GLAZING FOR FRAMING AND CASE MAKING

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INTRODUCTION

The ideal glazing material would transmit without distortion all the light in the visible spectrum, reflecting none, and would be opaque to ultraviolet radiation. It would resist impact and abrasion, carry no static charge, and neither expand nor contract with changes in temperature and humidity. Available in any size, this material would also be of light weight, rigid, inexpensive, and show no effects of aging.

Sad to say, no miraculous glazing material exhibits all of these qualities. At best, our options today satisfy only three or four of the dozen requirements listed above; our task, then, is to sort out the best choice for each circumstance.

The purpose of this paper is to examine and summarize the issues which must be faced in designing and working with glass or acrylic. Particular attention is paid to the practical concerns of those who execute the designs, store and handle these fragile materials, and pack and ship them. To this end, I provide as much detail as possible about specific products. If information has been supplied by manufacturers, and we have no experience with the material, I say so. We ourselves use many of the referenced products, and have conducted informal tests on some of them. It goes without saying, however, that in so large and diverse a field we have made mistakes and allowed omissions. We strongly suggest that for sensitive installations case and frame designers either contact manufacturers or perform their own tests. We plan to update this material occasionally, and would appreciate hearing from colleagues with corrections or new information.
The first section, BACKGROUND, includes a brief historical overview of the development of flat glass and an outline of acrylic manufacturing processes. In the section titled PROPERTIES I treat in alphabetical order those properties of glass and acrylic that are relevant to framing and case making, with a few references to polycarbonate.

BACKGROUND

GLASS.
Structure.

Glass seems simple, since it requires only three basic and common ingredients. But its structure is complex, and it is quite difficult to accurately describe. Glass is classified as a ceramic, but might best be understood as a liquid that has the properties of a solid. A more precise definition would be: an inorganic material, structurally similar to a liquid, but with a viscosity so great that it can be considered to be a solid. Sand (silicon dioxide), soda (sodium carbonate), and limestone (calcium carbonate) are the essential ingredients of the most common glass--known as 'soda-lime glass'. Sand makes up 60-70% of the whole. Soda (also called 'soda ash', or simply 'ash') accounts for about 15-20%. Soda is a flux, and makes sand fusible at a moderate temperature. Limestone is a stabilizing agent, and is added for durability. In the early days of glass making, the purest sources of sand were sought, and soda was produced by burning trees or plants. The best source was the plant Salicornia herbacea, or glasswort, which has a particularly high salt content. Salicornia grows in salt marshes along the Mediterranean coasts (as well as in our own salt marshes of eastern North America). Kelp, fern and various woods were also burned for soda.

To make glass with special qualities other materials may be used. Lead, for instance, may replace limestone to make especially dense and brilliant glass. In making contemporary float glass small amounts of iron oxide are added to enhance the melt. Glass is melted at about 1500 degrees centigrade, just below the melting point of iron. The ribbon of molten glass flows onto a surface of molten tin. As it floats on the tin, the glass is attenuated to give it the proper thickness. At the end of the line, stresses in the glass are relieved by annealing, a process of controlled cooling.

History.

Natural glass in the form of obsidian had long been used for weapons and tools in many areas of the world, including the Eastern Mediterranean. It was in this region that glass was first fabricated, probably in Babylonia or Egypt, around 3000 BC. Glass vessels have been discovered from Mesopotamia, Egypt, and Mycenaean Greece dating from the first two millennia BC. During the Roman Empire, around 30 BC, the blowpipe was invented and glass blowing developed. The Phoenicians (who were Syrians living on the Mediterranean coast in what is now Lebanon) are usually credited with this discovery. The development of blown glass represents certainly the first, and probably the greatest innovation in the history of glass manufacture, and glass blowing remained the dominant glass making technology well into the 19th century. In fact, the glass blower's pipe has remained essentially unchanged since its discovery.

During the first three hundred years AD, the knowledge of glass making spread throughout the Roman Empire from the Mediterranean rim through Italy and into much of northern Europe. The root of our word 'glass' probably dates from this time. The Latin term 'glesum' was used, perhaps derived from Old Teutonic 'gla', meaning to shine or glow. A related word is Old English 'glaer', for amber. The knowledge of glassmaking spread from Europe and the Middle East to the rest of the world. China was the only other area where glass making was independently developed, but even China imported Roman glass via the silk routes.

The use of glass for glazing windows seems to have lagged at least two thousand years behind its use in making vessels. But by the early Roman period glass was one of the materials used in windows. Pompeian bath- house windows of thick glass, about 30 by 40 inches, have been recovered. The glass was greenish blue, and probably cast on stones or into clay moulds. Since this glass was not ground and polished, it was translucent but not transparent. Roman window glass adequately satisfied two of the three modern requirements of window glazing; it admitted some light, while keeping out the weather. But people within could not see the outer world through it. Similarly limited were the other materials used to glaze Roman windows, such as alabaster, marble and mica.

