THE IMPORTANTANCE OF DETAILED FRACTURE ANALYSIS TECHNIQUES TO CORRECTLY EVALUATE BOTTLE BREAKAGE

by
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INTRODUCTION

Fracture analysis techniques are a set of skills and procedures that are critical to determine the cause of failures of food/beverage containers, pharmaceutical glassware, cosmetic containers, glass decorative items, windows, and other glass items. These procedures have been developed and advanced by notable glass scientists such as F.W. Preston, J.B. Kepple, J.S. Wasylyk, R. C. Bradt, G. D. Quinn, and others. Fracture analysis techniques are commonly accepted and are documented in:

ASTM C1256 Practice for Interpreting Glass Fracture and Surface Features;

ASTM C1678 Fractographic Analysis of Fracture Mirror Sizes in Ceramics and Glasses;

ASTM C1322 Fractography and Characterization of Fracture Origins in Advanced Ceramics; and

NIST #960-16 Fractography of Ceramics and Glasses.

Fracture analysis techniques generally consist of:

a. An evaluation of the fracture pattern in order to determine the load that resulted in breakage.

b. Examination of the fracture pattern and surface markings to determine the location of the fracture origin and position relative to the original glass surface (i.e. inside, outside, or buried).

c. An identification of the type and severity of the flaw at the fracture origin.

d. A conclusion stating if the breakage was due to the tensile stress magnitude, the severity of the flaw at the fracture origin, or a combination of both.

Additionally, these techniques can be further divided into a “Cursory Fracture Analysis” and a “Detailed Fracture Analysis”. Cursory Fracture Analysis generally is limited to an examination of the fracture pattern (see item a above). Detailed Fracture Analysis is much more comprehensive (see items a-d), and provides significantly more useful information.

For example, a cursory fracture analysis, in which only the fracture pattern is examined, can provide some useful information as shown in Figure 1:

> Sample A1 is typical of an internal pressure failure with a sidewall origin;
> Sample F2 is typical of an impact with an origin at the heel bulb; and
> Sample H2 is typical of breakage due to a thermal shock load.

Furthermore, the intensity of the fracture pattern can often provide qualitative information concerning the magnitude of the load. In Figure 2 for bottles broken under the action of an internal pressure load with origins in the sidewall, sample A1 has a much shorter vertical fracture and more forking than B1. This shows that the magnitude of the internal pressure was much greater for A1 than for sample B1.

The overall aim of fracture analysis is to determine the corrective actions needed to resolve a breakage problem. An erroneous corrective action will likely not alleviate the problem and, may even adversely affect ongoing production. Therefore, Detailed Fracture Analysis is usually needed to identify the cause of failure and to indicate the appropriate corrective actions. Summarized in the following sections of this report are examples illustrating the importance of undertaking Detailed Fracture Analysis to solve breakage problems.

DISCUSSION OF EXAMPLES

I: When the Fracture Pattern is Insufficient to Determine the Cause of Failure even if the Load is Known.

<u>Similar Fracture Patterns With Different Origin Locations</u>

While the fracture patterns of various items may be identical, there can be entirely different fracture origin locations and flaw types.

Samples A1 and B5, as shown in Figure 3, exhibit classic internal pressure fracture patterns. It is clear from a cursory understanding of internal pressure breakage, that the fracture origins of both bottles are located between the crack branching in the vertical portion of the sidewall fractures.
Close examination of the markings on the fracture surface reveals important differences. Sample A1 failed at an outside surface fracture origin, while sample B5 failed at an inside surface origin. This information is critical to solving the breakage issue since outside surface flaws can be due to bottle manufacturing conditions or to damage from subsequent handling of the item from bottle manufacturing, through filling, to usage. The sources of inside surface flaws are more commonly related to glass manufacturing issues.

As shown in Figure 4, samples E2, E3, and E4 exhibit the classic "D" shaped fragments from the bottom of the container, which is a fracture pattern that is typical of internal pressure breakage. However, only by examination of the fracture surface markings, can the precise location of the origin be determined. For example:
E2 has a fracture origin at damage (scratch) located at the center bottom area;
E3 has a fracture origin at a defective baffle/blank seam near the bearing surface; and
E4 has the fracture origin at a damaged knurl in the bearing surface.

Thus, while the fracture patterns were identical and caused by the same load (internal pressure), the flaws responsible for the failures were entirely different and unique. Specifically: the flaws at the fracture origins of E4 and E2 were due to abusive, improper handling; while the flaw at the fracture origin of E3 is a glass manufacturing defect.

