To: James W. Bales, Christina Silcox
From: Strobe 6: Adam Seering, Aubrey Tatarowicz, Daniel Hernandez, John Hawkinson
Date: 7 November 2008
Subject: Mark I Report

Summary and Recommendations

In this lab, we have studied the feasibility of measuring the breaking of glass with a high-speed video camera. We have made a number of different types of measurements, and made substantial progress towards establishing what is and what isn't possible to measure effectively.

Our goal is to reproduce the work of a previous lab group ([1]) in creating an image illustrating the manner in which glass deforms immediately prior to shattering. This group only obtained video of the glass breaking due to impact with a BB. We intend to expand on that work, and obtain data on glass breaking due to a slower-speed impact with a heavier object (such as a large screwdriver), as well as data on glass breaking due to other types of stresses, such as heat shock. We would also like to analyze this data more closely, in an attempt to determine how quickly both shock waves and cracks propagate through glass of different thicknesses.

The specific goal of this Mark I project is to determine if a longer-term project based on this material would be feasible and useful. Based on our experiments thus far, we believe that such a project is feasible. We recommend executing such a project. We also have specific recommendations regarding further experiments to process; these are described in detail in the "Discussion" section below, but include repeating past experiments with a BB gun, shattering thick pieces of heated glass with water, and testing reflective-lighting techniques.

Background

For our Mark 1 we wanted to determine what kinds of things we can see and measure with breaking glass. What first marked our curiosity was that there exists a standing rumor that a popular way for car thieves to break the glass windows of cars is to hit them with a very hot object. The combination of the impact and the heat shock is allegedly sufficient to easily crack sturdy automotive glass.

In researching how we should go about breaking the glass and what we can measure, we found a previous group's lab report where they investigated certain aspects of breaking glass. This group investigated glass breaking by impact by a metal rod and also by a BB shot from a BB gun. We want to use this information to get more useful data and also combine this with the thermal aspect of glass breaking. This group recommends a study on the thermal effects on glass breaking which is one of the things we wish to pursue [1].

Glass Breaking Process

Glass breaks by way of fracturing where a stress fracture forms by some sort of stimuli, which we would apply, and this fracture travels though the glass until the glass breaks. This fracture speed has been measured in the past and is expected to be between 1000m/s and 1500m/s [1].

Fractures formed by impact take two distinct forms: radial fractures and concentric fractures. The radial fractures are considered primary fractures and form on initial impact. The concentric fractures form around the point of impact. The glass bends before breaking which causes these different shaped breaks [1]. We want to see how the glass bends and try to analyze this data.

Measuring Glass Fracture Speed

There are several techniques used to measure glass fracture speed. One is the high speed camera, which we have tested in our mark 1 project. This technique uses the, frames captured by a high speed camera to take data in so that the movement of a fracture can be analyzed with time [2]. We can do this analysis my hand by calibrating the image with something like the length of the glass slide. With this data, we can extract position information and make velocity calculations. This is the same method as used in memo 3.

Another method that can be used to calculate fracture speed is the electrical grid method. This can be done by using electrically conductive paint or wires that lay in the path of the glass fracture. When the fracture severs the wires or paint's connections, it essentially creates an open circuit. The voltage readings can be obtained by putting different load resistors with different paths so the change in voltage can be read as the fracture breaks this path [2]. This is a technique that we want to keep in mind for the final lab report.

Bending of Material

The bending of materials is typically analyzed in terms of stress:

[1] $\rho = \frac{F}{A}$

where ρ is the nominal-stress tensor, describing how stress is distributed throughout the beam.

If you're not familiar with stress, you can think of it as an internal pressure. Stress and pressure have the same units; "stress" is frequently used to describe solid objects where "pressure" would be used to describe fluids.

Objects such as panes of glass seldom break due to linear forces; rather, they break due to the internal torques that cause them to bend. Rewriting the equation in terms of the torque M on the rod, you get

[2] $\rho \cdot y = \frac{M}{A}$

If the stress of an object varies with position, such as with an object that's being bent, this equation can be rewritten as

[3] $M = \int_A \rho \cdot y dA$

In most simple rods, ρ has been shown to be a simple constant. This makes this equation quite simple to work with.

High Speed Video Camera - Phantom

The Phantom High-Speed Video camera is capable of recording 800x600-pixel video at 47,000 frames per second. It has a maximum frame rate of approximately 150,000 frames per second at a resolution of 32x32 pixels. This reasonably-high resolution and very high frame rate make it a very versatile choice for capturing useful video of sudden or rapid events.

The Phantom captures data at a higher data rate than bulk recording devices, such as hard drives, can handle. As a result, it stores up to about a second of video in an onboard memory buffer. When triggered, it saves the state of the buffer, and spends the better part of a minute shipping its contents off to a connected laptop. Once on the laptop, the video can be played back and converted to various data formats for analysis.

The Phantom can be triggered either by an electric trigger or by an attached computer. The Phantom controller software installed on the laptop that comes with the camera, includes a "Trigger" button in its user interface for this purpose.

When the Phantom is triggered, this can tell it to stop collecting video immediately. It can also tell the Phantom to continue collecting video until an arbitrary fraction of its memory button has been overwritten. As a result, the camera can be set up to cope with a trigger occurring at any arbitrary frame within its capture window. The Phantom software has a slider to control this setting.

Goals

Based on this information, our goals were

- To establish whether it would be feasible to crack glass using a variety of different means, including impact by a falling object, heat, and thermal shock by quick changes in temperature.
- To obtain useful numeric data about the shattering process.
- To figure out if our project is feasible based on the above two criterion and if we find this project interesting and challenging.

Procedure

The experiments composing this lab spanned two sessions. During the first session, we studied several types of heat shock on microscope slides and various trigger mechanisms. During the second session, we studied glass impact on different-sized sheets of glass, and various lighting techniques.

Heat Shock

For the tests of heat shock, we used the materials listed in Table 1.

The lab setup was as shown in Figures 1 and 2.

