# Automated Mirror Cover for Telescope Application

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# Project Proposal

Document

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## Problem Statement

The NPOI needs an automated mirror cover that can operate without interfering with current equipment while maintaining a nitrogen purge.

### Introduction

The NPOI (Navy Precision Optical Interferometer) located at the top of Anderson Mesa in Flagstaff, Arizona, is a United States Naval Observatory (USNO). This facility uses a series of expensive aluminum coated mirrors to reflect starlight down vacuum tubes, where the starlight is then captured by sensors. The data is then analyzed by astronomers to produce a high resolution image of stars.

### Background Research

The capstone's contact and client, James Clark, has been working at the NPOI since 1990. James Clark has become concerned about the potential safety risks associated with removing the mirror caps. The mirrors aluminum coating is only a few molecules thick, so the mirrors need to be covered when not in use or the coating can be damaged by moisture or debris. Currently the mirrors are protected by a Lexan cover with a nitrogen purge. The Lexan protects the mirrors from debris and the nitrogen purge maintains 10 psi of pressure that prevents moisture from condensing on the mirror. This requires NPOI employees to crawl into each siderostat housing, remove the mirror cap, and crawl out either late at night or before dawn with no light, this process can be very dangerous particularly in winter and is a major safety concern with the addition of 2 new taller telescopes.

The aluminum mirrors are re-coated once every three years. In order to lengthen the time between coatings, the mirrors are cleaned three to four times in three years. This practice ensures that no unnecessary contact with the mirror is made which can damage the coating. A protective dome closes to protect the siderostat and when the facility is not is use. Within the dome, there is a climate controlled environment which protects the mirror from harsh weather and debris. While the dome is closed, moisture can condense on the mirrors surface, if left uncovered, frost may form, significantly reducing the useable life of the mirror. In order to counteract this process, a Lexan cover was built which creates a nitrogen blanket on the mirror's surface.

## Needs Identification

After reviewing the initial project outline presentation put together by our client, a meeting was arranged with the client at the location this project will be implemented. Although the project outline stated the problem and requirements for our deliverable, all of the purpose of the cover was still unclear. Questions that we were particularly interested in having answered were:

- What is the intended use of our device?
- Who are the people this project affects most directly?
- What were the motivating factors for our client to seek NAU capstone as a solution venue?
- What was the physical environment our device would operate in?
- Had our client already given thought to any possible solutions?

While touring the facility grounds and being shown the physical locations of the project's environment, it became obvious to our group that the driving force for our project was the safety of the employees who interact with the current system. Although the automation of these mirror covers will eliminate unnecessary man hours; more importantly, the current system involves an unacceptable level of danger for the operators. Coupled with the possibility of damage to highly sensitive equipment that is put at risk with the current procedure, our needs statement is as follows:

> "Needs Statement"-Potential for injury to employees of the Navy Precision Optical Interferometer is unacceptable.

## Project Goal and Scope of Project

A solution for removing and replacing essential mirror dust covers must be found while maintaining functionality of existing equipment, adding a minimum amount of mass to the system while incorporating autonomous/ semi-autonomous operation during power loss situations.

## Objectives

The new cover must operate remotely, from outside of the equipment housing, keeping observers out of potential danger and protecting the equipment from accidental impacts. The mirror must be kept in a nitrogen environment in order to displace moisture. In order to do this, an orifice, 4 thousands of an inch in diameter must allow 10 psi of nitrogen to be injected through the mirror cover, purging atmospheric air. The nitrogen flow needs to automatically shut off when the cover is open. In addition, the equipment must maintain balance so that motor components are not exposed to excess stress during rotation. The new equipment should enhance the performance of the equipment that is in place and should in no way hinder the operations of the equipment.

**Constraints**

The cover must not block any light from the mirror's lens. The full range of motion of the siderostat must be maintained after installation of the automated cover. This includes a vertical tilt from -10 to 60 degrees and a horizontal pan of -60 to 60 degrees. The cover must be able to close in the event of a power failure.

The siderostats are precision instruments that use small movements to track celestial objects while the Earth is rotating. Anything that is mounted on them cannot interfere with this task. The facility is located at the top of Anderson Mesa, which experiences high winds therefore a low profile cover is required. It has been requested by the sponsor that no fabric folds be exposed to the wind, as this type of system may act as a sail, disrupting observation. All of the moving components need to have tight tolerance, allowing essentially zero unanticipated movement.

The cover must be able to open and close while the dome is closed, allowing maintenance to be performed at any time. The critical clearances that must be accommodated are the clearance between the bottom of the mirror cell and the base as well at the clearance between the top of the mirror cell and the dome when it is closed. The top and bottom clearances are measured to be 10 inches and 4 inches respectively.

The siderostats are outside so the cover must be able to operate in the temperature range of -40ºC to 40ºC. The mirror cell is made of caste aluminum and anything mounted to the mirror cell must have close to same rate of thermal expansion. Caste aluminum is expensive but 6061-T6 aluminum has a similar thermal expansion and will be used for any parts that will be directly mounted to the mirror cell. It would be possible to drill into the cast aluminum cell but not preferred. This requires the design and implementation of a mounting band or other device, allowing for relatively easy installation and removal while maintenance is performed on the mirror itself.

The only grease that is allowed near the mirror is high specific weight grease because if the grease evaporates then the vapor can get on the mirror and jeopardize the mirrors resolution. This option is out of the project budget because this grease cost approximately $600 per ounce so any cover cannot use grease.

If a polymer is used, it must be able to withstand small to moderate amounts of ultraviolet radiation without ceasing to function. The plastic must not be hydroscopic, such as nylon. It will be exposed to moisture and a hydroscopic material will swell and could cease to function properly.

