Flexi-focus Lens; PDMS Variable Focal Length Lens

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Statement of Confidentiality

The complete senior project report was submitted to the project advisor and sponsor. The results of this project are of a confidential nature and will not be published at this time.

Statement of Disclaimer

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Chapter 1: Introduction

The design of a variable focal length, or flexi-focus, polydimethylsiloxane (PDMS) lens incorporating a light emitting diode (LED) source is intended for future use on board commercial aircraft. Specifically, the design is intended for the Boeing 787 Dreamliner aircraft, serving as a personal reading light for the passengers seated in the cabin. Most current reading lights on board aircraft are rigid, incandescent, and have very limited freedom in terms of adjusting the emitted light. Incandescent lamps are also inefficient with respect to energy consumption and light output as well as a high heat output. In an economy of increasing demand for cost efficiency, environmentally friendly solutions, and user friendly devices, this lighting configuration is a hindrance in its application.

The Flexi-Focus LED light system will remedy this problem by allowing the passenger the freedom to refocus the light from broad flood lighting to precise spot lighting, adequate for reading. A table of user needs can be seen in Table I of Appendix F. This system involves a variable-focal length lens fabricated with PDMS, incorporated with an LED, which has the ability to flex into a range of convex surfaces when the pressure in an airtight chamber behind it is increased, thus enabling optimization for a broad range of applications. The focal length of the lens is a function of the refractive index of the lens material and the radius of curvature created by the deflection. With a known refractive index for the material, the light can be made to focus at specific distances. In the application of interest for this project, this enables the area illuminated by the LED to vary.

There are several important groups who are stakeholders in this project because of various interests in its success:

- Boeing is the company responsible for the funding of this project. The value of this project includes a potentially new, viable design of a reading light apparatus. Success of this project will allow Boeing obtain an improved lighting system to specifically integrate into the 787 Dreamliner aircraft.

- Doctor Richard Savage of California Polytechnic State University in San Luis Obispo is the team project advisor.

- The project team consisting of Patrick Angulo, Alex Doyle, Dylan McDaniel, and Michael Olivarez. The value in completing this project is to serve as a college senior project requirement for graduation.

- The California Polytechnic State University in San Luis Obispo serves as a base of operations for this project.

- End users such as airline passengers who will be directly impacted and use the final product.

Project Management

The development of this project can be separated into three major sections; design, build, and test. Within each section are milestones that marked our progress. The Gantt charts for each stage are illustrated in Appendix F. In the Gantt charts are the activities completed for each stage. The design stage involved the team familiarizing themselves with the desired material, developing theoretical data that will measure success of the product, and learning the methods to fabricate the product. The build stage incorporated application of the learned methods from the previous stage to develop the chosen conceptual design. In addition, integration of the final design to both the ThorLabs equipment and Fiber-lite equipment were major milestones in the build stage of the project. Finally, three major tests we're completed by the end of the third and final stage of the Flexi-Focus project; Lens thickness, applied pressure vs. focal length, and transmission and absorption.

In order for proper management of the tasks described, the Flexi-Focus team held weekly meetings for a minimum of 6 hours a week. Additional meetings and lab work would be scheduled when necessary. Included in the weekly team meetings, is a weekly meeting with the project advisor, Dr. Richard Savage. A Google group was created and was the primary form of communication. All data collected, literature researched, and project information was uploaded to a private file sharing service DropBox.com. Although all responsibilities will be shared among all team members, assignments for major responsibilities for each group member are listed in table I below

Table I: Team Member Responsibilities

Team member	Responsibility
Patrick Angulo	Information and Data Control
Alex Doyle	Quality Assurance
Dylan McDaniel	Team Liaison
Michael Olivarez	Testing and Manufacturing

On the next page is a risk assessment detailing potential risks and solutions. During the duration of the project, the team experienced some but not all of the risks seen below, most notably the risk of ineffective system design in the rapid prototyped part for the PDMS base. The surface finish of the part was insufficient for proper plasma bonding between PDMS parts. This caused delays in the testing stage.

Table II: Risk Assessment

Stage	Risk	Likelihood	Impact	Contingency Plan
Build	Inability to get material	Low	Low	Buy from another source or vendor
	Equipment or machines down	Medium	High	Find alternative processes
	Spin coating Process difficulties	High	High	modify PDMS mix ratio's or resort to casting lens
	Ineffective system design	Medium	High	Modify system design
Test	Unreliable test data	Medium	High	Reevaluate testing methods and processes
	Ineffective testing procedure	Medium	High	Research other testing methods
	Change in functional requirements	High	High	Retest system and/or redesign design

Chapter 2: Background

In both military and commercial aviation, traditional incandescent and halogen lighting systems are being replaced with new LED solid state lighting systems. The extent of LED applications involving aircraft range from threshold runway lighting, to passenger reading lights, to interior mood lighting systems. The shift in technology from incandescent and halogen lighting systems to LED lighting systems is largely due to the benefits LED lights offer. The primary benefits include; reliable illumination with long life, 40% lighter than incandescent systems, a high degree of design freedom, and they consume about 40% the power of incandescent systems[2,3]

The use of an LED light source rather than an incandescent offers the advantage of superior energy efficiency, increased durability, and reduced heat output. The main disadvantage of using LEDs is that producing white light is difficult, as they produce a single wavelength of light in a chromatic color like blue or red. For this reason, one of two solutions will be implemented to correct the light wavelength.

One solution is to use a blue LED with a wavelength of 475 nm with an embedded yellow phosphor film, which would cover the emitted light and 'correct' the wavelength to produce white light. The drawback to this choice is that the phosphor film is somewhat opaque, absorbing much of the light as it shines through the film, resulting in lower efficiency.

An additional solution is to use quantum dots embedded in the LED or lens. In this case, quantum dots could be integrated directly into the Flexi-Focus lens material so that the lens will both adjust the focus of the light and correct the wavelength. The advantage to this configuration over the phosphor film solution is in its transparency, allowing significantly more light to transmit through the lens. The drawback in this case is that this concept has not yet been fully developed and proven to work. However, there are other projects currently working on this concept[1]

Research for LED technology inside the aircraft cabin and specifically passenger reading light has been a new area of interest. Nadarajah Narendran of Rensselaer Polytechnic Institute performed a study in which an LED light source was tested in a simulated aircraft setting as passenger reading light. Three LED prototypes and one halogen prototype were developed and tested to be in compliance with SAE ARP378. Illuminance and flux versus color tests were performed resulting in all reading light prototypes meeting SAE specifications. The LED light sources had significantly higher correlated color temperature (CCT) values than halogen, and consumed up to 50% less energy than the halogen light source. A mock aircraft cabin was constructed using the light source prototypes. A sample of 60 diverse individuals who have traveled at least once a year on an aircraft were selected to perform random tasks, in order to conduct a passenger opinion study. It was concluded that LED reading lights and halogen reading lights perform similarly in terms of passenger response. A second study was performed to identify the appropriate CCT, illuminance level, and beam distribution for aircraft reading lights based on additional passenger response surveys. It was concluded test subjects preferred a CCT value of 3600 – 5200 K and an illuminance of 220 – 400 lux at a distance of about 3 feet[4].

The design and construction of high powered LED lighting modules involves an array of soldered surface mounted LEDs to a copper layer that is separated from a rigid aluminuim substrate by an electrically isolating dielectric material[2]. Instead of wires, the electrical interconnections between the LEDs are made in printed and etched copper. The use of the small individual LEDs mounted on the flexible dielectric materials allows for parts to be formed in 180 degree and 360 degree orientations, which gives designers the ability retrofit LED modules into existing applications. Existing retrofitting applications include cabin lighting on the Quantas Boeing 747-300 and 747-500 fleet[2]. In addition, B/E Aerospace has currently provided interior LED lighting installation for over 50 aircraft including Gulfstreams, Challengers, Falcons, Boeing business jets, Sabreliners and Merlins. B/E Aerospace is one of the industries leaders in development of LED lighting systems in aircraft applications. The company has a RGB+W LED mood lighting system which has the capability of expressing over 16 million colors which can effectively create a variety of different displays such as, sunrise, sunset, red-eye nighttime, visual effects for equator crossing and beverage service displays. Despite all the new technology in aircraft lighting systems, the ability for a passenger to have control over their personal light is a relatively new field of research.

Current applications that utilize variable-focal length technology include microscopy and camera applications, which use many mechanical glass or polymer lenses that change the focal length by physically modifying the lenses positions[5]. These current lens systems can be large, heavy and require extensive labor to produce. An alternative solution and new field of research is a pressure actuated transparent thin membrane with the ability to vary the focal length by adjusting the amount of applied pressure to an enclosed chamber behind the membrane.

Zenon Carlos, a recent California Polytechnic University graduate from the department of Materials Engineering, conducted a research project in which PDMS was used to create a pressure actuated variable-focal length lens. The PDMS material, which is commonly used in current lens applications, was chosen for its low modulus (1.77 – 2.6 MPA), high transparency of over 97% and hydrophobic nature[6]. Spin coating was used to create a thin membrane of PDMS with a uniform thickness of 20 microns and a diameter of 3 mm. The thin membrane lens was assembled to a cast PDMS cavity using argon plasma. A syringe was used to mechanically apply pressure to the PDMS assembled cavity. Goniometry was used to determine the relationship between the applied pressure and radius of curvature of the PDMS thin membrane. The results showed that with an increase in applied pressure there was a increased radius of curvature, which in theory could allow the light source to act as a flood light and spot light[6].However, this project was limited in its scope to producing and testing a small and basic variable-focal length lens constructed from PDMS. There was no integration with an LED light source, or use of the lens to adjust the light in any capacity other than to prove that it could be done.

A PDMS microlens and microfluidic chip was fabricated and tested at various applied pressures to determine the radius of curvature, numerical aperture and contact angle. Photolithography and photoresist reflow methods were used to create the mold of a plano-convex micro-lens with a diameter of 1400µm[7]. PDMS was then cast onto the photoresist mold to create a mother mold, which once cured, PDMS was spin coated onto to create a thin film micro-lens 1400µm in diameter and 85µm tall in the center of the lens[7]. A microfludic chip consisting of a PDMS chamber block bonded with epoxy to a silicon substrate chamber was fabricated, then using epoxy to bond the PDMS microlens to the surface of the silicon substrate [Figure 1]. Volumes of fluid air ranging from 10µL to 70µL were applied to the fabricated lens system at which the contact angle, curvature and numerical aperture were determined. There was a consistency in the data that as the applied pressure increased the radius of curvature of the micro-lens decreased, an applied volume of 10µL rendered a radius of curvature of 3238µm and a volume of 70µl rendered a radius of curvature of 1210µm; in theory being able to focus at a variety of lengths7. The study demonstrated a successful fabrication of micro-lenses ranging 600µm to 1400µm diameters and their ability to be deflected with applied pressure to an enclosed chamber. In addition, it was determined that the area affected greatest by the applied pressure resulted at the edge of the PDMS microlens on the side that was bonded to the silicon substrate.

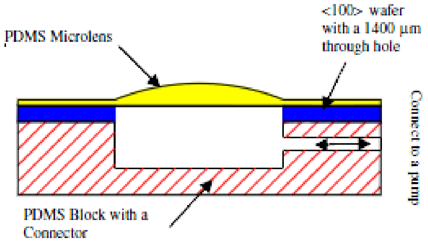


Figure 1: A drawing of a PDMS microlens fabricated as a PDMS microfluidic chip[7]

An adaptive fluidic PDMS-lens system was developed with an integrated piezoelectric pumping actuator. The design consisted of a lens chamber, a cast PDMS membrane sealed with a Polycarbonate (PC) film and a Silicon wafer, and is hardened using a hot embossing machine, and a pump chamber, fabricated in similar fashion with an embedded piezo-bending actuator, separated by a glass substrate with orfice[5]. The chambers are both filled with either water or oil, which is able to flow from the pump chamber to the lens chamber by the applied voltage of the piezo-bending actuator, thus causing the focal length to change [Figure 2]. The focal length of the lens as a function of applied pressure was determined using multiple membranes ranging 100μm to 380μm thick[5]. It was evident that as the applied pressure increased there was a decrease in the focal length of the lens. Stress-strain analysis was done to determine the elastic modulus of the PDMS membrane, showing constant elastic modulus of 1.53 MPa up to 40% strain[5]. Since the membrane experiences a constant elastic modulus up to 40% strain, it is possible to design around the parameters of applied pressure that will render below a 40% strain, knowing that the membrane will not be plastically deformed. The lens resolution as a function of the focal length was determined using multiple membranes ranging 100μm to 380μm thick[5]. It was evident that with a decrease in the focal length there is an increase in resolution. It was concluded that the optimum lens thickness was 150μm which was capable of a maximum resolution of 117lp/mm at a contrast of 50%[5].