Item	*Manufacturer*	*Model*	*S/N*
HSV Camera	Vision Research	Phantom v7.1	Phantom HSV
Laptop Computer	Dell	Latitude D830	MIT-0422773
HSV Software	Vision Research	Phantom 640	not recorded
Microscope Slides	VWR International	VWR VistaVision	cat. no. 16004-422
Multimeter w/ Thermocouple	Fluke	179	93810559
Lens (for Phantom Camera)	Tamron	90 mm Macro	TAMRON1
Digital Still Camera	Sony	DSC-P72	338694
Hot Air Gun	Accupro	1500 Watt	n/a
Tripod (for Phantom Camera)	Manfrotto	3021BPRO	n/a
Hex Plate for Tripod	n/a	n/a	n/a
Lamp	Lowel	Pro 250 Watt	n/a
Fiber Optic Illuminator	Dolan-Jenner Industries	190	n/a
Safety Glasses	n/a	n/a	n/a
Black Rolling Cart	n/a	n/a	n/a
Wooden Boxes (2)	n/a	n/a	n/a
Eyedropper	n/a	n/a	n/a
Metal Lab Stands (2)	n/a	n/a	n/a
White Paper (for diffusion)	n/a	n/a	n/a
Water	n/a	Tap	n/a

Table 1: Materials for heat shock experiment.

We measured all temperatures with the thermocouple listed under "Materials".

In our first test, we tried applying a soldering iron (with a tip temperature of around $150°C$) to the microscope slide. Upon impact, the slide did not react. Upon extended exposure, the slide continued to not react. We then removed the soldering iron and, after allowing the glass to cool, applied a second iron, with a higher tip temperature of around $250°C$. (Note that we did not record the exact tip temperatures.) Once again, the glass did not react.

In our second test, we tried heating up the glass with a heat gun. We were able to heat the glass to a measured temperature of $375°C$. This is much hotter than the soldering iron. However, the glass remained unaffected.

In our third test, we tried heating the glass with the heat gun, then dropping cold water on the glass to cool it rapidly. We tried a number of application methods, with varying results as discussed in the "Results" section below. Specifically, we tested an eyedropper, a cup, and a titration flask held at different heights relative to the glass.

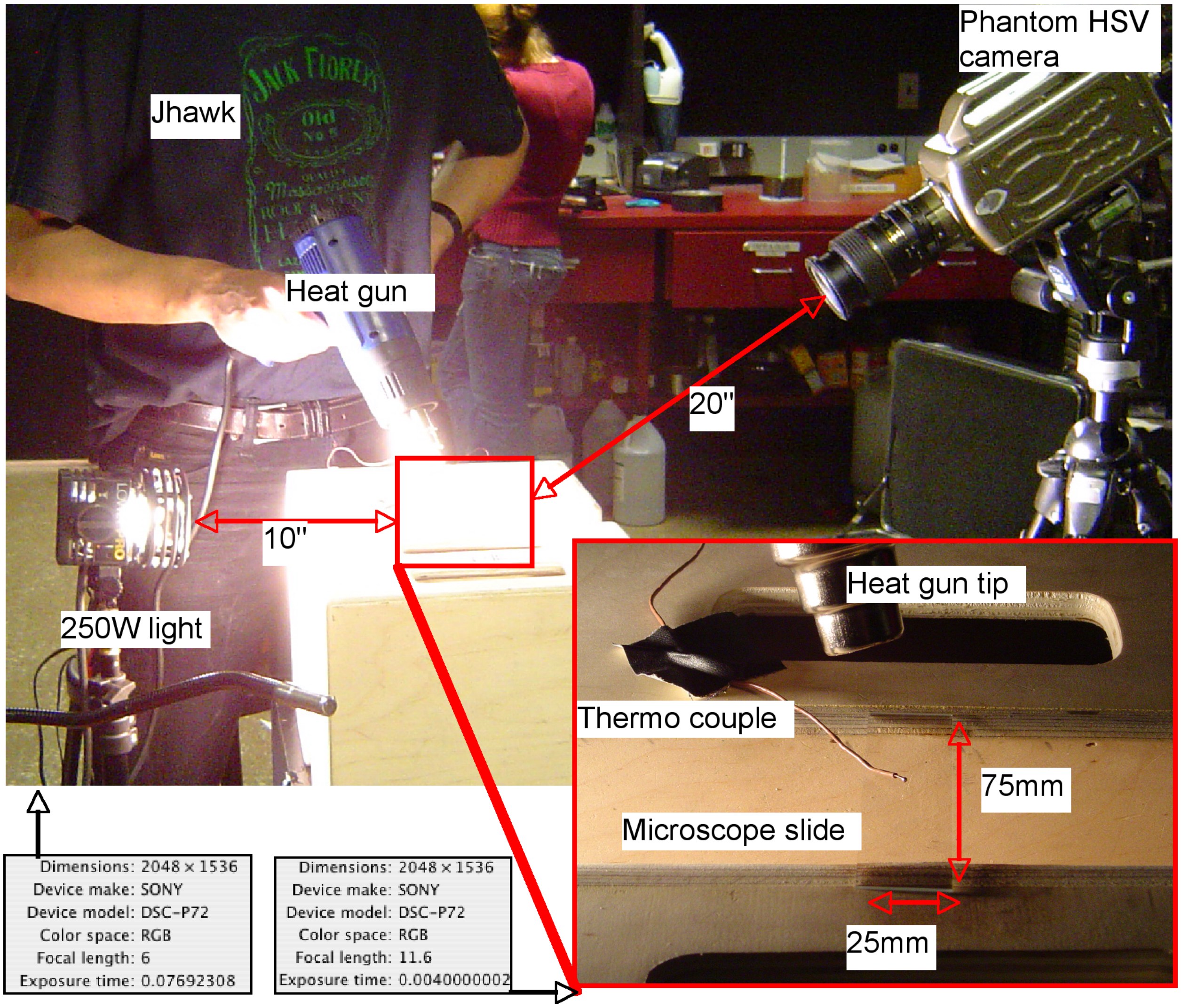


Figure 1: This is the first setup used to do the heat tests. We found that the apple boxes started to get singed by the applied head from the heat gun, so the setup in Figure 2 is the setup we started to use later. The lower image in the figure is a closer look at the setup of the microscope slide with the heat gun and thermo couple. The thermo couple is connected to the multimeter. The camera takes about a 45 degree angle with the slide. The 250 W light lights the far edge of the slide. Both images were taken with Dan's digital camera. The camera settings are also in the figure.

Trigger Mechanisms

For testing different trigger mechanisms, we kept the setup from the heat-expansion experiments, and added a number of ring stands to support an optical trigger and a beam-break trigger. The triggers were arranged as shown in Figure 3.

