Invisible Glass Display

Rochester Museum & Science Center

Design Description Document

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Revisions Level	Date
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Authentication Block

Revision History

Rev	Descriptions	Date	Authorization
A	Initial DDD	24-JAN	WHK
B	Museum Testing	7-FEB	WHK
C	Mechanisms	21-FEB	WHK
D	New Revenue Sources	27-FEB	WHK
E	Added Pictures	10-APR	WHK
F	Additional Math and Proofs	23-APR	WHK

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1. Introduction

The invisible glass display is a designer driven product with approval given from the Rochester Museum & Science Center. The design is inspired by Katherine Blodgett's work on antireflective coatings. Input for the design has been taken from Calvin Uzelmeier, a representative for the museum, as well as Duncan Moore, a past member of the board for the museum as well as the adviser for the project. Its design is dependent on being able to withstand consistent use and misuse while fostering entertainment and education to the public – both children and adults. The design is also requested to be centered around a female scientist and/or a local tech and Dr. Blodgett fits the request perfectly.

Dr. Blodgett was the first woman to earn a Ph.D. from the University of Cambridge which she was awarded in 1926. She was able to utilize her work at the GE Research Lab in Schenectady, NY on monomolecular coatings to help improve several optics including glasses and cameras. She has been awarded a long list of awards consisting of the following:

1. Progress Medal. The Photographic Society of America
2. Achievement Award of the American Association of University Women
3. Outstanding Woman of the Year. American Woman Magazine
4. Garvan Medal of the American Chemical Society
5. Boston First Assembly of American Women of Achievement honored scientist
6. Honorary Doctorates: Elmira College, Western College, Brown University, Russell Sage College

She has also contributed to work on the improvement of the light bulb alongside Irving Langmuir as well as work in plasma physics. Her invention of non-reflective glass in 1939 which is the inspiration for the museum exhibit, was created by building up a 44 molecule thick film of barium stearate on glass. The concept behind this is the fact that the reflecting waves off of the glass and anti-reflective surface destructively interfere by carefully engineering the thickness of the film. The exhibit will not represent the exact science behind antireflective coatings (e.g. correlating coating thickness to wavelength), it will show concepts related to invisible glass.

2. Specifications

Environment:

As an exhibit, it is inherently intended for both education and entertainment, it needs to operate in the following environment:

Temperature

Room temperature (20-25 degrees Celsius)

Relative Humidity

Standard room humidity (40-60%)

Space

Preferably smaller than 9 ft^2 (floor space) and shorter than 3 ft

Regulatory Issues:

Needs to be able to withstand misuse in every conceivable way (knocking, pulling, pushing, excessive use of force, etc.)

Fitness for use:

The invisible glass display will:

- Use a sturdy container to hold two liquids (able to withstand a force TBD).
- Have a method for a user lowering a glass piece into the liquids without having the opportunity to cause damage to the individual or display.
- Have a method for preventing the two liquids from mixing when the glass piece is used consistently over a large period of time with as much force as the system allows (referencing back to the previous requirement to limit the force or speed that an individual can lower the glass piece).
- Have the first liquid cause the glass piece to be "invisible" and the second liquid to cause the glass piece to be "visible." The exact desired matching of refractive indices will be determined with experimentation seen in the section "Design." Once specifications are determined, pictures of test cases will be reviewed with the customer to decide what refractive indices satisfactorily causes the glass piece to become "invisible."
- The liquids are allowed to be flammable and/or inedible. The liquids are not able to be highly toxic with skin exposure.
- The liquids are allowed to be replaced a maximum of every two months. It is necessary that the liquids will not harbor bacteria or any undesired contaminants within this time frame.
- Create a caption for the display that offers a simple yet informative explanation of the processes at hand.
- There is no set cost for this exhibit – the museum will determine the amount they are willing to spend after prototyping.

- It is desired that a prototype is brought into the museum for testing. This prototype does not need to be finalized in any way. It is simply meant as a proof of concept.

3. Designs

Specifications

- $n_{liquid\ 1} = n_{glass} \pm .002$
- $n_{liquid\ 2} < n_{liquid\ 1} - .15$ **OR** $n_{liquid\ 2} > n_{liquid\ 1} + .15$
- $3\ inches < L < 6\ inches$ **AND** $6\ inches < W < 12\ inches$

The specifications were determined by modeling several cases of various refractive indices in Code V. The various test cases can be seen in the diagrams below.

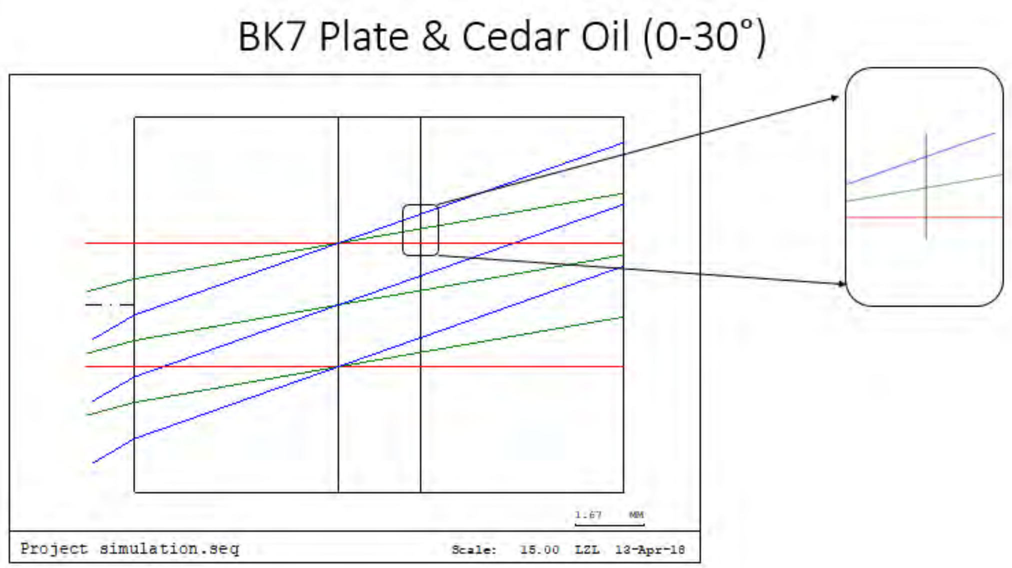

Figure 1: Code V Model of N-BK7 Plate in Cedar Oil (0.0012 Variation in Refractive Index).

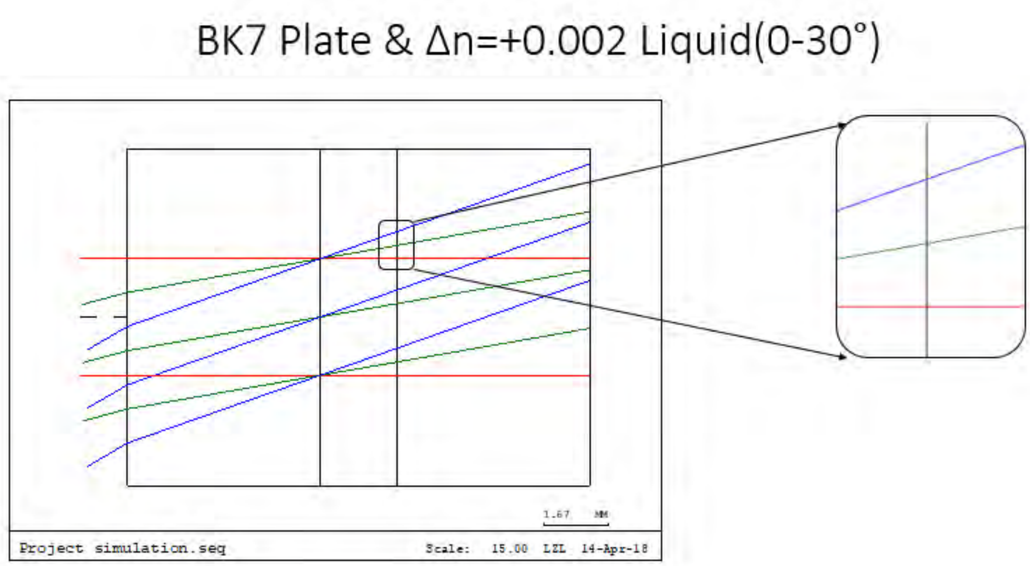

Figure 2: Code V Model of N-BK7 Plate in Liquid with 0.002 Variation in Refractive Index.

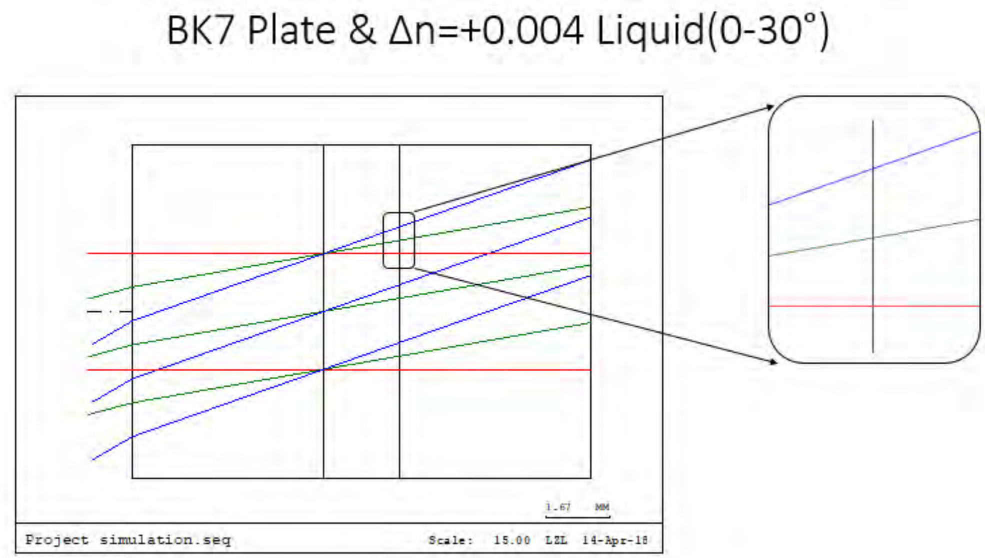

Figure 3: Code V Model of N-BK7 Plate in Liquid with 0.004 Variation in Refractive Index.