During the Middle Ages there were a number of centers of glass manufacture, both in the Islamic world and in Europe. Byzantine church windows were glazed with glass, and some of the glass panes in Hagia Sophia (6th c.) may be original. Islamic builders also used small panes of glass, often brilliantly colored, for mosque windows. In general, glass-making technology stagnated during the early Middle Ages. In this period, the Church was the most important patron for glassmakers as it was for most artists and artisans. And, although it was expensive and rare, glass was also used in domestic architecture.

The medieval makers of window glass were highly skilled and accorded great respect from other glassmakers. They employed two methods of blowing glass to make flat glass. One technique was to blow a large cylinder, which was cut along the side and flattened out, a method that was, much later, mechanized and continued into the 19th century. The more common product was 'crown' glass, made by first blowing a bubble, which was cut at the end; the pipe was then spun quickly, so that centrifugal force and heat caused the molten glass to 'flash' into a flat circular disc or 'crown'. After removal from the furnace, rotation continued, until the glass cooled. It was then cut from the rod, leaving a 'bull's eye' or 'knot' in the middle. This technique required several men and boys to make each piece. Although Crown glass was corrugated with concentric ridges, it was thin and had a lustrous surface.

Until the 1600's windows in northern Europe were leaded and often made of many small crown glass roundels, with the gaps filled with small triangular glass pieces. Another common design was to use rectangular or diamond shaped panes cut from either crown or cylinder glass, which were also mounted with lead in wooden frames. Windows of this style can be seen in the paintings of Vermeer.

These windows effectively admitted light and were transparent, but their surface anomalies made seeing through them difficult.

The first truly clear glass was developed during the seventeenth century, when the casting of glass was revived in France at St.Gobain during the reign of Louis XIV. In this process the molten glass was flattened with rollers, producing thicker panes than crown glass. It could, therefore, be ground and polished for use in large windows and mirrors. Sheets of this plate glass over six feet long were being produced in France by the end of the seventeenth century, and in French interiors of the eighteenth century plate glass mirrors had become essential design elements. At this point the glazing of windows directly in wooden frames without leading became a common practice, and abruptly lowered the cost of fenestration.

Cutting glass into panes was a delicate art. A hot iron was used, which started a crack, and as the hot tool was drawn along the intended line of break, the crack, in theory, followed. This risky technique was abandoned in favor of using diamond glass cutters, which may have appeared as early as the sixteenth century.

Throughout the sixteenth and seventeenth centuries glass became accessible to more people, largely because of a rising standard of living. For most residences, crown glass continued to be used for windows. Cast plate glass remained expensive, particularly since grinding and polishing was done by hand. In 1697 the English government, recognizing an opportunity in the surging demand, levied a window tax, a form of luxury tax.

Glass became much more common for residential glazing during the eighteenth century, and was used for picture framing. At the end of this century mechanical grinding and polishing of plate glass replaced tedious hand labor, thereby lowering production costs. By about 1830 the blowing of cylinders had virtually eclipsed the crown glass method. Hand blown cylinder glass was used in the great architectural glass marvels of the mid-nineteenth century; the railway stations, winter gardens, and conservatories. The most notable example was the Crystal Palace, built in England in 1851, with nearly one million square feet of glass. The glass workers, working day and night, produced 300,000 panes of glass in just a few months.

Although a method for producing rolled glass was patented in England in 1847, blown cylinder and cast plate glass continued to dominate the nineteenth century markets. The increasing capacities were remarkable: Saint Gobain, which is still one of the world's great glass manufacturers, could produce a piece of cast plate as large as five by eight feet in 1804. By 1899 they could make a single piece fourteen by twenty-seven feet.

In the United States during the nineteenth century prefabricated cast- iron technology made possible multi-story buildings with windows of great size. Buildings in the SoHo Cast-iron Historic District in New York City represent the best surviving examples of this once popular building method. The great spans achieved with cast iron columns and beams, when combined with large plate glass panes, made possible the design of interior spaces flooded with daylight. The early promise of window glass had been fulfilled. Most people at work, and increasingly at home as well, had access both to daylight and to a clear view of the world around them. The use of glass to visually dissolve walls came fully into its own during the twentieth century both in International Style urban architecture and in the widespread use of picture windows in suburban US housing after World War II. And as glass making improved, the permanent display of works of art on paper became feasible. Like paintings, prints and drawings could be hung on walls, rather than requiring storage in folios to be brought out for occasional view.

Making these achievements possible were a number of advances in flat glass technology throughout the first half of the twentieth century. Most notably, several processes were developed for drawing sheet glass. These efficient, high production methods produced good, inexpensive glass. They were plagued, however, with some typical defects, especially by distortions caused by differences in viscosity, and by parallel lines in the surface, known as music lines.