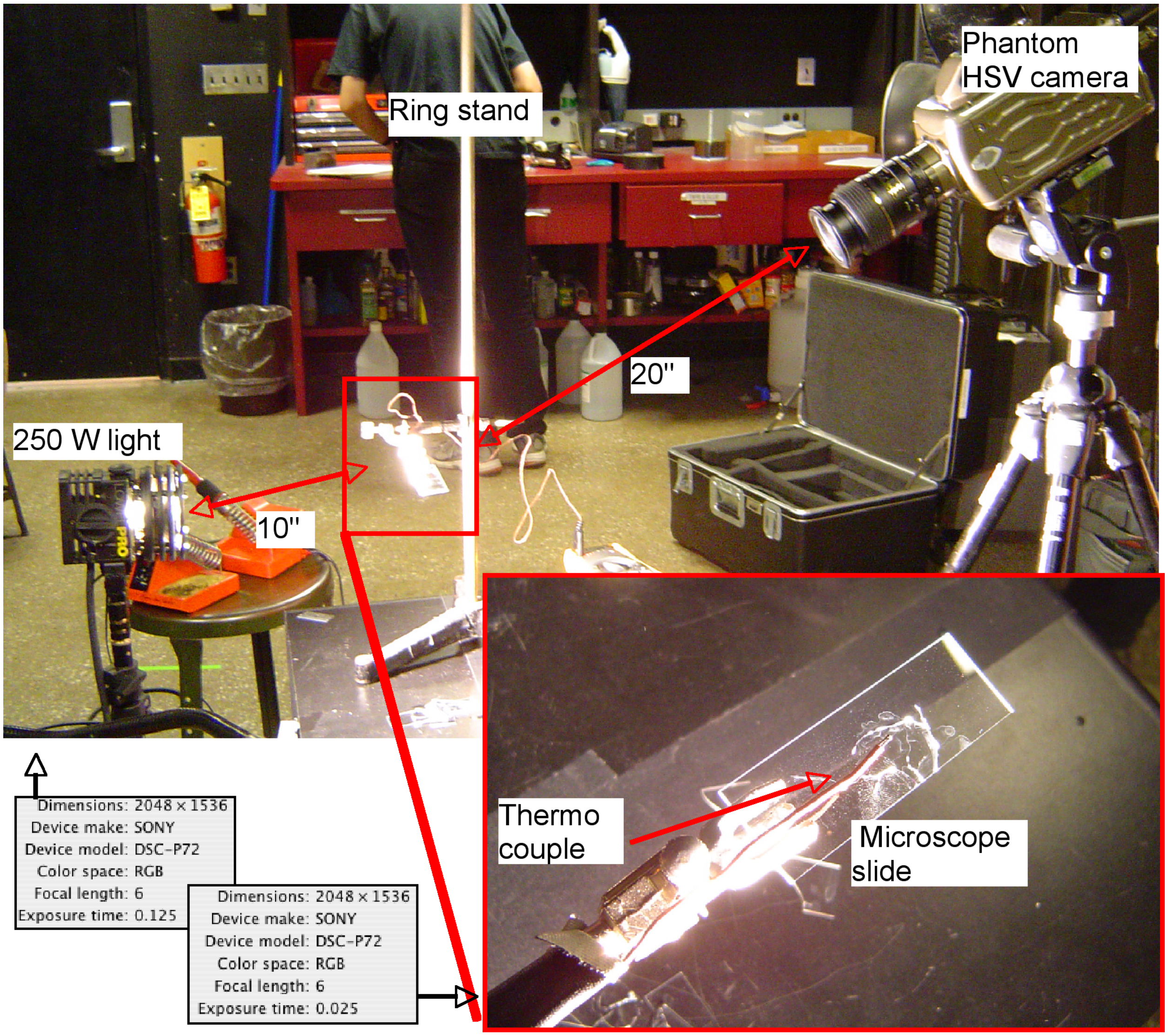


Figure 2: This is the setup we used for the thermal shock for the majority of the time. The a clamp on the ring stand holds the microscope slide by one end as seen in the lower photo in this diagram. Again the light is aimed directly into the far edge from the camera part of the microscope slide. Dan's digital camera was again used to take the setup photo and the camera settings are again in the diagram.

The goal was to have a drop of water pass through the beam of each trigger while airborne, prior to impacting the glass. We assumed that the water would fall in a very repeatable way, once released from its container. We tested for a successful trigger using the attached Time Machine device.

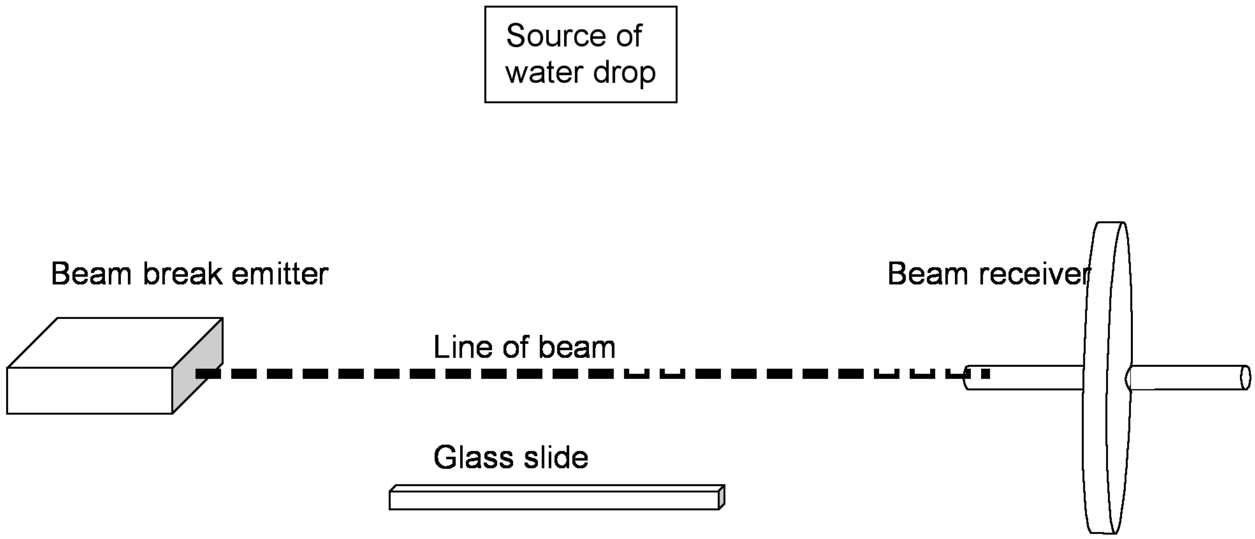


Figure 3: This is the basic beam break setup that we tried. The beam break components were secured in place with tape on lab stands and apple boxes until the beam was set so that the receiver lined up with the emitter and that the beam crossed over the glass slide and in the path of the water drop. The beam break trigger was connected to the time machine input and the output of the time machine was connected to the Phantom HSV camera. The camera was set to trigger at the beginning of the recorded segment with the triggering from the beam break.

