements are taken at the three different wavelengths (486, 589, and 656 nm). Lines representing the refractive index of the glass as a function of wavelength are recorded for each temperature. These data are then superimposed on a complex graph, known as the Hartmann net. The Hartmann net contains the correlation between the refractive index and the wavelength at fixed temperatures for the silicone oil. The point at which the dispersion lines for the glass samples intersect the dispersion lines for the silicone oil is where the refractive index of the glass sample is determined. Three separate indices of refraction are recorded: η_C, η_D, and η_F. Because three separate measurements are taken on each sample, this method, although more difficult to carry out, gives more precise refractive index measurements.

Refractive Index of Tempered versus Nontempered Glass

Often, a forensic examiner needs to determine whether the questioned glass sample is tempered or nontempered glass. Tempered glass can be distinguished from nontempered glass by heating the glass fragments in a furnace at a temperature higher than 600°C in a process known as **annealing**. If the questioned glass sample is large enough, it can be broken in two. Each piece is heated separately in the oven, is allowed to cool, and then has its refractive index measured. Because annealing alters the optical properties of the glass, the change in refractive index between the two annealed pieces can be used to determine if it is tempered or nontempered glass. After annealing, the change in refractive index for tempered glass is much greater than the change observed for nontempered glass.

Variations in Density and Refractive Index

As with other types of evidence, the properties of glass are more often used to exonerate suspects than to individualize samples and definitively prove a connection between a suspect and a crime scene. Indeed, if either the densities or the refractive indices of a questioned glass specimen and a reference glass sample do not match, the forensic scientist can easily prove that they did not share a common origin. However, glass is so ubiquitous, and so many manufacturers use the same processes to produce each type (e.g., rolling molten glass into flat sheets to make windows), that sometimes, even fragments from different sources may have similar indices of refraction or similar densities. Thus, individualizing glass samples accurately is particularly challenging.

To assist crime labs in making such distinctions, the FBI has compiled density and refractive index data about glass from around the world. These data indicate how widespread the use of a glass with a specific refractive index is. For example, a glass fragment having a refractive index of 1.5278 was found in only 1 out of 2,337 specimens in the FBI database, while glass with a refractive index of 1.5184 was found in more than 100 of the 2,337 specimens. The forensic scientist can access this FBI database whenever he or she needs to compare the refractive index of a questioned glass fragment to refractive index information and, thereby, calculate the probability that two such samples might be matches as a result of sheer chance (**FIGURE 5-11**).

The FBI has also correlated the relationship between their refractive indices and densities for 1,400 glass specimens (**FIGURE 5-12**). The results show that once the refractive index of a glass specimen is known, the subsequent measurement of its density will improve the discrimination capability of the measurements by approximately twofold. Most forensic examiners prefer to measure refractive index simply because refractive index measurements are faster and easier to make than density measurements, and often, the glass fragment size is too small to get an accurate density measurement. If the glass fragment is large enough, both the refractive index and the density should be determined unless other discriminating measurements, such as elemental analysis, are performed.

