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# Glows Co Automated Chemical Etching Machine for Fiber Optic Cable

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ENTITLED

# GLOWS CO AUTOMATED CHEMICAL ETCHING MACHINE FOR FIBER OPTIC CABLE

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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# GLOWS CO AUTOMATED CHEMICAL ETCHING MACHINE FOR FIBER OPTIC CABLE

By

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**SENIOR DESIGN PROJECT REPORT**

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# Abstract

This report summarizes the conceptualization and development of an automated machine designed for a fiber optic cable stripping process used by Lumentum LLC. This process is currently manually operated by Lumentum's technicians and involves unavoidable handling of corrosive chemicals. To increase technician safety, the process will be automated to reduce chemical - operator interactions. Improving safety conditions for technicians is the primary motivation for automating this process. Automation will also decrease process variation and increase product quality. GLOWS CO was tasked with creating this automated solution, leading to the design of the Automatic Chemical Etching Machine (or A-CHEM) for the fiber etching process for Lumentum LLC. At the conclusion of this project, the A-CHEM successfully fulfilled all of the requirements set out by Lumentum, namely improving technician safety and making the process more ergonomic.

# Acknowledgements

We wish to express our sincere gratitude to David Vecht, Senior Mechanical Engineer at Lumentum, for providing us with the opportunity to work with Lumentum LLC and for his insights in the design phase for our senior design project.

We sincerely thank our advisor Dr. Marks for streamlining our design process by instigating critical assessment of overall design as well as individual subsystems. His mastery in material properties alerted us of crucial design criterion for clean room and caustic environments.

We also wish to thank Mehdi Golshan, Director of Corporate Real Estate and Facilities at Lumentum LLC, for his clarification of materials used in highly volatile chemical processes. This led to the expedited selection of vital construction materials necessary for our senior design project.

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# 1 Introduction

## 1.1 Problem Statement

GLOWS CO has been contracted by Lumentum LLC, a laser research and development company, to automate a window stripping process for fiber optic cables. In window stripping processes, fiber optic cables are dipped into chemical baths to remove the protective cladding from the glass (silica) core of the cable. At Lumentum, this process is currently performed manually by technicians. The technician dips the optical fibers into a series of successive baths where the chemicals strip and clean the glass fibers. The close proximity of the technicians to these hazardous chemicals poses severe health risks including chemical burns and inhalation of toxic fumes. Additionally, the fibers are mounted on a Fiber Carrying Tool (FCT) designed by Lumentum. This tool weighs approximately 4.5 kg, posing an ergonomic risk to the technician as they maneuver it inside of the fume hood.

In addition to the safety risks of the current process, the nature of manual processes introduces precision errors. The technician currently measures time for all dipping processes with a digital stopwatch, introducing human timing errors. The stripping process requires a high degree of precision in timing and position to produce consistent results, meaning the existing method of timing contributes to product variations. The monitoring required by the existing timing method also prevents the technician from performing other tasks while the fibers are being treated, causing productivity losses.

GLOWS CO is improving the existing window stripping process by designing and building an automated solution, the Automated Chemical Etching Machine (A-CHEM). This system will limit technician interactions with chemicals and handle all dipping operations to increase safety and minimize product variation. Design specifications and limitations were provided by Lumentum and final delivery of the A-CHEM is scheduled for July 2016.

## 1.2 Laser and Fiber Stripping Background

Industrial lasers are a crucial and continuously expanding component of the world's manufacturing capabilities and the industrial laser market is expected to reach $17.36 billion by 2020[1]. These lasers are used in a variety of applications including satellite telecommunications, data transmission, and powerful laser cutters. Satellite lasers provide accurate signals across incredible distances, a critical technology in the modern age of communication. An image showing this type of communication is in Figure 1. For fabrication projects involving sheet metal, laser cutting is the most economical way to precisely shape metal for a variety of applications, whether large scale (shipbuilding) or small (company signs).

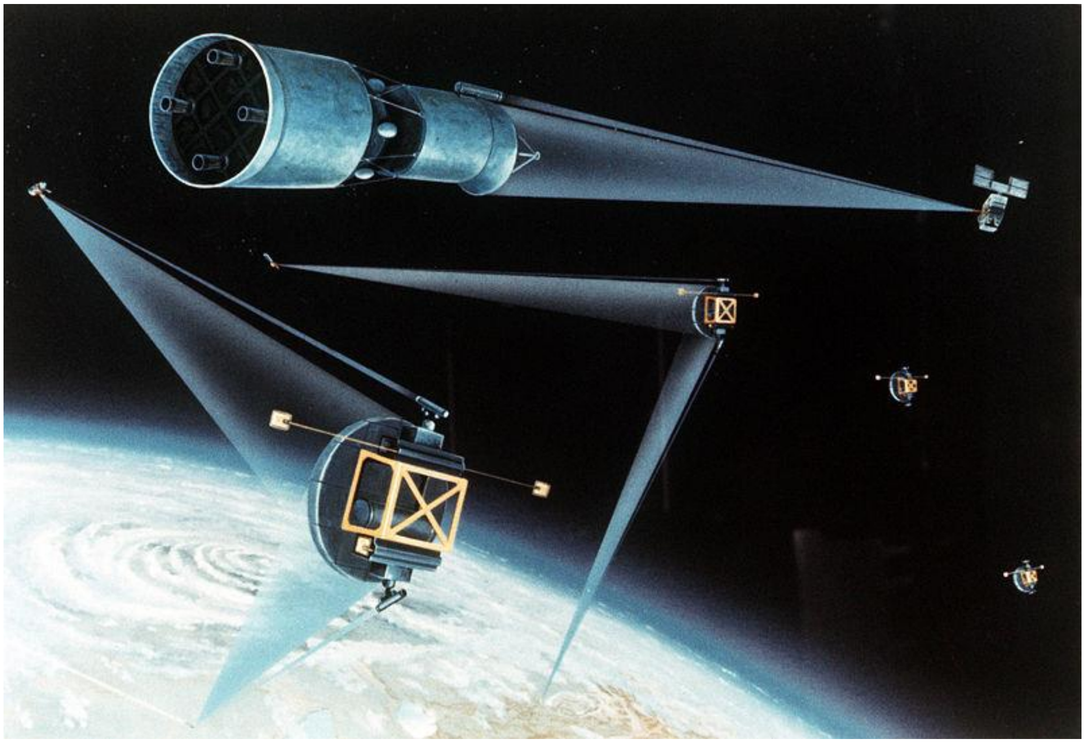

Figure 1- Satellite Laser Communication [2]

[1] Markets and Markets. *Laser Processing Market by Application (Cutting, Drilling, Marking), Laser Type (Gas, Solid, Fiber Laser), Machine Configuration (Moving, Fixed Beam), Vertical (Machine Tooling, Automotive), Geography - Global Forecast to 2020.* Marketsandmarkets.com, Nov. 2014. Web. 16 Nov. 2015.

[2] "Defensive Weapons." Defensive Weapons. N.p., 12 Aug. 2006. Web. 07 June 2016.

Typically when producing high powered lasers, a number of smaller fiber optic cables are joined together from the laser generator[3]. However, each fiber has a polymer protective coating. To join them together or metalize them for connection to electrical components, the protective cladding must be stripped off of the silica interior[4]. Depending on how the cables are joined, the cladding may need to be stripped off the ends of the fibers or removed from a “window” in the middle of the fiber. There are two general methods for doing this, mechanical stripping and chemical removal. Mechanical stripping cuts the fiber cladding and removes it physically. This can be done by hand with tools similar to wire strippers or with automated machinery. Using a mechanical method is effective but has a higher likelihood of nicking the fibers than chemical stripping methods. Chemical stripping uses a variety of chemicals to remove the fiber cladding and expose a window of silica beneath. The partially dissolved cladding fragments then need to be removed with a cleaning process. The downside to this process is the safety hazard posed by the chemicals used in this process.

# 1.3 Automated Manufacturing

Companies automate processes for a variety of reasons; they can reduce waste, increase quality and precision, and improve safety. Many of the processes that companies automate are ones that are dangerous or difficult for humans to perform. Tasks like these are usually the first to be automated. Automated machines typically come in two major categories: generalized industrial robots and specialized process solutions. General industrial robots are automated systems which are flexible and programmable to many different tasks. They are usually arrayed into assembly lines where they can be programmed to perform sequentially. For example, a robotic arm is a general industrial robot that may be used for many tasks across many industries. In automobile manufacturing robot arm lines perform tasks such as welding, drilling, and painting in sequence.

[3] O'Connor, Michael, and Bill Shiner. *Excerpt: High-power Fiber Lasers for Industry and Defense--Part III*. Rep. UBM Canon, 27 Apr. 2011. Web. 17 Nov. 2015.

[4] Doyon, Pete. "Optical-fiber Window-stripping: Why and How?" *Journal of Lightwave Technology* 19.9 (2002). *Lightwave Online*. IEEE. Web. 26 Oct. 2015.

Specialized process solutions are machines designed and built to perform a single task or stage in a process. Examples of these are the forming tools used in steel beam production.

Figure 2- Automation Machine Used in the Manufactuing of Steel Beams[5]

The use of automated systems in industrial production requires a thorough understanding of how the machine will fulfill its role. For industrial robotics to be a viable solution, technicians who currently work on that process must approve of the new solution[6]. Lumentum's technicians were a part of the discussion and decision making process for approving the automated machine developed by GLOWS CO; this procedure validates the construction for the A-CHEM and follows the safety requirements outlined in the Geneva Convention article on Safety for Industrial Robots. However, an automated process introduces new working hazards to the workspace. Therefore, it is important for technicians to be trained properly in the use of the A-

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5 Yangtong Group. "H Beam Assembly Machine,H Beam Automatic Assembling Machine." H Beam Assembly Machine,H Beam Automatic Assembling Machine. Yangtong Group, n.d. Web. 07 June 2016.

6 "Accident and Injury Statistics." Safety in the Use of Industrial Robots. Geneva: International Labour Office, 1989. 15-20. Print.

CHEM before they are qualified to utilize this tool. Part of this design and construction process is to identify potential dangers in the operation and fabrication of the A-CHEM.

# 2. Systems-Level

## 2.1 Current User Scenario

Lumentum currently employs a number of technicians to manually carry out the multi-stepped window stripping process. The process is conducted inside of a fume hood located in a clean room. The steps are laid out as follows:

1. The technician fills a number of heated baths with the first set of chemicals.
2. The technician waits roughly 5 minutes as the baths heat up.
3. The technician places the roughly 4.5 kg fiber carrying tool over each bath and dips the fibers into the chemicals. The tool rests on the fume hood surface so the technician does not have to hold it. After a prescribed amount of time the technician removes the tool.
4. The technician repeats the previous step for each of the filled baths.
5. The technician disposes of the used chemicals.
6. The technician fills a set of ultrasonically agitated baths with a new set of chemicals.
7. The technician places the FCT over each bath for a precise amount of time.
8. The technician disposes of the used chemicals.

The current process is dangerous because the technician is exposed to the hazardous chemicals for the entire operation. The heated baths also pose a burning risk. The precision of the current process is limited by the technician's ability to hold the FCT steadily and without bumping the fibers and by his or her ability to respond quickly and accurately to the process timer.

## 2.2 Customer Need

To increase safety and process quality, Lumentum contracted GLOWS CO to automate the chemical window etching process described above. The automated chemical etching machine, or A-CHEM, must complete the same process as the technician, but with more precision.

After the scope of the project had been informally discussed with Lumentum, interviews were conducted with a Lumentum technician, Juan Lugo, a Lumentum design engineer, David Vecht, and GLOWS CO's senior advisor, Dr. Robert Marks, to gather more information about the specifics of the project. All three interviewees consistently stressed the objectives of this project in order of importance: safety, process repeatability, and usability.

In addition to the emphasized importance of safety, reliability, and usability, each had individual elements of preference. David Vecht suggested that the machine should be very simple to operate, ideally requiring only one button for normal operation. Having a one-push-go system would provide simplicity to the design that could increase safety and help prevent misuse of the tool. Juan Lugo had the same opinions about a system that only required one button to operate, but the highlights of automating the process would be in improving the technician's capability of multitasking. Lugo found that while the process itself requires little thought, it requires a vast amount of time to prepare and requires constant monitoring from start to finish. With one-button-operation, more of a technician's time would be free to work on other portions of the manufacturing processes done in a clean room.

Robert Marks highlighted the importance of material selection. The materials used need to be corrosion resistant to the chemicals used in the process and to the fumes generated by the process. The materials for moving parts also need to be wear resistant to fulfill the clean room requirement for the project. Lastly, the materials need to meet the lifespan requirements. This means ensuring they are wear resistant to an extent that repeated use will not impact the accuracy of the machine. The materials must also withstand fatigue such that they do not weaken during the operational lifetime of the machine.

