Glass Breakage – Failure Mode and Stress Estimation

In most cases, forensic analysis of the fracture origin, also known as the break origin, can provide useful information about the glass breakage and often the root cause of the breakage.
If the break origin is obtained, analysis by experts can often provide:

- The mode of failure; such as by bending, thermal, pure tension, torsional, peel chip, etc.,
- The stress or tension level at which the glass breakage occurred and
- The cause of the breakage, e.g. impact, crush or digs caused by glass-to-glass or glass-to-metal contact, chips, edge or surface damage, or scratches.

This document discusses various modes of failure and is intended to provide the user a method with which an estimation of the stress levels that caused breakage can be determined.

Glass, like many brittle materials, breaks or fails when tension stresses approach or exceed the materials ultimate strength. There are two primary modes of glass failure. Breakage due to thermally induced stress (temperature difference within the glass) and breakage due to the tensile forces developed as a result of bending or impact (mechanical).

A common cause of breakage is damage to the edge of the glass. Edge damage can significantly reduce the strength of the glass by more than 50% and therefore its ability to resist both thermal and mechanical loads. Glass with existing edge damage could be functional for any amount of time until the necessary combination of thermal stress and/or mechanical loading conditions come together causing breakage.

Origin Traceability

The first step in breakage analysis is determining the origin or location where the breakage was initiated. The location of the break origin can often be determined if pieces of the broken light can be retained or reassembled into their pre-break orientation. Lines of fracture called “Wallner Lines” begin at the origin and radiate along break branches. When breakage occurs due to poor or damaged edges, the break origin will be at the edge of the glass where the damage was present. The direction of fracture can be determined by examining the lines on the fracture face as shown by the three different examples on the following page.

Whether annealed, heat strengthened, full thermally tempered, or chemically strengthened, regardless of failure mode, breaks always project into the concave face of these markings. The three samples in Photo 1 all broke from the left to right direction as shown.

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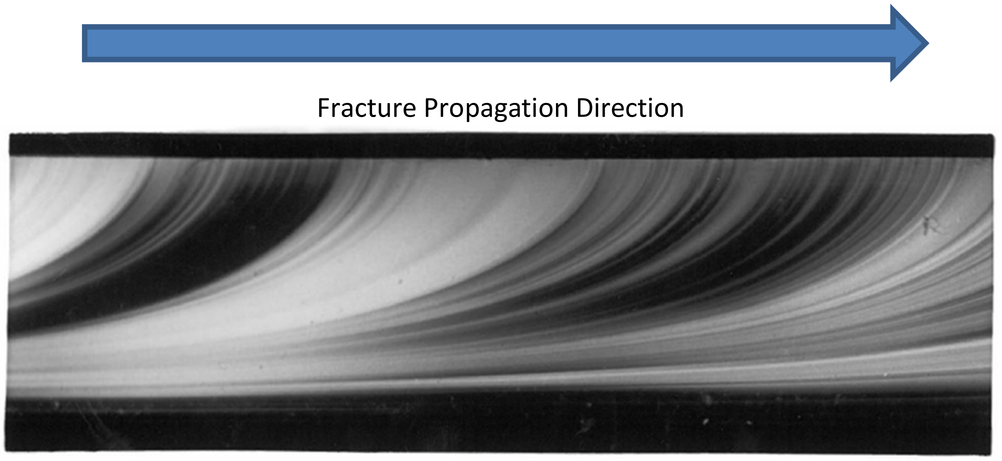

Photo 1A. - Fracture Face Produced by Bending (Edge View)

