Shattering glass cookware

R.C. Bradt and R.L. Martens

The shattering of glass cookware in household kitchens has been reported in Consumer Reports articles, television documentaries, complaints to the United States Consumer Products Safety Commission and Internet postings. This article examines the issue from a three-fold technical perspective: (i) reviewing the reported scenarios of the incidents, which are suggestive of thermal stress fracture; (ii) comparing the thermal shock resistance of borosilicate glass with soda lime silicate glass; and (iii) examining new and broken glass cookware. Together, these related perspectives suggest the thermal stresses that develop during temperature changes are the primary cause of the explosion-like breakages. The substitution of higher thermal expansion soda lime silicate glass for borosilicate glass in the manufacturing is a contributing factor.

Exploding or shattering glass cookware surfaced as an issue of concern during the past two decades, and reports of problems have been chronicled in several news stories. Collectively, the accumulated complaints suggest that there may be a fracture problem with some glass cookware products. However, none of the coverage has specifically addressed the scientific aspects of the reported failures. This article examines the technical aspects of the sudden, explosion-like failure of glass cookware products.

Background

Corning Inc. pioneered the development and market for glass cookware. The glass cookware products originally manufactured by Corning were made of a low thermal expansion borosilicate glass eventually marketed as Pyrex. (Many glass scientists also associate the name Pyrex with the original borosilicate glass products. Even today, Corning still produces high-quality borosilicate laboratory glassware under the name and trademark of Pyrex.)

The original Pyrex cookware was promoted as “oven to icebox” or “icebox to oven” cookware, presumably because the low coefficient of thermal expansion of the borosilicate glass made it highly resistant to the thermal stresses that develop during these types of temperature changes.

Corning retains the Pyrex registered trademark, but, in 1994, the company began licensing other companies to manufacture products under the Pyrex brand (see “From battery jars to kitchens: A short history of glass cookware,” page 35). Today, the Pyrex brand is manufactured for consumer markets in the US, North America, South America and Asia by World Kitchens LLC (Rosemont, Ill.) under a license from Corning. A separate company, Arc International (Arques, France), manufactures and markets Pyrex brand cookware for the European, Middle East and African consumer markets. Independently, the Anchor Hocking Glass Company (Lancaster, Ohio) makes its own line of glass cookware, and has been doing so for many decades under its own brand names.

Compositions of glass cookware

According to the World Kitchens website, Corning changed to a soda lime silicate composition for the glass cookware, and this is the Pyrex tech-
technology that World Kitchens (then Borden) bought from Corning in 1998. World Kitchens acknowledges that the glass cookware it markets under the Pyrex brand name is made from a soda lime silicate glass composition.

On its own, Anchor Hocking developed a “me too” line of cookware that also is based on a soda lime silicate glass. These soda lime silicate glass cookware products appear to be commercial successes. However, they are not made of a low thermal expansion, thermal stress resistant borosilicate glass as originally developed by Corning.

Arc International produces a line of glass cookware products. These are of a borosilicate glass composition, which it markets with the phrase “Authentic Pyrex” on the label (Figure 1).†† The three companies that currently manufacture glass cookware—World Kitchens, Anchor Hocking and Arc International—use different silicate glass chemistry formulations. The authors confirmed this by examining the glass chemistry formulations used in the products from each of the three companies using energy dispersive spectroscopy on a FEI Quanta 200 3D scanning electron microscope equipped with an X-ray analyzer Model Apollo XVF from EDAX. The Arc International cookware was determined to be a borosilicate glass with a distinctive, readily identifiable boron peak. It evidently is the original Corning Pyrex composition.5 The tests confirmed, as expected, that neither the World Kitchens nor the Anchor Hocking products are borosilicate glasses, but are soda lime silicate glasses of slightly different compositions. The chemical spectra clearly show the boron peak in the Arc International glassware, but the World Kitchens and Anchor Hocking glassware are free of boron. They are distinguishable by their calcium and magnesium peaks.