## 2.3 Market Availability

Mechanical or plasma fiber strippers are common methods of removing the cladding from fiber optic cables and perform efficiently to remove the cladding on the ends of fibers. Additionally, there are a wide variety of automatic and manual machines that perform these tasks; however, they are not well suited for performing window stripping due to their configurations and limitations. The available tools on the market require the cables to be threaded through the stripping mechanism which would introduce process variations for Lumentum. Also, it would interrupt Lumentum's assembly process which utilizes the FCT in other manufacturing processes. Using these machines also limits stripping to only one fiber at a time and introduces the possibility that the silica core is damaged as the cladding is stripped. Therefore, the available machines on the market do not meet Lumentum's needs and other alternatives must be considered.

Most industrial machines fall into two categories: standardized systems and unique problem solvers. Standardized processes are those that occur in a large number of practices, but have multiple methods of being solved. This makes machinery for these processes common due to its common usage throughout different fields. A unique process, however, is one that is either very new technologically or is only used in very specific applications. Currently there is no standardized automated window chemical etching solution for fiber optic cables on the market making Lumentum’s process unique. Automation company jobs are custom priced and are frequently subject to bidding as the contracting company chooses a solution provider. However, the bid-winning company gains access to sensitive manufacturing techniques which increases the risk of leaked proprietary information. Also, machines custom built by professional bid automation companies tend to be more expensive and must be serviced by the manufacturing company. These conditions are undesirable to Lumentum, and the company has not utilized this option, although it was considered.

Another solution is a general manufacturing solution: a robotic arm. Small robotic industrial arms can have positional repeatability down to +/- 0.02 mm, more than enough for this application. However, robotic arms have problems in terms of cost, design of a FCT interface, and fitting inside the fume hood. If a robotic arm was used, it would be mounted inside the fume hood and it would move the FCT to dunk it in each bath. A cradle for the FCT would have to be manufactured to hold the FCT to the arm, as well as a base plate for the arm. NACHI manufactures a small robotic arm (Figure 3) with a reach of 646 mm and a position repeatability of +/- 0.03 mm for $29,000 which is one and a half times the acceptable budget for this project. Denso also produces a robotic arm (Figure 4) that can move a maximum payload of 5 kg. It has a reach radius of 550 mm with a repeatability of +/- 0.02 mm. It faces very similar problems to the NACHI machine, but it can only move radially, so its movement will be limited within a fume hood. Also, the tool from Lumentum weighs approximately 4.5 kg, which only leaves 0.5 kg for the weight of the grabber with the Denso arm which is a small room for error.


Figure 3- NACHI MZ07L-01 Robot Arm


Figure 4- Denso HS-4555G-P10 Robot Arm

The current process used by Lumentum's technicians is a chemical stripping method that requires manual movement of the FCT from bath to bath. Its advantages are that it utilizes the chemical window stripping method, so center of fiber windows can be made with relative ease without damaging or introducing particulates to the exposed fibers. This detail is crucial for the manufacturing process because any defects in the fibers could lead to catastrophic failures for the end product. Also, this manual process does not require any extra tooling or machines that would require additional process training. One disadvantage of using a manual chemical stripping process is that the technicians themselves are exposed to dangerous and caustic chemicals that also produce volatile fumes. The close proximity to such liquids is required during the process because the technicians must oversee all steps of this method. Also, the technicians do produce errors in the stripping of the fibers due to their limitations in keeping accuracy and precisions throughout the process. This can cause major problems in product reliability and expense due to more units failing than if these errors did not occur. Although these methods are currently employed, they are not suitable for maintaining a high level of safety for Lumentum's technicians.

## 2.4 System Level Requirements

Synthesizing customer interviews, broad project guidelines, and field research together, a set of system level requirements was assembled.

The automated etching machine must fulfill a variety of requirements:

- Reduce risk of injury compared to current process
- Fit inside fume hood
- Operate in a clean room
- Hold chemical baths and FCT
- Start when button is pushed
- Heat baths
- Move baths and FCT to and from each other
- Dip FCT into baths for a precise time and to a precise depth
- Move back to starting position and shut down once the process is complete
- Stop safely when emergency stop button is pushed
- Sound alarm if a process problem occurs

The synthesis processes also revealed a number of additional criteria to improve the A-CHEM, but are not required:

- Require only 1 button to start
- Indicate time left in process by lights or display
- Move machine elements with buttons for manual control
- Facilitate cleaning by using easily removable parts

## 2.5 Core Design Principles

The needs and requirements detailed by Lumentum and its technicians are important and must be taken into consideration when designing a solution. However, many of these requirements are too broad or too specific to be directly applied when designing a full-spec system. To better adapt the project and customer requirements, three major design principles were created as operational guidelines: safety, process repeatability, and usability. These principles were applied to help filter designs and subassembly selections throughout the project. By consulting how well each solution addressed the core design principles, more subtle advantages in the design choices were highlighted, helping to select an optimal choice.

## 2.6 Design Principle: Safety

The safety of the technicians for this automated process is the largest weighting factor in determining suitable designs and subassemblies. The largest concerns that must be addressed by GLOWS CO's solution are all safety related: chemical hazards, high temperatures due to heating elements, pinching and entrapment from moving assemblies, and electrical hazards.

The dangerous chemicals used in window etching need to be properly contained and controlled throughout the span of use for this automated process. This means that the chemicals should never be in locations that could cause harm to a technician servicing or operating the machine. Additionally, the liquids must be highly visible from any viewing angle of the machine, and the chemical baths must be easily accessed, thereby promoting safety when they are loaded and unloaded from the machine. The chemicals should not compromise the machine either, and the design must properly address the possibility of chemicals escaping their respective baths. Instances such as chemical sloshing during bath movement and liquid dripping when fibers are dipped must be considered and addressed in the final machine. Finally, critical components that have the possibility of chemical contact should be designed in a manner such that critical failure does not occur if they are exposed to these corrosive materials.

This process requires the use of heating elements that are at temperatures hot enough to burn a person. Heat must be properly contained so that risks posed to the users of the machine and the machine itself are minimal. The design must include methods of insulating the heater blocks to prevent leakage heating of the surrounding assemblies. Upon activation, the machine must include a method of determining when the heating elements are active to warn operators of potential danger. If the nearby assemblies reach high temperatures due to leakage heating by the heater blocks, the technicians would be at risk of being burned.

Since the tool is automated, pinching and entrapment between moving assemblies is another factor that must be taken into consideration. Industrial application motors are capable of exerting high forces and torques when operating, so all systems that use them must have failsafe shutoff mechanisms to reduce risk. The priority of the A-CHEM is to improve the safety of the operator during the window etching process, and it must not violate Lumentum's safety requirements to be suitable as an industrial machine.

# 2.7 Design Principle: Process Repeatability

Lumentum requires high process repeatability to eliminate wasted production runs and to ensure its final products are of the highest quality. As such, GLOWS CO's A-CHEM must improve upon the repeatability of Lumentum's current manual process.

The alignment of the fibers as they are submerged into the chemicals is the first critical factor dictating process accuracy. The fibers must be perpendicular to the solvent surface as they are submerged. The dipping action must be smooth and controlled to minimize fiber and fluid motion. This will help to maintain a high level of accuracy and provide optimal stripping quality.

The length of time that the fibers are exposed to the chemicals is the second crucial factor determining the accuracy of the process. The chemistry involved in the chemical etching dictates a precise dip time must be executed; within 1 second or 1% of the total dip time, whichever is smaller. The fibers must enter and leave the chemicals within the time limit reliably to maintain product quality.

The horizontal location of the fibers relative to the baths is the one of the critical factors of process repeatability. The fibers must be centered above each bath properly to avoid collisions between the fibers and the walls of the bath as the fibers are dipped into the chemicals. There must also be enough clearance between the fibers and the bath walls to avoid the meniscus along the walls of the bath, maintaining a consistent etch between baths.

The chemical baths must not spill during movement. Loss of fluid would change the height of the chemicals in the bath and alter the length of fiber that is etched. Additionally, the surface of the chemicals must be stable when the fibers are dipped to avoid etching variations in the fiber cladding.

The following issues must be addressed to satisfy the aforementioned repeatability factors:

1. Vibrations may cause misalignment of the FCT or baths
2. Vibrations may disrupt the surface flatness of the chemical baths
3. Fatigue may degrade machine alignment over time
4. Rapid bath acceleration may cause chemical spilling
5. Debris may build up on moving components, disrupting smooth FCT or bath movement
6. Chemical spills may corrode any part of the machine, decreasing mechanical precision

## 2.8 Design Principle: Usability

The expected users of this machine are Lumentum's technicians, so the machine’s interface must serve them and improve over the current method used. The machine's systems are required to be user-friendly to increase technician safety and reduce confusion or mistakes made while using the product.

The technicians are responsible for loading the chemicals and the FCT into the Automated Chemical Etching Machine (A-CHEM). To facilitate this process and protect the technicians, the A-CHEM must leave space for the technician to safely prepare the chemical baths to further reduce chemical exposure time. The machine's design must minimize the need for technicians to reach under or around machine parts to reduce safety risks such as pinching and entrapment between moving assemblies.

To improve the functionality of the A-CHEM, a one-touch operation system will be used to initiate the window etching process. To streamline the process for the technicians, a simple control board with three main functions, start, reset, and emergency stop, will be used. Once the system is loaded with the proper chemicals and the FCT is secured to the machine, the fume hood door must be lowered to separate the technician from the fumes generated by the fiber etching process. To begin the process, the start button is depressed; if the machine, at any time, behaves differently than the prescribed process, the emergency stop button must be pressed. This will trigger all systems to shut down allowing the technician to remove the chemicals and then diagnose the errors in the system. Once this is completed, the reset button can be pushed to send the bath sleds to their original locations. During operation, the machine has methods of self-check to avoid possible failures. Limit switches and photogates, utilized along the length of the machine and on each cart, keep the baths from going too far and forcing stops at various checkpoints. These components increase the autonomy of the machine and ensure the technician does not need their undivided attention on the process, unlike the manual method.

Another key factor in the GLOWS CO design is the maintenance of the machine. This will affect the types of subsystems selected for lateral and vertical movement in the system. For both subsystems, minimal and less intrusive maintenance will improve the quality and user experience of the A-CHEM. The machine is expected to have an operational lifetime of 5 years, so high quality parts and materials must be used to improve the system's corrosion resistance and fatigue wear. By utilizing these types of parts, the A-CHEM will need to be serviced less often and the frequency of replacing parts will be minimal.

## 2.9 GLOWS CO Solution User Scenario

The GLOWS CO Solution User Scenario is as follows:

1. The technician fills all of the baths and places them into slots in the A-CHEM.
2. The technician places the FCT into the A-CHEM.
3. The technician pushes the start button.
4. The technician keeps reduced attention to the process until the A-CHEM is finished.
5. The A-CHEM executes the window stripping process.
6. The A-CHEM resets to its starting position and turns itself off.
7. The technician removes the FCT.
8. The technician disposes of the chemicals.

This solution exposes the technician to the chemicals for roughly 10% as much time as the current process. The technician is never exposed to heated baths which pose an increased safety risk. Finally, the technician spends less time carrying out the window stripping process and is free to work elsewhere for roughly 90% of the process. A drawing that was used while formulating the user scenario is in Figure 5.

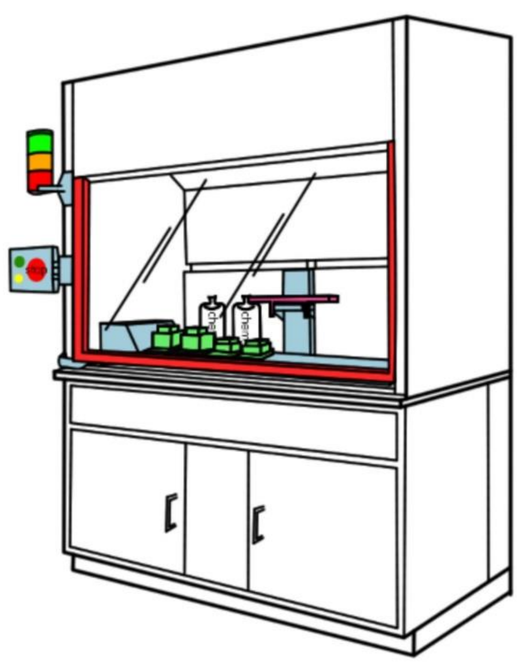

Figure 5- A-CHEM in Fume Hood during User Scenario

## 2.10 Design Priorities

GLOWS CO has informally prioritized a number of design guidelines to evaluate design choices and shape new designs to meet the 3 design principles of safety, process repeatability and usability.

Designs that do not require the technician to reach under or around any machine components are prioritized. Reaching awkwardly around or through the machine increases the risk of the technician spilling chemicals or entrapment between two moving assemblies.