## Functional Diagram

Figure 1 is a Quality Function Diagram; this figure shows how qualitative requirements can be quantified into a list of product features.

| | | Engineering Requirements | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Yield Strength | Young's Modulus | Moment of Inertia | Weight | Cost | Thermal Expansion | Dimensions | Power |
| Client Requirements | Durability | x | x | | | x | | | |
| | Inexpensive | x | x | | x | x | | | |
| | Protect mirror from the elements | x | | | | | | x | |
| | Maintain nitrogen purge | | | | | | | x | x |
| | Mitigate need for human interaction | | | | | | | | x |
| | Low weight | x | x | | x | x | | | |
| | Does not interfere with star light | | | | | | | x | |
| | Maintain range of swivel of siderostat | | | | | | | x | |
| | Withstand Extreme Temperatures (-20F TO 100F) | | | | | | x | | |
| | Units | psi | psi | $in^4$ | lb | $ | in/in *F | in | Volt |

**Figure 1 - Quality Function Diagram**

## Criteria Tree

Figure 2 is a tree diagram of the weighting factors

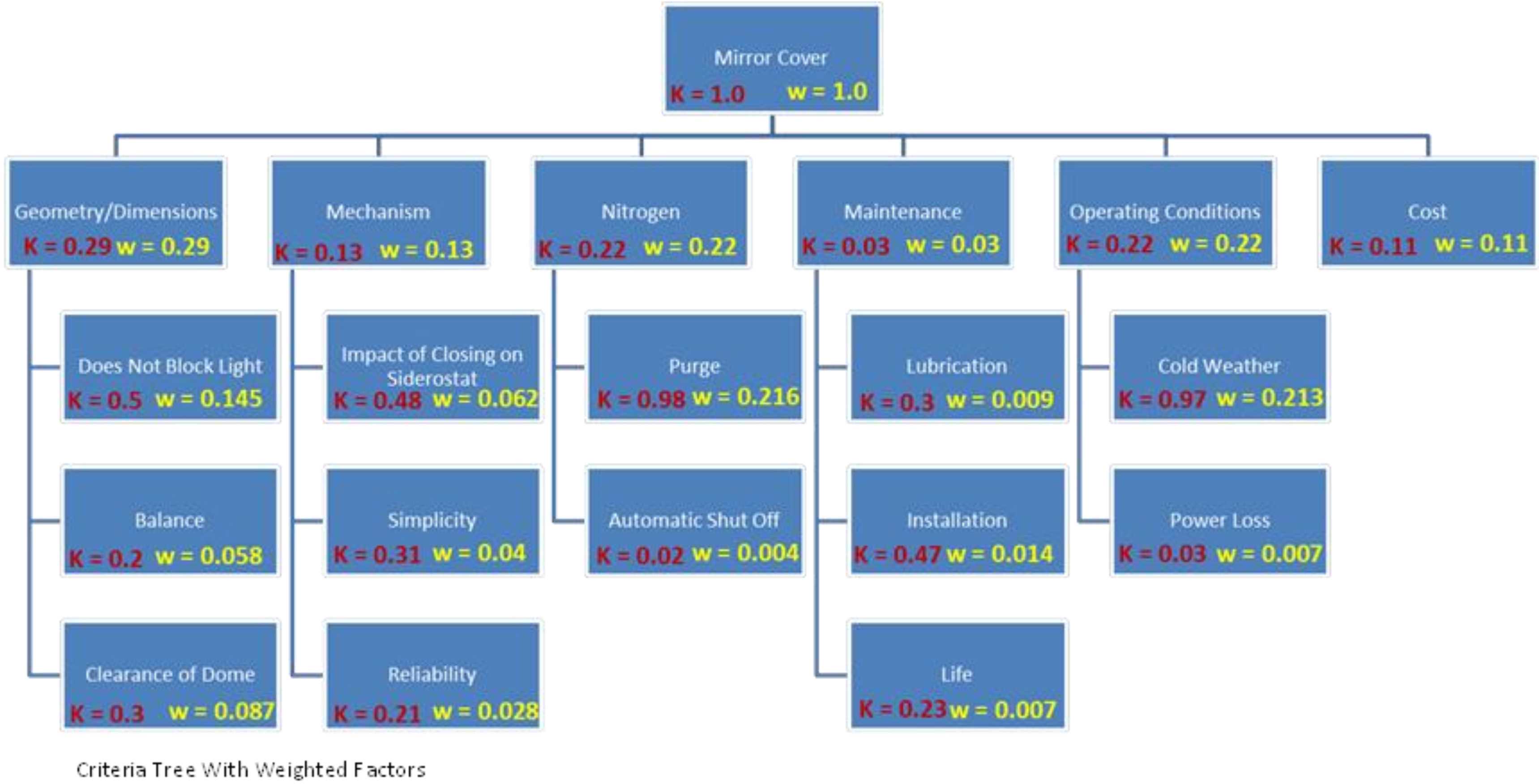


**Figure 2 - Weighting Factors**

**Quality Function Deployment**

Figure 3 is a House of Quality; this figure demonstrates the relationships between different product features.

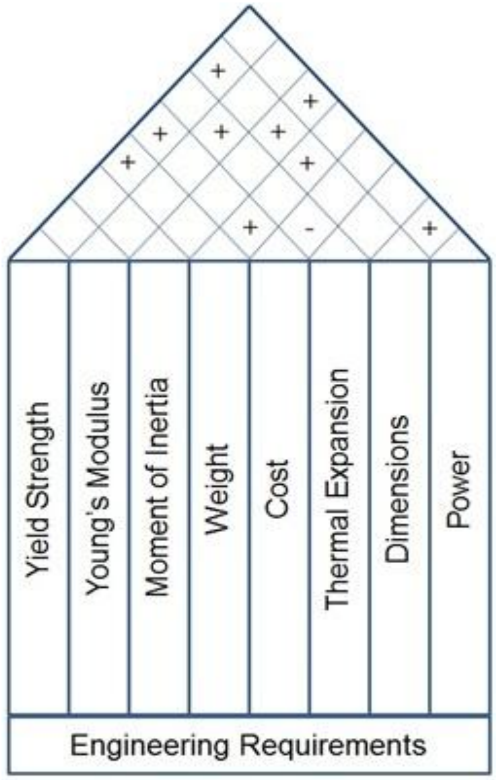


**Figure 3 - House of Quality, the + symbol represent a positive correlation, the – symbol represents a negative correlation.**