Glass Impact

For the tests of glass impact, we set up a piece of glass suspended between two appleboxes, as with the setup for testing heat shock. The camera and lights were not used, as the goal wasn't to gather imagery but rather to test the strength of glass. The glass was then hit with a pendulum and a screwdriver, each from varying heights ranging from 1" to 12".

This procedure was followed with both 1mm microscope glass and 2.4mm window-pane class. We cut the 2.4" window-pane glass into 2"x8" rectangular pieces.

The equipment used is listed in Table 2. The setup for this was as shown in Figure 4.

The object being dropped onto the glass was dropped once per test run listed in the "Results" section of the lab, at a height above the glass as noted in the table. The glass either broke on impact, or didn't break on impact. The state of the glass was noted.

Item	*Manufacturer*	*Model*	*S/N*
HSV Camera	Vision Research	Phantom v7.1	Phantom HSV
Laptop Computer	Dell	Latitude D830	MIT-0422773
HSV Software	Vision Research	Phantom 640	not recorded
Microscope Slides	VWR International	VWR VistaVision	cat. no. 16004-422
Lens (for Phantom Camera)	Nikon	28 mm	Nikon1
Digital Still Camera	Sony	DSC-P72	338694
Tripod (for Phantom Camera)	Manfrotto	3021BPRO	n/a
Hex Plate for Tripod	n/a	n/a	n/a
Screwdriver	Craftsman	Flat head 41578	n/a
Glass	RF Supply	8" x 10" x 3/32"	n/a
Lamps (2)	Lowel	Pro 250 Watt	n/a
Safety Glasses	n/a	n/a	n/a
Wooden Boxes (2)	n/a	n/a	n/a
Graph Paper	n/a	n/a	n/a
Gaffer Tape	n/a	n/a	n/a

Table 2: Materials for glass impact experiment.

Lighting Techniques

For the tests of lighting techniques, we used the same camera setup as for testing heat shock. We shifted the light around to test direct lighting, backlighting, and sidelighting (where light is passed straight through the long edge of the glass, so that cracks will reflect the light and appear to glow). The equipment used is listed in Table 3

Item	*Manufacturer*	*Model*
HSV Camera	Vision Research	Phantom v7.1
Laptop Computer	Dell	Latitude D830
HSV Software	Vision Research	Phantom 640
Microscope Slides	VWR International	VWR VistaVision 75 x 25 x 1 mm
Multimeter w/ Type K Thermocouple Attachment	Fluke	179
Lens (for Phantom Camera)	Nikon	28 mm
Digital Still Camera	Sony	DSC-P72
Tripod (for Phantom Camera)	Manfrotto	3021BPRO
Hex Plate for Tripod	n/a	n/a
Lamps (2)	Lowel	Pro 250 Watt
Lab Stand	n/a	n/a

Table 3: Materials for Lighting Experiment

These lighting setups were implemented as shown in Figure 5.