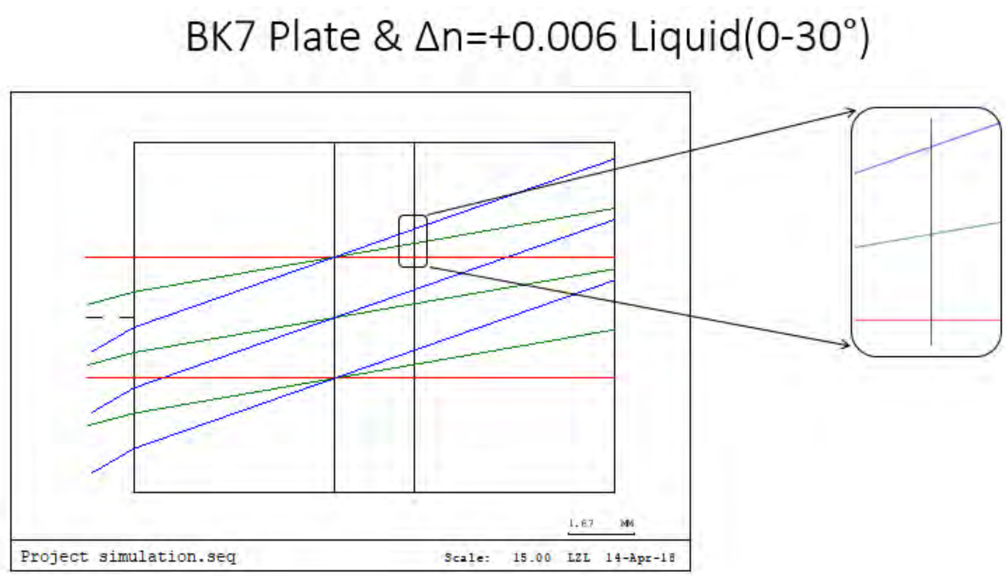

Figure 4: Code V Model of N-BK7 Plate in Liquid with 0.006 Variation in Refractive Index.

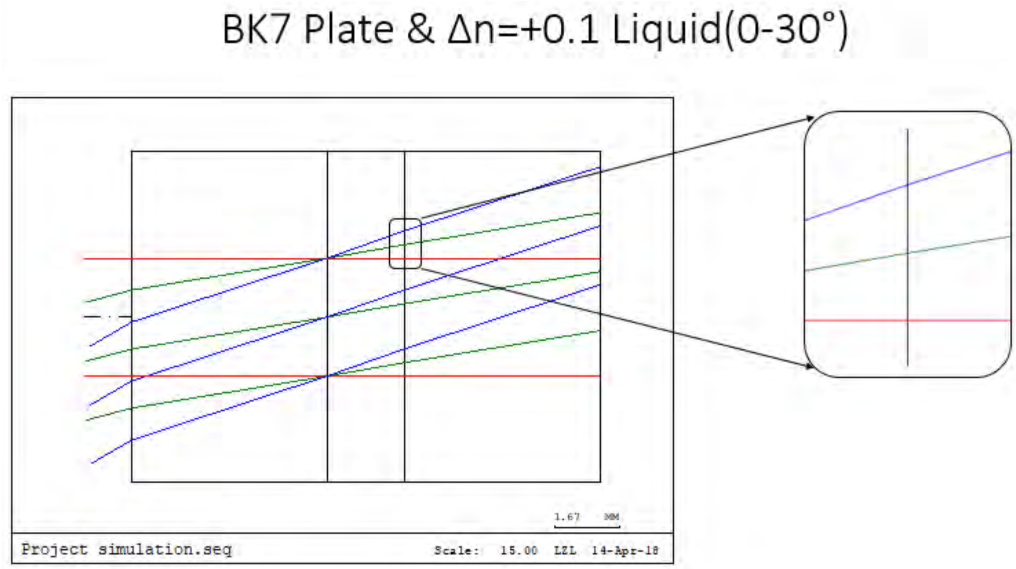

Figure 5: Code V Model of N-BK7 Plate in Liquid with 0.1 Variation in Refractive Index.

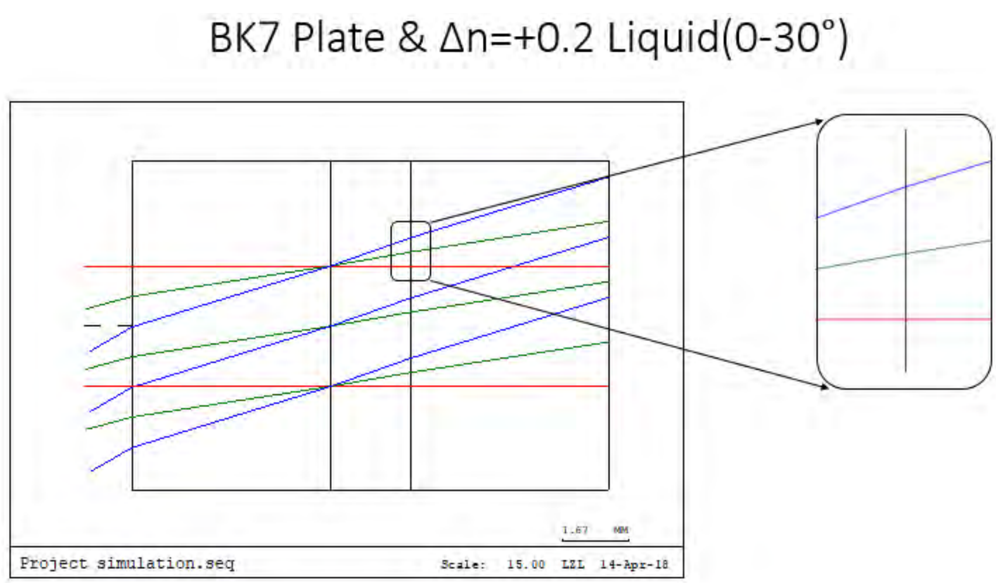

Figure 6: Code V Model of N-BK7 Plate in Liquid with 0.2 Variation in Refractive Index.

The current glass material in use is N-BK7, which has a refractive index of 1.5168. This is within our outlined specifications when matched with Cedar Oil, which has a refractive index of 1.518. This can be seen modeled in Figure 1 above. For future prototypes, Immersion Oil can also be used which is a synthetic cedar oil that is more stable and less yellow in color. The second liquid is currently water, which has a refractive index of 1.333. This is within our outlined specifications for separation of refractive indices of the two liquids. Although the models above make it hard to distinguish bending with a variation in refractive index of .1 to .2, the Fresnel Reflection

Coefficients which are calculated later will demonstrate why this is enough of a variation to easily see the N-BK7 plate.

Material Name	Index	Delta Index from Glass
N-BK7	1.5168	0
Air	1	-.5168
Water	1.33	-.1868
Cedar Oil	1.518	+0.0012

Table 1: Refractive Indices of Various Materials to be used in Phase I Prototype.

There are different possible ways of demonstrating invisible glass. Each case involves matching the glass and liquid to the specifications that were determined. One method to demonstrate the effect is to submerge a flat glass plate or disc in an index matched oil. This will demonstrate that the glass will be nearly impossible to distinguish while in the index matched oil yet be completely visible in both air and water. There are two different cases that can be used – a polished optic and an unpolished optic. While using a polished optic, the visibility in air and water is less than that of a dry unpolished optic. It is specified that this is only the case for a dry unpolished optic because oil residue remains on an unpolished optic once contact has been made. The oil fills in all of the small imperfections within the optic, and since the optic has the same refractive index as the glass, the optic no longer appears unpolished. For this reason, it does not necessarily matter which type of optic is used.

Working with Mike Pomerantz, the team took a disc of N-BK7 and from a rough diamond cut, ground and polished it into a finished product. Our disc was only finely ground with 9 micrometer Aluminum Oxide so that it remained opaque. Issues arose by the fact that chips in the glass were discovered; however, since this is just a prototype, the museum can purchase better quality glass for their final display.

Another method to demonstrate the effect is to submerge a lens in an index matched oil. If using a magnifying lens, a picture or object can be placed behind the lens. This method would show that while the magnifying lens is in air or water that the picture or object is magnified; and, when the magnifying lens is in the index matched oil, the picture or object is no longer magnified. This is due to the fact that light only bends at a lens due to a difference in refractive index. With negligible variation in the refractive index, the light no longer bends in a manner that magnifies. This is an exciting phenomenon that can be accomplished because of the index matching, but largely takes away from the focus on the glass being seemingly invisible. Since the focus is meant to be on invisible glass, it is not advisable to use this as the only demonstration; however, this is a great supplemental demonstration.

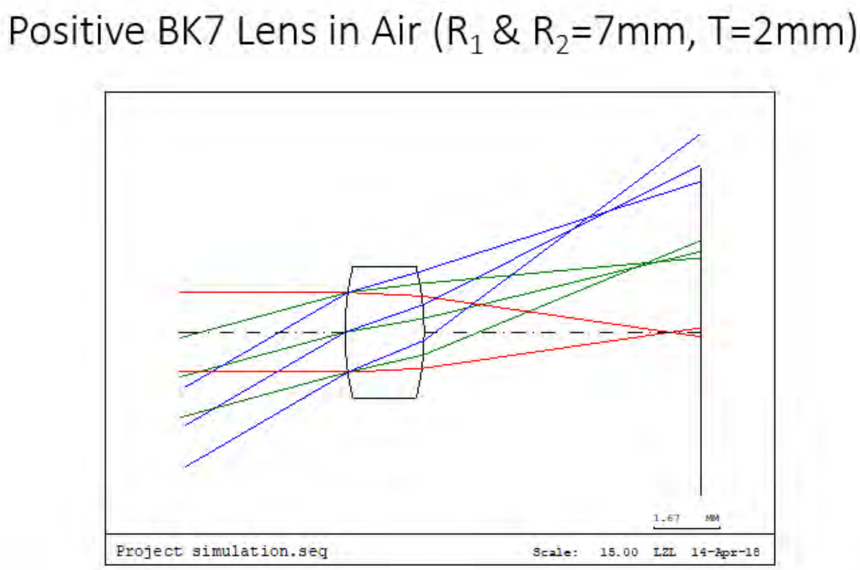

Figure 7: Code V Model of Positive N-BK7 Lens with Radii Equal to 7mm and a Thickness of 2mm in Air.