## Concept Generation

The team's initial concept generation resulted in the two viable designs but after meeting with James Clark, new design constraints were introduced that the original designs did not meet. The worm gear design, which can be seen below in Figures 4 and 5, incorporated a worm and gear assembly by which the cover is raised from the closed to open position. The entire drive mechanism would be mounted to the top side of the siderostat. Ideally, the whole assembly would be self-supporting and would require a simple bolt on installation. The drive system would operate with the use of a standard electric motor that would drive a shaft. The shaft would have a worm gear on its end which would drive a gear.  The gear would rotate with its shaft, on the shaft there would also be a fixed armature. The mirror cover would be attached to the armature which would complete the assembly. Other considerations are that due to the high torque characteristics of a worm and gear set up, a set of sensors would be used to determine when fully open and close positions were acquired. As a fail-safe, the key securing the gear to its shaft would be designed to fail before any harm would befall the siderostat and mirror. Lastly, the worm and gear assembly would need to enclosed in a gear housing which if designed correctly would replace the current mount securing the gear and armature assembly. However this design was not viable as there are clearance issues that would not allow the cover to close or open.

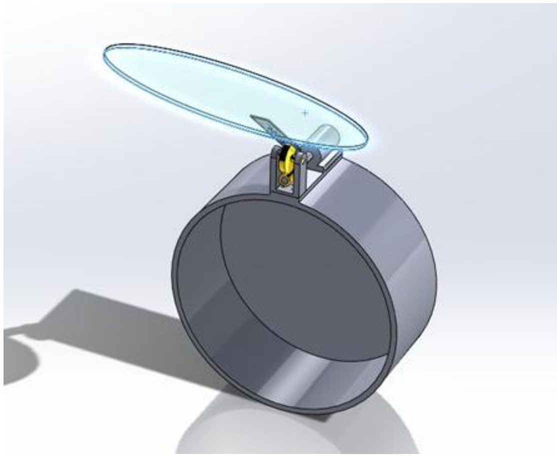

**Figure 4**

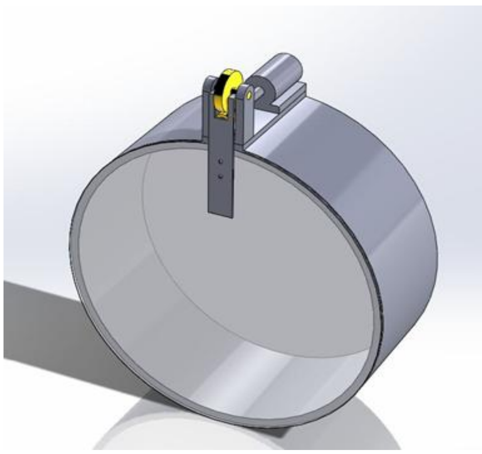

**Figure 5**

Our second design, the four link design which can be seen in Figure 6 below, proved to be more of a viable solution. The four link system can be designed with a geometry that does not interfere with the movement of the siderostat and the light of the stars. By choosing the right materials and making the right analysis it is possible to make it light weight, so the increase in mass of the whole system is minimal and the end results does not have a negative effect in the siderostat motors. The nitrogen purge can easily be installed on the mechanism and when the system is in the closed position should provide a good seal using rubber between the siderostat and the mechanism. The mechanism would need basic maintenance such as lubricating the pivot points and checking that the bearings of the links are in good condition. The cost would not be high because of the simple design. The siderostat would need to be adapted to accept the links of the mechanism. This design is a viable option but to implement the correct position of the bars using motion kinematics would be very difficult to achieve.

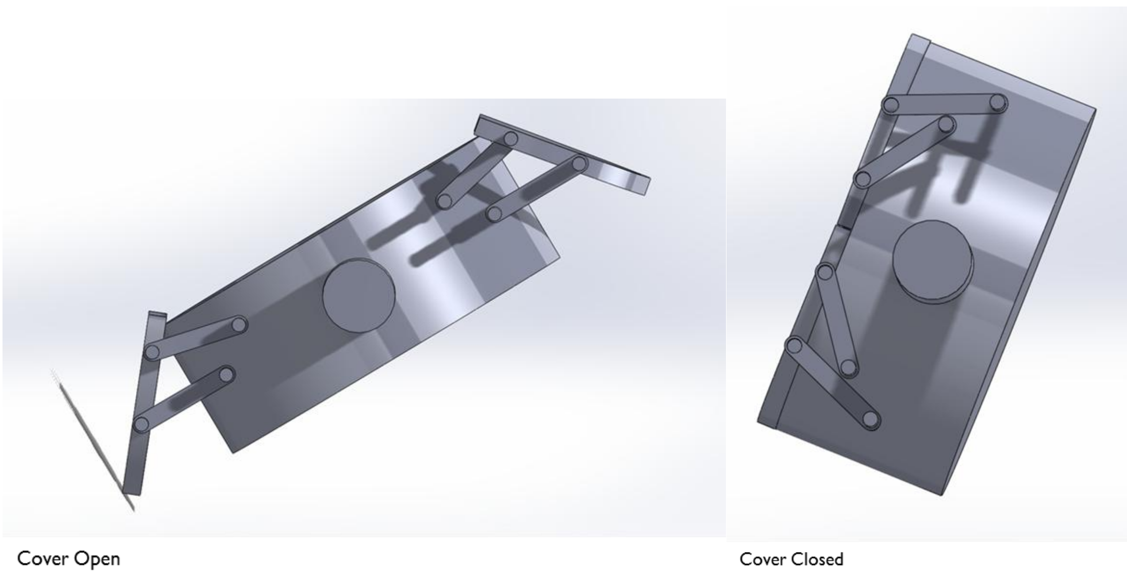


**Figure 6 - Four link design in open and closed positions.**

The worm gear design and four link design were immediately taken out of consideration once we presented these designs to James Clark due to newly found clearance issues and difficult implementation to the siderostat. As a result James Clark presented us a possible design solution. The design, which can be seen in Figure 7 below, is fundamentally a pair of rollers located at the top and bottom of the mirror, connected by a rope or belt to roll up and unroll a sheet of flexible material. The flexible material, while unrolled, would serve as an adequate barrier to the outside elements and provide and envelope for nitrogen to be continuously purged into, so that the environment directly in contact with the mirror surface can be controlled. While this design has many positive aspects; including low cost, ease of fabrication, material sourcing convenience and minimum machining, our group feels that the design also has negative aspects to be considered.