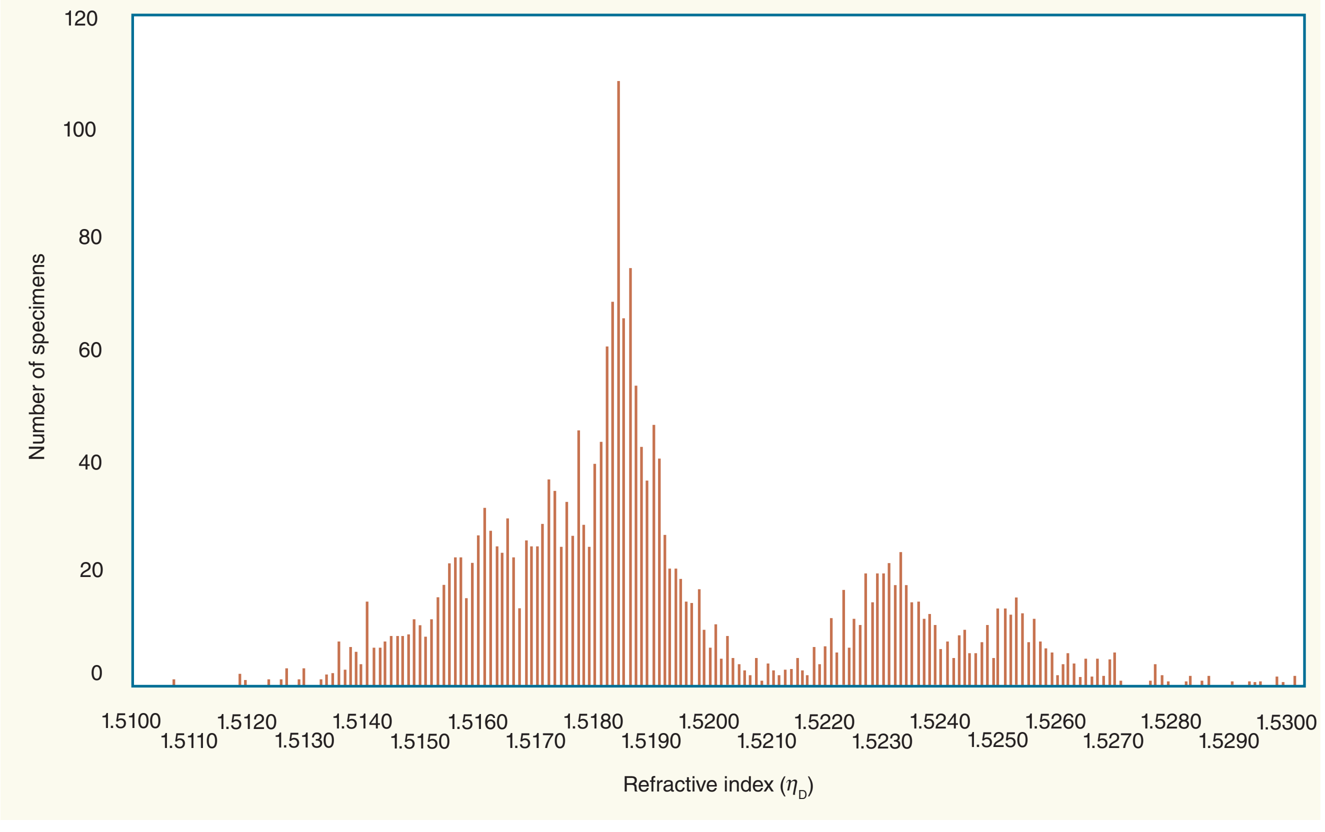

FIGURE 5-11 The frequency of occurrence of refractive indices of glass specimens has been determined by the FBI and is available to forensic examiners in an FBI database.

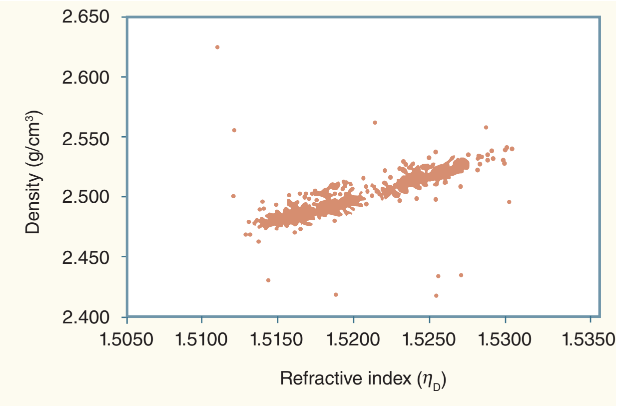

FIGURE 5-12 The FBI has correlated the densities and refractive indices for a wide variety of glass specimens.

Elemental Analysis of Glass

The physical and optical methods for forensic comparison of glass fragments are well established in crime labs and widely accepted in courts throughout the world. These analytical methodologies have two other advantages: (1) These tests are nondestructive, so the evidence is preserved for additional testing, and (2) the tests are performed using inexpensive instruments. These advantages ensure that these tests will remain the principal methods for the comparison of glass. Methods of elemental analysis—particularly those in which the specimen is consumed during the analysis—should be used only after all nondestructive methods of examination have been completed and in cases where additional discrimination is necessary.

The elemental composition of glass can be measured by surface techniques such as the use of a scanning electron microscope (SEM) or X-ray fluorescence (XRF). The SEM has several disadvantages that limit its value in the analysis of glass fragments. Primary among these is that, because of the irregular shape of the glass fragments, precise quantitative determination of element concentration is not possible.