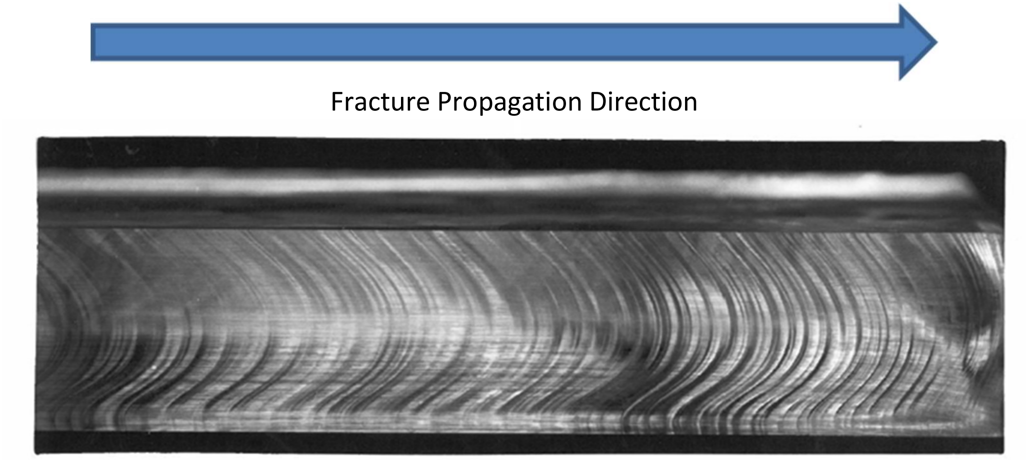

Photo 1B. – Fracture Face Produced by Temperature Difference (Edge View)

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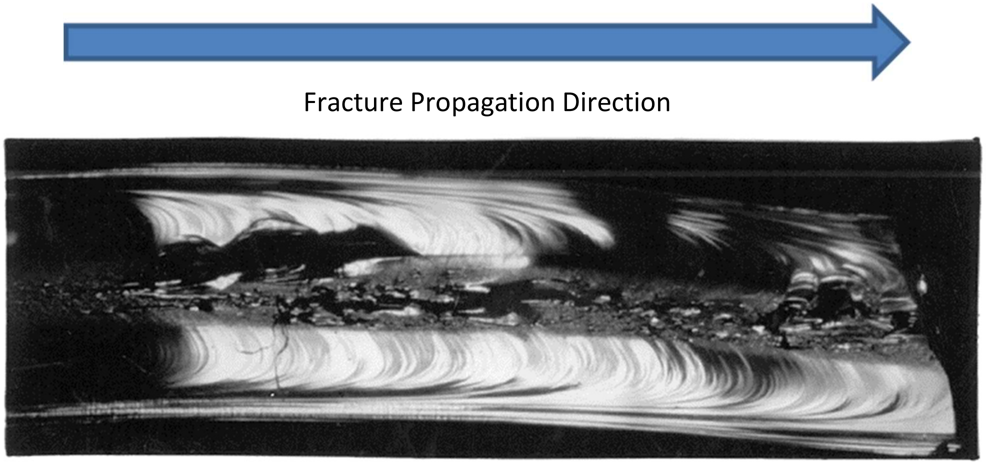

Photo 1C. – Fracture Face of 7/32" Full Tempered Glass (Edge View)

Note: The break fracture face does not always reveal break line markings as distinct as those shown in the previous Photos, particularly with low tension stress bending breaks below 1500 psi (10.4 M Pa) that are typical of damage frequently seen due to scratches, digs, chips and crush. However, the break line markings are usually sufficient somewhere along the fracture face of a broken section of glass to determine the direction of break propagation.

By examining fracture line direction on the edges of individual pieces, a diagram can be made like the example shown in Figure 1.

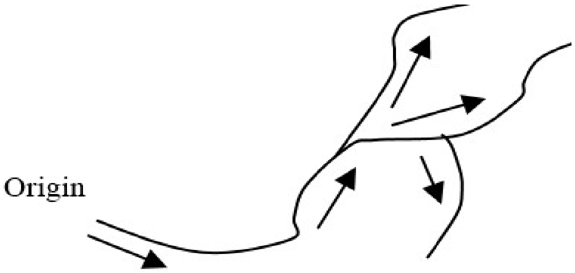

Figure 1 - Fracture Line Direction (Surface plan view)

The origin can then be obtained by:

1. Drawing arrows to indicate fracture line direction. These arrows point into the concave face of break wave markings in the edge.
2. Tracing point-to-tail of arrows back to the break origin.