To enhance process repeatability, designs with a minimum number of moving parts have been prioritized. Moving assemblies have a higher likelihood of mechanical failure due to dynamic loading scenarios. Additionally, their increased failure modes, such as alignment or binding issues, can easily disrupt the operation of the machine and requires a higher level of maintenance to continue operating smoothly. Reducing the number of moving systems reduces the overall chance that the machine fails to accurately perform its mechanical functions. Specifically, designs that require custom gear trains or custom mechanical assemblies like scissor lifts or cam systems were considered but rated lower than those without such systems.

Designs that take up less space in the fume hood and maintain a low overall profile were prioritized. Reducing the machine's center of gravity significantly reduces risks of safety hazards such as tipping as well as making the system easier for technicians to load and maintain.

A-CHEM designs with stable bath and FCT movement systems better met the design principles than ones that were not. The systems must resist vibrations that could disrupt the surface of the etching chemicals which must be flat and still. The movement systems must also resist deflection. To do this, all movement systems must be supported with guide rails to minimize the impacts of offset weights. The rails must be precise and rigidly attached to the frame of the machine.

Additionally, designs that utilized a high proportion of prefabricated parts instead of custom assemblies were preferred to reduce costs and simplify maintenance and replacement of subsystems.

## 2.11 Primary Subsystems

The Automated Chemical Etching Machine (A-CHEM) will have three primary subsystems: bath movement, FCT movement, and system controls.

The bath movement system will move the chemical baths into position with the FCT. It must hold the baths securely and move slowly and steadily to not spill fluids. The heated baths weigh approximately 1 kg so the system must be stiff enough to support their weight. The baths must be moved accurately so they properly align with the FCT. The guides for the bath movement must be precise to assist with preventing the fluids from spilling as well as to increase the accuracy of movement. The bath movement system must actively sense the location of the baths, using rotary encoders on the motors and linear encoders on the baths. Additionally, the motors that move the baths need to be precise enough to ensure alignment with the fibers.

The FCT movement system will dip the fibers into the aligned bath. It must securely hold the tool so that it does not shift during operation. This subsystem must not deflect under the load of the tool, but it must be able to move the FCT up and down. The rails that guide the system up and down must be precisely aligned and have sufficient surface smoothness so that the no vibrations impact the movement or deflect it from its predicted path. The system must also track the movement of the FCT to verify its location at all times. The motor that controls this system must have a high enough precision to meet the requirements for dipping accuracy.

The power and controls system will supply power and control data to the bath and FCT movement subsystems as well as to the bath heaters. This system must be capable of processing the control algorithms in real time; i.e., without computer lag. The system must also sufficiently supply power to the heaters, but that power will be strictly on/off. The system must be capable of processing sensor input from the rotary and linear encoders in the FCT and bath movement subsystems and continue to supply precise control data to the motors in those systems. Additionally the power and controls system must be able to interface with the user through a user control box.

The subsystems and their constituent parts will interact with each other. Figure 6 shows how the subsystems of the A-CHEM interact physically and digitally. The FCT movement subsystem will be bolted to the bath movement subsystem, so vibrations, if they occur, would be transferred between the systems. Likewise, the motors within each subsystem will transmit vibrations to the frame they are attached to which will transfer vibrations to the other components attached to the frame. Heat from the bath heaters will also transmit into the bath cart, and any chemicals spilled from their baths will fall onto the carts and possibly into the bath movement frame.

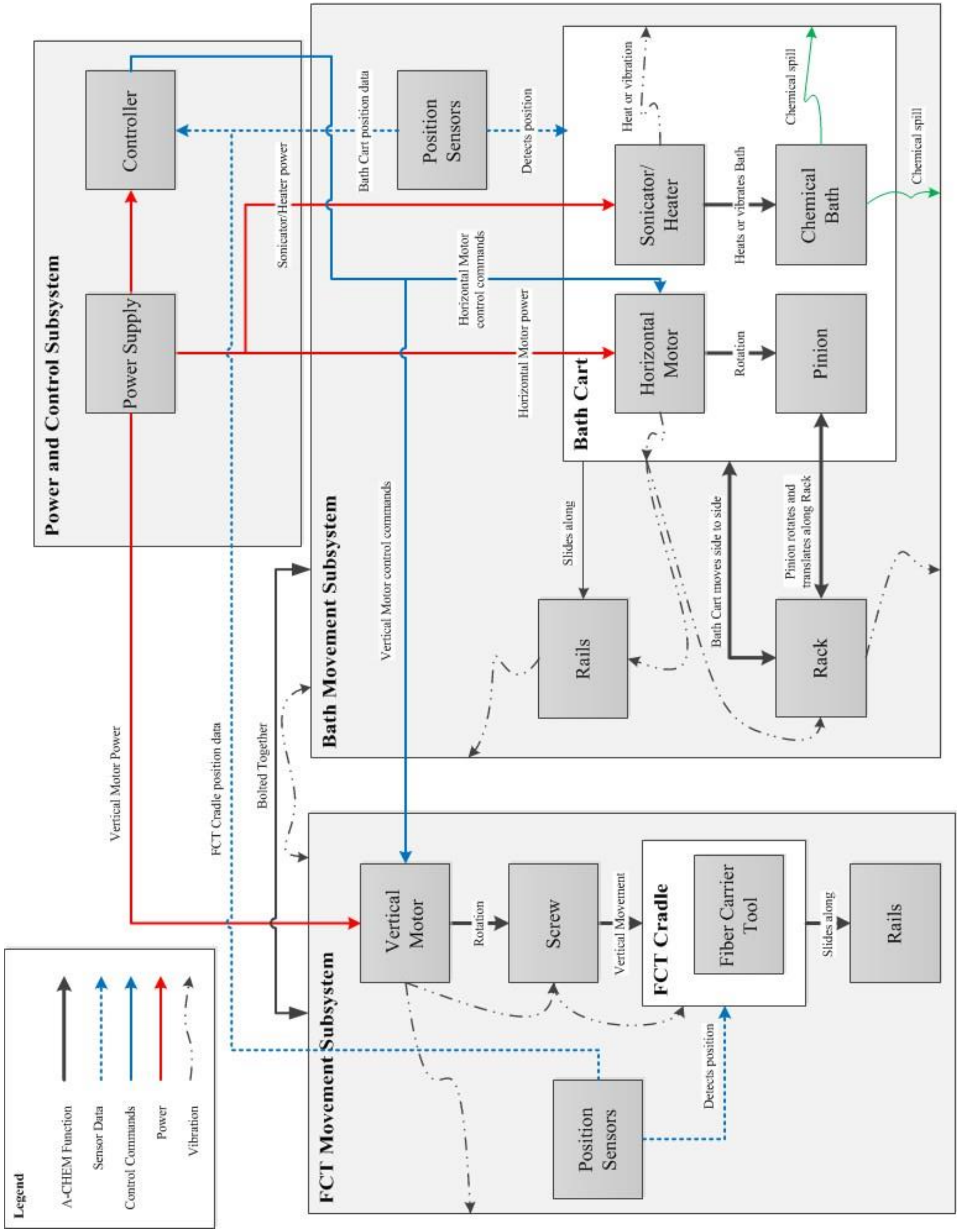


Figure 6- A-CHEM Layout Diagram Separated into Subsystems

## 2.12 Project Challenges and Constraints

One of the biggest challenges to this project is the lag time in communication with Lumentum. GLOWS CO met with Lumentum every 2 weeks and has little communication in the time between those meetings. Getting confirmation and paperwork to clear official channels can thus take long periods of time because our contact, David Vecht, must clear all of our paperwork with Lumentum's legal team before we get it back. Two examples of this were, getting NDA agreements, and the time required to get design requirements. GLOWS CO started initial work on this project during the summer of 2015 and was able to observe the manual stripping process in order to gain a better understanding of the process. This allowed GLOWS CO to begin work on designing the A-CHEM, but an official set of design requirements was not received until 6 weeks after this initial observation. Those then had to be reviewed and discussed by GLOWS CO before being returned to Lumentum for final confirmation. The NDA's took a similar amount of time to fully complete. It took three weeks to receive the papers, and an additional two weeks to sign and return.

The NDAs highlight another constraint for GLOWS CO, confidentiality. The process that GLOWS CO is automating for Lumentum is a trade secret, and GLOWS CO needs to respect that in the presentations and reports that are due. Trade secrets are an interesting legal entity in that they can be protected and are the legal property of the owning company until they get out and become public information. At that point they are no longer a trade secret. Trade secrets are usually general enough that they are not patentable, or the patent process would reveal them in such detail that other alternative methods would be easy to derive from the information. This legal status usually applies to corporate recipes, manufacturing processes, and other process oriented information.

Lumentum understands that GLOWS CO's disclosure of the A-CHEM in its entirety is essential to the senior design project parameters, and has agreed to release dimensionless images and 3D models of a select few of its components to support GLOWS CO's demonstration. Lumentum does not wish to reveal the intricacies of its process though. This means that GLOWS CO must conceal elements such as the exact chemicals used in the process, the number of baths used in the process, and the timing on each dipping, among others. GLOWS CO therefore must be careful to censor the released information to respect this secrecy, editing all published documents to reflect the barrier between public information for GLOWS CO's project and private information relating to the process itself.

Developing an accurate and realistic schedule to follow presented a difficult challenge to GLOWS CO  This is because of the relatively little experience GLOWS CO has with project management or schedule estimations. GLOWS CO developed a schedule with expectations of very rapid progressions in the design process, but found as the quarter progressed that many sections had a tendency to take longer than anticipated. Elements of the initial design process took far longer than expected and part selection was challenging as GLOWS CO learned about integrated systems. GLOWS CO recognized this delay early though and accelerated the project accordingly. Large buffer zones and over estimations of required time were incorporated into the schedule despite the rapid expectations, meaning that GLOWS CO could fall about a week behind schedule, and still meet the deadlines set by both the University and by Lumentum.

The complexity of this project posed a challenge in and of itself. This project required a lot of system integration and dealt with a wide variety of mechanical constraints in construction. The nature of autonomous systems also meant that the project incorporated the electrical and computer engineering fields in addition to its mechanical engineering core. This meant that the project required a high degree of dedication from the members of the GLOWS CO team to bridge the knowledge gaps and create a working product. The team members, having varied technical experiences in industry, were quite able to meet the challenge.

## 2.12.1 Budget

The budget of this project will be split into the different phases that lead up to and include the final production model. The financial phases of the project are design, prototyping refinement, and the final product. The split between these phases is roughly 5%, 45%, and 50% of the total budget, respectively. The expectation for the design phase is to use minimal financial resources as most modeling will be done in SolidWorks for visualization. Use of the SolidWorks software package is available to all students through the Engineering Design Center at no additional cost. The cost accumulated in this phase will most likely be due materials for a half-scale mock-up of the product (likely foam core and wood) used to more easily determine accessibility of subassemblies and their interfaces. The prototype phase will consist of purchasing and testing simpler concept parts to assemble a workable design that meets most of the required functions. The final product design will require all parts and assemblies are at full machine and clean room specifications, meaning the end results will cost more than the testing portion. An expectation of the projected cost breakdown for the final product can be found in the Appendix.

## 2.12.2 Timeline

While Lumentum was not directly involved in the setting of a project timeline, Lumentum was given a deliverable date of July 2016 for a final product. To meet this deadline, initial design and selection phases were completed in the Fall Quarter. By maximizing the time for design, fewer resources were wasted during the prototyping stage testing systems that would not be used in the final design. This prototyping phase took a considerable amount of time to ensure all subsystem met the prescribed design criteria. Additionally, since a significant number of parts were prefabricated, the timetable for construction was dependent on the arrival time of orders as opposed to fabrication time. Due to the clean room specification of the machine, custom parts underwent more rigorous development and cleaning; they also had to be manufactured by certified machine shops, which increased part delivery time.

The final stage of the GLOWS CO project was the preparation for the Senior Design Conference, beginning in the first week of April. During this phase, GLOWS CO developed their presentation slides and demonstration as well as the final drafts of the project thesis. After these two deadlines passed, the final month of the project focused on the construction of a final product for Lumentum, which extended into the summer of 2016.

### 2.12.3 Design Process

The primary design process for this project was to meet as a group to discuss requirements, goals and constraints, and then individually brainstorm and sketch these designs. The sketches and a description of each design were then presented to the group. The group then made suggestions and the design was refined and resubmitted to the group. To limit the number of designs, each team member worked on only two to three designs at a time. Once the number of feasible designs was reduced to around four, they were evaluated using decision matrices. Using a weighting method, the designs were further narrowed down to two that incorporated synthesized ideas from previous designs. The group then split to work on refining and improving these ideas for use as the final design choice. At this stage in design, each concept was 3D modeled using the Computer Aided Design program Solidworks to better visualize the end product. This process required continuous review and GLOWS CO was confident that the design given at the end of this CAD process was ready to begin prototyping.

# 2.13 Initial Designs

Initial brainstorming by GLOWS CO produced a plethora of subsystem designs, as exemplified in Figure 7 that could be further developed. In order to produce a design that could be refined into a working product, additional brainstorming and designing sessions were utilized. A sampling of the initial designs and their main design characteristics are listed below. Also included is a brief description of how these designs addressed the design principles and were either synthesized into future designs or eliminated.