The team found that the blinds concept would not be a viable option due to the following disadvantages:

- Wind
  - One major concern with any blinder type concept is that while in the open or closed position, the design would have fabric on either side of the siderostat. Fabric is susceptible to wind and could oscillate and vibrate with the wind, causing distortion of the mirror, which is unacceptable.
  - The tensioning ropes or belts that would be used to open and close the blind cover would always be exposed to the elements, potentially leading to further vibrations during operation of the mirror.
- Nitrogen Purge will be difficult to mount due to the rolling aspect of the cover.
- Concern over the lifespan of the curtain material in the cold environment, unrolling during the coldest part of the day (dawn).
- Mounting locations on the siderostat frame will be complicated.
- Clearance, specifically below the siderostat will be an issue. The triangular shape of the base will interfere with any roller below the mirror.

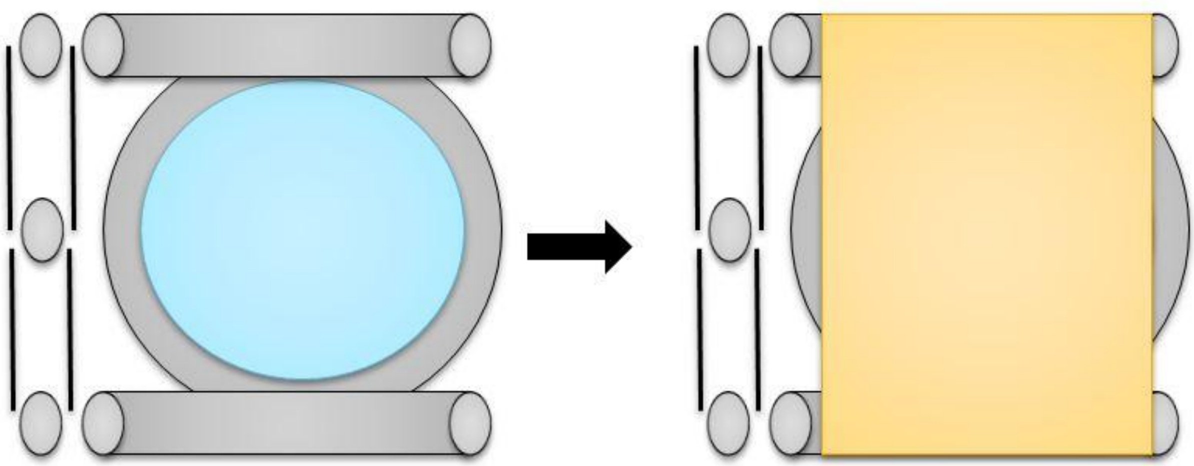

**Figure 7 - Blinds design that displaces a sheet of flexible material using a pair of rollers.**

The team took the blinds concept into mind and improved upon it by developing the Iris Lens Concept. This was found researching theatre spotlights. This design, which can be seen in Figure 6 below, is essentially composed of three major components: a lower frame ring that was fixed, an upper frame ring that rotated relative to the lower, and a series of interior leaflets. The movement of the interior leaflets is determined by the relative rotation of the two frame rings. This design solved many of the issues that our group was encountering with previous design concepts, including material concerns, mount location considerations as well as simplicity of design and fabrication. The Iris design has the smallest cross section of all designs that have been considered. The small area occupied by the iris will reduce the wind's ability to move the siderostat during observation. Figures 8, 9, and 10 show the iris in different modes of operation.

**Figure 8 - Fully Open**

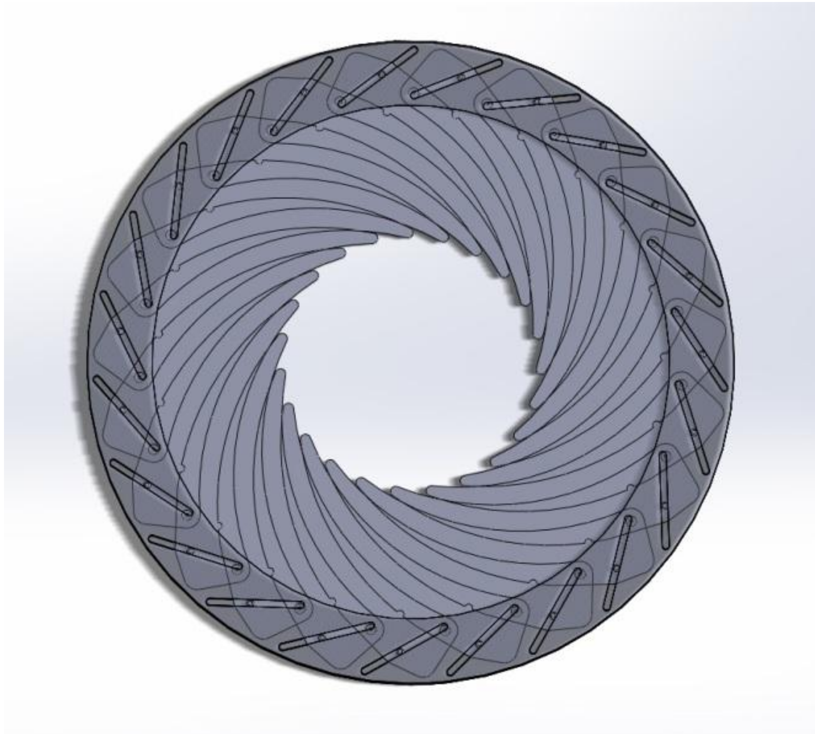

**Figure 9 - Partially Closed**

**Figure 10 - Fully Closed**

## Concept Selection

In order to assess the viability of each concept, the objectives and constraints for the project were evaluated thoroughly. Each criterion was broken down into specific descriptors that are applied to each concept.

