Solar Cooker Glass Failure Analysis

Peter Kolis
Junior, Mechanical and Aerospace Engineering
University of Dayton
Dayton, OH 45469-0238
kolispea@notes.udayton.edu

Andrew Haeck
Junior, Mechanical and Aerospace Engineering
University of Dayton
Dayton, OH 45469-0238

Robert Schlosser
Junior, Mechanical and Aerospace Engineering
University of Dayton
Dayton, OH 45469-0238

Paul Thomas
Junior, Mechanical and Aerospace Engineering
University of Dayton
Dayton, OH 45469-0238

Jeremy Kaczmarek
Junior, Mechanical and Aerospace Engineering
University of Dayton
Dayton, OH 45469-0238

Margaret Pinnell
Faculty, Mechanical and Aerospace Engineering
University of Dayton
Dayton, OH 45469-0238
Margaret.Pinnell@notes.udayton.edu

Abstract – The failure of a pane of glass from a solar box cooker made and used in Sabana Grande, Nicaragua, was analyzed to determine the cause of failure and to recommend possible solutions. Background research into solar box cookers, the environment in which the failure occurred, characteristics of glass and wood, methods of fractography, and glass cutting tools and methods was carried out. The type of glass used in the solar cooker was unknown, so the observable physical properties, an energy dispersive spectroscopic scan, and thermal analysis of the glass were used to identify the glass as soda-lime glass. The properties of the glass, the conditions of use, and an analysis of the fracture pattern and fracture surfaces were used to determine that the glass had been weakened by cutting processes and that the fracture occurred as a result of thermal stresses. Several recommendations were presented including altering the design of the solar cooker to provide more clearance for the glass panels, incorporating the use of improved glass cutting techniques and sanding the edges of the glass.

Index Terms – glass failure, solar cooker, glass cutting, thermal stresses

INTRODUCTION

Since 2001, Engineers in Technical Humanitarian Opportunities for Service-Learning (ETHOS) participants from the University of Dayton have worked with solar cookers in Sabana Grande, Nicaragua. The solar cookers are built and sold by Las Mujeres Solares de Totogalpa which is a women’s group that has been working together to promote the use of solar cookers in their communities and to work to enhance this technology. The solar cookers made and sold by Las Mujeres Solares de Totogalpa use panes of glass in a wood and sheet metal box to collect light from the sun, convert that light to heat, and cook food. These cookers are helpful to people who would otherwise cook with scarce wood over an open fire which is often located indoors with little ventilation. However, the glass panes used in the solar cookers were found occasionally to break during their initial uses. Recently, the failed pieces of glass from a solar cooker were
brought back to the University of Dayton to be studied. A failure analysis was conducted on the broken glass panes extracted from a solar cooker in order to determine the cause of failure and to identify possible solutions to prevent this from happening in the future.

Solar box cookers depend on the absorption of the sun’s rays and on the thermally insulating properties of the box. Light from the sun is absorbed by dark materials inside the solar box cooker, and the heat which is generated is trapped inside the box by insulated walls and a glass cover. Reflecting panels may be used to increase the amount of sunlight that falls into the box cooker and increase the temperature. Solar box cookers with reflectors are capable of reaching temperatures above 160°C. A solar box cooker manufactured by Las Mujeres Solares de Totogalpa with an aluminum foil reflector is shown in Figure 1.

Solar cookers are appropriate in the mountains of Nicaragua. Nicaragua is close to the equator and experiences both intense sunlight and high temperatures. Nicaragua has an average Global Horizontal Irradiance (GHI) which is 4.5-5.0 kWh/m²/day and is among the highest in the world. The rainy season in Nicaragua lasts from May to September, during which there are commonly torrential downpours. ETHOS students from the University of Dayton recorded daytime temperatures averaging 32° C on sunny days during the middle of the rainy season. In the dry season from November to April, temperatures are slightly lower (~ 30° C), but the likelihood of cloud cover is also much lower.