In 1957 Pilkington Brothers, Ltd. received the British patent for float glass, a radical departure in glassmaking. Float glass is made by floating liquid glass on the surface of a tub of molten tin. This remarkable process produces virtually perfect glass sheets. Picture framers and other fabricators who switched from sheet glass to float glass in the 1960's and 1970's were struck by the high quality achieved by the process. Now, almost all flat glass in Western Europe and the US is made by some version of this technology.

ACRYLIC.

Polymethyl methacrylate resin is the plastic from which acrylic sheets are made. There are several methods of manufacturing acrylic sheets.

Cell Cast Acrylic. This process dates back to the 1930's, when acrylic sheet was used for aircraft windows in England. Liquid acrylic resin is poured between two sheets of glass that have been separated by a thin gasket. Cell cast sheet exhibits great optical clarity, but is manufactured to greater thickness tolerances than sheet made by the other two methods. Its maximum size is limited by the glass mold, and, since the sheets are cast one at a time, they are expensive.

Continuous Cast Acrylic. A catalyzed liquid monomer is deposited on a moving stainless steel belt and formed between it and a similar overhead belt. The monomer polymerizes as it travels on the belts. Continuous cast sheet can be made much larger than cell cast. In order to make the steel belt wide enough for large sheets, however, strips of steel must be welded together. The resulting weld line leaves a visible distortion in the sheet of acrylic. Continuous cast acrylic is also subject to slight transverse distortions, sometimes called "chatter lines", which appear at right angles to the weld line. This distortion is very difficult to see unless the sheet is viewed at an angle of 5-10 degrees.

Continuously Manufactured/Extruded Acrylic. During the 1970's great advances were made in acrylic extrusion technology. The product was so improved that eventually a new designation 'continuously manufactured' was applied to it. Now a number of manufacturers have proprietary methods of extruding resin that produce a much higher quality product than what was traditionally known as extruded sheet. The methods and quality vary, and both advanced technology and greater care may be responsible for the better quality products. Apparently, in all of the versions, the thick liquid is pushed through a die, and then annealed. This much at least all the processes have in common. Proprietary distinctions, however, between processes remain nebulous.

Unlike pre-1970's extruded acrylic, the best continuously manufactured/extruded sheet is free from extrusion lines, and virtually free from distortions. All this material exhibits slightly different characteristics from cast sheets: its abrasion resistance is slightly less than cast acrylic, it is a little less resistant to chemicals and heat, and its cutting and bending characteristics differ -these properties are associated with its slightly lower molecular weight. The continuously manufactured/extruded processes are much more efficient than cell casting.

POLYCARBONATE.

Although rarely used in framing because, unless it contains a UV inhibitior, it develops a yellow tint when exposed to ultraviolet radiation, polycarbonate deserves a mention because it is the toughest transparent material available, from the standpoint of impact resistance. Therefore, it is sometimes called for in case design, and its impact resistance recommends it for public buildings. It is so tough that some municipalities require notification if buildings are glazed with polycarbonate because firemen or rescue squads may be unable to break through it. Polycarbonate's surface is less abrasion resistant than acrylic, but it is available with abrasion resistant surface coatings. Although polycarbonate has only modest utility in framing and case making, its special characteristics will be cited when appropriate. Gains have recently been made in limiting the yellowing of polycarbonate, so it may become more attractive for these uses. Polycarbonates have been on the market since the late 1950s. GE's Lexan dominates the field.

PROPERTIES

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Abrasion Resistance.

Glass is highly resistant to abrasion. Coated glasses, however, such as Tru Vue’s Museum Glass, Schott’s Mirogard and Amiran and Glas Troesch’s Luxar, can be scratched, and the scratches cannot be repaired. In informal razor blade scratch tests, we found that the anti-reflection coating on Schott's Amiran to be the toughest, followed by Schott's Mirogard and Tru Vue's AR glass. All of these anti-reflectant coated glasses should not deteriorate from normal cleaning.

Acrylic scratches easily. Framed works on paper, by rubbing against acrylic glazing during transport, have been known to seriously abrade the acrylic sheet. A number of companies make an abrasion resistant, coated acrylic sheet, the best known of which is Lucite S-A-R, made by DuPont (Lucite is a Continuous Cast sheet. DuPont also sometimes applies the S-A-R coating to Cell Cast material, made by others.)

Polycarbonate has a softer surface than acrylic. A number of companies, however, make an abrasion resistant coated polycarbonate. GE's Lexan MR5 (Margard) is the most readily available. According to GE, in three standard abrasion tests MR5 scored fairly close to glass.

Aging.

