UNIVERSITY OF MANITOBA

MECH 4860: ENGINEERING DESIGN

FINAL DESIGN REPORT

MDS AeroTest Lighting System

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December 7, 2016
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Dear Dr. Labossiere,

On behalf of Team #10, we are pleased to submit the MDSAT Lighting System Final Design Report for the completion of MECH 4860. The report covers project definition, concept generation, analysis, and details on our final design.

This project has given our team the opportunity to work with industry and communicate with clients in a professional atmosphere. The group has been tried as future engineers, performed the assigned design task to the best of our ability, and created a solution that successfully integrates all client needs.

We thank you for this opportunity and welcome you to provide us with feedback on the contents of this report.

Sincerely yours,

Hamidreza Yeganeh

EXECUTIVE SUMMARY

Our design team was tasked with providing MDS AeroTest (MDSAT) with a lighting solution for their Fan Waggle testing of a turbofan gas turbine engine: a test procedure which involves high-speed imaging of the test engine's moving fan inlet, resulting in still images captured of the rotating fan blades. These images are used for analysis by the test engine OEM; therefore, clarity and image quality are of high importance. During this test, camera shutter speeds of approximately 10 microseconds are used. Due to this limiting factor, we were constrained to using a light source that is sufficiently flicker-free and high intensity. In addition, there is an engine unsafe zone defined by a 50 ft. radius from the engine face where no object can enter during the test. Currently, MDSAT uses natural light from the sun reflected off mirrors, which are manually adjusted by MDSAT technicians to target the engine face. This solution was inconvenient as MDSAT had to wait for cloudless, sunny days to perform the test and configuration was time-consuming. Our team's design resulted in two solutions: one solution used during the day, and the other solution used at night. The overall cost of the solution is approximately $ 116 700.00 CAD.

The day-time solution utilizes the H1 Heliostat from LightManufacturing, mounted to a custom mount structure: the Pole Mount Structure. A heliostat is a computer controlled, autonomous reflector that continuously tracks the sun's positions and adjusts the reflector to always reflect light at a single target. A custom mirror profile was designed by our team to be used with the H1 Heliostat. The Pole Mount Structure is designed to be anchored into the concrete using four structural bolts and is adjustable up to 15 inches in height. In total, four heliostat assemblies are required to illuminate the desired regions on the engine inlet. The overall cost of this solution is approximately $ 19 000.00 CAD.

The night-time solution utilizes the Luminys SunSource 1500 Watt LED Luminaire: a light consisting of an array of highly focused, high intensity LED lights. The Pole Mount Structure is also designed to be utilized with the LED Light Assembly. The Luminys LED light is mounted to a custom mount called the LED Light Mount and is capable of dual-axis, adjustability. Four Luminys

lights are required in order to illuminate the desired regions on the engine inlet. The overall cost of this solution is $ 97 700.00 CAD.

Our analyses show that our final solution meets all design requirements as well as our team goals of generating a solution that will maximize the possible testing window of time and provide MDSAT technicians with a solution that is intuitive and relatively easy to configure and use.

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1. INTRODUCTION

Our client, MDS AeroTest is a company that mainly focuses on testing in the areas of cold weather engine certification, noise, greenhouse gas emissions, and alternative fuels and lubricants. In partnership with Rolls Royce and Pratt & Whitney, MDSAT manages, operates, and maintains the GLACIER facility located in Thompson, Manitoba [1]. The GLACIER facility is a ground-based, open-air test stand capable of testing on a wide range of gas turbine engines. The icing test design utilizes a direct feed, fog generation tunnel that seals against the edge of the fan inlet. Figure 1 shows the GLACIER facility operated by MDSAT.

Figure 1. The GLACIER Facility [2].

Recently, MDSAT initiated operations of summer testing in order to establish greater seasonal utilization of the test facility [3]. During the summer season, MDSAT performs a form of vibration testing on turbofan gas turbine engines called Fan Waggle testing. The Fan Waggle test procedure involves high-speed camera imaging of the rotating inlet fan blades. Rolls Royce uses the resulting still images for vibration analysis. Before each Fan Waggle test is performed, sample images of the illuminated fan blades must be approved by Rolls Royce [3].

In order to meet the requirements of the Fan Waggle test during the past summer testing season, MDSAT attempted to use LED lights fixed on the same mounting stand as the cameras. However, the light provided to the inlet of the engine did not exhibit required functional light characteristics such as light intensity and output frequency. A second, successful attempt was performed by MDSAT wherein they configured a set of mirrors mounted in a custom-made wood structure to direct light from the sun onto the blades of the turbofan inlet. The Fan Waggle test set-up can be seen in Figure 2.

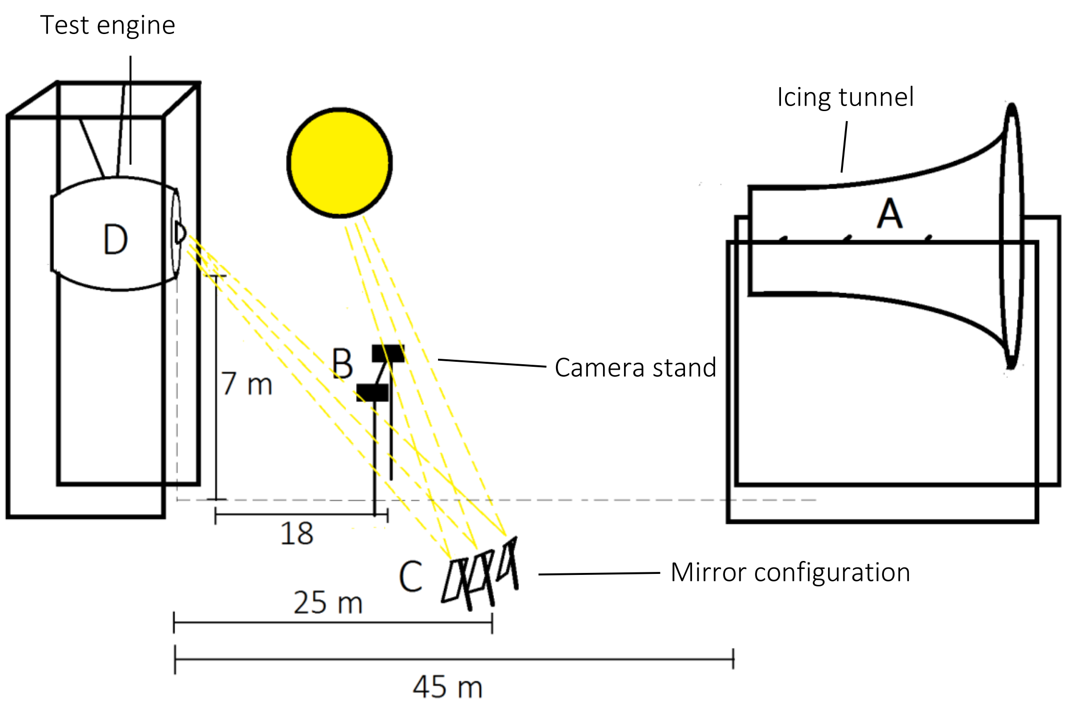

Figure 2. Current mirror lighting solution [4] used with permission.

These mirror units were placed approximately 25 meters (80 ft.) forward of the fan inlet and slightly off-set to the side. The mirror units were weighted down onto the ground with large concrete blocks and were pre-aligned with the sun the day before testing in order to be operational for a short window of time in which the test would be remotely performed [3].

1.1 Problem Statement

Due to the high rotation speeds of the fan blades, extremely high-speed camera imaging is required to capture still images that are clear and useable for analysis by Rolls Royce or Pratt & Whitney. To give an idea of the challenge of the design, the required shutter speed can be up to 10 microseconds [5]. In order to capture images with shutter speeds in the range of this magnitude, a high-intensity light is required. Because of the short duration time that the camera shutter is open for, the amount of light that can reach the image sensor is determined by how bright and intense the light on the object is. The shorter the shutter opening period, the brighter the light must be in order to obtain similar quality images. Additionally, the light must be characterized as being "flicker-free". As in, the light output frequency must be great enough such that it will not have an effect on the captured images. If the frequency is too low, the camera will capture an image at a time where the light is "flickering" and the result will be a completely black image. The design must meet these requirements:

- Provide high-intensity light to the required areas on the fan blades
- Provide light that is sufficiently flicker-free
- All design components must be positioned outside of the unsafe zone
- All design components must be self-contained to mitigate foreign object ingestion by the test engine

The lighting solution designed by our team must meet these requirements in order to provide MDSAT with a viable solution.

1.2 Project Scope

After initial discussion with Rick Hickey (Chief Facility Engineer at the GLACIER facility), our scope statement was as follows:

- Make improvements to the current lighting system for the Fan Waggle test
- Choose either a natural lighting solution or an artificial lighting solution

However, after further communication, it was made apparent that what would be most beneficial for MDSAT would be to create a solution that utilizes both: natural lighting to be used during the day, and artificial lighting to be used at night. A natural lighting solution that would meet the project requirements and that was originally proposed to us by MDSAT was the use of a heliostat. A heliostat is a computer-controlled, autonomous reflector, which continuously tracks the sun's movement and adjusts its position to reflect sunlight onto a single target. Since it would not be possible to pursue both a custom heliostat and an artificial lighting solution, our team developed options for how to proceed, which our team felt were within our capabilities. We presented these options to MDSAT.

Together, our team and MDSAT decided that it would be most beneficial to source a prefabricated heliostat to be used during the day, which could be verified by our team. Alongside this solution, we could then also pursue an artificial lighting solution to for use at night.

The refined scope of the project is to improve the camera lighting for MDSAT's Fan Waggle testing procedure. This will be done in two ways:

- Source and validate a commercial heliostat for day-time use
  - Source a commercial heliostat that suits the needs of our application
  - Design a mount structure
  - Determine how many heliostats are required to illuminate the necessary regions on the engine fan inlet
  - Validate the safety of all components
- Source and validate a highly focused, artificial light source for night-time use
  - Find a commercial artificial light that meets functional requirements
  - Determine how many lights are needed

- Design a mount structure

Adjusting the camera positioning and testing procedure are not within the scope of this project. The scope of this project covers needs analysis, requirements determination, concept selection, and preliminary design. Engineering design is still required by a qualified, professional engineer before our design can be implemented; however, this is outside of our team's capabilities and the determined scope of this project. Key deliverables to the client presented in this report are engineering drawings, a Bill of Materials (BOM), and Finite Element Analysis (FEA) results. Key stakeholders in this project are our client, MDSAT, as well as the engine OEM's such as Rolls Royce and Pratt & Whitney.

The current lighting system (mirror configuration) provides MDSAT acceptable lighting conditions to capture useable, still images for the Fan Waggle test. However, the current mirror solution used by MDSAT has many opportunities and areas for improvement such as image quality, ease of use, and possible operating conditions.

To improve in these areas, our team has decomposed the project purpose into objectives and sub-objectives that qualitatively describe the team's goals for the solution. These objectives are described and organized in Figure 3.

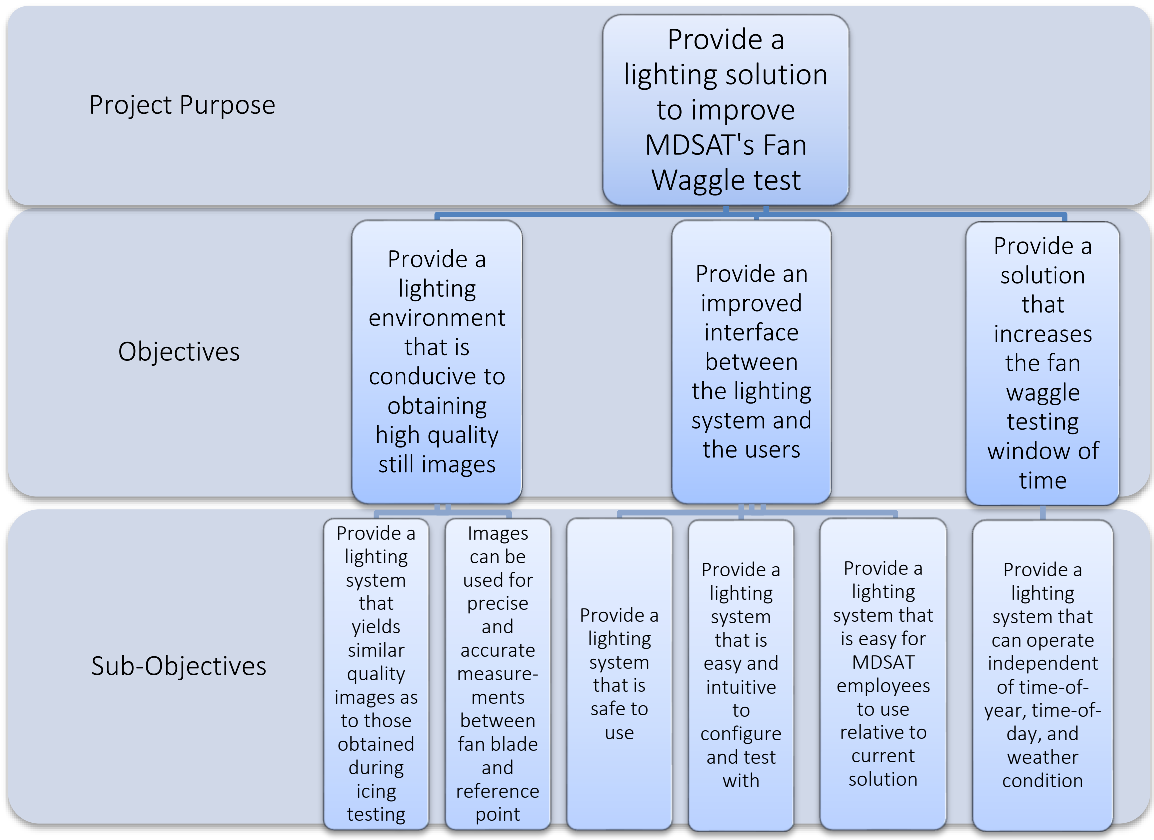

Figure 3. Objectives tree describing qualitative team goals [6] used with permission.

These project objectives must be successfully integrated into our design.

1.3 Customer Needs

A list of customer needs were compiled after visiting the MDS AeroTest Facility. TABLE I contains the rationale used for ranking each need statement in terms of importance to project success.

TABLE I

RANKING SYSTEM FOR CUSTOMER NEEDS

Scale	Description
5	Need must be satisfied in order to achieve project success
4	Need has a high impact on the success of the project
3	Need has a moderate impact on the success of the project
2	Need has a low impact on the success of the project
1	Need has very low impact on the success of the project

We identified the key needs of the client and ranked each need using the ranking system described in TABLE I. The results of this analysis are shown in TABLE II.

TABLE II

CUSTOMER NEEDS

Need Number	Customer Need	Rank
N1	The lighting system provides sufficient light intensity to obtain effective, high-quality, useable images	5
N2	Light targets the blades in the 12:00 region as well as the 9:00 region on the engine (from pilot's orientation)	5
N3	The lighting system is cost effective	3
N4	Light is uniformly distributed throughout the illuminated region	4
N5	The lighting system is capable of being used for a wide range of sun positions	3
N6	A sufficient proportion of incident light is effectively reflected toward the imaging sensor	2
N7	The lighting system has manual override capabilities	5
N8	The lighting system is outside of the unsafe zone and object-free zone (radius of 50 ft from engine inlet)	5
N9	The lighting system can meet future fan imaging needs	1
N10	The lighting system requires minimal maintenance	3
N11	The lighting system is long lasting	3
N12	The lighting system is durable and adequate for environmental conditions	5
N13	Structure is static, stable and rigid under influence of all external forces	5
N14	The lighting system can be quickly setup and configured	3
N15	The lighting system is intuitive and easy to use	3
N16	The lighting system features a modular design	5
N17	The lighting system is safe for both people and the test engine	5
N18	The lighting system is manufacturable (allows for tolerances)	3
N19	The lighting system must operate with sufficiently low flicker	5

To summarize, the highest ranking customer needs include that the lighting system must:

- provide sufficient light intensity for a high speed camera imaging
- provide lighting that is sufficiently flicker free
- provide a light that covers the entirety of the required target positions
- remain outside of the unsafe zone
- be safe for the people and the test engine

The results of this analysis were sent to the client and MDSAT did not request any changes.

1.4 Constraints and Limitations

The lighting system design is subject to a number of operational and performance limiting constraints. These constraints and limitations are:

- Camera shutter speed (exposure time period)
- Camera imaging frame rate
- Camera sensor spectral response
- Turbofan inlet geometry and fan diameter
- Turbofan engine operational airflow pattern interference
- Jet engine operational object free zone
- Test site's structures and mechanisms
- Test site existent ambient lighting conditions
- Budget limit

Each of these constraints and limitations have been elaborated on in the following paragraphs.

Camera shutter speed (exposure time period)

We are limited to using a light of sufficient brightness according to the camera's operational shutter speed. The solution must consistently provide a sufficient output of light such that the camera's electronic sensor receives the necessary quantity of light energy within the period of one shutter cycle. A reference value for shutter speed of 10 μs has been deemed reasonable for the purpose of evaluation [5].

Camera imaging frame rate

We are limited to using a lighting type with the appropriate output frequency. To repeatedly image the fan in the same orientation at every revolution, the camera must shoot at a frame rate that is in sync with this motion. Correspondingly, the light source must be outputting the entire duration of each of these dynamically timed camera frames. Near peak engine speeds, the camera will operate at around 45 frames per second.

Camera sensor spectral response

Additionally, we are limited to finding a light with an output frequency that corresponds to the camera's spectral response. The camera's CMOS (complementary metal–oxide–semiconductor) imaging sensor is a monochrome transducer array which is characterized by a specific spectral response. This response is graphically defined in the camera manufacturer's device operational manual seen in Figure 4.

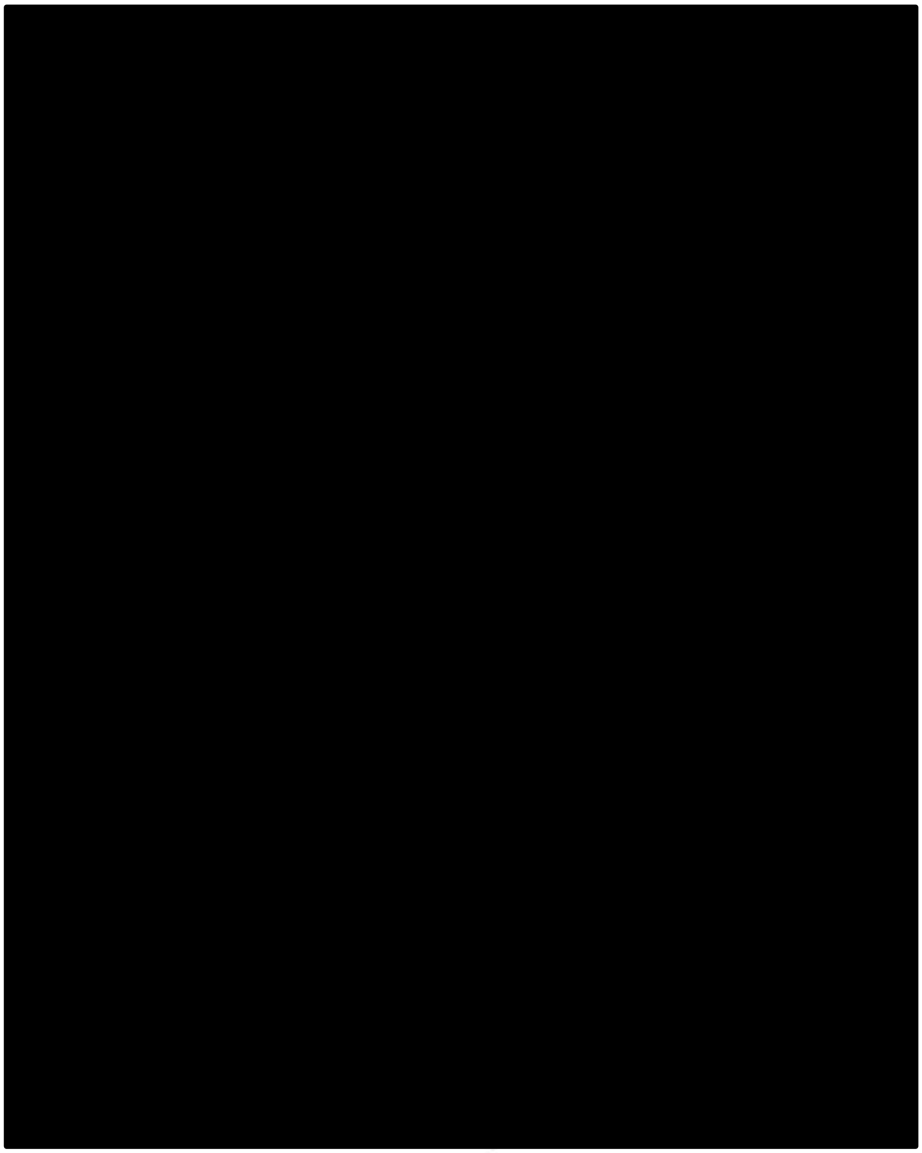

Figure 4. Spectral response of camera imaging sensor [7].

The light output frequency must target wavelengths that correspond to one of the peaks shown in Figure 4. This is subject to the complex interactions associated with the light path between the sensor and the light's origin.

Turbofan inlet geometry and fan diameter

We are constrained by the geometry of the fan itself and are limited to finding solutions that can illuminate the minimum area required of three full fan blades at the 12:00 and 9:00 position (pilot's viewpoint). The high-bypass turbofan's inlet fan is the subject of imaging. The dimensioned region(s) of fan illumination are dependent on the exact size of this inlet, including both the inlet fan diameter as well as the inlet ducts depth and geometry. The inlet depth also dictates the originating light's source location to an extent.

Turbofan engine operational airflow pattern interference

We are limited to placing a lighting solution in only certain areas at the test site. When engine testing is being actively carried out, it is essential to the test's validity that the airflow pattern is not critically affected by the presence of additional structural components. The verification of this will depend on the distance specified from the fan inlet to the lighting structure along with further verification as performed by MDS AeroTest test engineers.

Jet engine operational object free zone

The region directly forward of the engine inlet is banned from any unsecured objects [3]. This is due to the hazards of the engine potentially ingesting FOD (foreign object debris). It is typically communicated as a radial distance from the engine inlet when measured from a bird's-eye-view projection onto the ground. This region is a function of the specific engine being tested as well as its planned operating thrust level. As a conservative estimate in effort to avoid the contribution of dynamic factors, a value of 50 ft has been advised [5].

Test site's structures and mechanisms

We are constrained by the existing infrastructure at the GLACIER facility test site. The implementation and operation of any designed lighting system for the Fan Waggle test must not destructively interfere, or diminish the performance of the existent test site's mechanism pertaining to both active summer testing and future winter testing methods. This includes the operations of the icing tunnel, engine stand and all other components and processes involved in the simulation process.

Test site existent ambient lighting conditions

We are constrained by the geographical location of the test site. The location influences the ambient lighting conditions on the photographic subject as well as stray light falling into the imaging systems frontal lens element.

Budget Limit

We are constrained by a recommended budget limit of $100 000.00 CAD, as suggested by MDSAT. Funding for this project will not come from MDSAT, but rather from Rolls Royce, for whom the Fan Waggle testing will be performed. The solution will likely be presented to Rolls Royce and must win their approval in order to gain the funding. This $100 000.00 estimated budget is a recommendation to us by MDSAT, as they feel that any solution outside this cost amount may be difficult to gain funding for. The current mirror configuration at MDSAT forces them to wait for a bright and sunny day to perform the Fan Waggle test. For a $25 million dollar engine to sit and not be tested could cost Rolls Royce upwards of $20 000 per day [5]. If the facility does not see a sunny day for three days, the cost for the engine to sit and not be tested for that time period would be $60 000. It is possible that throughout the summer, multiple periods such as this could occur. Our team's goals are to maximize the testing window of time the MDSAT can perform the Fan Waggle test which would eliminate the need to wait specifically for a sunny day. The quality of the solution and the value it will add to the Fan Waggle test procedure will be the implicating factors in Rolls Royce's opinion and will ultimately determine whether or not the solution will receive funding. Due to the nature of the recommended, estimated budget, our team will prioritize quality over cost.

1.5 Target Specifications

In order to evaluate our possible solutions the team developed an array of performance metrics, each associated to a customer need. Each of the metrics have been given an importance rating to help us evaluate the performance of various options for solving the problem. The performance of each metric is bounded by an ideal target and a marginal pass. TABLE III contains descriptions of the rationale we used to rank each metric in terms of its ability and effectiveness in verifying that the associated need is satisfied.

TABLE III

RANKING SYSTEM FOR METRICS

Scale	Description
5	Metric is essential to be performed in order to verify the associated need(s)
4	Metric is highly recommended to be performed as it will be supplemental to verifying the associated need(s) directly
3	Metric is recommended to be performed as it will be supplemental to verifying the associated need(s) directly
2	Metric is recommended to be performed as it will be supplemental to verifying the associated need(s) indirectly
1	Metric is optional. If performed it will be supplemental to verifying the associated need(s) indirectly

TABLE IV shows the ranking for each metric, the customer need it corresponds to, and the marginal values and target value of each metric.

TABLE IV

METRICS TABLE FOR VERIFYING CUSTOMER NEEDS

Metric Numbers	Need Number	Metric	Rank	Units	Marginal Value	Target Value/Range
M1	N1	Intensity of light reflected off fan blades at imaging sensor	5	lx	19000	50000
M2	N1	Bypass Fan operating RPM range	5	RPM	0 – 2800	0 – 2800
M3	N1	Lighting system frequency output is optimal for current cameras used by MDSAT	5	Hz	tbd	tbd
M4	N1	MDSAT's customer confirms the Fan Waggle Test buy-off	1	% Yes	90% Yes	100 % Yes
M5	N2	Area of illumination	5	full blades	Minimum of 3 at each location	All
M6	N3	Entire project cost	3	CDN $	< 100 000	
M7	N4	Uniform spatial distribution of light	4	% difference (lx/lx)	60%	95%
M8	N5	Operates with minimal dependencies on ambient light conditions	5	Ambient lx	75000	0
M9	N5	Maximize testing window	5	hours/day	3	24
M10	N6	Amount of reflected light that reaches imaging sensor	2	%	tbd	tbd
M11	N7	Manual override capabilities	5	Yes/No	No	Yes
M12	N8	Clearance from engine bell mouth	5	Relative to Unsafe zone	Outside	Outside
M13	N9, N16	Adaptability	2	Subjective	low	high
M14	N10	Cost for Maintenance	3	CDN $	tbd	tbd
M15	N10	Time required for maintenance	3	hours	tbd	tbd
M16	N10	Required number of maintenance sessions	2	number/testing season	2	1

Metric Numbers	Need Number	Metric	Rank	Units	Marginal Value	Target Value/Range
M17	N10	Reparability	2	high/low	Low reparability, Must replace components	High reparability
M18	N11	Life of lighting system	3	testing seasons	20	40
M19	N12	Minimize corrosion effects	3	Time	resistance to occasional moist environment	Sustained resistance in wet environment
M20	N12	Corrosion rate	2	mm/year	Material with relatively low corrosion rate	
M21	N12	Sensitivity to the development of scratches on actively reflective components	3	hardness, Rockwell-C	tbd	tbd
M22	N13	Lighting structure deflection (design dependent)	3	mm	15	5
M23	N13	Holding strength subject to high wind speeds (including effects of nozzle)	4	m/s	tbd	9 + engine suction + nozzle effects
M24	N13	Endurance in cyclic loading scenarios	4	<composite>	tbd	Below Fatigue Limit
M25	N13	Vibration amplification	1	dB drop (attenuation)	tbd	tbd
M26	N13	Ingress Protection Standard	3		IP 55	IP 57
M27	N13	Withstand impact from dropping	3	Meters	1	4
M28	N14	Time to assemble/disassemble and configure	3	hours	16	3
M29	N15	Customer satisfaction	4	Subjective	80% approval	90% approval
M30	N17	Factor of safety	4	factor	3	3
M31	N17	State of engine in the case of a major failure	5	Affected/unaffected	unaffected	unaffected
M32	N17	State of people in the case of a major failure	5	Affected/unaffected	unaffected	unaffected
M33	N18	Allowances for variation, tolerances	3	mm	tbd	tbd
M34	N19	Temporal light uniformity	4	% deviation	tbd	tbd

Each of these target metrics have been used to create the lighting solution. The metrics that were given the greatest importance correspond with the highest ranked customer needs.

1.6 Overall Design Expectations

Our team is tasked with designing a lighting system specifically for MDSAT's Fan Waggle testing. The Fan Waggle test requires high-lux (lux is lumens per area), flicker-free lighting provided at the engine inlet to enable high-speed cameras to capture still images of the rotating fan blades, and must operate at a minimum distance of 50 ft. from the engine. Currently, MDSAT is using a mirror configuration aligned so that the reflected light from the sun's rays is directed onto fan blades at the test engine inlet. However, this current system of operating has many opportunities for improvement, such as increasing the testing window of time (ideally to be independent of the sun's position); allowing for remote control abilities rather than only manual control; and, finally, increasing the intensity of the light reflected off of the fan blades towards the high-speed camera such that the images obtained are of similar quality to those obtained during MDSAT's icing testing.

The next step taken by our team was researching and generating concepts based on our knowledge of the customer needs. Following concept generation, the concepts underwent a systematic selection process. After discussion with our client, a concept was chosen to move on to the preliminary design stage.

For components that required custom design, analyses were performed to validate that the required customer needs were met, using the target metrics. For commercial components, analyses were performed to validate their performance in our specific application. The design is presented through product specifications, cost analyses, BOMs, and technical drawings.

2. CONCEPT GENERATION AND SELECTION

The basis for each of the generated concepts was either a custom heliostat design, or sourcing and implementing a highly focused, artificial light. The concept generation process resulted in nine, unique concepts: five that used artificial lighting, and four for a custom heliostat. Each concept passed through an initial screening process which eliminated three of the concepts. The six remaining concepts were scored using weighted customer needs. The results of the concept selection are three concepts: Light Beam Single Stand (artificial lighting), Linear Actuator (heliostat), and the Lay Susan 1 (heliostat). These concepts can be seen in Figure 5, Figure 6, and Figure 7, respectively.

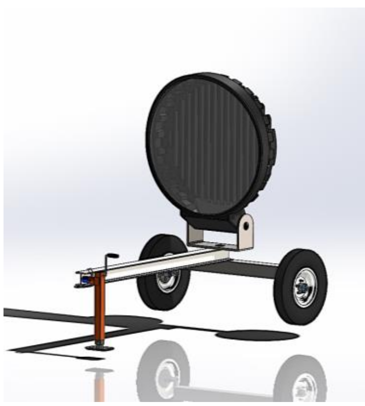

Figure 5. Light beam single stand model [8] used with permission.

Figure 6. Linear actuator [9] used with permission.

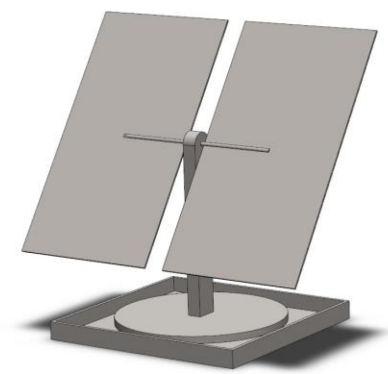

Figure 7. Lazy Susan 1 [10] used with permission

MDS AeroTest initially had shown interest in the Lazy Susan concept. However, they were still interested in an artificial lighting solution and had suggested to us that we use focused LED lights, for their low flicker characteristics. As previously mentioned, this is when our team and MDSAT collaborated and refined the scope of this project to focus on:

- Sourcing and validating a custom heliostat to be utilized during the day
- Sourcing and validating highly-focused LED lighting to be utilized at night

The next step from here was to source a prefabricated heliostat and research into focused LED lighting. The record of our concept generation and concept selection process can be found in APPENDIX A.

3. DESIGN OVERVIEW

The Fan Waggle test lighting system for MDSAT is comprised of two different sub-systems: one for day-time use, and one for night-time use.

The first sub-system provides natural light to the fan blades during day using an array of four prefabricated heliostats to reflect sunlight to the fan blades. The chosen heliostat is called the H1 Heliostat, from the company LightManufacturing. The selected heliostats use 4ft. x 4ft. flat reflectors whose movement is governed by an on-board microprocessor. Open loop control is used to continuously track the sun's movement and alter the reflector's position. The H1 Heliostat does not come with a pole for mounting; therefore, our team designed a custom pole structure that uses four anchor bolts to secure it to the concrete at the test site. The custom structure has 15 inches of adjustability vertically. A render of the heliostat assembly with both the custom mount structure and the H1 Heliostat is shown in Figure 8.

Figure 8. Heliostat assembly [11] [12] used with permission.

Each heliostat will be mounted approximately 60 ft. from the engine, which is outside of the defined unsafe zone of 50 ft. An example of what this may look like at ground level at the test site can be seen in Figure 9.

Figure 9. Example of Heliostat Assembly placement at MDSAT test site [11] [12] [13] [14] used with permission.

The heliostat placement can also be seen from the engine's point of view in Figure 10.