Once the origin is established, the mode of failure can often be determined by making a few observations of the glass immediately surrounding the source of breakage.

Failure Modes

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Thermal Stress

Thermal stress breaks normally originate at the edge of glass and form near 90° angles with both the edge and surface of the glass. Figures 2A and 2B illustrate two typical break patterns associated with thermally stressed glass. These thermal modes of failure can be further defined into high and low tension stress categories.

Low thermal stress breakage is indicated by a single break line starting from the origin at the edge and propagating ~ 2 inches (5 cm) or more before branching into more break lines. Low stress thermal breakage often occurs due to damaged glass edges.

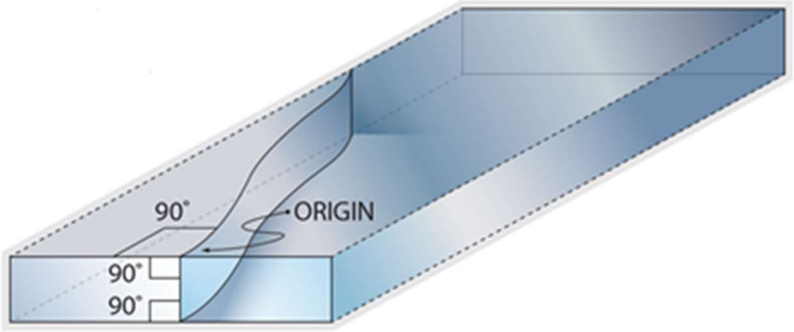

Figure 2A. – Low Stress Thermal Break

High thermal stress breakage is indicated by the single break at the origin branching into more breaks within 2 inches (5cm) of the edge. This indicates surrounding conditions and/or glazing conditions are causing high thermal stress. (e.g. severe outdoor shading on portions of the glazing, heating registers located between glass and indoor shading devices, closed, light colored drapes located within 2 inches of the glass, glazing in massive concrete, stone or other such framing, etc.).

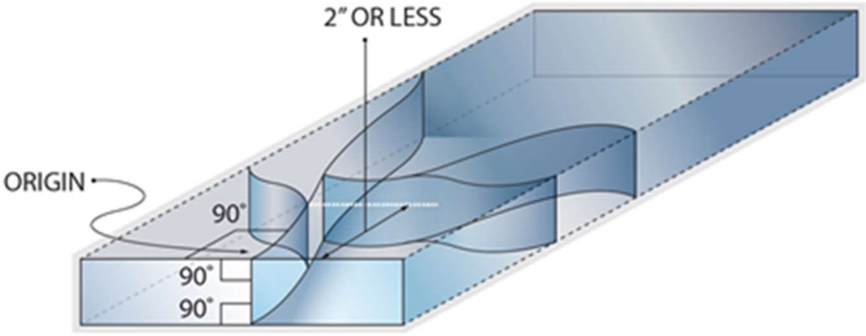

Figure 2B. – High Stress Thermal Break

Note: In architectural glazing applications, the potential for thermal breakage increases with colder temperatures and particularly, but not necessarily, when combined with sunshine.

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Vitro's *Technical Document, TD-109 Thermal Stress Update* discusses thermal stress and thermal stress analysis in much more detail. Vitro also provides an on-line thermal stress calculator which can be found at: http://technicalresources.vitroglazings.com/thermalstress/

Mechanical Stress

Another encountered mode of failure is that of mechanical applied tension stress. As indicated in Figure 3, the break origin is not 90° to the edge of the glass therefore this is a tension break from bending. Furthermore, this break propagates more than two inches as a single line fracture from the origin pointing to a low stress break. Low stress, mechanical tension breaks often occur from bending at less than 1,500 psi (10.4Mpa).