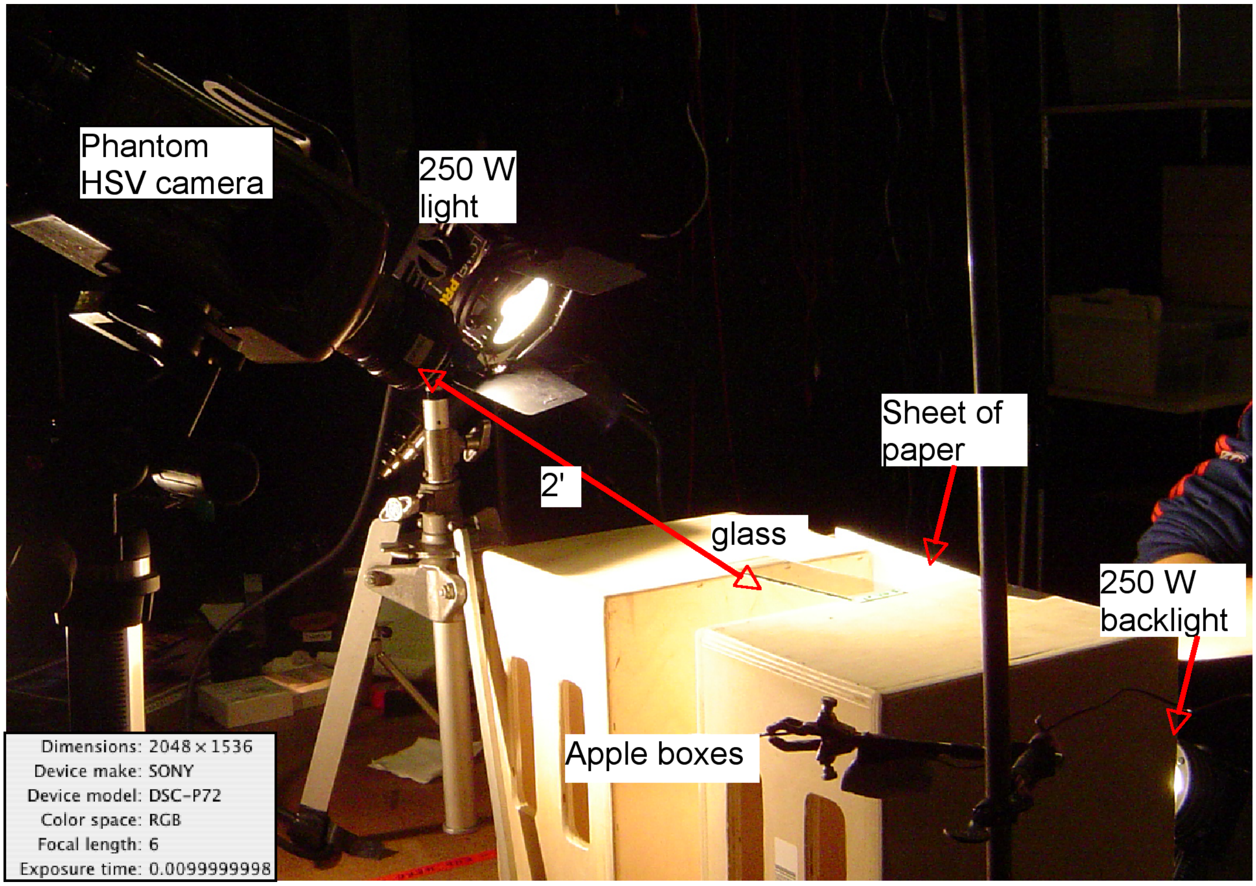


Figure 4: This is the setup used to perform the impact tests with the screwdriver. The glass is the 3/32" thick glass and the sheet is cut to 8" by 2" inches and is secured with tape. The sheet of paper is suspended in front of the back light to diffuse the light going into the camera. The lens used is the 28mm lens.

Additionally, we tried pointing the camera at the underside of slides rather than at the top.

We also looked into using digital still cameras to capture images of the glass. The camera was used to take still images of the slide at a useful frame rate. However, due to a lack of a trigger cable, still photos of shattering glass were not attempted.

Results

As mentioned under "Procedure", there were a number of pieces to this lab, each with a distinct set of results. To re-cap, we looked at the impact of heat shock, at the beam-break and optical trigger mechanisms, at means for breaking sheets of different thicknesses, and at

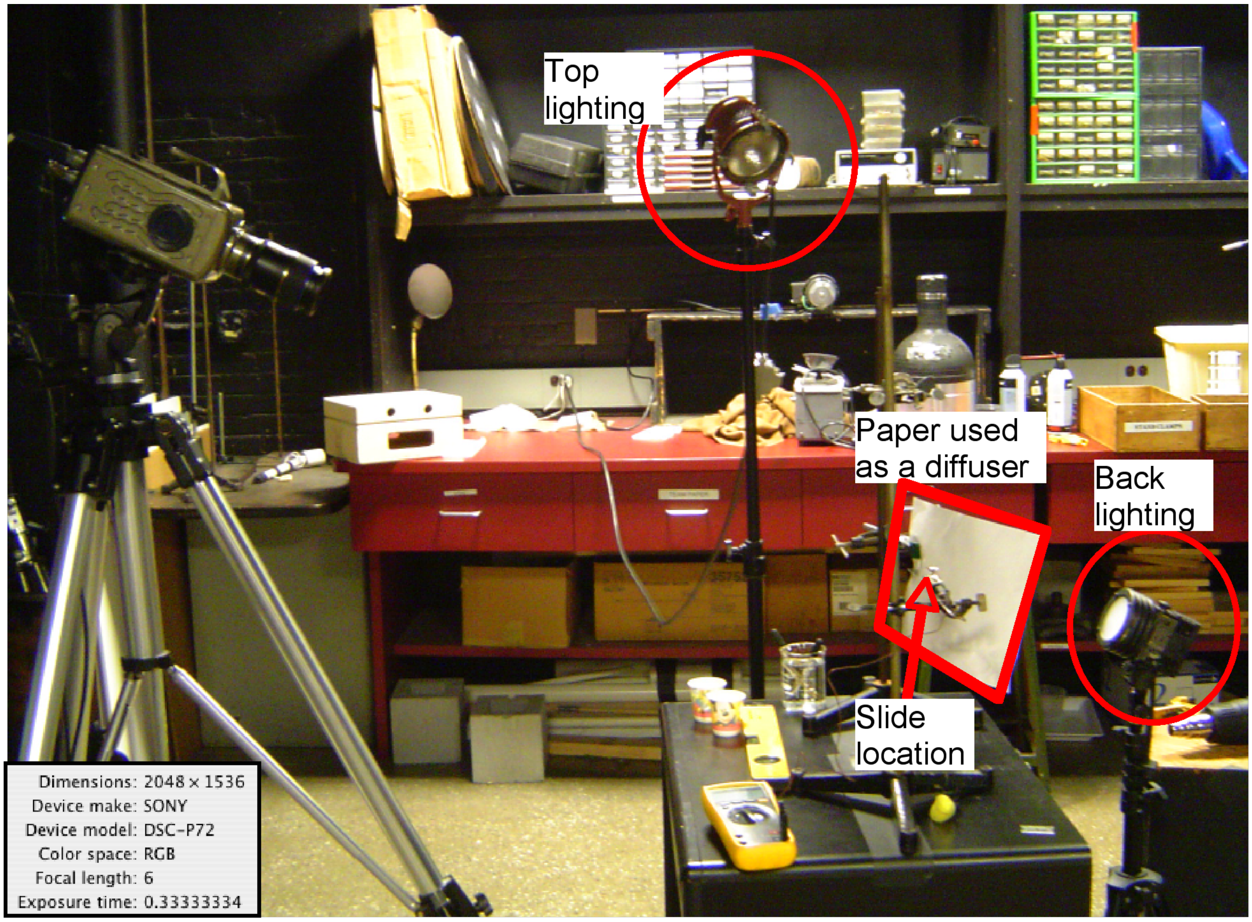


Figure 5: This figure shows the different lighting techniques we used. We used any combination of these techniques to obtain the results that we wanted. The paper diffuser was not used at all times and was helpful in some situations but not helpful in others.

different lighting techniques.

Heat Shock

For the testing of heat shock, as described under "Procedure", we determined that neither a heat gun nor a soldering iron alone were sufficient to crack glass.

Heating the glass and then rapidly cooling it with water, however, was able to break the glass under certain conditions. The initial height of the water-dropping mechanism, as well as the quantity of water dropped, both appeared to be important variables. Based on the high-speed video that we captured and on the images shown in Figures 6 and 7, we calculated a crack propagation rate of 430 m/s in microscope slides.

Figure 6: The first of two images showing a crack propagating through glass. HSV settings are shown.