Glass: the only aging process that may of interest for framing and case making is that with time microscopic surface scratches may slightly reduce light transmission. Since glass is a very viscous liquid, theoretically it should slowly flow, eventually resulting in sheets thicker at the bottom than the top. Whether or not this flow occurs is a matter of debate among scientists, but if glass does flow it would be at a rate slower than glacial, and even after hundreds of years imperceptible to the human *eye.* Although we might expect the coated glasses to show surface degradation over time, Schott has conducted tests in extreme weather conditions for 25 years, and report no surface changes. Tru Vue's products are new. We await the results of their accelerated aging tests.

Acrylic, like all organic materials, ages, but very slowly. Some tests have shown that it loses a small percentage of light transmission over a number of years of heavy weathering, and that it slightly yellows. These losses are so modest that they are unlikely to be perceptible by the human *eye.* CYRO (EVONIK) guarantees that their acrylic sheet, Acrylite, will lose no more than 3% light transmission over ten years. If acrylic becomes hazy after repeated cleanings, it can usually be repaired (see Cleaning). There is much concern that the UV shielding properties of UV absorbing acrylic glazing may diminish with time, but so far, studies have shown no loss of protection. This issue should be closely monitored. (**See our report on this topic in Writings.**) Polycarbonate yellows noticeably from UV absorption. GE's Lexan MR5 (Margard) is treated with a UV absorber that retards this process.

Chemical Resistance and Permeability.

Glass is impenetrable to gases and vapors, and resistant to most solvents and acids, except hydrofluoric acid, which is used to etch glass. Alkaline substances may also etch the surface of glass. This can pose a problem if alkaline papers are used to interleave sheets of packed glass. A permanently frosted surface may result, known as 'paper hum'.

Acrylic glazing allows some vapors and gases to slowly pass through. Thus, if substances in a frame are outgassing, such as solvents from a recently struck print, acrylic may eventually allow them to exit, but at the possible cost of crazing the surface of the sheet. Of course, gases can flow both ways; acrylic glazed frames or cases exhibited in areas of high air pollution may allow such gases to pass into the frame or case environment. For this to happen the concentration of such gases must be very high, so we think it unlikely to occur in actual exhibition conditions--but we are seeking more information on this issue.

Acrylic is more likely than glass to interact with some art media, such as acrylic paint, which, if pressed against the glazing may form a chemical bond, difficult or impossible to break without damaging the surface of the framed work. The following chemicals affect acrylic to varying degrees: benzene, toluene, carbon tetrachloride, alcohols, lacquer thinners, gasoline, ethers, ketones, and esters. Polycarbonate is generally compatible with alcohols. According to GE, benzene, toluene, lacquer thinner, paint thinner, acetone, and ketones all affect polycarbonate. It is attacked by alkalis, ammonia and amines.

Cleaning.

It is a good practice to apply cleaning liquids to the cleaning cloth or paper, rather than to the surface of a glazed frame. Matboard and paper will wick up organic solvents much faster than water, so special care must be taken that solvent cleaners do not penetrate the frame. Whenever solvents are used to clean glazing materials they should be followed by a water or soap and water cleaning.

Glass: We are unaware of any documented damage to framed works of art from commercial glass cleaners--nevertheless they are a cause for concern: most contain dyes, and since they are proprietary materials, they may contain undisclosed substances, which could pose a risk to art. All cleansers should be completely wiped off the glazing. Ammonia and other strong cleansers should not be used on the inner side of frames and cases.
Anti-reflectant glass(TruVue Museum Glass, Schott Mirogard and Amiran, Glas Troesch Luxar)can present cleaning problems. It ideally has optical properties similar to air; it is, therefore, close to invisible. Many substances contained in cleaning solutions, however, and the oil from fingerprints, are optically rather similar to glass; they reflect light. The goal, then, is to find glass cleaners that clean effectively and leave no residue of their own. After trying many products we now prefer to use pure water and a soft cloth. For persistent marks, we put a few drops of isopropyl alcohol on a cloth and rub that area.

Acrylic: detergent and water, with a soft cloth or paper, are the recommended cleaning agents for acrylic. 'Kaydrys', by Kimberly Clark, are effective, as are cloth diapers, though they may become roughened by repeated washings. Chamois skin with plain water has been highly recommended to us. To remove grease or oil, manufacturers usually recommend kerosene, high-grade hexane, or naphtha (VM&P). Do not use any alcohols since they cause crazing of the surface, which may become visible only the second or third time the sheet is cleaned. Beware of commercial glass cleaners, which may contain alcohol.
Polishing out superficial scratches is possible. The greatest challenge is the final polish--to remove the haze.
We have recently found '210 Plus Scratch Remover' and '210 Plastic Cleaner & polish' made by Sumner Laboratories, in Boston, MA, to be effective.
(For solvents to avoid, see Chemical Resistance and Permeability. For more on cleaning acrylic, see Static charge).

Color.