The six main categories are:

- Geometry/Dimensions
- Mechanism
- Nitrogen
- Maintenance
- Operating Conditions
- Cost

The geometry of the mirror cover is the most important category for this project. The cover must fit into each siderostat housing without obstructing the dome or movement of the siderostat. Also, the cover must not block any star light from being collected by the mirror. The third consideration for the geometry is balance. The Siderostat is a precision instrument that is balanced in order to be able to make minute angle adjustments. Our cover must not disrupt the overall balance of the mirror. In order to accomplish this, there are adjustable tungsten counterweights that will be moved to counteract the mass of the cover.

The mechanism is broken down into three categories. The most important consideration is the impact that the mechanism will have on the siderostat during opening and closing. In order to maintain the alignment of the siderostat, little to no shock or abrupt force should be applied to the housing during opening or closing. Simplicity and Reliability are also considered for the mechanism.

The nitrogen system is a vital component for the life span of each mirror. During storage, moisture contained in the atmospheric air condenses on the mirror causing corrosion. To counteract this, a steady stream of nitrogen is injected into the mirror cover, displacing atmospheric air and vapor. The current system does not employ a shut off valve for the nitrogen when the cover is open.  In order to conserve nitrogen and reduce operating costs for the facility, we will investigate the possibility of having an automated valve to turn off the nitrogen flow while the cover is open.

The maintenance was a small portion of the overall design considerations.  The life and ease of installation are directly related.  If a solution allows for increased life but difficult installation, the benefit of the long life will outweigh the inconvenience of an extended installation time.  The opposite is also true, a concept with a relatively short life could still be considered if replacement is simple.

The cost of each concept was also considered.  Due to the expense of the components the cover will be protecting, a higher cost is permitted granted the design achieves higher levels of protection.  This is also a government funded project, allowing further lenience over the budget.

Using the weighted values in the criteria tree, Figure 1, a decision matrix is created for each of the concepts.  A rating from one to nine is given based on competency for each category.  The values are then multiplied by their respective weights and summed to give a weighted score to each concept.  In the matrix, shown below in Table 1, the top three concepts are compared.

**Table 1 - The decision matrix shows that the Iris design is the best solution when compared to the four link design and blinds concept**

| Criteria | Design Options | | |
|---|---|---|---|
| | Two Piece Four Link | Curtain | Iris |
| Doesn't Block Light | 9 | 9 | 9 |
| Balance | 8 | 7 | 9 |
| Clearance | 4 | 7 | 9 |
| Impact | 8 | 8 | 9 |
| Simplicity | 8 | 8 | 3 |
| Reliability | 5 | 6 | 5 |
| Purge | 7 | 5 | 5 |
| Auto Shut Off | 7 | 7 | 7 |
| Lubrication | 3 | 9 | 9 |
| Installation | 5 | 6 | 9 |
| Life | 6 | 2 | 5 |
| Cold Weather | 5 | 3 | 6 |
| Power Loss | 6 | 6 | 6 |
| Cost | 8 | 8 | 5 |
| Total | 89 | 91 | 96 |
| Weighted Total | 6.739 | 6.152 | 6.648 |

The team concluded that the iris design is our most viable solution. Although the iris design contains many individual parts, they consist of only three major parts which are repeated. This will allow replacement and repair of the iris to be simple and easy compared to other designs. The iris is one piece when removed from the siderostat, further increasing the ease of installation and removal when maintenance is required. This will also reduce the risk of damaging the mirror during installation and removal.

## Engineering Analysis

Once analysis was completed for the four link design, it became clear that it was not the best design to implement. Clearance issues necessitated an advanced link assembly that would defeat the purpose of the design, which was to accomplish the goal simply and cost effectively. It became clear than the project must go in another direction. The two remaining concepts were the pull down curtain and the iris.

The pull down curtain represented, in theory, the simplest cover that would fin within the confined space of the siderostat housing. Materials selection for this concept quickly became an issue. While most of the components would be made of aluminum, the actual curtain material would have to be flexible, non-hydroscopic, and durable. The extreme temperature swings experienced on a daily basis at the facility provided added emphasis on the material to be used.

The iris, while more complex than the other concepts, satisfies the constraints and represents the most reliable and stable cover for the application. When fully open, a ring with an inner diameter of 23 inches and outer diameter of 28.75 inches is the only visible part of the cover. This provides minimal interference to the movement of the siderostat and provides a balanced addition to the siderostat which is easily balanced using static weights. In addition, there are currently produced iris mechanisms which closely match the proportions proposed by the team, however at a scaled size.

Conceptually, the iris is a simple design. It consists of a lower ring, an upper ring which rotates, and a repeated leaf design. The complexity lies in the overlapping leaves clearing one another without interfering with pivot point. One existing design that will be adapted to the required size has a maximum aperture of 3.94 inches and an outside diameter of 5.12 inches. This is a ratio of 77 percent. The design uses a total of 20 leaves to close to a zero aperture. The required dimensions for this project are a maximum aperture of 23 inches and a maximum outer diameter of 28.75 inches, yielding a ratio of 80 percent. The larger ratio requires that the design have a larger number of leaves.

## Final Design

In order to meet all of the goals of the project while complying with the constraints, the team decided upon an Iris Diaphragm cover. This type of mechanism will allow the cover to have a small cross sectional area when open, it will be light weight, and it will provide adequate protection to the mirror. The materials that will be used will be more rigid than for other viable designs and will provide a longer life span and durability that a flexible vinyl sheet. In addition, this is a design that has been proven to work in similar proportions; the challenge faced by the engineering team is to adapt smaller designs to the large scale needed for the project. The iris will be constructed of two materials. The rings will be made of plate aluminum which has a nearly identical thermal expansion to the cast aluminum that comprises the mirror cell. This is critical because of the extreme sensitivity of the observation mirrors. Any stress put on the mirror cell by dissimilar expansion or contraction of the iris ring will be translated into distortion of the mirror.