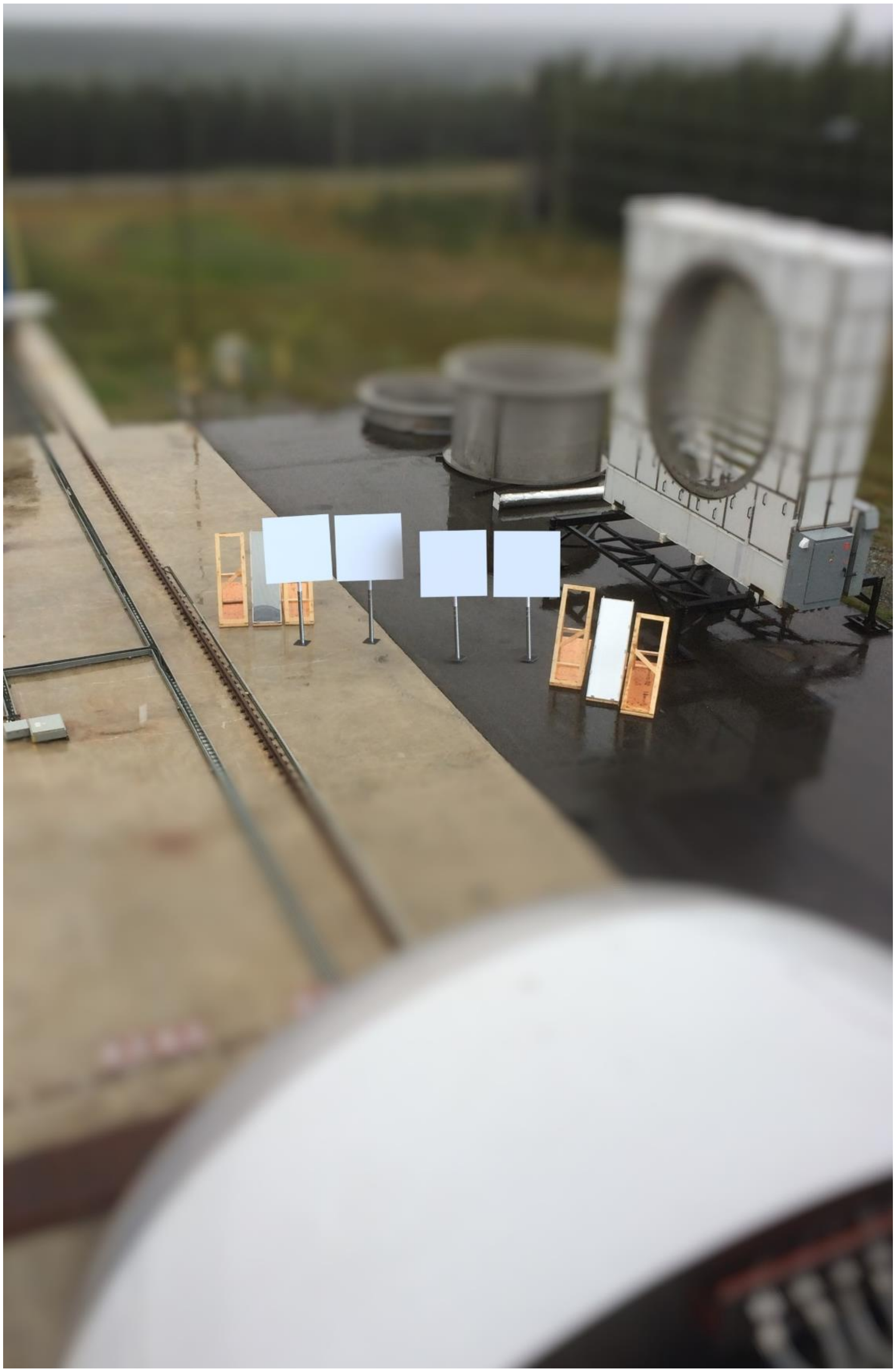

Figure 10. View from the engine of possible heliostat placement [11] [12] [13] [15] used with permission.

The current mirror configuration at MDSAT is present in Figure 10 as well.

The second sub-system is designed for use at night and provides highly focused, high intensity, flicker free light to the engine inlet using the Luminys SunSource 1500 Watt LED Luminaire. Another custom mount was designed to hold these lights and allow for dual-axis adjustability shown in Figure 11. The LED light, mounted to the custom light mount, will utilize the same Pole Mount Structure as the heliostat. Figure 11 shows a render of the full light assembly..

Figure 11. Luminys LED light with custom light mount on the pole mount structure [16] used with permission.

The combination of the highly focused LED light and the autonomous heliostat meet all customer needs and design requirements. Details of the methodology used and analyses performed to reach the detailed designs are presented in the remainder of the report.

4. HELIOSTAT SELECTION AND MODIFICATION

The day-time-use portion of our final solution utilizes a prefabricated heliostat. Research was conducted to find a heliostat that is best-suited for our application. After selecting a heliostat for our design, analyses were performed to validate its performance and on any custom components design by our team. Product details, cost details, and a BOM are provided for the heliostat assembly.

4.1 Research: Requirements and Results

The two most important criteria used to choose a heliostat from the market were footprint size and cost. Other characteristics were also taken into consideration such as reflector size (for vibrations), wind speed rating, overall weight, reflector efficiency, and delivered lux and watts. The research process ended with having seven different companies to choose a heliostat from, shown in TABLE V.

TABLE V

HELIOSTAT RESEARCH RESULTS

Company Name	Product Name	Ref.
Light Manufacturing	H1 Heliostat	[17]
Cebe Energy	S1+S2 max6	[18]
Wikoda	The Sunflower	[19]
SBP	Heliostat s-Stellio	[20]
SAT Control	SunTracer ST44M3V15P Dual -Axis ST44M3V15P	[21]
Heliotrack	1m Heliostat	[22]
Titan Tracker	125-228 Parabolic dish concentrator	[23]

A comparison was made between the different heliostats using the product specifications for each. The H1 Heliostat was selected from the company LightManufacturing. Other manufacturer's products were rejected by the team due to large foot prints, lack of a communication system, high cost, and high complexity. Most of the heliostats were too large to integrate into the existing infrastructure at the GLACIER Facility save for two options: The H1 Heliostat and the Sunflower. However, the Sunflower is a heliostat designed for residential use and has a lower wind speed rating than that of the H1 Heliostat. For these reasons, the H1 Heliostat was chosen for use with out lighting system. A picture of the H1 Heliostat is shown in Figure 12.

Figure 12. H1 Heliostat from LightManufacturing [17] used with permission.

The H1 Heliostat has many functional components that meet the needs of the design. However, in some cases, custom design components are required. For example, the heliostat does not come with a pole for mounting, therefore we have designed one for the design application. Figure 13 shows the functional breakdown of what our heliostat assembly will provide to the customer. The lowest level, depicted by the yellow boxes, are the functions of each sub-system.

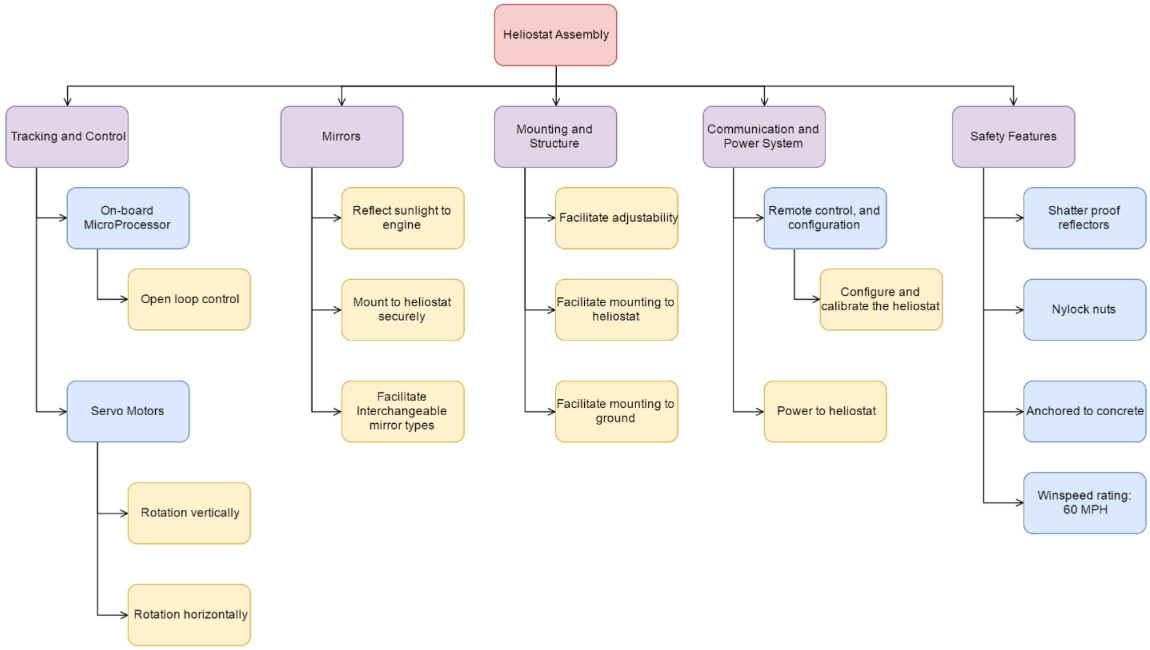

Figure 13. Functional block diagram for heliostat assembly [24] used with permission.

Our team was required to design a structure to facilitate mounting the H1 Heliostat and securing it to the concrete at the test site. Additionally, reflector analysis was performed and includes:

- Validation of the flat reflectors' performance (that come with the H1 Heliostat)
- Determination of how many reflectors (and H1 Heliostats) are required to meet project requirements

Both analytical and numerical analyses were performed.

4.2 Analysis

The custom mount structure was designed and analyzed to meet project requirements such as safety and rigidity. Calculations were performed on the H1 Heliostat's flat reflectors to determine how many heliostats are required for our application.

4.2.1 Pole Mount Structure

The heliostat mount structure is comprised of three main components: The Base Plate, the Base Pole, and the Adjustable Pole. The material was selected for each component to be AISI 1020 steel for its strength, machinability, weldability, and relatively low cost. The H1 Heliostat is designed to mount to a pole structure with an OD (outer diameter) of 2.75 inches (60.33 mm); therefore, our team designed the Adjustable Pole to have this same OD. To allow for some adjustability as well as additional rigidity, the pole mount was designed to slide inside a larger diameter pole: The Base Pole. To secure the structure to the concrete at the test site, the Base Pole is welded to the Base Plate where four bolts are used to anchor the entire structure to the ground. The assembly containing the Base Plate welded to the Base Pole, and the Adjustable Pole will be denoted at the Pole Mount Structure and is shown in Figure 14.

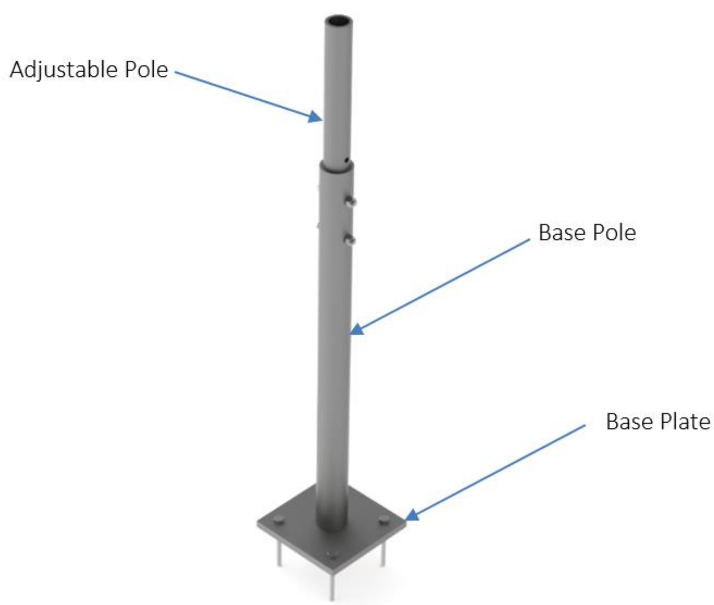

Figure 14. Pole Mount Structure [25] used with permission.

Numerical verification was performed using Finite Element Analysis (FEA) in two stages. First, a model of the Base Pole and Base Plate assembly was analyzed to determine the required plate thickness as well as the minimum size of the fillet weld that would join the two. A contour plot of the stress results is shown in Figure 15.

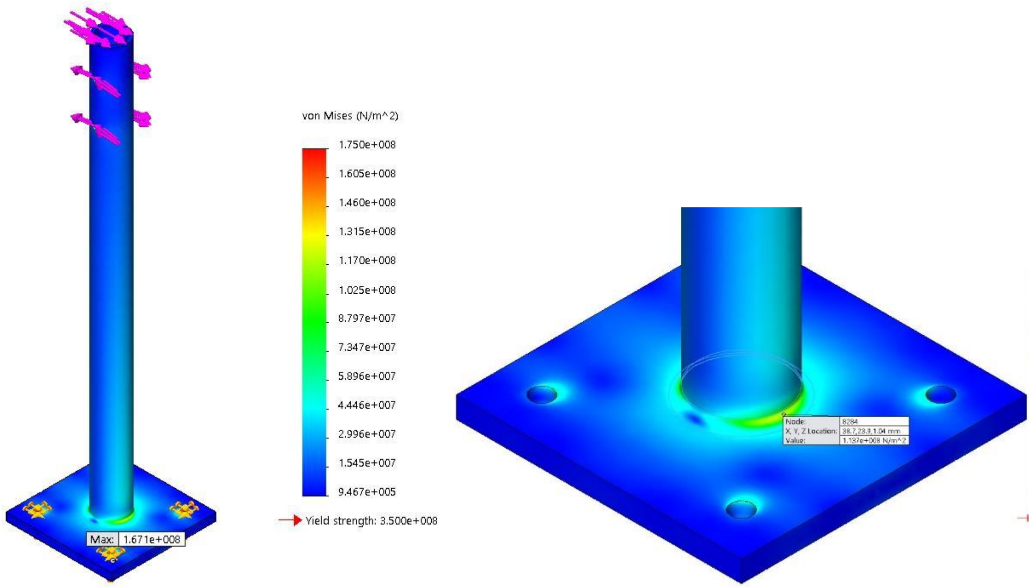

Figure 15. Contour plot of stress results – close view of fillet [26] used with permission.

The results showed that a minimum fillet size of 0.313 inches is required and a minimum base plate thickness of 0.75 inches is required. The methodology for both the analytical and numerical studies can be found in APPENDIX B.

The second simulation was performed on a model of the entire assembly in the highest position with focus on the areas that the two tubes interface, more specifically, where the transitions happen. The stress results at the pole interfaces are shown in Figure 16.

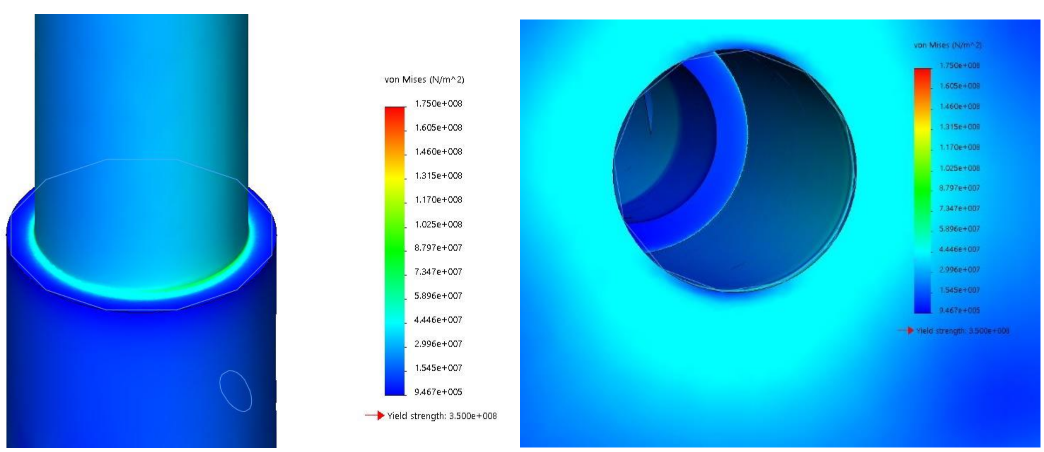

Figure 16. Contour plot of stress results – close view of pole interfaces [27] used with permission.

The results of this numerical analyses show that the heliostat mount structure has a safety factor greater than 2 and a maximum deflection of 0.04 inches with a tube thickness of 0.313 inches. The entire FEA analysis can be found in APPENDIX B.

The results of the bolt analysis show that the minimum length required for the bolts to be anchored into the concrete is 5 inches, with a minimum diameter of 0.75 in. The distance between each bolt required a minimum of 7 inches, and an edge distance of 1 inch. The results of the anchor bolt analysis are compliant with CSA standards. The full analysis can be found in APPENDIX B.

4.2.1 Flat Mirror Validation

Our team found the number of mirrors required to illuminate three full fan blades at the 9:00 and 12:00 positions (pilot's view) on the engine face. Figure 17 shows the diagram of three full fan blades of the Rolls Royce Trent XWB.

Figure 17: Trent XWB [28].

To maximize the area of one section that covers three full blades of the engine we set the length of one blade to be equal to the radius of the engine: 59 in. The result of the calculations to find the width of the three full fan blades is 50 in. Therefore, the area for illumination is a 50 in. (1.27m) x 59 in. (1.50 m) rectangle.

[redacted]

Figure 18. Required illumination area for Fan Waggle test [29].

Figure 19 shows how the incoming light from the sun reflects to the mirror.

[redacted]

Figure 19 Law of reflection [30].

The law of reflection states that the angle of incidence is equal to the angle of reflection for a light ray reflecting off of any object [30]. Therefore, theoretically the reflected area from the flat mirror has same dimensions as the mirror's area.

The length of one side of the square mirror is 48 in. (1.22 m) [17]. The required area for illumination is a 50 in. x 59 in. rectangle. However, since this is an over estimation and the fan blades are not, in reality, 59 in. long, and since the main focus of the Fan Waggle Test is at the tip of the three fan blades, one heliostat is sufficient to illuminate the entirety of the required region. Additionally, the reflected beam of light from the flat mirror will have diffusion effects, meaning that the area of the light that reaches the fan blades will be larger than the mirror itself.

Therefore, it was concluded that one heliostat is needed to illuminate the required area, for each of the required regions.

Also taken into consideration was the amount of light that one heliostat can deliver to the engine face and this was determined by the amount of light emitted from the sun. The target brightness value at the fan blades is 19 000 lux; however, the amount of lux delivered from the sun on a clear day is 10,000 lux [31]. Therefore, two heliostats per region are required to deliver 20,000 lux at the engine face. The target lux value at the engine inlet is 19 000 lux (analysis for the target lux value is in Section 5.2.1).

Four heliostats are required in total to illuminate three full blades at both the 9:00 and 12:00 positions.

4.3 Details of Heliostat Lighting System

The heliostat lighting system consists of the H1 Heliostat and the Pole Mount Structure. The inherent features of the H1 Heliostat, such as the tracking and control system, the communication system, power requirements, and safety features, have been detailed here. Further details on the custom component are also provided.

4.3.1 Tracking and Control Systems

Each H1 heliostat has an on-board microprocessor that continuously tracks the sun throughout the year. It utilizes open loop control with accuracy up to 0.5 degrees, depending on the accuracy of the set-up and configuration [17]. Each theoretical sunset, the heliostat resets, and any deviation that had occurred during the day will have been deleted when the heliostat begins the next day's sun tracking. The heliostat operates autonomously if desired and only needs to be accessed for configuration upon initial set-up [32]. The H1 Heliostat can be accessed via Wi-Fi and all parameters can be inputted such as target location, heliostat location, hours of operation, and safety position settings [32]. No modifications were made to the tracking and control system by our design team. Figure 20 shows the location of the microprocessor and the servo motors.

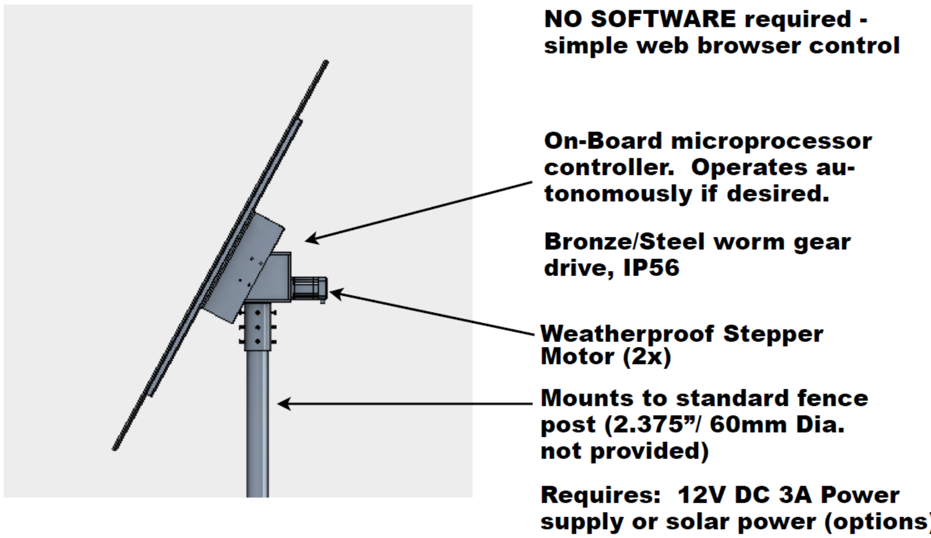

Figure 20. Locations of on-board microprocessor and servo motors [17] used with permission.

The heliostat uses two independent servo motors, each with durable worm gear transmissions to provide dual-axis control.

4.3.1 Mirrors

The H1 Heliostat reflector has 85% reflective efficiency. The reflector is made of an aluminum composite which if impacted, will dent rather than shatter. The reflectors are field replaceable in the case of any damage. As previously discussed, four standard H1 Heliostats are required to meet the performance metrics of the design.

4.3.2 Mounting and Structure

The H1 Heliostat is designed to mount to a standard galvanized 2.75 in. (60.33 mm) fence post as shown in Figure 21. The fence post is not included with the H1 Heliostat.

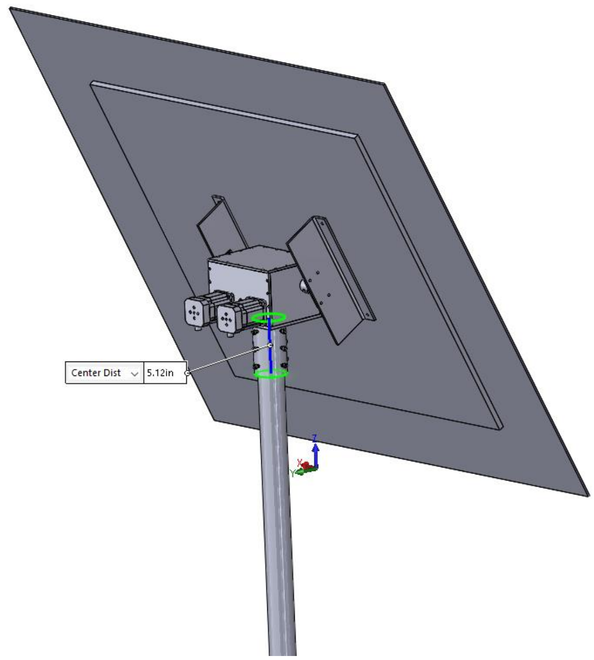

Figure 21. Mounting system for the H1 Heliostat [33] [11] used with permission.

Once the Base Plate has been welded to the Base Post, all parts can be finished by applying a galvanized coating for corrosion protection. The Pole Mount Structure has a total height adjustability of 15 inches with a maximum total height of 65.7 inches. Four concrete anchor bolts are used to secure the mount structure to the concrete at the test site. The diameter and length of these anchor bolts follow CSA standards. The two bolts that fix the height of the structure use nylock nuts to keep the structure self-contained. The full assembly of the H1 Heliostat mounted to the Pole Mount Structure can be seen in Figure 22.

Figure 22. Heliostat assembly [11] [12] used with permission.

The H1 heliostat is rated for 60 MPH wind speed and the heliostat mount structure was analyzed using the same maximum wind speed assumption [17].

4.3.3 Communication and Power System

The power supply that is required for this particular heliostat is 12VDC with 3A current draw (peak current). LightManfacturing has a product called the P1 Multiple Heliostat Power Supply which uses 30 W photovoltaic (PV) panels and battery charge regulation system than can provide 12 V DC to up to six H1 Heliostats [17]. This power supply is a sun-tracker which maximizes the amount of sunlight absorbed by the PV panels. Figure 23 shows the P1 Power Supply from LightManufacturing.

Figure 23. P1 Power Supply from LightManufacturing [34] used with permission.

The P1 Power Supply can be mounted on the same side of the engine test stand as the four heliostats, which will prevent the need to run cabling across the ground in front of the engine.

The H1 Heliostat uses Integral WiFi networking which can join the local network at the GLACIER facility. Each heliostat can be set-up via web browser interface without the need for additional software installation. The wireless range of the control system is 200 ft. Since the test site is over 1 km (> 3000 ft.) away from the control room, the heliostats must be configured with a laptop at the test site.

4.3.4 Safety Features

The H1 Heliostat reflector is made up of an aluminum composite which cannot shatter, and can only be dented [32]. This is a key safety feature for our application since we do not want the test engine to ingest any foreign material. To add to this, nylock nuts will be used for the two bolts that lock the height of the heliostat, to ensure the entire structure is self-contained. The heliostat mount structure will have a galvanized coating, which will help to prevent corrosion effects from weakening the structure. Finally, the entire structure will be anchored to the concrete at the test site.

As previously mentioned, the H1 Heliostat is rated for wind speeds of 60 MPH in all positions. The highest wind speed recorded in Thompson is 21 MPH [35], which is much less than the rated wind speed of the heliostat assembly. The heliostat placement will be outside the unsafe zone of the engine so any additional airspeed effects will not be a concern. However, physical testing of the heliostat in the actual operational environment should be performed before this solution is fully implemented.

4.4 Product Specifications and Compliance of Needs

The final product is a combination of the H1 Heliostat, the Pole Mount Structure, and the custom mirror design. TABLE VI contains the H1 Heliostat product specifications.

TABLE VI

H1 HELIOSTAT PRODUCT SPECIFICATIONS [17]

Performance	
Reflective efficiency	85%
Max. wind load (any position)	60 MPH
Max. wind load (safe position)	>70 MPH
Wireless range	200’
Angular range	120 degrees left-right 60/-5 degree vertical
Max delivered heat	1300 Watts
Physical	
Weight	45 lb.
Mounting points	3/8” (60 mm) pole
Reflector Types	48 in^2 (1.5 m^2 square) flat 48 in^2 (1.5 m^2 square) parabolic* *Vacuum adjustable focal length
General Specifications	
Power required	11.5-14VDC, 3A (peak current)
Electronics	Integrated circuit housed in NEMA/IP66 enclosure, integral WiFi
Motion	2x IP66 Stepper
Warranty/Support	
1 Year	Mechanical defects

TABLE VII contains information about the Pole Mount Structure.

TABLE VII

HELIOSTAT MOUNT STRUCTURE SPECIFICATIONS

Anchor bolts	CSA standard compliant
Material	AISI 1020 cold rolled steel
Finish	Galvanized
Force rating (Numerical analysis)	155 lbf max load
Torque rating (Numerical analysis)	310 ft-lbf.

TABLE VIII displays the product specifications for the custom mirror design.

TABLE VIII

CUSTOM MIRROR SPECIFICATIONS

Physical	
Height	0.1 m
Diameter	1 m
Shape	Paraboloid
Material	
Material	Carbon fibre
Performance	
Reflective Efficiency	98 %

The customer needs from TABLE II were revisited and each need was given a rating based on how well the natural lighting solution met each need. The rating system is explained in TABLE IX.

TABLE IX

RATING SYSTEM FOR HOW THE SOLUTION MEETS CUSTOMER NEEDS

Scale	Description
5	Need is fully satisfied
4	Need is satisfied but has area for improvement
3	Need is not fully met
2	Verification through testing is highly recommended
1	Need is not met

TABLE X shows each customer need and the rank of importance, with the additional columns of how well our natural lighting system meets each need and the rationale used when assigning a rating.

TABLE X

RATING AND RATIONALE FOR HOW EACH CUSTOMER NEED IS MET

Need No.	Customer Need	Rank	Need met?	Rationale
N1	The lighting system provides sufficient light intensity to obtain effective, high-quality, useable images	5	4	Natural sunlight is sufficiently flicker free to obtain useable images. However the quality of the images obtained using natural light is lesser than the quality of those obtained during the icing testing using the strobe lighting at a very close range.
N2	Light targets the blades in the 12:00 region as well as the 9:00 region on the engine (from pilot's orientation)	5	5	The number of heliostats recommended was derived using the targeted areas.
N3	The lighting system is cost effective	3	5	The heliostat is relatively cheap compared to other commercial heliostat available and to commercial artificial lights available.
N4	Light is uniformly distributed throughout the illuminated region	4	3	Since two heliostats need to be used for each position it's likely that there will be overlap in the illuminated region and that the light distribution will be uneven
N5	The lighting system is capable of being used for a wide range of sun positions	3	3	The autonomous nature of the heliostat allows it to be used for a wide range of sun positions however it is still restricted to a certain amount of hours in the daytime
N6	A sufficient proportion of incident light is effectively reflected toward the imaging sensor	2	5	This was proven during their prototype testing that natural light reflected from mirrors was sufficient light intensity.
N7	The lighting system has manual override capabilities	5	5	The heliostat can be configured however the user wants.
N8	The lighting system is outside of the unsafe zone and object-free zone (radius of 50 ft from engine inlet)	5	5	The lighting system can operate around 25 m from the engine and it is recommended that is it placed that far.
N9	The lighting system can meet future fan imaging needs	1	2	The lighting system is intended to be ground mounted, anchored to the concrete meaning that each heliostat will have a set position. It cannot be moved round once a position has been chosen.
N10	The lighting system requires minimal maintenance	3	4	The heliostat ground mount will be zinc coated which will help to prevent corrosion. The heliostat can be left mounted for the duration of the summer testing season if desired. The mirrors are replaceable. There is a 1 year warranty for mechanical defect of the commercial heliostat

Need No.	Customer Need	Rank	Need met?	Rationale
N11	The lighting system is long lasting	3	3	The heliostat mount structure will not fatigue. If anything happens to the reflector it can be replaced.
N12	The lighting system is durable and adequate for environmental conditions	5	5	Both the heliostat and the structure are rated for 60 MPH. The structure is corrosion resistant. The heliostat is designed to be outdoors for long periods of time.
N13	Structure is static, stable and rigid under influence of all external forces	5	2	This is rated low because of the mirror size. Testing will have to be conducted to make sure that the vibrations of the mirror will not have an effect on the performance. The structure however is rigid and stable.
N14	The lighting system can be quickly set-up and configured	3	3	Set-up will have to be set-up very carefully to ensure the target is illuminated accurately throughout the day. However once set-up is complete there is no need to interact with the heliostat as it can operate autonomously.
N15	The lighting system is intuitive and easy to use	3	5	It operate autonomously
N16	The lighting system features a modular design	5	3	The height of the structure can be adjusted. The placement on the site is not versatile as it has to be anchored to the concrete.
N17	The lighting system is safe for both people and the test engine	5	4	The distance and the load rating for the heliostat are safe however there is no guarantee without testing
N18	The lighting system is manufacturable (allows for tolerances)	3	4	The heliostat is pre-fabricated and the structure is made from standard tube sizes and plate sizes.
N19	The lighting system must operate with sufficiently low flicker	5	3	This will have to be verified through testing as we do not know what effects the wind will have on the vibrations of the reflector.

In conclusion, this natural lighting system meets all customer needs however some needs require verification through testing in order to be certain. Some needs that have been met have areas for improvement.

4.5 BOM and Cost Summary

The Heliostat Assembly consists of two sub-assemblies:

- Pole Mount Structure
  - Base Plate
  - Base Pole
  - Adjustable Pole
- H1 Heliostat
  - Custom mirror design
  - Power Supply

An exploded view of the heliostat assembly is shown in Figure 24.

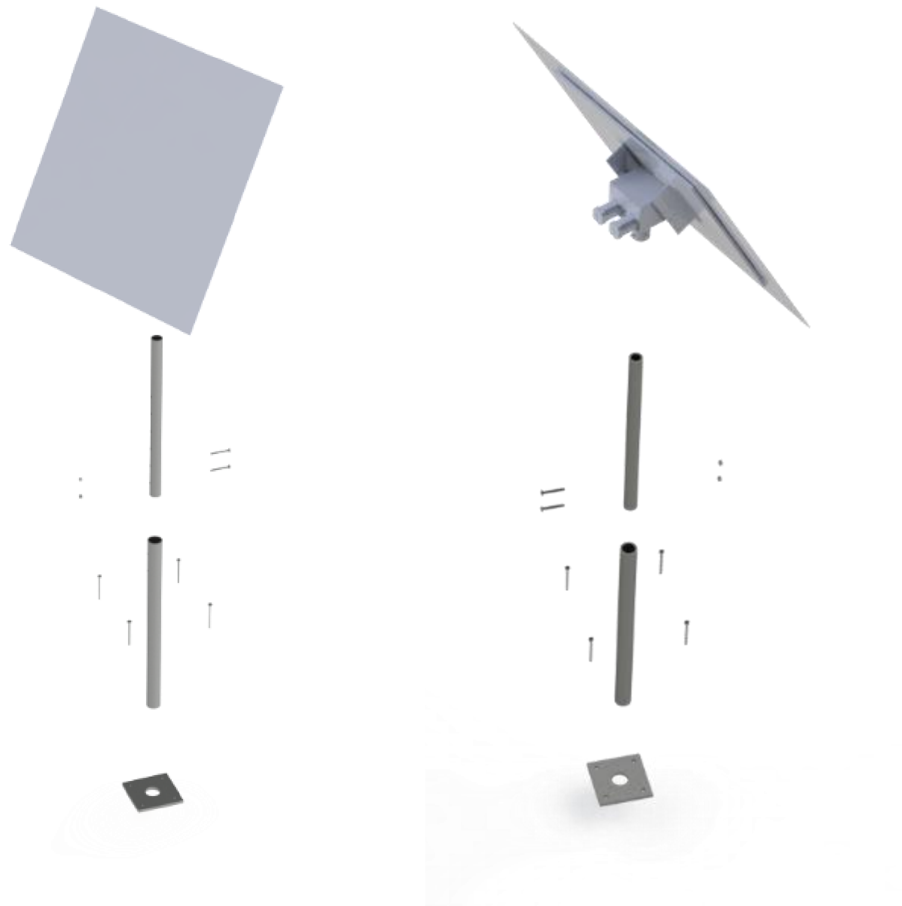

Figure 24. Full Heliostat Assembly exploded view [10] used with permission.

The BOM for the Heliostat Assembly is shown in TABLE XI, which includes raw materials, labour, and purchased parts required to complete the product. A cost analysis was performed on each item in the Heliostat Assembly BOM and can be seen in TABLE XII. The column titled "Unit cost w/factors" is the result of the unit cost multiplied by factors such as taxes and exchange rates.