Glass: although it can be made to be almost 'water white', most glass has a green tint. Some of the color is due to natural variations in the mineral content of the sand, which is its main ingredient, but the addition of iron oxide is the primary source. Iron oxide is used because it retards the hardening of glass so that it will melt uniformly. Otherwise, air bubbles may be trapped within or the glass may contain swirls, known as 'reams'. Low iron glass, once difficult to find is now easily sourced in thin sheets useful for framing. Unfortunately, low-iron, or "water white" glass, also transmits more UV in the 300-340 nm range.
Of course, the thickness of glass plays a role in the degree of tint, and shielding against ultraviolet radiation also contributes color to glass. Tru Vue Conservation Clear glass, which is coated to protect against UV, removes some visible violet as well. This would make the glass appear rather yellow, like UV shielded acrylic, but the manufacturers add dye to the coating to give the glass a gray-green tint.

Acrylic: acrylic sheets are virtually without tint, except for those which have been treated to shield ultraviolet. UV shielded acrylic is typically yellow, although manufacturers sometimes dye the sheet, making it grey-green to resemble glass.

Cutting.

Glass is first scored, with a steel or carbide wheel glass cutter (which lasts about ten times as long as a steel wheel), and then it is broken out, usually by the technique known as 'snap breaking' over the edge of a table. The proper distance over the edge (about 1/16") and evenness of force is necessary to achieve a square break. Sloppy technique may result in a flared break--which, on the underside, deviates slightly from the line, and is sharp and fragile. As glass ages its surface becomes harder and more difficult to score. Sometimes removing a very narrow strip of glass (a procedure called 'grozing') leaves a chipped edge. Any 'V' shaped chips in the glass, known as vents, are weak spots, which may fracture under tension. They should be ground so that the sharp points of the chips are removed. If glass is not broken out soon after scoring, it starts to 'heal'; the surface is under compression, so bonds between molecules start to re-form across the score line. After it has begun to heal, glass takes more force to break. To retard the healing process, apply kerosene to the line of cut before or during cutting. Both Fletcher and Toyo make glass cutters with reservoirs for kerosene. After cutting, glass can be lightly ground on the edge with a 'seamer,' a procedure which makes the glass less dangerous to handle and removes small vents.

Acrylic: Plastic scoring tips are used instead of wheels to cut acrylic by hand, requiring several passes. Table saws are commonly used for production work, but a good quality panel saw is safer and more accurate. Triple chip carbide blades (often used to cut aluminum) are usually used. Continuously Manufactured/Extruded sheet requires different cutting tools for some operations than cast sheet. Acrylic can be drilled, but drills specifically designed for this purpose should be used. Consult manufacturers' technical data for cutting and drilling advice.

Polycarbonate can be cut with the same tools and techniques as acrylic.

Defects.

Glass: Float glass is of much higher quality than sheet glass, its predecessor. Coated glasses, however, have their share of defects. Tru Vue Conservation Clear glass, which is coated on one side only, shows slight surface ripples in the coating. The non-reflective coatings on Luxar, Tru Vue Museum Glass, Mirogard and Amiran occasionally show small shiny spots, which are voids in the coating. Amiran is an architectural glass, and the defect specifications are not as rigorous in architectural applications as in picture framing. Since picture framing makes up a small portion of the market, these defects must sometimes be tolerated.

Acrylic sheet, in general, contains more defects than float glass. Black specks (inclusions) are common. Other routine defects are: scratches, water spots (caused by water getting under the facing paper), and swirls (from water, which sometimes contaminates the liquid resin). The requirements of framing and case-making sometimes demand a standard that is currently beyond the capacity of the acrylic industry.

Emissions and Outgassing

Glass: Float glass is not known to cause any problems by emission of gases or liquids. When glass undergoes additional processing, though, caution is advised. A few years ago a new 'non-glare' glass appeared on the market, which was much more finely etched than the conventional product. Framers soon discovered that it caused discoloration of mats, due, it turned out, to residual acid which was almost impossible to remove from the etched surface (we have heard no reports regarding damage to artwork.) This glass was taken off the market. It is not inconceivable that other new products, such as the coated glasses, may present risks. They should be separated from the surface of art works.

Acrylic sheet may emit small quantities of monomer after manufacture. Engineers at major US manufacturers, however, have found their products emit very little, if any. Under extreme environmental conditions, such as temperatures in the 180 degree F. range and above, measurable amounts of monomer may be emitted. This should not present a serious risk, and, to our knowledge there have been no reports of damage to artwork by emissions or outgassing from acrylic glazing. When acrylic sheet is masked with paper, the adhesive is rubber based and contains sulfur compounds which could, in theory, be absorbed by the acrylic and later emitted in the frame or case environment.

Expansion and Contraction.

Glass expands so little with changes in temperature that it is not of concern for framing or case making; it expands and contracts not at all with changes in humidity.