Two panes of glass are used as a cover for the solar cookers produced in Sabana Grande, Nicaragua. Glass is an amorphous ceramic material formed primarily from molten silica. Additives in glass can increase strength, decrease its solubility, and affect other properties. Glasses made with boron oxide are very stable and have low coefficients of thermal expansion (CTE). Aluminosilicate glasses are also useful at high temperatures. Fused silica, glass made from pure silica, has the best resistance to failure under high temperature. The most commonly used glass, however, produced at compositions varying but near 75% silicon oxide, 15% sodium oxide, and 10% calcium oxide, is known as soda-lime glass. Soda-lime glass is inexpensive to
Glass demonstrates very low thermal conductivity. Glasses have thermal conductivities ranging from 0.159 to 2.09 W/m*K. Glass is also very brittle, exhibiting little to no plastic deformation when it is stressed. Due to the presence of a large number of very small holes and flaws, glass is weak under tensile loads. Under compressive loads, those flaws are closed and glass demonstrates a higher strength. Pristine glasses demonstrate a variety of strengths depending on their composition. The mean observed strength for a 0.03mm-diameter rod of pristine, pure silica has been reported as 5.86 GPa. The same value for a 0.5mm-diameter rod of pristine borosilicate glass is 2.93 GPa, and for a 0.5mm-diameter rod of pristine soda-lime glass, 3.93 GPa.

Flaws, such as scratches and abrasions, in glass have a noticeable negative effect on its strength. Pristine soda glass had a strength of 3.93 GPa, but slightly abraded soda-lime glass (a 1.3mm-diameter rod) had a strength of 0.45 GPa, nearly a tenth of the strength of the pristine glass. A rectangular sheet of abraded soda-lime glass was found to have a strength of 0.05 GPa.

The presence of humidity has a negative impact on the strength of glass. When water comes in contact with silicon oxide, it undergoes a chemical reaction, separating the silicon and oxygen atoms in glass. The presence of water, even as humidity in the air, promotes crack growth and substantially weakens glass. An increase in temperature has a negative effect on the strength of glass. Internal stresses have been found to decrease with increasing temperature.

Fracture toughness, the resistance of a material to fracture when flaws are present, varies with composition. Fused silica, pure silicon oxide, has a fracture toughness of 0.79 MPa√(m); aluminosilicate, 0.91 MPa√(m); borosilicate, 0.77 MPa√(m); and soda-lime, 0.75 MPa√(m). The thermal expansion of glass varies with its composition. Fused silica has a thermal expansion of 0.55 E-6 m/m°C. Borosilicate glass expands much more, with a thermal expansion of 3.2 E-6 m/m°C. Soda-lime glass expands the most, with a thermal expansion value of 8.5 E-6 m/m°C.

The strength of glass may be increased through tempering. Tempering is a heat treatment in which glass is heated to a temperature just below its annealing point (under 450°C for most glasses) and then cooled at its surface more rapidly than in its bulk, leaving compressive stresses in the surface layer and tensile stresses in the bulk of the glass. These integrated stresses help tempered glass to better withstand tension and shock. The integrated stresses also cause a recognizable failure pattern; tempered glass breaks into a large number of dull fragments when its critical stress limit is exceeded. Annealing is a stress-relieving heat treatment for glass. Annealing requires heating glass to a temperature above its annealing point (near 450°C, far below the melting point) and cooling it slowly. Cooling the glass slowly prevents the formation of stresses which occurs during tempering. Annealing removes stresses which may have been introduced during manufacturing, processing, transport, scoring, cutting, or use.