TABLE XI

BILL OF MATERIALS FOR HELIOSTAT ASSEMBLY

ITEM NO.	LEVEL	NAME	DESCRIPTION	TYPE	UNIT	IN ASSEMBLY/PART	QTY.
1	1	Heliostat Assembly	combination of commercial heliostat and custom components	Assy	ea.		4
2	2	Pole Mount Structure	For supporting and mounting the H1 helliostat	Assy	ea.	Heliostat Assembly	4
3	3	Base Plate	Welded to Bottom Post	Part	ea.	Pole Mount Structure	4
4	4	3/4 inch THICK A36 Steel Plate	Base plate raw material	Raw Material	ea.	Base Plate	1
5	4	Laser cutting	For plate holes	Process	in.	Base Plate	188.496
6	4	Labour	laser cutting	Labour	hr.	Base Plate	1
7	3	Base Pole	Welded to Base Plate	Part	ea.	Pole Mount Structure	4
8	4	3" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	bottom post raw material	Raw Material		Base Pole	1
9	4	Milling	Holes in tube	Labour	hr.	Base Pole	1
10	3	Welding	welding base plate to bottom post	Process	in.	Pole Mount Structure	9.425
11	3	Labour	welding	Labour	hr.	Pole Mount Structure	1
12	3	Adjustable Pole	Slides inside Bottom Post	Part	ea.	Pole Mount Structure	4
13	4	2.375" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	top post raw material	Raw Material	ea.	Adjustable Pole	1
14	4	Milling	Holes in tube	Labour	hr.	Adjustable Pole	1
15	4	Lathing	turning down the top post	Labour	hr.	Adjustable Pole	1
16	3	Galvanizing	coating each structure (after welding and lathing)	Process	lb.	Pole Mount Structure	276.6
17	3	HHBOLT 1/2"-13 X 3.75" X 1-N	For holding Top Post in desired position	Hardware	ea.	Pole Mount Structure	8
18	3	HH NUT 1/2"-13-D-N	For holding Top Post in desired position	Hardware	ea.	Pole Mount Structure	8
19	3	HHS BOLT 3/4"-10 X 5.5" X 1.375"	Anchor bolts to concrete	Hardware	ea.	Pole Mount Structure	16
20	2	H1 Heliostat	Commercial heliostat assembly (does not come with pole)	Assy/Purchase Part	ea.	Full Heliostat Assembly	4
21	3	P1 Multiple Heliostat Power Supply	Power supply for H1 Heliostat	Purchase Part	ea.	H1 Heliostat	1

TABLE XII

COST ANALYSIS FOR HELIOSTAT ASSEMBLY

ITEM	DESCRIPTION	QTY	UNIT COST	UNIT COST w/FACTORS	TOTAL COST	VENDOR	NOTES
POLE MOUNT STRUCTURE MATERIAL							
3/4 inch THICK A36 Steel Plate	For base plate	1	$551.20	$833.41	$833.41	Metals Depot	1 USD = 1.35 CDN 11/15/16
3" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	For bottom post	4	$135.88	$205.45	$821.80	Online Metals	1 USD = 1.35 CDN 11/15/16
2.375" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	For top/adjustable post	4	$72.42	$109.50	$438.00	Online Metals	1 USD = 1.35 CDN 11/15/16
Shipping		1	$1,000.00	$1,000.00	$1,000.00		Estimation for all shipping
TOTAL MACHINING COST							
Laser cutting (and Labour)	for base plate	4	$35.00	$35.00	$140.00		Estmated CNC Maching $70/hr.
Lathing (and Labour)	for top post	4	$35.00	$35.00	$140.00		Estmated CNC Maching $70/hr.
Milling (and labour)	For drilling holes	32	$8.75	$8.75	$280.00		Estmated CNC Maching $70/hr.
Welding (and labour)	Welding base plate to bottom post	4	$38.33	$38.33	$153.30		Estimated welding $0.35/in. +$35.00/hr
Galvanizing (labour)	Finishing	4	$28.00	$31.36	$125.44		Estimated $0.40 / lb.
HARDWARE							
Zinc Yellow-Chromate Plated Hex Head Screw, Grade 8 Steel, 1/2"-13 Thread Size, 3-3/4" Long	For adjustability	2	$8.11	$12.26	$24.52	McMaster Carr	packages of 5
High-Strength Steel Nylon-Insert Locknut, Grade 8, Zinc Yellow-Chromate Plated, 1/2"-13 Thread Size	For containment	1	$4.31	$6.52	$6.52	McMaster Carr	package of 10
Zinc Yellow-Chromate Plated Hex Head Screw, Grade 8 Steel, 3/4"-10 Thread Size, 5-1/2" Long, Fully Threaded	For anchors	16	$9.48	$14.33	$229.34	McMaster Carr	per item
HELIOSTAT AND POWER SUPPLY							
H1 Heliostat	Heliostat	4	$2,271.00	$3,433.75	$13,735.01	LightManufacturing	
P1 Multiple Heliostat Power Supply	Power Supply	1	$699.00	$1,056.89	$1,056.89	LightManufacturing	
				TOTAL	$18,984.23		

The heliostat solution, has a final cost estimation of $18 984.23 CAD. Technical Drawings for each component and sub-assembly can be found in APPENDIX C of this report.

5. LED LIGHTING SYSTEM

The night-time-use portion of our team's solution utilizes a high-intensity artificial light. Research was directed to sourcing an LED that meets the required design performance metrics. After selecting a light for our design, analyses were performed to validate its performance, as well as on any custom components designed by our team. Product details, cost details, and a BOM are provided for the LED light assembly.

5.1 Research: Requirements and Results

The criteria that governed our search for the artificial light source are that:

- The light source must be flicker-free
- The light outputs a highly focused beam
- The size of the highly focused beam is reasonable for the application
- The light maintains high lux output at far distances

Other characteristics were also taken into consideration such as cost, and size. The research process resulted in 12 different lighting products to choose from shown in TABLE XIII.

TABLE XIII

RESULTS OF ARTIFICIAL LIGHT RESEARCH

Company Name	Product Name	Ref
Edmund Optics Worldwide	AI High Intensity LED Spot Lights	[36]
Advanced Illumination	SL185 - High performance Spotlight	[37]
Stemmer Imaging	Opto Engineering LT CL and LT CL HP - Collimated (Telecentric) LEDIlluminators	[38]
Stemmer Imaging	VisionLight ProVision - High-frequency area lights	[38]
Effilux Illumination	Effiring	[39]
Effilux Illumination	EffiFlex	[39]
Litepanels	sola 9	[40]
Litepanels	sola 12	[41]
ARRI	Arri Compact 6000 HMI Fresnel Light	[42]
ARRI	Arri L10-DT LED Daylight Fresnel	[43]
luminys	sunsource 1500W LED	[44]
RAY Tec	RAY Lux	[45]

While numerous lighting products were researched, the majority failed to meet the critical aspects of the systems design constraints. Specifically, the high luminous intensity in combination with the extended operating distance presented a critical challenge to the majority of the lighting products researched. Each of the Sola lights and Arri Lights along with the Luminys LED operated with illumination output on the scale of what would be required, but only the Luminys SunSource LED provided a solution that was appreciably effective. The Sola 12 and the Arri L10-DT LED lights would each require upwards of 30 individual Luminaires in order to achieve the intensity required to meet the design constraints, making them impractical to implement within the testing environment. These two lights also are not designed for high speed imaging in terms of flicker specifications. The Arri HMI light is also limited to a 1000 Hz flicker rate which cannot be expected to be functionally flicker free within the testing environment. The Luminys SunSource 1.5K LED Direct Light is explicitly designed for high luminous intensity within a highly focused beam angle while also being effectively flicker free at all shutter speeds. This, along with the light's highly robust self-contained weather proof housing make the SunSource the standalone choice for our lighting system design. The Luminys SunSource 1500 Watt LED is shown in Figure 25.

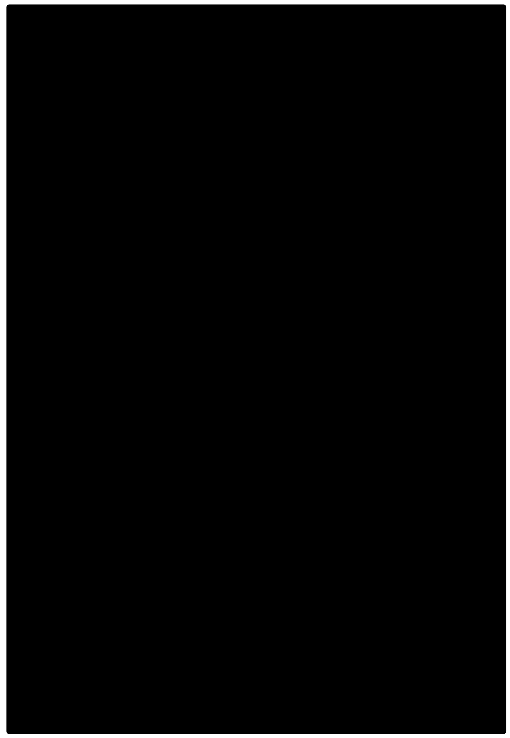

Figure 25. Luminys SunSource 1500 Watt LED [46].

A functional analysis of the LED light solution was broken down into three sub-systems: the light source, the light mount, and the power source. Each sub-system's functionality is shown in Figure 26.

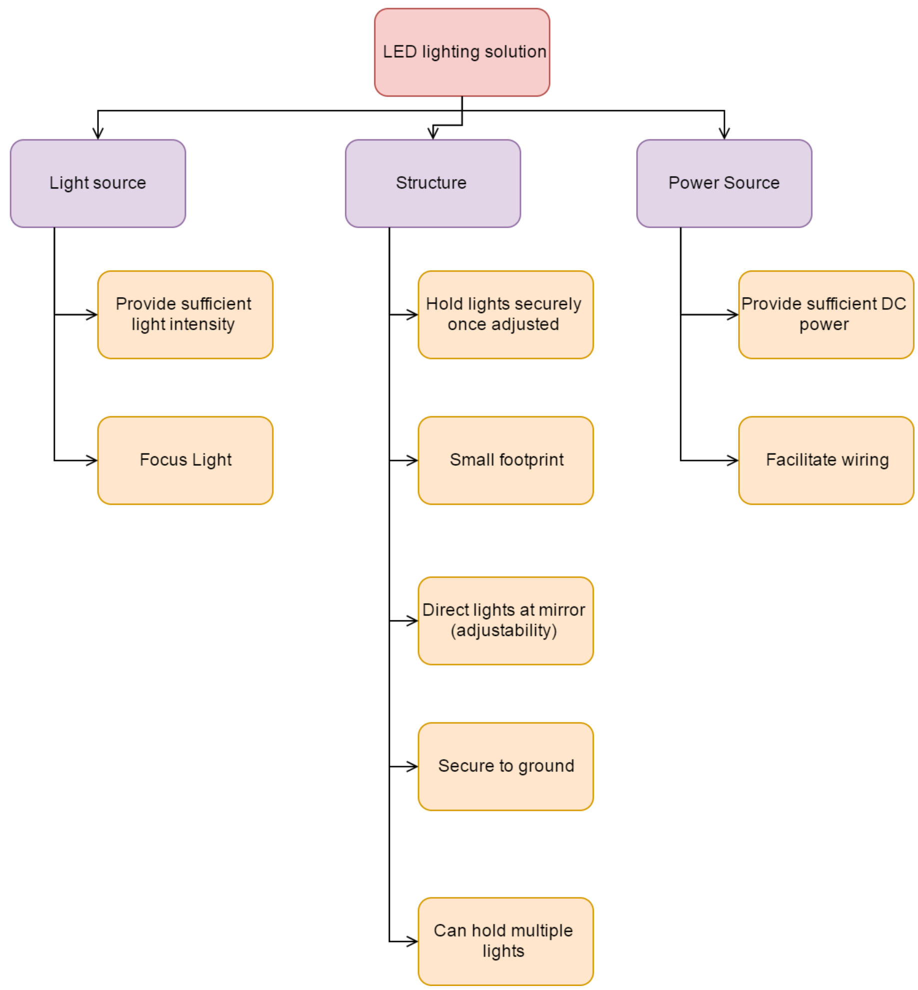

Figure 26. Functional breakdown of the LED Light solution [47] used with permission.

The LED and power source are both off-the-shelf, sourced items. It was decided to design a custom light mount rather than source one, to ensure its safety in the operational environment as well as to ensure it meets all functional requirements such as adjustability.

5.2 Analysis

The analysis for the LED light involved first extrapolating data from the details on the photometrics of the Luminys light and producing a light intensity map for distances applicable to our design problem. This allowed our team to determine the number of lights required to meet the target performance metrics. Analyses were performed when designing the custom light mount structure to ensure that the structures could hold the light securely while allowing for adjustability.

5.2.1 Light Intensity Mapping

In order to quantify the luminous intensity required to effectively light up the intake fan, the winter testing configuration was characterized and referenced. The winter testing configuration utilizes 8, Unilux H8D “Sentry” synchronous stroboscopic light sources to illuminate the engine inlet [5].

Each Sentry luminaire is located roughly 1.8 meters from the fan face. From the plot in Figure 27, at a distance of 1.8 meters, the luminous output of each strobe could be said to have a conservative estimate of at most 1800 lux per luminaire. When factoring the combined contribution of all eight units, we resolve the system to produce a luminous intensity of 14 400 lux onto the entire engine inlet fan. In order to incorporate an extra margin of error associated with the complexities of lighting dynamics, a 30% margin is added resulting in an intensity of around 19 000 lux.

[redacted]

Figure 27. Unilux Sentry Spacial Intensity Output (vertical) [48].

The selected luminaire, the Luminys SunSource 1500 Watt LED, utilizes an 11” x 11” array of LED units, each with its own individual lens configuration. This configuration allows each panel to produce an effectively focused region of luminous output. Shown in Figure 28, the output of a single Luminys light unit is a function of distance from the source. Using a distance estimate of 55 feet from the light systems output to the engine inlet fan, we can resolve from the Photometrics diagram that each luminaire will produce, as a low estimate, an intensity of 6000 lux on the fan face. If four luminaires are configured to be used in combination, the engine fan inlet should receive a luminous intensity of 24 000 lux. This would again be a margin above our conservative estimate of the luminous intensity required.

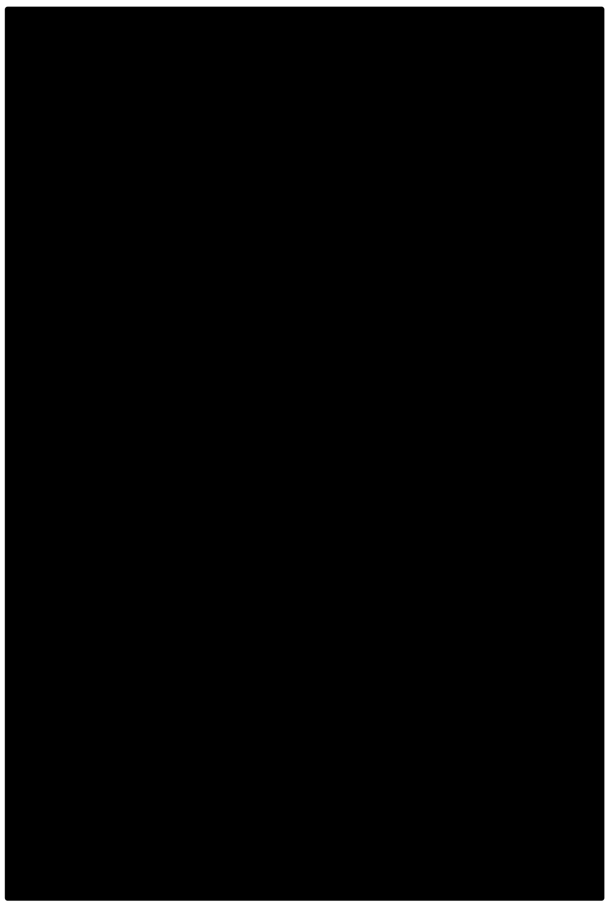

Figure 28. Luminys SunSource 1.5K LED output [44].

The light beam size, at a distance of 55 ft., can be extrapolated from Figure 28 to be approximated 3 m in diameter. Since the largest engine tested at the GLACIER Facility is the Rolls

Royce Trent XWB with a total engine inlet diameter of 2.99 m (fan size is smaller), we can conclude that only one Luminys light is needed to provide the appropriate area of light at the engine inlet.

In total, four Luminys lights, all pointed directly at the engine inlet center are needed to meet design requirements

5.2.2 Custom Light Mount

For the custom light mount design, we are required to consider the weight of the light and wind speed loading effects. The weight of the selected light is 80 lb. [49]. To distribute this force, the selected design utilizes two mounting points which also act as a hinge to allow for adjustability. The structure will be mounted to the Pole Mount Structure that has been designed for the heliostats. The Pole Mount Structure has been analysed for both the H1 Heliostat and LED light and meets all design requirements. The full analysis can be found in APPENDIX B. The custom light mount design is shown in Figure 29 and will be denoted as the LED Light Mount.

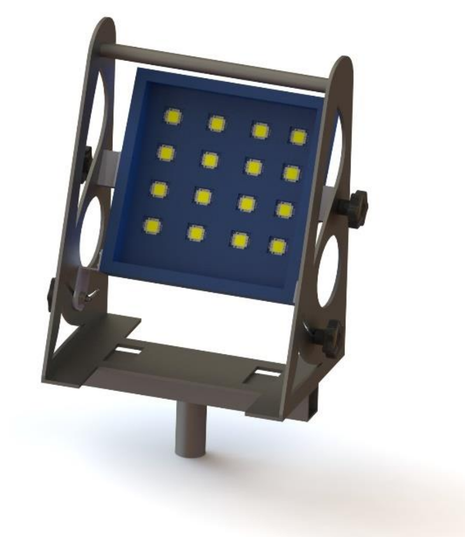

Figure 29. Model of the LED Light Mount [50] used with permission.

To remain consistent with the Pole Mount Structure, the material for the LED Light Mount was selected to be AISI 1020 steel. The weld size should be no larger than the thinnest material used and this will be determined by the minimum plate thickness required. Three separate FEA studies were conducted to validate the design and to determine the minimum required thickness of the side plates.

The first FEA study was set up with the same 155 lbf force used to analyze the Pole Mount Structure, as well as an 80 lb downward force from the weight of the light. The minimum required plate thickness is 0.75 inches and the entire structure had a safety factor of over 2. The structure was analyzed with a weld thickness equal to the plate thickness.

The second FEA analysis performed was to determine if the top bar could be used as a lifting point for the LED light assembly. The study showed that the top bar could indeed be utilized as a handle for transporting the light.

The third and final FEA analysis considered a sideways loading scenario for the possible case of the light being held in a horizontal orientation. With the plate thickness of 0.75 in., all stresses within the structure remained to have a safety factor of over 2. The full analysis is in APPENDIX B.

5.3 Details of the LED Lighting System

The LED lighting system consists of the Luminys SunSource 1500 Watt LED Luminaire, the custom LED Light Mount, and an appropriate power source. Details for each are provided in this section.

5.3.1 Light Source

The Luminys SunSource 1500 Watt LED Luminaire is configured into a panel array of individual LED outputs. The square 11” x 11” grid sees 121 individual LED light sets, each of which are characterized by the same operational structure [51].

At the core of each light is a high performance CREE XML Solid State LED component. The Cree XM-L LED design is characterized by both high unit output and luminous power efficiency. The XM-L LED outputs light at a wide 125 degree viewing angle [52]. Each XM-L LED output is then projected into a focused beam using a static focusing lens. The back of each XM-L LED is thermally adhered to the main body of the luminaire which is designed to act as a single large aluminum heat sink. The heat sink is actively cooled using integrated fans within the fixture. The Lighting fixture as a whole is contained within a highly robust sandwiched construction. The front face is constructed out of Lexan, which is used for its properties of toughness and transparency.

The face is surrounded by an aluminum bezel that is securely screwed down to the aluminum back panel. There are 4 additional screws used to secure the Lexan face to the body of the unit. The enclosure of the luminaire is designed to withstand all types of adverse weather.

As previously stated, four lights are required to illuminated the engine face with the desired lux values.

5.3.2 Mounts and Structure

The LED Light Mount is designed to mount to the same Pole Mount Structure used for the H1 Heliostat.

Figure 30. Custom LED Light Mount Structure [53] used with permission.

The side plates of the structure were selected to be 0.75 in. thick. Attached to the light itself are four brackets used to keep the light suspended. Each bracket is fastened to the light using four #10 nominal size hexagon socket head cap screws. Two brackets hold the light in the middle of the body and the other two are used adjust the angle of light. To hold and adjust the light, 1/2-inch knob bolts are used.

To ease transportation the top bar is designed to be used as a handle to carry the light assembly. This mount allows for axial adjustment via the sliding bolts in the slots in the side of the mount. The entire structure can be positioned in any desired direction by turning it while it is resting on the pole.

The entire structure is finished with a galvanized coating to provide corrosion resistance.

5.3.3 Power Source

Each Luminys SunSource 1500 Watt LED luminaire is driven by a purpose-built power supply. This power supply is capable of driving a highly conditioned DC voltage to the light head that is substantially free of AC ripple characteristics. The DC supply is regulated as a current source by the units' control systems. This current control corresponds to the light heads flicker-free dimming capabilities. Each power supply unit is also configured to power the light heads fan motors, as well as to integrate communication feedback from the light head's systems. Each unit requires 220 V AC service with 7.5 amps of current capacity [46]. Each of the four power supply units require four units of rack mount capacity and may be housed within the test sites available rack mount space [54]. The Power Supply can be seen in Figure 31.

[redacted]

Figure 31. Luminys SunSource 1.5K Power Supply [46]

The SunSource 1.5 K LED Power Supply is controlled using a 5-pin DMX control interface and can be seen in Figure 32.

[redacted]

Figure 32. DMXking eDMX1 PRO module [55]

In order to allow the operation of the SunSource LED units actuation from the control room, we have configured the lighting design to be integrated into the existing network infrastructure. Each of the four SunSource LED Power Supply unit's 5-pin DMX interfaces are daisy-chained together and connected to an Art-Net protocol network module. The DMXking eDMX1 PRO Ethernet DMX Controller (5-Pin) is a simple professional module that integrates one DMX512 node onto the local area network via Ethernet connection [55]. Once connected, the lights may be controlled from any location on the network with a simple open source software suite such as DMXControl.

The primary cabling required run from each of the power supply units to each LED lighting head. Each cable set is comprised of seven leads. Standard lengths of cable are included from Luminys when purchasing each SunSource LED lighting set. The cost of additional length in cabling was added into the purchase price per unit [46]. Five short length DMX cables (5-pin) will also be required for configuration.

5.4 Product Specifications and Compliance of Needs

TABLE XIV contains the Luminys SunSource 1500 Watt LED Luminaire product specifications.

TABLE XIV

LUMINYS SUNSOURCE LED LIGHT [44]

Luminys LED Light Head	
Dimensions	26 x 20.25 x 3.25 inch
Weight	80 lbs
LED type	CREE XM-L LED
Colour Temperature	5000 Kelvin
LED count	121 Units Per Head
Power Usage	1500 Watts
Luminys LED Power Supply	
Width	19 inch
Height	4 U (7 inch)
Form Factor	Standard 4 U Rack Mount
Weight	25 lbs
Power per unit	7.5 Amps (@220 V)
	15 Amps (@110 V)
Control Interface	DMX512
Control Connection Type	XLR5 (Input + Passthrough)
Light Head Connection Type	820/870 600 V Binder
DMXking eDMX1 DMX512 Control Interface	
Dimensions	40x36x78 mm
Weight	0.15 kg
DMX512 Connector	5 Pin XLR Female
Network Connector	cat 5 Ethernet
Power Connector	USB Type-B Socket
Network Addressing	IPv4
Lighting Protocols	Art-Net, Art-Net II, Art-Net III

TABLE VII contains information about the LED Light Mount specifications and ratings.

TABLE XV

LED LIGHT MOUNT SPECIFICATIONS

Material	AISI 1020 cold rolled steel
Finish	Galvanized
Wind speed loading	155 lbf max load
Weight	115 lbs

The final product is a combination of the Luminaire LED light, the LED Light Mount, and the Pole Mount Structure. The customer needs from TABLE II were revisited, and each need was given a rating based on how well this artificial lighting solution met each need. The rating system is the same as used previously and can be found in TABLE IX.

TABLE XVI shows each customer need and the rank of importance, with the additional columns of how well our artificial lighting system meets each need and the rationale used assign each rating.

TABLE XVI

RATING AND RATIONALE FOR HOW EACH CUSTOMER NEED IS MET

Need No.	Customer Need	Rank	Need met?	Rationale
N1	The lighting system provides sufficient light intensity to obtain effective, high-quality, useable images	5	2	The calculations of the LED systems light intensity compared to the winter testing system indicate that the light intensity should be sufficient. Luminys Corp has verified to us through anecdotal evidence that the SunSource 1.5K LED performs successfully at 1 microsecond shutter speeds. Regardless, it is there professional opinion that the lighting be tested for use in the specific scenario in order to validate its functionality.
N2	Light targets the blades in the 12:00 region as well as the 9:00 region on the engine (from pilot's orientation)	5	5	At the prescribed distance, the LED light output produces footprint which covers the entire engine inlet fan.
N3	The lighting system is cost effective	3	4	The SunSource (SS) 1.5K LED unit price is prohibitive and given the requirement of four light heads, accounts for 75% of the $100K target budget. The SS 1.5K LED was the only product found on the market to offer the appropriate operational characteristics for the design requirements.
N4	Light is uniformly distributed throughout the illuminated region	4	4	Light output beam characteristics are effectively uniform but not completely so.
N5	The lighting system is capable of being used for a wide range of sun positions	3	2	Effectiveness of the LED system's illumination in the presence of the sun's indirect illumination requires validation by means of direct testing. It is possible that the LED lighting system will be fully effective in the presence of full daylight conditions.
N6	A sufficient proportion of incident light is effectively reflected toward the imaging sensor	2	4	This need is subject to the exact placement of the lighting structure within the testing grounds as well as effected by the dynamics of the blade geometry. Nevertheless, the added light intensity that has been factored into the LED lighting systems specifications should be sufficient to account for the previously indicated dynamics.
N7	The lighting system has manual override capabilities	5	4	Aiming of the LED light sources is carried out manually at the unit. The lighting system may be shut down manually at the light head, the power supply, or through the Art-Net networking interface.

Need No.	Customer Need	Rank	Need met?	Rationale
N8	The lighting system is outside of the unsafe zone and object-free zone (radius of 50 ft from engine inlet)	5	5	The LED lighting system has been designed to effectively operate at a 50 Ft distance associated with the object free zone.
N9	The lighting system can meet future fan imaging needs	1	2	The large light footprint of the SunSource LED should account for variation of the engine inlet size. Functionality would need to be verified experimentally.
N10	The lighting system requires minimal maintenance	3	4	The LED light head is of weather-proof construction and the external mounting structure operates using a simple static design.
N11	The lighting system is long lasting	3	4	The long lifespan of the LED source used on the light head along with their implementation onto a large, actively cooled heatsink enable the lights to operate for an extensive period of time. The light head structure's robust design should prevent it from requiring any appreciable amount of maintenance, assuming proper operation.
N12	The lighting system is durable and adequate for environmental conditions	5	4	The light head is designed to be highly durable and weather resistant. The Lexan frontal face and LED lighting components are all highly resistant to mechanical shock.
N13	Structure is static, stable and rigid under influence of all external forces	5	2	The mounting structure has been designed to safely and securely house the light panel. It is advised that the system be tested within the working environment to confirm maintained rigidity.
N14	The lighting system can be quickly set-up and configured	3	4	The LED lighting system operates using a simple static design and is comprised of very few components. After mounting, each light only needs to be aimed at the engine inlet fan and secured down with the built in hand fasteners.
N15	The lighting system is intuitive and easy to use	3	4	The simple, static mounting structure of the light and its incorporation into the existent network infrastructure allow it to be physically set up on site and controlled with ease from any access point on the network. This includes wireless control via mobile device
N16	The lighting system features a modular design	5	3	Each light head and structure operates independently of existing equipment, but requires ground anchors to be installed. Each power supply is designed to be incorporated into existent rack mount space at the test site.

Need No.	Customer Need	Rank	Need met?	Rationale
N17	The lighting system is safe for both people and the test engine	5	4	The light head is designed to be self-contained and well secured to the mounting structure.
N18	The lighting system is manufacturable (allows for tolerances)	3	4	The prefabricated light head is validated to have a manufacturable design as it is an existent production. The simple design and operating mechanism of the light head mounting structure leaves little concern for problems to come up in manufacturing.
N19	The lighting system must operate with sufficiently low flicker	5	2	The Luminys SunSource 1.5K LED luminaire has been specifically designed to be utilized for high speed imaging. Successful results of the systems being utilized for imaging at 1 microsecond shutter speeds have been conferred anecdotally by Luminys Corp. Luminys has recommended that the LED lighting system be tested within the working environment confirm operational validity.

In conclusion, this natural lighting system meets all customer needs; however, some needs require verification through testing in order to be certain. Some needs that are satisfied have areas for improvement.

5.5 BOM and Cost Summary

The LED Light Assembly consists of purchased parts as well as two sub-assemblies:

- Luminys 1500 LED Luminaire
- Power Supply
- Pole Mount Structure
    - Base Plate
    - Base Pole
    - Adjustable Pole
- LED Light Mount
    - Top Handle
    - Mounting Tube
    - Side Plates
    - Bottom Frame Tube
    - Bottom Plate
    - Centre Bracket
    - Positioning Bracket

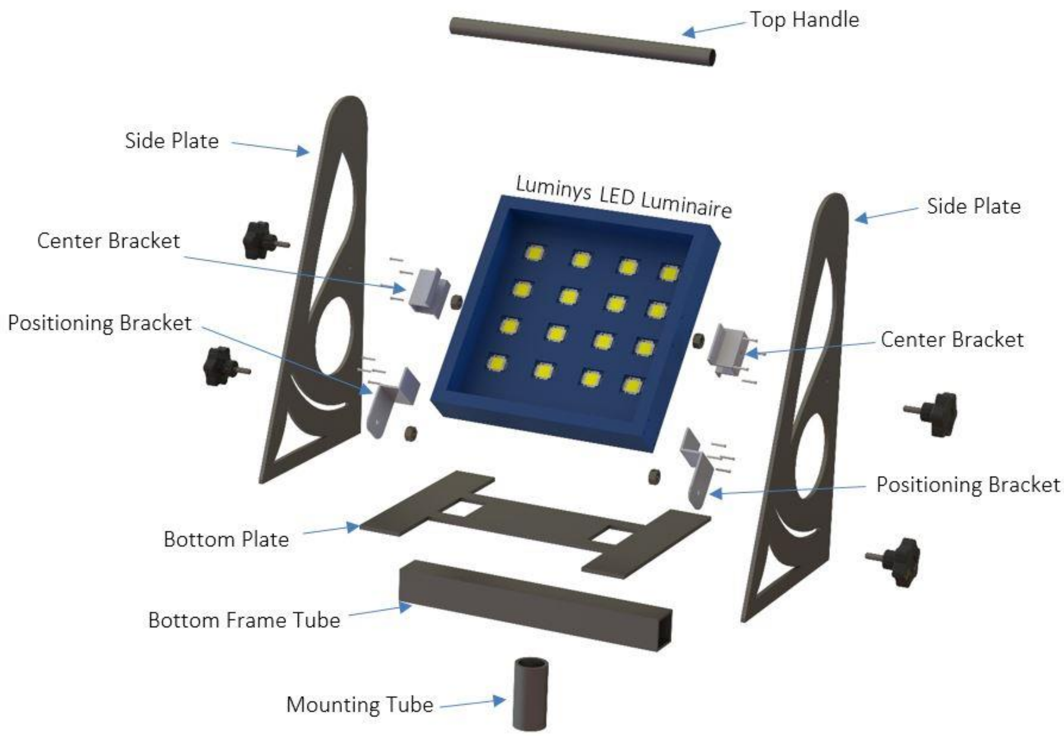

Figure 33. Exploded view of LED light mount assembly [53] used with permission.

The BOM and the cost analyses for the LED Light assembly are presented in TABLE XVII and TABLE XVIII, respectively.