The leaves will be made out of Polyoxymethylene, commonly referred to as Acetal or Delrin. This is a high quality thermoplastic with a very low coefficient of friction and it is non-hydroscopic. The benefits of such a material are twofold: it is available in easily machined sheets or plates, and it exhibits all of the properties required for use in facility's environment. A non-hydroscopic material will not absorb moisture that could evaporate and condense on the mirror's surface, the wide temperature range of the plastic is suitable for the temperatures experienced in the region, and the low friction will allow for smooth operation of the iris with minimal power from the drive mechanism.

Opening and closing the iris requires that the outer ring be rotated approximately 10 degrees. In order to produce this motion, a motor will be mounted to the top of the mirror cell. The motor will drive the ring through a rack and pinion system. The rack gear will be mounted along the portion of the ring that contacts the pinion gear of the motor. This will reduce the cost of the motor, allowing the operation speed to be determined by gear ratios and not a motor controller.

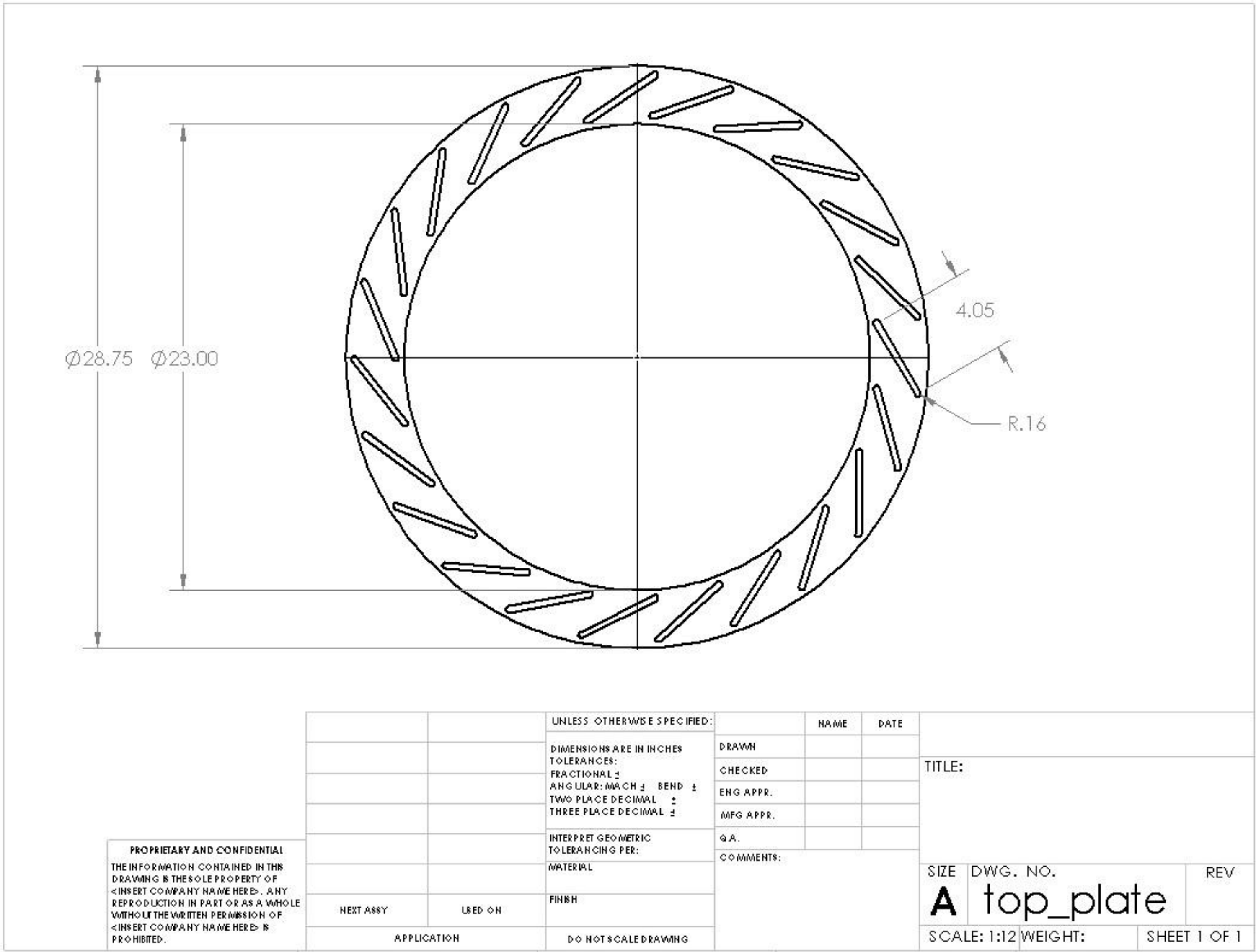


**Figure 11 - Top Plate with Dimensions**

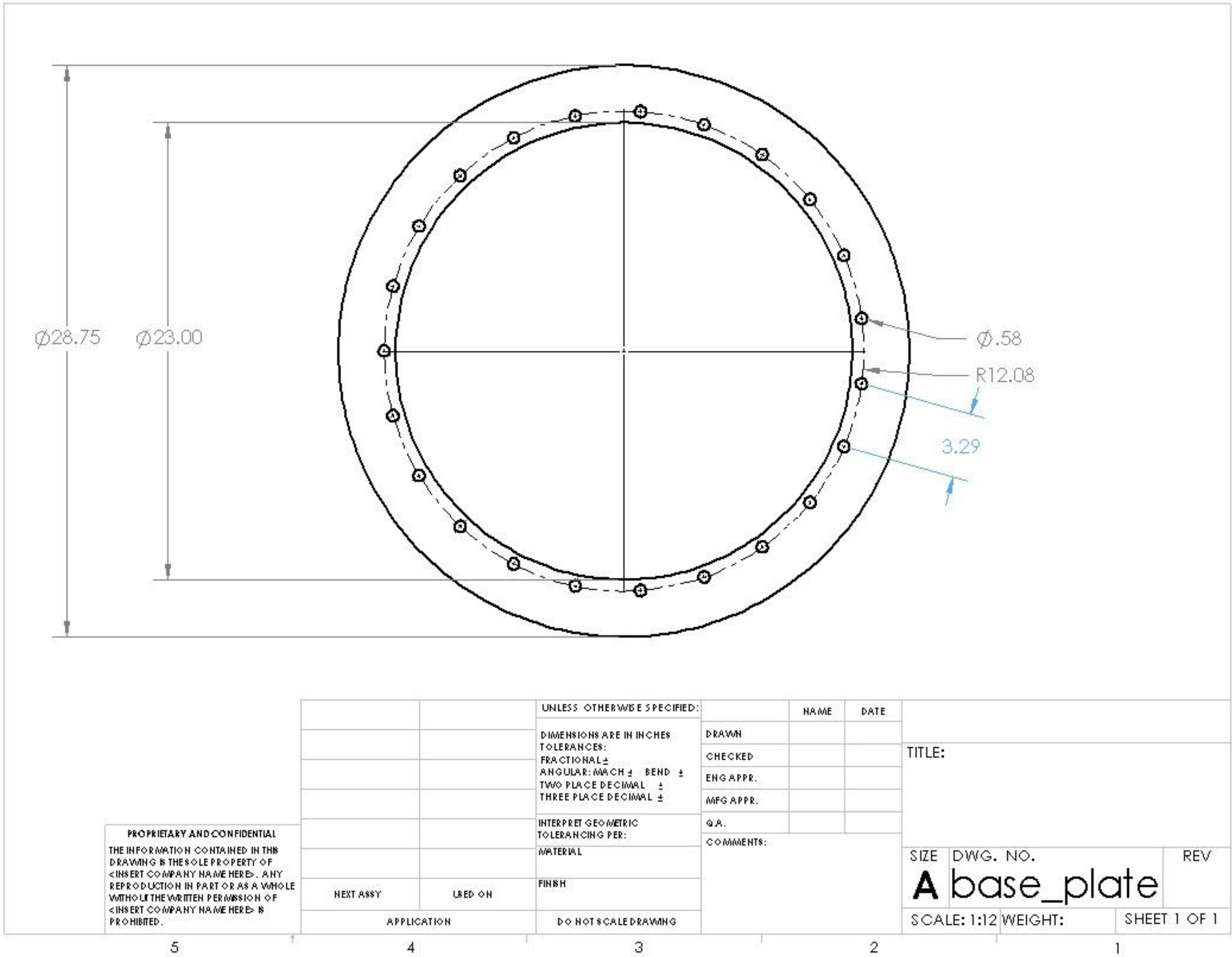


**Figure 12 - Base Plate with Dimensions**

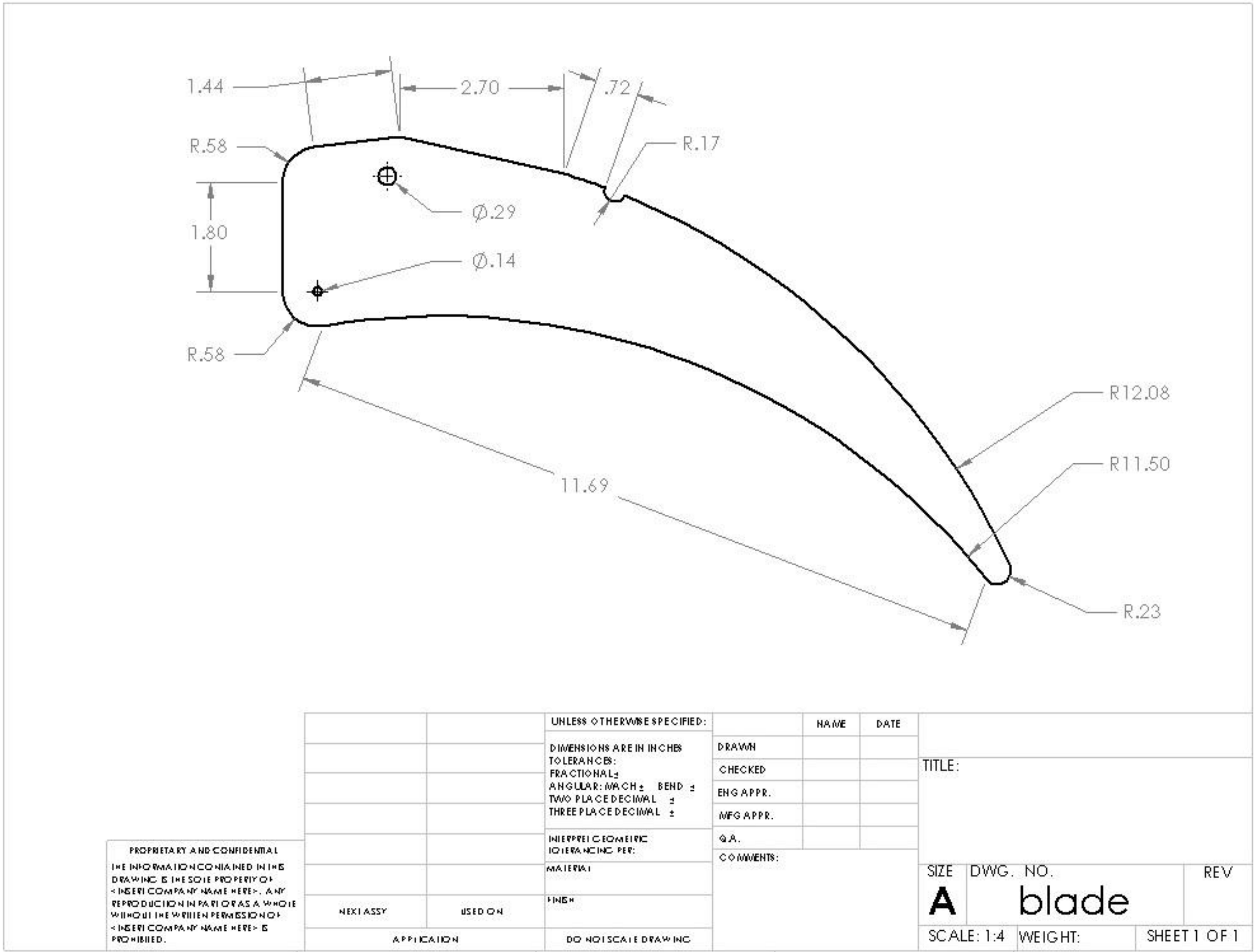


**Figure 13 - Iris Leaf with Dimensions**

## Future Tasks

For our team to be successful in the spring semester, we will need to outline definable goals, and categorize those goals in stepwise chronological order. In order to be efficient in our work over the next semester, this report will detail the necessary actions our team will need to take.