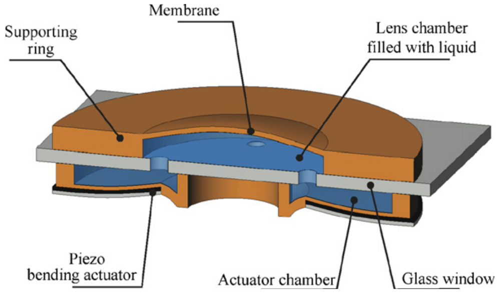


Figure 2: An adaptive fluidic PDMS-lens with integrated piezoelectric pumping actuator[5].

Though the field of variable focal length lenses and optofluidics is a relatively new and emerging science, much has been done to advance the technology. The ability to mechanically adjust the focal length and numerical aperture of a PDMS lens by applying pressure using either piezoelectrics or microfluidic chips has been documented[5,7,8]. As the applied pressure to the enclosed chamber of a PDMS membrane lens system increases the focal length decreases and the numerical aperture increases[5,7,8]. In addition, as more pressure is applied and the focal length is decreased, there is also an increase in the lens resolution[5,8]. With this information, further research and experimentation with PDMS is necessary in order to develop an LED with a flexi-focus lens that adequately adjusts passenger lighting on board the Boeing 787 Dreamliner. Due to the light weight, customizability, and low power consumption of an LED, an integration of these two technologies could lead to large financial and technological gains.

Chapter 3: Design Development

Using the components of the system block diagram seen in Figure 1 of Appendix F, two conceptual design solutions were developed. Both designs were planned with the ability to make use of a ThorLabs LED light source in mind. This light source currently consists of a blue LED with a yellow phosphor film embedded in the LED's dome, that absorbs the emitted light and 'corrects' the wavelength to produce white light. Another design still in development involves the use of quantum dots integrated into a PDMS layer in order to correct the incoming light's wavelength. This alternative provides an advantage of allowing more light through the "filter" because of its significantly higher efficiency. Key hurdles in the development of the design were to create an airtight chamber in which pressure can be applied to actuate the lens, integrating the lens with both the ThorLabs LED housing and the Fiber-lite system and protecting the Flexi-Focus lens from rupturing. For information regarding the ThorLabs and Fiber-lite equipment see Appendix D.

Conceptual Design 1

The first concept design involves utilizing as many ThorLabs accessories as possible to integrate the flexi-focus lens system with the LED light source [figure 3].

Components:

1. *LED and housing*
    - ThorLabs blue LED with yellow phosphor film enclosed in 1 inch diameter metal housing, powered by ThorLabs power source.
2. *Retaining Ring*
    - 1 inch outer diameter with ½ inch inner diameter and 0.38 inch depth, ThorLabs retaining ring.
3. *Glass Slide*
    - Thin glass sheet fixed to ThorLabs retaining ring and bonded to PDMS base using argon plasma.
4. *PDMS base*
    - Cast PDMS part with air tight chamber and inlet passage to allow pressure to be applied.
5. *PDMS thin film*
    - Spin coated thin membrane capable of being as fairly as 50 µm.

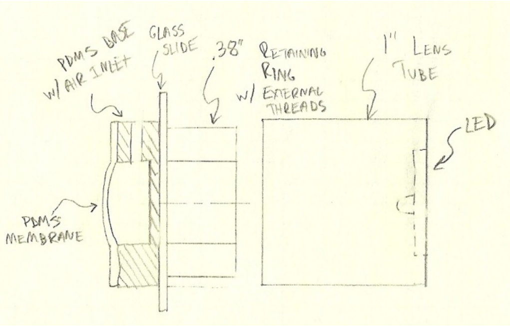


Figure 3: A sketch of conceptual design 1.

The retaining ring has the capability of screwing into the LED housing assembly allowing for an adjustability of about 0.3 inches. Having an adjustable design is beneficial during testing because it gives the operator the ability to fine tune the object distance. The entire flexi-focus assembly is not enclosed in any housing which allows for pressure to be applied to the chamber without bypassing any rigid housing. This also will make analyzing any problems that may arise during testing easy as there is no housing to hide sources of failure or error. This could also be a disadvantage, since the PDMS membrane is only microns thick, being exposed to the environment could result in rupturing. The glass slide allows for emitted light to pass through while acting as a foundation for the flexi-focus lens system, separating it from the LED housing. Since the glass slide has a high silica (Si02) content is has the capability of being plasma bonded to the PDMS base, and because of its rigid physical nature at room temperature it has the ability to be fixed to the ThorLabs retaining ring.

Conceptual Design 2

A second conceptual design solution utilizes a PDMS washer to secure the lens on the base and an external housing to integrate the ThorLabs LED and flexi-focus lens [Figure 4].

Components:

1. *LED and housing*
    - ThorLabs blue LED with yellow phosphor film enclosed in 1 inch diameter metal housing, powered by ThorLabs power source.
2. *Metal washer covering LED*
    - This covers the LED to seal it from the external environment while providing a circular hole for light to pass through.
3. *PDMS base disk with channel and cavity*
    - This goes over the Metal washer, sealing the hole. The base disk has a channel to inject air to adjust the pressure in the cavity, which is uncovered
4. *PDMS Lens*
    - This covers the open cavity of the PDMS base disk, and will deflect as air pressure is increased in the sealed cavity.
5. *PDMS washer*
    - This will cover the edges of the PDMS Lens and the Base Disk, sealing them together to reduce risk of lens detaching from the base.

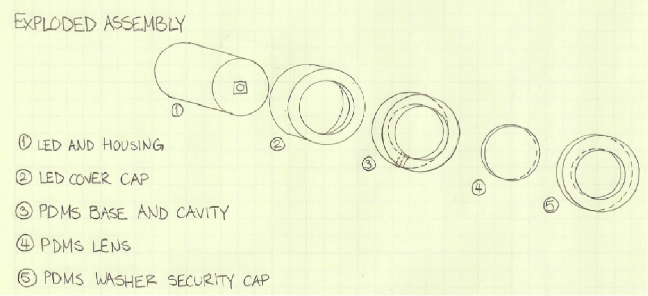


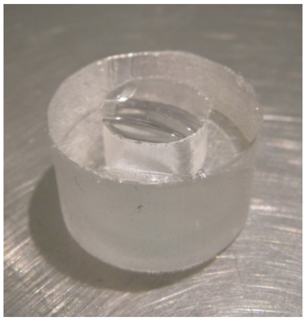
Figure 4: A sketch of conceptual design 2.

The key advantage to this design configuration is believed to be that the PDMS lens will be securely fastened onto the PDMS base with an additional ring of PDMS that covers over the edges of the lens and the base. This will minimize the risk of the lens separating from the base when pressure is increased inside the cavity underneath the lens. The idea of having a separate piece of PDMS to serve as a base allows the option to alter the consistency of the material to be more rigid, reducing unwanted deformation when air pressure changes. The PDMS base layer was set outside of the metal washer covering the LED in order to grant access to the air channel that regulates the cavity pressure behind the lens. This setup allows for easier integration with an auxiliary system to regulate the air pressure with a more simplified assembly of the parts.

The main disadvantage this concept fails to address is how the PDMS washer can be made such that it seals over the lens and base without any faults or air pockets. Another disadvantage to this concept is that the PDMS components are directly exposed to the external environment which could result in premature rupture of the thin PDMS lens due to environmental affects.

Concept Selection

The final concept chosen was neither of the previous two designs, but rather a simplified integration of the two conceptual designs. The resulting design was a PDMS base with cavity similar to the one shown in figure 3, and thin lens chemically bonded via plasma bond to the opening [figure 5] .



The washer securing the lens to the base was omitted as well as the glass slide. Eventually the cavity was filled with water in one experimental case, and in another with a silicone liquid. It was determined that a washer securing the lens onto the base was unnecessary because the plasma bonding technique would be sufficient in holding the two PDMS components together so long as the bonding surfaces were clean and particle free. A liquid medium was added in the base cavity in order to increase the lens index of refraction, improving the focus of the light. The deflection of the PDMS base compared to the lens was small enough that a supporting glass plate would not be necessary.

Once the the PDMS lens and PDMS base were plasma bonded, for the first prototype, a syringe was inserted into the cavity so that air could be injected or withdrawn via syringe. As expected, the change in air pressure caused the lens to deflect [figure 6]. After repeated injecting and withdrawing of air, it was observed that the lens had been securely attached to the base without failure in the chemical bond provided by the plasma bond. The assembled prototype was placed in front of a white light source to observe how effectively it could deflect the light passing through it. There was no significant change in light focus observed when inflating and deflating the air behind the lens.

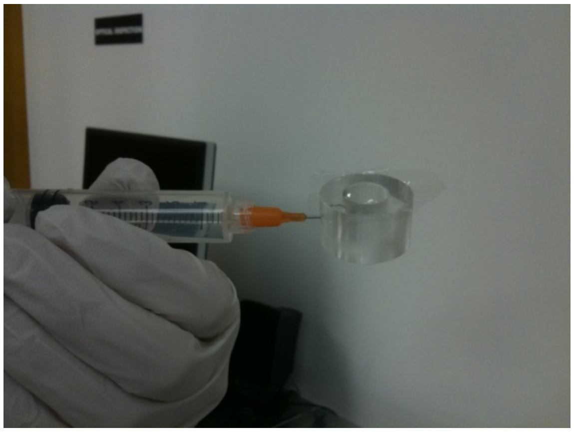


Figure 6: Image of the final design deflected by applying pressure.

Water was used to fill the cavity in the base which has a refractive index closer to that of PDMS than air. This significantly changed the index of refraction that the light was passing through and resulted in a noticeable focusing of the light in the preliminary test. Silicone oil was also used to experiment with in place of the water in order to more closely imitate the PDMS material's index of refraction. Additionally, the injected water in the fluid cavity evaporated over time which would not be a concern when using silicon oil. Testing provided no observable differences between the use of water and the use of silicone oil in terms of refracting light. However, it was decided that water would be used instead of silicon oil for later testing purposes of the lens due to the fact that the differences in index of refraction were negligible, and water more accessible, easier to inject, and less messy in the event of a ruptured lens.

Chapter 4: Description of the Final Design

The Flexi-Focus lens system has evolved since working preliminary testing of the conceptual designs. The design has been simplified and streamlined to improve production and processing of the design. The final design remains a thin membrane of PDMS chemically bonded to a base PDMS with fluid cavity, which can be integrated with both ThorLabs LED components and Fiber-lite light source.

Detailed description

The design begins with a thin film of PDMS that was spin coated to a controlled and desired thickness. The spin coating thickness can be varied with ± 5 micron precision, as will be discussed in chapter 5. The final lens is 0.5” in diameter, but a larger area was produced to allow for bonding between the lens and base.

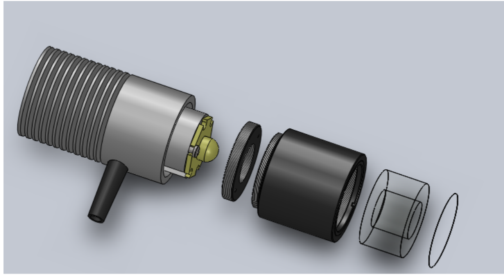


Figure 7: A SolidWorks assembly drawing showing the lens system integrated with the ThorLabs components.