Similar Fracture Patterns with Different Breakage Modes

While the fracture patterns of various items may be similar, there can be entirely different causes of failure, often referred to as "breakage modes".

Samples H1 and H2, as shown in Figure 5, both exhibit somewhat similar fracture patterns consisting of a long, vertically aligned crack in the sidewall. While the general fracture patterns indicate that both bottles failed as the result of thermal shock, the fracture origin location and flaw type are not apparent. Detailed fracture analysis established that the fracture on H1 originated at small check in the heel area. The fracture on H2 originated at damage located in the sidewall, that may have been created well after the glass manufacturing operation. The actions that are required to solve these breakage issues are unique and involve correction of a forming defect (H1) and a handling issue (H2).

Samples F1 and F2, shown in Figure 6, exhibit somewhat similar fracture patterns consisting of a number of fractures traveling outward from a single point in the heel contact region. These patterns are consistent with bottles that have been impacted at the heel contact. However, the cause of breakage was unique for each bottle.

The fracture surface markings showed that all the fractures on F2 originated on the inside surface opposite the outside surface impact site. This fracture type is referred to as the "flexure" mode of impact failure. The flaw is most likely due to a glass manufacturing related problem that significantly decreased the strength of the inside glass surface.

By comparison, sample F1 exhibited a somewhat similar fracture pattern except that there was an additional fracture that radiated across the bottom. The surface markings revealed that the primary fracture originated on the outside glass surface in the bearing surface region. The primary fracture traveled across the bottom and also upward to the impact site. This is commonly termed the "bearing surface hinge" mode of impact failure.

Samples F4 and F3, shown in Figure 7, exhibit somewhat similar fracture patterns which are characteristic of an impact applied to the mid-sidewall area of the bottles. However, close examination revealed that the fracture on F4 originated on the inside surface at the impact site (termed flexure impact breakage as noted previously). Examination of the fracture pattern on sample F3 revealed a second fracture system to the left side of the impact site. The primary fracture originated on the outside surface at this second fracture system. This is referred to as the "sidewall hinge" mode of impact failure. While these two samples exhibited somewhat similar fracture patterns, the two samples broke due to two entirely different failure modes. Additionally, there were different flaw types at the fracture origins, requiring different corrective actions.

II: When the Fracture Pattern Alone is Insufficient to Determine the Cause of Failure, Especially if the Load is Unknown.

Examples of Similar Patterns with Different Failure Types

As shown in Figure 8, samples G1, G3, and G6 exhibit nearly identical fracture patterns consisting of the bottom separated in one piece from the remainder of the bottle. However, a detailed fracture analysis reveals some critical differences in the cause of these three failures.

Sample G1 was a bottle which contained a carbonated soft drink. The fracture originated on the inside glass surface at the junction of the sidewall and bottom. This is a classic internal pressure failure with an inside knuckle origin. The primary cause of this failure was a severe flaw that is usually forming related.

Sample G3 was used for a cold filled, non-carbonated juice product that was pasteurized. This bottle failed as the result of a thermal shock load in which the inside surface was much cooler than the outside surface, a situation referred to as "reverse thermal shock". The origin was located on the inside surface at a manufacturing flaw.

Sample G6 was a bottle which contained a carbonated product. The fracture surface markings were moderately intense and showed that the fracture originated on the outside surface in the heel. The location of the fracture origin was inconsistent with internal pressure as the breaking load, since internal pressure stresses are typically minimal on the outside surface at the heel. Furthermore, this bottle would not typically experience significant thermal shock loads or heel impact loads. Thus, an alternative load must have acted on the bottle at the time of failure.

Detailed fracture analysis indicated that the bottle failed under the action of a force applied to the center portion of the bottom rather than the bearing surface, as normally intended. This force is referred to as a "bottom vertical load". Due to the unusual application of the force, much higher than expected bending stresses were created on the outside surface of the heel area. The cause of failure was an improperly applied force to the bottom, that most likely occurred during capping.

While these three samples exhibited similar fracture patterns, the type of the applied load, the fracture origin locations, and the ultimate causes of breakage were significantly different. Therefore, different corrective actions were needed to remedy the breakage issue.

As shown in Figure 9, samples F4 and I2 exhibit somewhat similar fracture patterns. This similarity could mistakenly indicate a common cause of failure. However, detailed fracture analysis indicated otherwise.