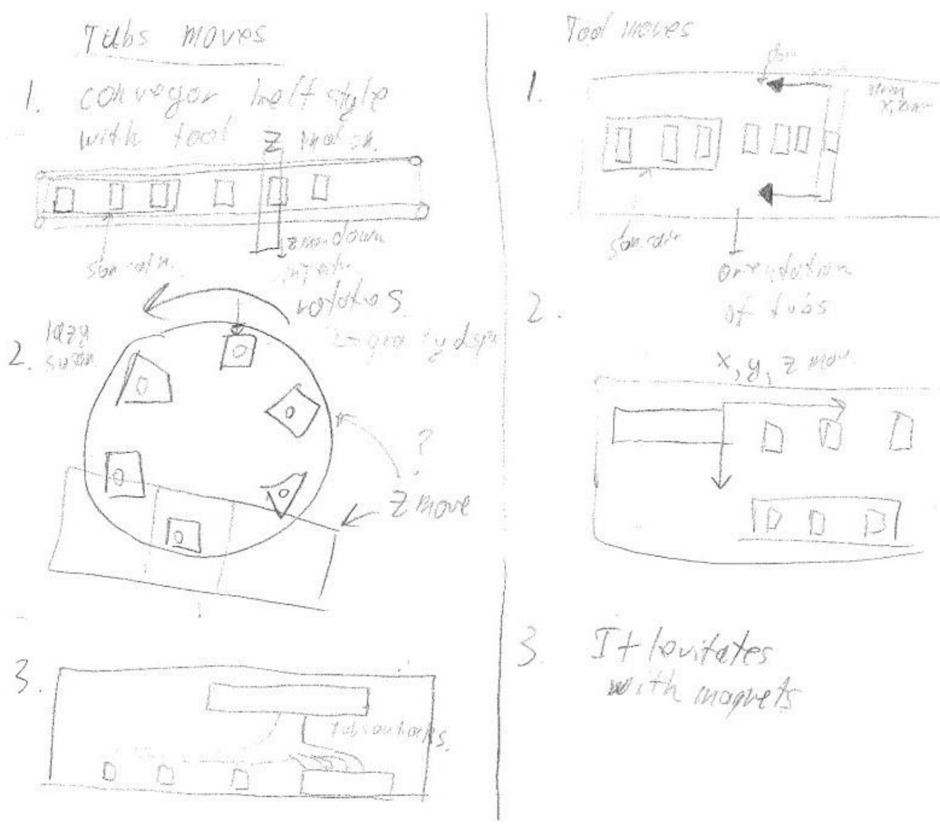


Figure 7- Images of Initial Design Sketches for Multiple Processes

### 2.13.1 Gantry Slide

Figure 8 shows one of the earliest designs, a gantry-slide designed to translate the FCT and raise the stationary baths to the FCT. In this tool, the FCT would be secured to an overhead framework operated using a lead screw system to maneuver the tool along the rails over stationary chemical baths spaced beneath the framework. The baths are then raised using an unspecified lifting mechanism to dip the hanging fibers into chemicals and then lowered so that the system could drive the FCT to the next bath position. This process is repeated until all baths have been used. The primary advantage of this system is the efficiency of space it had, making the system more compact. However, the steps required to reset the position of the FCT made the design cumbersome for operation, reducing the usability. Also, the overhead configuration of the frame hindered the loading and unloading of the chemical baths before and after each process, further limiting usability. For these two reasons, this design was removed from further consideration

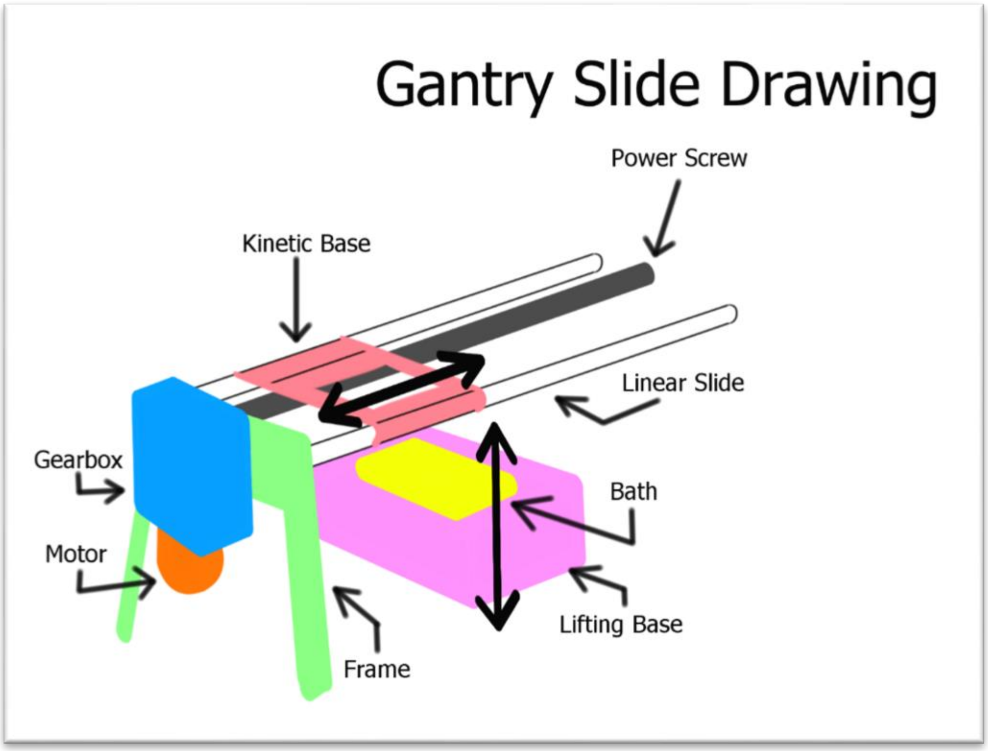


Figure 8- Gantry Slide Initial Drawing

## 2.13.2 Rotary Bath

Another initial design utilized a rotary base to cycle through the baths, as seen in Figure 9 above. All of the baths are loaded and secured to a circular base. After loading the Fiber Carrying Tool, the tool would dip into the baths and the base would rotate after each bath treatment. This design would require only two motors, one for the base and one for the FCT movement system. However, this system has some key design flaws that make it undesirable for use within the fume hood. The loading and unloading of the chemical baths could be a potential safety hazard because reaching over other filled baths or movement of the rotary subsystem is required. Additionally, this might have created an electrical hazard because the twisting motion might have damaged the rigid wires connecting the heating blocks to the power supply.

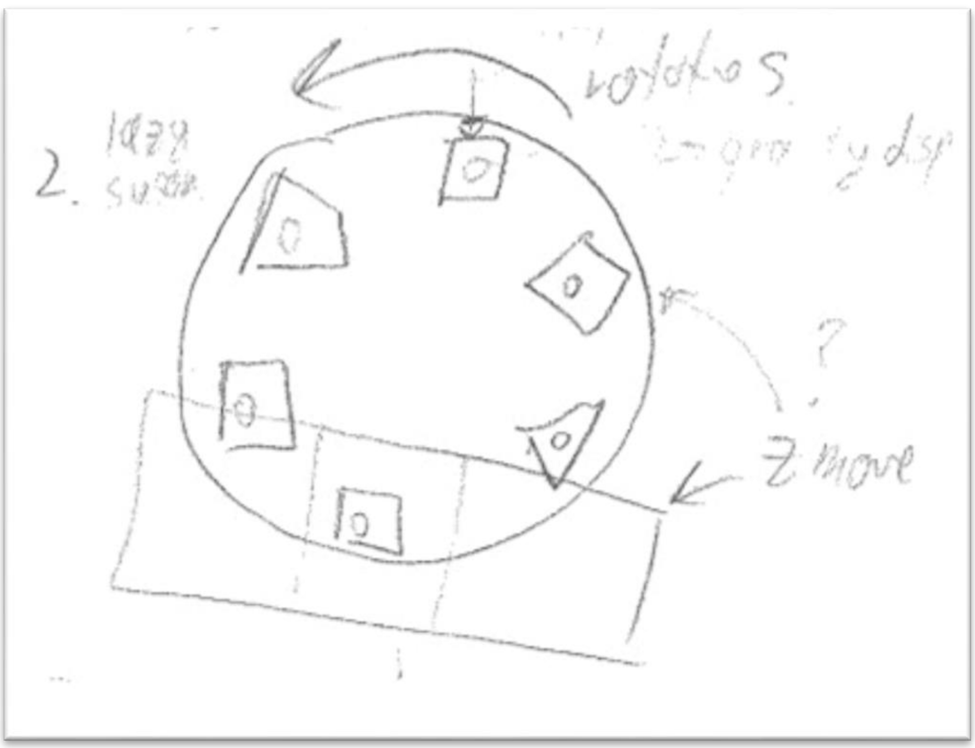


Figure 9- Rotary Bath Design Sketch

## 2.13.3 Cable Car

One of the other initial designs for the A-CHEM was a cable car design, as seen in Figure 8. This design is similar to the rotary base design, with the baths loaded onto individual carts set on a track. This design would be powered by some form of a pulley system (likely a power cable), powering and pulling the interconnected baths around a circular track. When a car was properly situated beneath the FCT, a vertical movement system would dip into the solvents and remove the fibers once the step was complete. From a usability and safety standpoint, this design faces the same issues when it comes to electrical hazards as the rotary system. In addition, the process repeatability raised a problem with the interconnected cars carrying the baths, where the lack of control over individual cars leads to a lack of accuracy for bath placement. These factors led to the elimination of this design.

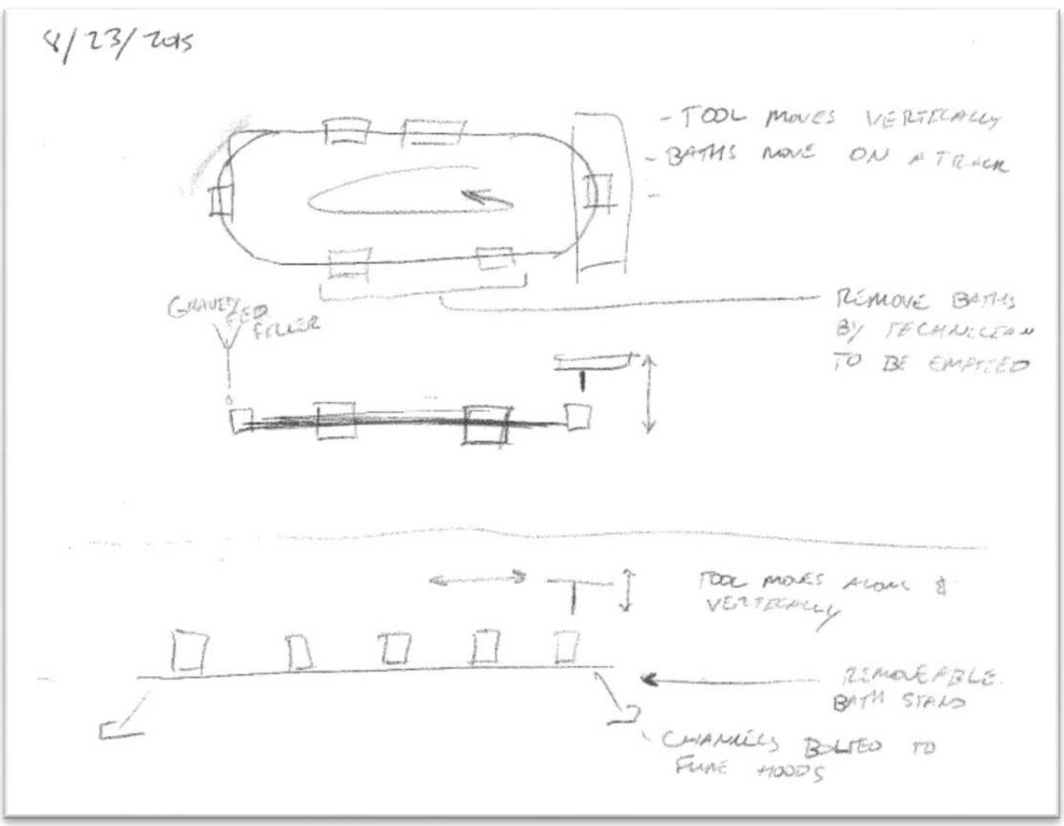


Figure 10- Cable Car Design Sketch

## 2.13.4 Fork-Car

After the initial brainstorm and the establishing the design principles of safety, process repeatability, and usability, many of the designs were eliminated as viable options for the current design. However, the design concepts were refined into more developed conceptual designs. One of these designs is pictured in Figure 11, named Fork-Car.