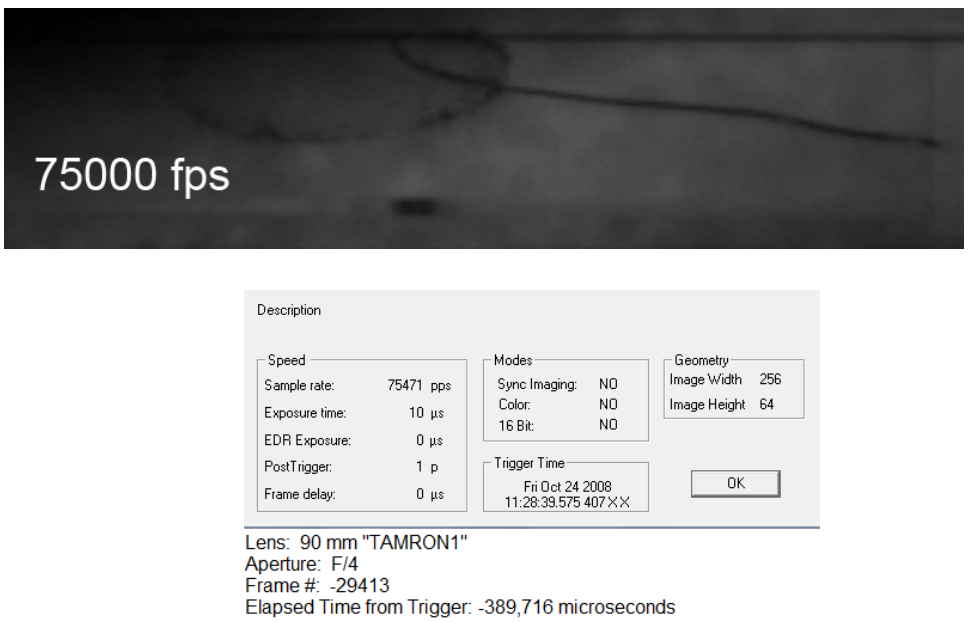


Figure 7: The second of two images showing a crack propagating through glass, taken 93 microseconds after the first frame. HSV settings are shown.

Trigger Mechanisms

We had relatively good results with the beam-break trigger but relatively poor results with the optical trigger. The beam-break trigger seemed to fire relatively consistently when water was dropped through its beam, though during setup and informal trials we did experience droplets that failed to cause a trigger.

The optical trigger, however, frequently failed to trigger at all in the presence of a drop of water. We were not able to gather useful data on it because we were unable to get it to work reliably.

Experimentally, it seems that lighting has a significant impact on the optical trigger. If a light was pointed directly at the trigger's sensor mechanism, it was likely to not trigger at all, whereas it seemed to work when only in the presence of ambient room light. Adjusting the sensitivity of the Time Machine that interfaced with the trigger helped, but did not entirely resolve the problem.

Glass Impact

We found that the thicker 2.4mm sheet glass was much harder to break than the thinner microscope slides. We tried dropping objects from various different heights onto the glass. Based on this data, we gathered the glass-breakage data listed in Table 4.

Glass	*Implement*	*Height*	*Break?*
Slide	Pendulum	1"	Yes
Slide	Screwdriver	1"	Yes
$\frac{3}{32}''$	Pendulum	1"	No
$\frac{3}{32}''$	Pendulum	3"	No
$\frac{3}{32}''$	Pendulum	12"	No
$\frac{3}{32}''$	Screwdriver	2"	No
$\frac{3}{32}''$	Screwdriver	4"	No
$\frac{3}{32}''$	Screwdriver	8"	Yes
$\frac{3}{32}''$	Screwdriver	12"	Yes

Table 4: Glass Impact Data

Note that, while our control experiment was able to break 3/32" glass at a height of 8" with a screwdriver, later tests were unable to do so consistently.

Lighting Techniques

For testing different lighting techniques, the goal was to find the most visually effective form of lighting rather than to calculate any specific data. Towards that goal, we generated images from backlit and side-lit slides, as shown in Figures 8 and 9.

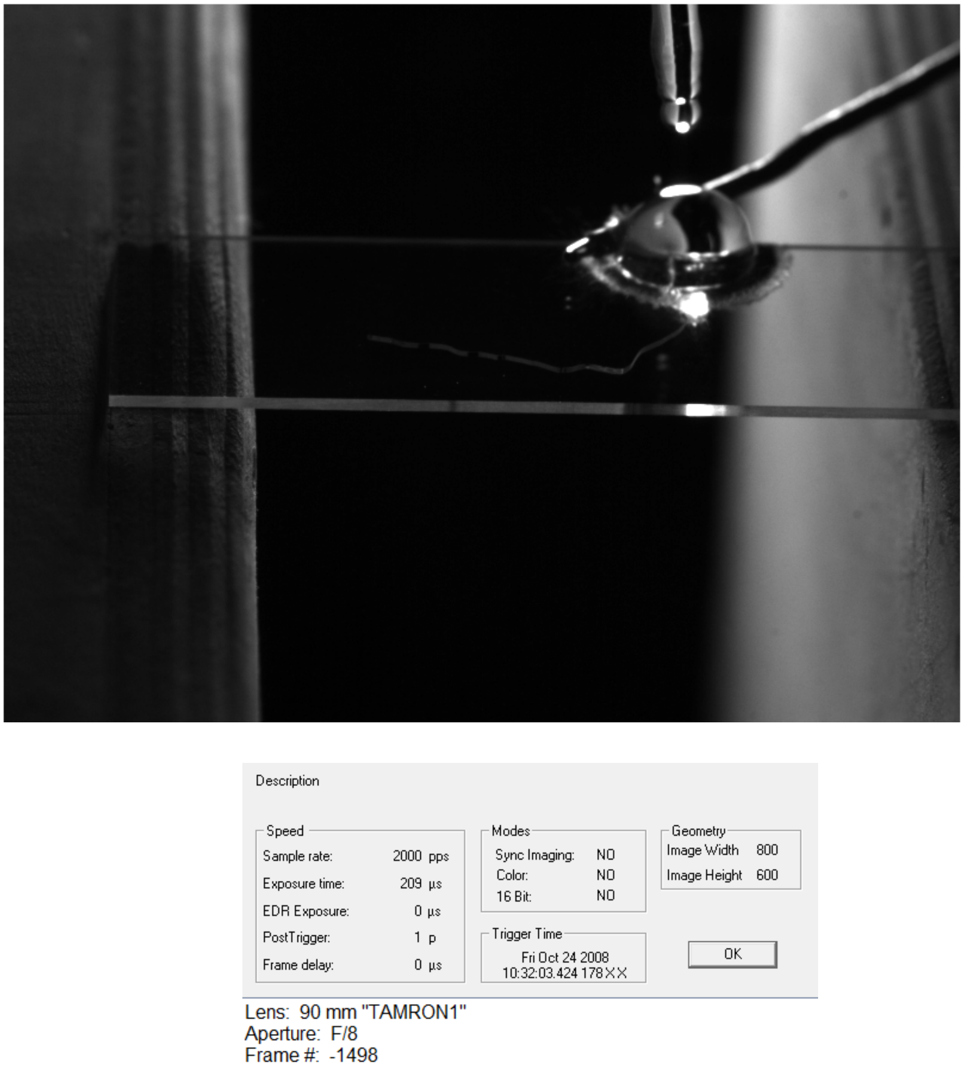


Figure 8: This image was captured with a side-lit microscope slide, lit against a black background. The displayed settings were used.