TABLE XVII

BOM FOR LED LIGHTING SYSTEM

ITEM NO.	LEVEL	NAME	DESCRIPTION	TYPE	UNIT	IN ASSEMBLY/PART	QTY.
1	1	LED Light Assembly	Combination of commercial LED light and custom components		ea.		4
2	2	LED Mount Structure	For moutning the LED Light	Assy	ea.	LED Light Assembly	4
3	3	Top Handle	Top bar of light mount	Part	ea.	LED Mount Structure	4
4	4	1.5" OD X 0.083" Wall 4130 Alloy Cold Rolled Round Tube	for the top handle	Raw Material	ea.	Top Handle	4
5	3	Mounting Tube	tube that interfaces with the pole mount structure	Part	ea.	LED Mount Structure	4
6	4	3" OD X 0.125" WALL 4130 ALLOY STEEL TUBE	for the bottom tube	Raw Material	ea.	Mounting Tube	4
7	4	Tapping holes	for the #10 screws to clamp to pole mount structure	Labour	hole	Mounting Tube	8
8	3	Side Plate	Holes for mounting the light	Part	ea.	LED Mount Structure	8
9	4	3/8" inch THICK A36 Steel Plate (2 x 4 ft)	For the whole frame	Raw Material	ea.	Side Plate	2
10	4	Laser cutting	For the design of the frame	Process	in.	Side Plate	419.86
11	3	Bottom Plate	Spacing between the side plates	Part	ea.	LED Mount Structure	4
12	4	3/8 in. THICK A36 Steel Plate (2 x 4 ft)	For the whole frame	Raw Material	ea.	Bottom Plate	1
13	4	Laser cutting	For the design of the frame	Process	in.	Bottom Plate	135.56
14	3	Bottom Frame Tube	Structural support	Part	ea.	LED Light Mount	4
15	4	2-1/2 X 2-1/2 X 1/4 wall A500 Square Steel Tube (4ft)	For holding the top frame and the bottom tube	Raw Material	ea.	Bottom Frame Tube	4
16	3	Centre Bracket	Fastening to frame and used to bolt to the side plates	Part	ea.	LED Light Mount	8
17	4	3/16 inch THICK A36 Steel Plate (1x1 ft)	Raw material for centre bracket	Raw Material	ea.	Centre Bracket	1
18		Laser cutting	For the dimension of the bracket	Process	in.	Centre Bracket	32.16
19	4	Breaking	bending into shape	Labour	hr.	Centre Bracket	2
20	3	Positioning Bracket	Mounted to frame and used for fixing position after adjusted	Part	ea.	LED Light Mount	8
21	4	3/16 inch THICK A36 Steel Plate (1x1 ft)	Raw material for centre bracket	Raw Material	ea.	Positioning Bracket	1
22		Laser cutting	For the dimension of the bracket	Process	in.	Positioning Bracket	45.48
23	4	Breaking	Bending Positioning bracket into shape	Labour	hr.	Positioning Bracket	2
24	3	Labour	For welding and laser cutting	Labour	hr.	LED Light Mount	16
25	3	Welding	The entire light mount assembly together	Process	in.	LED Light Mount	60.18
26	3	Galvanizing	Finishing	Process	lb.	Adjustable Pole	140.45
27	3	HHBOLT 1/2"-13 X 3.75" X 1-N	For adjusting the light in the desired position	Hardware	ea.	LED Mount Structure	4
28	3	HH NUT 1/2"-13-D-N	For adjusting the light in the desired position	Hardware	ea.	LED Mount Structure	4
29	3	#10-32 X 1.25" Socket Head cap screw	For holding Top and Bottom Brackets of light	Hardware	ea.	LED Mount Structure	16

ITEM NO.	LEVEL	NAME	DESCRIPTION	TYPE	UNIT	IN ASSEMBLY/PART	QTY.
30	2	Pole Mount Structure	To support the LED light mount structure	Part	ea.	LED Light Assembly	4
31	3	Base Plate	Welded to Bottom Post	Part	ea.	Pole Mount Structure	4
32	4	3/4 inch THICK A36 Steel Plate	Base plate raw material	Raw Material	ea.	Base Plate	1
33	4	Laser cutting	For plate holes	Process	in.	Base Plate	188.496
34	4	Labour	laser cutting	Labour	hr.	Base Plate	1
35	3	Base Pole	Welded to Base Plate	Part	ea.	Pole Mount Structure	4
36	4	3" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	bottom post raw material	Raw Material	ea.	Base Pole	1
37	4	Milling	Holes in tube	Labour	hr.	Base Pole	1
38	3	Welding	welding base plate to bottom post	Process	in.	Pole Mount Structure	9.425
39	3	Labour	welding	Labour	hr.	Pole Mount Structure	1
40	3	Adjustable Pole	Slides inside Bottom Post	Part	ea.	Pole Mount Structure	4
41	4	2.375" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	top post raw material	Raw Material	ea.	Adjustable Pole	1
42	4	Milling	Holes in tube	Labour	hr.	Adjustable Pole	1
43	4	Lathing	turning down the top post	Labour	hr.	Adjustable Pole	1
44	3	Galvanizing	Finishing	Process	lb.	Pole Mount Structure	276.6
45	2	SunSource1500Watt LED and power source	LED light and power source	Purchase Part	ea.	SunSource 1500Watt LED	4

TABLE XVIII

COST ANALYSIS FOR THE LED LIGHTING SYSTEM

ITEM	DESCRIPTION	QTY	UNIT COST	UNIT COST w/FACTORS	TOTAL COST	VENDOR	NOTES
LIGHT MOUNT MATERIAL							
1.5" OD X 0.083" Wall 4130 Alloy Cold Rolled Round Tube	for the top handle	1	$61.48	$92.96	$92.96	Online Metals	1 USD = 1.35 CDN 11/15/16
3" OD X 0.125" WALL 4130 ALLOY STEEL TUBE	for the bottom tube	1	$16.50	$24.95	$24.95	Online Metals	1 USD = 1.35 CDN 11/15/16
1/2 inch THICK A36 Steel Plate (2 x 4 ft)	For the whole frame	1	$220.48	$333.37	$333.37	Online Metals	1 USD = 1.35 CDN 11/15/16
2-1/2 X 2-1/2 X 1/4 wall A500 Square Steel Tube (4ft)	For holding the top frame and the bottom tube	1	$60.76	$91.87	$91.87	Online Metals	1 USD = 1.35 CDN 11/15/16
3/16 inch THICK A36 Steel Plate (1x1 ft)	For holding the LED	4	$15.34	$23.19	$92.78	Online Metals	1 USD = 1.35 CDN 11/15/16
POLE MOUNT STRUCTURE MATERIAL							
3/4 inch THICK A36 Steel Plate	For base plate	1	$551.20	$833.41	$833.41	Metals Depot	1 USD = 1.35 CDN 11/15/16
3" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	For bottom post	4	$135.88	$205.45	$821.80	Online Metals	1 USD = 1.35 CDN 11/15/16
2.375" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	For top/adjustable post	4	$72.42	$109.50	$438.00	Online Metals	1 USD = 1.35 CDN 11/15/16
Shipping		1	$500.00	$500.00	$500.00		Estimation for all shipping
TOTAL MACHINING COSTS							
Welding (and Labour)	All Welding	1	$59.39	$94.39	$94.39		Estimated welding $0.35/in. +$35.00/hr
Laser cutting (and Labour)	for base plate, light mount, and brackets	4	$70.00	$70.00	$280.00		Estmated CNC Maching $70/hr.
Milling (and labour)	For drilling holes	32	$8.75	$8.75	$280.00		Estmated CNC Maching $70/hr.
Galvanizing (labour)	Finishing	4	$56.18	$62.92	$251.69		Estimated $0.40 / lb.
HARDWARE							
Zinc Yellow-Chromate Plated Hex Head Screw,Grade 8 Steel, 1/2"-13 Thread Size, 3/4" Long	For locking the light	4	$14.90	$22.53	$90.12	MCmaster Carr	package of 25
High-Strength Steel Nylon-Insert Locknut, Grade 8, Zinc Yellow-Chromate Plated, 1/2"-13 Thread Size	For containment	4	$4.31	$6.52	$26.07	McMaster Carr	package of 10
Nylon-Tip Socket Head Screw 10-32 Thread Size, 1" Long	For holding Top and Bottom Brackets of light	16	$3.27	$4.94	$79.11	McMaster Carr	
Medium-Strength Grade 5 Steel Hex Head Screw,Zinc-Plated, 3/8"-24 Thread Size, 1/2" Long	For adjustability of the top post.	8	$7.21	$10.90	$87.21	McMaster Carr	package of 25
LIGHT AND POWER SOURCE							
Luminys SunSource 1500 W LED Luminaire	LED light head and power supply	4	$17,500	$23,275.00	$93,100.00		1 USD = 1.33 CDN 12/03/16
LIGHT SYSTEM ACCESSORIES							
DMXking eDMX1 PRO Art-Net to DMX512 node	For adjusting the light intensity, power supply over tnetwork	1	$129	$195	$195	DMXking	Purchase Price
American DJ Accu-cable 5-pin DMX Cable (5')	Connects each luminaire to control interface	4	$7	$10	$39	B&H Photo Video Pro Audio	
				TOTAL	$97,712.75		

The cost of the entire LED lighting system amounts to $97 712.75 CAD.

Technical Drawings for each component and sub-assembly can be found in APPENDIX C of this report.

6. RECOMMENDATIONS

There are several options for both the natural and the artificial lighting systems. Our team had done research into designing a custom mirror specifically for our application. The H1 Heliostat has an accessory that allows the flat reflectors to be interchanged for variable focus, parabolic reflector. The Luminys LED light has the option to be rented for testing before making a purchase. Finally, the Pole Mount structure is designed to have a single fixed position per structure. To allow for testing of different positions, our team has designed a different configuration of the Pole Mount Structure called the Test Mount. A cost estimate for the custom mirror design as well as the other recommendations.

6.1 Custom Mirror Design

Our team designed a custom parabolic mirror profile to be used with the H1 Heliostat in place of the flat aluminum reflectors. The custom mirror design will increase the performance efficiency of the natural lighting solution by providing higher intensity light at the engine inlet, in comparison to the flat aluminum reflectors.

A parabolic mirror is the best shape to focus the light at one point and will be used for the custom mirror design. It should be noted that at the focal point, temperature increases rapidly [56]. However, setting the focal point to be beyond the engine the inlet engine will help to minimize the heat at the reflected area.

The diameter and the height of the custom mirror will vary depending on its distance from the engine face. For a distance of 80 ft. (location of current mirror configuration at MDSAT test site), the dimensions of the parabolic mirror were calculated to be 0.1 m (height) by 1 m (diameter). Figure 34 shows a 2D proposed diagram of the parabolic mirror.

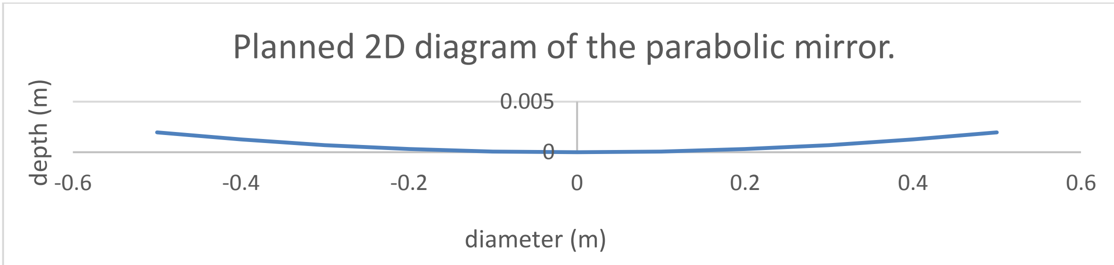

Figure 34. Calculated 2-D profile of the parabolic mirror [57] used with permission.

The mirror material was selected to be carbon fibre for its relatively low weight, high strength, corrosion resistance, and low cost of maintenance. If we set the desired wind speed rating to be equal to that of the H1 Heliostat reflectors (60 MPH [17]), CIC (Composites Innovation Centre) can perform analysis to determine the required thickness of the carbon fibre mirror. CIC can manufacture and test the mirror as well [58]. A disadvantage of using carbon fibre as the mirror material is high cost. Figure 35 shows a 3-D model of the custom mirror design, using the previously shown 2-D profile (Figure 34) derived in our analysis. The resulting shape is a paraboloid.

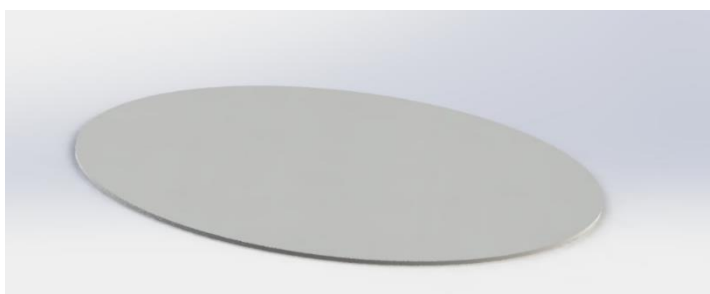

Figure 35. Model of the custom mirror [53] used with permission.

The custom mirror will utilize the existing mirror mounting system on H1 Heliostat shown in Figure 36. The left-hand side of Figure 36 shows that a plate is fastened to the mirror using an adhesive. The plate is connected to the frame using four screws (right-hand side).

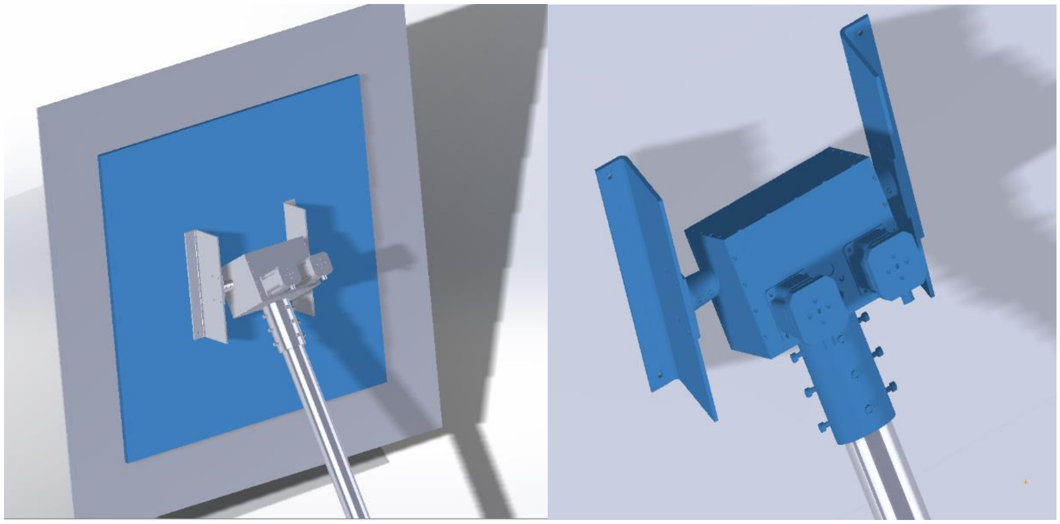

Figure 36. Heliostat frames that connect the mirror to the controller [11] used with permission.

The team recommends sending the dimensions of the Custom Mirror to CIC to be manufactured as well as tested. The full custom mirror design and analysis can be seen in APPENDIX B.

The Custom Mirror BOM and cost analysis are shown in TABLE XIX and TABLE XX respectively.

TABLE XIX

BOM FOR CUSTOM MIRROR

ITEM NO.	LEVEL	NAME	DESCRIPTION	TYPE	UNIT	IN ASSEMBLY/PART	QTY.
1	1	Custom Miror	Parabolic mirror	Purchase Part	1		1
2	2	Labour	For making the parabolic mirror	Labour	hr.	Custom Mirror	1

TABLE XX

COST ANALYSIS FOR CUSTOM MIRROR

ITEM	DESCRIPTION	QTY	UNIT COST	UNIT COST w/FACTORS	TOTAL COST	VENDOR	NOTES
Carbon fibre ply	Ply for laying up the custom mirror	19	$4.00	$76.00	$1,444.00	CIC	300 grams/square meter, 1 ply is 0.01" carbon fiber
Labour cost	Typical labour cost	40	$70.00	$70.00	$2,800.00	CIC	$70 / hour, assuming it takes 5 days, 8 hrs a day
				TOTAL	$4,244.00		

The custom mirror shape and material analysis are found in APPENDIX B. Further analysis is necessary to determine how many custom mirrors are required to illuminate the desired regions on the engine inlet.

6.2 H1 Heliostat Accessory: Variable Focus Mirror

A disadvantage of using a flat mirror is that it does not stop the sunlight from scattering [60]. To make light delivery more efficient the team recommends that MDSAT purchase and perform testing with the Vacuum Focus Mirror from LightManufacturing, an accessory for the H1 Heliostat. This product can be seen in Figure 37.

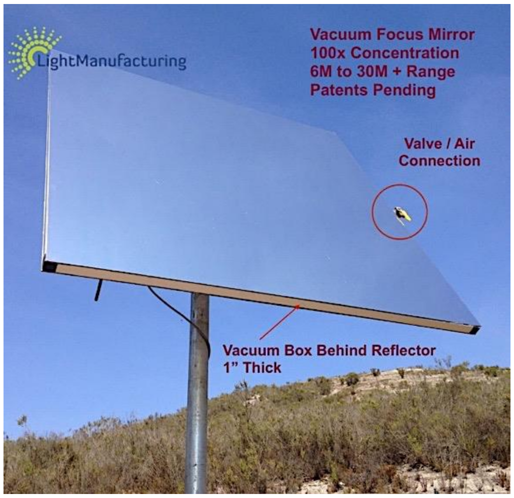

Figure 37. Vacuum Focus Mirror [61] used with permission.

The mirror is made of a rigid aluminum composite panel reflector with an air pressure chamber behind the reflector to create a pressure differential between the chamber and the atmosphere [61]. By adjusting the pressure in the chamber, the shape of the flat reflector changes to a shape that is very near a parabola to create a sharp circular focus area of light [61].

Using inexpensive vacuum pumps (hand-powered or electric) to adjust the focus, the focal distance can be adjusted from 6 m (20 feet) to 30 m (100 ft.) or more and it has focal spot size of 13 cm (5 inches) at 20 meters (65 feet) [61]. If desired, the reflector can be plastically deformed to a desired depth.

6.3 Renting Luminys Lights for Testing

Since lighting is a method known to require testing rather than analysis, Luminys offers rentals of their products for this purpose. The Luminys LED light can be rented daily for testing purposes. Our team highly recommends MDSAT perform testing to verify that four lights are needed to provide the required amount of light at the engine inlet before making any purchases regarding the LED lighting system.

6.4 Test Mount Structure

To allow for testing of different heliostat and LED light positions at the test site, our team has designs a Test Plate to be used in place of the Base plate with the Pole Mount structure

Figure 38. Test Mount with H1 Heliostat [62] used with permission.

The entire structure can be weighted down with concrete blocks at any desired test position that lies outside of the unsafe zone. Additional Base Pole components will have to be manufactured and welded to the test plates. Technical Drawings for the Test Mount structure are found in APPENDIX C.

The overall cost of the recommendations can be seen in TABLE XXI.

TABLE XXI

COST ANAYSIS FOR RECOMMENDATIONS

ITEM	DESCRIPTION	QTY	UNIT COST	UNIT COST WITH FACTORS	TOTAL COST	VENDOR	NOTES
TEST MOUNT STRUCTURE MATERIAL							
3/4 inch THICK A36 Steel Plate	For Test plate	1	$551.20	$833.41	$833.41	Metals Depot	1 USD = 1.35 CDN 11/15/16
3" OD x 0.313" Wall Mild Steel A513 Type 5 DOM	For bottom post	4	$135.88	$205.45	$821.80	Online Metals	1 USD = 1.35 CDN 11/15/16
Shipping		1	$1,000.00	$1,000.00	$1,000.00		Estimation for all shipping
TOTAL MACHINING							
Laser cutting (and Labour)	for base plate	4	$35.00	$35.00	$140.00		Estmated CNC Maching $70/hr.
Lathing (and Labour)	for top post	4	$35.00	$35.00	$140.00		Estmated CNC Maching $70/hr.
Milling (and labour)	For drilling holes	32	$8.75	$8.75	$280.00		Estmated CNC Maching $70/hr.
Welding (and labour)	Welding base plate to bottom post	4	$38.33	$38.33	$153.30		Estimated welding $0.35/in. +$35.00/hr
HARDWARE							
Zinc Yellow-Chromate Plated Hex Head Screw, Grade 8 Steel, 1/2"-13 Thread Size, 3-3/4" Long	For adjustability	2	$8.11	$12.26	$24.52	McMaster Carr	packages of 5
High-Strength Steel Nylon-Insert Locknut, Grade 8, Zinc Yellow-Chromate Plated, 1/2"-13 Thread Size	For containment	1	$4.31	$6.52	$6.52	McMaster Carr	package of 10
HELIOSTAT OPTIONS							
Variable Focus Mirror Upgrade	Testing	4	$395.00	$597.24	$2,388.96	LightManufacturing	
LED LIGHT OPTIONS							
SunSource1500Watt LED and power source	LED light and power source	4	$1,000	$1,000	$4,000		Rental of the LED light and the power source per day.
				TOTAL	$5,788.52		

A cost summary of the entire solution including the custom mirror and the recommendations is shown in TABLE XXII.

TABLE XXII

COST SUMMARY OF SOLUTION INCLUDING RECOMMENDATIONS

Product	Cost
Heliostat Lighting	$18,984.23
LED Lighting	$97,712.75
Custom Mirror	$4,244.00
Recommendations	$5,788.52
Total	**$126,729.50**

Although this total cost estimate is over the recommended budget of $100,000.00, we recommend that testing be performed with the Test Mount prior to installment of the Pole Mount Structures using the anchor bolts. The Test Mount will provide MDSAT with an idea of the response of the design in the actual operating environment, without having to fully implement the solution.

All designs, calculations, and technical drawings contained within this report are a product of our team's preliminary design. Engineering design is required to verify the details of each component before moving on to fabrication and testing. No design or drawing should be used without the consultation of a qualified, professional engineer.

7. CONCLUSIONS

Our design team was assigned the project of providing MDSAT a lighting solution for their Fan Waggle test. Due to limiting factors such as camera shutter speed and camera frame rate, we were constrained to using a light source that is sufficiently flicker-free and high intensity. Additionally, the engine unsafe zone, defined by a 50 ft. radius from the engine face, required our lighting system to be at least this distance from the engine inlet. Our team's design resulted in two solutions: one solution to be used during the day, and the other solution to be used at night.

The day-time solution utilizes the H1 Heliostat from LightManufacturing, mounted to a custom mount structure: the Pole Mount Structure. The Pole Mount Structure is designed to be anchored into the concrete using four structural bolts and is adjustable up to 15 inches in height. Our analyses shown that a total of four heliostat assemblies are required to illuminate the desired regions on the engine inlet.

The night-time solution utilizes the Luminys SunSource 1500 Watt LED Luminaire: a light consisting of an array of highly focused, high intensity LED lights. The Pole Mount Structure is dual-purposed to be utilized with the LED Light Assembly as well. The Luminys LED light is mounted to a custom mount called the LED Light Mount and is capable of dual-axis, adjustability. Our analyses revealed that four Luminys lights are required in order to illuminate the desired regions on the engine inlet.

Physical testing lies outside of the capabilities of our team and the determined scope of this project; however, our team has compiled a list of recommendations for MDSAT to implement during their testing of our solution in the proper operational environment. A custom mirror profile was designed by our team to be used with the H1 Heliostat.

A cost summary of the solution (excluding the cost of recommendations) is shown in TABLE XXIII.

TABLE XXIII

COST SUMMARY FOR SOLUTION

Product	Cost
Heliostat Lighting	$18,984.23
LED Lighting	$97,712.75
Total	**$116,696.98**

As seen in the cost summaries, each different solution option is over the recommended budget of $100 000.00. However, this amount was a recommendation rather than a fixed budget, and the decision to provide funding will not only depend on the solution cost, but on the quality of the solution as well. Our solution will provide MDSAT with the ability to test at night rather than only for a short period of time during a sunny day, potentially saving the engine OEM high inventory costs. The high cost can be attributed to the cost of on Luminys light, which was found to be the only light capable of meeting our design requirements. The quality of the lighting system and the value it will add to the Fan Waggle test at the GLACIER facility justify the high cost of the solution.

Our analyses show that our final solution meets all design requirements as well as our team goals of providing MDSAT with a solution that maximizes the testing window of time and providing a solution that is intuitive and easy to use and configure.

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APPENDIX A: CONCEPT SELECTION

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1. CONCEPT GENERATION

Our team approached concept generation by separating our search into external and internal searches. This flow can be seen in Figure A1.

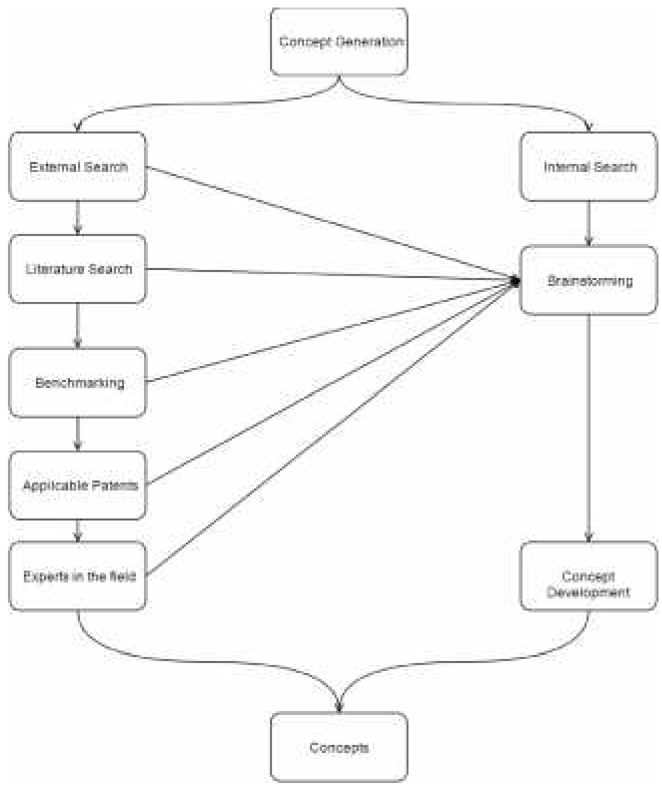

Figure A1. Concept exploration and generation methodology [1] used with permission.

Our external search includes different literature sources, benchmarks, patents, as well as talking to experts in the field. All of this collected information could be used independently or even within the internal search as inspiration. As seen in Figure A1, the external search results were integrated into the internal search.

1.1 Concepts

Using both internal and external research results, our team generated nine different concepts for analysis seen in Figure A2, Figure A3, Figure A4, Figure A5, Figure A6, Figure A7, Figure A8, Figure A9, and Figure A10 in TABLE A II, TABLE A III, TABLE A IV, TABLE A V, TABLE A VI, TABLE A VII, TABLE A VIII, and TABLE A IX respectively.

TABLE A I

CONCEPT A1: ICING TUNNEL

A1: Icing Tunnel		

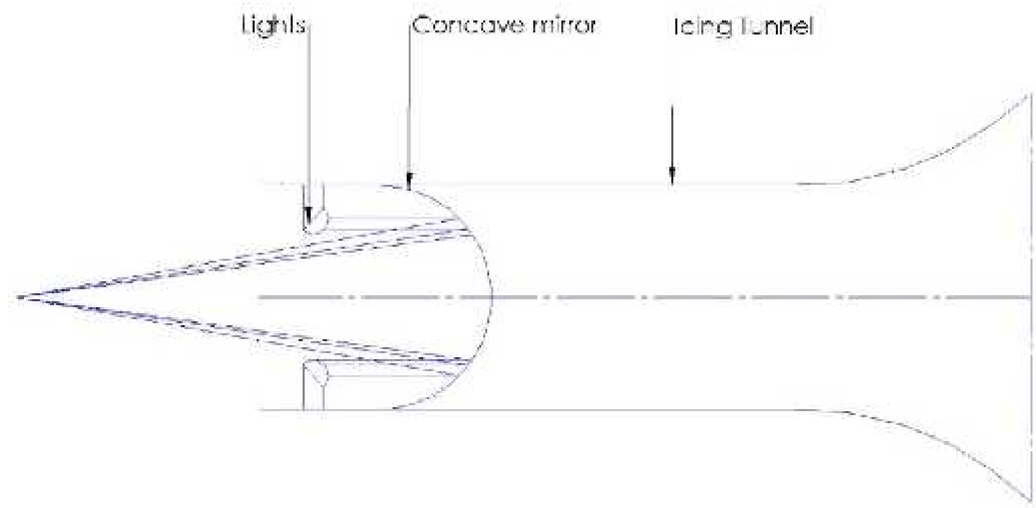

Figure A2. Icing tunnel concept [2] used with permission.

Pros:	Cons:	Risks:
- No need for communication - Light is always directed at the engine	- Lot of time to set up - High maintenance design	- Manufacturability - Increased wind forces due to nozzle effect

TABLE A II

CONCEPT A2: BOLTED TO ENGINE STAND

A2: Bolted to engine stand

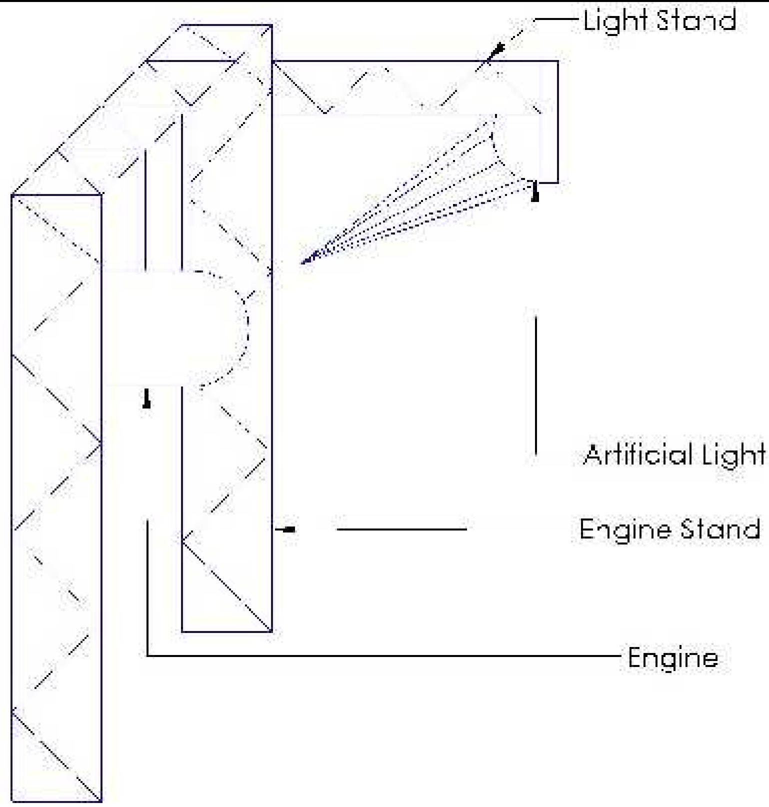

Figure A3. Bolted to engine stand concept [3] used with permission.

Pros:	Cons:	Risks:
- Higher light intensity - Easy to use	- High manufacturing cost - Long configuration time	- if the structure fails it can destroy the engine - Can ruin the intake airflow of the engine

TABLE A III

CONCEPT A3: LIGHT BEAM SINGLE STAND

A3: Light beam single stand

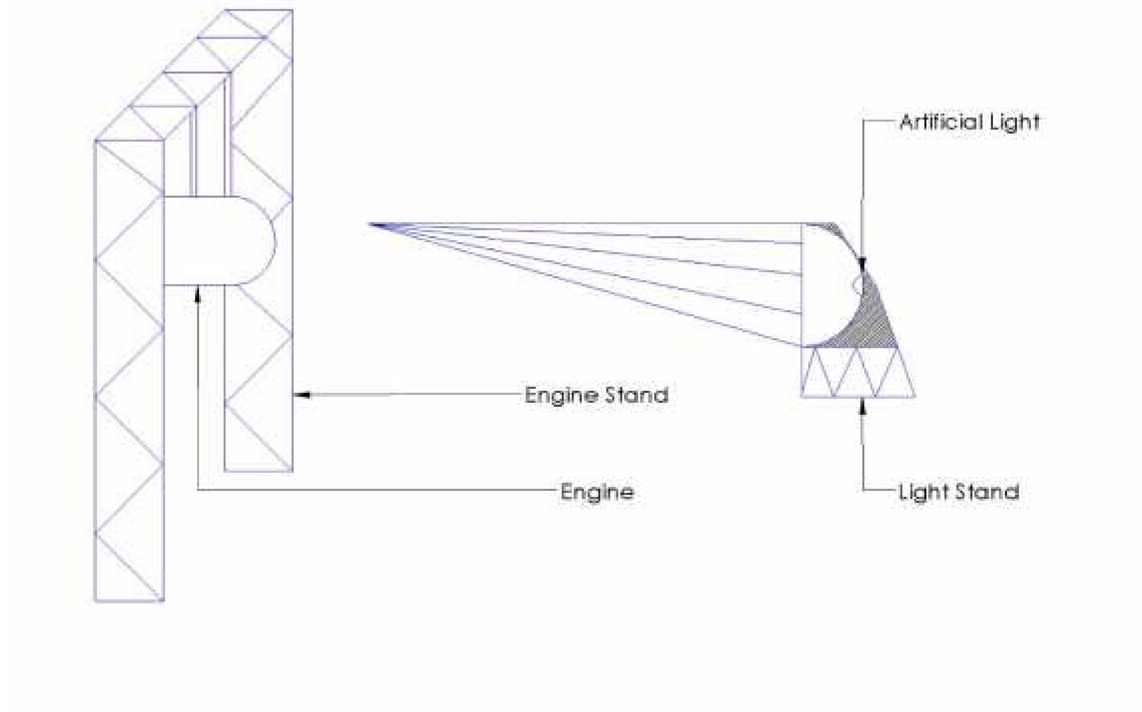

Figure A4. Light beam single stand [4] used with permission.

Pros:	Cons:	Risks:
• Independent of engine test rig and icing tunnel • Easy to use, put in storage, and transport	• Can not use in a full bright daylight • Different power voltage compare to MDSAT available Power outage • Lighting would be very expensive	• Might not be able to find sufficient artificial light source • Might only be able to use this in the dark (at night)

TABLE A IV

CONCEPT A4: SURFACE LIGHTING

A4: Surface Lighting

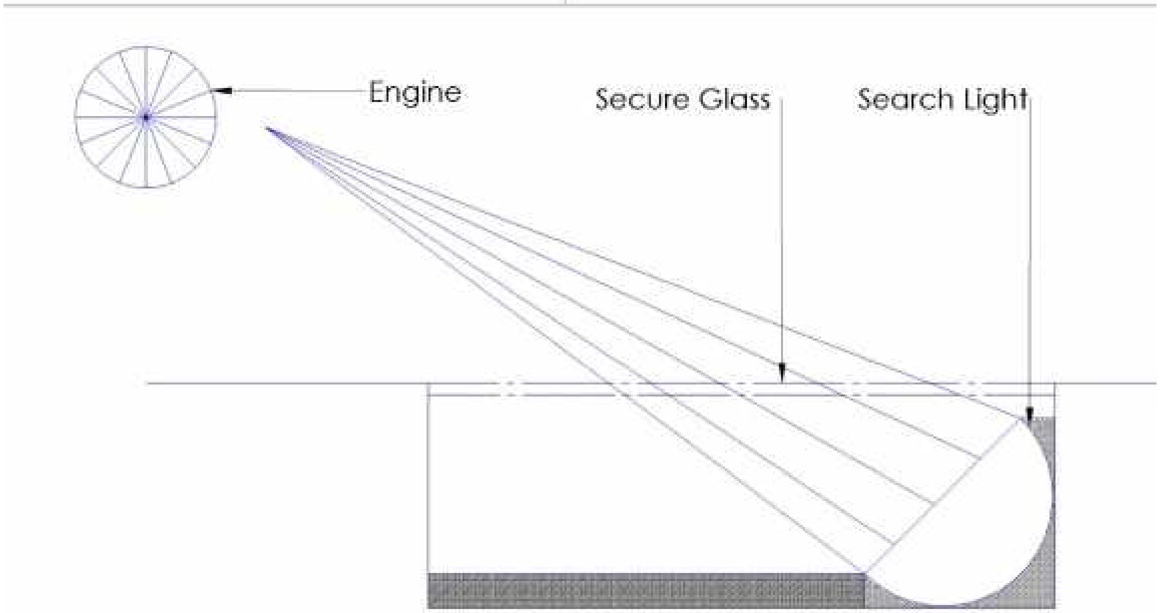

Figure A5. Surface lighting concept [5] used with permission.

Pros:	Cons:	Risks:
• Have a multiple light for multiple locations at the same time	• Lot of time to dig the system to the concrete • Not usable for a brightest sunlight	• Angle of entry of the light may not be functional

TABLE A V

CONCEPT A5: TOWER LIGHTING

A5: Tower Lighting

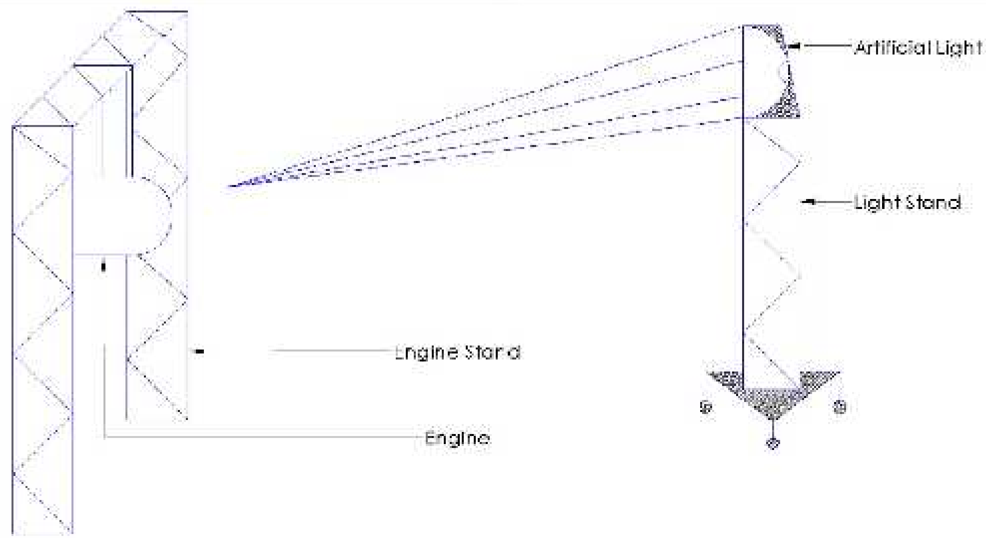

Figure A6. Tower lighting [6] used with permission.