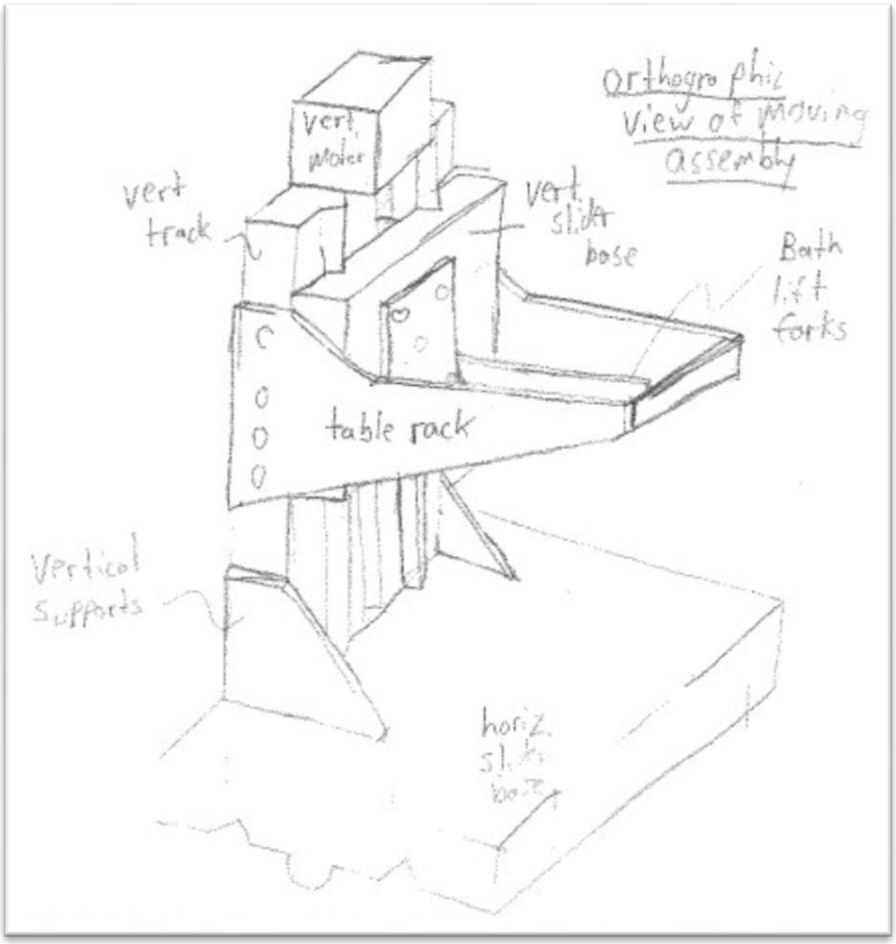


Figure 11- Fork-Car Design Sketch

The Fork-Car design had stationary baths mounted to a baseplate, and the FCT was mounted to a forklift lifting mechanism and moved along a rail also mounted to the baseplate. This design was ultimately abandoned because of physical constraints that prevented the baths from being set up in a way which would allow them to be dipped correctly.

## 2.13.5 Apollo

After eliminating more A-CHEM designs, two final designs were selected for a final design review to select the current design. Both of these designs drew from previous design iterations, creating two synthesized designs nicknamed Apollo and Artemis. At this stage of the design process, a rough 3D model of each model was generated as seen in Figure 12 and 13.

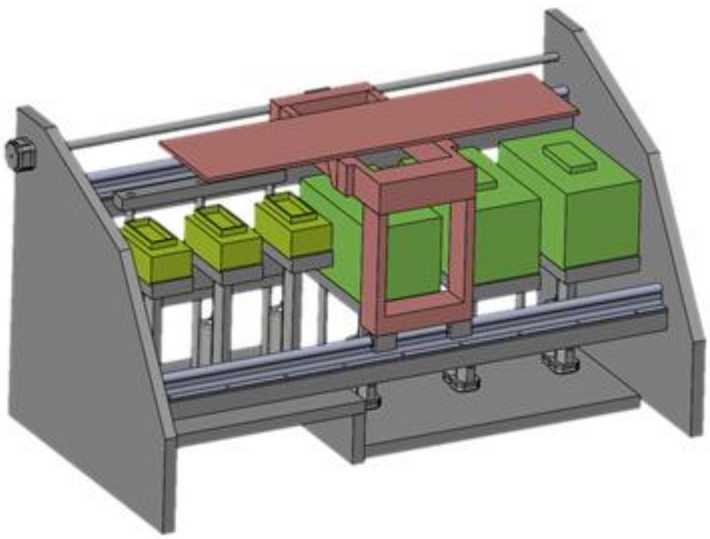

Figure 12- Apollo Design CAD Model

Apollo was designed to translate the FCT above stationary baths using a custom FCT carrier. Once the FCT was in place, the baths would be raised with linear actuators that were mounted beneath them. This design addressed a number of design principles, namely that of safety and system repeatability. The design itself is compact and rigid, designed to prevent chemical sloshing from the bath movement. With vertical movement, the sloshing risks of the chemicals are significantly lower than with lateral movement for the baths. Additionally the design addressed the problem of the Gantry-Slide mentioned earlier in this section; the front linear slide was moved to a lower position to make it easier to load the chemicals and chemical baths into their respective spots in the A-CHEM. Despite this improvement, the usability of this design was hindered by the FCT carrier. The FCT carrier made the act of loading the FCT more difficult.

### 2.13.6 Artemis

As mentioned in the previous section, the GLOWS CO team chose to work with the design nicknamed Artemis. In the Artemis design, the baths are moved laterally while the FCT is moved vertically. Each bath and its associated heater is mounted on a powered sled as seen in Figure 13.

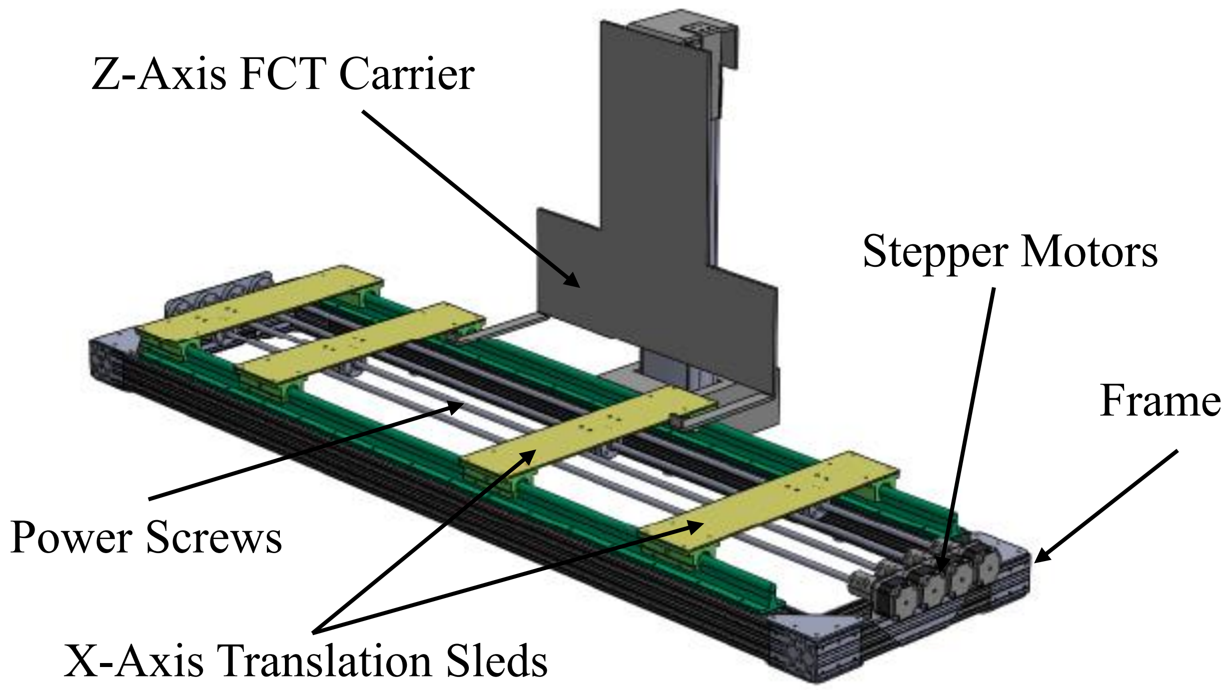


Figure 13- Isometric View of Artemis

When the process was started, the sled would move the first bath to the center position on the track beneath the FCT. Here, the FCT will wait a period of time before dipping to allow the chemicals to settle within the baths; this was estimated to be in the range of 10-20 seconds. After the liquid settled, the process would continue with the lowering of the FCT, dipping the fibers into the chemical baths. After the prescribed time had passed to properly window etch, the FCT would be raised to its resting level. The bath sled would then move to the opposite end of the track to clear room for the next bath. This process was repeated for each bath. This sequence of events is shown in Figure 14.

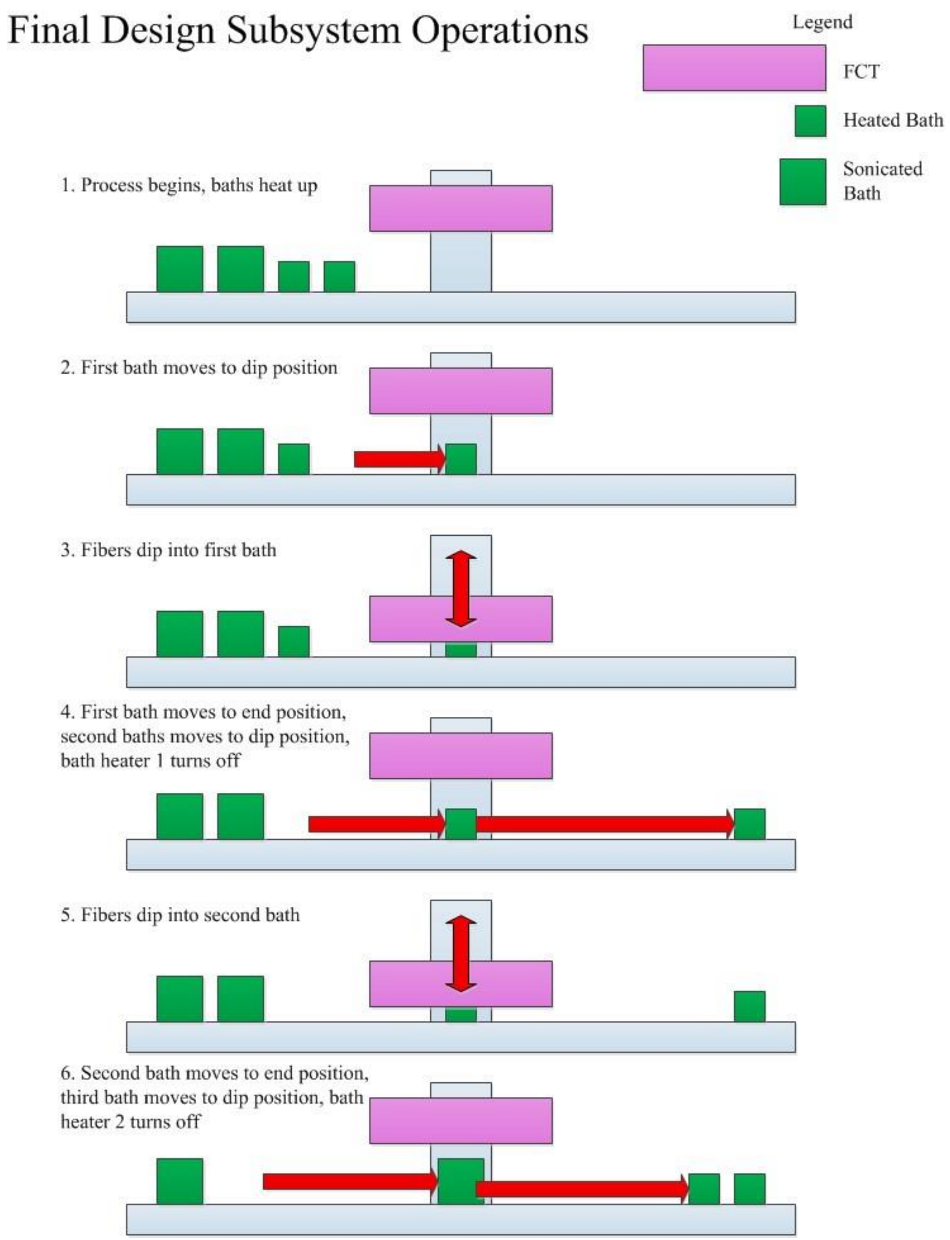


Figure 14- Artemis Subsystems Process Operation from Start to Finish

This design had several advantages over the initial designs: it had an open design, heavy usage of prefabricated parts, and efficient use of space in the fume hood. The orientation of the bath movement system greatly improved the safety and usability of the machine because there are no obstructions within the technician's operating space. With this configuration, the baths and FCT could be easily unloaded and loaded. This would help avoid spills when filling the baths and prevent overextension when loading the FCT onto its cradle. Although the horizontal motion of baths can be undesirable because of sloshing, the speed and accelerations could be controlled in such a way as to minimize this potential problem.