Pine wood is another material used in the solar cooker. Wood can experience a volume change under two conditions: when exposed to moisture and when exposed to heat. These effects are also coupled with one another. When dry pine wood is heated, it will expand linearly according to its CTE. When wood is moderately moist, the wood will first expand, and then shrink due to loss of moisture. The difference in the volume of the wood will be negative, so that the overall effect is a decrease in size. During shrinking, wood will warp as one edge or side of the wood shrinks faster than another, especially if there is a temperature or moisture gradient present.
Wallner lines are useful in determining fracture speed, the energy involved in a fracture, and the point of failure of glasses and ceramics. In *Fractography of Ceramics and Glasses, a NIST Practice Guide for Fractography*, George Quinn defines a Wallner line as “A rib shaped mark with a wavelike contour caused by a temporary excursion of the crack front out of plane in response to a tilt in the axis of principal tension.” Wallner lines emanate away from the fracture point. The distance between each ripple may be used to determine the speed of the fracture. Ripples which are farther apart suggest larger stresses. The pattern in which a piece of glass fractures has the potential to give clues regarding the cause of the failure. Glass can fracture in a number of different ways, and fractures often exhibit unique characteristics for varying failure causes. The branching angle of a glass fracture is a key characteristic. In *Fractography of Ceramics and Glasses*, Quinn presents a chart of branching angle versus stress ratio which describes the type of stress (uniaxial, biaxial, flexure, tension, or torsion) that is associated with certain ranges of branching angles. Generally, small branching angles are associated with flexure or tension. The number of branches and the shape of fracture lines may also give clues as to the cause of fracture. Quinn shows a number of pictures which demonstrate that fractures due to thermal shock have both a small number of branches and wavy fracture paths. Fractures where no thermal gradients were present did not show these characteristics.

Another method which is used to examine glass and to determine fracture causes involves polarizing lenses. Stresses in glass change the polarization of light while unstressed glass does not. When two polarizing lenses are crossed at right angles, no light may pass through. If a stressed piece of glass is placed between the crossed polarizing lenses, the light passing through the stressed areas is realigned and some portion will pass through the second polarizer, highlighting stressed regions in an often dazzling array of color. This technique may be used to examine glass before or after failure.

Glass cutting is a cause of unwanted stresses and defects in glass. Glass is commonly scored with tungsten-carbide blades using a blade size and an angle appropriate for the thickness of the glass being cut and the blade being used to cut the glass. It is recommended that oil be spread over the line to be cut, and the same oil be used to oil the cutting blade. The oil serves to protect the cut area of the glass from the damaging effects of atmospheric moisture. After scoring the glass, a light and constant pressure is applied to the score mark to complete the glass cutting process. Common problems that occur during the glass cutting process include having an incomplete break occur due to uneven scoring pressure or an insufficient cutting angle; open edge defects on the scored edge of the cut due to the method used to break the glass; opened edge defects on the opposite edge due to the method used to break the glass; and a break which leaves the scored line and runs to the edge of the glass due to its proximity. These problems are both recognizable and avoidable with proper precautionary steps.

**Failure Analysis**

*Background Information*

As previously discussed, the solar cooker glass that is being analyzed came from a box solar cooker, similar to that shown in Figure 1. The solar cooker was manufactured in Sabana Grande, Nicaragua by Las Mujeres Solares de Totogalpa. The bottom pane of glass in the solar cooker failed upon initial exposure to the sun in the Spring of 2008. The maximum temperature achieved by this type of solar cooker has been measured to be approximately 150° C. The glass
panes used in the construction of the solar cookers are purchased at a local hardware store, but little is known about the type of glass used or the methods used to cut the glass. The technical contact at Las Mujeres Solares de Totogalpa wished to identify the cause of failure since this type of failure occurs with some regularity. Typically, the glass panes of the solar cooker fail early in their lifecycle during the initial one or two uses. However, some cases have been reported where the glass fails unexpectedly after the solar cooker has been used for several years.