Pros:	Cons:	Risks:
- Movable - Height can be configured	- Not usable for a brightest sunlight - Very tall - Lighting would be very expensive	- The height can be dangerous and cause it to fail (due to high windspeeds)

TABLE A VI

CONCEPT H1: THREADED ROD CONTROL

H1: Threaded rod control

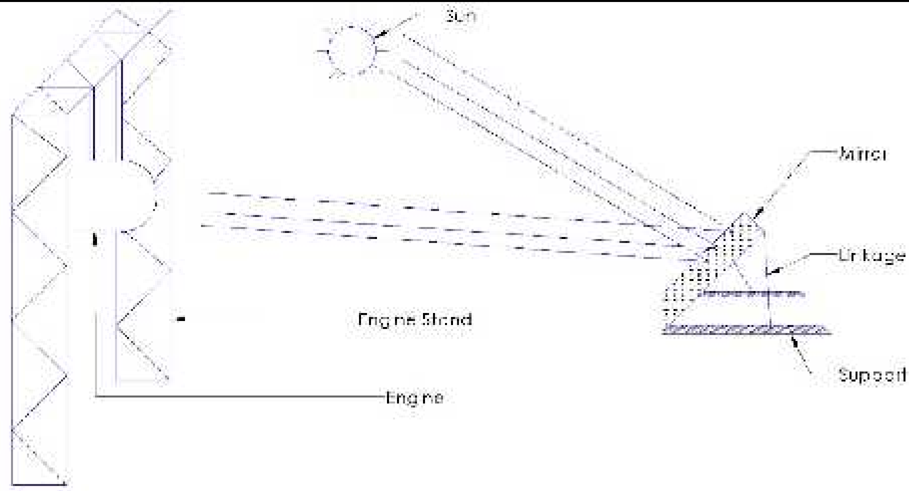

Figure A7. Threaded rod control concept [7] used with permission.

Pros:	Cons:	Risks:
• Easy to use (automated) • Easy to manufacture • Very simple	• Might not be very strong in the case of high windspeeds	• The mirror itself can be blown away with a higher engine RPM • Could result in engine damage if the mirror stand were to fail

TABLE A VII

CONCEPT H2: LINEAR ACTUATOR

H2: Linear actuator

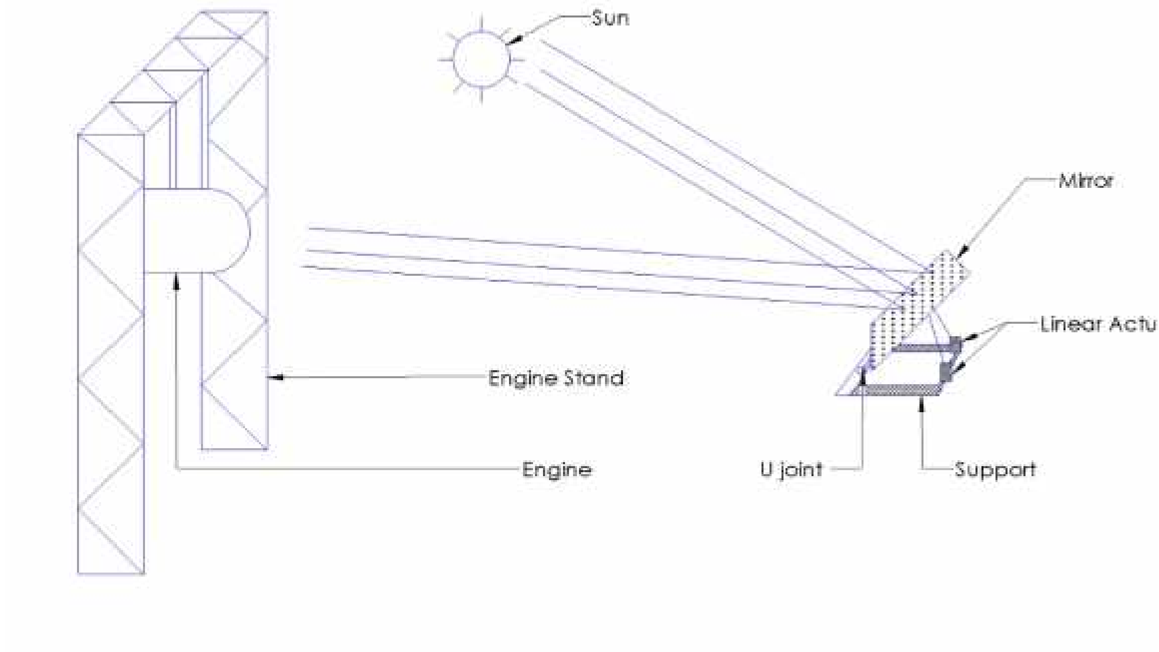

Figure A8. Linear actuator concept [8] used with permission.

Pros:	Cons:	Risks:
- Easy to use (automated) - Easy to manufacture - Very simple	- Might not be very strong in the case of high windspeeds	- The mirror itself can be blown away with a higher engine RPM - Could result in engine damage if the mirror stand were to fail

TABLE A VIII

CONCEPT H3: CONCAVE MIRROR WITH HOLE

H3: Concave mirror with hole

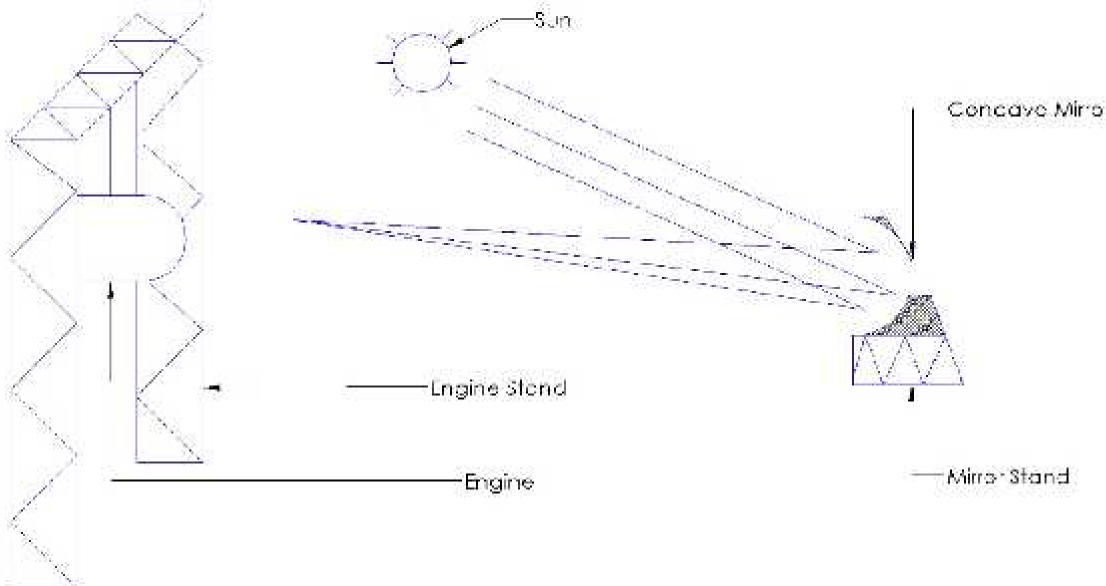

Figure A9. Concave mirror with hole concept [9] used with permission.

Pros:	Cons:	Risks:
• The hole would reduce the effects of high wind speeds • Concave shape would allow for brighter lighting • Automated	• Would not be able to be positions any where without changing the mirror as well	•

TABLE A IX

CONCEPT H4: LAZY SUSAN 1

H4: Lazy Susan 1

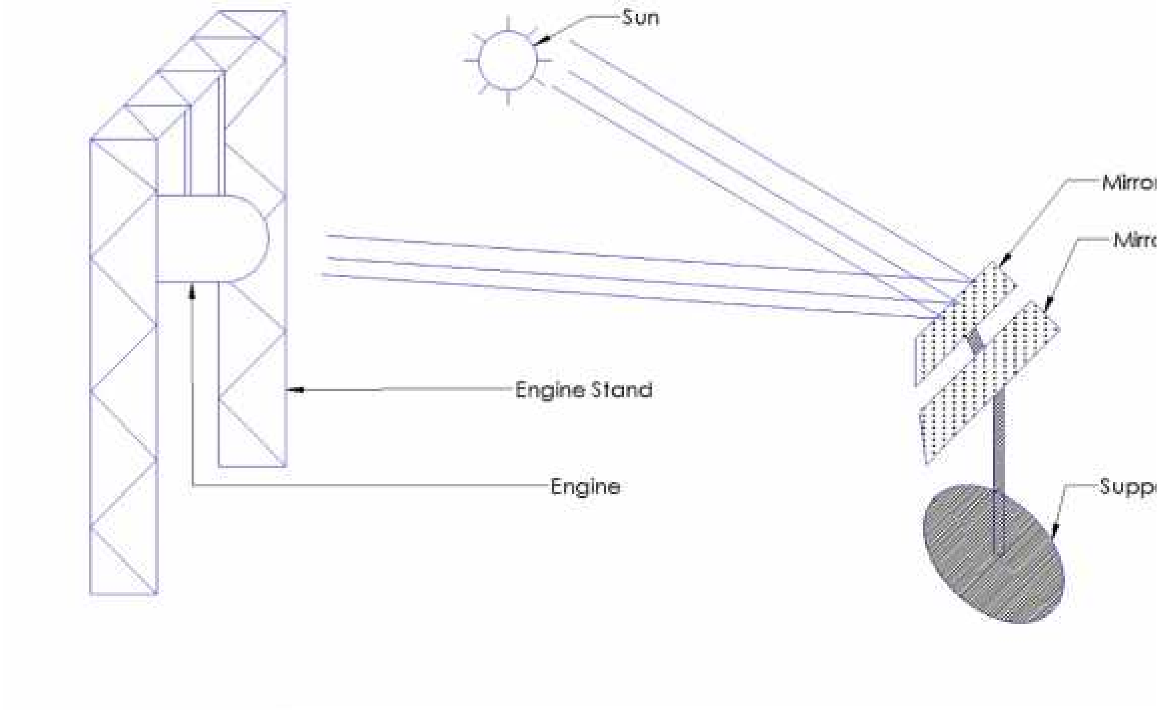

Figure A10. Lazy Susan 1 concept [10] used with permission.

Pros:	Cons:	Risks:
• Two-mirrors on one stand • Automated	• Requires entire base to move rather than just the mirror	• If mirrors cannot move indepently then they might be too far apart to be effective at focusing the light

Each of the concepts will pass through screening and scoring in order to finalize a concept for design.

2. CONCEPT ANALYSIS AND SELECTION

After knowing the base concepts to design, the team came up with nine concepts as explained in the previous section. TABLE A X shows the design number and the design name of each concepts.

TABLE A X

CONCEPT DESIGN NUMBERING

Design Number	Design Name
(reference)	Current Mirror Solution
A1	Icing tunnel
A2	bolted to the engine stand
A3	Light beam single stand
A4	surface lighting
A5	Tower lighting
H1	Threaded Rod Control
H2	Linear Actuator
H3	Concave mirror with hole
H4	Lazy Susan 1 (LS1)

To limit the number of concepts that pass through a final, thorough scoring process, first these nine concepts will pass through an initial screening.

2.1 Initial Screening

After creating nine concepts, the team screened each concept by classifying each concepts as much better (++), better (+), the same (0), worse (-), or much worse (--). The Pugh chart in TABLE A XI shows how the team screened each of the concepts with reference to MDSAT's current mirror system.

TABLE A XI

DETAILED CONCEPT SCREENING

		Concept Variant								
Selection Criteria	Ref	A1	A2	A3	A4	A5	H1	H2	H3	H4
Author		CB	KD	KD/RR	HY	HY	CB	CB	KD	RR
Cost	0	--	--	--	--	--	-	-	--	-
Safety	0	+	+	0	+	+	0	0	0	+
Ease of use	0	0	+	+	+	+	+	+	+	+
Mobility	0	---	0	+	0	+	-	+	+	+
Durability	0	+	+	+	+	-	+	0	-	+
Rigidity	0	+	+	+	+	-	0	0	0	+
Adaptability	0	-	+	0	-	0	0	0	-	0
Sufficient light intensity	0	0	+	+	+	0	0	0	+	0
Easy to maintain	0	-	-	-	-	-	-	-	-	-
Total	+	3	6	5	5	2	2	2	3	5
Total	0	2	1	2	1	2	4	5	2	2
Total	-	7	3	3	4	5	3	2	5	2
	Net	-4	3	2	1	-3	-1	0	-2	3
	Rank	9	1	3	4	8	6	5	7	1
	Continue?	NO	YES	YES	YES	NO	YES	YES	NO	YES

From the Pugh chart in TABLE A XI, the top six design concepts are as follows:

- bolted to the engine stand
- Light beam single stand

- surface lighting
- threaded rod control
- linear actuator
- lazy susan 1

In order to better judge these remaining concepts, further assessment will use the customer needs statements from TABLE A XII as selection criteria.

TABLE A XII

CUSTOMER NEEDS

Need Number	Customer Need
N1	The lighting system provides sufficient light intensity to obtain effective, high-quality, useable images
N2	Light targets the blades in the 12:00 region as well as the 9:00 region on the engine (from pilot's orientation)
N3	The lighting system is cost effective
N4	Light is uniformly distributed throughout the illuminated region
N5	The lighting system is capable of being used for a wide range of sun positions
N6	A sufficient proportion of incident light is effectively reflected toward the imaging sensor
N7	The lighting system has manual override capabilities
N8	The lighting system is outside of the unsafe zone and object-free zone (radius of 50 ft from engine inlet)
N9	The lighting system can meet future fan imaging needs
N10	The lighting system requires minimal maintenance
N11	The lighting system is long lasting
N12	The lighting system is durable and adequate for environmental conditions
N13	Structure is static, stable and rigid under influence of all external forces
N14	The lighting system can be quickly setup and configured
N15	The lighting system is intuitive and easy to use
N16	The lighting system features a modular design
N17	The lighting system is safe for both people and the test engine
N18	The lighting system is manufacturable (allows for tolerances)
N19	The lighting system must operate with sufficiently low flicker

2.2 Criteria Weighting

Before the team scored the designs, we defined the weight for each need statements by comparing each using a pair-wise weighting matrix. TABLE A XIII shows a sample of one team member's results from filling out the matrix.

TABLE A XIII

SELECTION CRITERIA WEIGHTING

Need	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19
N1		N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1	N1
N2			N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2
N3				N4	N3	N6	N7	N8	N3	N3	N3	N12	N13	N3	N3	N3	N17	N18	N19
N4					N4	N6	N7	N8	N4	N4	N4	N12	N13	N4	N4	N4	N17	N18	N19
N5						N6	N7	N8	N5	N5	N5	N12	N13	N5	N5	N5	N17	N18	N19
N6							N6	N6	N6	N6	N6	N6	N6	N6	N6	N6	N17	N6	N6
N7								N8	N7	N7	N7	N12	N13	N7	N7	N7	N17	N7	N19
N8									N8	N8	N8	N8	N8	N8	N8	N8	N17	N8	N19
N9										N10	N11	N12	N13	N14	N15	N16	N17	N18	N19
N10											N11	N12	N13	N14	N15	N10	N17	N18	N19
N11												N12	N13	N14	N15	N11	N17	N18	N19
N12													N13	N12	N12	N12	N17	N12	N19
N13														N13	N13	N13	N17	N13	N19
N14															N14	N14	N17	N18	N19
N15																N15	N17	N18	N19
N16																	N17	N18	N19
N17																		N17	N19
N18																			N19
N19																			
	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19
Total Hits	18	17	7	8	6	15	10	13	0	2	3	11	12	5	4	1	15	9	15
Weight (%)	10.5	9.94	4.09	4.68	3.51	8.77	5.85	7.60	0.00	1.17	1.75	6.43	7.02	2.92	2.34	0.58	8.77	5.26	8.77
Rank	1	2	12	11	13	3	9	6	19	17	16	8	7	14	15	18	3	10	3

Three team members filled out the pair-wise weighting matrix and each of the results were compiled. To begin analyzing the gathered data, our team decided to average the weights to see how the results would represent each of our individual weightings of importance. TABLE A XIV shows the average pair-wise matrix from the three members who did the pair-wise matrix.

TABLE A XIV

RESULTS FROM EACH CRITERIA WEIGHTING

Needs	CB	HY	KD	Average	Rank
N1	10.53%	9.94%	7.02%	9.16%	2
N2	9.94%	9.36%	7.02%	8.77%	3
N3	4.09%	1.75%	2.92%	2.92%	14
N4	4.68%	4.68%	8.19%	5.85%	9
N5	3.51%	4.09%	5.26%	4.29%	11
N6	8.77%	8.77%	8.19%	8.58%	4
N7	5.85%	5.85%	1.75%	4.48%	10
N8	7.60%	6.43%	10.53%	8.19%	5
N9	0.00%	1.17%	4.09%	1.75%	18
N10	1.17%	2.92%	1.75%	1.95%	16
N11	1.75%	2.34%	2.92%	2.34%	15
N12	6.43%	7.02%	5.26%	6.24%	8
N13	7.02%	7.60%	8.77%	7.80%	7
N14	2.92%	1.17%	1.75%	1.95%	16
N15	2.34%	2.34%	4.68%	3.12%	13
N16	0.58%	0.58%	3.51%	1.56%	19
N17	8.77%	10.53%	8.77%	9.36%	1
N18	5.26%	5.26%	0.00%	3.51%	12
N19	8.77%	8.19%	7.60%	8.19%	5

TABLE A XIV shows that the top three needs are N17 (the lighting system is safe for both people and the test engine), N1 (The lighting system provides sufficient light intensity to obtain effective, high-quality, useable images), and N2 (Light targets the blades in the 12:00 region as well as the

9:00 region on the engine from pilot's orientation.) The team agreed that the average of the weight results was reasonable. By meeting Need 17, the lighting system should be stable and rigid enough to withstand any external forces (N13).

2.3 Concept Scoring

Once the relative weights of each need had been generated, we proceeded to establish a thoroughly considered comparative rating on a five point scale. In all cases, ratings were established one need at a time. For any given need, the matrix shown in TABLE A XV works such that a given concept's rating number, out of five, is only meaningful relative to the associated ratings of the other concepts for that same need. This implies that the meaning in rating is found in the differential values between each concept. For each need, each concept was scored with this understanding in mind, placing them relative to each other in performance for that needs nature. The needs associated with the highest weights result in the greatest sensitivity to the differential rating values. As such, the highly weighted needs were given the most time in consideration and were done first. All members of the team reviewed the results, and adjustments were made until all members expressed satisfaction. To aid in the process of observing the rating numbers for each need, a streamlined table was first used linking only the necessary data of need, concept and weight value.

TABLE A XV

CONCEPT SCORING MATRIX AND RESULTS

		bolted to the engine stand		HMI single stand		surface lighting		Threaded Rod Control		Linear Actuator		Lazy Susan 1 (LS1)	
Need Number	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
N1	9.16%	5	0.458	4	0.366	4	0.366	3	0.275	3	0.275	3	0.275
N2	8.77%	4	0.351	4	0.351	4	0.351	4	0.351	4	0.351	4	0.351
N3	2.92%	2	0.058	3	0.088	0	0	4	0.117	4	0.117	4	0.117
N4	5.85%	2	0.117	4	0.234	2	0.117	4	0.234	4	0.234	4	0.234
N5	4.29%	5	0.215	5	0.215	5	0.215	2	0.086	2	0.086	3	0.129
N6	8.58%	4	0.343	3	0.257	2	0.172	3	0.257	3	0.257	3	0.257
N7	4.48%	2	0.09	3	0.134	2	0.09	4	0.179	4	0.179	4	0.179
N8	8.19%	2	0.164	5	0.41	4	0.328	5	0.41	5	0.41	5	0.41
N9	1.75%	2	0.035	3	0.053	2	0.035	3	0.053	3	0.053	3	0.053
N10	1.95%	4	0.078	3	0.059	2	0.039	2	0.039	3	0.059	3	0.059
N11	2.34%	4	0.094	4	0.094	3	0.07	3	0.07	4	0.094	4	0.094
N12	6.24%	4	0.25	4	0.25	3	0.187	3	0.187	3	0.187	4	0.25
N13	7.80%	4	0.312	4	0.312	4	0.312	3	0.234	3	0.234	4	0.312
N14	1.95%	2	0.039	4	0.078	3	0.059	3	0.059	3	0.059	3	0.059
N15	3.12%	5	0.156	4	0.125	5	0.156	3	0.094	3	0.094	3	0.094
N16	1.56%	0	0	2	0.031	0	0	2	0.031	2	0.031	5	0.078
N17	9.36%	2	0.187	3	0.281	4	0.374	2	0.187	2	0.187	3	0.281
N18	3.51%	3	0.105	4	0.14	1	0.035	2	0.07	3	0.105	3	0.105

		bolted to the engine stand		HMI single stand		surface lighting		Threaded Rod Control		Linear Actuator		Lazy Susan 1 (LS1)	
Need Number	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
N19	8.19%	4	0.328	3	0.246	3	0.246	5	0.41	5	0.41	5	0.41
	Total score		3.38		3.72		3.15		3.34		3.42		3.74
	Rank		4		2		6		5		3		1
	Absolute percentile of perfection		67.57		74.43		63.01		66.82		68.38		74.85

.

The results produced substantially higher values for two of the designs; one of the artificial source concepts along with one of the heliostat reflector designs. Errors due to high sensitivity in ratings were primarily mitigated by means of thorough evaluation and re-examination of our judgment pertaining to the rating values.

3. CONCEPT SELECTION AND RECOMMENDATIONS

As stated from the previous section, the top three designs were Light Beam Single Stand, Linear Actuator, and Lazy Susan 1. Figure A11 shows a model of the light beam single stand; Figure A12 shows a model of the Linear Actuator, and Figure A13 shows a model of the Lazy Susan 1.

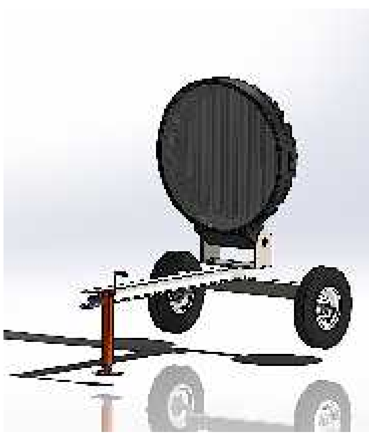

Figure A11. Light beam single stand model [11] used with permission.

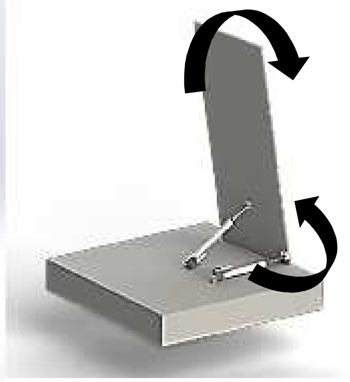

Figure A12. Linear actuator [12] used with permission.

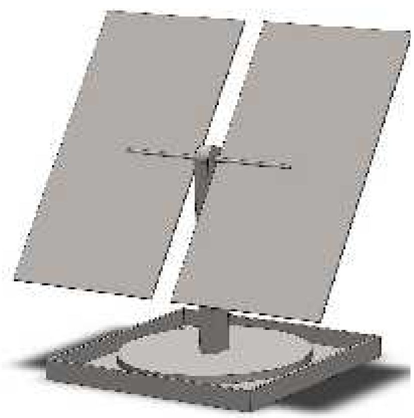

Figure A13. Lazy Susan 1 [13] used with permission.

These three concepts each are relatively simple and have a small footprint. After speaking with Rick from MDSAT about the selected concepts he had initially shown interest in the Lazy Susan 1. However, he was still interested in an artificial lighting solution and wanted us to pursue both. We as the design team, were honest with our limitation and expressed concern with the scope of the work suggested. Our team worked together with Rick to refine the scope and decided that the best course of action was to source a commercial heliostat for day-time use, rather than have us design a custom one. We could also then look into sourcing an artificial lighting solution to utilize at night.

4. REFERENCES

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[5] H. Yeganeh." Surface lighting concept. " Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 27, 2016.

[6] H. Yeganeh."Tower lighting." Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 27, 2016.

[7] H. Yeganeh." Threaded rod control." Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 27, 2016.

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[9] H. Yeganeh." Concave mirror with hole." Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 27, 2016.

[10] H. Yeganeh." Lazy Susan 1 concept." Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 27, 2016.

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[12] C. Benga." Linear actuator concept model." Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 25, 2016.

[13] R. Rechik." Lazy Susan 1." Winnipeg: Design Eng., University of Manitoba, Winnipeg, Manitoba, October 23, 2016.

APPENDIX B: ANALYSIS OF FINAL DESIGN

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LIST OF FIGURES

LIST OF TABLES

1. HELIOSTAT

Material properties for AISI 1020 are found in TABLE B I.

TABLE B I

MATERIAL PROPERTIES OF AISI 1020 STEEL [1]

Elastic Modulus	205 GPa
Poisson's Ratio	0.29
Mass Density	7870 kg/m^3
Tensile Strength	420 MPa
Yield Strength	350 MPa

There material properties will be used for both analytical and numerical calculations.

1.1 Analytical Results

Failure modes considered were yielding, buckling, and fatigue. Analysis was performed on the anchor bolts using CSA standard.

1.1.1 Yielding

The entire structure was thought of as a cantilever beam with a rigid support. The forces applied onto the support structure were derived from the 60 MPH wind speed rating for the H1 Heliostat [2]. Since the mirror is constrained to a position outside of the unsafe zone of the engine, no additional airspeed effects were considered. Since we are already assuming that the H1 Heliostat can, in fact, withstand wind speeds up to 60 MPH in any direction, and that that rating would be sufficient enough for our application, then we are also assuming that the force effects from a 60 MPH wind will be a maximum value for the support structure analysis. From a wind speed to pressure conversion chart, the 60 MPH wind speed was converted to 464.8 Pascals which equals 9.71 lbf/ft^2 [3].The mirror dimensions of the H1 Heliostat is a 48 inch square which has an area of 16 ft^2. Using the full area of the mirror will result in a maximum force value. From the full area of the mirror, and the pressure from the wind speed on the mirror, the force applied at the very top of the center post support equals 155.36 lbf. The bending loading scenario can be seen in Figure B1

Figure B1. Bending loading scenario for support structure [4] used with permission.

The shear force throughout the structure can be seen in Figure B2. The internal shear force throughout the entire structure is 155 lbf. The moment diagram for the support structure can be seen in Figure B3. The greatest internal moment is seen at the base with a moment of 10 385 lbf-in.

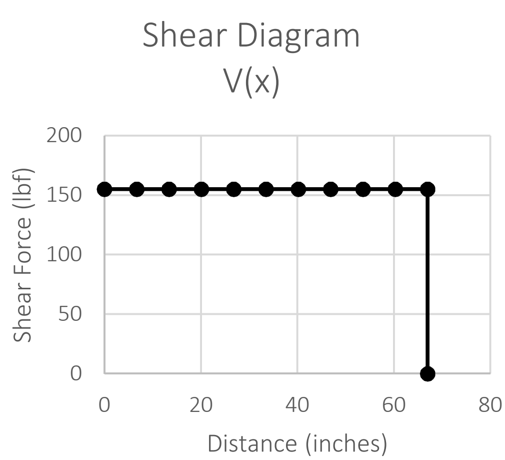

Figure B2. Shear diagram for bending structure [5] used with permission.

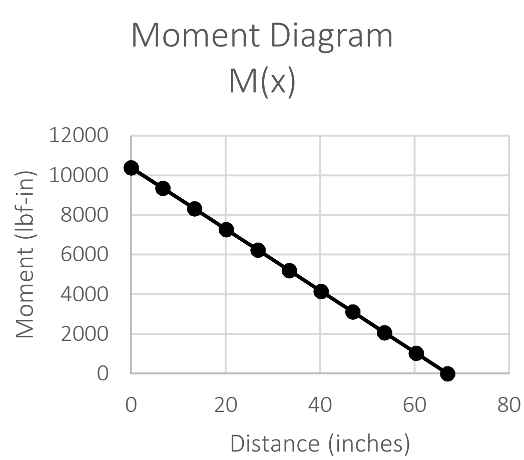

Figure B3. Moment diagram for bending in structure [6] used with permission.

The support structure also sees a torque from possible uneven loading on the heliostat reflector. The same maximum force value was used to calculate the torque. The distance used is from the centre of the mirror to the very edge which can be seen at Figure B4.

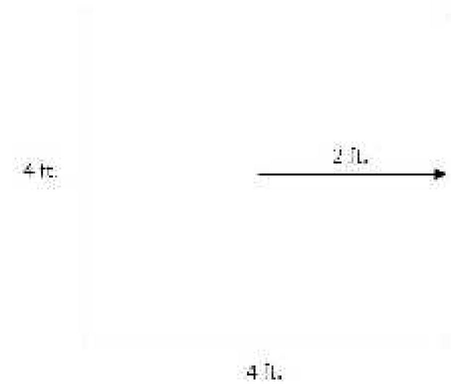

Figure B4. Mirror dimensions [7] used with permission.

The derived torque is equal to 310.7 lbf-ft. and can be visualized using Figure B5.

Figure B5. Torque loading scenario for support structure [8] used with permission.

The weight of the heliostat is 45 lbs. [2] which causes a load in the negative y-direction as shown in Figure B6.

Figure B6. Compression loading scenario for support structure [9] used with permission.

Now to determine if the structure will fail due to yielding we will analyze it at a location of high stress relative to the rest of the structure. This would be the base of the structure which has the greatest internal moment depicted by the red square in Figure B7.

Figure B7. High stress area for analysis [10] used with permission.

The state of stress at this location of interest can be characterized by a 3-dimensionsal cube as shown in Figure B8.

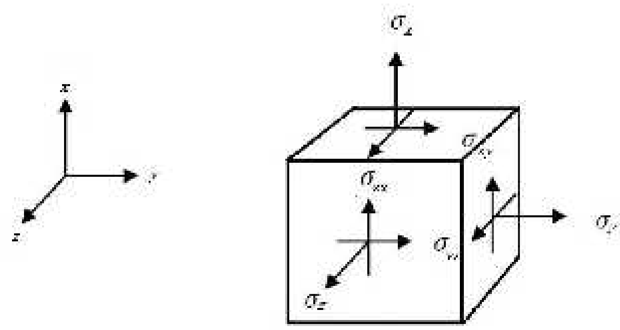

Figure B8. State of stress [11] used with permission.

The equations used to calculate the state of stress at the location of interest are shown in TABLE B II.

TABLE B II

EQUATIONS USED TO CALCULATED STATE OF STRESS

Moment of inertia	$I = \frac{\pi\left(r_C^4 - r_i^4\right)}{4}$	$r_C = o$ r $r_i = in$ r
Polar moment of inertia	$J = \frac{\pi\left(r_C^4 - r_i^4\right)}{2}$	
Normal stress due to bending	$\sigma = \frac{M}{I}$	$M = b$ m $y = d$ f n a
Shear stress from torsion	$\tau = \frac{T}{J}$	$T = a$ t $c = r$ d f c
Normal Stresses due to axial loading	$\sigma = \frac{F}{A}$	$F = a$ a f $A = a$ o c $- s$

The results of the calculations are shown in TABLE B III.

TABLE B III

STATE OF STRESS AT HIGH STRESS LOCATION

σ_x	0 MPa
σ_y	44.4 MPa
σ_z	0 MPa
σ_x	26.1 MPa
σ_x	0 MPa
σ_y	0 MPa

Using a graphical method to solve for the principal stresses, the following plot was obtained and can be seen in Figure B9.

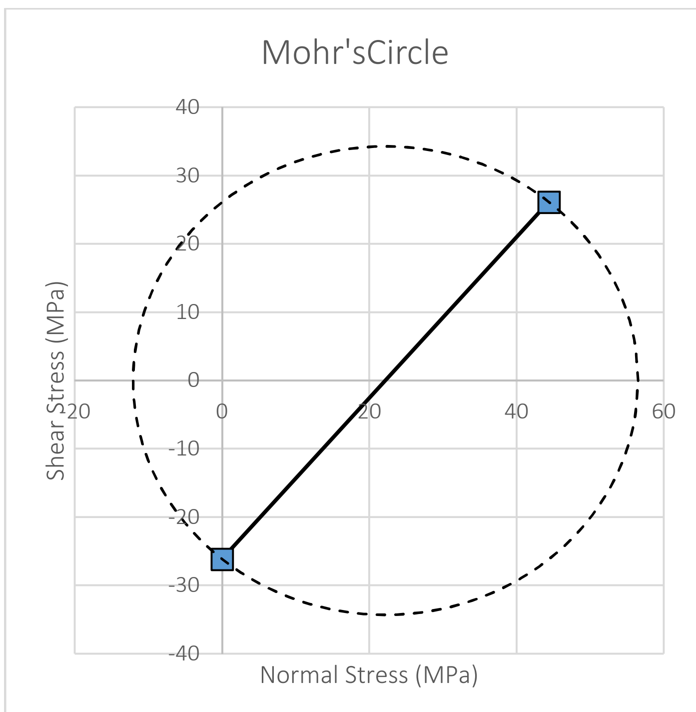

Figure B9. Mohr’s circle for the state of stress at location of interest [12] used with permission.

The results for the principal stresses are seen in TABLE B IV.

TABLE B IV

PRINCIPAL STRESSES

σ_1	56.5 MPa
σ_2	-12.1 MPa
σ_3	0 MPa

The yield criterion is the maximum von Mises stress calculated using Equation (1).

$$\sigma_y = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}} \quad (1)$$

$$\sigma_y = 63.4\ M$$

To achieve a safety factor of 2, the maximum von Mises stress cannot exceed half of the yield strength from TABLE B I. The allowable stress to achieve a safety factor of 2 is 175 MPa which is greater than the maximum von Mises stress calculated. Therefore, the structure will not fail due to yielding.

1.1.2 Buckling

The critical buckling load was found using Equation (2).

$$P_c = \frac{n^2\pi^2 E}{L^2} \quad (2)$$

$$P_c = \frac{(1)^2\pi^2(205\ G\quad)(6.37 \times 10^{-7} m^{-4})}{(1.6\ m)^2}$$

$$P_c = 4.06 \times 10^5 N > 100\ 000\ N$$

Since the critical buckling load is much greater than the actual applied load the mount structure will not fail due to buckling.

1.1.3 Fatigue

Most steels have a fatigue limit of about have of their tensile strength [13]. In our case that would be 87.5 MPa. Since the maximum von Mises stress is less than that, the structure should not fail due to fatigue. However, the structure does have a slender shape with a relatively heavy load at the very top of the structure. Physical testing should be performed in the actual operational environment to determine true vibration effects that could occur due to wind loading such as resonance.