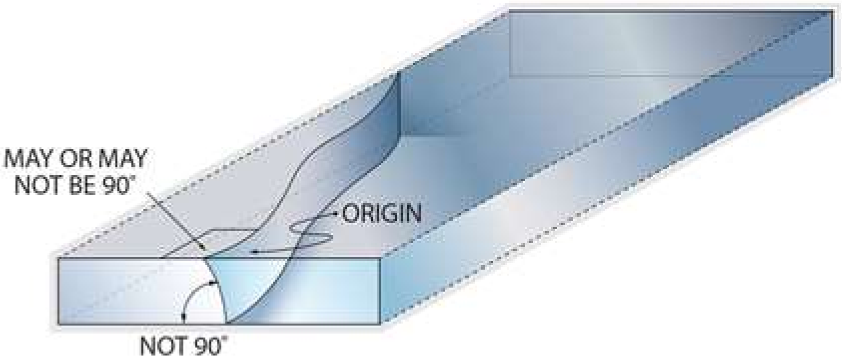

Figure 3A. – Low Stress Tension Break

This is the type of breakage most experienced by residential window and I.G. unit manufacturers. The origin is located at damaged areas of the edge or surfaces near the edge such as crush, digs, scratches, or chips. In many cases, breakage from damaged glass occurs after the initial edge damage occurred, such as in I.G. unit stacks, sashing operations, or later, after the window has been installed. Examination of the origin can reveal scratches, digs, crush, chips, or weak edges due to poor cutting demonstrated by deep shark teeth or serration hackle at the edge. Refer to Vitro *Technical Document 119 - Cut Edge Quality* for more information.

Lastly, high stress mechanical breaks are typically the easiest to identify as multiple fractures emanate from the point of impact in a spider web fashion. The breakage pattern, shown in Figure 3B, is a tell-tale sign that either the glass edge or surface has been struck with a foreign object with a high level of force.

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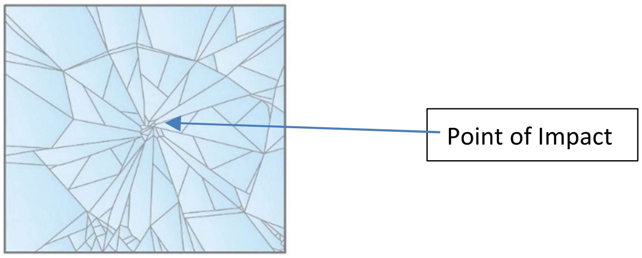

Figure 3B. – High Stress Mechanical Tension Break

Stress Estimation using Crack Propagation Velocity Characteristics

Note: Using a powerful point source of light with a 7 to 10 power magnifier (e.g., Bausch & Lomb Measuring Magnifier, Catalog No. 81-34-35) will be required for the following definitive break origin analysis techniques.

A crack propagates itself through glass with increasing velocity as it moves away from the origin. The photo below defines three appearances commonly encountered.