The PDMS base component of the lens system was cast in a mold made of a pair of custom designed rapid-prototyped ABS parts Appendix B. The base was made of a single piece of PDMS, 1” in diameter, and has a cavity, 0.5” in diameter, for filling with fluid to actuate the lens. The cast base and lens were plasma bonded together using an argon plasma which chemically bonds the components together, discussed further in chapter 5.

Once the lens system was been tested for a complete seal between the lens and base the cavity is filled with fluid. The fluid used was water since it has a refractive index similar to PDMS, which makes for a highly efficient lens. Additionally, water has a relatively low vapor pressure which results in little evaporation, making it an ideal fluid for the closed environment within the Flexi-Focus lens system. Because the lens system has the ability to be integrated with either the Thorlabs equipment, or the Fiber-lite system two integration set-ups were developed. With the ThorLabs components the lens system was simply placed inside one of the ThorLabs 1” lens tubes, which allows for the complete integration with the ThorLabs mounted LED [Figure 7]. Behind the lens system, a 1” to 0.5” adapter was placed in the housing, which reduces the beam of light to the same diameter as the lens. The adapter was screwed in to the 1” lens tube and has the ability to be adjusted to optimize the distance from the LED to the lens. To stop the adapter from moving once the distance was optimized, another retaining ring was placed behind the adapter. The ThorLabs 1" lens tube was screwed directly in to the ThorLabs mounted LED and resulted in a completely integrated system.

The other integration option was to insert the fabricated PDMS lens system into the ABS parts which were designed for use with the Fiber-lite system [Figure 8]. The PDMS lens was mounted securely into the ABS part, and the ABS part was securely fixed over the end of the Fiber-lite system. Pressure can be applied to actuate the lens.

Figure 8: Photograph of the ABS fitting for integrating the lens with the Fiber-lite system.

Once the system has been fully integrated pressure was applied in order to actuate the lens. Pressure was applied using a tank of compressed nitrogen gas connected to a length of tubing. The tubing runs to a gas-to-liquid interchange syringe which, when gas pressure was applied, pressure was applied to the water. The water then ran through another length of tubing to an 18 gauge syringe which is inserted through the wall of the PDMS base into the cavity. When pressure is applied via the tank of nitrogen gas, the pressure increased in the cavity in the lens system allowing the thin PDMS lens deflect in response [Figure 9].

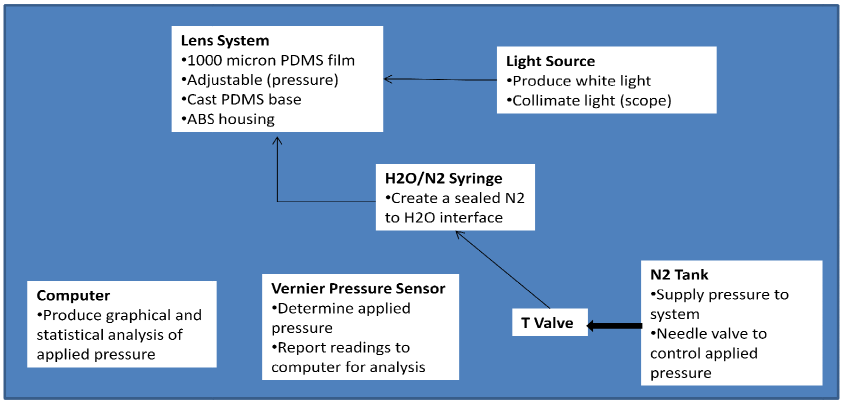


Figure 9: System block diagram of Theoretical Analysis of the Final Design

The optical properties of the Flexi-Focus lens device depend on the specifications required by the application. Appendix F depicts the theoretical functionality of the device. The Flexi-Focus lens system can be altered to fit the requirements of the specific application in question. Depending upon the application of the Flexi-Focus lens system the focusing distance has the ability to be modified. The lens maker's equation was used to determine focal length. Equation 1 shows the thin lens formula; where n is the index of refraction and R1 and R2 are the inner and outer radii of curvature, respectively. For the purposes of this project, the lens can be treated as a thin film and thus R2 is equal to negative R1. The focal length is a function of the index of refraction of the PDMS, the index of refraction of the fluid, and the radius of curvature; where the radius of curvature is limited by physical properties of the lens. In other words, a small radius of curvature requires a large deflection which is possible by exerting a large pressure, resulting in increased stress on the material. The larger the pressure, the larger the stress and the increase risk of failure of the product. Table II of Appendix F displays the resulting focal length from the radius of curvature and index of refraction that can potentially be achieved with the final design.

$$\frac{1}{f} = (n-1)\left[\frac{1}{\mathrm{R}_1} - \frac{1}{R_2}\right]$$

Equation 1: Lens Maker's Equation (Thin film)

The deflection of the thin lens was calculated using principles of geometry. Illustrated in Figure 2 in Appendix F are the components necessary for the calculation. The central angle results from the arcsine of the radius of the lens divided by the radius of curvature. The central angle multiplied by the radius of the lens results in the arc length of the lens. The deflection is then the function of the arc length and radius of curvature Table III also in Appendix F displays the resulting deflection utilizing Equation 2.

$$X = r_1 - \left(r_1 \cos\frac{L}{r_1}\right)$$

Equation 2: Deflection Equation

To achieve the desired deflection, and therefore the proper radius of curvature, an appropriate amount of pressure must be applied to the lens. As mentioned above, the required pressure must not stress the material to failure. To calculate pressure, the radius, thickness, and desired deflection of the lens must be known, as well as properties of PDMS, such as Poisson's ratio and elastic modulus. The physical properties of PDMS can be seen in Table VI, Appendix F. Pressure is calculated by back solving using Equation 3 below, where Z is equal to the deflection of the lens. Stress was then calculated using the pressure, lens thickness, and radius of curvature values [Equation 4]. IV in Appendix F displays pressure and stress for various deflections

$$z = \frac{3r^4P\left[\left({}^{1}/_{v}\right)^2 - 1\right]}{16E\left({}^{1}/_{v}\right)^2 t^3}$$

Equation 3: Deflection at Center

$$\sigma = \frac{3r^2P}{4t^2}$$

Equation 4: Stress

The Image and object distance is related by equation 5 below. Equation 5 is used to determine the appropriate distance of the LED source to focus a collimated beam at a desired distance. O is the object distance (LED light source) and I is the image distance. In these calculations, the image distance is fixed at 300mm for conceptual purposes; this distance can be modified to fit customer requirements. Table V in Appendix F displays object distances for focal lengths with a fixed image distance of 300mm.

$$\frac{1}{f} = \frac{1}{O} + \frac{1}{I}$$

Equation 5: Image and object distance related by Focal Length

Analyzing the resulting calculations in Appendix F allows for full knowledge of the theoretical functionality of the Flexi-Focus lens. The final design should theoretically perform as detailed above and in Appendix F.

Cost Breakdown

The cost of the complete prototype is the cost of fabricated PDMS base and thin film. PDMS fabrication is a 10:1 ratio of parts Slygard184 to curing agent. To produce one device, 30mL of Slygard 184 and 3mL of the curing agent is capable of producing one thin film and two bases. The cost for the lens is calculated by utilizing the equation for the volume of a cylinder with a height equal to the thickness of the lens (50µm) and a diameter of 1”. The amount of PDMS used for one base is estimated to be the total amount of Slygard 184 and the curing agent mixed minus the volume of the thin lens, divided by two. The resulting costs for these parts are illustrated in Table III. For full description of parts refer to the bill of materials in Table 1 Appendix C.

Table III: Individual Part Cost

Part Name	Unit Price	QTY	Units	Cost
PDMS Lens	$54.97	0.03	ml	$0.003
PDMS Base	$54.97	16.5	ml	$1.87
Retaining ring	$3.75	1	Unit	$3.75
Power Supply	$279.00	1	Unit	$279.00
LED	$395.00	1	Unit	$395.00
Lens Tube	$28.60	1	Unit	$28.60
Adapter	$18.75	1	Unit	$18.75
			Total	**$726.972**

Material Selection

The primary material used in the production of the lens was polydimethylsiloxane (PDMS). PDMS is a synthetic polymer made of an alternating silicon-oxygen-silicon backbone with two methyl groups attached to each silicon atom. The specific product used was Sylgard 184, manufactured by Dow Corning. PDMS was selected because of its ease of processing and the material properties meet all of the mechanical and optical requirements of the design. PDMS has the ability to be cast, plasma bonded, and spin coated which are available and relatively simple processes. PDMS itself is also relatively inexpensive and non-toxic, thus there were no necessary saftey precautions taken while processing the lens system. PDMS is optically transparent, easily deformable, and has the ability to be plasma bonded to itself. A summary of the properties of PDMS can be found in Table VI in Appendix F.

The secondary material used in the design of the flexi-focus lens system is acrylonitrile butadiene styrene (ABS). ABS was used to produce molds to cast the liquid PDMS and a housing component used to integrate the PDMS lens system with the Fiber-lite light system. ABS was selected because it is commonly used in rapid prototype processing, which is an efficient and cost effective way to produce solid parts. Additionally, rapid prototyped ABS has the ability to be printed at high resolution adequate for creating a fine surface finish on the cast PDMS part. The fine surface finish is necessary on the cast PDMS part in order to be chemically bonded to the lens during the plasma bonding process.

Chapter 5: Product Realization

Rapid Prototyping

To develop a cast PDMS base with a cavity for the actuating fluid, a mold of ABS was developed using a uPrint rapid prototyping machine. SolidWorks modeling software was used to design three dimensional drawings of the molds. The files were saved in proper .stl format and uploaded to the uPrint machine to print the ABS molds [Figure 1 and 2, Appendix B]. The molds were printed as solid pieces to reduce the amount of retained gas within the molds, and on the highest resolution setting to produce a fine surface finish on the cast PDMS parts. Once the molds were printed they were placed in a vacuum chamber to remove any retained gas within the ABS molds. Any retained gas would be released into the liquid PDMS during the curing process and create bubbles within the solid PDMS cast parts.

Casting

Dow Corning Sylgard 184 and curing agent were mixed in a 10:1 ratio and placed in a vacuum chamber to release any gas contained within the mixture. Any gas immersed within the mixture during the curing process could potentially create bubbles within the PDMS base, which would distort light throughput of the system. Once fully degassed, the liquid PDMS was poured into the ABS mold in excess with a glass slide placed on top of the mold [Figure 10]. The casting was then placed in an oven set to 70c for approximately one hour, then removed from the ABS mold once fully cured.

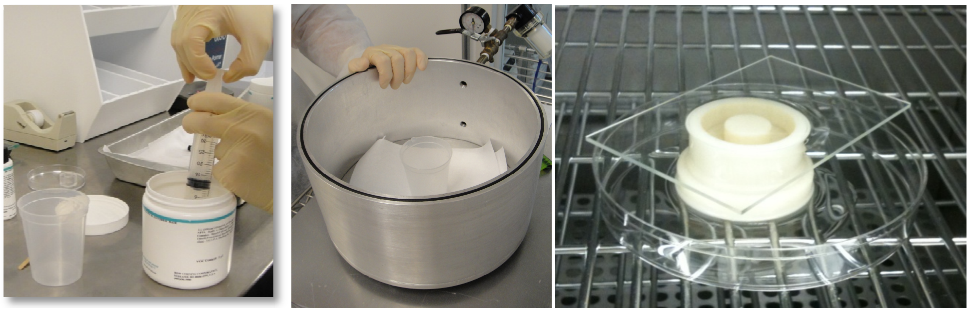


Figure 10: Liquid PDMS mixed, degassed, and prepared for curing

Spin Coating

PDMS thin films, used as the lens of the system, were made using a Laurell Technologies 400WX spin coater [Figure 11]. Spin coating is a process in which a liquid is poured onto a disc that spins at a specified rpm, the resulting centrifugal forces evenly spread the liquid on top of the disc. The thickness of the film is dependent on the rotating speed (rpm) and viscosity of the material. Spin coating curves were used in order to determine a rotational speed of 1150rpm to produce a film thickness of 50µm [Figure 3, Appendix F]. Viscosity was held constant using the same 10:1 ratio as the PDMS base. Optical Microscopy was used to determine proper film thickness. A block piece of PDMS was plasma bonded to the thin film and viewed on edge using optical microscopy to measure the film thickness [Figure 11].