Most importantly, the technician would never have to place his or her hands between two moving parts during normal operation. The technician would be loading the baths in the working area of the A-CHEM, and all of the moving components are located either below or behind the working area. This configuration reduced the chances of pinching or entrapment between components, improving the overall safety of the tool.

Another advantage to this design is that it made heavy use of off the shelf parts, minimizing the need for custom parts. Custom parts are very expensive compared to prefabricated parts because they require a larger number of hours to produce, especially when stricter tolerances are required. Mass production improves the cost effectiveness of the design through economy of scale. In this design, Figure 13, the only parts that were custom made were the FCT cradle, the bath sleds, and the stepper motor mounting brackets. The projected cost for this design was $6,883 (Appendix F), which was below GLOWS CO's target range of $7,000 to $12,000 largely due to the number of prefabricated parts. This cost was expected to rise as not all of the system’s components were fully specified by the time the quote was generated.

Lastly, the slim profile of the tool also meant the baths are nearer the operating technician's waist. This is an ergonomically comfortable level for humans to work at. The FCT loading position is 20cm above that, still in an easily accessible and ergonomically comfortable level to work at. This low profile and effective use of space in the fume hood also gave space to store the chemicals inside of the fume hood. This would make filling the baths safer and easier by giving easy access to the chemicals. The design also left space for protected containment of the electronic components outside of the fume hood

# 3. Current Design

The current design, called the A-CHEM, was built on the Artemis design seen in Section 2. The A-CHEM made several improvements on the core Artemis design while keeping the same general form. The changes to the design included the replacement of the stepper motor and screw drive with a rack and pinion drive system, refinement of the vertical stage and the strengthening of the frame. This design is shown in Figure 15 with the FCT and a single Heater Bath in place.

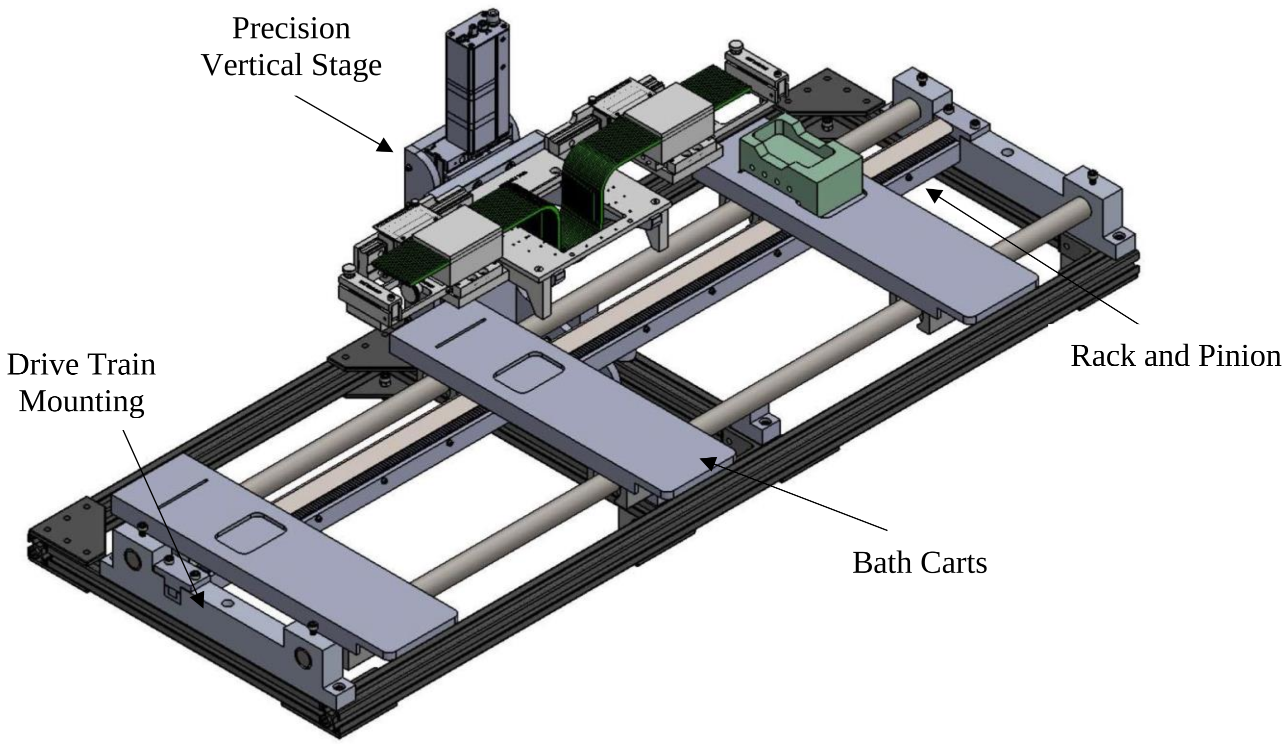


Figure 15 - Final A-CHEM Design

The operational process of the A-CHEM functioned very similarly to the operational process of Artemis, seen in section 2.6. The process started with the technician loading the chemical baths and FCT into the device. With Lumentum's hardware in place and the baths filled, the technician would activate the heater blocks to heat the chemicals. These heater blocks were assumed to be operated independently from the A-CHEM and could not be interfaced with by the A-CHEM (mandated by Lumentum). The fume hood door was then lowered to the appropriate level and the start button is depressed. The process would not start if the fume hood had not been lowered properly, this would be confirmed by sensor verification. The operation would begin on a delay, such that the heater blocks would have sufficient time to reach their full temperature. Once the delay period had elapsed and the operating temperature reached, the first sled would move the first bath to the center position on the track beneath the FCT. This center location would be verified by an optical switch attached to the frame. The process is then paused 10-20 seconds to allow the chemicals to settle. The exact time period varies due to the fill height of each bath and can be tuned accordingly. The exact fill heights are considered trade secrets by Lumentum and are concealed by GLOWS CO's NDA, sample calculations for an arbitrarily selected bath fill height can be found in appendix B.2.

After the liquid was settled, the process would continue by lowering the FCT and dipping the fibers into the chemical baths. After the prescribed time had passed to properly window etch, the FCT would move back to its resting level. The bath sled would then move back to its starting position to clear room for the next bath. This process is repeated for each bath, and can be seen in Figure 16.

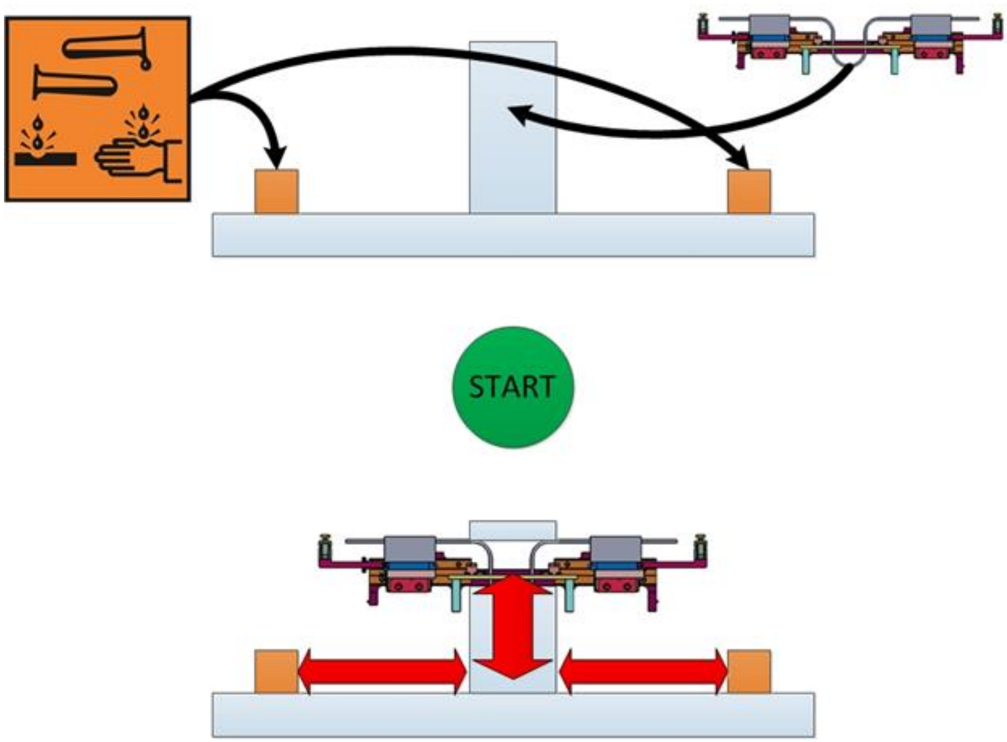


Figure 16- Subassembly Loading and Process Overview

The A-CHEM design has a number of advantages. Its construction is low profile, giving easy access to the machine for both maintenance and loading. Similar to the Artemis design, since the frame and the bath carts are close to the bed of the fume hood, it keeps the loading location slightly above waist level. This also applies to the vertical stage which is lowered to frame level when not in use. The A-CHEM is also a very modular design. The bath carts have all been designed identically, including sensor mounting locations, allowing for the installation of as many bath carts as can fit onto the design, at this point 6. The change from a stepper motor and lead screw design to a rack and pinion design was key in enabling this modularity.

The desire for modularity was not the only reason for the change in drive system. The stepper motor and lead screw drive from the Artemis design was abandoned in favor of a rack and pinion design to save on cost, minimize disruptive vibrations, increase spill durability, and to allow for a more modular design. While researching lead screws for the Artemis design, it was found that lead screws with the required length of 4 feet or greater were very difficult to source in corrosion resistant materials; the cost per unit of approximately $400. This led to a cost of over $1600 for the lead screws alone, not including the cost of the drive motors. This cost was deemed excessive and another solution was sought. Due to the size constraints of the fume hood and the difficulty in finding long lead screws, reducing to a single lead screw that moved all bath carts was not possible. To allow for sufficient space for the chemical baths on a single lead screw, the lead screw would need to be long enough to accommodate the travel path of all carts on the system, too long for the size constraints of the fume hood. To compress the space required for each bath and to allow for independent movement of each bath, a rack and pinion drive system was selected. This system allows for the baths not in use to stack in a compressed manner at the ends of the track and not underneath the FCT. This prevents fumes from rising and either damaging the FCT or corroding the protective cladding of the fiber optic cable in undesired locations. The rack sourced for this prototype costs $79.37, significant savings compared to the cost of a lead screw, and allows for carts to be added or removed at will as space allows. Additionally, the geometry of the rack allows for additional support of the rack to help increase rigidity and reduce vibrations, as will be seen in later sections.

There were 2 other major changes from the Artemis core design. The first is the replacement of the lifting column with a precision actuator from Zaber. This modification gave the A-CHEM increased dip accuracy in a compact form. The change is covered in more detail in the Vertical Translation subsystem (Section 4.4). The other change is frame strengthening. Two additional cross members have been added near the center of the frame. These serve dual purposes: to increase frame rigidity and to provide additional mounting space for the vertical translation subsystem.

The longevity of the A-CHEM depends highly on the materials used in its construction due to the strenuous environmental conditions that it must operate under. While the prototype frame has be constructed out of less durable 6061 extruded aluminum tubing, the machined parts have be primarily made out of 6063 aluminum for its corrosion resistant qualities. Additionally the final design has a frame specified for construction from 6063 U-channel tubing, and all aluminum components will be anodized to increase their corrosion resistance.  This will help to give the complete machine an expected lifetime of 5 years.

# 4. Subsystems

For ease of development, assembly, and documentation, the A-CHEM was split into four major subsystems: the control system, the power grid, the vertical translation assembly, and the horizontal movement assembly. The controls and power system exclusively deal with electronic components as well as the logic required to code the A-CHEM. The vertical and horizontal translations relate to the mechanical components which make up the final build and include a few key electronic devices.

## 4.1 Controls

The Control Subsystem acts as the regulating body for the A-CHEM. In this subsystem the logic controller is set up to receive feedback signals from the sensors that are set up in each of the other subsystems. A condensed version of this system is shown in Figure 17; the complete system can be seen in Appendix B. This subsystem is made up of the logic controller, sensors, and the motor controllers. The logic controller used in the design is the National Instruments cRIO-9063, a four module controller that allows for the complex logic that is needed to run the A-CHEM. It was chosen for its versatility, its compatibility with a variety of sensors, and its ability to run the motor controllers that were selected. The motor controllers of this system are Victor SP slim motor controllers, manufactured by Victor Control Systems. These were chosen due to their voltage characteristics, and Pulse Width Modulation (PWM) inputs. Additionally the Control subsystem must allow for inputs that are generated by the user and relayed through the User Interface.