1.1.4 Bolt Analysis

The analysis for the anchor bolts determine that a headed bolt is recommended as the most efficient type anchorage to use for both tension and shear loads. Figure B10 shows the shear and tension loads on bolts. Anchor bolt design ductility is assured by causing a failure mechanism that is controlled by yielding of the anchor bolt steel, rather than brittle tensile failure of concrete. This is can be accomplished by designing the pullout strength of the concrete failure cone, U_p.

Figure B10. Tension and shear of bolts [14].

In order to specify size and length for the headed bolts required to anchor the heliostat mount structure, we need to consider some design input based on our existing requirements. These inputs can be seen in TABLE B V.

TABLE B V

BOLT SPECIFICATION INPUTS

Base Material	
Description	Non- cracked concrete
Thickness	>200 mm
Concrete strength $f'_{c,cyl}$	> 20 MPa
Anchors layout	
Number of anchors	4
Edge distance – c	>150mm
Spacing- S_1-S_2	178 mm
Plate area	254×254 mm
Applied Loads	
Tension – N_{Sd}	35 kN
Shear-V_{Sd}	1 kN

The base plate has been chosen to be 7 inches in width and length. By having an applied force of 155lbf on the pole we find the moment on the bolts using Equation (3).

$$M = \frac{w\,L^2}{2} \qquad (3)$$

$$M = \frac{156\ \times 5.42'^2}{2} = 2291\ ll \quad - f$$

The tension can be found using the calculated moment and Equation (4).

$$T = \frac{M}{d} \qquad (4)$$

$$T = \frac{2291}{0.292} = \ 7855\ ll \quad o \quad 35\ K$$

The shear force on all bolts can be found using Equation (5).:

$$F_{she\ \ r_{t}} \quad = 156 \times 5.42 = 846\ li \qquad (5)$$

The shear on each individual bolts is:

$$F_{she} \quad = \frac{846}{4} = 212\ li \quad o \quad 1\ K$$

The theory explains that for four headed bolts used as anchors, there will be tension on two bolts, and compression on the other two. So Tension of 35 KN will distribute to two headed bolt which will gives us load of 17.5 KN for each individual. By considering a safety factor of 2 for our design, will conclude the tension on each individual bolt would be 35 KN.

When sourcing headed bolts we have to make sure that our design can meet the Canadian Standards Association (CSA) requirements. In this case our design has to follow design parameters shown in TABLE B VI and TABLE B VII These parameters are based on CSA requirements.

TABLE B VI

DESIGN PARAMETERS FOR NOMINAL ANCHOR BOLT SIZE M12 [14].

Design parameter	Symbol	Units	Value
Effective embedment depth	$h_{ef,min}$	mm	80
Concrete material resistance factor for concrete	ϕ_c	-	0.65
Steel embedment material resistance factor for reinforcement	ϕ_S	-	0.85
Yield strength of anchor steel	f_y	MPa	640
Ultimate strength of anchor steel	f_{ut}	MPa	800
Effective cross section area of anchor	A_{se}	mm^2	84.5
Factored steel resistance in tension	N_{sr}	KN	46
Factored Steel resistance in shear	V_{sr}	KN	41.8

TABLE B VII

DESIGN PARAMETERS FOR NOMINAL BOLT SIZE M8 [14].

Edge Distance, Spacing and member Thickness Requirements	Symbol	Units	Value
Minimum Concrete thickness	h_{min}	mm	160
Critical Edge distance	C_{ac}	mm	120
Minimum edge distance	C_{min}	mm	90
Minimum anchor spacing	S_{min}	mm	80

HILTI Canada group is ta company who provides products for construction, building maintenance, and mining industry. We chose their products because their products meet CSA requirements for design. As we know MDSAT will assemble heliostats for summer testing and disassemble them for winter so they will need removable anchors, by referring to HILTI handbook, HSL-3Heavy Duty Sleeve Anchors would be the best option. The Hilti HSL-3 Heavy Duty Sleeve Anchor is a torque-controlled expansion bolt designed for high performance in static and dynamic application, including the tension zone of concrete structure where cracking can be expected. HSL-3 anchors are available in metric sizes from M8 to M24. With a variety of head configurations, including bolt, stud and torque cap. All versions are available in zinc-plated carbon steel. TABLE B VIII shows the design specifications for the specified bolts.

TABLE B VIII

DETAILS AND SPECIFICATION FOR SIZE M12 HSL-3 ANCHOR BOLTS

Design Specification	Symbol	Unit	Value
Nominal drill bit diameter	d_{bit}	mm	18
Minimum base material thickness	h	mm	160
Minimum hole depth	h_o	mm	105
Effective embedment depth	$h_{ef,min}$	mm	80
Minimum clearance hole diameter	d_h	mm	20
Maximum thickness of part fastened	t	mm	25
Overall length of anchor		mm	131
Washer diameter	d_w	mm	30
Installation Torque	T_{inst}	Nm	80

TABLE B IX shows the parameter for the selected bolt size.

TABLE B IX

FACTORED RESISTANCE FOR FOUR EQUALLY SPACED HSL-3 ANCHORS SUBJECT TO TENSILE LOAD

Size	h_{ef} (mm)	h_{min} (mm)	V_{sgr}- Shear strength of Anchor (KN)	N_{sr}- Tension strength of Anchor Group (KN)	Spacing S (mm)	C-edge distance min (mm)
M12	80	160	167.2	184.0	200	150

In conclusion a minimum depth of 200 mm is required for the bolt length with a minimum edge distance of 150 mm for the bolt holes and spacing distance of 200m.

1.2 Numerical Results

Numerical Finite Element Analysis (FEA) was performed on the Pole Mount Structure in two configurations. On study used just the Base assembly and the other considered the entire assembly.

1.2.1 Base Post

FEA was performed on the base post with the goal of determining the minimum required base thickness as well as the minimum required weld size. For the purposes of simulating a weld, a fillet was used. Figure B11 shows the initial mesh plot for the base post.

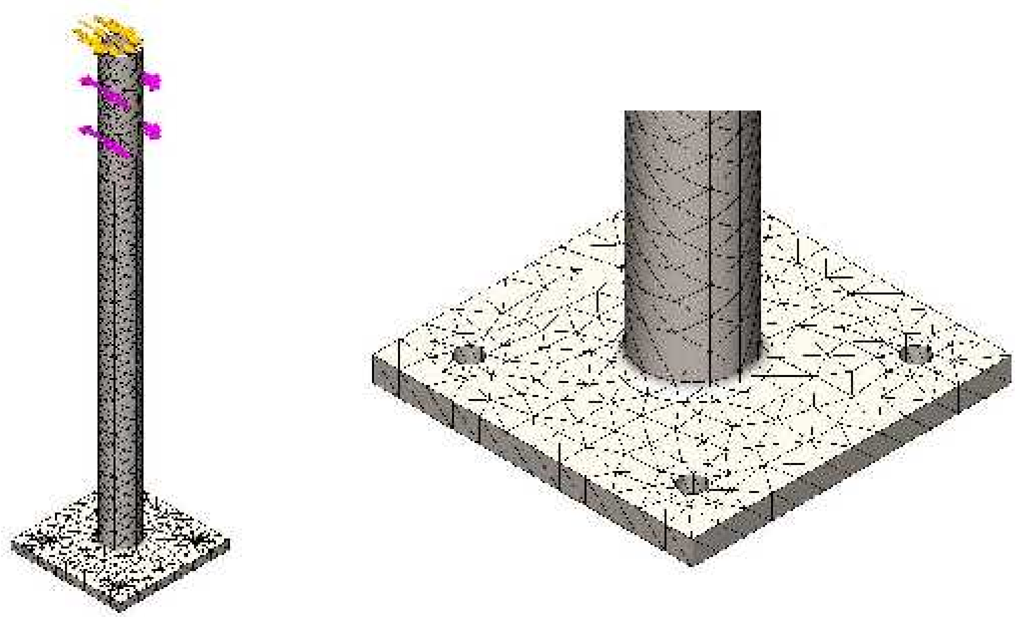

Figure B11. Overview of initial mesh details for base post analysis [15] used with permission.

TABLE B X shows the initial mesh plot details for the base post analysis.

TABLE B X

INITIAL MESH DETAILS FOR BASE POST

Jacobian points	4 points
Element size	22.2268 mm

Tolerance	1.11134 mm
Total nodes	9406
Total elements	4678

As the base will be secured using bolts screwed into asphalt anchors, the entire base was fixed at each of the bolt holes shown in Figure B12.

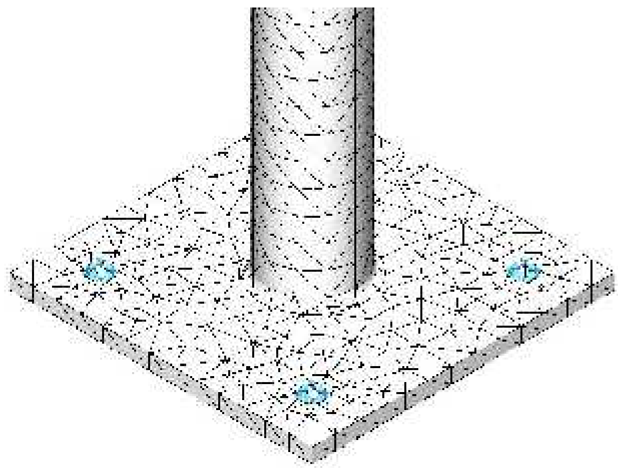

Figure B12. Fixtures at the bolt holes for base post analysis [16] used with permission.

Since we are not analyzing the entire structure and only the base of the base post, an equivalent force was derived from the previously calculated force of 155.36 lbf.

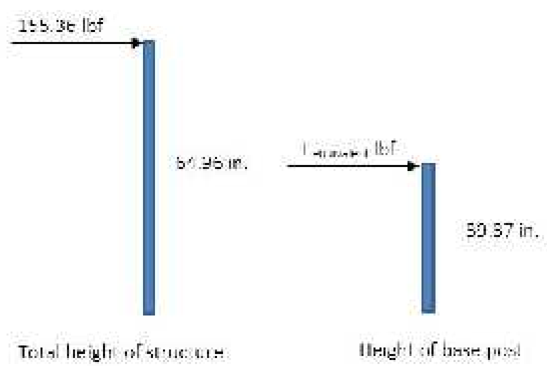

Figure B13. Equivalent moments diagram [17] used with permission.

Setting the moments equal to one another, the equivalent force was determined to be 256.2 lbf which can be rounded to 260 lbf for simplicity.

A torque was anticipated and included in the base post analysis from the wind being applied more to one side of the mirror than the other. This was previously calculated to be 310 lbf-ft which is equal to 3728.6 lbf-in.

The force is applied at the very top of the base structure and the torque is applied at the bolt holes shown in Figure B14.

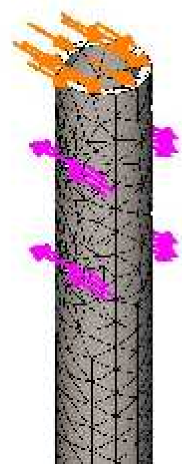

Figure B14. Force and torque applied on base post [18] used with permission.

The study conducted used h-adaptive convergence to validate results. Target accuracy was set to 99%. The target accuracy was set to 99% and mesh coarsening was turned on to eliminate unnecessary mesh refining at areas that have already converged.

The study ran 9 iterations after which the target accuracy of 99% was not reached, however a target accuracy of over 97% for total strain energy was reached and therefore these results will be considered acceptable. The adaptive study convergence plot can be seen in Figure B15.

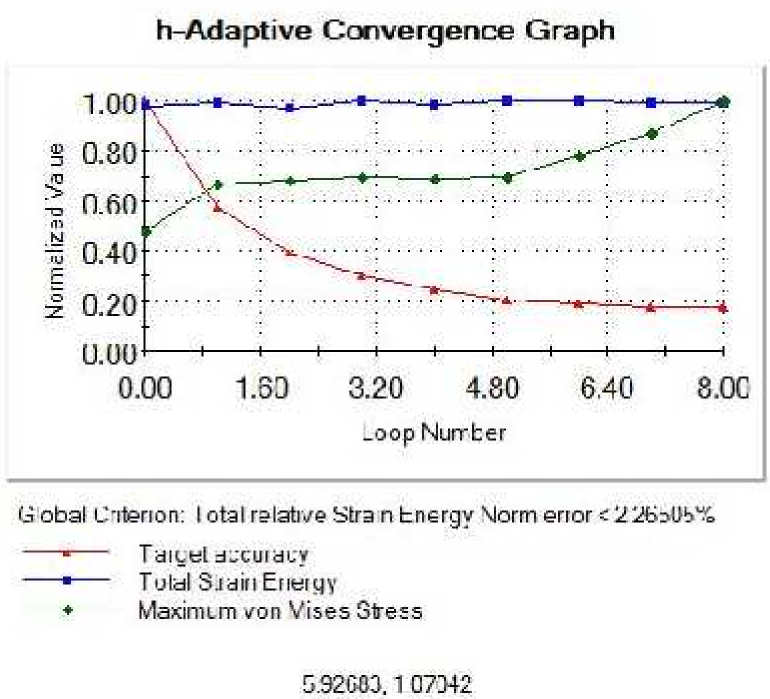

Figure B15. H-adaptive convergence plot for base post analysis [19] used with permission.

It should be noted that the maximum von Mises Stress did not converge and this is due to the sharp geometries that were left in the model to save meshing time between iterations.

The chart maximum is set to the maximum allowable stress to achieve a safety factor of 2: 175 MPa. As can be seen in Figure B16, the majority of the structure has a much higher safety factor than 2 with stresses around 15.4 MPa and also shows a close-up view of the filleted area which is an area of high stress relative to the rest of the model. The fillet size was chosen to be the same thickness as the thinnest width of the two welded pieces: 0.313 in.: the width of the tube. This fillet size is sufficient for realizing a safety factor of 2 with maximum stresses around 113.7 MPa.

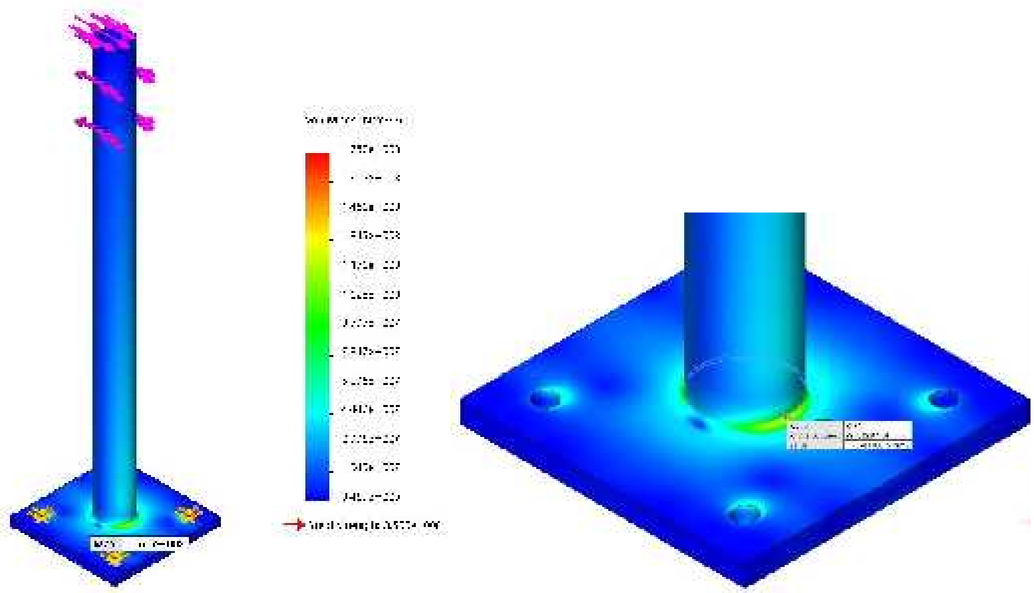

Figure B16. Contour plot of stress results – close view of fillet [20] used with permission.

The numerical value obtained at the fillet is close to the analytical value obtained at the same location.

Numerical	Analytical	% error
113.7	63.4	79.3 %

Discrepancies can be attributed to the study not reaching 99 % convergence and the model containing sharp geometries.

Figure B17 shows a close up of the stress distribution near one of the bolt holes. This another location of high stress in the model however the stresses are still below the allowable stress at around 167 MPa. The plate thickness equals 0.75 inches.

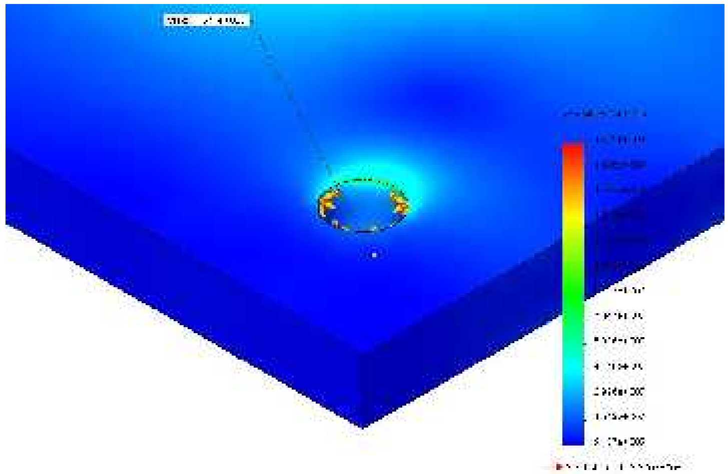

Figure B17. Contour plot of stress results – close view of bolt hole in base [21] used with permission.

All model features satisfy a safety factor of 2.

Figure B18 shows the displacement results in an exaggerated view with a deformation scale of 38.15. The base of the structure is quite rigid. The top of the structure sees the most deformation of approximately 2.67 mm.

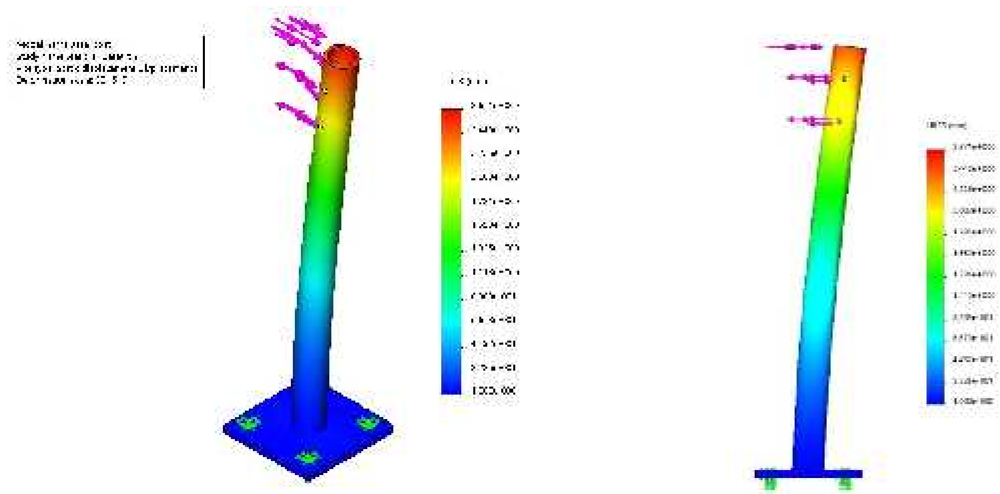

Figure B18. Contour plot of displacement results for the base post analysis [22] used with permission.

There is no minimum deformation requirement however, in order to increase the performance of the structure, vibrations should be minimized. If a 2.67 mm maximum deflection at maximum load allows for too much vibrations that it affects the heliostat performance, then our team recommends to shorten the base post height to decrease the moment applied to the Pole Mount Structure.

Figure B19 shows the final mesh plot of the h-adaptive study.

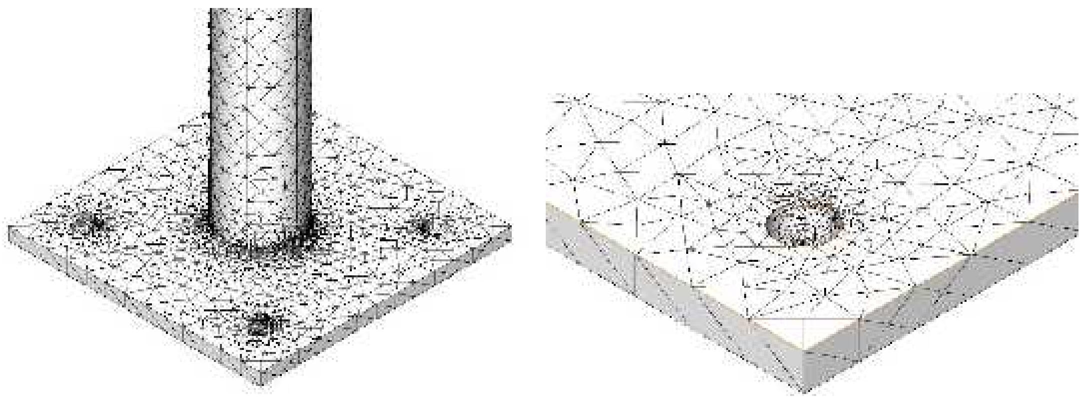

Figure B19. Final mesh plot of the base post analysis [23] used with permission.

TABLE B XI shows the final mesh plot details for the h-adaptive study.

TABLE B XI

FINAL MESH PLOT FOR BASE POST ANALYSIS

Jacobian points	4 points
Element size	22.2268 mm
Tolerance	1.11134 mm
Total nodes	107716
Total elements	65975

The results of the numerical study show that the structure requires a minimum fillet size of 0.313 in. between the base plate and the post and that the minimum plate thickness required of 0.75 inches.

1.2.2 Numerical Results: Pole interfaces

A FEA study was also performed on the interfaces between the two poles with the goal of determining if the tube thicknesses were sufficient. Initially, FEA was conducted on standard, galvanized fence posts however they were found to be insufficiently strong for the application. Instead, cold-rolled AISI 1020 steel was used because of its strength, weldability, and relatively low cost. A model was constructed specifically for the purpose of FEA in which the entire structure is one solid piece of material. The areas of focus for this study are where the poles meet which is simulated by the removal of material with the same dimensions as if they were two separate pieces meeting.

A similar initial mesh was used as in the previous study.

A force of 155 lbf was applied at the top of the structure and a torque was anticipated and included in the base post analysis from the wind being applied more to one side of the mirror than the other. This was previously calculated to be 310 lbf-ft which is equal to 3728.6 lbf-in. The torque was also applied at the top of the structure. Final, the weight of the heliostat is 45 lbs. which was applied as a downward force onto the structure. Figure B20 shows the forces and the torque applied at the top of the structure.

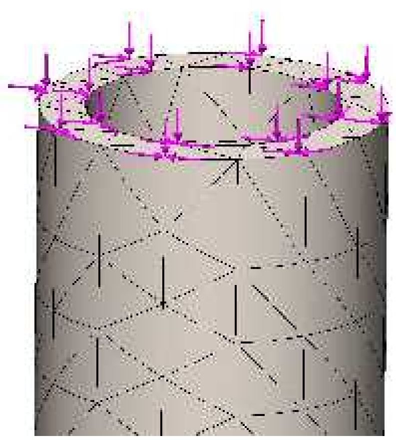

Figure B20. Force and torque applied on structure [24] used with permission.

The study conducted used h-adaptive convergence to validate results. The target accuracy was set to 99% and mesh coarsening was turned on to eliminate unnecessary mesh refining at areas that have already converged. The study ran 9 iterations after which the target accuracy of 99%

was not reached, however a target accuracy of over 98% for total strain energy was reached and therefore these results will be considered acceptable.

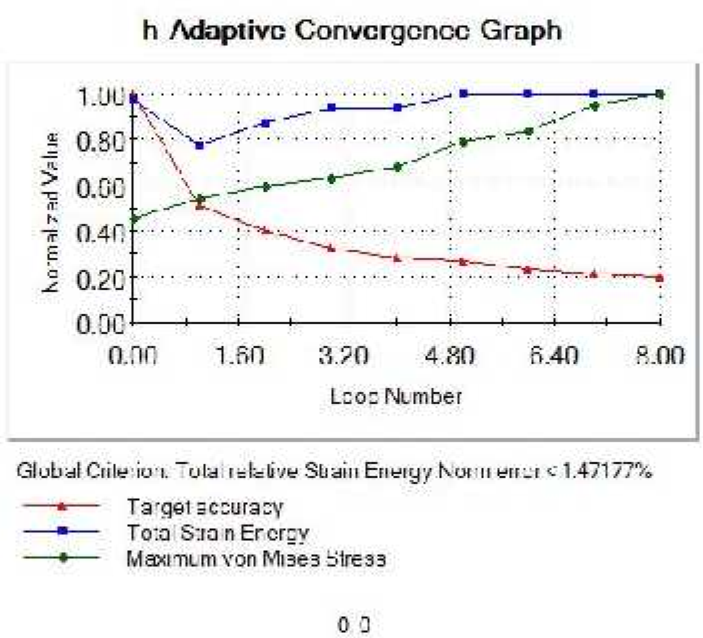

Figure B21. H-adaptive convergence plot for pole interface analysis [25] used with permission.

It should be noted that the maximum von Mises Stress did not converge and this is due to the sharp geometries that were left in the model to save meshing time between iterations.

The chart maximum is set to the maximum allowable stress to achieve a safety factor of 2: 175 MPa. As can be seen in Figure B22, the majority of the structure has a much higher safety factor than 2 with stresses around 15.4 MPa. Figure B22 shows a close up of the filleted area which is an area of high stress relative to the rest of the model. The stresses around the fillet are approximately 131 MPa which coincides with the previous numerical study.

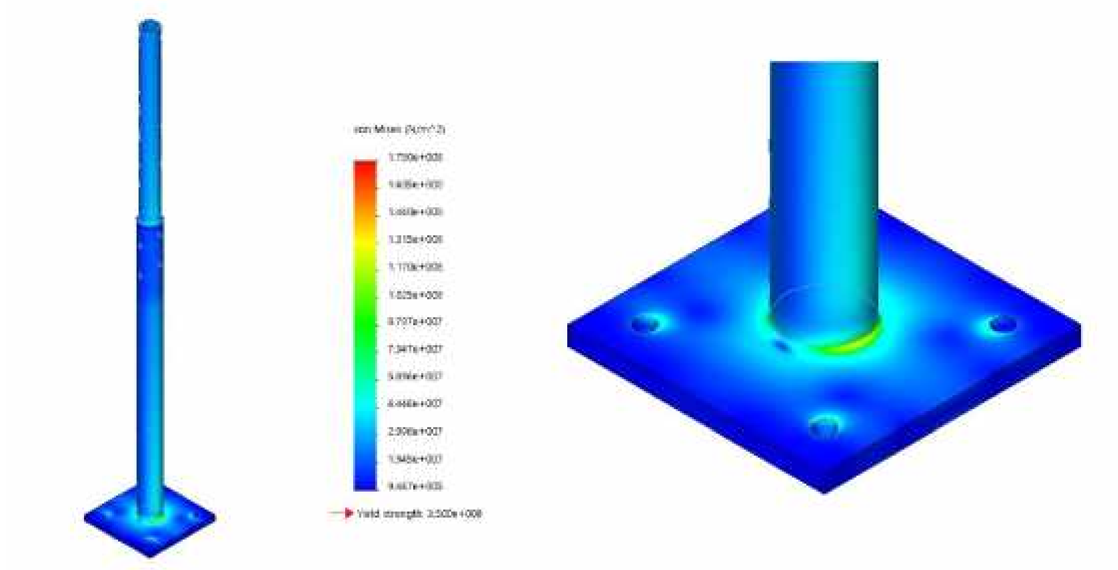

Figure B22. Contour plot of stress results – close view of fillet [26] used with permission.

Figure B23 shows a close up of the stress distribution at the pole interfaces. These are e the areas of focus for this study as they are anticipated areas of high stress. Stresses are still below the allowable stress at around 102 MPa for the top interface and about 58 MPa for the lower interface.

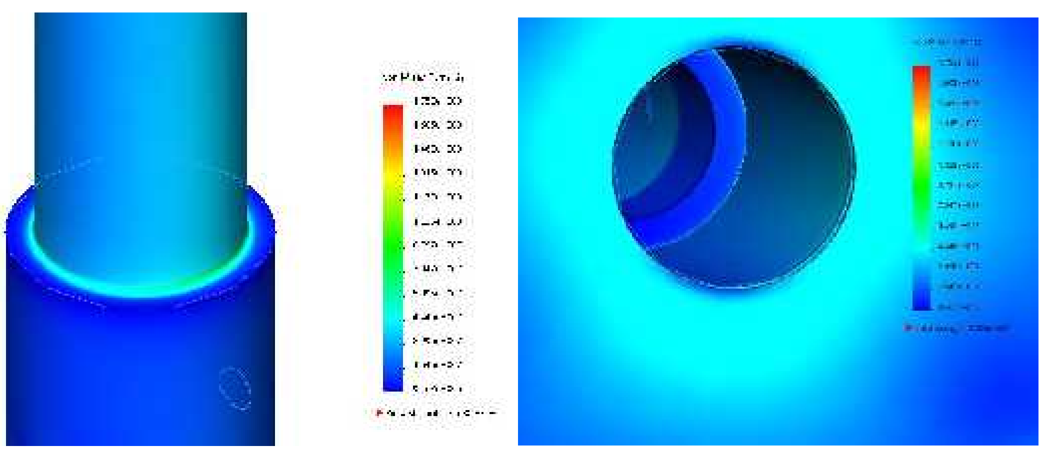

Figure B23. Contour plot of stress results – close view of pole interfaces [27] used with permission.

All model features satisfy a safety factor of 2.

Figure B24 shows the displacement results in an exaggerated view with a deformation scale of 24.84. The base of the structure is quite rigid. The top of the structure sees the most deformation of approximately 6.72 mm.

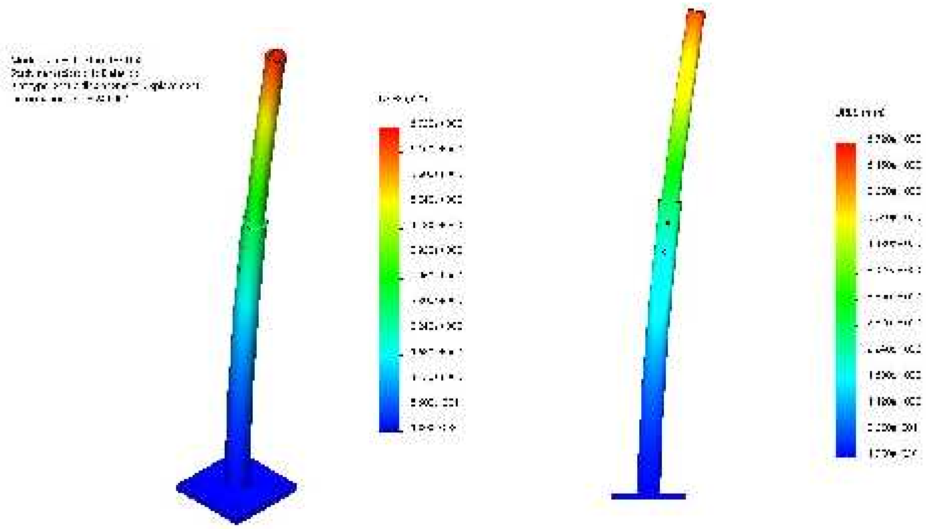

Figure B24. Contour plot of displacement results for the base post analysis [28] used with permission.

There is no minimum deformation requirement however, in order to increase the performance of the structure, vibrations should be minimized. If a 6.72 mm maximum deflection at maximum load allows for too much vibrations that it affects the heliostat performance, then our team recommends using a shorter height setting the structure provides.

The final mesh is similar to the previous study. The results of the numerical study show that the size and thickness of the nominal tube sizes are of sufficient strength for our application.

1.3 Tolerances and Finishing

The stock tube sizes for the Pole Mount Structure result in the OD of the sliding post and the ID of the base post being equal. To allow for ease of sliding, it was determined that the sliding post have a clearance of least 0.003 in. with a tolerance of +/- 0.0015 in. off of the radius [29]. It was also determined, after welding, to galvanize each of the structure components which can add around 0.003 inches of thickness to a wall. Therefore, the sliding post should be turned down on a lathe 0.006 inches off of the radius. The galvanized coating will provide protection against corrosion for outdoor environments. It is also recommended to purchase zinc-coated hardware.

2. CUSTOM MIRROR DESIGN

Both a shape, and material analysis were performed for the custom mirror design.

2.1.1 Mirror Shape Analysis

A flat reflector cannot be 100% smooth and therefore will cause the reflected light to scatter in many different directions. By changing the shape of the mirror profile, a focal point can be created where both light and energy are amplified. Figure B25 shows how the spherical mirror focuses.

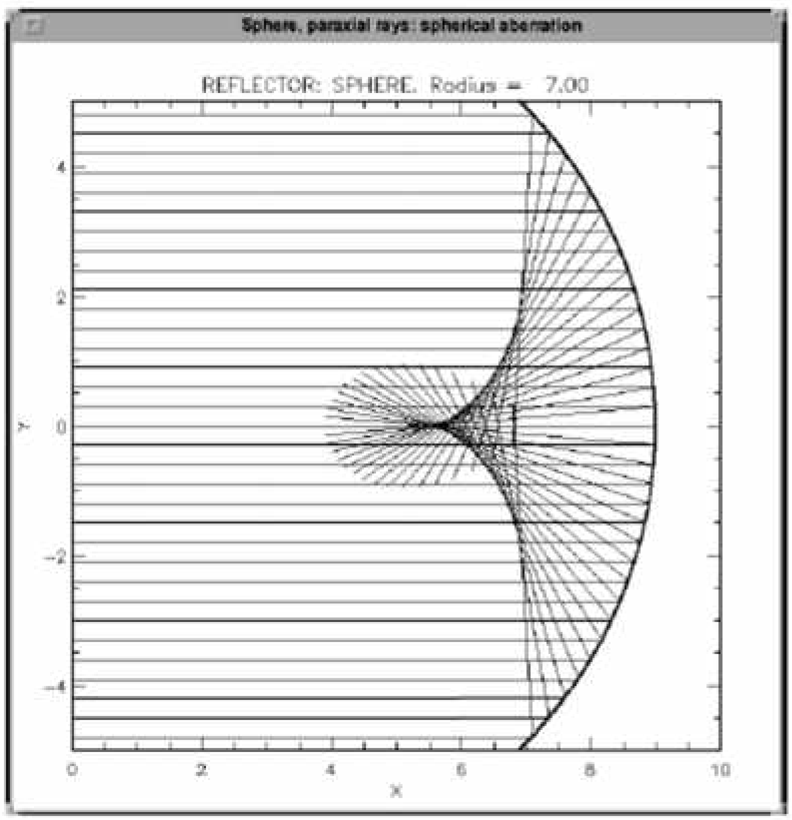

Figure B25. Image of the reflected rays of a spherical mirror [30] used with permission.

One disadvantage of a spherical mirror is that it creates spherical aberration: where the reflected rays have different focal points. This is not ideal for illuminating the engine with a uniform distribution of the sunlight. Figure B26 shows how the directed incident rays reflect off a parabolic shape.