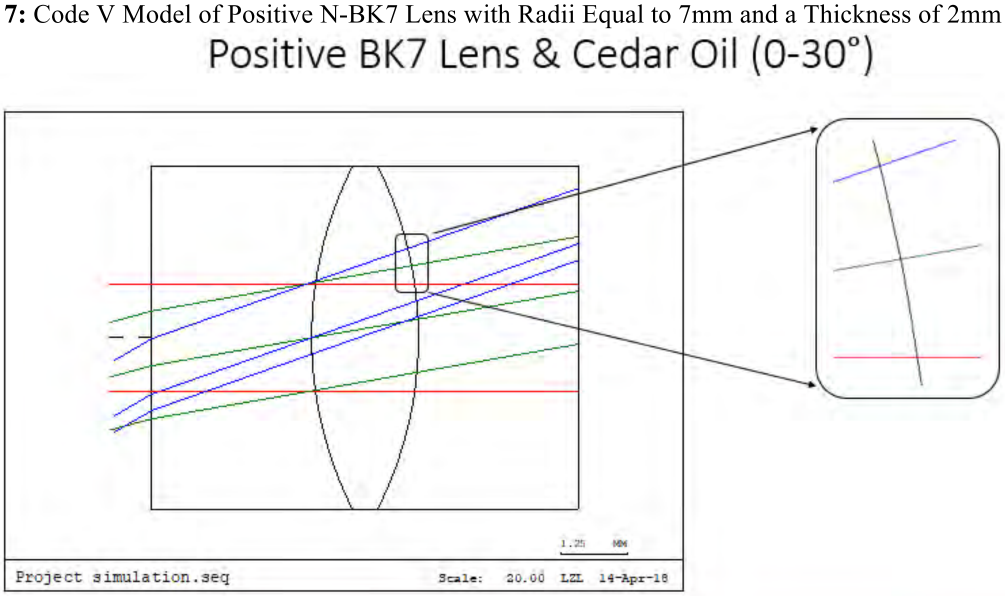

Figure 8: Code V Model of Positive N-BK7 Lens in Cedar Oil (0.0012 Variation in Refractive Index).

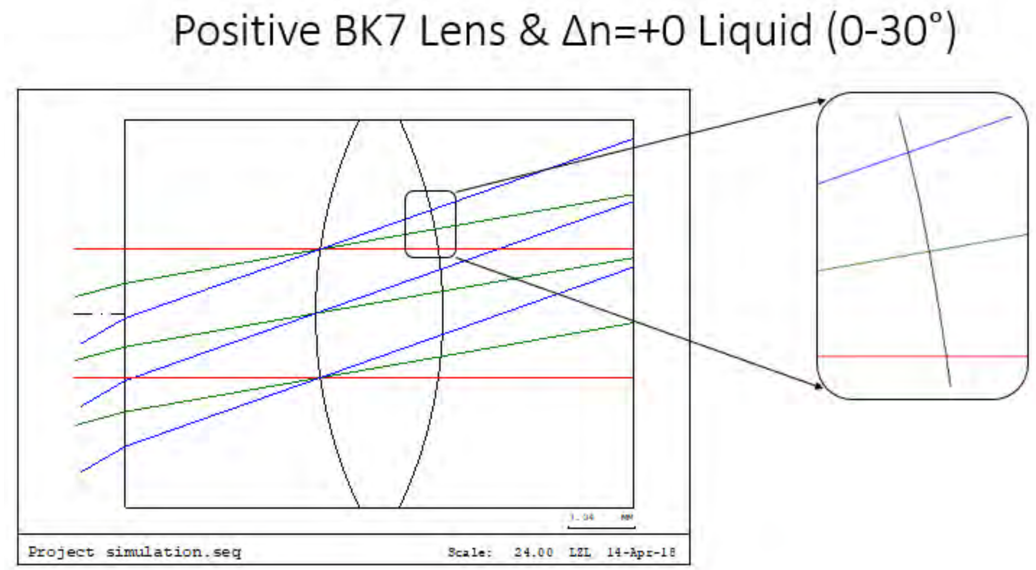

Figure 9: Code V Model of Positive N-BK7 Lens in Liquid with 0 Variation in Refractive Index.

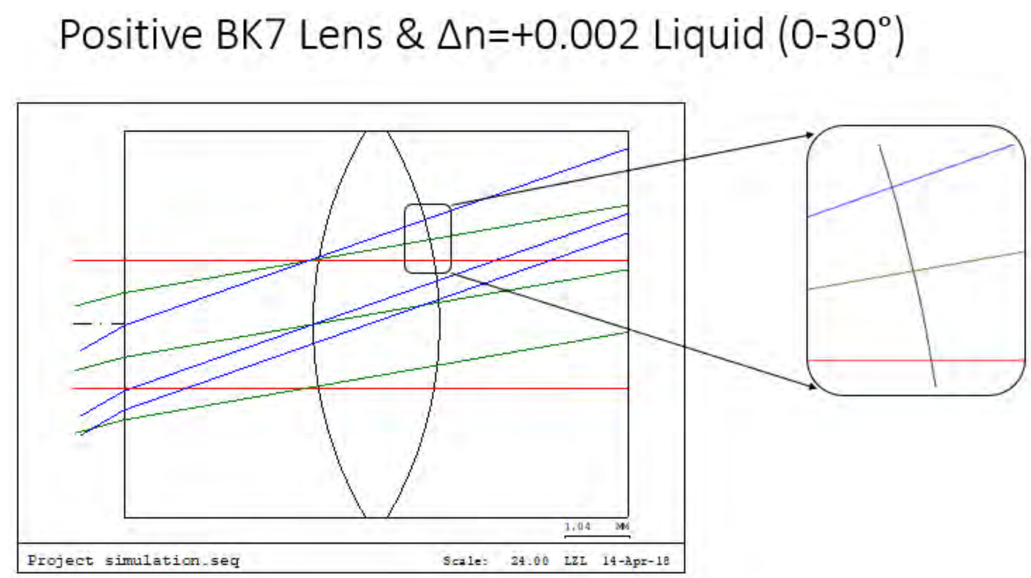

Figure 10: Code V Model of Positive N-BK7 Lens in Liquid with 0.002 Variation in Refractive Index.

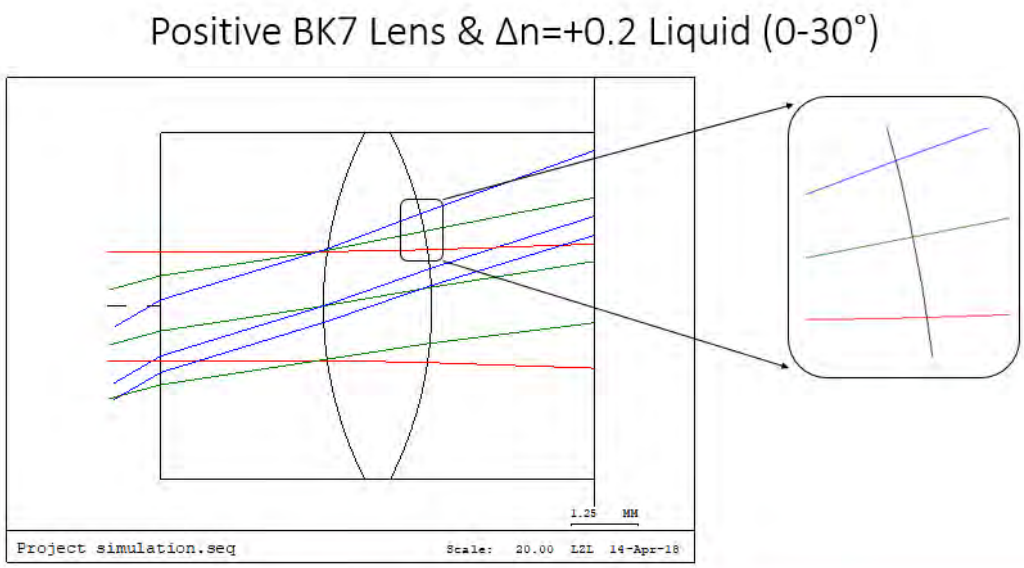

Figure 11: Code V Model of Positive N-BK7 Lens in Liquid with 0.2 Variation in Refractive Index.

It is important to note that the lighting of the exhibit is important while using a glass plate. This is because reflections are dramatically increased with the increased light exposure. For this reason it is important to not put the exhibit near large windows. This issue can be fixed by internally lighting the glass optic or applying an anti-reflecting coating to the tank. This is also not an issue if a lens is used rather than a plate. The lens would still be visible due to the increased reflection in sunlight; however, the magnifying effect would be unaltered.

The containment of the liquids for demonstration purposes is a simple fish tank; however, any transparent container for liquid can be used.

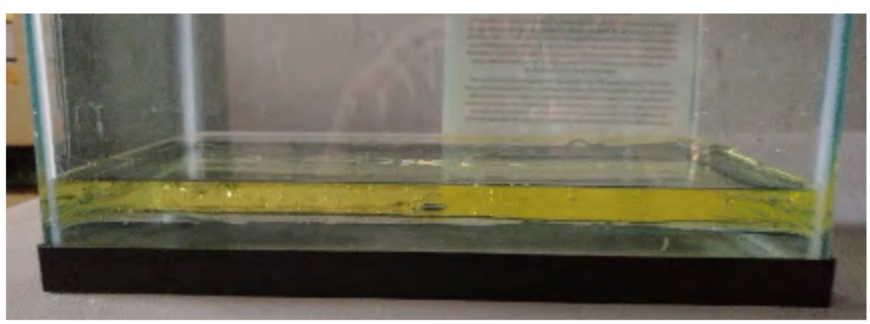

Figure 12: Fish Tank that will be used for Phase I Prototype.