Sample F4 exhibited a number of cracks originating from a single point on the inside surface underneath the impact site. This is the “flexure” mode of impact failure having an inside origin, as previously discussed. The corrective actions would be to identify and eliminate the inside surface flaws.

Close examination of sample I2 showed that the fractures originated on the outside surface at the center of the fracturing. The fracture pattern and forking generally resembled a flexure impact failure, but from an impact to the inside surface with a flaw on the outside. This is a type of “hydrodynamic” breakage resulting from inappropriate rough handling of a filled, vacuum packed product. The handling problem caused a bubble to form within the liquid product which then collapsed on the inside surface, creating a tensile stress on the outside surface. The analysis showed that the flaw was not excessively severe. This information showed that the magnitude of the applied load was excessive and the primary cause of failure. The corrective action would be improved handling.

FIGURE 1
Basic Fracture Patterns

A1
Internal Pressure
Sidewall Origin

F2
Impact
Sidewall Origin

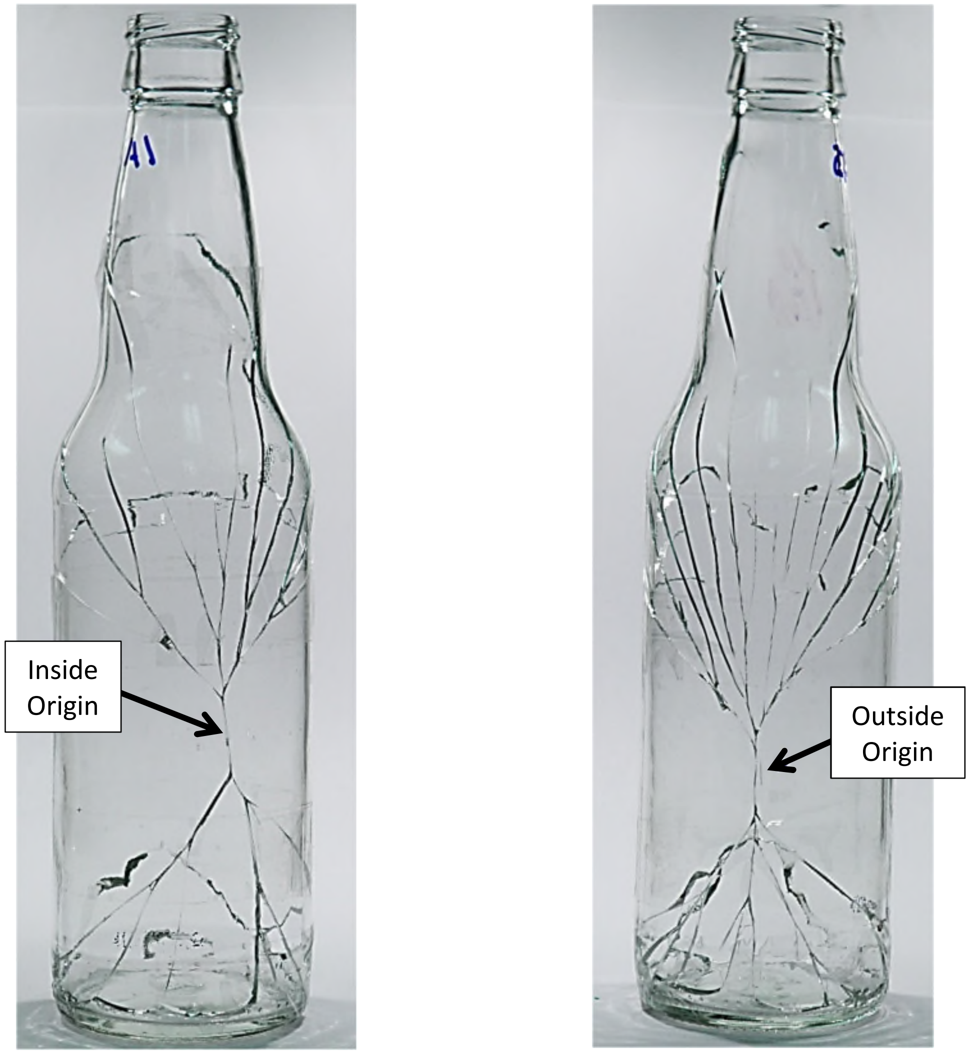
H2
Thermal
Sidewall Origin

FIGURE 2
Comparing Fracture Patterns to Evaluate Magnitude of Load

A1
Short Initial Split
High Load Level

B1
Long Initial Split
Low Load Level

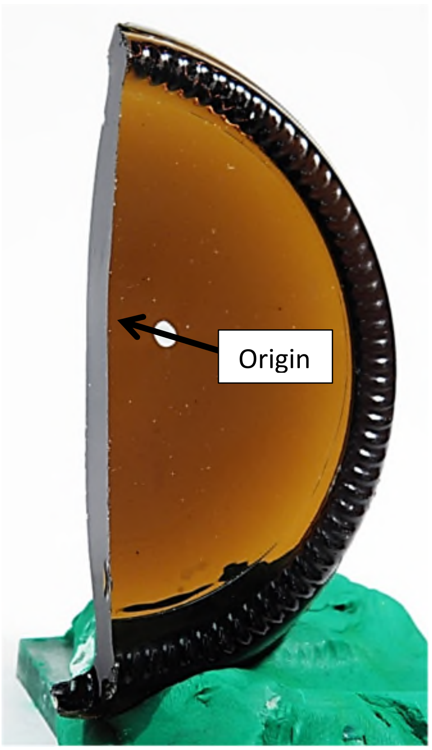
FIGURE 3
Similar Fracture Patterns with Different Origin Locations



A1
Internal Pressure
Inside Surface Origin

B5
Internal Pressure
Outside Surface Origin

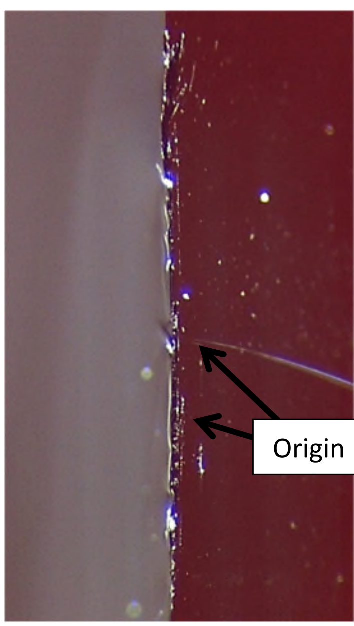
FIGURE 4
All Internal Pressure
Similar Fracture Pieces with Different Origin Locations/Types