**Visual Observations**

The solar cooker in which the fracture occurred had two panes of glass. Between the panes of glass was an air gap of 12.7 mm. Both of the panes of glass rested in channels cut into the pine wood frame. The glass panes were not glued or attached to the frame. The failure occurred in the bottom pane that was located closest to the interior of the solar cooker. Since this pane of glass was in contact with the cooker interior, it was exposed to a temperatures that ranged from the ambient night time temperature of approximately 20° C to the interior temperature of the cooker which can go as high as 150° C. The solar cooker was used and stored outside and was opened daily to the sunlight and closed at night and when it rained.

The pane of glass was measured to be 4.8 mm thick. Both the bottom and top panes of glass rested in 6.4 mm grooves that were cut into the pine wood. The planned clearance above each pane of glass inside the groove was 1.6 mm, and the planned clearance on each of the four sides of the pane of glass was 3.2 mm. Theoretically, this clearance permitted enough space for the glass to slide freely in the grooves without contacting the sides. However, it was noted that in many instances the grooves had to be sanded, sometimes heavily, to allow the glass to slide into position. The overall fracture pattern of the glass is shown in Figure 2 and close-up photographs of the fractures are shown in Figures 3 and 4.
FIGURE 2
OVERALL FRACTURE PATTERN OF THE SOLAR COOKER GLASS FAILURE

FIGURE 3
POINT ON THE GLASS (ABC) WHERE THE FRACTURE DIVIDES
Material Characterization

A Thermomechanical Analysis (TMA) of the fractured glass was used to assess the thermal properties of the glass. Additionally, a semi-quantitative chemical analysis was performed using energy dispersive spectroscopy (EDS). Results from these analyses are provided in Figures 5 and 6, respectively. From the TMA the CTE of the glass was found to be $10.17 \times 10^{-6}$ m/m°C. Results of the EDS indicated the presence of Si, O, Na, Mg and Ca.
FIGURE 5
TMA RESULTS OF BROKEN GLASS

FIGURE 6
EDS RESULTS OF BROKEN GLASS
Fractography

The fracture surface of the glass was examined at low and high magnifications. Through this inspection, lines were found to radiate in a ripple like fashion, from a point on the bottom right edge of the piece of glass marked as A, Figure 7. The point from which the fracture appears corresponds to the lower surface of the pane of glass located at the top edge of the solar cooker (edge where the reflector panel is connected to the box). A side view of this piece of glass is shown in Figure 8. As can be seen in Figure 8, the cut edge of the glass was found to be very rough which is believed to be an artifact of the glass cutting process used to cut the glass to size.
DISCUSSION

Comparing the CTE of the solar cooker glass obtained from the TMA to published values for soda-lime and borosilicate class suggest that the CTE is closer to that of soda-lime glass than to borosilicate glass. Results of the EDS indicate the solar cooker glass to contain Si, O, Na, Mg and Ca. Comparing these results to the chemical compositions of soda-lime and borosilicate glass, it was noted that borosilicate glass does not contain calcium. Furthermore, the EDS results obtained for the solar cooker glass, closely match those obtained for soda-lime glass by the United States Geological Survey. The EDS and TMA results suggests that the glass used in the solar cookers is common soda-lime glass.

Information presented in the literature indicates that moderate branching angles in glass fractures are generated when the glass is exposed to uniaxial flexure. The branching angle for the failed glass in the solar cooker was found to be approximately 54° suggesting that the glass failed as a result of uniaxial flexure. In addition to the branching angles, the practice guide correlates thermal fractures with wavy fracture lines, such as those noted for the solar cooker glass emanating away from points A, B and C in Figure 2. In the case of the solar cooker glass, two branching locations are visible. One is located at the rear of the solar cooker and is seen in Figures 2 and 3. The second branching location is visible in the top right of Figure 2, a short distance from the edge of the wooden frame, between the piece marked B, E, and F. A third location where the fracture appears to divide is evident at the very edge of the solar cooker glass, between the points marked D, E, and F. This point is shown in Figure 4. Examination of the faintly visible Wallner lines on the fracture surfaces (Figure 2) suggests a fracture pattern and two fracture points. The fracture points, as well as the pattern and progression of cracking, is shown schematically below in Figure 8. The arc of the Wallner lines suggests that the panel of glass was in tension on its lower surface and in compression on its upper surface. The fracture origin appears to be on the lower surface (tensile surface) of the piece of glass marked A. The bottom surface is the surface which was in contact with the hot air inside the solar cooker. This suggests that the temperature gradient had an effect on the cause of the fracture.