Fresnel reflections were calculated to determine if there is a need for the exhibit to be viewed within a certain angle. The graphs for this can be seen below for S polarized, P polarized, and non-polarized light.

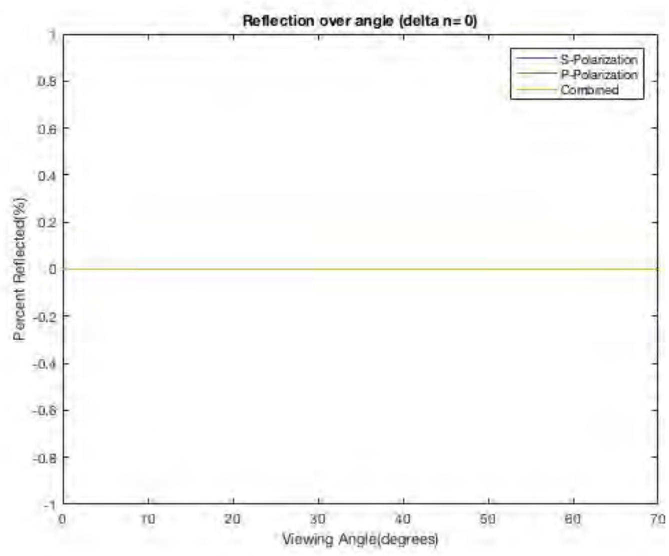

Figure 13: Fresnel Reflection Coefficients for 0 variation in refractive index.

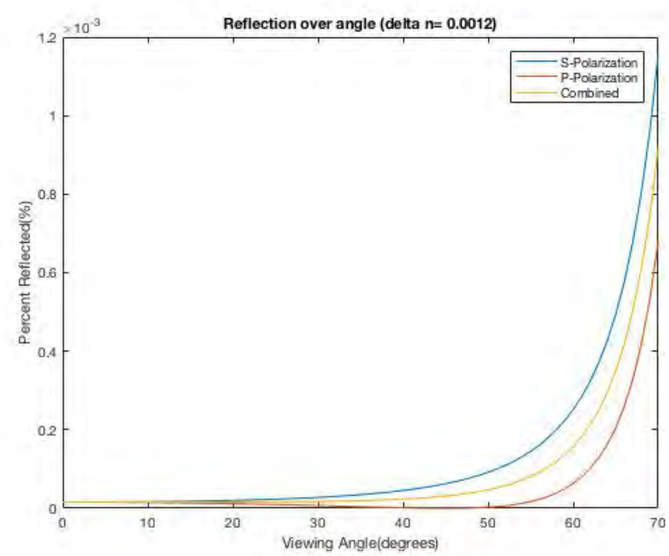

Figure 14: Fresnel Reflection Coefficients for 0.0012 variation in refractive index.

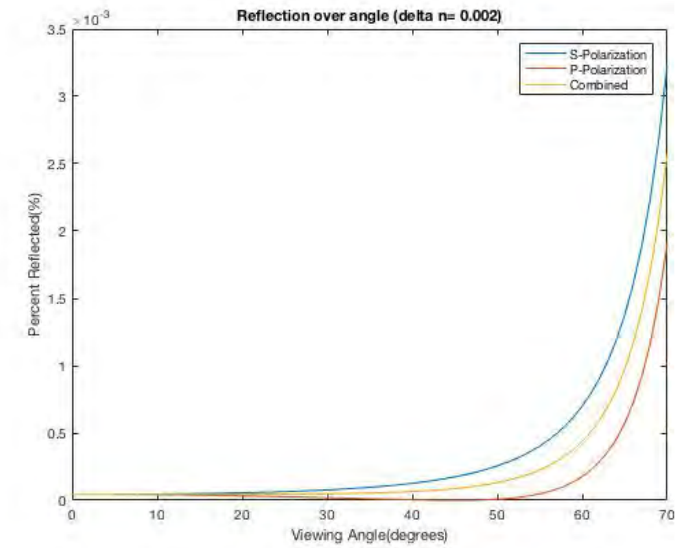

Figure 15: Fresnel Reflection Coefficients for 0.002 variation in refractive index.

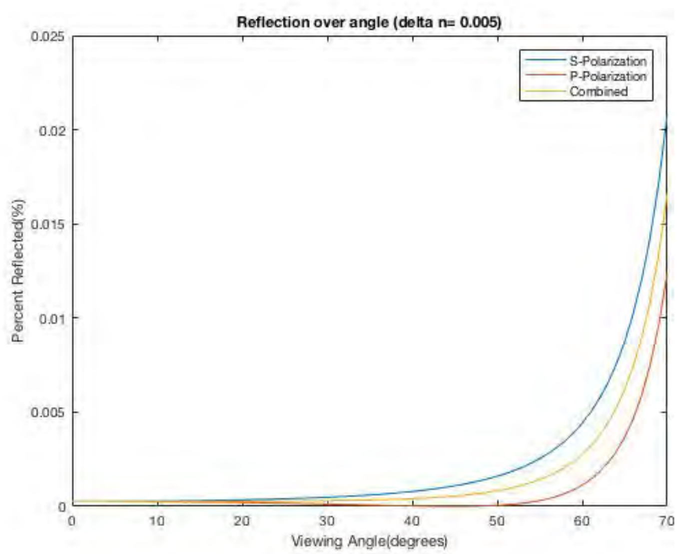

Figure 16: Fresnel Reflection Coefficients for 0.005 variation in refractive index.

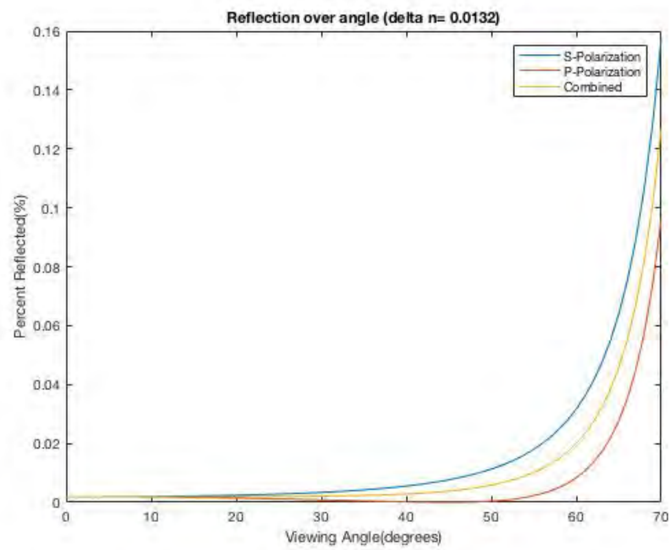

Figure 17: Fresnel Reflection Coefficients for 0.0132 variation in refractive index.

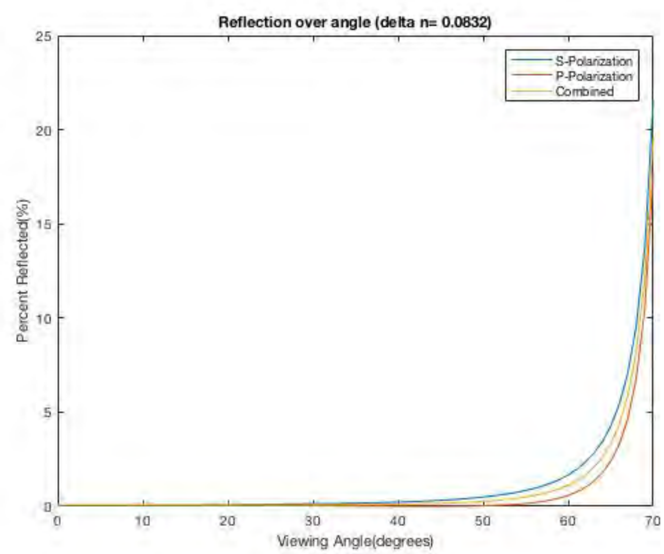

Figure 18: Fresnel Reflection Coefficients for 0.0832 variation in refractive index.

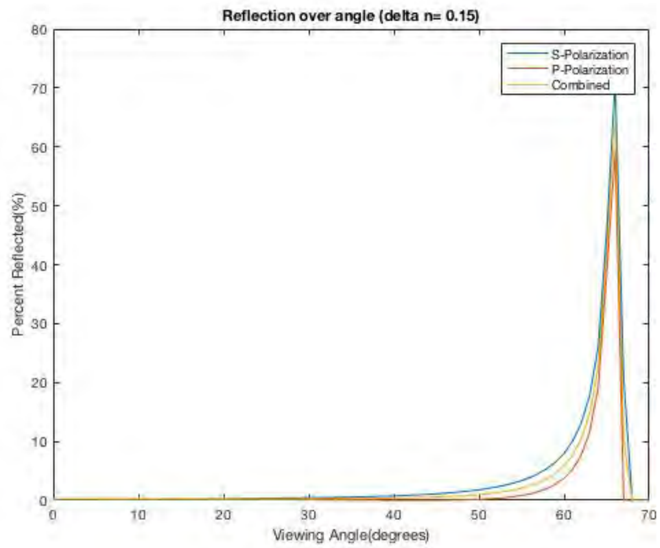

Figure 19: Fresnel Reflection Coefficients for 0.15 variation in refractive index.

It is desired that the reflection of the glass in oil is less than that of a typical antireflective coating – a typical value being .5%. For an index variation of .002, the exhibit could have a 140 degree field of view with a reflection of less than .005%. This means that reflection is extremely negligible for the specifications given. For an index variation of .0012, which is equal to the variation of cedar oil and N-BK7, the reflection is less than .0012% for a 140 degree field of view. For an index variation of .15, the reflection is upwards of 50% for a 140 degree field of view. This is beneficial because the glass would be quite visible with such high reflection.