Acrylic sheet expands and contracts in response to changes in temperature (its coefficient of thermal expansion is .00004 inches/inch/degree F.) An example might be useful: a sheet of acrylic 100 inches long, installed in a frame in a 70 degree shop, and then shipped in an unheated truck on a 10 degree winter day would shrink about 1/4 inch. To compare with other materials: under the same circumstances, aluminum would shrink about 1/16", glass or steel would shrink about 1/32", and pine or oak would shrink in length about 1/64".

During the summer, a similar sheet, 100 inches long, framed in an air- conditioned 65 degree shop and exhibited or stored in a space where the temperature is allowed to rise to 95 degrees would expand about 1/8 inch. Continuously Manufactured/Extruded sheet, if heated above 180 degrees F, will shrink slightly, once only, parallel to the direction of extrusion (sheet made by the other two methods also is subject to one- time shrinkage at high temperatures, but equally in both directions. Pre-shrunk sheet can be specified).

Acrylic glazing will also respond to changes in relative humidity. For architectural glazing, the customary allowance for linear dimensional change due to changes in relative humidity in acrylic is 0.1% of the length. By this standard, for a 100 inch sheet about 1/10 of an inch should be allowed. We feel that this allowance will not always be sufficient; under conditions where extreme humidity change may be encountered, the allowance should be doubled to 0.2%. Acrylic's response to changes in relative humidity is much slower than its response to changes in temperature. Although reliable data is hard to find, one test performed by DuPont suggests that relative humidity's influence on expansion or contraction will continue over a number of days, whereas temperature change affects acrylic over minutes or, at most, hours.

Great care should be taken in the use of mechanical fasteners, otherwise acrylic sheet may warp or fail. If fasteners are necessary, using oversized holes and fastening only at the midpoint of a long length are two strategies which may be effective.

Polycarbonate's coefficient of thermal expansion is similar to acrylic's. It is, however, much less responsive to moisture.

Glass is rigid, and in picture framing or display case conditions, deflection is barely perceptible and unlikely to pose a risk to framed art.

Acrylic sheet is flexible, and subject to deflection, which distorts reflections. The major concern of framers is that glazing may bow in, touching a framed work of art. This likelihood is increased by lighting conditions; in tests we have performed, the interior of a frame lighted with incandescent exhibition lights is typically five to six degrees Fahrenheit warmer than the outside air. This difference may be enough to cause the glazing to bow slightly inward. Over time, differences in relative humidity inside and outside the frame or case may also cause deflection, with the acrylic bowing toward the more humid side (see Packing and Shipping for more on deflection.)

Impact Resistance.

Glass: Though conventional soda-lime-silica glass is naturally brittle, by changing the components specialty glasses can be made which are much more flexible. The economics of glass production, however, make the prospect of ever seeing such glass for picture framing unlikely. Two other options are currently available: laminated and safety glass. Laminated glass is composed of two sheets of glass bonded by a layer of flexible plastic (polyvinyl butyral). UV absorbers can be added to the pvb layer. Laminated glass is commonly used for automobile windshields, since it will crack but not shatter. Where security against theft is a major consideration, laminated glass is often chosen.

Heat tempered glass, which must be cut to size before tempering, is about five times stronger than regular annealed glass. This glass, if broken, shatters into granules with blunt edges, which are much less likely to damage framed art. The side and back windows of most automobiles are made of tempered glass. Tempered glass is vulnerable at its edge. Therefore, the edges of tempered glass are always rounded or seamed. In frames or cases the edges of tempered glass should probably be cushioned to prevent shock. Available now is a second kind of tempered glass, which has been chemically tempered. Its properties are similar to heat tempered glass. Tempered glass can be made thinner than laminated glass since it is only one layer thick. We have been advised to specify "tempered safety glass" when we order, since lower quality tempered glass is sometimes sold.

Acrylic: the impact resistance of acrylic glazing is at least several times that of glass, and this property is almost unaffected by changes in temperature.

Polycarbonate's impact resistance is said to be 250-300 times that of single strength glass.

Light Transmission and Reflection.

Un-tinted glass and acrylic sheet transmit close to 90-92% of the light which enters perpendicular to its surface. Only about 8-10% of the light, therefore, is reflected; but even this small percentage of specular reflection may produce a veiling glare and manufacturers have sought means of reducing it further.

Glass: for many years the only reflection controlled picture glass was acid etched, "non-glare" glass. Recently the clarity of this glass has been much improved by better control of the etch, and by etching only one side. Etched glass lessens reflectance by diffusion of the light--a diffusing surface scatters light rays in all directions. Some manufacturers achieve a similar result by impressing a faint pattern into the surface of the glass to diminish reflectance. Etched glass, unfortunately, diffuses light transmission as well as reflection. It therefore interferes with viewing images and is inappropriate for case- making or archival framing

About 1970 a useful alternative, "anti-reflectant" glass, appeared. The glass is coated with an optical film similar to that on eyeglasses and camera lenses. This an-reflectant glass reflects only about 1% of incident light (from 425-675 nm) and in the right circumstances it can be an effective alternative to regular glass or acrylic. It is not, however, a miracle product, and is, arguably, no better than ordinary glazing when hung opposite a window. Under such conditions its purple, and sometimes green, reflections, may be very distracting. A German glass company, Schott, manufactures a similarly coated glass under the names Mirogard and Amiran. Available in Europe for the past twenty years, they have recently become accessible to the North American market. Amiran is made for exterior shop display windows and its coating is harder than the surface of Mirogard, which is designed specifically for picture frames. The Swiss company Glas Troesch now exports Luxar, similar to the Schott products.