FIGURE 9
FRACTURE ORIGINS AND PROGRESSION
Since similar failures have been noted in the past for the solar cookers and none of these failures could be attributed to any type of physical impact, it is likely that the failure is associated with the glass or the construction or use of the solar cooker. Factors that could have contributed to the failure of the solar cookers included the cold rain falling on the hot glass plates, the humidity which is associated with rain and is known to have a negative effect on the properties of glass and/or the expansion of the solar cooker frame due to moisture. Since the solar cooker was kept outside all of the time, the sudden presence of cold rain on the hot glass could have caused the glass to fail as a result of thermal shock. However, at the center where the solar cooker was manufactured and used, it is common practice to close the lids of the solar cookers prior to a rain storm. This combined with the fact that the fracture occurred in the lower of the two glass panes, which was protected from direct contact with the rain, makes it unlikely that failure occurred from thermal shock associated with the solar cooker being exposed to rain. Nonetheless, the humidity in the area where the solar cooker was used is very high during the rainy season. As a result, the wood may have absorbed some of the water causing the wood frame to expand and applying a load on the glass pane. This coupled with the fact that humidity reduces the strength and fracture toughness of glass suggests that the high humidity likely contributed to the failure of the solar cooker glass. The dimensions of the channel were designed to allow the glass to slide freely in the grooves. Furthermore, the design would accommodate thermal expansion of the glass as well as expansion of the wood frame due to moisture. However, during construction of the solar cookers the ETHOS students noted that many of the channels often needed to be sanded. This suggests that the planned clearances may not have been achieved during construction of the solar cookers. If the clearances were not achieved, thermal expansion could have led to stresses in the glass panes as the glass pane tried to expand but was constricted by the wooden frame. Furthermore, the glass panes were found to have very rough cut edges. The notches observed on the cut edges serve as crack initiation sites in a material that is known to have very low fracture toughness. Additionally, the fracture toughness of glass decreases in high humidity.

It is believed that stresses imparted on the glass due to the physical constraint of the glass pane in the grooves have induced a fracture at the lower side of Point A. This fracture initiated at a defect in the glass pane that was introduced during the glass cutting process. If a lubricant was not applied to the glass cutter or the glass was not properly scored, a defect may have formed on the edge of the glass pane. The defect served as a crack initiation site in a material (soda-lime glass) that is known to have a very low fracture toughness. The presence of moisture could have also contributed to the failure since moisture is known to have a significant effect on the strength and fracture toughness of glass. The glass fracture initiated on the side of the glass which was in tension, and not on the side which was in compression. This would be expected since glass is known to have a lower tensile strength than compressive strength. The Wallner lines observed at the fracture surface support this observation as the arc of these lines indicated that the glass was in tension on the lower surface and in compression on the upper surface and that failure occurred as a result of uniaxial flexure, Figure 7. Since, the bottom surface of the glass pane was exposed to higher temperatures (temperature of the inside of the solar cooker) than the top surface of the glass pane, the resultant thermal expansion on the lower surface of the glass would have been higher than that at the top surface. As such, the glass would have been subjected to this flexural load with the bottom surface being placed in tension and the upper surface being placed in compression.
CONCLUSIONS

The solar cooker glass failed due to defects introduced in the glass during the glass cutting process and stresses that were imparted on the glass as a result of the glass being constrained in the grooves of the solar cooker. Although the design was supposed to allow the glass to free float in the grooves, poor dimensional tolerances as well as the possibility that the wood expanded due to moisture, reduced the clearance of the grooves. A number of factors weakened the glass before it failed. As previously mentioned, the glass had defects on its cut edge which served as a crack initiation site. These defects were most likely the result of poor cutting techniques. Furthermore, humidity in Sabana Grande may have compromised the properties of the glass including the fracture toughness. Upon initial exposure to the sun, the glass was exposed to stresses associated with the temperature gradient at the top and bottom surface of the glass pane. This imparted a flexural load on the glass which caused it to fail.