**Indications of thermal stress fracture of glass cookware**

Before going further, two things should be noted. First, the manufacturers of soda lime silicate glass cookware claim that it has superior mechanical strength and is less likely to fracture on impact, for example by dropping it, a not unreasonable concern in kitchen settings. Second, because of the extensive handling of glass cookware, it is expected that surfaces will become damaged or scratched over time. With these provisos noted, the focus of the authors has been to isolate the effects resulting from thermal stress. What follows below focuses only on the thermal shock properties of the two glass types.

Generally speaking, thermal stress fracture of glass is not an uncommon event. For example, impingement of bright sunlight on a portion of large windows can cause them to crack from the shady cold edge, and cold water splashing on hot glass marine light covers frequently fractures them. Much is known and understood about thermal stresses and thermal shock fracture.11 The nature of the published reports of the shattering incidents with the soda lime silicate glass cookware suggests a thorough consideration of thermal stresses because the failure incidents are often associated with significant temperature changes.1–4

The documented and reported glass cookware incidents1–4 suggest that the thermal stress resistance of present day soda lime silicate glass cookware is less than that of low-expansion borosilicate glass, such as the original Pyrex. For example, some of the glass cookware items have been reported to fracture immediately on a change in temperature, while other cookware fractures occur during a short time after removing the cookware with its contents from a hot oven. (See Consumer Reports example, Figure 2.) Fractures that occur at a time interval after a temperature change, such as after removal of the cookware from a hot oven, are characteristic of thermal stress failures. However, there also are reports of failure while the cookware with its contents is inside the oven. These thermal gradients may have different origins, such as might develop during the baking of foods or the heating of the oven.
if frozen contents are placed in the cookware before being inserted into a hot oven.

As described in Introduction to Ceramics, by Kingery, Bowen and Uhlmann, delayed thermal stress fractures will often occur after temperature changes. This is because the maximum thermal stress is achieved only as a temperature gradient develops after the temperature change. That delay time for thermal stress fracture depends on the heat transfer conditions of the cookware and the heat capacity of the contents within. For example, preparing a roast, a chicken or a ham in a glass cookware dish would each have different heat capacities and present different heat transfer conditions, and the cooking temperatures of their surroundings would be different as well. Therefore, time delay intervals to fracture are expected to vary. The reports that the soda lime silicate glass cookware experiences these delayed shattering fractures suggests that the thermal stresses that develop exceed its strength.

The time dependence of thermal stresses is a function of the heat transfer conditions during the temperature change. These factors determine the magnitude of the temperature gradients and cause the thermal stresses. For example, transferring a hot dish containing a roast directly from the oven to a cold wet stone countertop would be a much more severe thermal shock than putting the same dish on an insulating pad surface.

Because it is impossible to consider all of the possible variations that might occur in household kitchens, a simple, linear elastic approach to a sudden temperature change is applied to estimate and compare the thermal stress resistance of the two glasses.

As noted in Kingery, Bowen and Uhlmann, the simple formula for the fully restrained development of a linear elastic thermal stress, $\sigma_{ts}$, from temperature change is

$$\sigma_{ts} = cE\Delta T$$  (1)

where $c$ is the coefficient of thermal expansion, $E$ the elastic modulus and $\Delta T$ the temperature differential over which the thermal stress or thermal expansion restraint is generated. The $\Delta T$ may occur during either heating or cooling. Note that this simple estimate does not include the heat transfer factors, nor time factors, nor does it account for the size and shape of the glass cookware pieces in question. Equation (1) is applicable to an instantaneous, rapid temperature change.

To compare the thermal shock fracture resistance of borosilicate and soda lime silicate glasses, Equation (1) is rearranged to express the $\Delta T$ values required to achieve fracture by the thermal stresses generated in the glass cookware during a temperature change. These $\Delta T$ values can be compared with typical cooking temperatures and other temperature changes that are regularly encountered in a household kitchen. Equating $\sigma_{ts}$ to the fracture stress of the glass, $\sigma_f$, then rearranging Equation (1) yields

$$\Delta T = \sigma_f / cE$$  (2)

where the thermal stress, $\sigma_{ts}$, is now $\sigma_f$, the failure strength of the glass object.