To raise and lower the glass an electronic motor will be utilized that can have a set speed and stop movement at the position the user chooses. The motor is 12V and raises or lowers the arm based on the polarity of the current. The speed of the motor can be adjusted by using various voltages; however, 12V is what will be used for the Phase I Prototype due to the desirable speed that results. We are using a polarity controlling switch such that the wires do not need to be switched in order to change the direction of the arm.

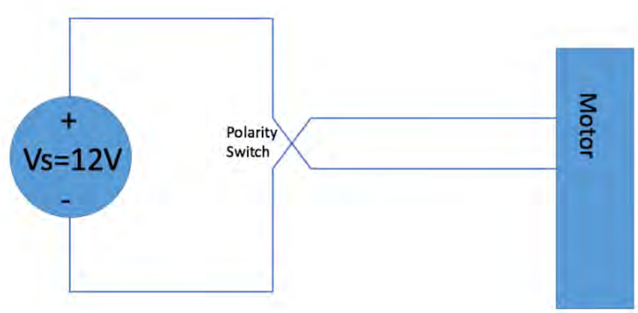

Figure 20: Schematic for Motor Mechanism, Voltage Source, and Control Switch

4. Testing

Preliminary Material Testing

The use of a latex membrane between liquids was tested in order to see if it would significantly reduce the time that it took for two liquids to mix. This had unnoticeable benefits to prevent mixing. It was also found that using hydrophilic liquids next to hydrophobic liquids prevents mixing over a large period of time, even if there are thorough mixing attempts.

It was found that Calcium Fluoride and Ethylene Glycol are close enough in refractive index for the desired transparency; however, Calcium Fluoride was found to be expensive and Ethylene Glycol is hydrophilic (making it such that it will mix with water quickly). For these reasons, this combination is not viable for the exhibit. Pyrex was found to have a close enough refractive index to vegetable oil such that the combination is within specifications and both of these materials have reasonable prices. Further, vegetable oil is hydrophobic, which means that mixing will not be an issue. N-BK7 in Cedar Oil was also found to be a sufficient match for refractive index. The "invisibility" effect works better than the Pyrex and vegetable oil combination; however, the combination is more expensive.

Preliminary Museum Testing

Using Pyrex in Canola Oil and distilled water as well as N-BK7 in Cedar Oil and distilled water, testing was conducted at the museum. Both combinations worked well and all of the general public that participated saw the glass "disappear" in both cases.

Several methods of explaining the science behind the exhibit were attempted to test the public's understanding. It was found that only introducing one unfamiliar word ("refractive index") was optimal for children to grasp the general concept. It was explained similar to the following statement:

> *"Light interacts with objects based on their refractive index. If two objects have the same refractive index, light is unable to distinguish between the two objects if they are in one another which is what causes the glass to seemingly disappear in the oil."*

It is desired that simple explanation such as the one above is given, followed by a more in depth explanation for people that are curious to learn more.

Upon further evaluation and editing, the following statement was written:

> *"Light interacts with objects based on their refractive index; therefore, if two objects have the same refractive index, light is unable to distinguish between them.*
>
> *When light travels from one transparent object to another, it refracts based on each object's refractive index due to Snell's Law. If the two objects have different refractive indices, the light will bend and allow us to see the boundary between the surfaces; however,*

when the glass is placed in the oil, their refractive indices match, and the light does not bend making the glass seemingly invisible."

The blurb is talking about refraction rather than reflection because this is the easier scientific phenomenon to explain, which will help the readers understand the concepts behind the exhibit better. Reflection will not be mentioned as well as refraction due to the length requirements of the blurb as stated by the museum and recommended by the Smithsonian Guidelines for Accessible Exhibition Design[3], to be one hundred words or less. Both concepts cannot effectively be explained to the public in this number of words.

This blurb was tested at the museum and was still too complicated for many children, and did not meet the recommendations made by the Smithsonian Guidelines. For this reason, the following two captions were crafted depending on whether the museum would like to explain the exhibit in terms of reflection or refraction:

"Notice that the glass disappears when it enters the oil. This is due to the way that light behaves with objects. Light bends when it hits the edge of a new object which allows us to see it.

This is known as refraction. Light bends different amounts depending on what material it is passing through. The amount light bends is determined by a property known as refractive index. If an object is in a liquid with a similar refractive index, the light will not bend in the object – this makes it appear invisible."

"At home you may notice that at night you can see yourself in the windows, kind of like a mirror. This is because the windows in your house are reflecting a lot of light – allowing you to see that the window is there. It is much harder to see your reflection during the daytime because a smaller amount of light is reflected - this makes the window much harder to see. The oil makes it so almost no light is reflected from the glass - this makes it extremely difficult to see the glass at all."

It is desired by the museum that there be a sketch that demonstrates refraction or reflection. Below are some possible diagrams that the museum can base their sketch off of for the final exhibit. The museum desires to create their own sketch for the final exhibit.

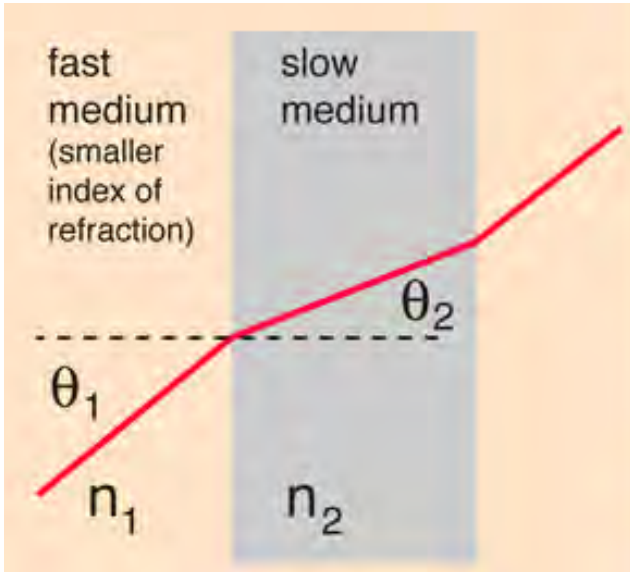

Figure 21: Ray Model of Snell's Law. [4]

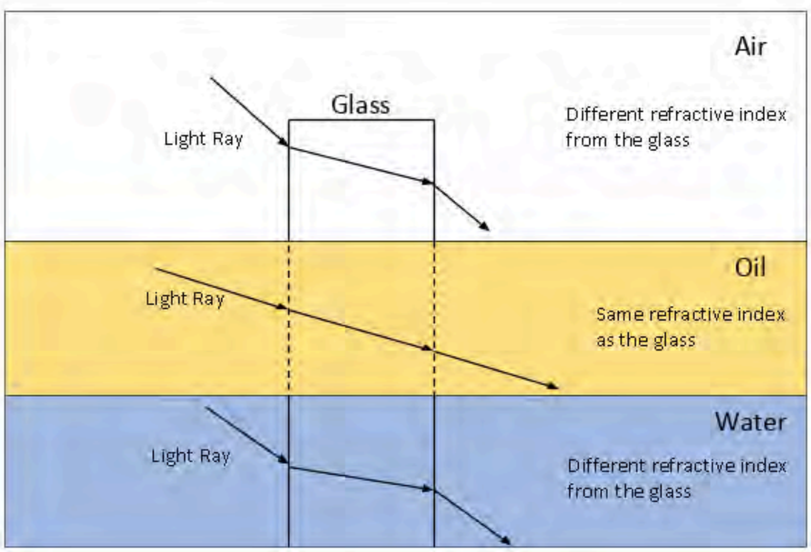

Figure 22: Ray Model of Snell's Law Created by Our Team (not to scale).

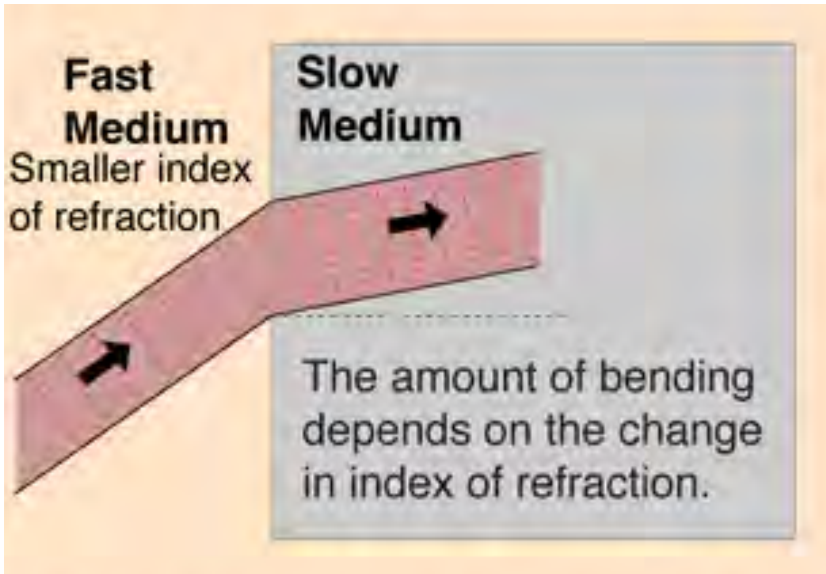

Figure 23: Wave Model of Snell's Law. [4]

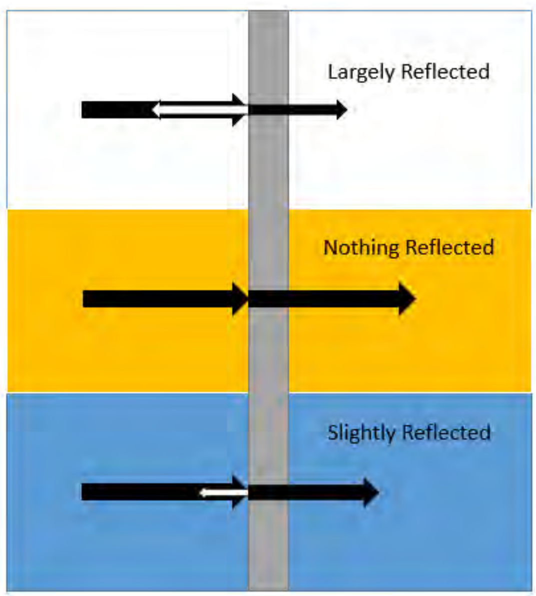

Figure 24: Ray model created by the team (not to scale).