Acrylic: Cell Cast acrylic sheet is said to be clearer than sheet made by any of the other processes, though in side-by-side tests we can see no difference between it and Continuously Manufactured/Extruded sheet. Tru Vue has developed a non-reflective acrylic sheet sold under the brand name Optium. A conventional sheet of acrylic, with or without UV blocking agents, is coated with a similar crystalline coating to the material used on non-reflective glass. It is a bit more reflective and it is a bit less abrasion resistant. On the other hand, the coating renders the acrylic free of static charge, which is an enormous virtue, especially when framing loose media.

Polycarbonate, in thicknesses used for framing and case making, transmits about 85% of the visible light.

Over-sized Pieces.

Glass: 2mm glass is readily available up to 40" x 60". We would, however, consider it risky to use in sizes above about 30" x 40". 2.5mm glass is appropriate within this same size range, but when glass is required in very large sizes, 1/8 inch (3.3mm) glass, known as double strength, may be used. Of course, glass much thicker than this is also on the market, and tempered or laminated glass should be considered for the largest frames which require glass. Tru Vue, Schott and Glas Troesch can provide laminated, UV shielded glass. Since the thicker the sheet the greater the tint, low iron (and reduced color) glass presents a useful option for thicknesses from 3.3 mm. and up (but the trade off is that UV blocking will be diminished.). Tru Vue Conservation Clear (UV shielding) is available up to 50" x 72" on special order. Schott Mirogard is available up to 48" x 71" (2-3 mm. thick). Amiran (4-10 mm. thick) is made in very large sizes, up to 10+' x 12+' on special order. Experience and circumstances will determine which thickness to use and whether acrylic is called for.

Acrylic: The three methods of manufacture have various upper limits (see Thickness for more on over-sized sheets.)

Cell Cast: up to 72" x 120"

Continuous Cast: up to 108" x 240" (on special order)

Extruded: 102" x 150" (not UV blocking)

Polycarbonate: Lexan is made in sheets up to 96" x 144".

Packing and Shipping.

Glass: It is generally recommended that if frames are to be shipped, glass should be masked over its entire surface. The traditional method is to cover the glass with parallel strips of tape, touching each other; one end of each strip should be folded over about 1/4", to act as a tab for ease of removal, and, of course, the tape should not touch the frame. A second similar layer of strips may be laid down at right angles to the first. If the tape is not removed immediately after arrival, it may leave considerable residue, which must be scraped off. It is risky to use solvents to remove adhesive residue while the artwork is still in its frame. Taping coated glass poses a serious problem for removal of adhesive residue, since the surface will be damaged by scraping. "Glass Skin" is reported to be an effective and easily removed masking material. There are tapes made for low-adhesion masking, such as Patco 5560, that may be useful, but we have no experience with them. Laminated and tempered glass should be considered for works that are to be shipped (see Impact Resistance.)

Acrylic: the impact resistance of acrylic is so great that it rarely cracks or breaks in shipping, and if it should, the broken edges are not as sharp as glass. For these reasons, and because tape removal is very difficult, it should not be taped. Since acrylic glazing is flexible and subject to horizontal deflection frames glazed with it should never be shipped lying flat. Horizontal deflection of 1/8" acrylic, size 36" x 36", is 5/16"; for 48" x 48", deflection is 1/2". Increasing the thickness to 3/16" will only decrease the deflection of a 48" x 48" sheet to 7/16". Clearly, unless very deep fillets are used, it is likely that in horizontally shipped frames acrylic glazing will contact, and vibrate against, the surface of the framed work of art.
Acrylic glazing is subject to dramatic expansion or contraction if it is shipped in trucks that are not climate controlled (see Expansion and Contraction.)

Static Charge.

Glass is not a good conductor, but its surface properties are such that electrostatic charge rarely poses a problem. By rubbing glass with wool, silk, and linen we could develop only a negligible static charge. Acrylic glazing is subject to high electrostatic charge, especially when humidity is low. Rubbing acrylic glazing also increases the static charge, so in cleaning it, a blotting, rather than a rubbing motion is recommended by manufacturers. We have found, however, no difference in static charge, whether wiping or blotting, as long as an anti-static cleaner is used. These acrylic cleaning solutions contain detergent and will reduce the charge temporarily, but at present there is no practical means of permanently reducing static charge. Loose media and thin or lightly sized papers are especially subject to attraction to acrylic glazing. Increasing the distance between acrylic glazing and framed artwork lessens the attraction, but to be effective a separation of several inches may be necessary.