We found that standard lighting was not particularly effective. Both side- and backlighting were useful, but they do look different. Shooting a slide from underneath, however, produced images that were surprusingly unclear: we quickly discontinued this strategy as we couldn't easily tell what was going on in the images that it produced.

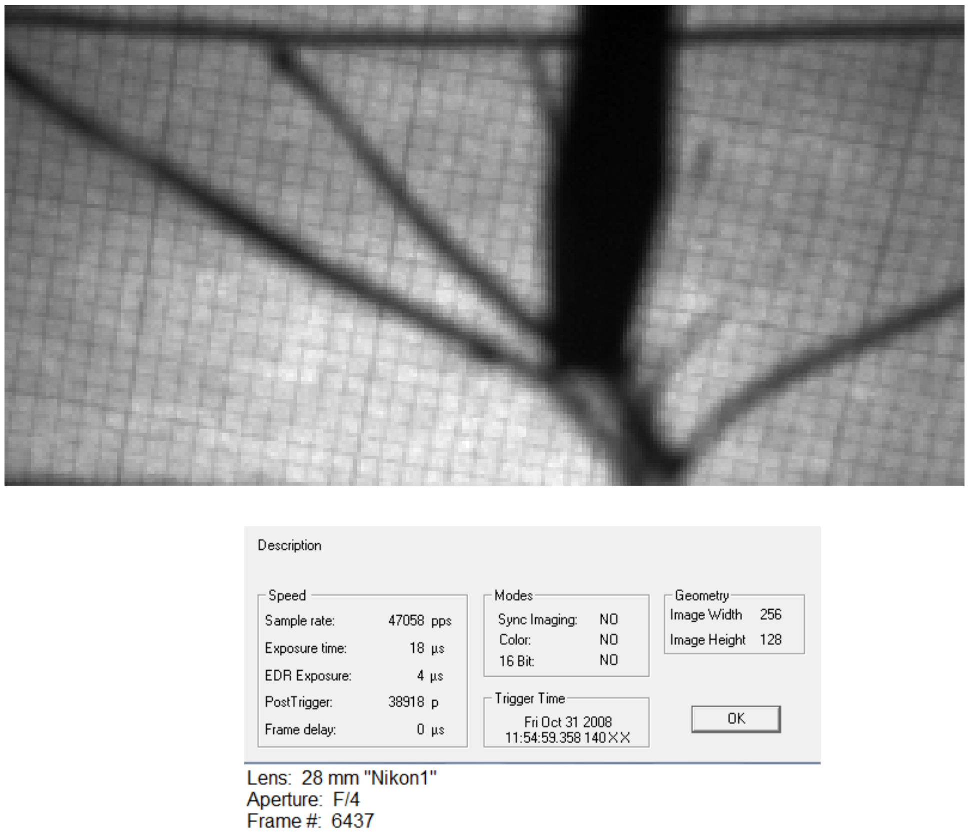


Figure 9: This image was captured with a back-lit microscope slide. The displayed settings were used.

Discussion

We found that, while we don't yet fully understand how heat shock causes glass to crack and shatter, we are able to cause it to shatter very consistently. We have thus far only tested microscope slides, though; we will need to do further experiments to see how thicker glass reacts.

As mentioned in "Results", the inconsistency of the optical trigger seemed to be correlated with background light. We suspect that the sensor was flooded with too much light. It might well work better in a darker room (though such a setup wouldn't work for HSV recording). Because the sensor is infrared-based, and because the HSV camera in monochromatic and sensitive to an array of different light frequencies, we might also be able to run the experiment with a strong monochromatic visible-spectrum light. We could also use a still camera in a dark room with a flash. However, since the beam-break trigger works much of the time, we may be able to just stick with it.

One fundamental failing with light-based triggers in this experiment is that drops of water are clear. They do act as lenses, distorting light passing through them; but they don't block light. We hypothesized that using a darker-colored fluid (such as water containing a great deal of food coloring) might lead to better results with both trigger mechanisms.

We established that glass that is 2.4 times as thick requires an impact with much more than 2.4 times the energy in order to shatter. This is not terribly surprising: From Mechanics, we know from equation [3] above that the resistive moment M is

[4] $M = \int_A \rho \cdot y dA = \rho \frac{h}{2}^2 \cdot w$

This means that the strength of the glass varies with both its width and with the square of its thickness. Dividing these two, we get that

[5] $\frac{h^2 \cdot w}{h^2 \cdot w}$

is the ratio of the moments. Calculating the ratio between a 75x25x1mm slide and a 203x51*2.4mm pane of glass, and assuming that the two different panels of glass are made from the same glass compounds so that their ρ costants are the same, we get

[6] $\frac{2.4^2 \cdot 51}{1^2 \cdot 25}$

$= 12$

which would predict that the thicker glass can withstand 12 times the moment of the thinner slide. Our experiments were not targeted at calculating this moment; nonetheless, given their very limited resolution, they do seem to support this estimate.

We found both the backlighting and side-lighting techniques to be effective. They tend to produce inverted images: white-on-black vs. black-on-white. We don't have an immediate use for this fact, but it may well prove useful in future analysis and so is worth keeping in mind.

We woud like to take still photos of this event. From our feasibility tests, we believe that it should be possible to do so, but that doing so will require finding parts for the D200 camera.

Future Work

Our future goals will be to capture an array of images of glass breaking using the techniques described above as well as other techniques such as BB's and Schlieren imagery. The longterm goal is to produce measurements of the rate of flexing and crack propagation in glass.

Based on this preliminary data, we feel that the thicker glass is likely to produce more-interesting results than the thinner glass. We would also like to try a broader array of lighting techniques and camera angles since these factors will be key in making data extrapolation and analysis possible.