The XRF, by contrast, is routinely used for elemental analysis of glass. For instance, the glass industry uses XRF as an accurate, precise method of enforcing quality control during glass manufacturing. The XRF instrument focuses a beam of X-rays on the surface of the glass and then measures the energy of the X-rays that are emitted from the glass. The energy of the emitted X-rays can be correlated to the presence of specific elements. In one study, XRF was used to measure the ratios of 10 elements in window glass samples that had virtually identical indices of refraction. When the elemental ratios determined by XRF were compared, the source of 49 of the 50 glass specimens could be correctly determined. Also, a major advantage of XRF is that it does not destroy the sample.

The elemental composition of glass can also be measured by flameless atomic absorption spectrophotometry (FAAS) or inductively coupled plasma (ICP) methods. There are two major disadvantages of using these methods for the analysis of glass fragments. First, the glass fragment must be dissolved in acid and small samples of the resulting solution then injected into the instrument, which means that the original sample is destroyed. Second, these methods entail the use of hazardous chemicals, such as hydrofluoric acid.

BACK AT THE CRIME LAB

Documentation related to glass fragments should include the condition of recovered fragments, their approximate size, the presence (or absence) of the original surface, the amount of debris on the sample (which may come from locations other than the collection location), and the presence of any nonglass material. The FBI provides detailed guidelines for processing of glass evidence, and these guidelines are repeatedly reviewed and updated.

Nondestructive methods of glass analysis begin with an assessment of the condition of the glass under a microscope prior to cleaning. The sharpness of the edges, fractures, and transparency assist in identifying freshly broken surfaces, which are important in interpreting the significance of evidence. Color is used to distinguish between two or more sources of glass. Because both sample size and thickness affect color, the samples being compared must be similar in size and thickness.

Viewing the sample under natural light, as well as incandescent and fluorescent light, can help to distinguish color and tone as well as identify the true color and the presence of thin film coatings on the glass surface. Observing the glass fragment over a nonfluorescent background under short- and long-wave ultraviolet light can also identify the presence of surface coatings. In such a case, samples should be viewed under short-wave light (254 nm) followed by assessment under long-wave light (350 nm).

Surface features formed during manufacture or later during use should be noted and used for comparison purposes. Manufacturing features include mold marks and polish lines. Surface scratches, abrasions, and pitting are usually post-manufacture features. These and other physical properties of the glass sample can be used to exclude fragments originating from a given source. When the initial examinations do not exclude fragments, further examination (usually chemical analysis) is required.

Despite these disadvantages, the ICP method, when coupled with an optical emission spectrometer (ICP-OES), has been shown by the FBI to be a dependable method for the determination of 10 elements in glass: aluminum, barium, calcium, iron, magnesium, manganese, sodium, strontium, titanium, and zirconium. The FBI studies also demonstrated that the determination of the concentrations of these 10 elements provides a great degree of discrimination capability. An ICP-OES study of the elemental distribution of automobile side-window glass, for example, found that the probability of two glass samples from different cars being indistinguishable was 1 in 1,080, compared with 1 in 5 when just the refractive indices were used as the basis of comparison.

Wrap Up

You are the Forensic Scientist Summary

1. Police should detain the suspect and get a warrant to examine his or her hair and clothing for glass shards. If the suspect was near the car when the window was broken, he or she should be covered with glass fragments. The police should also examine the suspect's skin for any cuts or scratches from the broken window. In addition, the police should gather eyewitness testimony. If glass fragments are found, they should be analyzed by the methods described in this chapter.
2. The number of glass fragments found on the suspect is important: The more shards found, the closer the suspect's proximity to the event. Police should determine whether the glass is tempered glass, which is used in the side windows of cars.