A standard two-and-a-half-gallon fish tank was used to test whether the silicon seal would be deteriorated by oil. Tests have shown that the oil has no observable impact on the seal. This can be seen in Figure 12.

5. Fabrication

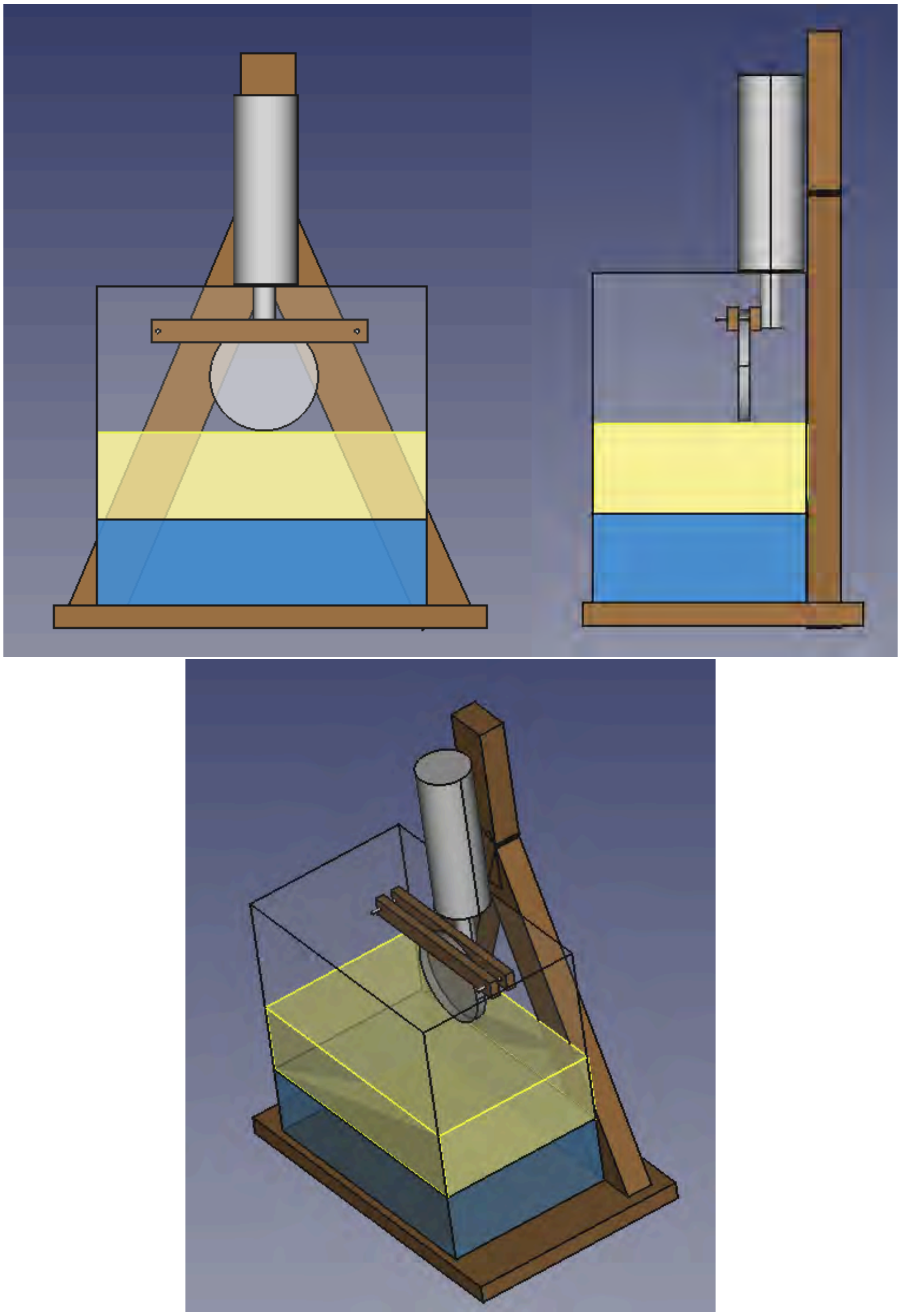

Figure 25: Front, Side, and Angled View of CAD design for Phase I Prototype.

Phase I:

During phase I building, a mount was made for the optic as seen in figure 26. The museum created a 3D printed piece to connect the mount to the motor which will be used to move the glass.

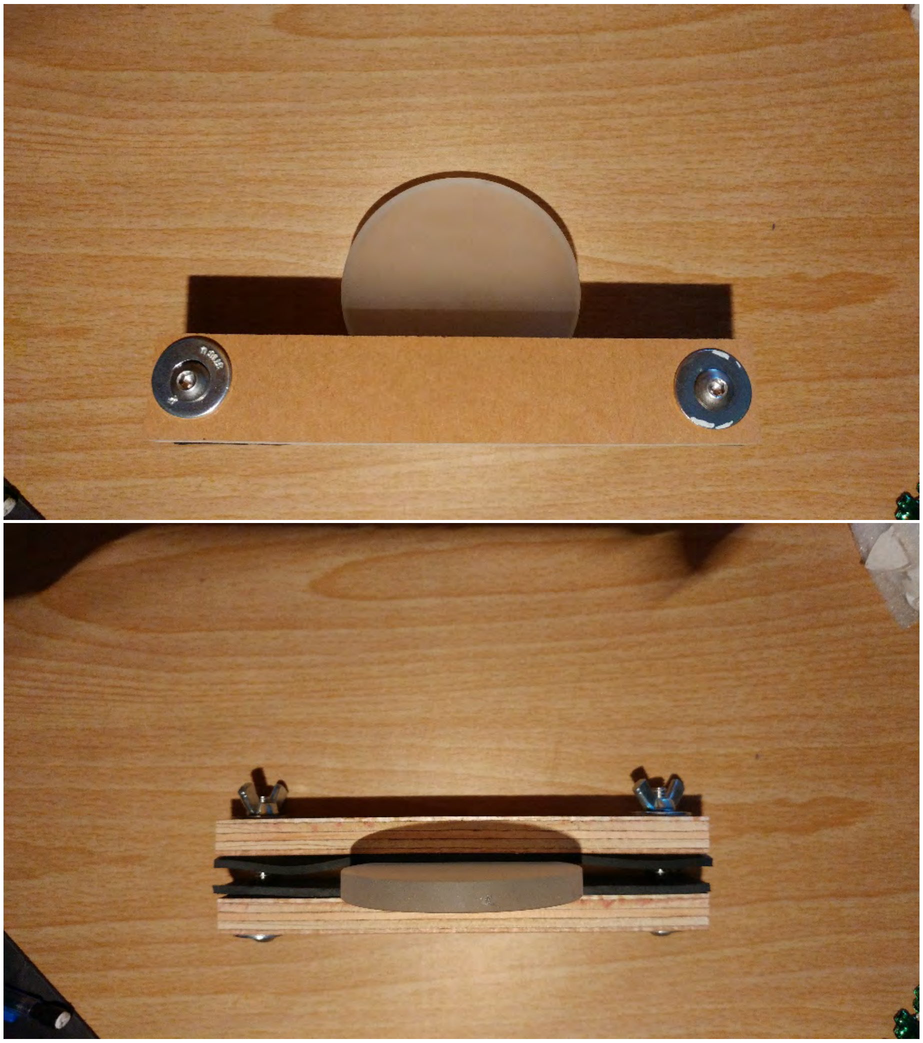

Figure 26: Front and Bottom View of Clamp for Phase I Prototype.

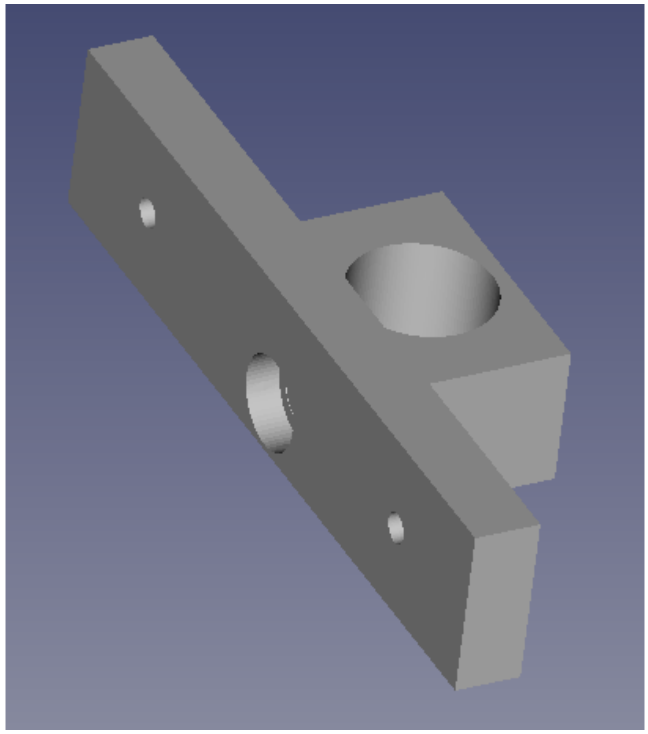

Figure 27: CAD model of 3D printed part to attach clamp to motor for Phase 1 prototype.

Figure 28: Front, Side, and Angled Views of Phase I Prototype.

6. Quote from Vendors

Currently there is a potential investor from the museum that would be willing to purchase more expensive and higher quality materials. The current price for materials that will be used if the investor does not decide to dedicate money to this exhibit are as follows:

Item	Price	Quantity
N-BK7 Glass	$0 (Scrap)	1
Cedar Oil	$2.50/ounce	72 oz
Container	$10 (Donated)	1
Motor	$20 (Donated)	1

Table 2: Price of Materials.