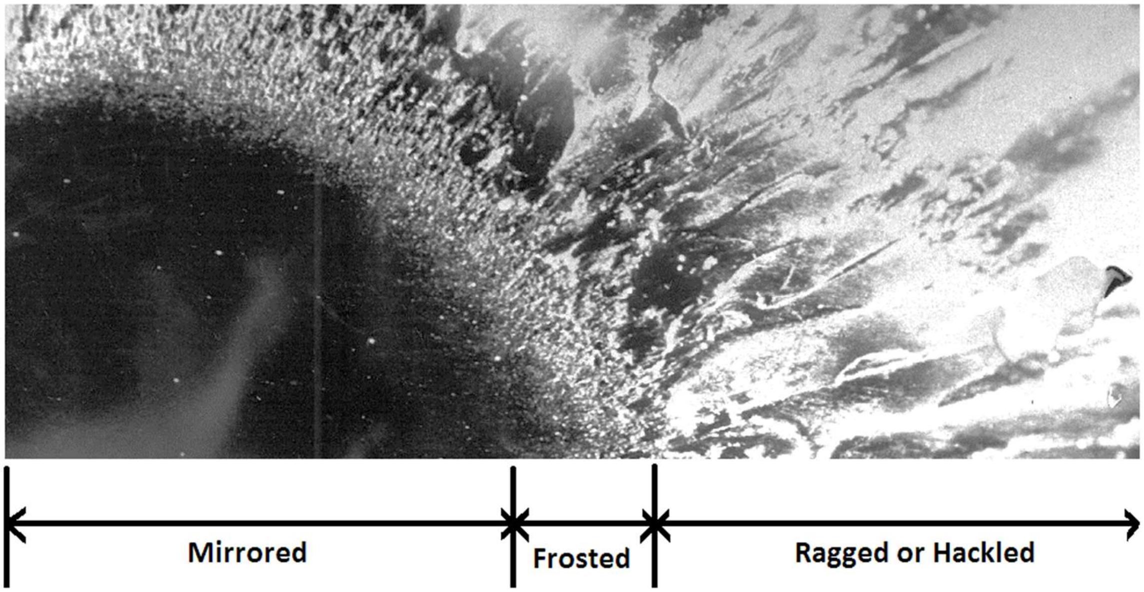

Photo 2. – Fracture Face (Edge View)

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Near the point of origin, the fracture face is smooth and mirror-like (crack velocity low), but as the propagation velocity increases with higher tension stress, the fracture face appearance becomes frosted (in a band), then ragged or hackled. Branches develop in the ragged area and the sequence starts again. The mirror radius of the fracture origin is defined as the radius of the smooth portion of the fracture face as measured 90̊ from the direction of the applied tension stress.

Analyzing the mirror radius of the break origin can provide an estimate of the tension stress level that caused failure in addition to possible causes of the breakage. Mirror radii (R), present themselves in a variety of fashions as seen in Figures 4A and 4B.

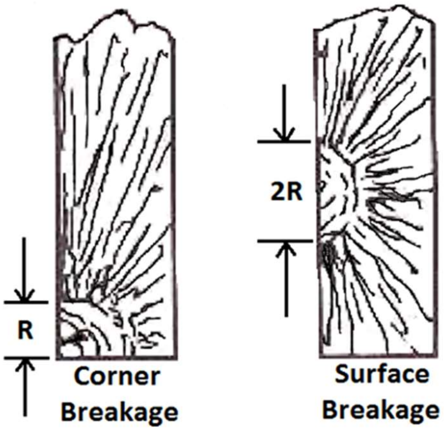

Figure 4A. – High Stress Mirror Radii

The two sketches in Figure 4A show break origins from high tensile stresses, e.g., bending or thermal stress breaks. When high tension stress breaks originate on a surface, the smooth area includes a double quadrant (second sketch from left). The mirror radius is one-half the smooth fracture face which is shown as 2R in the sketch.

The two sketches of Figure 4B illustrate break origins caused by bending. Keep in mind that fracture face appearance may be entirely different, because in bending, the stress varies across the thickness of the glass approaching zero at the neutral axis. For high stresses causing breakage, the smooth area mirror radius is small.

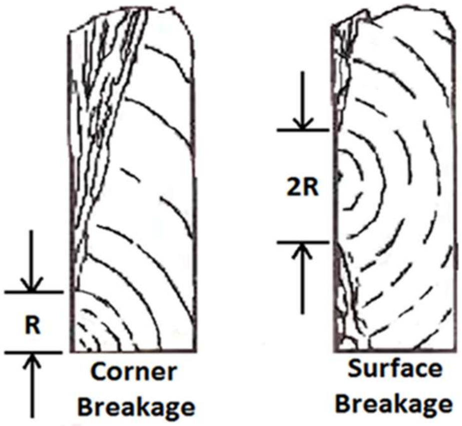

Figure 4B. – Low Stress Mirror Radii

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For thinner glass or as the breaking stress is low, the smooth area of the mirror radius extends deeply into a lower tensile zone. The smooth area is radial and the mirror radius is larger. The two sketches of Figure 4B represent the break origins of thin glass breaking at low bending stresses. A smooth fracture face forms across the entire side of the break origin. For edge breakage, a single frosted wedge is formed, for surface breakage; a double frosted wedge is evident.