# 4.2 Power System

The Power System consists of all of the electrical components in the A-CHEM and its control system. The main goal of this system was to convert the lab's 110 VAC power source into the DC power needed to power the motors and devices used by the A-CHEM and its control systems. A diagram of the wiring required for this project is shown in Figure 17, along with a full page version in Appendix B.

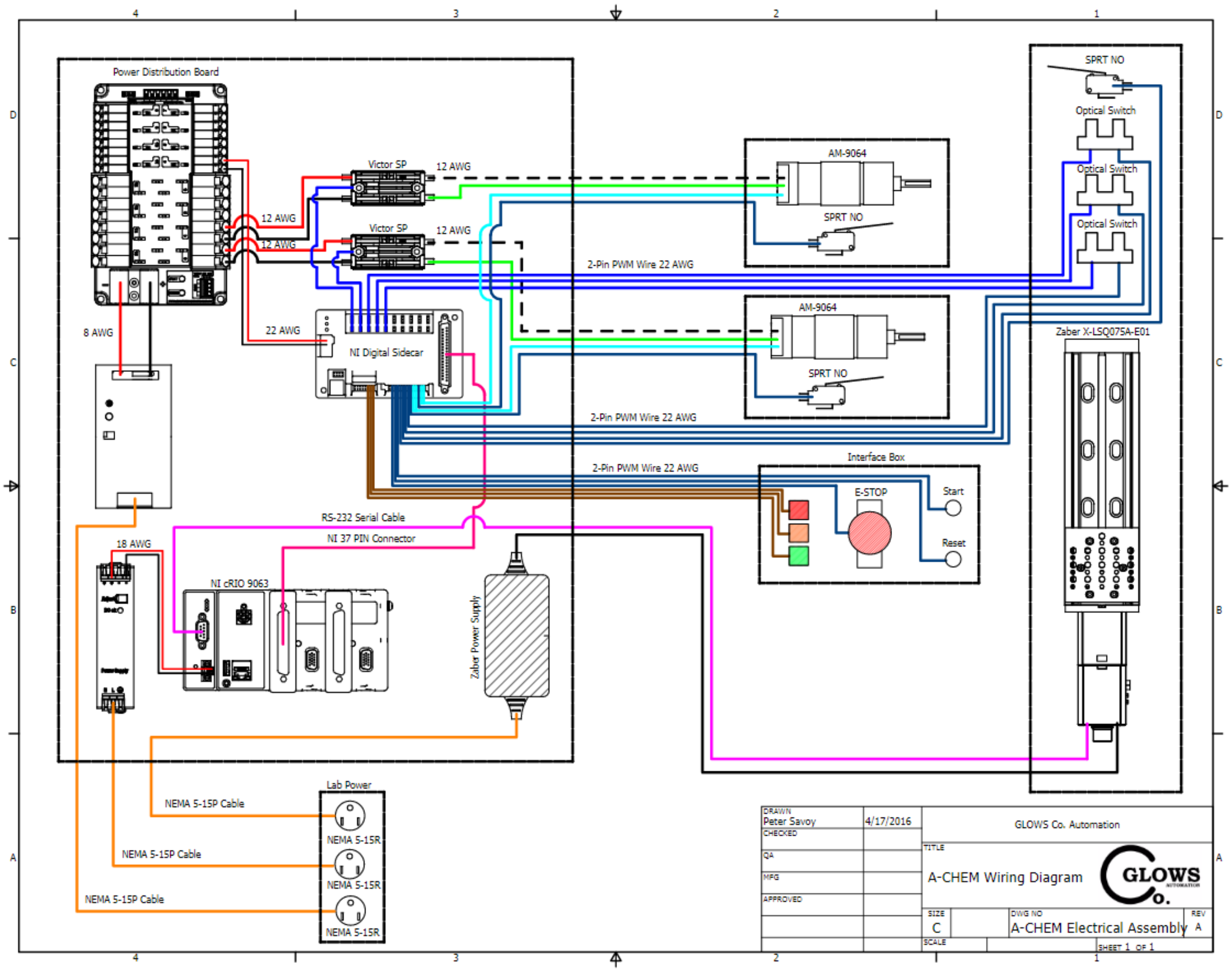


Figure 17- A-CHEM Wiring Diagram

# 4.3 Sensor System

The sensors are used for positional location the bath carts on the A-CHEM and to communicate that information to the controller. The sensors are wired to the digital sidecar, which routes their input information to the C-RIO. This information verifies that the bath carts are at the center of the track, and is used to determine if it is safe to perform the dipping operation. There are 3 types of sensors that are used in the A-CHEM: limit switch, optical switch, and encoder.

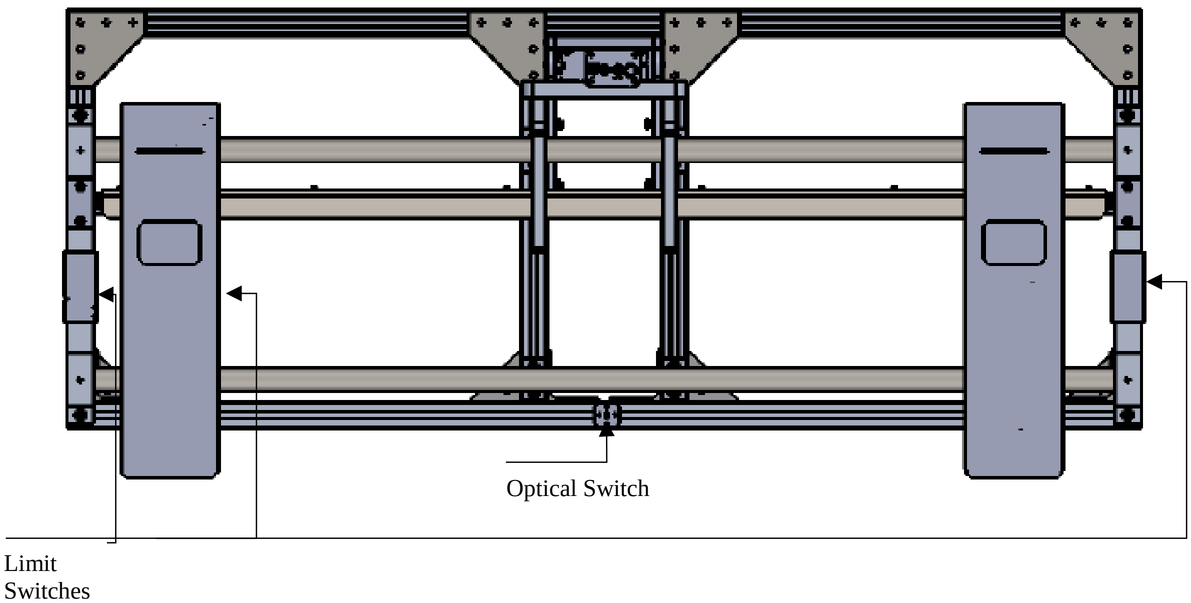


Figure 18- Diagram of Sensor Locations.

Limit switches are switches that open/close when physically depressed. The limit switches used in the A-CHEM were wired to be normally open. This means that the circuit running through them is normally disconnected which prevents electricity from flowing through. When the switch is depressed due to contact with another bath cart or the end block, the circuit is connected, and a signal is passed through the wire to the controller. In practice, this is used as binary feedback to tell the controller if something has gone wrong. If this is tripped during normal operation, then the process is stopped immediately and the problem is communicated user through the control panel. Additionally, this is used to calibrate the system, providing starting locations for the bath carts.

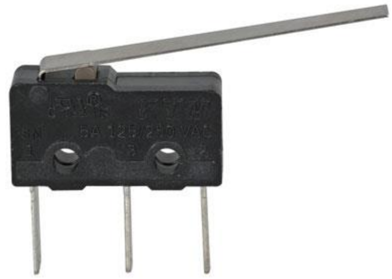

Figure 19- Picture of the Normally-Open Limit Switch [7]

The optical switch is combination of a light emitter and a light receiver that triggers a transistor. When the emitted light is blocked, the transistor acts as a switch to open/close the connection. This is mounted at the center of the frame, across from the vertical translation subsystem, and is used to set the center position on the track for calibration and to verify the bath cart position during normal operation. The optical switch used for the A-CHEM is normally closed. This function is opposite to limit switch wiring described earlier, cutting the signal when the switch is tripped. A small sheet metal tab hanging down from the underside of each bath cart acts as a trigger for the optical switch. There is only one optical switch that is used in the A-CHEM currently; however, an additional optical switch is planned to serve as the sensor to verify that the fume hood door is lowered.

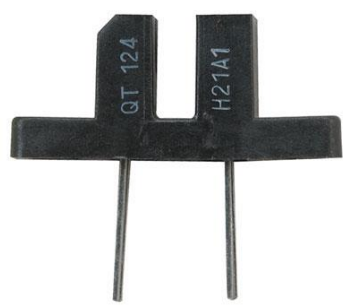


Figure 20- Picture of Optical Switch [8]

[7] "Switch Micro Straight Lever Single Pole Single Throw5 Amp @ 250 Volt AC 5 Amp @ 30 Volt DC 0.127"" BSM2-0508-13: Jameco Valuepro: Electromechanical. N.p., n.d. Web. 07 June 2016.
[8] "Digital Devices, Inc." Digital Devices, Inc. N.p., n.d. Web. 05 June 2016.

An encoder is the last type of sensor used in the A-CHEM. They are integrated into the Andy Mark motors that drive the bath carts across the A-CHEM. These function by detecting variations in the magnetic field within the sensor. As the encoder rotates, a notched ring passes in front of a permanent magnet creating distinct fluctuations. It rotates with the motor shaft and provides information as to both the rotational speed and the angular position. The changing angular position can be used to determine the number of rotations, which can be converted into distance and a position on the movement track that can be tracked. The positional information is used to provide real time information to the controller regarding the position of the cart and to give movement commands to the bath carts. The final position can then be cross-referenced with the optical switch to verify that the cart is in the center of the track. The rotational speed of the shaft can also be converted into linear velocity and controlled, ensuring same movement speeds for the chemicals transported in the baths.


Figure 21- Picture of the Encoder [9]

[9] "Digital Devices, Inc." Digital Devices, Inc. N.p., n.d. Web. 07 June 2016.

## 4.4 Vertical Translation

This subsystem is in direct conjunction with the design specification presented by Lumentum (Appendix D) to hold and improve the tolerances used in the manual process. To do this automatically, a high precision vertical stage must be used. Additionally, the tool used must be stable enough to ensure dip accuracy and keep the FCT stable during operation. This vertical stage, derived from Artemis, is intended to meet all specification criteria, but takes up a significant portion of the cost for the A-CHEM. The stage selected is produced by Zaber, a manufacturing company that produces single and multi-axis high precision stages which can be programmed and controlled with LabVIEW. Due to its very high functional capabilities and ease of programmability to the control system implemented in the A-CHEM, the Zaber X-LRQ075BL-E01-KX13C model was chosen. With a resolution capability of 0.50 micrometers and speed resolution of 0.30 micrometers/second, this tool fits all the specifications and requirements needed to keep the dip accuracy required by Lumentum. Finally, it also meets the loading criteria of the FCT when operating in the upright position needed to raise and lower the fibers.

To attach the FCT to the Zaber stage, a cradle was designed and fabricated. This bracket used the geometry of Lumentum's tool to grip, for locational accuracy, and to maintain a parallel with the floor beneath. This is shown in Figure 22, the cradle with two long arms connected to a base attached to the Zaber, as can be seen; this cradle allows for simple assembly and for very high function. By using the central plate of the FCT as a registration point, the location of the fibers can be controlled while at the same time maintaining a balanced holding point to keep the FCT from tipping. To offset the high center of gravity the FCT and motor of the Zaber would produce, a weighted machined block was designed to mount the Zaber in. Weighing over 10kg, the block moved the center of gravity roughly 8cm down, increasing the stability of the subsystem. This block was also used to designate a registration point to control the starting location of the vertical stage. By controlling where the Zaber mounts to the A-CHEM, the vertical accuracy will be more controllable and its motion will be smoother.

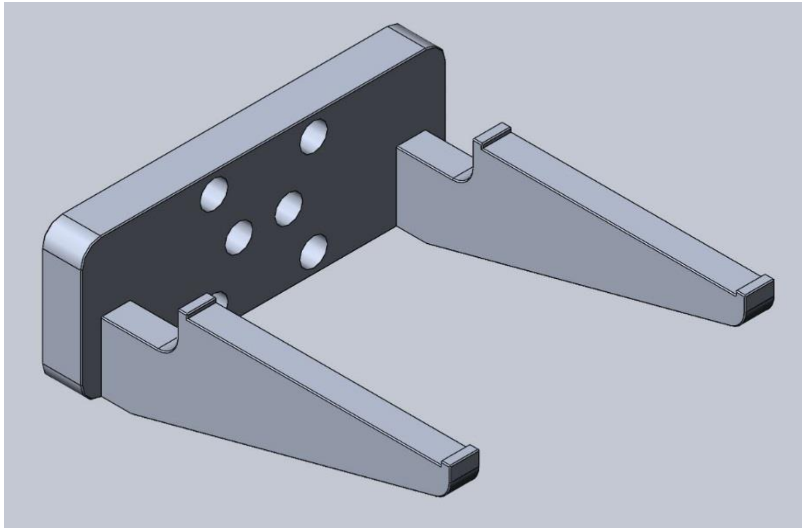

Figure 22- Solidworks Model of the FCT Cradle.