RECOMMENDATIONS

Several recommendations can be made that would help reduce the chances of failure of the glass. Since the crack initiated at a defect in the glass that was most likely introduced during the glass cutting process, it is recommended that careful attention is paid to the method used to cut the glass. Although little is known about the process used to cut the glass, some common glass cutting practices such as lubricating the tool used to score the glass is important. Although oil is the preferred lubricant, water may also be used. The addition of water to the glass cutting process is extremely simple, does not take much time. Furthermore, water is available in the community where the glass was purchased. If the imperfections are removed from the surface then the likelihood that the glass will break due to stresses from heating will be greatly reduced. This process would be the most efficient because all previously made solar cookers would not need to be altered, just the glass that will need to be modified or replaced.

Along with addition of water while cutting glass, another suggestion would be to use sandpaper lubricated with water to smooth the cut edges of the glass. This will greatly reduce the number of edge imperfections in the glass which will make it more resistant to cracking. This is another relatively simple process, however it is a bit more time consuming than just adding lubrication during the cutting process. Furthermore, this would require purchasing sandpaper and would make the manufacture of the solar cookers more labor intensive which could raise the overall price of the solar cooker.

Another way to reduce stress in the glass would be to increase the gap in which the glass is placed. Increasing this gap would allow thermal expansion to occur without constraint from the solar cooker itself. However, this is not a guarantee that the glass will not break from stresses due to the temperature of the glass, it will only insure that there is ample room for the glass to expand. Also, if this recommendation is used all previously made solar cookers would have to be altered to prevent failure in the glass. This would be an extremely time consuming procedure depending on the amount of solar cookers, and would be costly because of labor. Furthermore, the efficiency of the solar cooker may be compromised by the presence of these gaps.

The last suggestion is to use polarizing lenses to see where there is stress on the glass before it is installed in the cooker. Using the polarized lenses while cutting each individual piece of glass may be useful to insure that the glass is not developing stresses because of the way it is being cut. It will provide a useful piece of information when deciding if a piece of glass will be
sufficient enough to use in the solar cooker. Negative impacts of this would be the cost of polarizing lenses and the time it would take to look at each piece of glass before installation. It will provide information as to which piece of glass is suitable to use but ultimately will not result in the reduction of imperfections in the glass.

In summary, it is believed that adding lubrication to the cutting instrument during the glass cutting process is the best suggestion to prevent future failures of the solar cooker glass. This is the simplest and most effective solution to the problem. The women’s group that manufactures the cookers could easily be instructed on how to do this. Furthermore, they would not have to change their current glass supplier as they could simply purchase oversized glass and cut it to the desired dimensions. Additionally, sanding the edges of the glass may also be implemented as an extra precaution. Using polarizing lenses to evaluate the edges and surface of the glass after being cut with lubrication and sanded would be a good way to see if these methods are suitable for removing imperfections from the glass, but do not need to be done for every piece of glass. It is recommended that they be facilitated as a future research project through the volunteers provided by ETHOS or another organization. If remaining solar cookers are to be manufactured, the gap in which the glass sits in should be large enough for the glass to sit in and have room for expansion. This may require more careful manufacturing of the solar cookers. Cooking with the door open is extremely inefficient and will not guarantee anything except that cooking time will take longer.
REFERENCES

2 http://swera.unep.net