: Laurell Technologies 400WX spin coater
al Microscopy Image of Film Thickness

The spin coating process successfully produced films with a range of thickness which were all within ±5 microns from the value predicted by the spin coating curve9 [Figure 3 Appendix F].

Plasma Bonding

The PDMS base and PDMS film were fabricated together using a process known as plasma bonding. Argon plasma was used to treat the contact surface of the PDMS film and PDMS base. This removes the methyl (CH3) groups from the siloxane (Si-O) backbone, leaving reactive silanol (Si-OH) groups on each surface [Figure 12]. The plasma treated surfaces were then brought into contact to allow the silanol groups to react and form covalent Si-O-Si bonds that chemically bond the lens and base together.

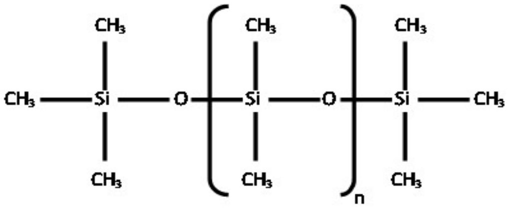


Figure 12: Drawing of the PDMS chemical structure

Cost estimation for future mass production

The Boeing 787-8 is estimated to hold 250 seats while the Boeing 787-9 is estimated to hold 290 seats. Assuming that the true cost to manufacture a single Flexi-Focus device is correctly reflected in the BOM in Appendix C Table I, then the cost to produce 250 devices is $467.50 and the cost to produce 290 devices is $542.30. This does not include the cost of labor and equipment. Large scale manufacturing of the Flexi-Focus device would be cost justified only if the amount saved from switching to an LED light source is relatively large.

Chapter 6: Design Verification (Testing)

Testing

Once the product was built and could be successfully integrated with the two different light sources, ThorLabs and Fiber-Lite, testing was performed on the lens. The first test was designed to verify the relationship between applied pressure and focal length.

Applied Pressure

The ThorLabs LED was mounted using a v-clamp on an optical bench. The white light produced by the LED was collimated using a mechanical lens system placed in front of the LED. When a collimated light source hits a converging lens it focuses the light at a distance from the lens that is equal to the focal length. The Flexi-Focus lens system was then placed in between a screen and the mechanical lens system. The distance of the screen and the lens was mechanically adjusted and measured to determine the focal length of the PDMS lens system at various applied pressures[Figure 13]. A nitrogen gas tank was used to vary the applied pressure to the PDMS lens system, resulting in a change in radius of curvature. As the curvature of the lens varied the distance of the screen was adjusted to refocus the light and then the resulting focal length was measured. Simultaneously the applied pressure from the nitrogen tank was measured during the lens actuation using a Vernier Gas Pressure Sensor. The Vernier Pressure Sensor outputs were read using the LoggerLite computer software. For each focal length the peak applied pressures were recorded and plotted against the corresponding measured focal lengths.

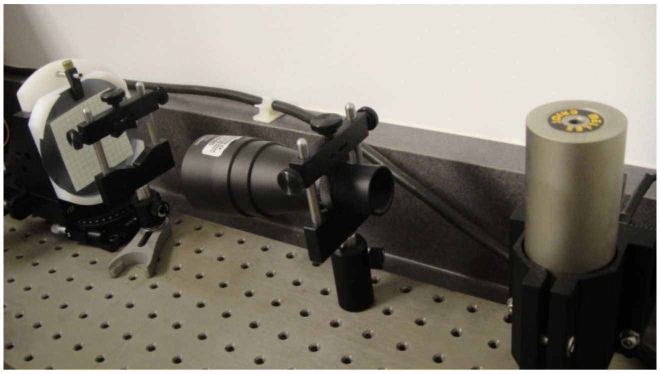


Figure 13 Image of the applied pressure test set up

Light throughput

The next test performed on the lens system was measuring the throughput and absorption properties. A halogen and deuterium light source were used to provide a strong light signal across the entire visible light spectrum. Fiber optic cables were connected from the light source to a mount on an optical bench. An OceanOptics USB4000 spectrometer was used to measure the intensity of light at a wide range of wavelengths. Maxiumum light transmission was achieved by aligning two fiber optic cables from the source to the spectrum. The spectra produced by the light source was measured and stored as a baseline reference. Then the Flexi-Focus lens system was placed in between the fiber optic cables, connecting the light source and spectrometer [Figure 14].The new spectra of light that was incident on the fiber running to the spectrometer was measured using SpectraSuite software program. The spectrum of light that passed through the lens was compared to the values when, no lens was in place, and the percent transmission across the visible light spectrum was plotted by the SpectraSuite software. The lens system was filled with water and the spectra and percent transmission was again measured.

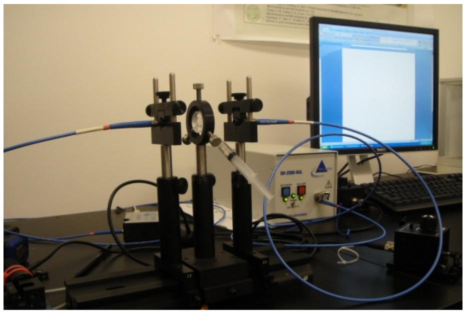


Figure 14 Image of the light throughput test set up

Results

Recorded applied pressures and corresponding focal lengths were plotted to determine any significant trends [Figure 15].

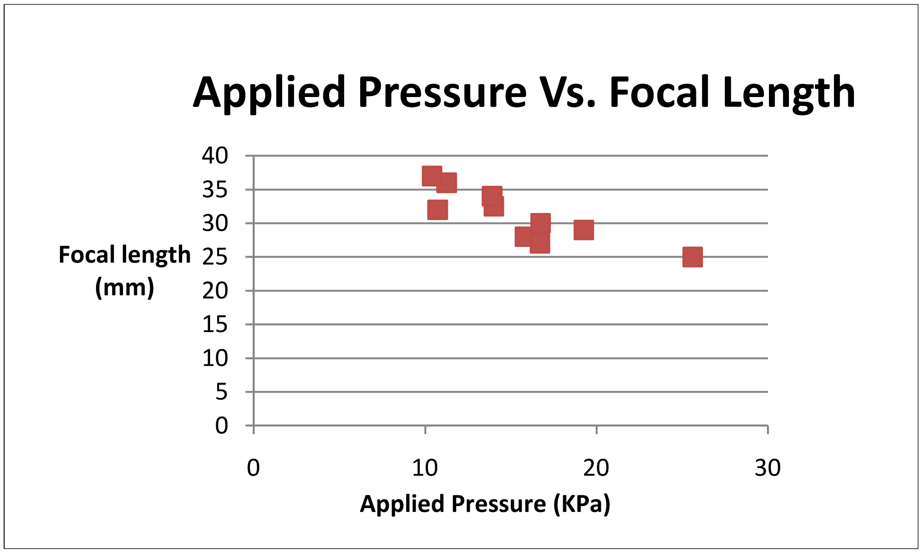


Figure 15: A plot of applied pressure vs. focal length for the Flexi-Focus lens system.

Once the spectra transmitted by the lens was measured and stored by the SpectraSuite software then the percent transmission of the lens was calculated. This was done by comparing the intensity of light across the spectrum when the lens was in place to when the source was transmitting directly to the spectrometer. The percent transmission was plotted and compared to the wavelength of light [Figure 16].

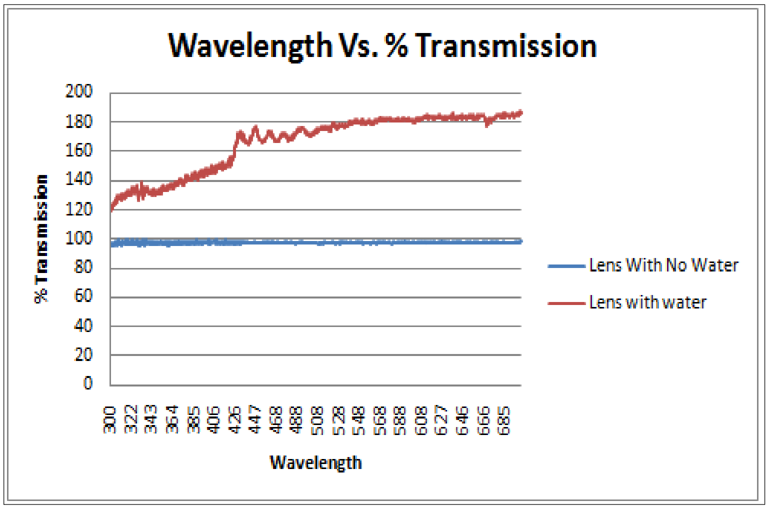


Figure 16 A plot of percent transmission vs. wavelength for the Flexi-Focus lens system.

Analysis

Figure 15 demonstrates a linear relationship between the applied pressure and focal length of the Flexi-Focus lens system. During testing, the applied pressure from the nitrogen tank was manually applied via needle valve. The manual valve offered enough control to properly apply an amount of pressure to the lens without causing premature rupture. However, the needle valve did not allow for enough control to precisely apply a predetermined pressure, thus a design of experiment was not executed, since no variable qualified to be independently changed.

Analyzing the results of the focal length testing it is evident that the Flexi-Focus lens system does effectively focus light with a variation in applied pressure as predicted by the theoretical model. However, the quantitative numbers that were gathered during the testing deviate largely from the expected values determined using theoretical calculations. The general correlation between pressure and focal length was consistent with the theory that an applied pressure will cause the lens to deflect and decrease the focal length. This was seen by the negative slope of the plot of pressure vs. focal length [Figure 15]. The measured pressures, however, where magnitudes greater than the expected values that were calculated.

There are a number of reasons for this potential variation. One is that our testing setup did not accurately measure the applied pressure in the lens. This is possible because we used the greatest applied pressure measured by the pressure sensor during each actuation because there were a large number of leaks in our system. This may have resulted in using an applied pressure that was much greater than what was actually experienced by the lens. Another problem was that the pressure measured was the maximum air pressure, but the pressure applied to the lens was actually water pressure. To apply the pressure to the water a syringe was used that passed the pressure from the air to the water. The air pressure applied may have been higher than the pressure that was actually applied to lens. The other potential problem could be the equations used to calculate our theoretical numbers. The equations may not be applicable to the situations in which they were used in the calculation of the applied pressures.

The light throughput tests confirmed that the Flexi-Focus lens met the expectations that it have greater than 95% throughput. This was for the system when not filled with water so none of the focusing effects of the lens system were present. The water-filled lens system performed even better in the throughput tests than when no lens was present, indicating by the greater than 100% throughput that more light was gained by having the focusing effects of the lens than was lost by the light passing through the system.

Chapter 7: Conclusions and Recommendations

The Flexi-Focus lens system has been shown to vary focal length with an applied pressure. The lens system was integrated with both basic ThorLabs off-the-shelf components and with a custom housing to integrate with Fiber-lite flexible lighting system for demonstration purposes. The manufacturing process of the Flexi-Focus lens system was optimized and lens systems can be repeatedly and consistently produced. The completed lens system with bonded lens and base was created and tested. The focal length with respect to pressure applied to the lens was measured and the correlation matched with the expected trends. Quantitative results showed a significant decrease in focal length as applied pressure was increased. The absorption and light throughput of the lens was also tested and analyzed. The lens system produced greater than 95% transmission across the entire visible light spectrum. When the lens system was filled with water it increased the amount of light incident on the spectrometer to greater than before the lens was in place indicating the focusing potential of the lens. It is recommended that further testing be performed on the lens system. Specifically, a design of experiment in which applied pressure can be controlled in a way that it may act as the independent variable to determine the significance it has on quantitative dependent variable such as, focal length, radius of curvature, and light intensity. Further testing of the fatigue and failure analysis of the lens system should be pursued. An additional test for the intended application that should be performed are tests to see if the lens system met the DO160 requirements for components of aircraft cabins including thermal tolerance and vibration tolerance.