Project Plan

We plan to proceed along the following timeline:

Week 1 (of Nov. 3)

- Shoot glass with a BB gun, try to obtain HSV and still images of the glass breaking
- Test grid reflection: obtain several images of the glass breaking with a reflected grid, see if deformation can be observed.
- Measure for consistency between slides/sheets, pendulum break of slides; see how consistently these break under the same amount of force.
- Apply heat to the sheets (hotter than heat gun, flame); obtain high-speed video of sheet glass breaking.
- Rotate the glass, break it on-end. Obtain high-speed video of the glass breaking on-end.

Week 2 (of Nov. 10)

- Try Schlieren imaging to capture heat distribution and flexing when breaking. Obtain high-speed video of glass flexing and breaking in the Schlieren imager (or determine that flexing or breaking glass does not produce interesting diffraction as displayed by the Schlieren imager)

Week 3 (of Nov. 17)

- Run lots of trials of what we found works well during Weeks 1 and 2. Gather multiple sets of video of any imagery that we found effective for analyzing the glass. Do this analysis.

Week 4 (of Nov. 24)

- Capture still photos of all interesting events for which video was captured during Week 3. Analyze more data.

Week 5 (of Dec. 8)

- Write-up – do whatever we need in lab to finish the final lab report

We plan to work as a group in lab. We have not allocated specific tasks to specific people at this point. We expect one member of our group to keep lab notes each week, with the position rotating for fairness and balance. For portions of the lab where this makes sense, we expect one member of the group to manage the HSV camera, including its trigger; one to drop the water or object on the glass; one to take notes; and one to supervise and manage lighting. The person handling lighting could deal with a still camera should one come into play. If we have sufficient equipment, we can have two tests running simultaneously, in which case at both test sites, one person will drop the water or object and record results, and the other person will manage the camera.

We will divvy up lab write-ups and manufacturing of hardware that we find we need, as such things come up.

References

[1] Sarah Longenbaker Bhuyan, Sanjeeb and Dmitry Portnyagin. *Impacts on Glass - Final Report*. 1989.

[2] K Ravi-Chandar. *Dynamic fracture of nominally brittle materials*. International Journal of Fracture 90, 1998.

EXP. NUMBER	EXPERIMENT/SUBJECT	DATE
Mark I	Breaking Glass	October 24, 2008

NAME	LAB PARTNER	LOCKER/DESK NO.	COURSE & SECTION NO.
Daniel Hernandez	Aubrey Tatarowicz John Hawkinson Adam Seering	—	6.163 / Strobe 6

Materials

slides	VWR Itnl.	VWR VistaVision 75x25x1 mm	cat. no. 16004-422 72 per box
digital camera (for setup photos)	Sony	DSC-P72 3.2 MP	S/n 338694
HSV camera	Vision Research	Phantom v7.1	"Phantom HSV"
laptop	Dell	Latitude D830	S/n MIT-0422773

software : Phantom 640

· Acquisition → setup & recording

Capture then Trigger
start rec. stop recording

- Click OK to view video
- mark Begin and mark end to trim file
- Save
  - "All HSV Files here" folder → Strobe 6
  - Save as *.cin

for .avi, - Border data, standard
- 5 fps

SIGNATURE	DATE	WITNESS/TA	DATE

EXP. NUMBER	EXPERIMENT/SUBJECT	DATE
Mark I	Breaking Glass	October 24, 2008

NAME	LAB PARTNER	LOCKER/DESK NO.	COURSE & SECTION NO.
Daniel Hernandez	AT, JH, AS —	—	6.163/Strobe 6

Fluke 179 multimeter s/n 93810559
w/ Type K thermal couple attachment

Lowel Pro 250W lamp

Fiber-Lite Fiber Optic Illuminator Model 190 made by Dolan-Jenner Industries

~~375°C~~

Accupro 1500W hot air gun no s/n

(2) wooden boxes
black rolling cart 31" high
tripod Manfrotto 3021BPRO
safety glasses

eyedropper
metal stands
white paper
water

video #	aperture	pps	temperature	notes	resolution (pixels)
Video #1 at	F/4	4700	375°C	crack not recorded	800x600
Video #2	F/8	2000	365°C	crack and break recorded	800x600
#3	F/8	4700	390°C	crack, break recorded	800x600
#4	F/8	15037	390°C	crack, break recorded	512x256
#5	F/8	47058	~~350°C~~ 350°C	height of water drop matters!; crack	256x128
#6	F/4	47058	360°C	crack not recorded	256x128
#7	F/4	47058	370°C	crack recorded	256x128
#8	F/4	75471	360°C	crack recorded	256x64
#9	F/4	75471	360°C	crack recorded	256x64

SIGNATURE | DATE | WITNESS/TA | DATE

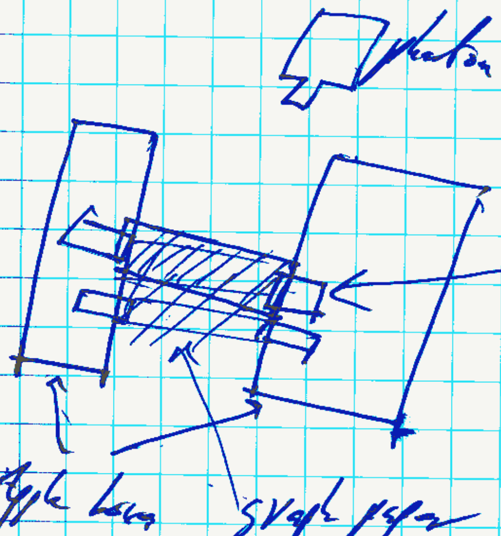
John Hawkinson / Strobe 6 — 31 Oct 2008

Mark I Week 2

Trial	Eff Rate Frame	Res.	Exp.	Ap.	Temp.
1	97,560	128x64	7.25µs	f/4	250°C
2	"	"	"	"	

EDR 4µs

• both recorded from "below" angle



3/32" glass

Adam drops screwdriver. Craftsman 41578

Lens	
50mm	Nikon 2 (not used)
28mm	Nikon 1

8"x2" cut from old glass

#3 didn't break 8½" height — no good HSV data

#4 DID BREAK 12" height — graph paper

47,058 fps 256x128 res. 18.25µs ~~EDR~~ EDR 4µs

#5 posttrigger 38,918 p (also for #4)

#6 focus on graph paper