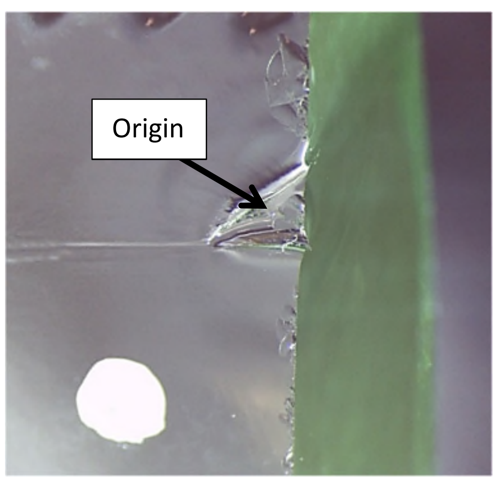
E2

E3

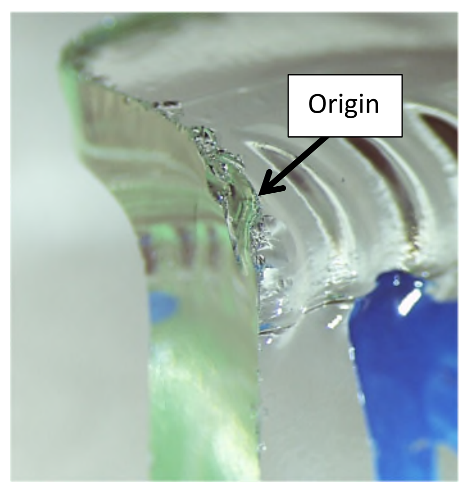
E4



Bottom Origin
At Scratch



Bottom Origin
At Baffle/Blank



Bearing Surface Origin
At Damaged Knurl

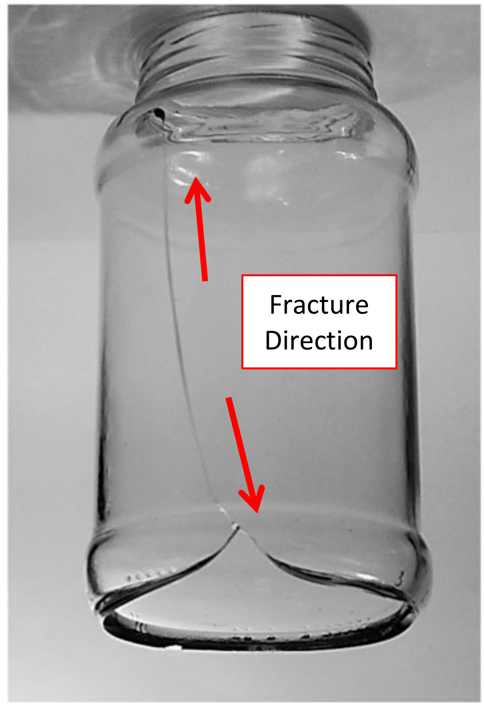
FIGURE 5

Fracture Patterns That Do Not Show Origin Locations

H1 – Thermal Shock with Heel Origin

H2 – Thermal Shock with Sidewall Origin

H1
Thermal Shock
Heel Origin



H2
Thermal Shock
Sidewall Origin

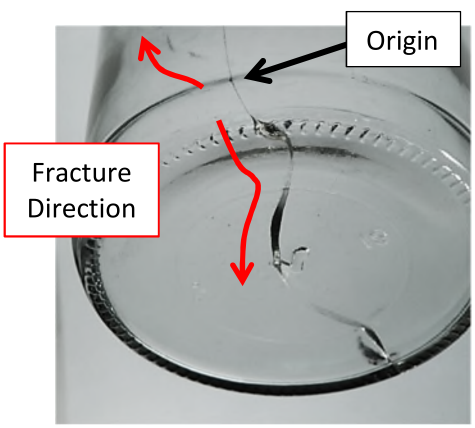


FIGURE 6

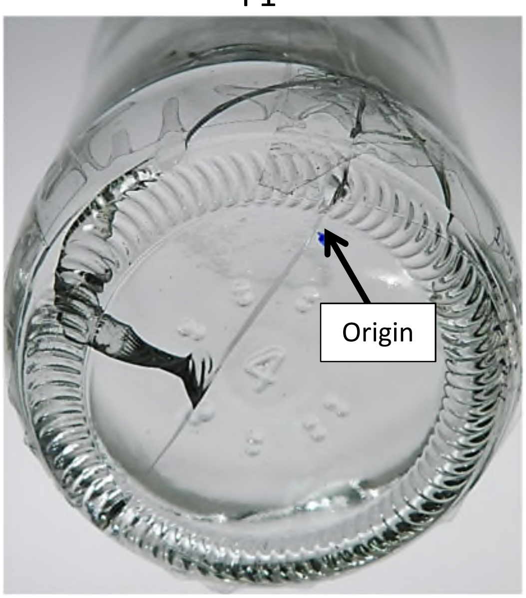
Similar Fracture Patterns with Different Breakage Modes