Note: Mirror radius is independent of glass thickness.

A relationship has been established between the radius of the mirror surface of the origin and the tensile stress that caused the breakage. This relationship is known in the industry as Vitro/Orr's Equation. For Vitro float processed glass, the relationship between breaking stress and the mirror radius can also be expressed using the following equation or graph where R, as shown in the figures above, is measured in inches:

$$\sigma_{stress} = \frac{1950}{\sqrt{R}}$$

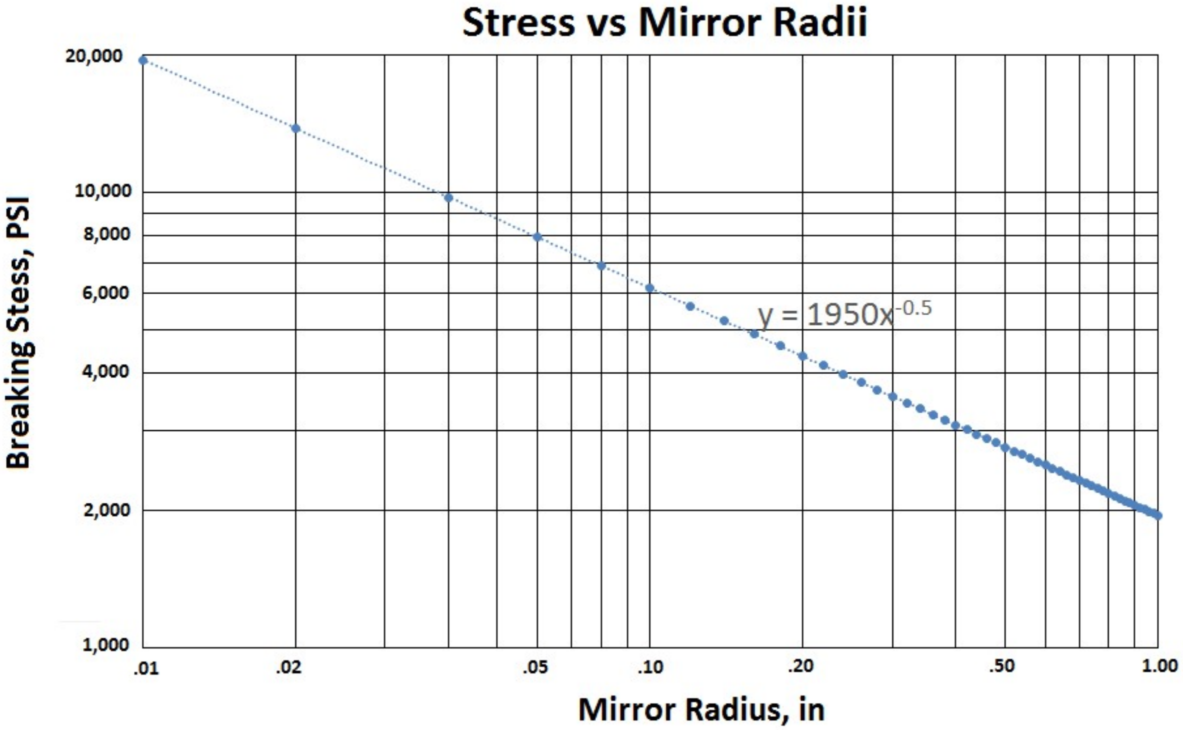

Figure 5. – Stress to Radius Relationship

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Photograph 4 shows an example of the break origin and the mirror radius of the break origin at the corner of a 1/4-inch (6 mm) thick glass.