Chapter Spotlight

- Glass is a solid that is not crystalline; rather, it has an amorphous structure.
- Soda-lime glass is the glass commonly used in windows and bottles. A variety of metal oxides can be added to this glass to give it a special appearance.
- Tempered (safety) glass is more than four times stronger than window glass.
- Automobile windshields are made from laminated glass. The plastic film holds the glass in place when the glass breaks, helping to reduce injuries from flying glass.
- Many nonoptical physical properties—such as surface curvature, texture, special treatments, surface striations, markings, surface contaminants, and thickness—can be used to compare a questioned specimen of glass with a known sample.
- Glass fractures when it is subjected to compressive, tensile, and shear forces that exceed its elasticity. The excessive force produces radial and concentric cracks in the glass.
- The 3R rule: Radial cracks create rib marks at right angles on the reverse side from where the force was applied.
- Glass density tests are performed using the density gradient column method. The density of a glass fragment taken from a suspect may be compared with the density of a glass sample from the crime scene in this way, either proving or disproving a link between the two.
- Optical physical properties of glass include color and refractive index.
- Comparing the color of a suspect piece of glass can distinguish between glass from different sources.
- To determine the refractive index, forensic examiners often use the oil immersion method. It involves placing glass pieces in specialized silicone oils. The temperature then is varied until the match point is reached and the Becke line disappears.
- Tempered glass can be distinguished from nontempered glass by heating the glass fragments.
- The FBI maintains a database of density and refractive index data that forensic scientists can use as the basis of comparison when analyzing their own sample.
- The elemental composition of glass can be measured by flameless atomic absorption spectrophotometry (FAAS) or inductively coupled plasma (ICP; sometimes with use of optical emission spectrometer, known as ICP-OES) methods or by use of surface techniques such as a scanning electron microscope (SEM) or X-ray fluorescence (XRF).

Key Terms

Annealing Heat treatment that produces tempered glass.
Compressive force Force that squeezes glass.
Concentric cracks Cracks that appear as an imperfect circle around the point of fracture.
Crystalline solid A solid in which the atoms are arranged in a regular order.
Density gradient tube A tube filled with liquids with successively higher density.
Entrance side The load side of a projectile.
Exit side The unloaded side of a projectile.
Fracture match The alignment of the edges of two or more pieces of glass, indicating that, at one time, the pieces were part of one sheet of glass.
Laminated glass Two sheets of glass bonded together with a plastic sheet between them.
Mohs scale A scale that measures the hardness of minerals and other solids.
Projectile The load of a bullet shot at a pane of glass.
Radial cracks Cracks that radiate in many directions away from the point of fracture.
Rib marks The set of curved lines that are visible on the edges of broken glass.
Shear force Force that moves one part of the material in one direction while another part is moving in a different direction.
Striations Fine scratches left on bullets, formed from contact of the bullet with imperfections inside the gun barrel.
Tangential cracks Cracks that appear as an imperfect circle around the point of fracture.
Tempered glass Glass that has been heat treated to give it strength.
Tensile force Force that expands the material.

Putting It All Together

Fill in the Blanks

1. Glass is often found on burglary suspects as _______ evidence.
2. Glass is a solid that is not crystalline, but rather a(n) _______ solid.
3. The atoms of an amorphous solid have a(n) _______, _______ arrangement.
4. Tempered glass is rapidly _______, which makes the surface and edges compress.
5. Automobile windshield glass is laminated with a(n) _______ layer between two layers of glass.
6. When sheet glass is rolled, the rollers leave parallel _______ marks in the surface.
7. The thickness of a questioned glass sample can be measured with a(n) _______.
8. The accepted scale of glass hardness is the _______ scale.
9. On the Mohs scale, the softest material, _______, is given a value of 1 and the hardest material, diamond, is given a value of _______.
10. A force that squeezes glass is called a(n) _______ force.
11. A(n) _______ force expands glass.
12. A force that slides one part of glass in one direction and another part in a different direction is called a(n) _______ force.
13. A(n) _______ crack radiates outward, away from the load point.
14. A(n) _______ crack grows from one radial crack to another and from the loaded side to the unloaded side.
15. When comparing glass fragments for the purpose of matching their color, the fragments should be viewed on _______ over a white surface.
16. The refractive index is a measure of how much light is _______ as it enters a material.
17. The bending of a light beam as it passes from air into glass is known as _______.
18. The _______ and _______ of the light being refracted influence the refractive index for any substance.
19. The D line, which is used to designate the refractive index, indicates _______.
20. The oil immersion method of refractive index measurement uses _______ oils.
21. For the oil immersion method of refractive index measurement, the refractive index of the immersion oil is varied by raising its _______.
22. The halo that is observed around the glass fragment in the oil immersion method is known as the _______ line.
23. The Emmons procedure for measuring the refractive index of glass makes measurements at three different _______ of light.
24. By using a(n) _______ microscope, the Emmons procedure increases the precision of the refractive index measurements.
25. Heating glass in a furnace at temperatures above 600°C is called _______.
26. The scanning electron microscope cannot take precise measurements of elemental concentrations in glass fragments because of the _______ of the glass fragments.