F1 – Bearing Surface Hinge

F2 – Flexure with Inside Origin

F1

F2 – Flexure at Heel Contact



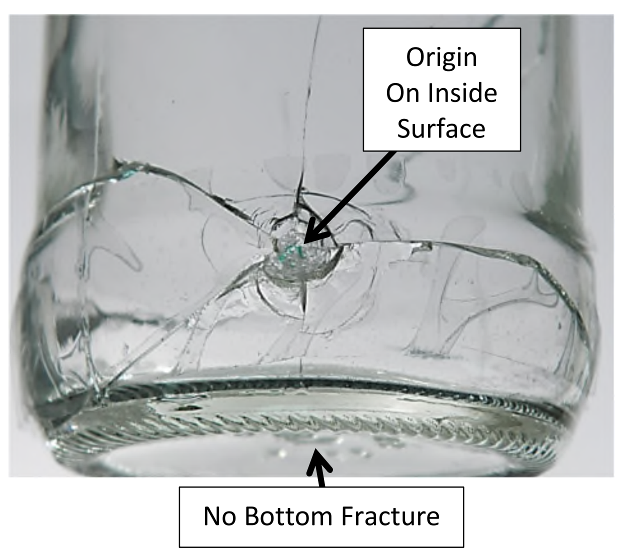
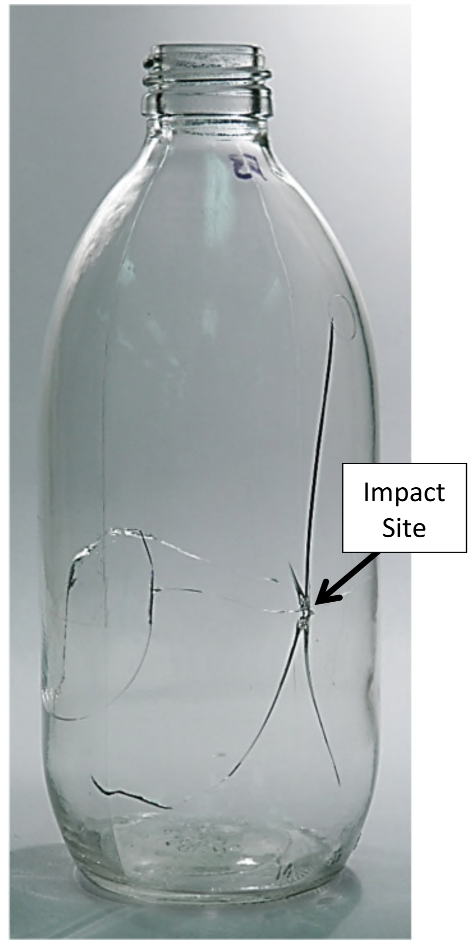
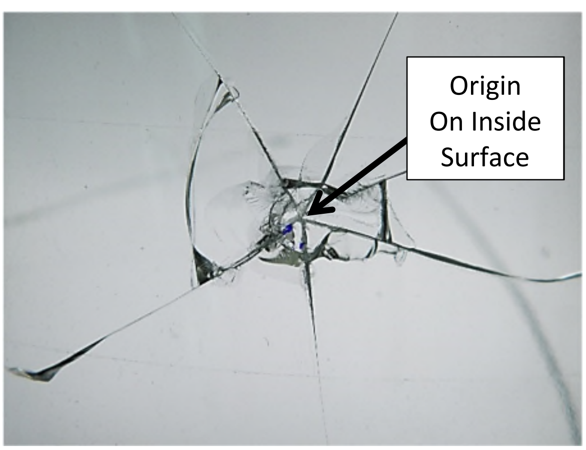
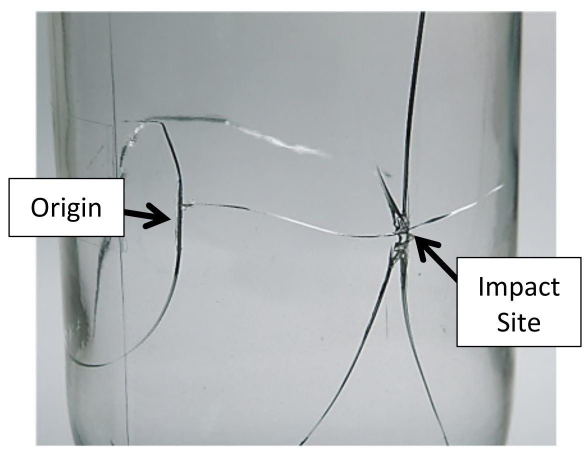


FIGURE 7
Similar Fracture Patterns with Different Breakage Modes
F4 – Flexure with Inside Origin
F3 – Sidewall Hinge with Outside Origin