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8 Zhang D., Justis N., Lien V., Berdichevsky Y., and Lo YH, *High-performance fluidic adaptive lenses,* WWW Document, (http://www.ncbi.nlm.nih.gov/pubmed/14960070)

9 Mayer, Hans. "PDMS Spin Coating Curve." Chart. Print

Appendix A

Performance Objectives	Weight (out of 100)	Engineering Requirements and Measurable Objectives
Efficient	17	Light Throughput
Appropriate Lighting (A function of LED used)	17	Correlated Color Temperature between 3600K and 5200K
Operation	25	Change in Area of Illumination (∆ ft.2)
Safety	7	Low risk of injury
Schedule	10	Finished by June 2011
Cost	9	Inexpensive Currently undefined budget
Reliability	10	Reproducibility (± 0.10) Repeatability (±0.08)
Sustainability	5	Energy Use

Appendix B

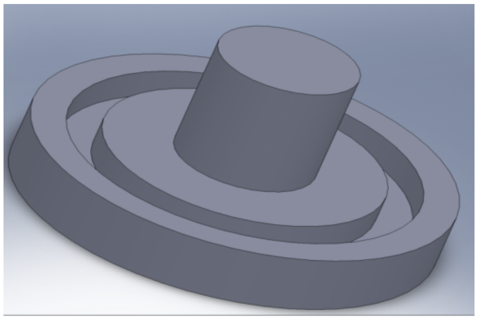


Figure 1: ABS Part 1

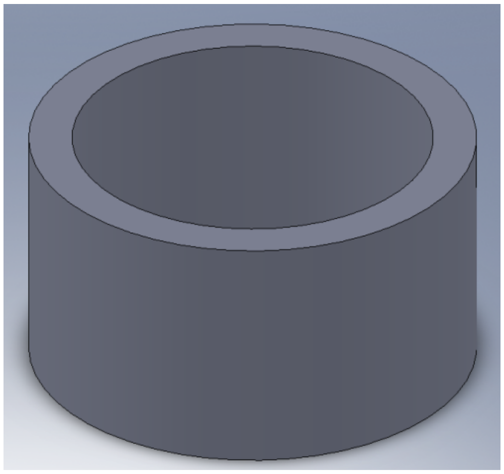
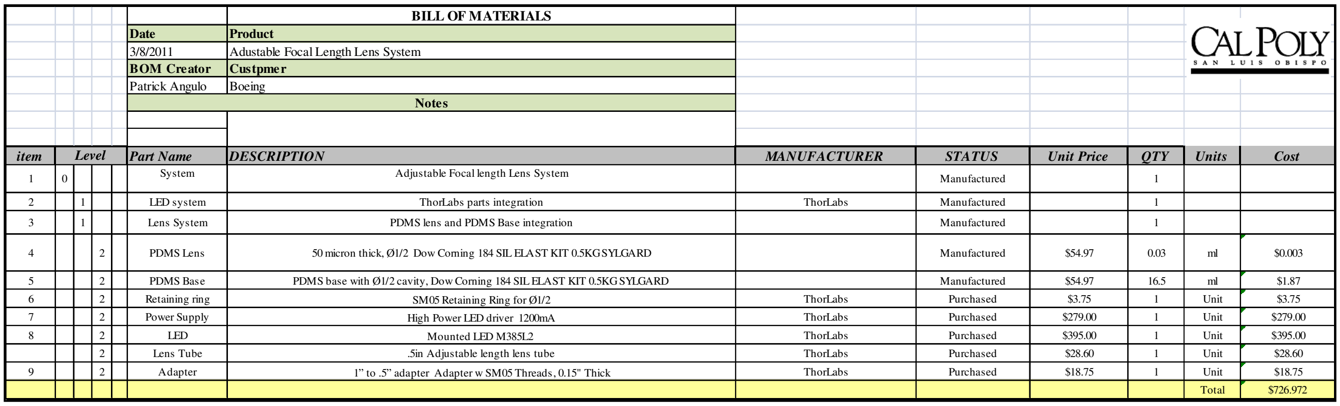


Figure 2: ABS part 2

Appendix C

Table I: BOM with Pricing



BILL OF MATERIALS

Date	**Product**
3/8/2011	Adustable Focal Length Lens System
BOM Creator	**Custpmer**
Patrick Angulo	Boeing

Notes

item	*Level*				*Part Name*	*DESCRIPTION*	*MANUFACTURER*	*STATUS*	*Unit Price*	*QTY*	*Units*	*Cost*
1	0				System	Adjustable Focal length Lens System		Manufactured		1		
2		1			LED system	ThorLabs parts integration	ThorLabs	Manufactured		1		
3		1			Lens System	PDMS lens and PDMS Base integration		Manufactured		1		
4			2		PDMS Lens	50 micron thick, Ø1/2 Dow Corning 184 SIL ELAST KIT 0.5KG SYLGARD		Manufactured	$54.97	0.03	ml	$0.003
5			2		PDMS Base	PDMS base with Ø1/2 cavity, Dow Corning 184 SIL ELAST KIT 0.5KG SYLGARD		Manufactured	$54.97	16.5	ml	$1.87
6			2		Retaining ring	SM05 Retaining Ring for Ø1/2	ThorLabs	Purchased	$3.75	1	Unit	$3.75
7			2		Power Supply	High Power LED driver 1200mA	ThorLabs	Purchased	$279.00	1	Unit	$279.00
8			2		LED	Mounted LED M385L2	ThorLabs	Purchased	$395.00	1	Unit	$395.00
			2		Lens Tube	.5in Adjustable length lens tube	ThorLabs	Purchased	$28.60	1	Unit	$28.60
9			2		Adapter	1" to .5" adapter Adapter w SM05 Threads, 0.15" Thick	ThorLabs	Purchased	$18.75	1	Unit	$18.75
											Total	$726.972

Table II: List of vendors and contact information

Product	Vendor	Online Source	Telephone Number
Sylgard 184	Dow Corning	http://www.dowcorning.com	1-800-248-2481
LED Light Source	ThorLabs	http://www.thorlabs.us/index.cfm?	1-973-579-7227
Pressure Sensor	Vernier	http://www.vernier.com/	1-888-837-6437

Appendix D

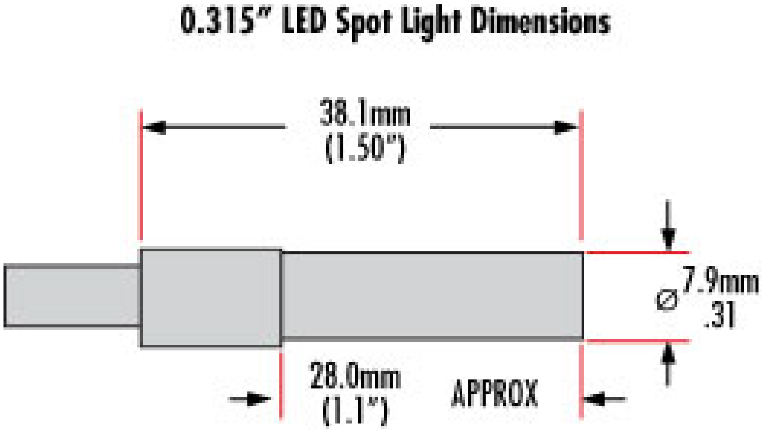


Figure 1: Techical Specs of Fiber-lite LED

Figure 2: Image of Fiber-lite LED

Table I: ThorLabs LED specifications

Item #	Color	Dominant Wavelength*	Minimum Power LED Output*	Typical Power LED Output*	Maximum Current CW	Forward Voltage	Halfwidth (FWHM)	Typical Lifetime
M365L2	UV	365 nm	190 mW	360 mW	700 mA	4.4 V	7.5 nm	>10,000 h

Figure 3: Image of ThorLabs LED

Appendix E

Table I: User Requirements

Performance Objectives	Weight (out of 100)	Engineering Requirements and Measurable Objectives
Efficient	**17**	**Light Throughput**
Appropriate Lighting (A function of LED used)	**17**	**Correlated Color Temperature between 3600K and 5200K**
Operation	**25**	**Change in Area of Illumination (∆ ft.2)**
Safety	**7**	**Low risk of injury**
Schedule	**10**	**Finished by June 2011**
Cost	**9**	**Inexpensive** **Currently undefined budget**
Reliability	**10**	**Reproducibility (± 0.10)** **Repeatability (±0.08)**
Sustainability	**5**	**Energy Use**