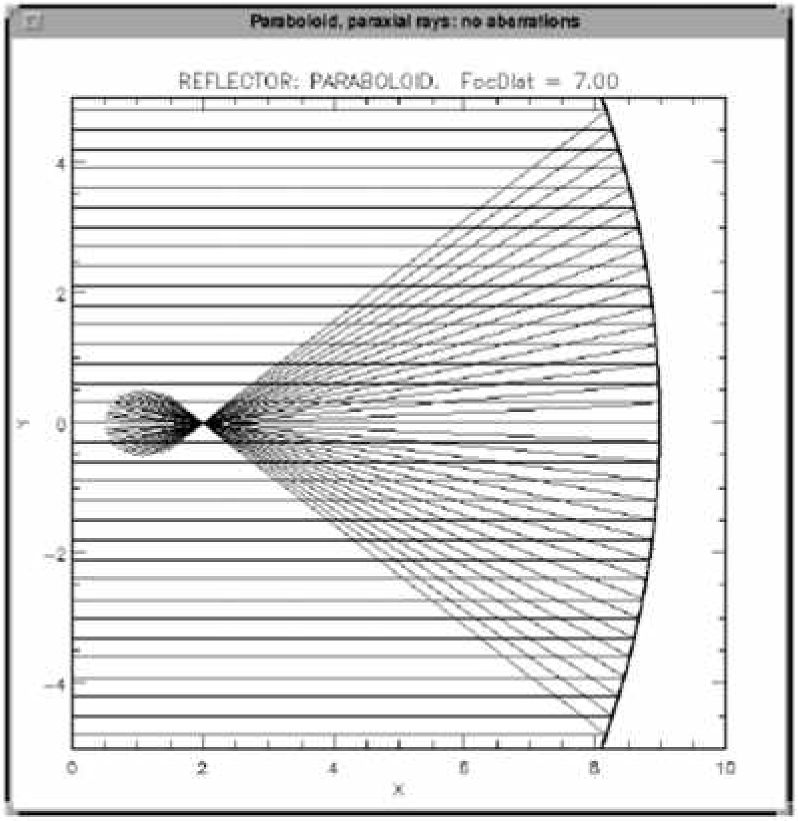

Figure B26. Image of the Reflected Rays of a Parabolic Mirror [30] used with permission.

The parabolic mirror reflect the parallel incident light rays to a single focal point in front of the mirror. This can be used to increase the light intensity at the test engine. A parabola was chosen as the ideal mirror shape for its ability to create a single focal point. The circular mirror profile was rejected due to spherical aberration.

To find the focal point of the parabolic mirror, consider a parabola that is described by the Equation (6) [30]

$$y = Ax^2 \qquad (6)$$

For some positive constant, A, then $d\ \ /d\ \ = 2A$. Inserting these results into Equation (7) gives the following result for the focal length: [30].

$$f = Ax^2 + \frac{x(1 - 4A^2x^2)}{4A} = \frac{1}{4A} \qquad (7)$$

The results for different dimensions for different areas relating to different focal length are shown in TABLE B XII.

TABLE B XII

RESULTS FOR PARABOLA DIMENSIONS FOR DIFFERENT FOCAL LENGTHS

Plot Name	Direct Distance to Engine (m)	A	X values (m)	Y values (m)
Y	28.04211119	0.008915163	-2	0.03120893
			-1	0.007802232
			0	0
			1	0.007802232
			2	0.03120893
Y2	32.57852053	0.007673768	-2	0.027338449
			-1	0.006834612
			0	0
			1	0.006834612
			2	0.027338449
Y3	37.23385556	0.006714319	-2	0.024251916
			-1	0.006062979
			0	0
			1	0.006062979
			2	0.024251916
Y4	41.96855966	0.00595684	-2	0.021753999
			-1	0.0054385
			0	0
			1	0.0054385
			2	0.021753999
Y5	46.75852863	0.005346618	-2	0.019701123
			-1	0.004925281
			0	0
			1	0.004925281
			2	0.019701123
Y6	51.58837078	0.004846053	-2	0.017989374
			-1	0.004497344
			0	0
			1	0.004497344
			2	0.017989374

By graphing the values in TABLE B XII the shapes of the parabolas can be visualized and are shown in Figure B27.

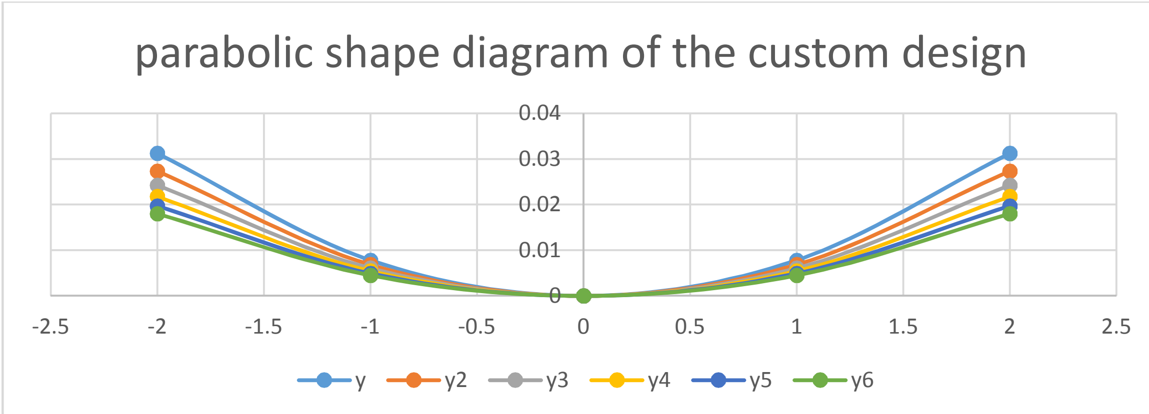

Figure B27. Plot of different parabolic profiles [31] used with permission.

As seen from the Figure B27, changes in the value of A do not have any significant impact on the profile of the parabola. We decided that the parabolic mirror should be used at a distance similar to the current mirror configuration.

2.1.2 Mirror Material Analysis

When compared to other materials, carbon fiber has relatively high strength, high modulus, and low weight. Carbon fibre cost about $2.00 - $4.00 per sq. ft. plus the manufacturing cost [32]. The glass fiber has a cost of $0.30 - $1.00 per sq. ft.. Using carbon fiber for the mirror will allow for long product life since the carbon fiber is resistant to corrosion, has good durability, is damage tolerant, and has dimensional stability [32]. For these reasons, even though the price to produce a carbon fiber mirror is more expensive, it can cut the cost for the maintenance therefore it can be useful for a long run. Carbon fiber reinforced polymer has a 98 % reflectivity [33].

An acrylic mirror has 97 % reflectivity, and has lesser weight compare to a glass and an aluminum mirror. Their plastic can be molded into an exact shape, coated with a reflective coating for much less than the price of any other reflective solution [34]. The the life span of the acrylic mirror is about 15 years in full sun [34]. Acrylic mirrors can be bought through the company of the Patriot Solar group.

TABLE B XIII shows the Pugh chart of different reflective materials and their reflectivity and also shows the scoring of the materials with respect to its reflectivity, cost, strength, and product life.

The reference surface coating is the stainless steel. The materials were given a rating based on the reference material: much better (++), better (++), the same (0), worse (-), or much worse (--).

TABLE B XIII

PUGH CHART OF THE REFLECTIVE MATERIALS AND THEIR REFLECTIVITY

Material of the surface coating	Reflectivity		Cost	Strength	Life of the material	Total Count
	Max(%)					
Stainless steel (REF)	65	0	0	0	0	0
Aluminum foil, bright	97	++	+	-	0	2
Reflective Mylar film	93	++	+	-	+	3
PET	90	++	+	-	+	3
Acrylic Mirror	97	++	+	-	++	4
Aluminum sheet	95	++	+	-	+	3
Carbon Fiber	98	+	-	++	++	4

From TABLE B XIII, it shows that the acrylic and carbon fibre mirrors are both suitable options for our application. The acrylic mirror will have higher life span, higher reflectivity, and has lower cost than the reference stainless steel mirror. The carbon fiber will have higher cost but it will have higher strength than the acrylic mirror and it can be made fire-proof which is a plus in a design. It was decided to go with a carbon fibre mirror, as it can be manufactured in Winnipeg at CIC, who then could also perform testing on the composite to determine the required thickness of the mirror for the operational environment.

3. LED LIGHTING: NUMERICAL RESULTS

FEA was conducted for the custom light mount and the pole mount structure.

3.1 Custom Light Mount

FEA was conducted on the light mount in three different stages. The first stage of FEA was for a scenario with the LED Light Mount in a high-wind, operational environment, to determine the minimum weld size and plate thickness of the mount structure. The second stage was to determine if the top bar could indeed be used as a handle. The third study was to verify that the structure would hold when subject to a sideways loading scenario.

The study first study's convergence plot is shown in Figure B28.

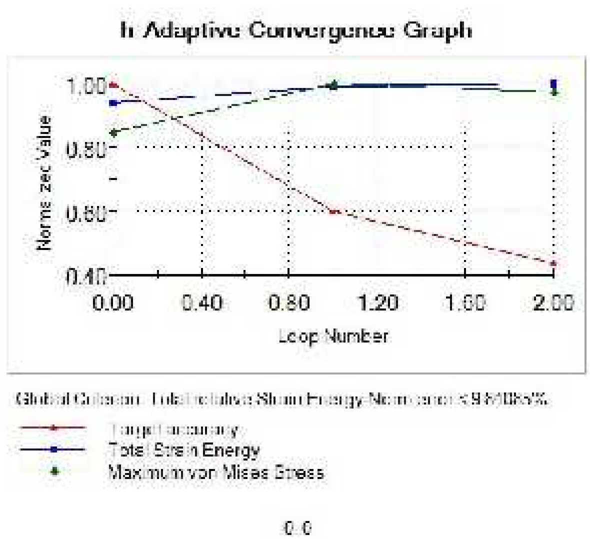

Figure B28. Convergence plot for operational loading scenario [35] used with permission.

The study ran for only three iterations before reading the error code "Mesh Adaptation Failure". Although the study did not converge, the study can be used to visualize the deformations and highlight areas of high stress. The structure was subjected to an 80 lb downward force and a 155 lbf force, both applied at the light hinge holes. One area of high stress is where the square tube used for the bottom frame member is welded to the bottom plate. A plate thickness of 3/8 in. is required to achieve a safety factor of 2. The stress results are shown in Figure B29 and the displacement results are shown in Figure B30. The stress results for this study have a colour chart with the maximum stress set to the allowable stress to attain a safety factor of 2.

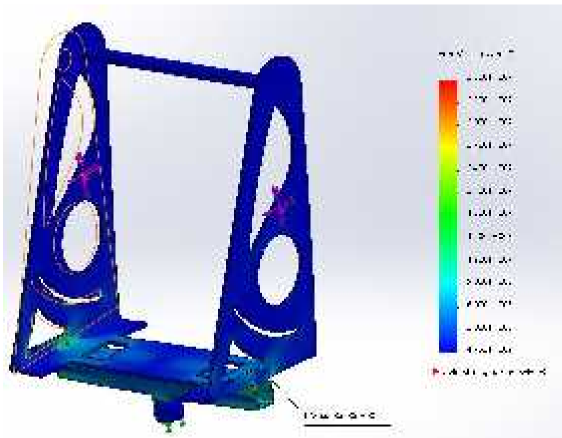

Figure B29. Stress contour for operational loading [36] used with permission.

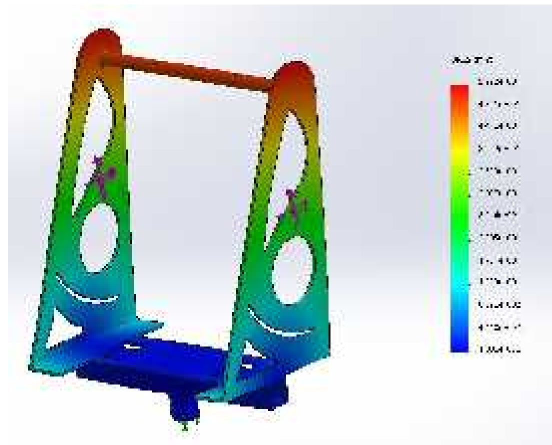

Figure B30. Displacement contour for operational loading [37] used with permission.

The displacement results show a maximum displacement of 0.529 mm and appears at the very top of the structure.

The second study mimicked a scenario where the top handle is in use. The simulation ran for six iterations and the convergence plot results are presented in Figure B31.

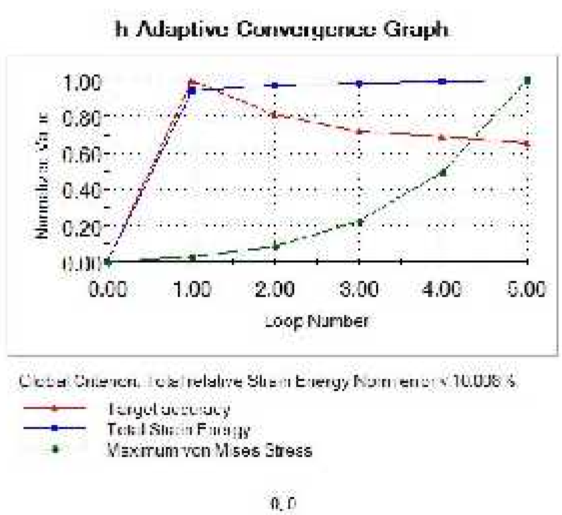

Figure B31. Convergence plot for the hand use study [38] used with permission.

The study did not reach 99% convergence however the results show that the stress and displacement are relatively low. The stress results for this study is shown in Figure B32, and the displacement results are shown in Figure B33.

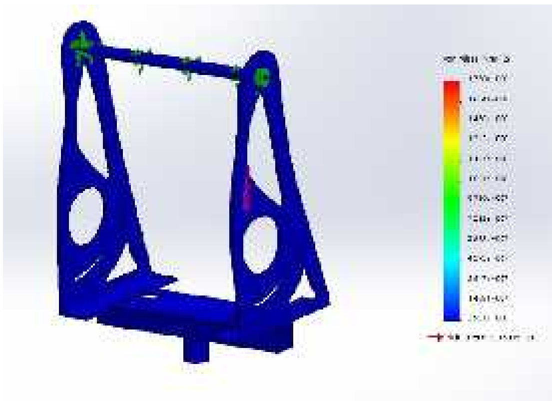

Figure B32. Stress contour plot for handle use [39] used with permission.

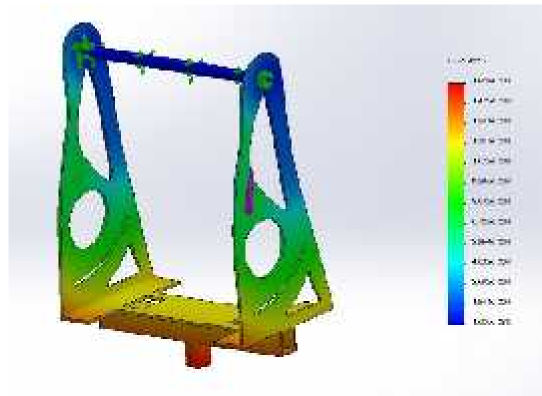

Figure B33. Displacement contour plot for handle use [40] used with permission.

The maximum displacement calculated by the study was 0.00161 mm and all stresses in the study satisfy a safety factor of 2. The handle bar size is sufficient to be used as a handle bar.

The third study simulated a scenario where the light is suspended sideways from the pole mount. The stress and displacement results are shown in Figure B34 and Figure B35, respectively

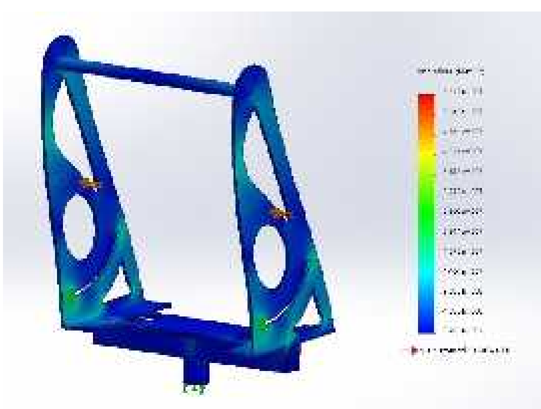

Figure B34. Stress contour plot for side loading scenario [41] used with permission.

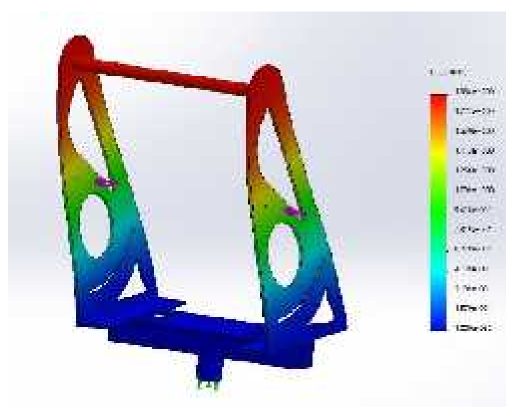

Figure B35. Displacement contour plot of side loading scenario [42] used with permission.

3.2 Pole Mount Structure for LED Light Mount

A numerical finite element analysis (FEA) was run on the heliostat mounting structure again to see if it could also support the LED lights. The initial mesh and set up are similar to the previous static studies with the exception of the downward force, and the applied torque values. The downward force applied for this application is 80 lbf, equal to the weight of one light plus the weight of the light structure. The assumption of 60 MPH wind speed was assumed again and from this an applied force on the back of the light was calculated to be 27.65 lbf with a torque of 278 lbf-in^2.

The target accuracy was set to 99% and mesh coarsening was turned on to eliminate unnecessary mesh refining at areas that have already converged. The study ran seven iterations after which the target accuracy of 99% was not reached, however a target accuracy of over 98% for total strain energy was reached and therefore these results will be considered acceptable. The convergence plot can be seen in Figure B36.

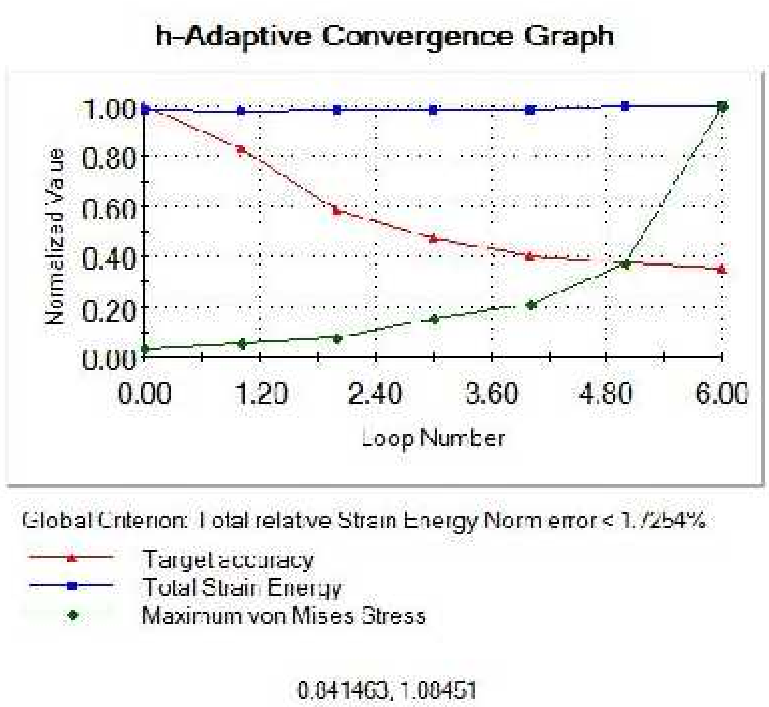

Figure B36. H-adaptive convergence plot for light post analysis [43] used with permission.

It should be noted that the maximum von Mises Stress did not converge and this is due to the sharp geometries that were left in the model to save meshing time between iterations.

The chart maximum is set to the maximum allowable stress to achieve a safety factor of 2: 175 MPa. As can be seen in Figure B37, the majority of the structure has a much higher safety factor than 2 with stresses around 0.0015 MPa.

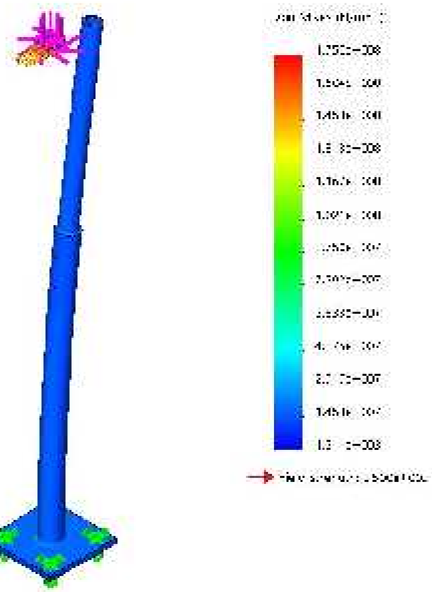

Figure B37. Contour plot of stress results – full view [44] used with permission.

Figure B38 shows a close up of the filleted area which is an area of high stress relative to the rest of the model. The stresses around the fillet are approximately 5.8 MPa.

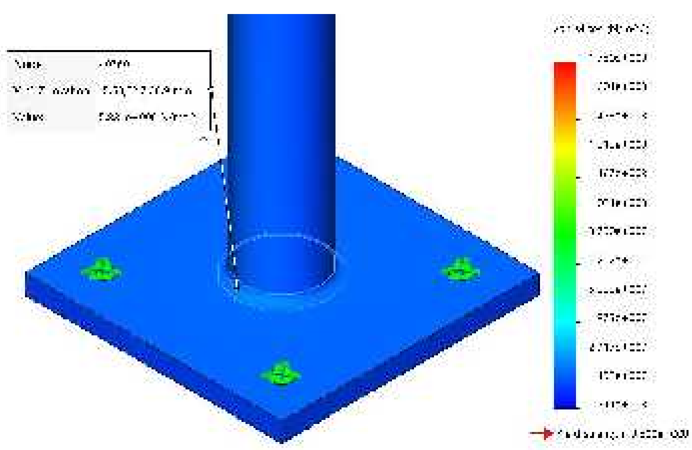

Figure B38. Contour plot of stress results – close view of fillet [45] used with permission.

Another area of high stress is located at the interfaces between the two tubes. One of the interfaces can be seen in Figure B39.

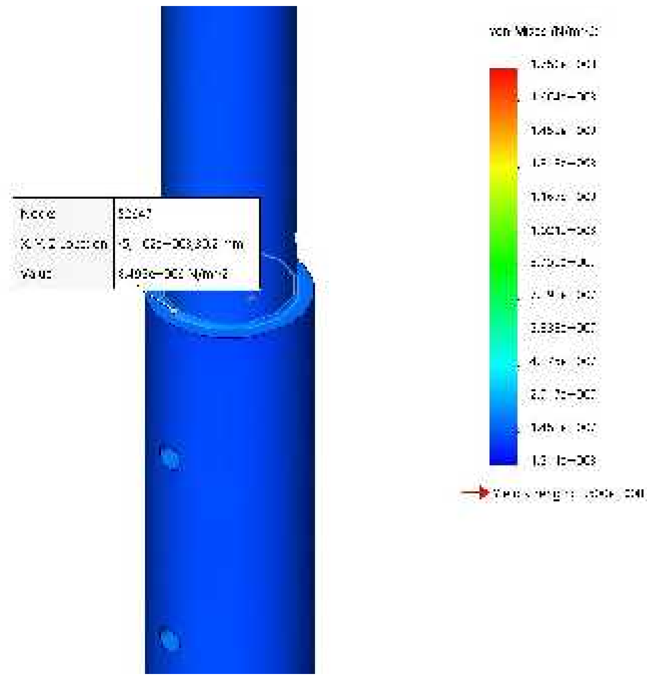

Figure B39. Stress at interface [46] used with permission.

All model features satisfy a safety factor of 2.

Figure B40 shows the displacement results in an exaggerated view with a deformation scale of 174. The top of the structure sees the most deformation of approximately 0.96 mm.

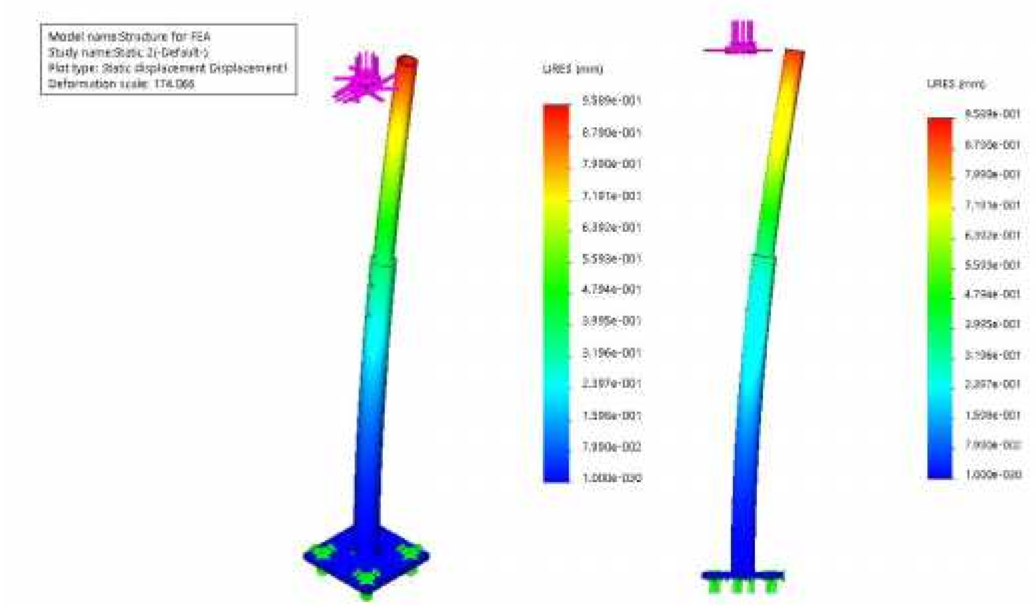

Figure B40. Contour plot of displacement results for the base post analysis [47] used with permission.

There is no minimum deformation requirement however, in order to increase the performance of the structure, vibrations should be minimized.

The results of the numerical study show that the size and thickness of the nominal tube sizes are of sufficient strength for both the Heliostat and the LED light mount structure.

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APPENDIX C: TECHNICAL DRAWINGS

TABLE OF CONTENTS

LIST OF FIGURES

1. HELIOSTAT SOLTUION: CUSTOM COMPONENTS

1.1 Pole Mount Structure

The Pole Mount Structure consists of three components:

- The Base Plate
- The Base Pole
- The Adjustable Pole

A technical drawing for each component can be found in Figure C1, Figure C2, and Figure C3.

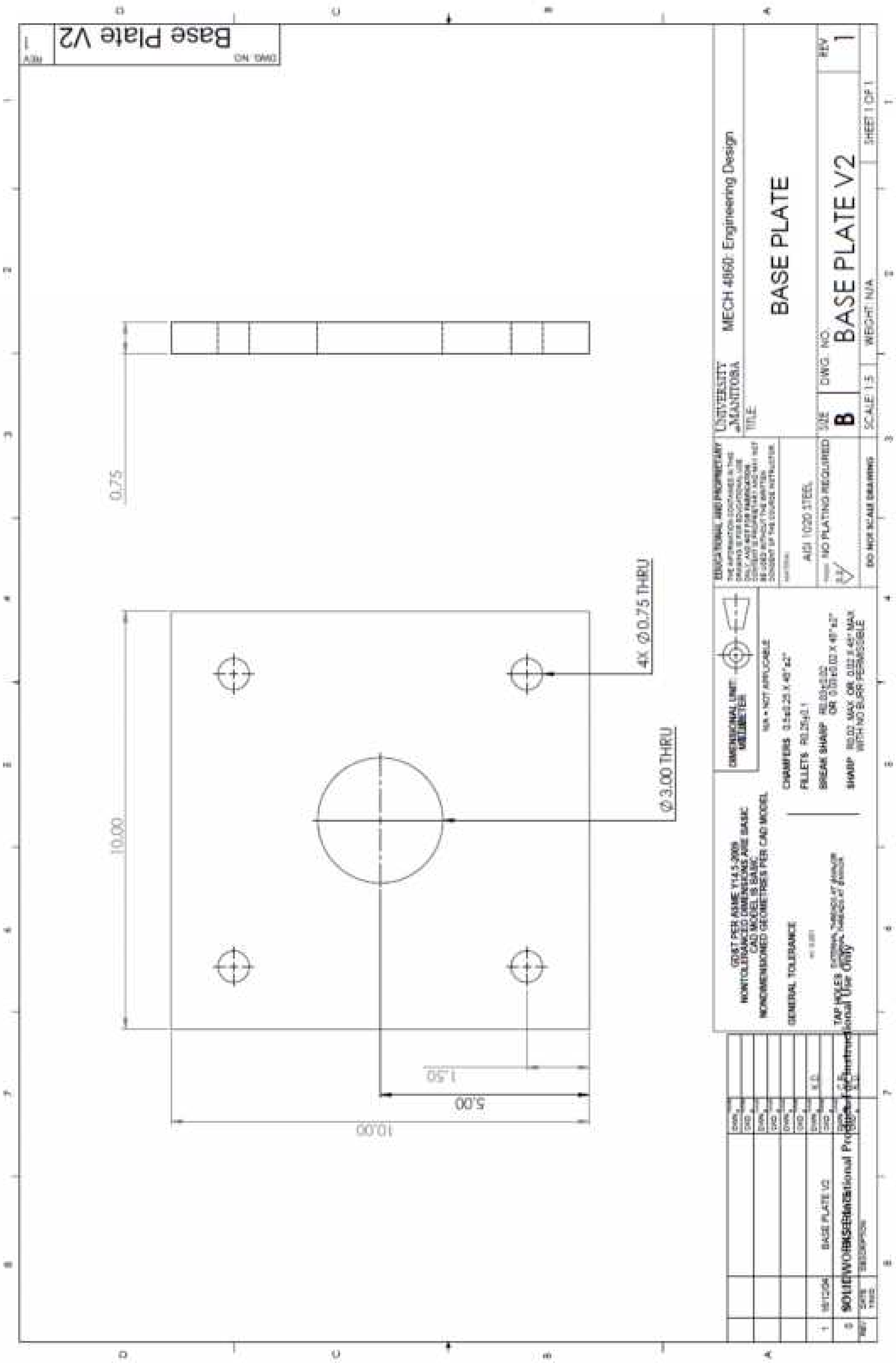

Figure C1. Technical drawing for the base plate [1] used with permission.

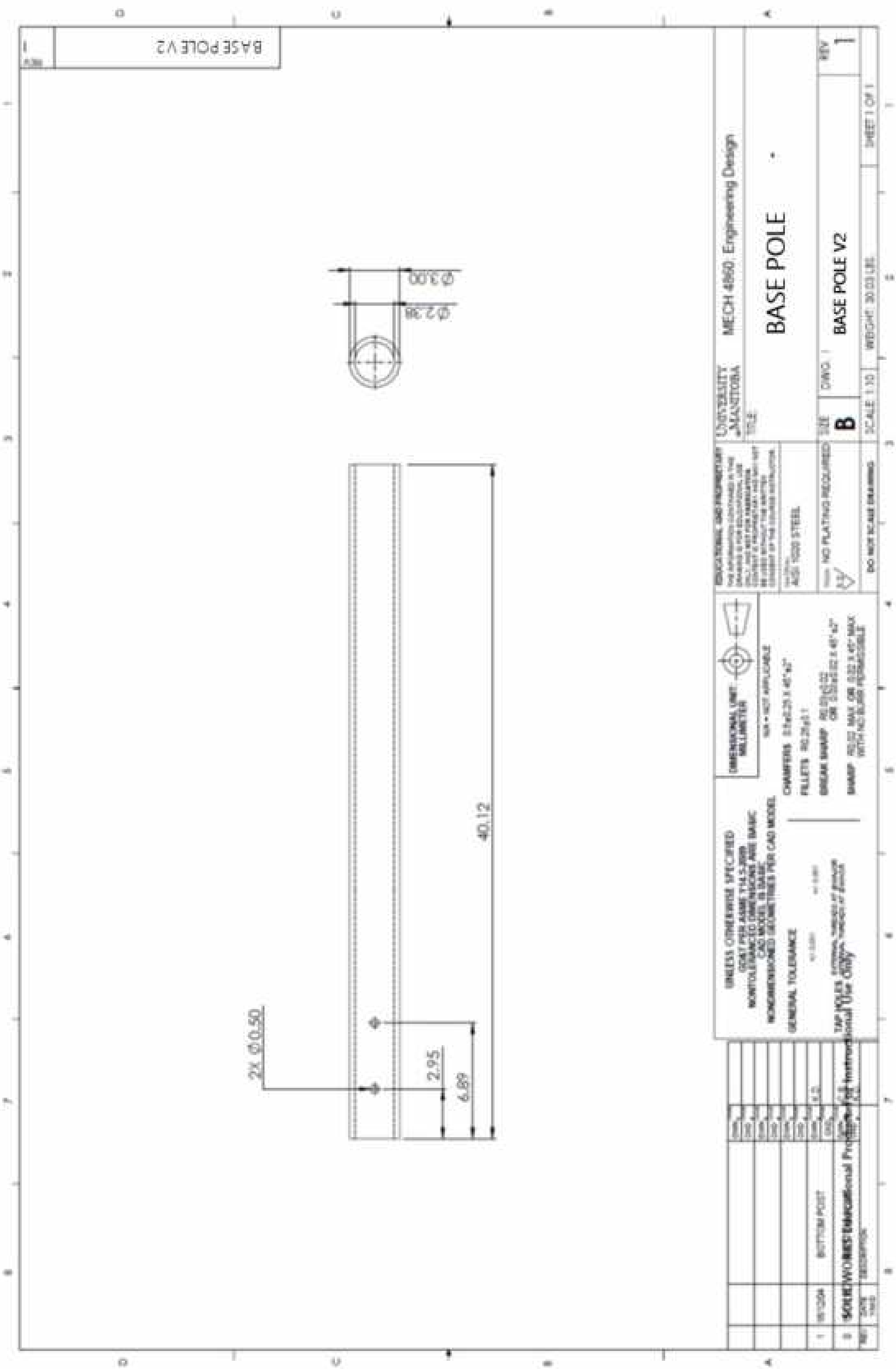

Figure C2. Technical drawing for the base pole [2] used with permission.