A typically used benchmark value for glass strength, as noted by Mould and also by Kurkjian is about 5,000 pounds per square inch (about 30 megapascals). The elastic moduli of the two glasses are slightly different, but similar—about 10,200,000 psi (about 68 gigapascals) for soda lime silicate glass and about 9,100,000 psi (about 62 gigapascals) for borosilicate glass. Their coefficients of thermal expansions are very different. The $\alpha$ of borosilicate is about $3 \times 10^{-6}$°C$^{-1}$, The $\alpha$ of soda lime silicate glass is about $9 \times 10^{-6}$°C$^{-1}$, about three times greater.

Substituting these values into Equation (2) yields the $\Delta T$ values of the rapid temperature change necessary to initiate thermal shock fracture. For borosilicate glass, the calculated temperature difference is about 183°C (about 330°F), but it is only about 55°C (about 99°F) for the soda lime silicate glass. This is a substantial difference.

Carter and Norton, in their text Ceramic Materials, Science and Engineering, use a somewhat more complicated
form of Equation (1) that includes heat transfer terms. They address many ceramics as well as glasses. Their results will be compared with the calculations of this simple approach. The $\alpha E A T$ term is common to all mathematical models.

Carter and Norton\textsuperscript{13} provide an example (which includes heat transfer terms), estimating thermal stress $\Delta T$ values for fracture that are about 270°C (about 486°F) for the borosilicate Pyrex and about 80°C (about 144°F) for soda lime silicate glass. Based on these two independent results, it is evident that the temperature differential—the $\Delta T$ for fracture initiation by severe thermal stress—is much larger for the borosilicate glass.

A brochure posted on Corning’s website\textsuperscript{17} presents thermal stress resistance estimates of several glasses of various compositions, including its 7740 borosilicate glass and a soda lime silicate glass (Corning 0080). The reported thermal stress resistance value for the borosilicate glass is 54°C (97°F), whereas that of the soda lime silicate glass is 16°C (29°F)—a factor of about three. Thermal stress resistance is defined for this calculation as “the temperature differential between two surfaces of a tube or constrained place that will cause a tensile stress of 0.7 kg/mm (1000 psi) on the cooler surface.”

It is important to note that, according to this brochure, the primary use of 0080 is Petri dishes, not household cookware. Also, it must be noted that soda lime silicate glass compositions vary widely, and values of thermal properties will vary, too. However, these data illustrate the magnitude of the difference in thermal stress resistance that is possible between the two categories of glasses. The superior thermal stress resistance of borosilicate glass for cookware was confirmed in empirical tests performed on glass cookware objects by Consumer Reports.\textsuperscript{1,2}

It is informative to compare the $\Delta T$ values that have been determined to achieve the fracture stress from the three calculations. Table 1 lists those for the soda lime silicate glass and for Pyrex borosilicate. This tabulation shows that in every instance the $\Delta T$ for the soda lime silicate glass is much lower than that for the borosilicate. The difference is about a factor of three times for each despite the differences in the calculations. This is because the thermal expansion of the soda lime silicate glass is about three times that of the borosilicate. Clearly, soda lime glass is much more susceptible to thermal shock than the borosilicate glass because of its higher thermal expansion of coefficient.

![Table 1](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAIgAAAGCAIAAADf0eZAAAAGXRFWHRTb2Z0d2FyZQBBZG9iZSBJbWFnZVJlYWR5ccllPAAAAySURBVHheF7TIAkAG1zalaAAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAWWAAf6wAAgAIAW...
example, fractures by dicing into small fragments. McMaster, Shetterly and Bueno\(^2\) depict this form of fragmentation in their review, and creation of these dicing fragments has been analyzed in detail by Warren.\(^3\)

The authors’ examination of fracture pieces of several dishes, including some that were intentionally broken by thermal stress and some by impact, revealed no dicing fragmentation. The soda lime silicate cookware consistently fractured into extended glass shards.