F4



F3 – Sidewall Hinge

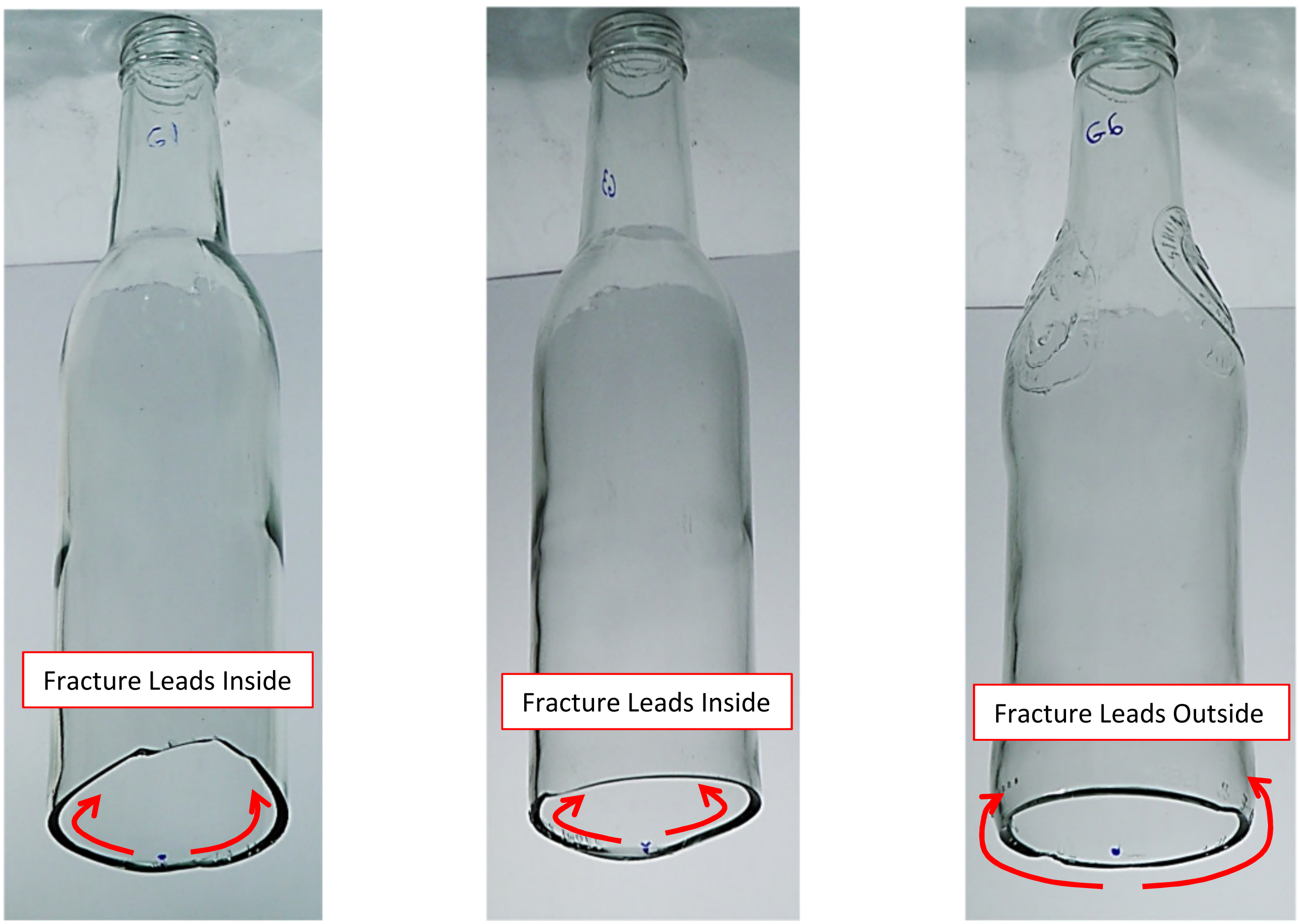
FIGURE 8

Similar Fracture Patterns with Different Breakage Modes

G1 – Internal Pressure with Inside Knuckle Origin

G3 – Reverse Thermal Shock with Inside Knuckle Origin

G6 – Bottom Vertical Load with Heel Origin



G1 G3 G6