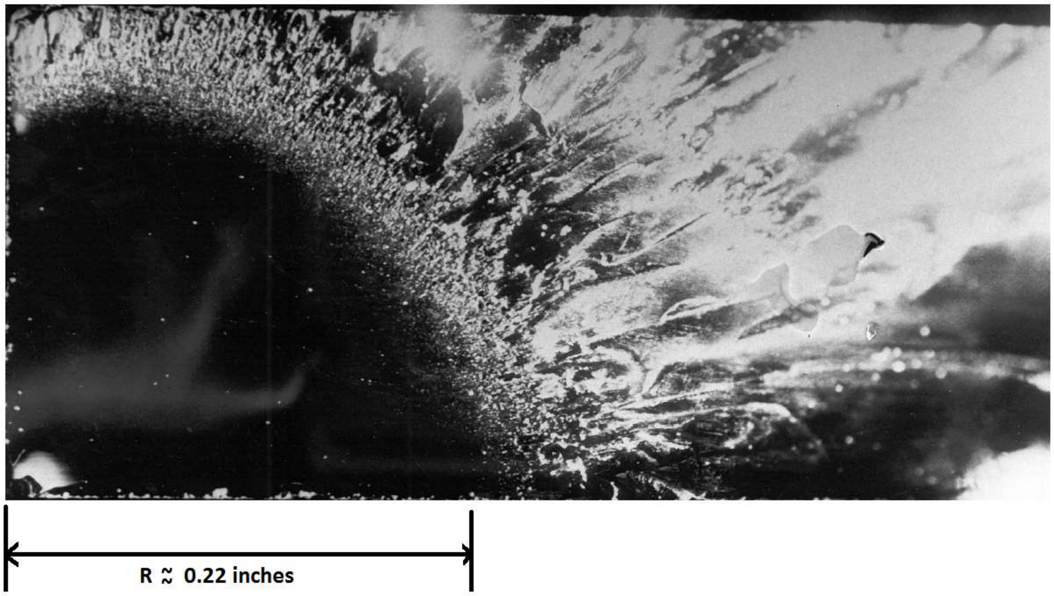

Photo 4. – Mirror Radius (Edge View)

$$\sigma_{stress} = {}^{1950}\!/_{\sqrt{R}} = {}^{1950}\!/_{\sqrt{0.22}} = 4{,}157 \approx 4{,}200\ PSI$$

Using the methodology outlined above, this break appears to have occurred at a high breaking stress of approximately 4,200 psi (29 MPa). This is an example of a tension stress break possibly with high thermal load. The breaking stress level of 4,200 psi also indicates that the glass edges were of relatively good cut edge quality and no edge damage was present. See Vitro *Technical Document 119 - Guidelines for Cut Edge Quality* for more information.

Fracture origin analysis is a definitive methodology to take the "mystery" out of glass breakage. Much of the information presented here relates to distinctive features associated with breaking stresses greater than 1,500 psi (10.4 MPa). With high breaking stresses, fracture face markings, break direction, location of the origin, and mirror radius analysis are more evident and provide accurate, detailed information about the cause of breakage. Conversely, less definitive or less evident fracture face markings, break direction, location of the origin, and mirror radius suggests low breaking stress which is normally the result of pre-existing glass damage.

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Thermal Stress Impact of Fired Ceramic Enamel and Silver Frit

Additional tension stresses can be induced when a substrate is coated with a fired ceramic enamel or frit. This stress can be due to a Coefficient of Thermal Expansion (CTE) mismatch between the glass and frit or incompatible viscoelastic behaviors. The frit expands or contracts faster than the glass substrate when heated or cooled, resulting in stresses that may push either past their breaking points. This tension stress can reduce the glass basic strength as much as 40% for enamel frit and 70% for silver frit. Care should be taken to closely match the CTE (as determined by ASTM E831) of the frit to that of the substrate glass. An approximation of stress induced can be found using the methodology below:

Residual stress induced between two layers in a system can be modeled as:

$$\sigma_A = \frac{1}{\delta_A}\left(\frac{1-v_A}{\delta_A E_A} + \frac{1-v_B}{\delta_B E_B}\right)^{-1} \cdot \int_{T_o}^{T_1} (\alpha_B(T) - \alpha_A(T))\delta T$$

Where,

$$\sigma = Stress\ on\ the\ frit \qquad E = Young's\ modulus$$

$$\upsilon = Poisson's\ ratio \qquad \alpha = CTE \qquad T = Ambient\ Temperature$$

(The subscripts A and B refer to the frit and substrate respectively)

Assuming the substrate is much thicker than the frit and the CTEs are linear, this equation simplifies to:

$$\Delta\sigma_A = \frac{E_A \Delta T(\alpha_B - \alpha_A)}{1 - v_A}$$

For Vitro float glass,

$$\alpha_B = 8.6\ x\ 10^{-6}\ °F^{-1}\ \ (4.8\ x\ 10^{-6}\ C^{-1})$$

Entering material properties given by the frit manufacturer into this equation will provide a reasonable estimate of the stress on the frit. The magnitude of stress on the glass will be the same but in the opposing direction. There are two additional methods or experiments that can determine the compatibility of the frit to the glass substrate. Measuring the stress in the glass at the frit/glass interface and conducting concentric ring tests with the enamel and comparing it to the basic strength of glass. Photo 8 is an example of a high stress thermal break originating at the glass/frit interface.

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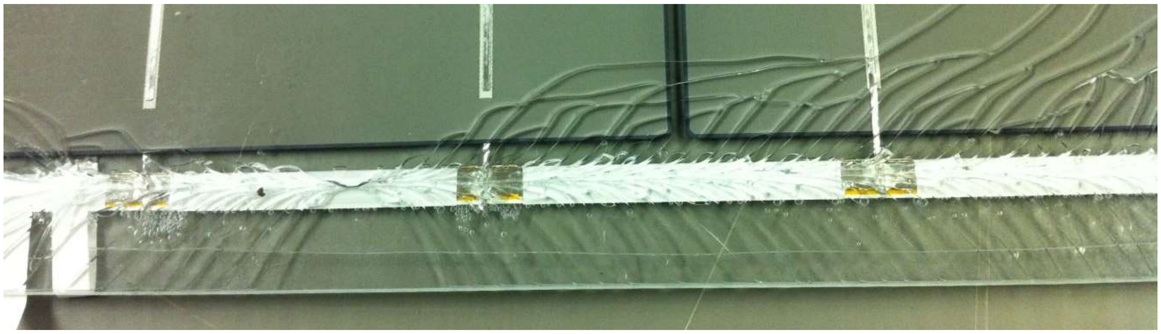

Photo 8. - Thermal Breakage at Frit

Further sources of breakage and additional information are available through Vitro's Technical Services department.

REFERENCES:

1. Vitro Technical Service Report #130 - Installation Recommendations Tinted and Reflective Glass.
2. Leighton Orr - Practical Analysis of Fractures in Glass Windows - Materials Research and Standards, Volume 12, No. 1, American Society for Testing and Materials.
3. Vitro Thermal Stress Update, 1998.
4. Vitro Poster - Guidelines For Cut Edge Quality

Additional Suggested Reading for engineering practice of scientists and engineers:

1. Fractography of Ceramics and Glasses, George D. Quinn, National Institute of Standards and Technology Recommended Practice Guide, SP 960-16, 2007

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HISTORY TABLE		
ITEM	DATE	DESCRIPTION
Original Publication	December 1995	
Revision #1	1/15/2002	Revised & transferred to TD-110
Revision #2	9/9/2014	Updated header on pg. 2
Revision #3	9/7/2016	Improved photographs and figures; added CTE discussion and various other text updates.
Revision #4	10/04/2019	Updated to Vitro Logo and format
Revision #5	1/24/2019	Updated the Vitro Logo and format
Revision #6	5/7/2019	Update to description of some photos and figures.
Revision #7	12/17/20	Removed reference to TD-111.