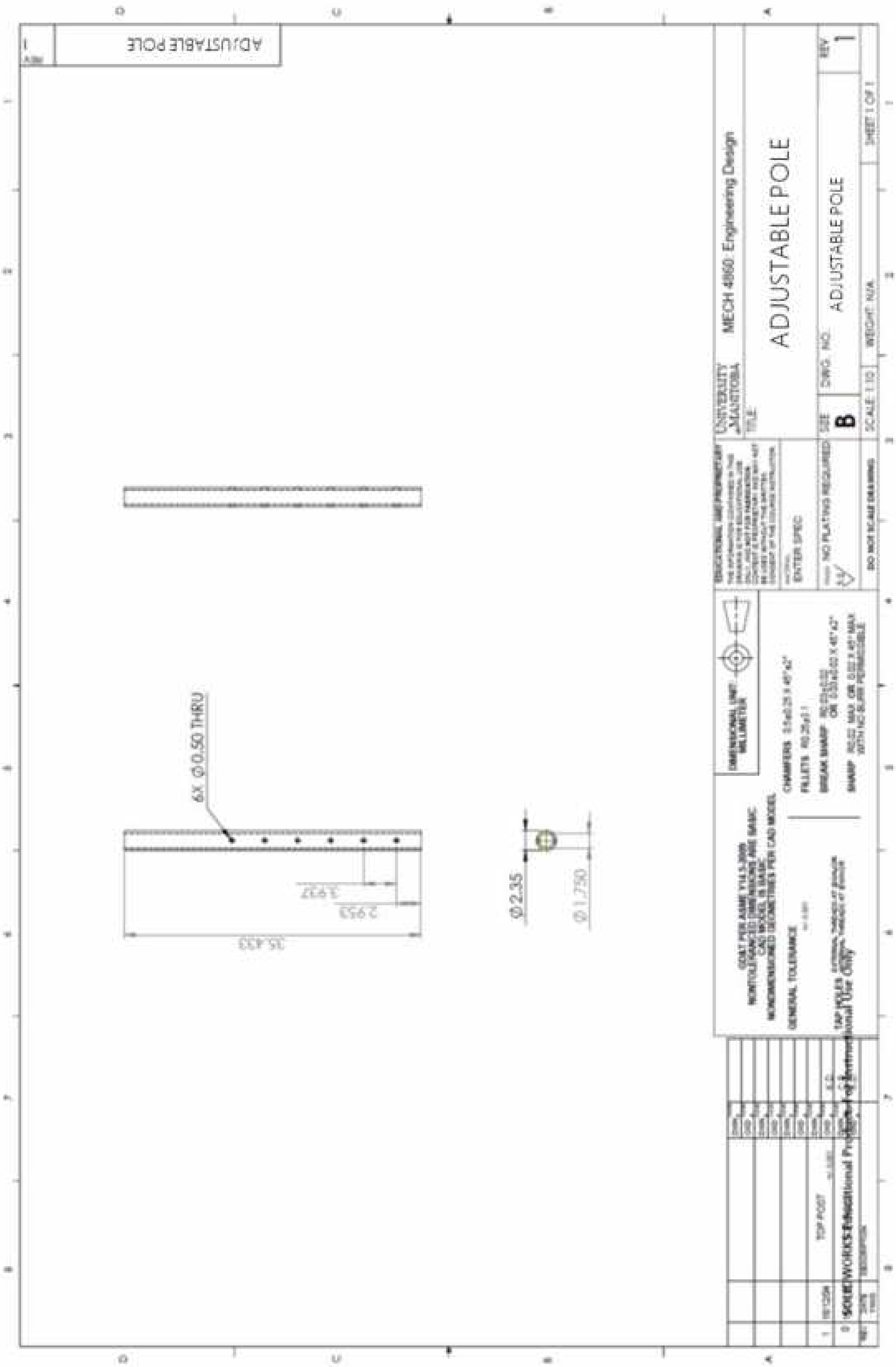

Figure C3. Technical drawing for the adjustable pole [3] used with permission.

1.2 Test Mount Structure

The test mount structure is a different configuration of the pole mount structure. The technical drawing for the test plate is shown in Figure C4. The test plate is to be used in place of the base plate with the Pole Mount Structure.

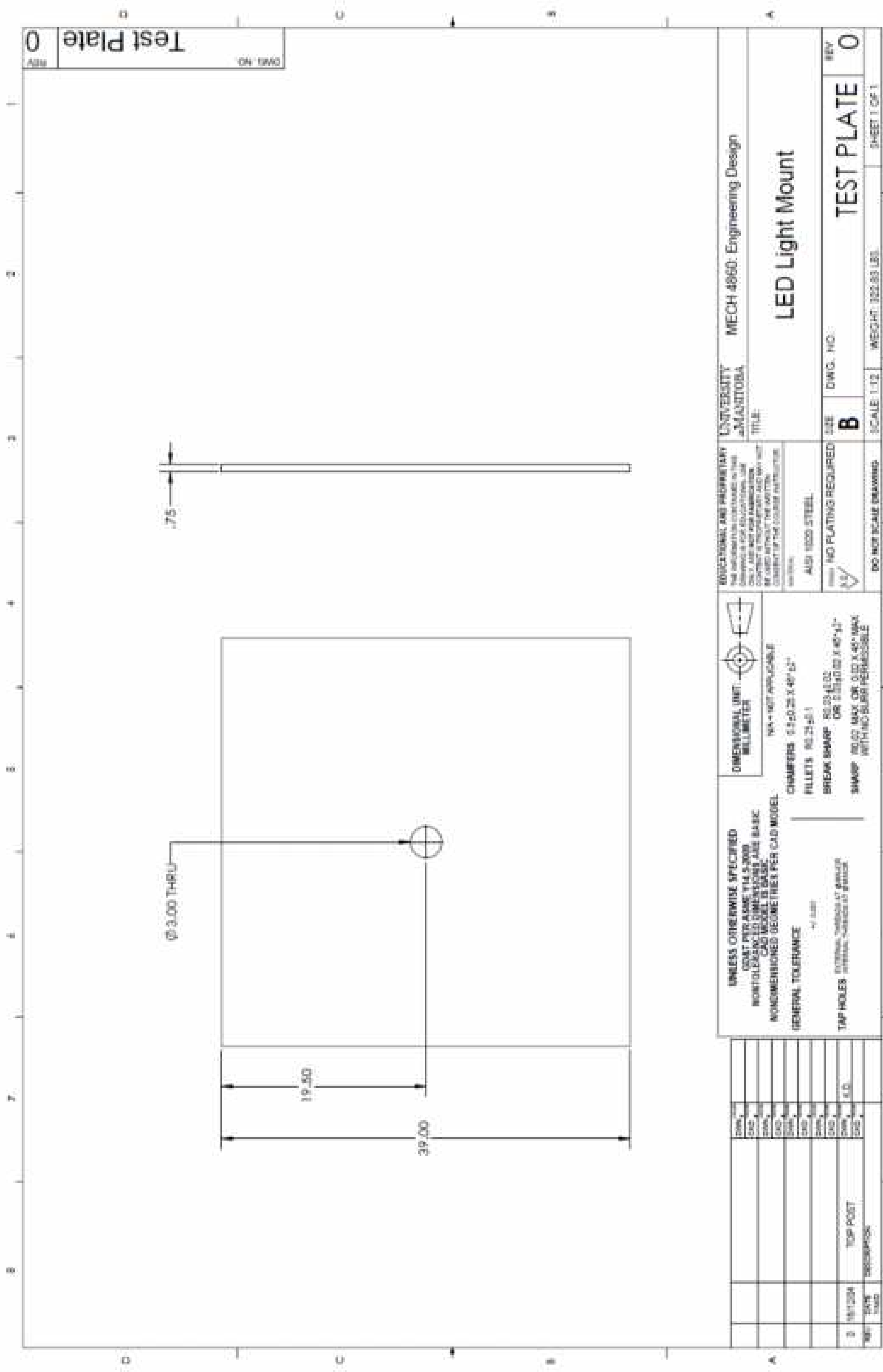

Figure C4. Technical drawing for the Test Plate [4] used with permission.

2. LED LIGHT SOLUTION: CUSTOM COMPONENTS

2.1 LED Light Mount

The custom LED Light Mount consists of seven components:

- Bottom Plate (Figure C5)
- Side Plates (Figure C6)
- Mounting Tube (Figure C7)
- Bottom Frame Tube (Figure C8)
- Top Handle (Figure C9)
- Centre Bracket (Figure C10)
- Positioning Bracket (Figure C11)

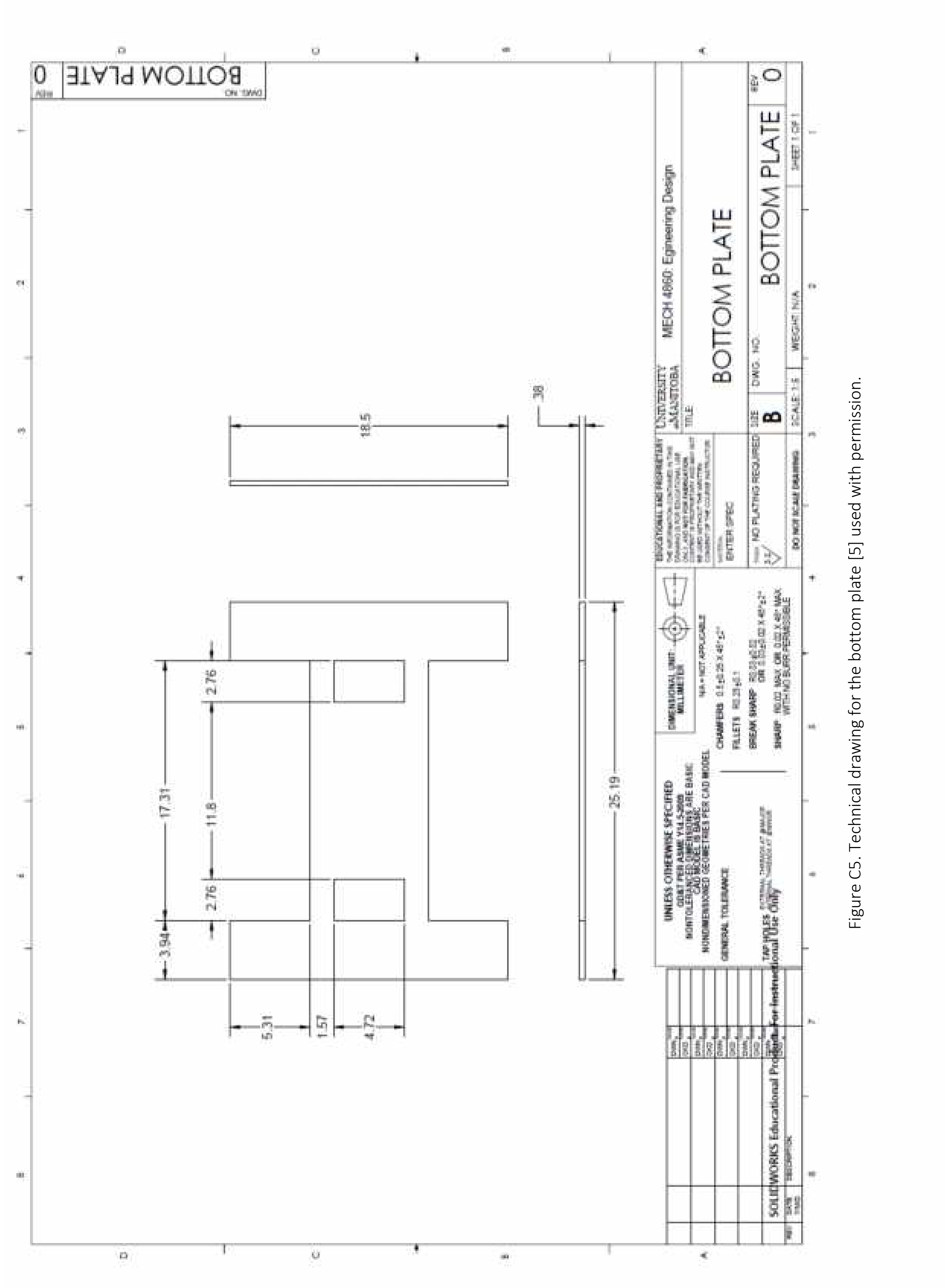

Figure C5. Technical drawing for the bottom plate [5] used with permission.

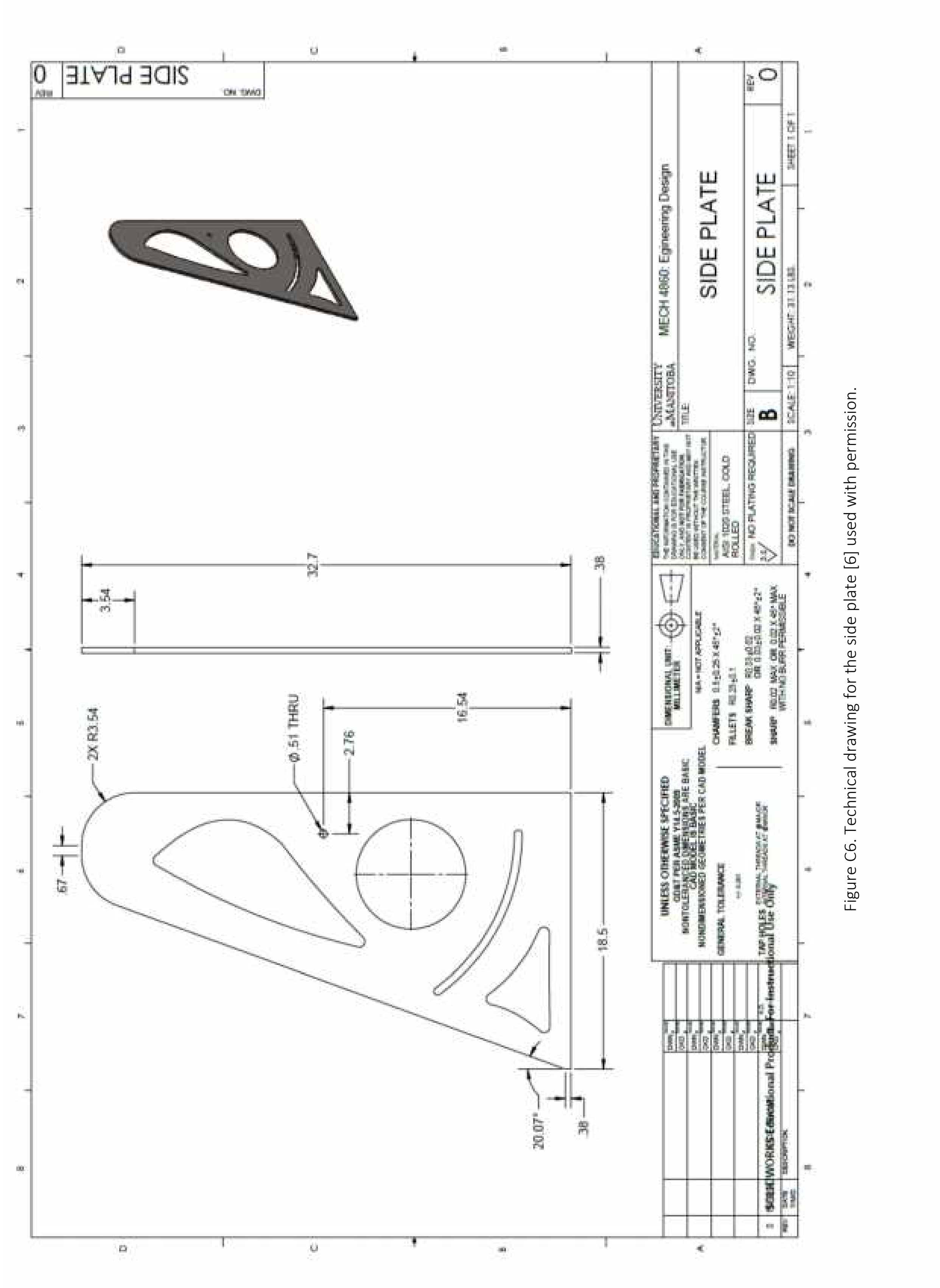

Figure C6. Technical drawing for the side plate [6] used with permission.

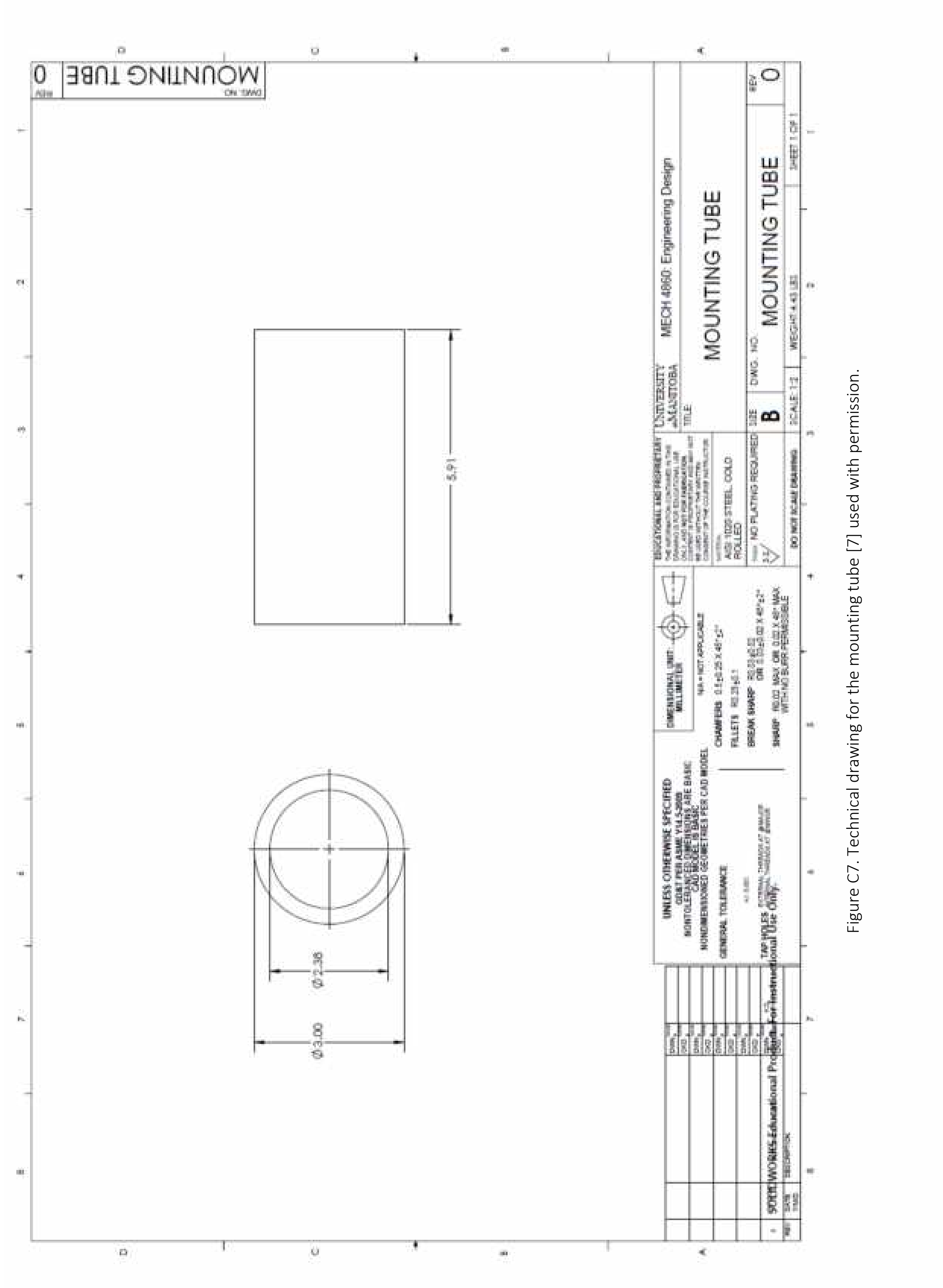

Figure C7. Technical drawing for the mounting tube [7] used with permission.

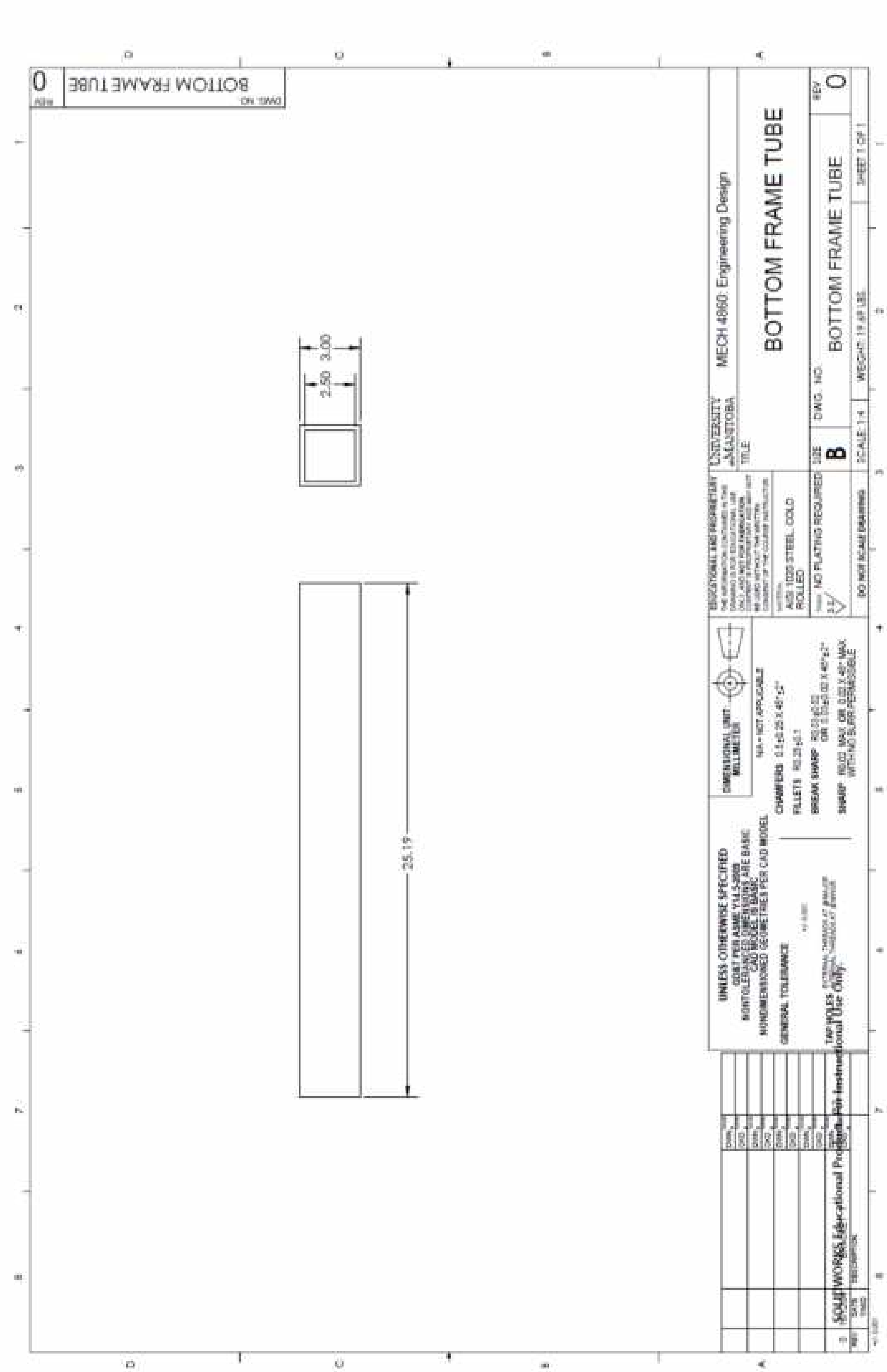

Figure C8. Technical drawing for the bottom frame tube [8] used with permission.

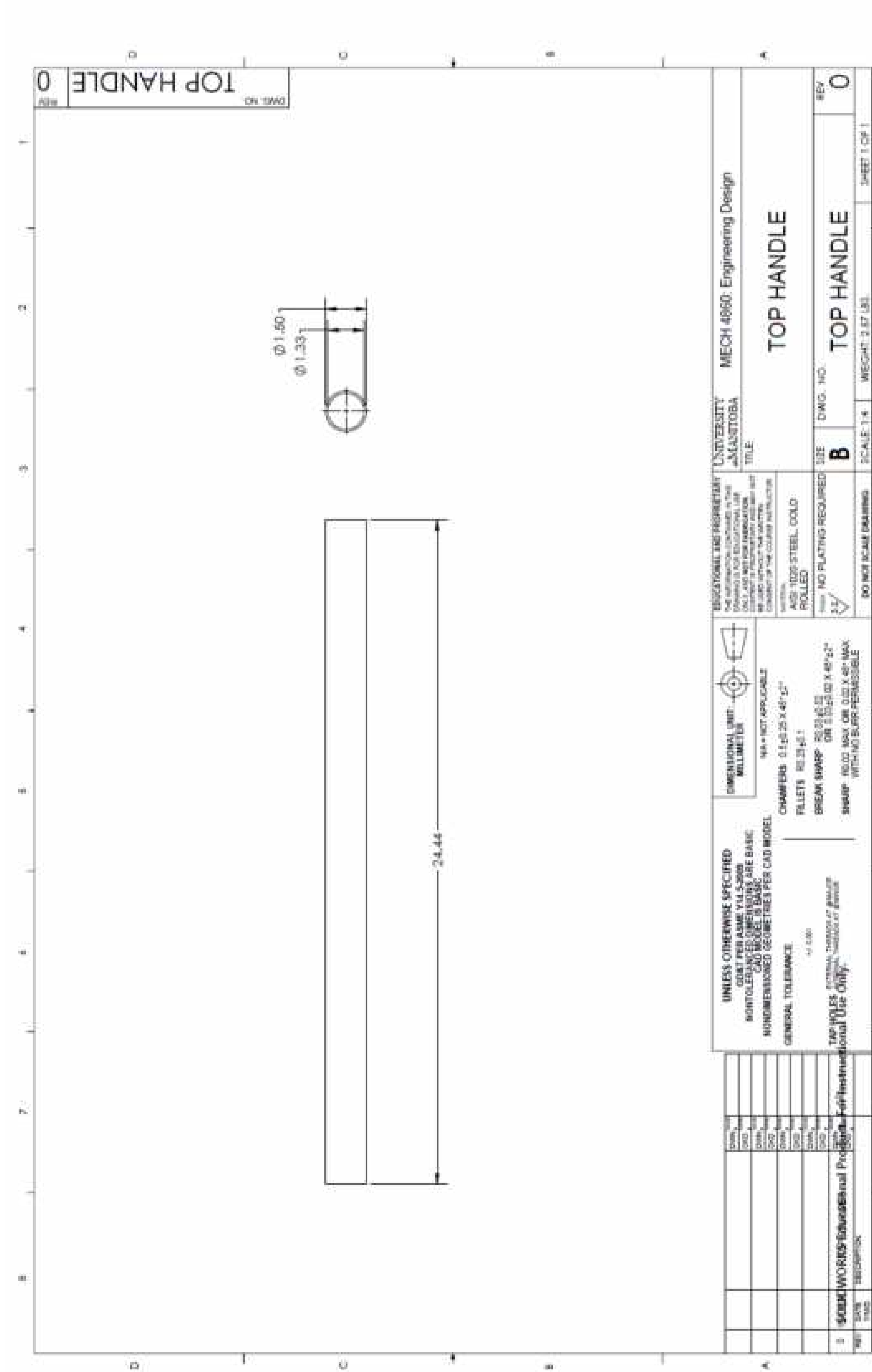

Figure C9. Technical drawing for the top hande [9] used with permission.

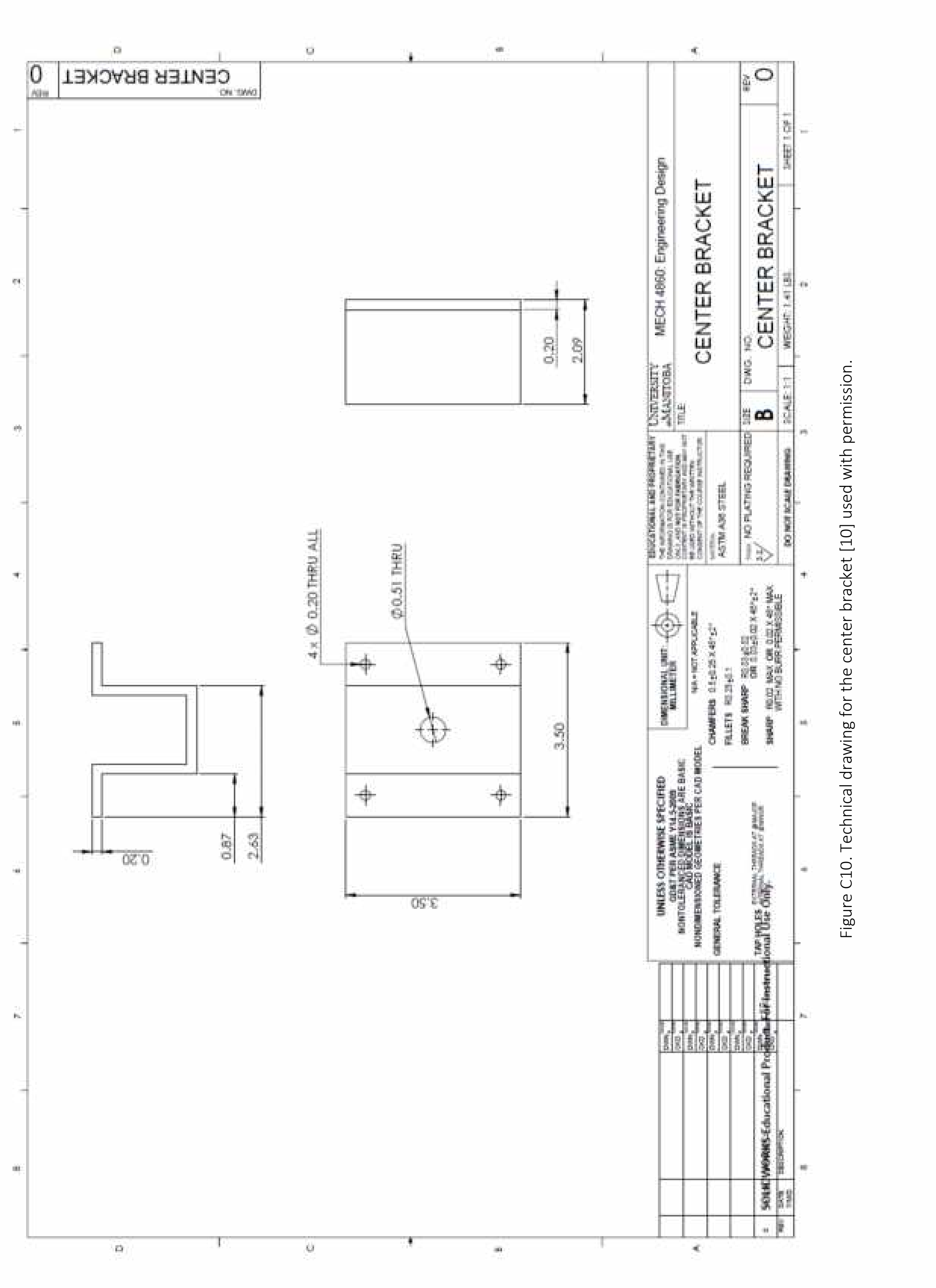

Figure C10. Technical drawing for the center bracket [10] used with permission.

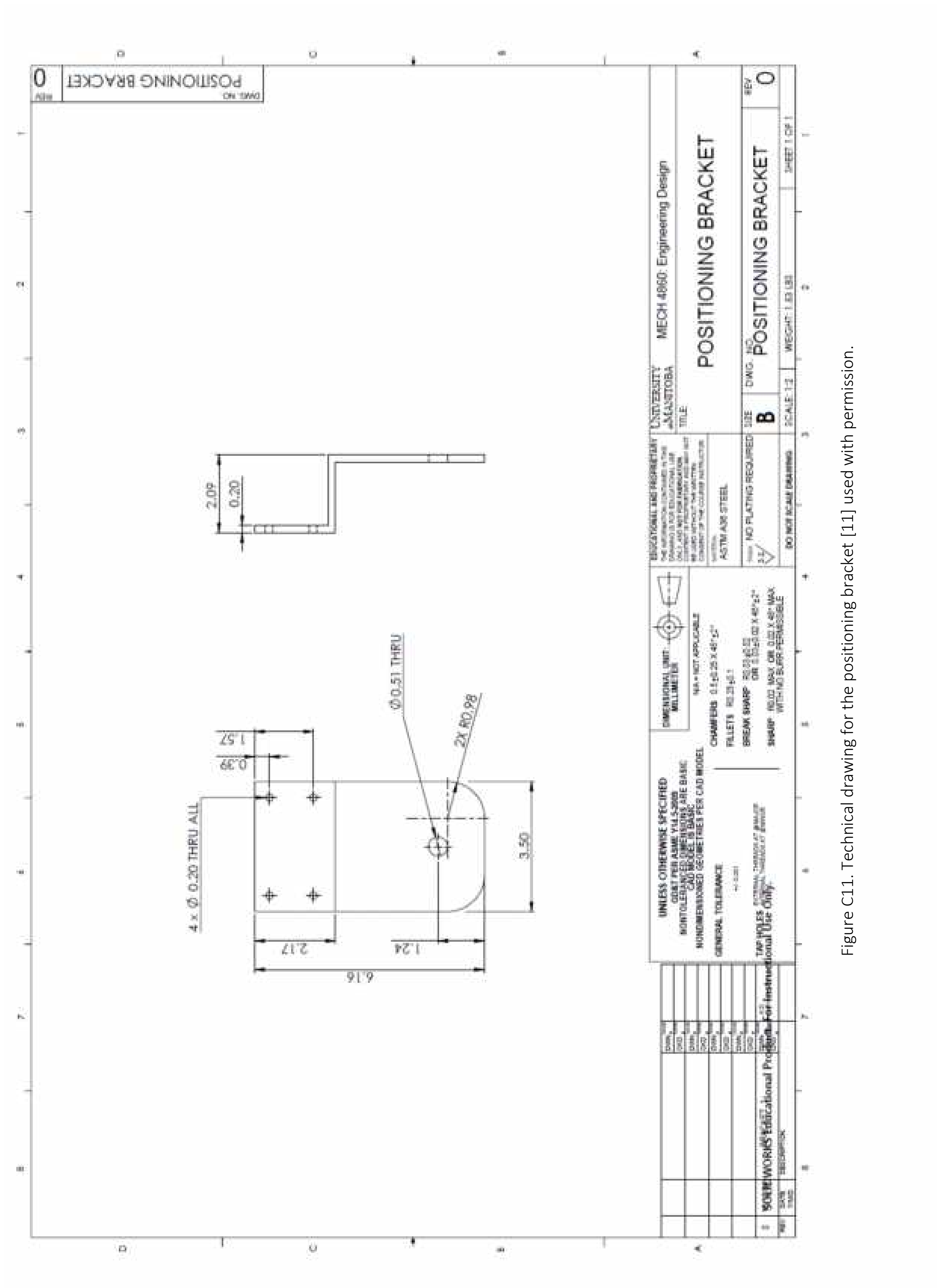

Figure C11. Technical drawing for the positioning bracket [11] used with permission.

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