7. Timeline

Date	Action
December 9	Preliminary Material Testing
January 27	Preliminary Museum Testing
February 1	Glass Polishing
February 13	Mechanisms Museum Meeting
March 24	Product Testing with SWE
April 15	Finalize Phase I Prototype
April 21	Final Museum Testing
May 4	Design Day

Table 3: Timeline of Activities

1. Appendix A

Pictures from Testing

Shown below are images taken while testing at the Society of Women Engineer's Girls Workshop. Both the children and adults were interested and engaged about the topic during the demonstration.


We dedicate this building
of knowledge and the
It is my hope that these
and common spaces will
groundbreaking research,
collaboration across
generations to come
Robert B. Goergen
May 17, 2007
Volunteer SIGN-IN

Codes:

BK7 Plate & Cedar Oil (0-30°)

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YAN   0.0 15.0 30.0
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VUY   0.0 0.0 0.0
VLY   0.0 0.0 0.0
PRV
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END
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S     0.0 2.0 NBK7_SCHOTT
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GO
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BK7 Plate & Δn=+0.002 Liquid(0-30°)

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S     0.0 2.0 NBK7_SCHOTT
  STO
S     0.0 5.0 '002'
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SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

BK7 Plate & Δn=+0.004 Liquid(0-30°)

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RDM;LEN       "VERSION: 11.0      LENS VERSION: 82      Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   3.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUY   0.0 0.0 0.0
VLY   0.0 0.0 0.0
PRV
  PWL 656.2725 587.5618 486.1327
  'cedar' 1.518 1.518 1.518
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
  PWL 656.2725 587.5618 486.1327
  '004' 1.5208 1.5208 1.5208
END
SO    0.0 0.1e14
S     0.0 5.0 '004'
S     0.0 2.0 NBK7_SCHOTT
  STO
S     0.0 5.0 '004'
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

BK7 Plate & Δn=+0.006 Liquid(0-30°)

```
RDM;LEN       "VERSION: 11.0       LENS VERSION: 82       Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   3.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUY   0.0 0.0 0.0
VLY   0.0 0.0 0.0
PRV
  PWL 656.2725 587.5618 486.1327
  'cedar' 1.518 1.518 1.518
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
  PWL 656.2725 587.5618 486.1327
  '004' 1.5208 1.5208 1.5208
  PWL 656.2725 587.5618 486.1327
  '006' 1.5228 1.5228 1.5228
END
SO    0.0 0.1e14
S     0.0 5.0 '006'
S     0.0 2.0 NBK7_SCHOTT
  STO
S     0.0 5.0 '006'
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

BK7 Plate & Δn=+0.1 Liquid(0-30°)

```
RDM;LEN       "VERSION: 11.0       LENS VERSION: 82       Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   3.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUY   0.0 0.0 0.0
VLY   0.0 0.0 0.0
PRV
  PWL 656.2725 587.5618 486.1327
  'cedar' 1.518 1.518 1.518
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
  PWL 656.2725 587.5618 486.1327
  '004' 1.5208 1.5208 1.5208
  PWL 656.2725 587.5618 486.1327
  '006' 1.5228 1.5228 1.5228
  PWL 656.2725 587.5618 486.1327
  '01' 1.5268 1.5268 1.5268
  PWL 656.2725 587.5618 486.1327
  '1' 1.6168 1.6168 1.6168
END
SO    0.0 0.1e14
S     0.0 5.0 '1'
S     0.0 2.0 NBK7_SCHOTT
  STO
S     0.0 5.0 '1'
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

BK7 Plate & Δn=+0.2 Liquid(0-30°)

```
RDM;LEN       "VERSION: 11.0      LENS VERSION: 82      Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   3.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUY   0.0 0.0 0.0
VLY   0.0 0.0 0.0
PRV
  PWL 656.2725 587.5618 486.1327
  'cedar' 1.518 1.518 1.518
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
  PWL 656.2725 587.5618 486.1327
  '004' 1.5208 1.5208 1.5208
  PWL 656.2725 587.5618 486.1327
  '006' 1.5228 1.5228 1.5228
  PWL 656.2725 587.5618 486.1327
  '01' 1.5268 1.5268 1.5268
  PWL 656.2725 587.5618 486.1327
  '1' 1.6168 1.6168 1.6168
  PWL 656.2725 587.5618 486.1327
  '5' 1.6668 1.6668 1.6668
  PWL 656.2725 587.5618 486.1327
  '15' 1.6668 1.6668 1.6668
  PWL 656.2725 587.5618 486.1327
  '2' 1.7168 1.7168 1.7168
END
SO    0.0 0.1e14
S     0.0 5.0 '2'
S     0.0 2.0 NBK7_SCHOTT
  STO
S     0.0 5.0 '2'
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

Positive BK7 Lens in Air (R_1 & R_2=7mm, T=2mm)

```
RDM;LEN       "VERSION: 11.0      LENS VERSION: 82      Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   2.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUX   0.853448423043801le-10 -0.002794564207345474 -0.0116663475676808l
VLX   0.853448423043801le-10 -0.002794564207345474 -0.01166634756768081
VUY   0.853448423043801le-10 -0.02093143379010254 -0.06594750070724588
VLY   0.853448423043801le-10 0.003321690961041734 0.7620955438794428
PRV
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
  PWL 656.2725 587.5618 486.1327
  '15' 1.6668 1.6668 1.6668
END
SO    0.0 0.1e14
S     0.0 3.0
  CIR 2.7736
  ADX 0.0
S     7.0 2.0 NBK7_SCHOTT
S     -7.0 7.0
  STO
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

Positive BK7 Lens & Δn=+0 Liquid (0-30°)

```
RDM;LEN       "VERSION: 11.0       LENS VERSION: 82       Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   2.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUX   -0.2664535259100376e-14 -0.2442490654175344e-14 -0.1776356839400251e-13
VLX   -0.2664535259100376e-14 -0.2442490654175344e-14 -0.1776356839400251e-13
VUY   -0.2664535259100376e-14 0.01243337967533309 0.02506834790368295
VLY   -0.2664535259100376e-14 -0.01243337964180968 -0.02506834788739742
PRV
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
END
SO    0.0 0.1e14
S     0.0 3.0 NBK7_SCHOTT
  CIR 2.7458
  ADX 0.0
S     7.0 2.0 NBK7_SCHOTT
  STO
S     -7.0 3.0 NBK7_SCHOTT
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

Positive BK7 Lens & Δn=+0.002 Liquid (0-30°)

```
RDM;LEN       "VERSION: 11.0      LENS VERSION: 82      Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   2.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUX   0.9944378653869999e-10 0.6746715020766736e-5 0.2642296537125333e-4
VLX   0.9944378653869999e-10 0.6746715020766736e-5 0.2642296537125333e-4
VUY   0.9944378653869999e-10 -0.01449793661655496 -0.02917907322591962
VLY   0.9944378653869999e-10 0.01454196718798584 0.6963588057321731
PRV
  PWL 656.2725 587.5618 486.1327
  '002' 1.5188 1.5188 1.5188
END
SO    0.0 0.1e14
S     0.0 3.0 '002'
  CIR 2.0475
  ADX 0.0
S     6.0 2.0 NBK7_SCHOTT
S     -6.0 3.0 '002'
  STO
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

Positive BK7 Lens & Δn=+0.2 Liquid (0-30°)

```
RDM;LEN       "VERSION: 11.0      LENS VERSION: 82      Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   2.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUX   0.9944378653869999e-10 0.6746715020766736e-5 0.2642296537125333e-4
VLX   0.9944378653869999e-10 0.6746715020766736e-5 0.2642296537125333e-4
VUY   0.9944378653869999e-10 -0.01449793661655496 -0.02917907322591962
VLY   0.9944378653869999e-10 0.01454196718798584 0.6963588057321731
PRV
  PWL 656.2725 587.5618 486.1327
  '2' 1.7188 1.7188 1.7188
END
SO    0.0 0.1e14
S     0.0 3.0 '002'
  CIR 2.0475
  ADX 0.0
S     6.0 2.0 NBK7_SCHOTT
S     -6.0 3.0 '002'
  STO
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

Positive BK7 Lens & Cedar Oil (0-30°)

```
RDM;LEN       "VERSION: 11.0       LENS VERSION: 82       Creation Date: 13-Apr-2018"
TITLE 'Project simulation.seq'
EPD   2.0
DIM   M
WL    656.2725 587.5618 486.1327
REF   2
WTW   1 1 1
TEM   22.5
INI   'LZL'
XAN   0.0 0.0 0.0
YAN   0.0 15.0 30.0
WTF   1.0 1.0 1.0
VUX   0.994437865386999e-10 0.674671502076736e-5 0.2642296537125333e-4
VLX   0.994437865386999e-10 0.674671502076736e-5 0.2642296537125333e-4
VUY   0.994437865386999e-10 -0.01449793661655496 -0.02917907322591962
VLY   0.994437865386999e-10 0.01454196718798584 0.6963588057321731
PRV
  PWL 656.2725 587.5618 486.1327
  'cedar' 1.516 1.516 1.516
END
SO    0.0 0.1e14
S     0.0 3.0 '002'
  CIR 2.0475
  ADX 0.0
S     6.0 2.0 NBK7_SCHOTT
S     -6.0 3.0 '002'
  STO
S     0.0 0.0
SI    0.0 0.0
CLS   WVL RED FOR BLU
GO
```