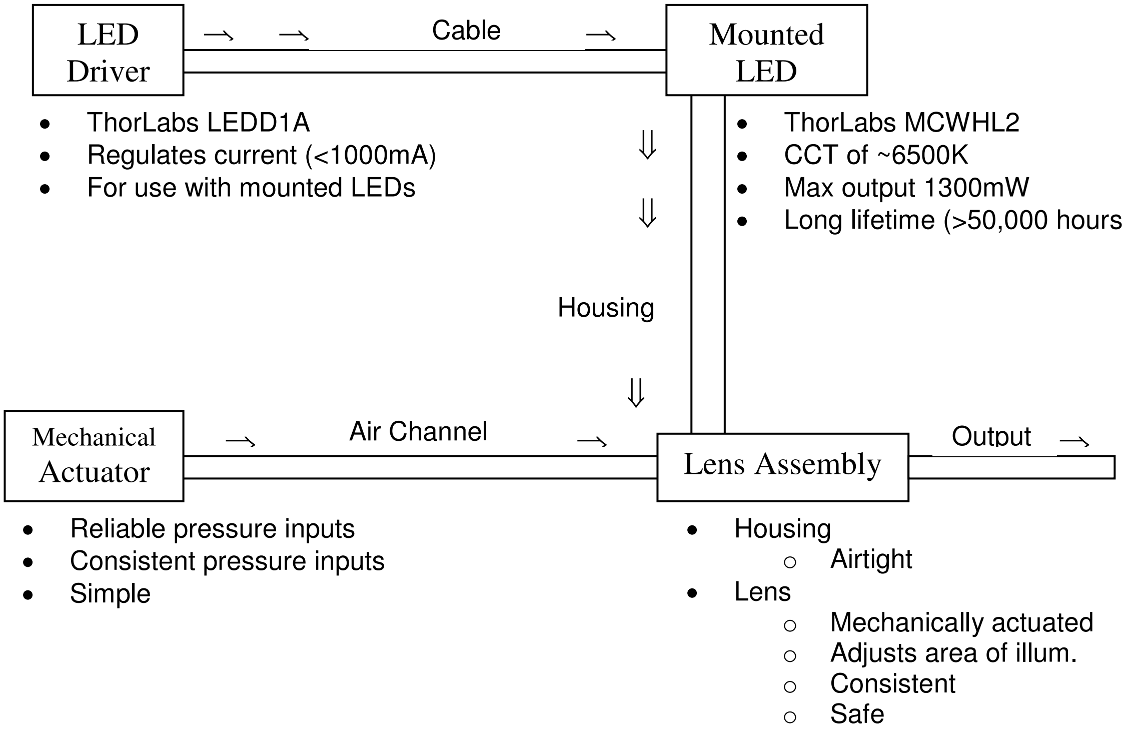


Figure 1: System Block Diagram for Flexi-Focus System

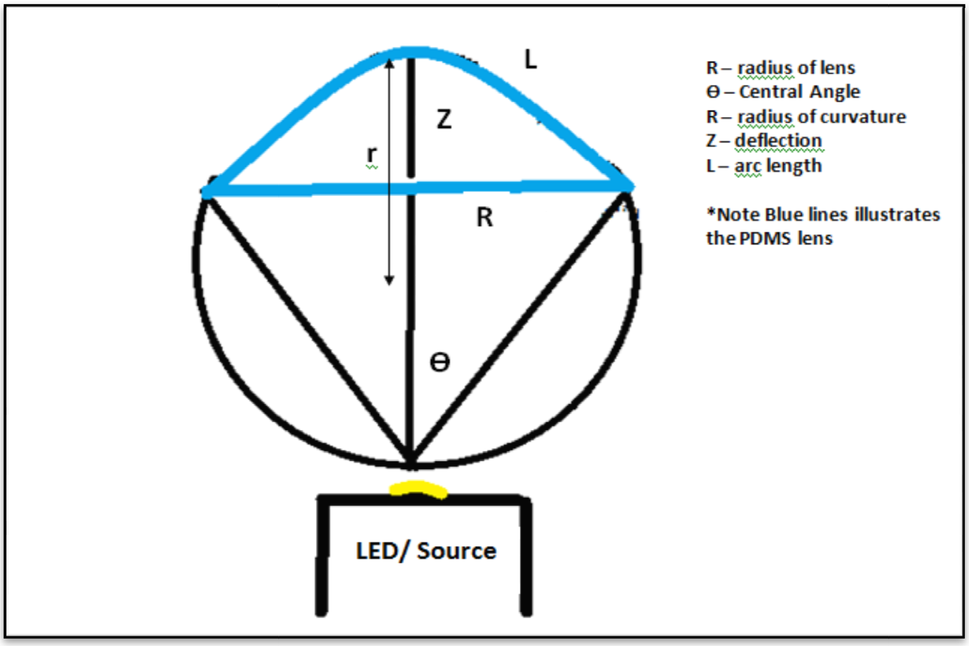


Figure 2: Variables for deflection calculations

Table II: Lens Maker Equation sample data

focal length	Radius of Curvature 1 r1 (mm)	Radius of Curvature 2 r2 (mm)
15	14.1	-14.1
15.1	14.2	-14.2
15.2	14.3	-14.3
15.3	14.4	-14.4
15.4	14.5	-14.5
15.5	14.6	-14.6
15.6	14.7	-14.7
15.8	14.8	-14.8
15.9	14.9	-14.9
16	15	-15
16.1	15.1	-15.1
16.2	15.2	-15.2
16.3	15.3	-15.3
16.4	15.4	-15.4
16.5	15.5	-15.5
16.6	15.6	-15.6
16.7	15.7	-15.7
16.8	15.8	-15.8
16.9	15.9	-15.9
17	16	-16
17.1	16.1	-16.1
17.2	16.2	-16.2
17.3	16.3	-16.3
17.5	16.4	-16.4
17.6	16.5	-16.5
17.7	16.6	-16.6
17.8	16.7	-16.7
17.9	16.8	-16.8
18	16.9	-16.9
18.1	17	-17

Table III: Deflection sample raw data

Central Angle (rad)	Radius 1 (mm)	arc length (mm)	Deflection (mm)
0.408	16	6.53	1.314
0.395	16.5	6.52	1.271
0.383	17	6.51	1.230
0.371	17.5	6.50	1.193
0.361	18	6.49	1.157
0.350	18.5	6.48	1.124
0.341	19	6.47	1.093
0.332	19.5	6.47	1.063
0.323	20	6.46	1.035
0.315	20.5	6.46	1.008
0.307	21	6.45	0.983
0.300	21.5	6.45	0.959
0.293	22	6.44	0.936
0.286	22.5	6.44	0.915
0.280	23	6.43	0.894
0.274	23.5	6.43	0.874
0.268	24	6.43	0.855
0.262	24.5	6.42	0.837
0.257	25	6.42	0.820
0.252	25.5	6.42	0.803
0.247	26	6.41	0.787
0.242	26.5	6.41	0.772
0.237	27	6.41	0.757
0.233	27.5	6.41	0.743
0.229	28	6.41	0.730
0.225	28.5	6.40	0.716
0.221	29	6.40	0.704
0.217	29.5	6.40	0.692
0.213	30	6.40	0.680
0.210	30.5	6.40	0.668
0.206	31	6.40	0.657
0.203	31.5	6.39	0.647
0.200	32	6.39	0.636

Table IV: Pressure and Stress sample data1

z (deflection)	radius of curv	pressure (pa)	stress (pa)
1.656	13.00	0.325999952	3943.539922
1.587	13.50	0.31227765	3777.544665
1.523	14.00	0.299731548	3625.777604
1.464	14.50	0.288209041	3486.392721
1.410	15.00	0.277583915	3357.863224
1.360	15.50	0.267750689	3238.913152
1.314	16.00	0.258620398	3128.466295
1.271	16.50	0.250117379	3025.607408
1.230	17.00	0.242176812	2929.552348
1.193	17.50	0.234742784	2839.624768
1.157	18.00	0.227766775	2755.237733
1.124	18.50	0.221206443	2675.87904
1.093	19.00	0.215024648	2601.099416
1.063	19.50	0.209188659	2530.502914
1.035	20.00	0.203669503	2463.739058
1.008	20.50	0.198441429	2400.496362
0.983	21.00	0.193481467	2340.496942
0.959	21.50	0.188769051	2283.492019
0.936	22.00	0.184285708	2229.258136
0.915	22.50	0.180014794	2177.593955
0.894	23.00	0.175941269	2128.317541
0.874	23.50	0.172051505	2081.264043
0.855	24.00	0.168333122	2036.283698
0.837	24.50	0.164774846	1993.240124
0.820	25.00	0.161366386	1952.008828
0.803	25.50	0.158098326	1912.475925
0.787	26.00	0.154962037	1874.537017
0.772	26.50	0.15194959	1838.096208
0.757	27.00	0.149053692	1803.065246
0.743	27.50	0.146267615	1769.362768
0.730	28.00	0.143585148	1736.913635
0.716	28.50	0.141000544	1705.648333
0.704	29.00	0.13850848	1675.50246
0.692	29.50	0.136104016	1646.416253
0.680	30.00	0.133782559	1618.334175
0.668	30.50	0.131539839	1591.204547
0.657	31.00	0.129371873	1564.979209
0.647	31.50	0.127274948	1539.61323

Table V: Pressure and Stress sample data

Object distance from Source (mm)	Image/ Length of beam (mm)	Focal Length (mm)
15.79	300	15
16.90	300	16
18.02	300	17
19.15	300	18
20.28	300	19
21.43	300	20
22.58	300	21
23.74	300	22
24.91	300	23
26.09	300	24
27.27	300	25
28.47	300	26
29.67	300	27
30.88	300	28
32.10	300	29
33.33	300	30
34.57	300	31
35.82	300	32
37.08	300	33
38.35	300	34
39.62	300	35
40.91	300	36
42.21	300	37
43.51	300	38
44.83	300	39
46.15	300	40
47.49	300	41
48.84	300	42
50.19	300	43
51.56	300	44
52.94	300	45
54.33	300	46
55.73	300	47
57.14	300	48
58.57	300	49

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Table VI: Focal length vs. Applied pressure raw data

Screen distance (mm)	Offset (mm()	Focal length (mm)	Applied Pressure
35	7	28	15.82
43	7	36	11.25
39.5	7	32.5	14.01
37	7	30	16.73
32	7	25	25.6
34	7	27	16.7
36	7	29	19.25
39	7	32	10.73
41	7	34	13.9
44	7	37	10.4

Table VII: PDMS properties

Mechanical Properties	• **Young's Modulus, E ~ 750 kPa** • **Poisson's Ratio = 0.45** • **Density (cured) = 1030 kg/m^3**
Thermal Properties	• **CTE = 310 µm/m-^{o}C** • **Thermal Conductivity ~ 0.2 W/m-K**
Optical Properties	• **Apperance – clear/tansparent** • **Optically transparent down to ~ 280 nm** • **Refractive Index, n ~ 1.4 (adjustable)**
Chemical Properties	• **Surface Energy ~ 20 erg/cm (hydrophobic)** • **Compatability – consult literature (not good with solvents)**
Miscellaneous	• **Shrinks ~ 1% after curing** • **Uncured viscosity ~ 3900 mPa-s** • **Addition of iron powder can made PDMS magnetic** • **Addition carbon black can make PDMS conductive**

Table VIII: Light throughput sample raw data

%T	Wavelength	%T 2	w water	%T
88.577	308.56	97.681	308.56	127.877
89.472	308.77	98.122	308.77	129.507
90.087	308.98	97.229	308.98	127.647
88.886	309.2	98.025	309.2	127.261
89.852	309.41	97.144	309.41	128.057
88.02	309.62	95.754	309.62	127.633
88.955	309.84	96.778	309.84	128.344
88.695	310.05	97.043	310.05	129.49
90.642	310.26	97.426	310.26	129.795
88.498	310.47	96.855	310.47	126.902
89.167	310.69	97.231	310.69	127.37
88.92	310.9	97.632	310.9	130.058
89.389	311.11	97.572	311.11	129.018
88.84	311.32	96.674	311.32	128.226
88.786	311.54	97.312	311.54	129.393
89.901	311.75	98.096	311.75	131.163
88.529	311.96	95.407	311.96	127.834
89.445	312.18	98.025	312.18	129.286
90.572	312.39	98.136	312.39	126.84
88.976	312.6	98.299	312.6	128.679
90.58	312.81	98.715	312.81	130.911
88.503	313.03	97.612	313.03	128.129
89.547	313.24	98.508	313.24	130.108
88.197	313.45	97.306	313.45	130.199
88.77	313.66	97.345	313.66	130.796
89.663	313.88	98.487	313.88	130.162
90.252	314.09	97.11	314.09	130.16
90.967	314.3	98.237	314.3	129.998
90.287	314.52	96.704	314.52	129.77
89.578	314.73	98.977	314.73	128.285
89.168	314.94	96.991	314.94	128.741
89.624	315.15	96.684	315.15	127.099
87.757	315.37	96.14	315.37	128.612
88.777	315.58	96.822	315.58	128.876
88.983	315.79	96.31	315.79	129.772
90.988	316	98.563	316	131.913
89.007	316.22	95.734	316.22	128.914