The large shards produced by the fracture of the soda lime silicate cookware imply that the thermal or heat strengthening of the soda lime silicate cookware was not substantive. Figure 3 illustrates a reconstructed “Pyrex” bowl that was purchased new and intentionally thermal shocked in a household kitchen. There is no evidence of dicing fracture. The occurrence of long sharp glass shards is also described in numerous reports on the Internet and in the CPSC literature.

Another tool for evaluating whether there is significant heat strengthening of soda lime silicate glass is fractography, which can reveal information about the stress state of a fractured piece. When a glass object with surface compressive stresses fractures, the propagating crack front in the glass proceeds ahead of the crack at the object surface because the near-surface advance is inhibited by the surface compressive stresses.\(^4\)

Indeed, the crack growth pattern on the fracture surface of shards of soda lime silicate glass cookware, as shown in Figure 4, indicates that the soda lime silicate glass has been heat strengthened. Note the Wallner line ripples on the cross section clearly are trailing at the glass surfaces, indicative of surface compressive stresses. (Wallner lines are slight ripples on a fracture surface that are indicative of the direction of crack propagation and the state of stress.)

Thus, although the cookware definitely has been heat strengthened as stated by the manufacturer,\(^1\) it does not appear to be sufficient to increase substantially the thermal stress fracture resistance of the cookware, nor is it sufficient to create a desirable dicing fracture pattern for the glass cookware.

Extensive, in-depth fractography of the fracture surfaces of shards from a large number or series of different reconstructed broken soda lime silicate cookware pieces would make it possible to identify the causes of individual failure events. Such studies, as described by Quinn\(^2\) in Fractography of Ceramics and Glasses, are recommended, but are beyond the scope of this article.

**Conclusions about shattering glass cookware**

The above analyses of shattering soda lime silicate glass cookware indicate that the phenomenological cause of these fractures is thermal stress fracture that develops from temperature changes to which the glass cookware is subjected in the household kitchen. This conclusion is substantiated by three observations: (i) occurrence of the shattering incidents during temperature changes; (ii) the frequent presence of a time delay to fracture initiation after a temperature change; and (iii) calculated temperature differentials, the \(\Delta T\) values for the initiation of thermal shock fracture during temperature changes of soda lime silicate and borosilicate glasses. In addition, the creation of fracture shards instead of desired dicing of broken pieces of cookware suggests that manufacturers’ heat strengthening is insufficient.

Fracture-initiating temperature differentials can be exceeded during household kitchen cooking. However, not all kitchen procedures create \(\Delta T\) values that are sufficient to cause thermal stress fracture of the soda lime silicate glass cookware. Time-dependent heat transfer conditions also will affect the magnitude of the thermal stresses that develop.

The original Corning Pyrex borosilicate glass is considerably more resistant to thermal stress fracture than the soda lime silicate glasses that currently are used for most glass cookware products in the US. The estimated \(\Delta T\) values for...
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thermal stress fracture of that borosilicate glass suggest that normal kitchen cooking temperatures are unlikely to cause thermal stress failures. However, the estimated ΔT values for thermal stress fracture of soda lime silicate glass cookware are well within the range of kitchen temperatures.

Estimates of the ΔT temperature differentials indicate that soda lime silicate glass cookware can be expected to survive moderate temperature changes that are experienced in a household kitchen. However, documented reports of incidents of dramatic shattering failures during what most kitchen cooks would consider normal use suggest that the margin of safety for avoiding thermal stress failures of soda lime silicate cookware is borderline. It does not appear to be adequate for all household cooking. Caution is in order when using soda lime silicate cookware in applications that may involve temperature changes, as print warnings on the product labels indicate.

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About the authors
R.C. Bradt is the Alton N. Scott Professor in the College of Engineering at the University of Alabama, Tuscaloosa, Ala. He presented an invited paper at ACGS Glass & Optical Materials Division meeting in 2011. He also has served as an expert witness in litigation cases involving glass cookware failures.

R. Martens is manager of the Central Analytical Facility at the University of Alabama.

Contact: rcbradt@eng.ua.edu

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