```
ng=1.5168;
no=[1.5168,1.518,1.5188,1.53,1.5168+.15,1.6,1.5168+.005];
thetai=0:70;
thetat=zeros(7,71);
for k=1:length(no)
    thetat(k,:)=asind(no(1,k)./ng.*sind(thetai(:)));
end
for j=1:length(no)
    Rs(:)=((no(j)*cosd(thetai)-ng*cosd(thetat(j,:)))./((no(j)*cosd(thetai)+ng*cosd(thetat(j,:))))).^2;
    Rp(:)=((no(j)*cosd(thetat(j,:))-ng*cosd(thetai))./((no(j)*cosd(thetat(j,:))+ng*cosd(thetai)))).^2;
    for l=1:length(Rs)
    if(Rs(l)<1*10^-28)
        Rs(l)=0;
    end
    if(Rp(l)<1*10^-28)
        Rp(l)=0;
    end
    end
    R=(Rs+Rp).*.5;
    figure
    plot(thetai,Rs*100,thetai,Rp*100,thetai,R*100)
    delta(j)=no(j)-ng;
    title(num2str(delta(j)))
    xlabel('Viewing Angle')
    ylabel('Percent Reflected')
    legend('S-Polarization','P-Polarization','Combined')
end
```

Letter to the Museum

A letter was requested in simplified form for the museum. This can be seen below.

History of Katherine

Katherine was the first woman to earn a Ph.D. from the University of Cambridge which she was awarded in 1926. She was able to utilize her work at the GE Research Lab in Schenectady, NY on monomolecular coatings to help improve several optics including glasses and cameras. She has been awarded a long list of awards consisting of the following:
1. Progress Medal. The Photographic Society of America
2. Achievement Award of the American Association of University Women
3. Outstanding Woman of the Year. American Woman Magazine
4. Garvan Medal of the American Chemical Society
5. Boston First Assembly of American Women of Achievement honored scientist
6. Honorary Doctorates: Elmira College, Western College, Brown University, Russell Sage College

She has also contributed to work on the improvement of the light bulb alongside Irving Langmuir as well as work in plasma physics. Her invention of non-reflective glass in 1939 which is the inspiration for the museum exhibit, was created by building up a 44 molecule thick film of barium stearate on glass. The concept behind this is the fact that the reflecting waves off of the glass and anti-reflective surface destructively interfere by carefully engineering the thickness of the film.

Use of Exhibit

Building:

- Glass plate or lens that is matching in index to the oil within a refractive index of .002
  - If using a magnifying lens, it is important to put a picture behind the glass so that the viewers can see the change in magnification - recommended to use refraction blurb if using a lens
  - Recommended to use reflection blurb if using a plate

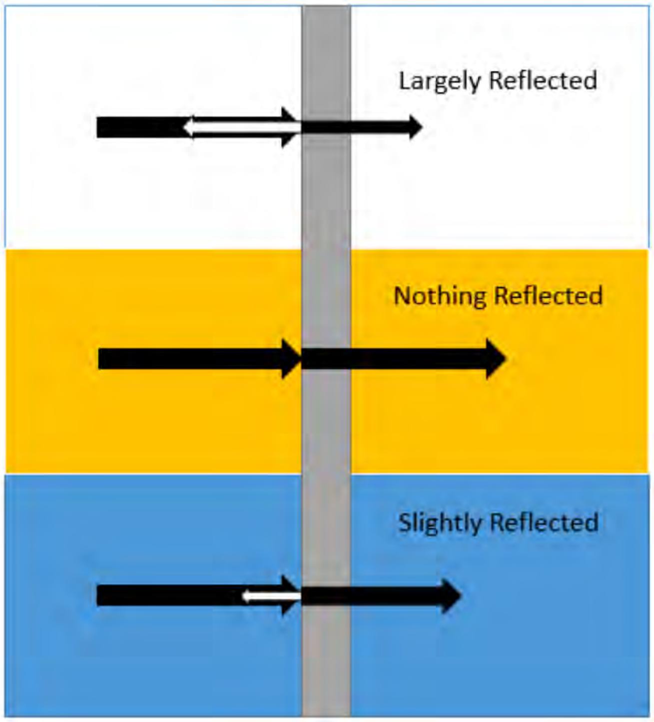
Material Name	Index	Delta Index from Glass
Glass-BK7	1.5168	0
Air	1	-.5168
Water	1.33	-.1868
Cedar Oil	1.518	0.0012

- Another liquid (currently using water) that has a refractive index variation of more than .15 from the optic
- One liquid MUST be hydrophobic and one liquid MUST be hydrophilic
- Container that can hold enough liquid to complete submerge the optic in any of the three layers (water, oil, air)
- Mount to hold motorized arm upside down over the liquid container
- Voltage source that hooks up to motorized arms via a polarity switch

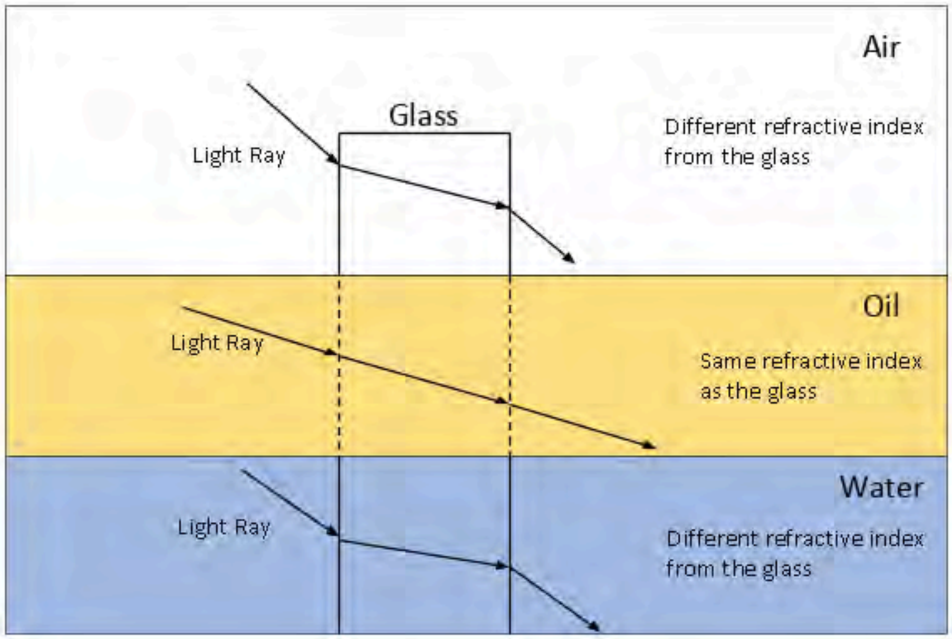
Operating:
Use the switch to move the mechanical arm up or down.

Exhibit Caption

Explanation in terms of reflection:
“At home you may notice that at night you can see yourself in the windows, kind of like a mirror. This is because the windows in your house are reflecting a lot of light, allowing you to see that the window is there. It is much harder to see your reflection during the daytime because a smaller amount of light is reflected - making it harder to see the window is there. The oil makes it so almost no light is reflected from the glass - this makes it extremely difficult to see the glass at all.”



Explanation in terms of refraction:
“Notice that the glass disappears when it enters the oil.
This is due to the way that light behaves with objects. Light bends when it hits the edge of a new object which allows us to see it. This is known as refraction. Light bends different amounts depending on what material it is passing through. The amount light bends is determined by a property known as refractive index. If an object is in a liquid with a similar refractive index, the light will not bend in the object – this makes it appear invisible.”



Info Learned through testing

Exhibit should not be near windows if possible. A large amount of light shining on the exhibit increases reflection and therefore reduces the invisibility effect. The less light coming from the viewer side of the exhibit the better. However, if it is forced to be near a window, a black background and sides along with its own illumination helps solve the problem.

Kids seemed to like the idea of adding lasers. The lasers will add additional light allowing the glass to be seen. Feel free to decide if this is a bug or a feature.

They also liked the idea of adding color. The oil itself would be difficult to change color, but if you would like to color the water something fun, simple food dye should work and will not leak into the oil. We would also recommend not trying to create purple, it usually comes out as a strange black/brown color.

People when seeing the exhibit from afar believe it to be a mixing demo. There should be a clear and distinct sign that says “Invisible Glass” so as to prevent this misconception from taking away from the purpose of the exhibit.

Materials Needed

Cedar Oil- $18.95 for 8oz at Home Depot **OR** Immersion oil- $348.5 for 500mL at :
https://www.fishersci.com/shop/products/carl-zeiss-immersol-immersion-oil-6/p-3205247

Note: Giles and Kendell that was bought has an extraordinary red color and does not work as well as the oil tested before. Test in small batches before buying large.

Cedar oil can be used, but the Immersion oil will be lighter in color and will stay lighter in color over the course of Time. They are the exact same index but Immersion is synthetic while Cedar oil is natural. Any of the “types” of immersion oil can be used since the main differences are fluorescent properties.

Glass:
Plate similar to what is currently on it: N-BK7 window uncoated 2”, $125 from
https://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=1117
Large Glass plate or Rod: $TBD. These would need to be made specially for the exhibit. This can be done through any optical fabrication shop such as Edmund Optics. The size can be up to you, it is all personal preference.
Lens-Uncoated, Positive Meniscus Lens 50.8mm, $39.53 from
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=130

Polarity electrical switch- $16 Amazon.

Motor- $20, Use the same motor as we borrowed to raise and lower the glass material.
Container:

The Container should be a clear see through material. The material should try to minimize reflection by either buying an anti-reflective glass, or using a plastic that does not reflect. Feel free to choose the size of container as wanted, but it should be thin but tall. The glass should be able to reside completely out of any liquid at the top so that the effect is not spoiled. The liquids should fill ⅓ of the tank each.

Design Day Demo

For the final review day presentation there will be a working model of the final exhibit. This will utilize an electric motor that is controlled by the user to move the glass up and down through the liquids. There will be a finalized caption for the exhibit. There will also be a caption describing Katherine Burr Blodgett, the woman the exhibit is based off of.

Reference

1. Whelan, M., and Dr. Edwin Reilly. “Katharine Burr Blodgett.” *Katharine Burr Blodgett - Engineering Hall of Fame*, Edison Tech Center, 2014, www.edisontechcenter.org/Blodgett.html.
2. “Irving Langmuir and Katharine Burr Blodgett.” *Chemical Heritage Foundation*, 30 Oct. 2015, www.chemheritage.org/historical-profile/irving-langmuir-and-katharine-burr-blodgett.
3. Majewski, Janice. “Smithsonian Guidelines for Accessible Exhibition Design.” Smithsonian Institution, Smithsonian Accessibility Program, www.si.edu/Accessibility/SGAED#page_21.
4. Nave, R. “Refraction of Light.” Refraction of Light, Georgia State University, hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html.