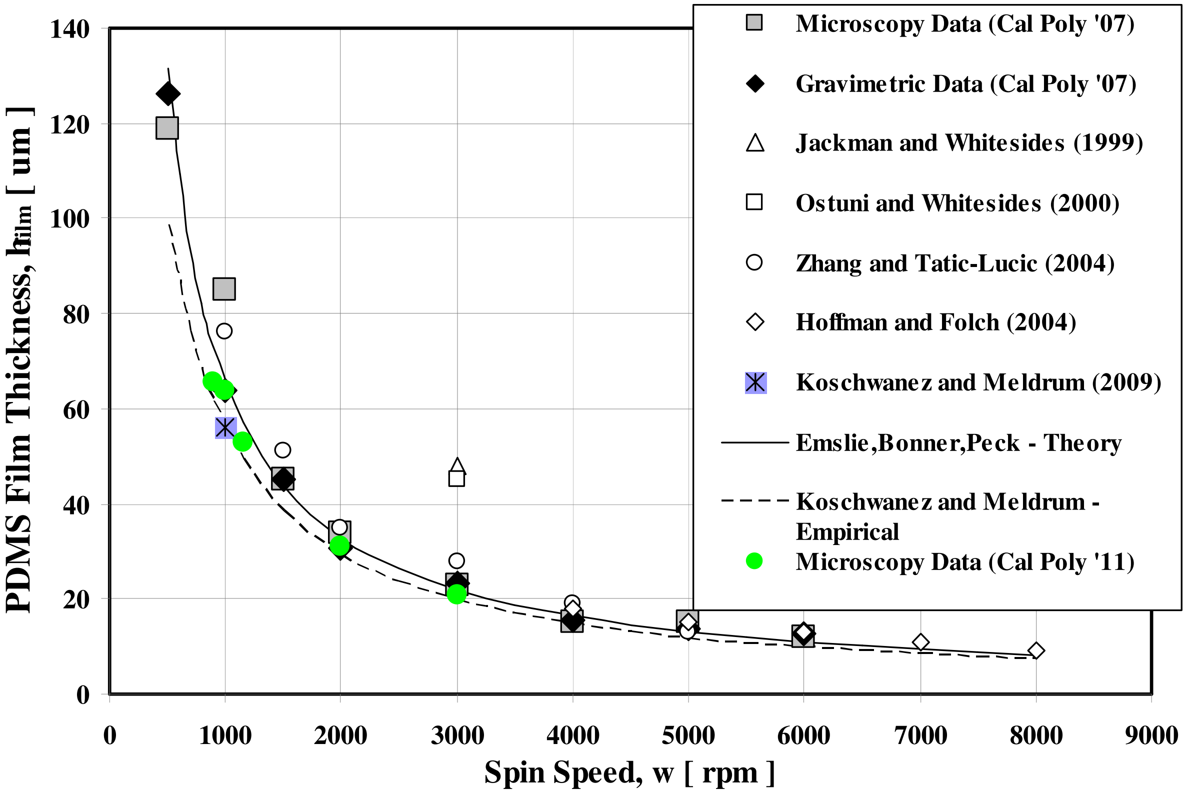
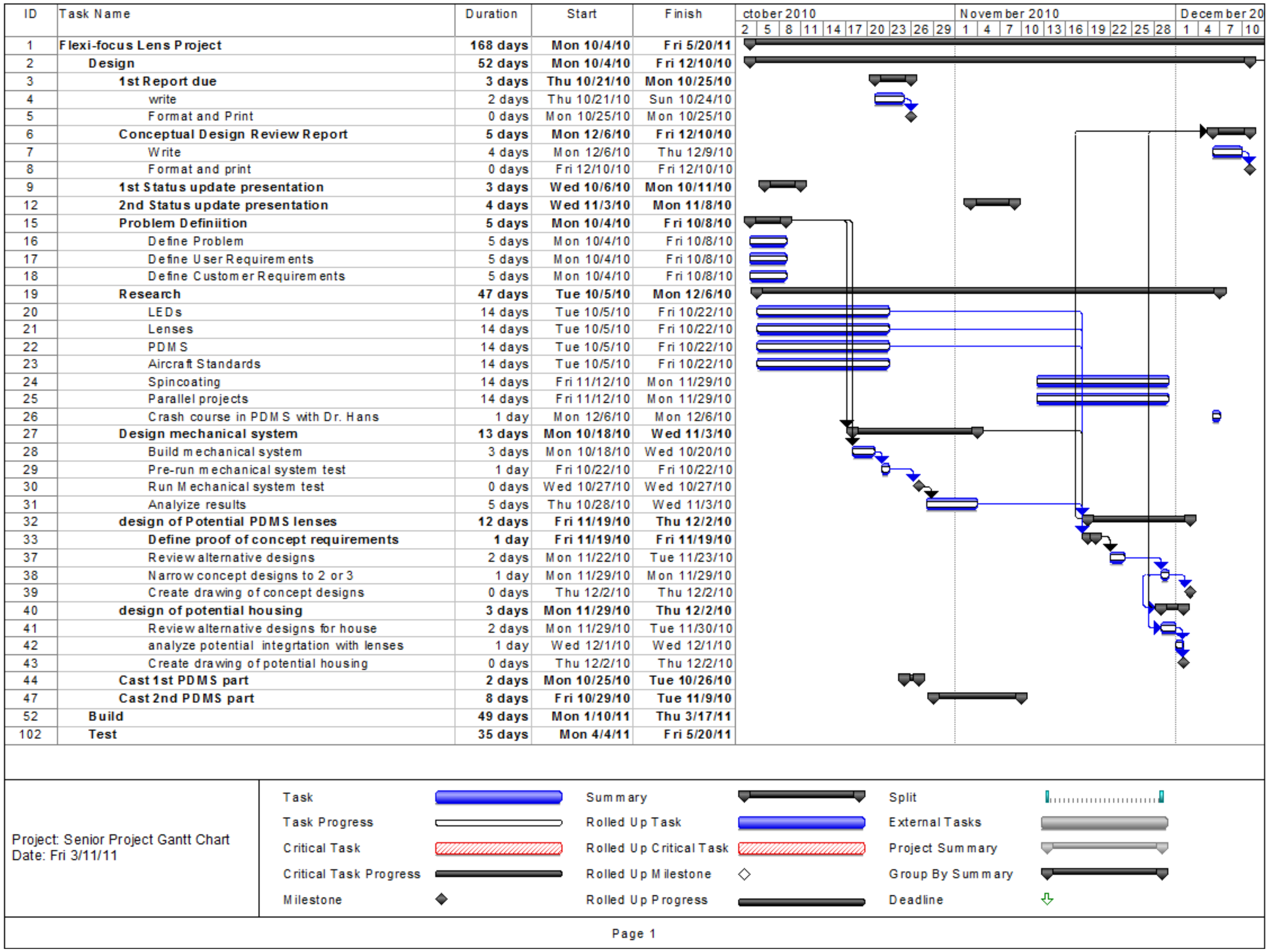


Figure 3: Spin Coat curve with previous data and Flexi-Focus team data

Appendix F

Table I: Fall 2010 Gantt Chart



ID	Task Name	Duration	Start	Finish
1	**Flexi-focus Lens Project**	**168 days**	**Mon 10/4/10**	**Fri 5/20/11**
2	**Design**	**52 days**	**Mon 10/4/10**	**Fri 12/10/10**
3	**1st Report due**	**3 days**	**Thu 10/21/10**	**Mon 10/25/10**
4	write	2 days	Thu 10/21/10	Sun 10/24/10
5	Format and Print	0 days	Mon 10/25/10	Mon 10/25/10
6	**Conceptual Design Review Report**	**5 days**	**Mon 12/6/10**	**Fri 12/10/10**
7	Write	4 days	Mon 12/6/10	Thu 12/9/10
8	Format and print	0 days	Fri 12/10/10	Fri 12/10/10
9	**1st Status update presentation**	**3 days**	**Wed 10/6/10**	**Mon 10/11/10**
12	**2nd Status update presentation**	**4 days**	**Wed 11/3/10**	**Mon 11/8/10**
15	**Problem Definiition**	**5 days**	**Mon 10/4/10**	**Fri 10/8/10**
16	Define Problem	5 days	Mon 10/4/10	Fri 10/8/10
17	Define User Requirements	5 days	Mon 10/4/10	Fri 10/8/10
18	Define Customer Requirements	5 days	Mon 10/4/10	Fri 10/8/10
19	**Research**	**47 days**	**Tue 10/5/10**	**Mon 12/6/10**
20	LEDs	14 days	Tue 10/5/10	Fri 10/22/10
21	Lenses	14 days	Tue 10/5/10	Fri 10/22/10
22	PDMS	14 days	Tue 10/5/10	Fri 10/22/10
23	Aircraft Standards	14 days	Tue 10/5/10	Fri 10/22/10
24	Spincoating	14 days	Fri 11/12/10	Mon 11/29/10
25	Parallel projects	14 days	Fri 11/12/10	Mon 11/29/10
26	Crash course in PDMS with Dr. Hans	1 day	Mon 12/6/10	Mon 12/6/10
27	**Design mechanical system**	**13 days**	**Mon 10/18/10**	**Wed 11/3/10**
28	Build mechanical system	3 days	Mon 10/18/10	Wed 10/20/10
29	Pre-run mechanical system test	1 day	Fri 10/22/10	Fri 10/22/10
30	Run Mechanical system test	0 days	Wed 10/27/10	Wed 10/27/10
31	Analyize results	5 days	Thu 10/28/10	Wed 11/3/10
32	**design of Potential PDMS lenses**	**12 days**	**Fri 11/19/10**	**Thu 12/2/10**
33	**Define proof of concept requirements**	**1 day**	**Fri 11/19/10**	**Fri 11/19/10**
37	Review alternative designs	2 days	Mon 11/22/10	Tue 11/23/10
38	Narrow concept designs to 2 or 3	1 day	Mon 11/29/10	Mon 11/29/10
39	Create drawing of concept designs	0 days	Thu 12/2/10	Thu 12/2/10
40	**design of potential housing**	**3 days**	**Mon 11/29/10**	**Thu 12/2/10**
41	Review alternative designs for house	2 days	Mon 11/29/10	Tue 11/30/10
42	analyze potential integrtation with lenses	1 day	Wed 12/1/10	Wed 12/1/10
43	Create drawing of potential housing	0 days	Thu 12/2/10	Thu 12/2/10
44	**Cast 1st PDMS part**	**2 days**	**Mon 10/25/10**	**Tue 10/26/10**
47	**Cast 2nd PDMS part**	**8 days**	**Fri 10/29/10**	**Tue 11/9/10**
52	**Build**	**49 days**	**Mon 1/10/11**	**Thu 3/17/11**
102	**Test**	**35 days**	**Mon 4/4/11**	**Fri 5/20/11**

Project: Senior Project Gantt Chart
Date: Fri 3/11/11

Task		Summary		Split	
Task Progress		Rolled Up Task		External Tasks	
Critical Task		Rolled Up Critical Task		Project Summary	
Critical Task Progress		Rolled Up Milestone	◇	Group By Summary	
Milestone	◆	Rolled Up Progress		Deadline	⇩

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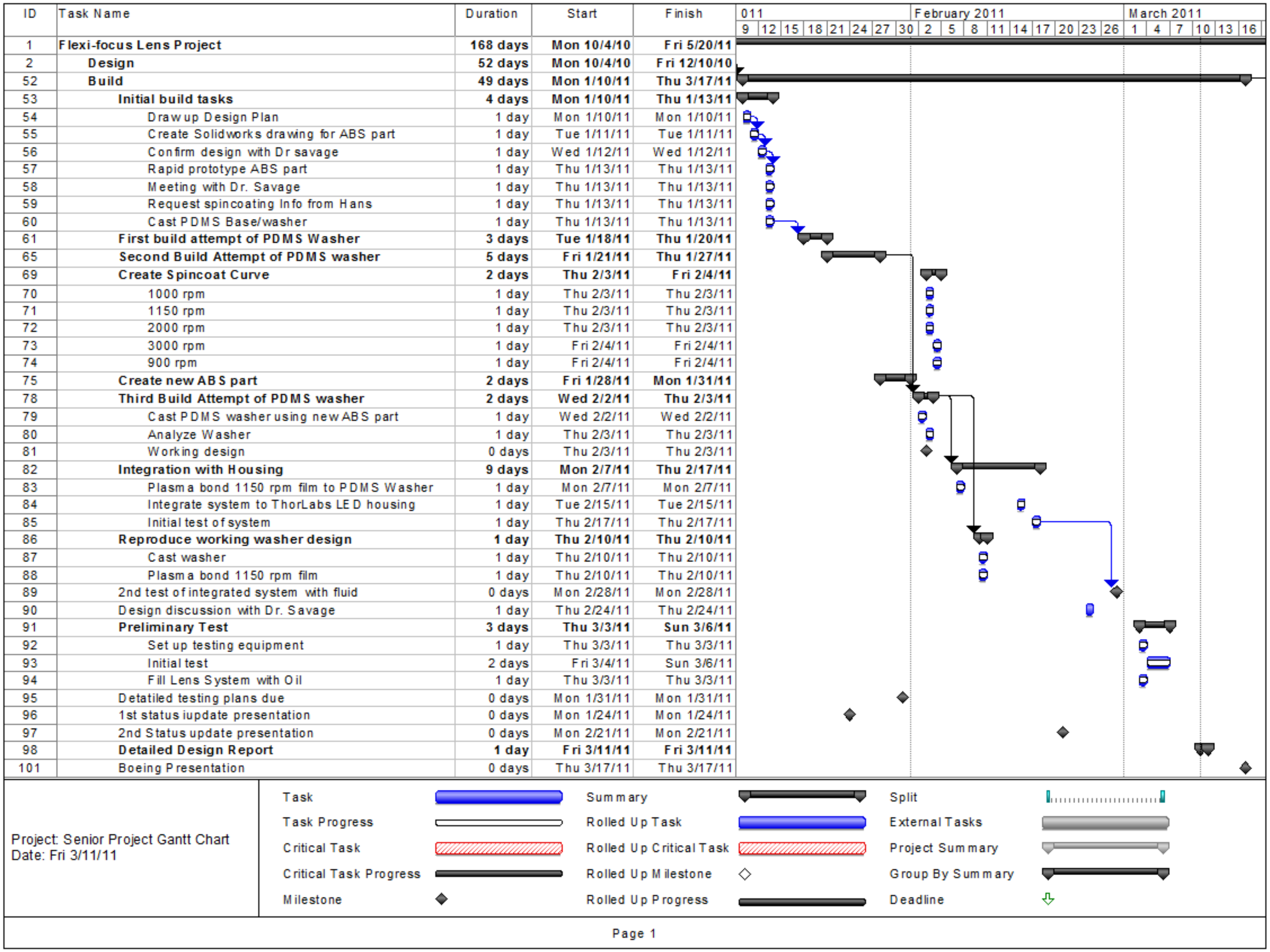
Table II: Winter 2011 Gantt Chart