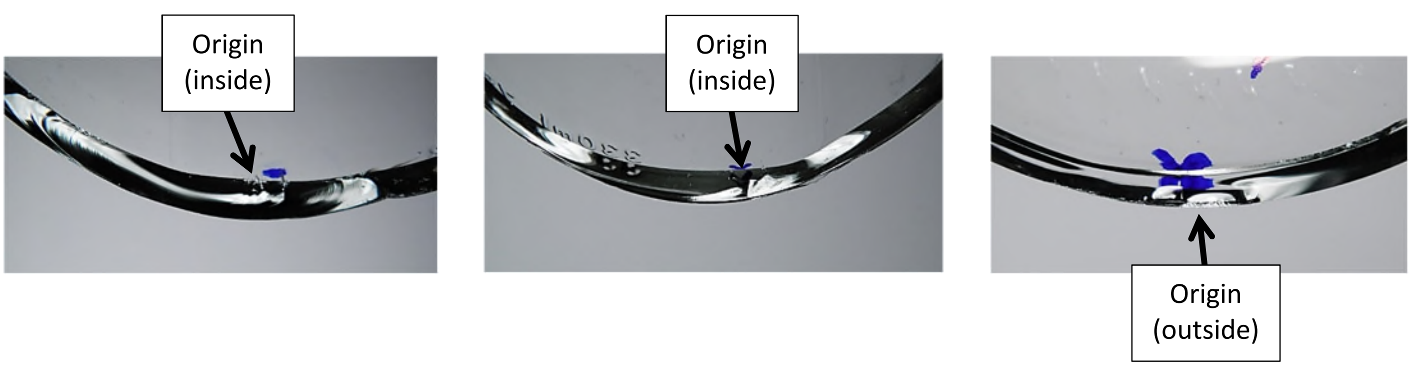
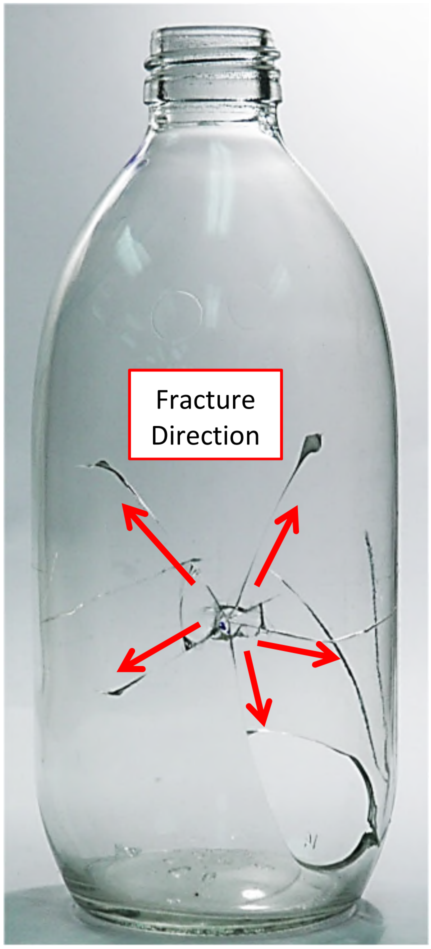


FIGURE 9

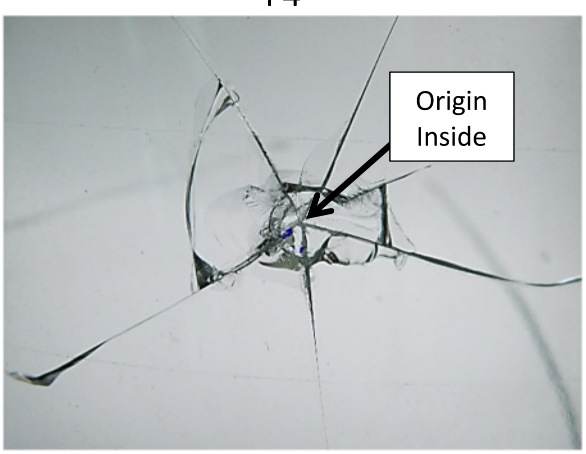
Similar Fracture Patterns with Different Breakage Modes

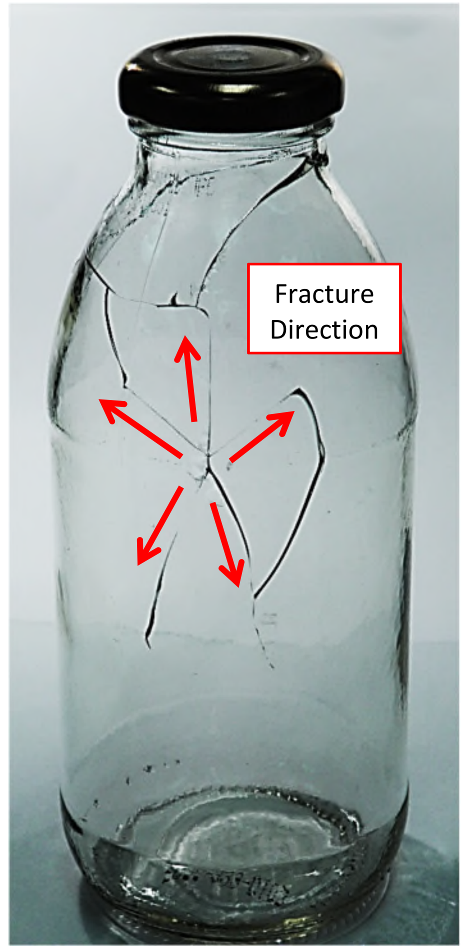
F4 – Flexure with Inside Origin

I2 – Hydrodynamic with Outside Origin



F4





I2