Our first goal will be to obtain the material we have researched during this semester. Delrin polymer plastic is available from multiple online retailers with different pricing structures as well as different sizing specifications. Our team will need to identify the best supplier of this material for our needs, and order the appropriate amount of material. We will also be ordering plates of aluminum for the outer rings of our design, this material can be found from many sources, and should be readily available.

Our first prototype will be mounted and dimensioned for a scale model of the full sized mirror cell. This scale mirror cell will be given to the team for testing by the project sponsor. Physically picking up and moving the model to NAU campus machine shop, building 98c, will be the next goal our team needs to accomplish.

Once we have daily accesses to the scale model of the mirror cell, we can begin to refine our SolidWorks drawing. Making absolutely certain the solid drawing model our team is designing from is accurate to the real world situation is critical to the quality of our final product.

Now that our team has a correct working drawing, we can quickly dimension for G-Code and begin production of prototype leaflets. At the same time our leaflets are getting produced in the rapid prototyping laboratory, our group can also begin fabrication of the two outer rings of the design. For this step, we will be using the CNC controlled Bridgeport mill in 98c. Both these actions are made possible by having a correctly dimensioned solid model with associated G-Code.

With fabricated outer rings and leaflets prepared, our group can begin assembly of the physical prototype. This is a critically important step because this is where our group will identify potential design flaws or oversights. Details for best practice assembly of our design can be documented and modified during the assembly and operations testing of our first prototype. With a working and assembled iris and mirror cell, our group will design and fabricate an appropriate gasket for mounting the iris to the mirror cell face.

At this point we have a fully working and totally operational scale mirror cell assembled with our scale iris. Improvement modifications have been documented and standard practices have been worked out for the full sized model. With our sponsors' approval, we will reorder raw materials for the final deliverable.

It is our hope the prep work we will have invested into our scale prototype will guide us during the full sized model creation. Essentially, our team hopes to be in very familiar territory for the fabrication and production of the full sized leaflets and aluminum rings. With all assembly details previously worked out, the full sized iris should come together smoothly.

Now our team will document and develop different engineering properties for the materials that we use. This step is where our team will identify and verify the thermal explanation of the Delrin plastic over the temperature ranges required in our project description. Also during this stage, our team can verify our previously calculated friction coefficient for the system and specify the drive motor that will operate the iris. Our team would also like to perform a deflection test to be able to rate the maximum static load the iris could withstand. Our team would also like to do a destructive test of one leaflet to calculate what the maximum impact load our design could be rated for.

We feel that scheduling these goals and outlining them in this report will position our team for the successful development of a thoughtful and useful deliverable to our client.

## Project Plan

### Finding the Needs

The project started with background research. Each of the members investigated the background of NPOI before meeting the client. Meeting the client took place in the NPOI facility. In the NPOI facility the members had the opportunity to identify the client's needs. After meeting with the client, the members got together to define the objectives and constraints of the project. This took place in the engineering building, all the members of Team got together to discuss about it. Once the objectives and constraints of the project were identified the team created a report and presentation for the class.

### Concept Generation

Once the needs were found it was possible for the team to come out with some concepts to present to the client. For this the group had a couple of meetings. The first meeting was for brainstorming where the group came out with many ideas of how to protect the siderostat mirror from the elements. After brainstorming our team met to find out which of the concepts were more realistic to make under the budget. The group selected four designs for further analysis in a design matrix and in a tree diagram. From there the group selected two designs for further analysis.

### Analysis and Modification

After the team selected the two designs for further analysis, they visited the NPOI for a second time. By talking to the sponsors the team found out new constraints that were not taken into consideration. The design previously chosen did not meet the new constraints. The team had to come out with a new design in a short period of the time for the analysis. For this the team had to do the concept generation all over again to find out a new solution. After many long nights of brainstorming to find a solution, one of the members came out with a clever solution to the problem, a camera iris diaphragm design to protect the mirror. Once the team decided it was a good solution to the problem, the team started analysis in it. The work was divided into material selection, cost of parts, cost of manufacturing and SolidWorks drawings.

## Conclusion

The opportunity to work on this project is greatly appreciated by our team.  In order to provide the highest quality final product, we have thoroughly examined the client's needs and constraints and set appropriate goals for the final design.

The finished product will be an automated iris diaphragm that is a modified design, scaled to the size required at the facility.  In order to test the design, an eight in model will be built and tested at Northern Arizona University.  The scale model will provide valuable insight into the final design requirements.  Once the design is proven at scale, the full size iris will be constructed.

Materials selection for the iris has been dictated by the environmental concerns.  The facility's location subjects the mirror cell to large temperature swings in a short period of time. The temperature may vary as much as 50 degree Fahrenheit in ten hours or less.  Due to this, the thermal expansion of the ring material must match or be very close to the thermal expansion of the cast aluminum mirror cell.  As a result plate aluminum is chosen for these components.  The iris leaves must be durable, resistant to the environment, and slightly flexible. Polyoxymethylene is the chosen material.  It is a non-hydroscopic thermoplastic that is readily available and fairly inexpensive when compared to similar materials.  It is also easily machined.

In the months following this proposal, the team will produce a scale model in order to work out any unforeseen manufacturing difficulties.  Once the scale model operates correctly, any design modifications will be applied to the full scale prototype.  A working, installable unit will be constructed by the end of April, 2013.

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