Lucite S-A-R dissipates electrostatic charge more quickly than plain acrylic.

Optium, in tests we performed, exhibited no noticeable static charge. Its manufacturer, Tru Vue, says the static charge is very lower, less than glass.

Polycarbonate sheet is less subject than acrylic to static charge. (see Cleaning)

Thermal Conductivity.

Glass is a fairly good thermal conductor; a poor thermal insulator. In practice, this means that in conditions of rapid and/or significant changes in temperature or humidity, condensation may form on the inner surface of glass in a frame.

Acrylic is a poor thermal conductor; a good thermal insulator. Temperature or humidity spikes are less likely to cause condensation problems on the surface of acrylic than on glass. Acrylic provides a somewhat greater measure of thermal protection to framed art.

Thickness.

Thicker glass may, of course, be used for larger frames--specify float glass. Picture glass can also be obtained in thinner sheets: 2 mm and even 1/5 mm. Schott's two laminated glasses, Mirogard and Amiran are made in a variety of thicknesses. Laminated Mirogard (called Mirogard Protect) is 4+mm thick (48″ x 69 5/8″ sheet size). Laminated amiran is 8+mm thick (69″ x 126″ sheet size).Laminated Luxar is 4+mm thick (58″ x 75″ sheet size), or 6+mm thick (75″ x 118″ sheet size).

Acrylic: We commonly use 1/8" (3mm) material up to about 40" x 40". Above these dimensions, 3/16" (4.5mm)sheet is preferable to minimize deflection. 1/4" (6mm) acrylic may be used on the largest pieces. Because even 1/4" material is virtually water clear, color is a minor issue with thick acrylic. Weight and cost are the primary dissuaders.

Thickness nomenclature is confusing; glass is commonly described in millimeters, but acrylic is usually still described in fractions of an inch, or increasingly in thousandths of an inch. This is misleading because acrylic is actually manufactured to metric thicknesses.

Shown below for glass are inch decimal equivalents and approximate fractions. Other terms are also occasionally used: 2.5 mm glass may be called 'single strength b' or 'ssb', and 3.3 mm glass may be called 'double strength'. Until recently, 2 mm was commonly called '16 ounce' and 2.5 mm was called '19 ounce'.

Acrylic, described as 1/8 inch, is actually about 6% thinner--.118 inch, or 3 mm. It would be helpful for both the glass and acrylic industries to switch to metric nomenclature.

Glass	Acrylic
1.5 mm = .059 inch, (<1/16")	.118 inch «1/8") = 3 mm
2 mm = .078 inch, (>1/16")	.177 inch «3/16")= 4.5 mm
2.5 mm = .098 inch, (3/32")	.236 inch «1/4") = 6 mm
3.3 mm = .130 inch, (1/8")	

Ultraviolet Protection.

Although all light is potentially damaging to organic materials, UV light, under 400 nanometers, is both invisible to the human eye and more destructive to paper and most art media than light within the visible range. We prefer, therefore, to use glazing which totally protects artwork from light in the UV range, but is transparent to light in the visible spectrum. No glazing material fully satisfies this requirement, but the ones described below come very close.

Glass: Although standard picture glass absorbs almost all ultraviolet radiation up to 340 nm, until fairly recently there was no true UV shielding glass on the market. The first was UV Denglas, a laminated (impact resistant) glass whose pvb layer contained UV absorbers (Denton, manufacturer of Denglas, stopped making it in 1996.)The options for UV blocking glass are: Tru Vue Conservation and Museum Glass; Glas Troesch Luxar laminated glass; Schott Mirogard and Amiran laminated glass.

Acrylic: Evonik (CYRO) Acrylite OP-2 and OP-3, DuPont Lucite S-A-R UF-3 and Spartek Polycast UF-96, are all effective shields against UV. They are all designed to block 100% of UV under 390 nm but, since they also remove some visible violet, they all have a slight tint.

Polycarbonate: According to GE, manufacturer of Lexan, this product shields all UV below 385 nm.

Weight.

Glass:
2.5 mm glass, also known as 'single strength glass' (ssg), the most common thickness used in framing, weighs ca. 1 1/4 lbs/square foot. 2 mm. glass weighs ca. 1 lb./ square foot.

Acrylic:
1/8 inch (actually .118 inch or 3 mm.) weighs just under 3/4lb/square foot.
3/16 inch (.177 inch or 4.5 rom) weighs just over 1 lb/ square foot.

Glass is about twice as heavy as acrylic. 3 mm acrylic weighs almost ¾ lb/sq. foot. Glass this thick weighs 1 ½ lb/sq. foot.