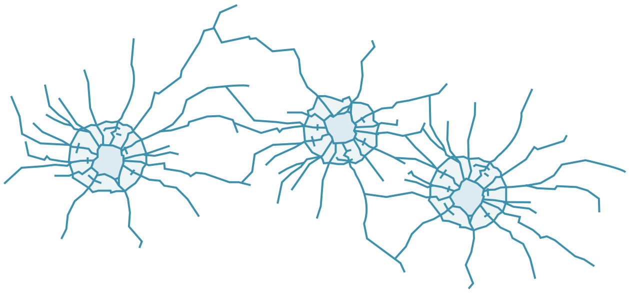

FIGURE 5-13

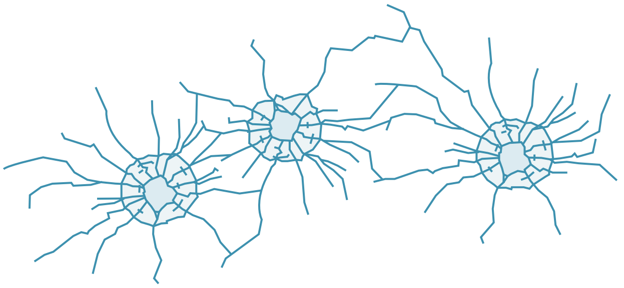

FIGURE 5-14

True or False

1. Glass fragments have a sharp melting point.
2. When tempered glass breaks, it shatters into pieces with sharp edges.
3. Density measurements on cracked glass are not to be trusted.
4. Plate glass has a uniform refractive index across the entire pane.
5. One big advantage of the XRF measurement is that it does not destroy the sample.

Review Problems

1. Refer to **FIGURE 5-13**. Determine the order in which these bullet holes were made. Justify your answer.
2. Refer to **FIGURE 5-14**. Determine the order in which these bullet holes were made. Justify your answer.
3. Compare the bullet holes in Figures 5-12 and 5-13, and indicate which (if any) were made by a higher-velocity bullet. Justify your answer.
4. Using the equation $\eta_D^x = \frac{V_{air}}{V_{glass}} = \sin\theta_{air} / \sin\theta'_{glass}$, determine the index of refraction for the following glass fragment. The incident angle of the D line light is 45°. The light passing through the glass is refracted at an angle of 28°.
5. Using the equation $\eta_D^x = \frac{V_{air}}{V_{glass}} = \sin\theta_{air} / \sin\theta'_{glass}$, determine the index of refraction for the following glass fragment. The incident angle of the D line light is 45°. The light passing through the glass is refracted at an angle of 27°.

Further Reading

Bottrell, M. C. (2009). Forensic glass comparison: Background information used in data interpretation. *Forensic Science Communications*, *11*(2). http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/april2009/review/2009_04_review01.htm.

Houck, M. M. (2001). *Mute witnesses trace evidence analysis*. San Diego, CA: Academic Press.

Houck, M. M. (2004). *Trace evidence analysis: more cases in mute witnesses*. San Diego, CA: Academic Press.

Koons, R. D., Buscaglis, J., Bottrell, M., & Miller, E. T. (2002). Forensic glass comparisons. In R. Saferstein (Ed.), *Forensic science handbook* (2nd ed., Vol. 1). Upper Saddle River, NJ: Prentice-Hall.

Petraco, N., & Kubic, T. (2004). *Color atlas and manual of microscopy for criminalists, chemists, and conservators*. Boca Raton, FL: CRC Press.

Scientific Working Group for Materials Analysis (SWGMAT). (2005). Elemental analysis of glass. *Forensic Science Communications*, *7*(1). http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/standards/2005standards10.htm.

Scientific Working Group for Materials Analysis (SWGMAT). (2005). Glass density determination. *Forensic Science Communications*, *7*(1). http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/standards/2005standards8.htm.

Scientific Working Group for Materials Analysis (SWGMAT). (2005). Glass fractures. *Forensic Science Communications*, *7*(1). http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/standards/2005standards7.htm

Scientific Working Group for Materials Analysis (SWGMAT). (2005). Glass refractive index determination. *Forensic Science Communications*, *7*(1). http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/standards/2005standards9.htm.

Scientific Working Group for Materials Analysis (SWGMAT). (2005). Introduction to forensic glass examination. *Forensic Science Communications*, *7*(1). http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2005/standards/2005standards4.htm.