ID	Task Name	Duration	Start	Finish
1	**Flexi-focus Lens Project**	**168 days**	**Mon 10/4/10**	**Fri 5/20/11**
2	**Design**	**52 days**	**Mon 10/4/10**	**Fri 12/10/10**
52	**Build**	**49 days**	**Mon 1/10/11**	**Thu 3/17/11**
53	**Initial build tasks**	**4 days**	**Mon 1/10/11**	**Thu 1/13/11**
54	Draw up Design Plan	1 day	Mon 1/10/11	Mon 1/10/11
55	Create Solidworks drawing for ABS part	1 day	Tue 1/11/11	Tue 1/11/11
56	Confirm design with Dr savage	1 day	Wed 1/12/11	Wed 1/12/11
57	Rapid prototype ABS part	1 day	Thu 1/13/11	Thu 1/13/11
58	Meeting with Dr. Savage	1 day	Thu 1/13/11	Thu 1/13/11
59	Request spincoating Info from Hans	1 day	Thu 1/13/11	Thu 1/13/11
60	Cast PDMS Base/washer	1 day	Thu 1/13/11	Thu 1/13/11
61	**First build attempt of PDMS Washer**	**3 days**	**Tue 1/18/11**	**Thu 1/20/11**
65	**Second Build Attempt of PDMS washer**	**5 days**	**Fri 1/21/11**	**Thu 1/27/11**
69	**Create Spincoat Curve**	**2 days**	**Thu 2/3/11**	**Fri 2/4/11**
70	1000 rpm	1 day	Thu 2/3/11	Thu 2/3/11
71	1150 rpm	1 day	Thu 2/3/11	Thu 2/3/11
72	2000 rpm	1 day	Thu 2/3/11	Thu 2/3/11
73	3000 rpm	1 day	Fri 2/4/11	Fri 2/4/11
74	900 rpm	1 day	Fri 2/4/11	Fri 2/4/11
75	**Create new ABS part**	**2 days**	**Fri 1/28/11**	**Mon 1/31/11**
78	**Third Build Attempt of PDMS washer**	**2 days**	**Wed 2/2/11**	**Thu 2/3/11**
79	Cast PDMS washer using new ABS part	1 day	Wed 2/2/11	Wed 2/2/11
80	Analyze Washer	1 day	Thu 2/3/11	Thu 2/3/11
81	Working design	0 days	Thu 2/3/11	Thu 2/3/11
82	**Integration with Housing**	**9 days**	**Mon 2/7/11**	**Thu 2/17/11**
83	Plasma bond 1150 rpm film to PDMS Washer	1 day	Mon 2/7/11	Mon 2/7/11
84	Integrate system to ThorLabs LED housing	1 day	Tue 2/15/11	Tue 2/15/11
85	Initial test of system	1 day	Thu 2/17/11	Thu 2/17/11
86	**Reproduce working washer design**	**1 day**	**Thu 2/10/11**	**Thu 2/10/11**
87	Cast washer	1 day	Thu 2/10/11	Thu 2/10/11
88	Plasma bond 1150 rpm film	1 day	Thu 2/10/11	Thu 2/10/11
89	2nd test of integrated system with fluid	0 days	Mon 2/28/11	Mon 2/28/11
90	Design discussion with Dr. Savage	1 day	Thu 2/24/11	Thu 2/24/11
91	**Preliminary Test**	**3 days**	**Thu 3/3/11**	**Sun 3/6/11**
92	Set up testing equipment	1 day	Thu 3/3/11	Thu 3/3/11
93	Initial test	2 days	Fri 3/4/11	Sun 3/6/11
94	Fill Lens System with Oil	1 day	Thu 3/3/11	Thu 3/3/11
95	Detatiled testing plans due	0 days	Mon 1/31/11	Mon 1/31/11
96	1st status iupdate presentation	0 days	Mon 1/24/11	Mon 1/24/11
97	2nd Status update presentation	0 days	Mon 2/21/11	Mon 2/21/11
98	**Detailed Design Report**	**1 day**	**Fri 3/11/11**	**Fri 3/11/11**
101	Boeing Presentation	0 days	Thu 3/17/11	Thu 3/17/11

Project: Senior Project Gantt Chart
Date: Fri 3/11/11

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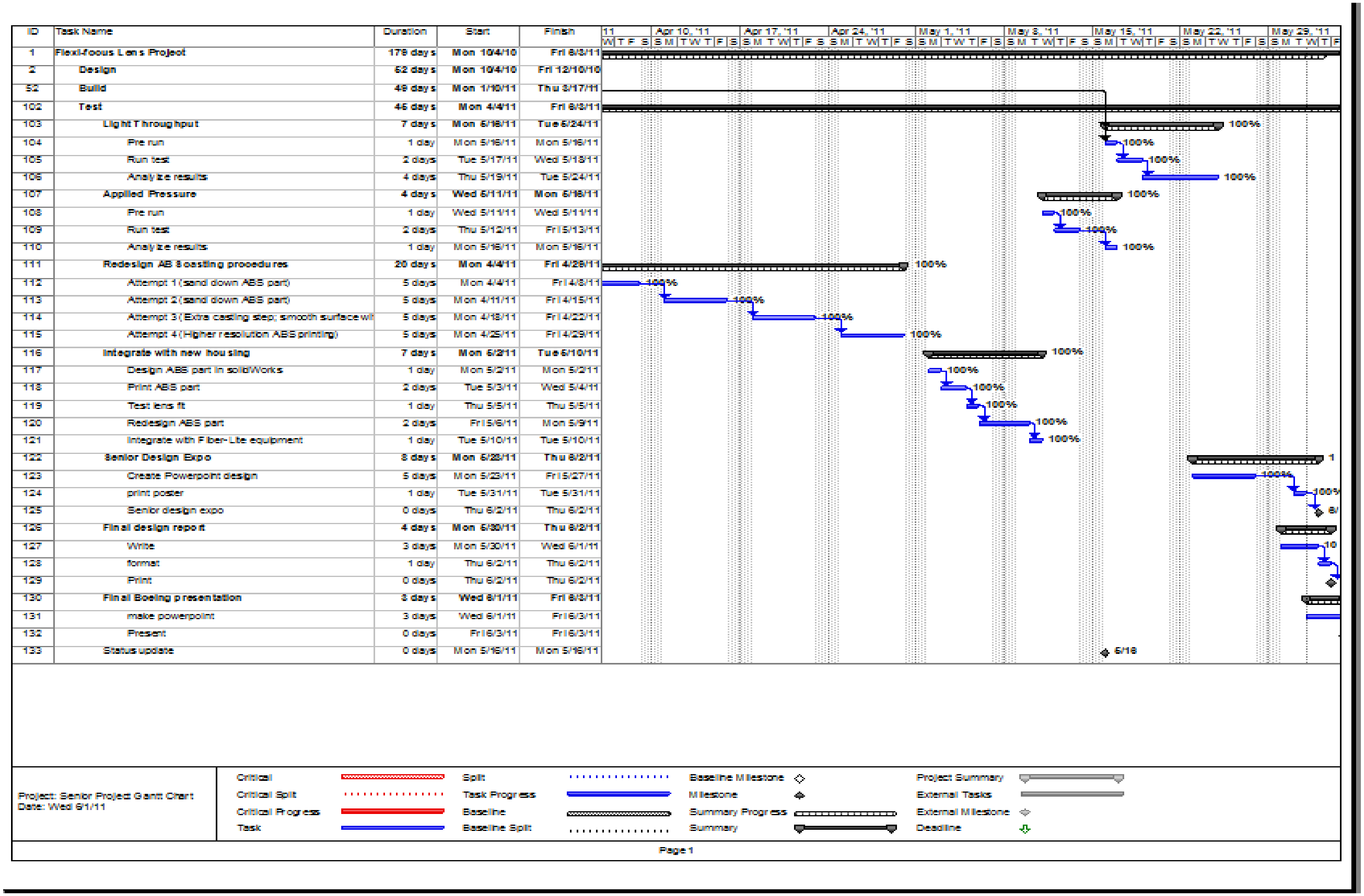
Table III: Spring 2011 Gantt Chart



ID	Task Name	Duration	Start	Finish
1	**Flexi-focus Lens Project**	**178 days**	**Mon 10/4/10**	**Fri 6/3/11**
2	**Design**	**52 days**	**Mon 10/4/10**	**Fri 12/10/10**
52	**Build**	**49 days**	**Mon 1/10/11**	**Thu 3/17/11**
102	**Test**	**45 days**	**Mon 4/4/11**	**Fri 6/3/11**
103	**Light Throughput**	**7 days**	**Mon 5/16/11**	**Tue 5/24/11**
104	Pre run	1 day	Mon 5/16/11	Mon 5/16/11
105	Run test	2 days	Tue 5/17/11	Wed 5/18/11
106	Analyze results	4 days	Thu 5/19/11	Tue 5/24/11
107	**Applied Pressure**	**4 days**	**Wed 5/11/11**	**Mon 5/16/11**
108	Pre run	1 day	Wed 5/11/11	Wed 5/11/11
109	Run test	2 days	Thu 5/12/11	Fri 5/13/11
110	Analyze results	1 day	Mon 5/16/11	Mon 5/16/11
111	**Redesign ABS casting procedures**	**20 days**	**Mon 4/4/11**	**Fri 4/29/11**
112	Attempt 1 (sand down ABS part)	5 days	Mon 4/4/11	Fri 4/8/11
113	Attempt 2 (sand down ABS part)	5 days	Mon 4/11/11	Fri 4/15/11
114	Attempt 3 (Extra casting step; smooth surface wi	5 days	Mon 4/18/11	Fri 4/22/11
115	Attempt 4 (Higher resolution ABS printing)	5 days	Mon 4/25/11	Fri 4/29/11
116	**Integrate with new housing**	**7 days**	**Mon 5/2/11**	**Tue 5/10/11**
117	Design ABS part in solidWorks	1 day	Mon 5/2/11	Mon 5/2/11
118	Print ABS part	2 days	Tue 5/3/11	Wed 5/4/11
119	Test lens fit	1 day	Thu 5/5/11	Thu 5/5/11
120	Redesign ABS part	2 days	Fri 5/6/11	Mon 5/9/11
121	Integrate with Fiber-Lite equipment	1 day	Tue 5/10/11	Tue 5/10/11
122	**Senior Design Expo**	**8 days**	**Mon 5/23/11**	**Thu 6/2/11**
123	Create Powerpoint design	5 days	Mon 5/23/11	Fri 5/27/11
124	print poster	1 day	Tue 5/31/11	Tue 5/31/11
125	Senior design expo	0 days	Thu 6/2/11	Thu 6/2/11
126	**Final design report**	**4 days**	**Mon 5/30/11**	**Thu 6/2/11**
127	Write	3 days	Mon 5/30/11	Wed 6/1/11
128	format	1 day	Thu 6/2/11	Thu 6/2/11
129	Print	0 days	Thu 6/2/11	Thu 6/2/11
130	**Final Boeing presentation**	**3 days**	**Wed 6/1/11**	**Fri 6/3/11**
131	make powerpoint	3 days	Wed 6/1/11	Fri 6/3/11
132	Present	0 days	Fri 6/3/11	Fri 6/3/11
133	Status update	0 days	Mon 5/16/11	Mon 5/16/11

Project: Senior Project Gantt Chart
Date: Wed 6/1/11

Critical	🟥	Split	┈	Baseline Milestone	◇	Project Summary	▬
Critical Split	┈	Task Progress	▬	Milestone	◆	External Tasks	▬
Critical Progress	▬	Baseline	▨	Summary Progress	▭	External Milestone	◆
Task	▬	Baseline Split	┈	Summary	▬	Deadline	⇩

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