For Scale: Base Plate Length is 183mm

To increase the stability of the system and firmly fix the vertical stage to the frame, two support brackets were designed. These brackets are in the form of "L" shapes, attached to the weighted mounting block and to the frame's center, which can be seen in Figure 23. Using these brackets, the frame would be able to counteract any moments produced by FCT movement and keeps the assembly in one piece for ease of total system movement and adjustment. Additionally, the connection to the frame helps distribute any vibrations generated by the Zaber tool during its operation, greatly reducing the risk of dislocation of the FCT.

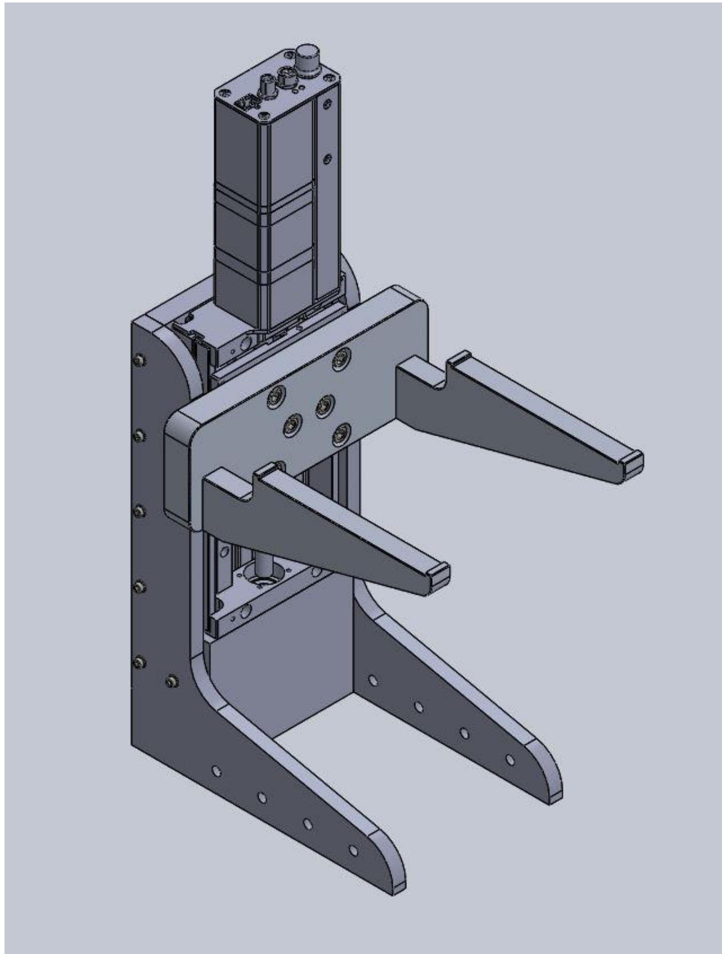

Figure 23- Solidworks Model of the Vertical Stage Subassembly.

For Scale: Overall Height of Assembly is 417mm

# 4.5 Horizontal Translation

To move the acid baths to the FCT, a frame must first be established. The frame consists of extruded aluminum channels connected together, providing a robust base for the horizontal movement system with the durability required to sustain the weight of the carts and a drive system. Focusing on the design principles from Section 2, the usability of the design must be very high, so the frame was adapted from Artemis. However, the key change from the synthesized design to the A-CHEM was the introduction of crossbars near the center, as seen in Figure 24, to mount the vertical stage rigidly.

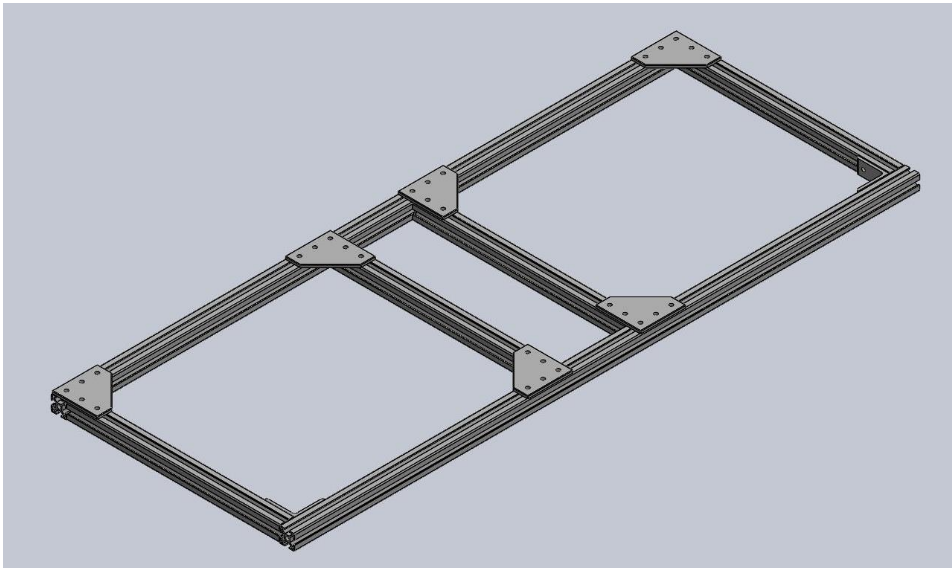

Figure 24- Solidworks Model of Frame Subassembly

For Scale: Overall Length of Assembly is 1219mm

Fixed atop this structure is the support system for the horizontal translation required to move the baths. The A-CHEM utilizes a rack-and-pinion drive system due to its higher availability and lower overall cost in comparison to the stepper motor driven lead screw design used in Artemis. To do this, a rack and two sliding rails were designed and selected to fix to the frame at two points per beam. These connection points are at the ends, supported by pillow blocks as shown in Figure 25.

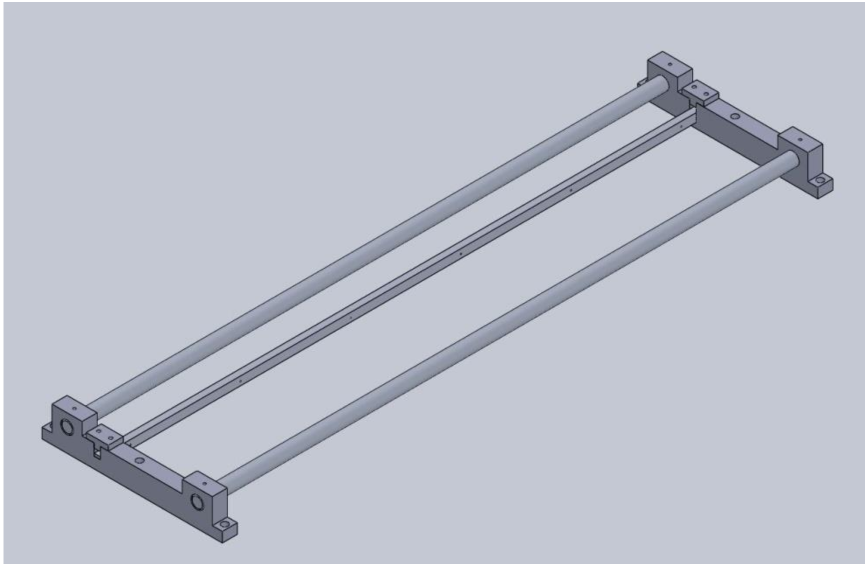

Figure 25- Solidworks Model of Beams

For Scale: Overall Length of Assembly is 1219mm

After the support structure was designed, the carts to deliver the baths to the FCT were laid out. The pinion on each cart is driven by an Andy Mark Neverrest 40 motor which has a high torque output and built in encoders for controlling. Designed around the motor, the carts required a flat base to fix the motor and sliding bearings to. The bearings used were high precision, Teflon bearings procured from McMaster. These were attached at both ends of the cart for increased stability.

To protect the electronic components below the base of the cart, a Teflon shield, as seen in Figure 26, was used. This plate also serves as the interface point for the heater elements attached to the acid baths, and so the Teflon shields are machined to create friction-fit mounting locations for the heater blocks. The Teflon material was selected because of is high corrosion resistance and low thermal conductivity. The low thermal conductivity thermally isolates the heater blocks, preventing thermal runoff into the aluminum base plate of the bath cart.

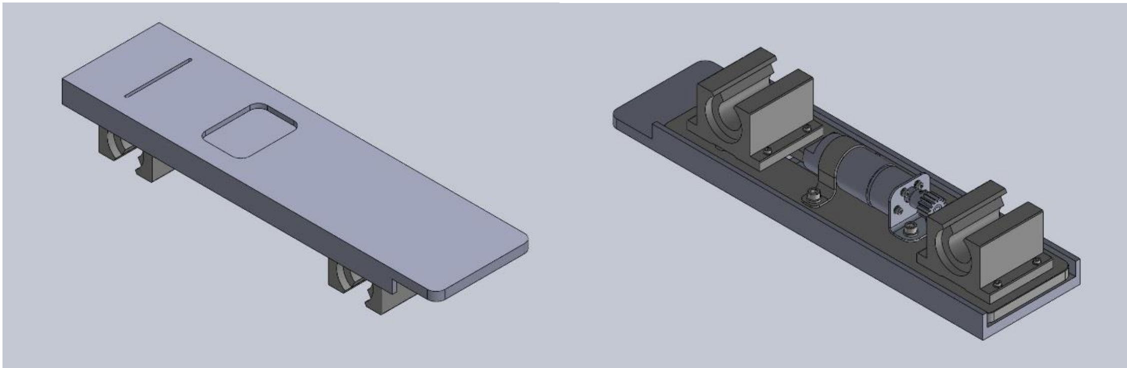

Figure 26- Solidworks Model of Bath Sled Subassembly

For Scale: Overall Length of Assembly is 424mm

After initial evaluations of this system using Solidworks and Ansys modeling, the system was deemed unsafe due to natural frequency vibrations operating around 60Hz occurring in the support structure. That is, the beams would be excited by the frequencies of the electrical grid this machine will be operating in, causing a large safety and operational hazard. For full vibration cases see Appendix B.2. To solve this design problem, the effective length of each beam can be shortened. Two support pillars were added to each beam, fixing them to the cross channels that the frame provides. By fixing the beams at two additional points, their natural frequencies were driven to a range of 200Hz-300Hz, greatly improving the operational safety of the system. As a consequence of this design change, the support beams were also strengthened in bending.

# 5. Design-Build and Testing

## 5.1 Initial Build

Once the CAD models were complete and the initial revisions made, the CAD models were made into engineering drawings for the machining process. Machining was completed by a professional machining company that specializes in metric machining. The parts were received and initial prototype building began in lab space provided to us through the School of Engineering and by our advisor Professor Marks.

This process was well documented with pictures taken during each stage of assembly to assist in the creation of Work Instructions that are part of the final delivery to Lumentum. A sample of the pictures taken is shown in Figure 27 which shows the unassembled pieces that make up the FCT Cradle which were manufactured according to the detailed drawings found in Appendix C.

Figure 27- Picture of the FCT Cradle Parts Unassembled

Another part of the build was the construction of an enclosure to contain the A-CHEM during testing. This enclosure was constructed of wood and Plexiglas to the dimensions of the fume hood that was specified in the PDS. This enclosure also acted as the electronics box because all of the electronics were attached to the inside left-hand plane of the enclosure. Additionally, the interface box with the control buttons and status light were attached to the front of the enclosure. A picture of this initial prototype assembly with its enclosure is shown in Figure 28.


Figure 28- Picture of the Completed Initial Prototype of the A-CHEM

## 5.2 Revisions

The biggest problem with the initial design was the alignment of the bearings on the bath sleds. The rails, bearings and machine frame all required precise alignment in order for the bath carts to move effectively. Even with the team's best efforts at aligning the machine, the bearings tended to get stuck on the rails as they moved.

Ideally, the pinion that drives the bath cart would be aligned in the center of the two linear bearings, but this was not possible due to size constraints. This caused the motor to push unequally on the two bearings, causing the bearings to bind on the rails.

To resolve this issue, the front bearing was replaced with a flat block of HDPE that sat on the rails, as shown in Figure 29. Because the new flat bearing had no contact with the sides of the front rail, it could not bind on the rail if it came out of alignment. However, this meant that the back bearing would be all that kept the cart straight because the front bearing could not resist torque on the sled. The decrease in precision that resulted from the change in bearings was deemed acceptable, as the lateral position of the bath carts has a large tolerance of about 1cm.

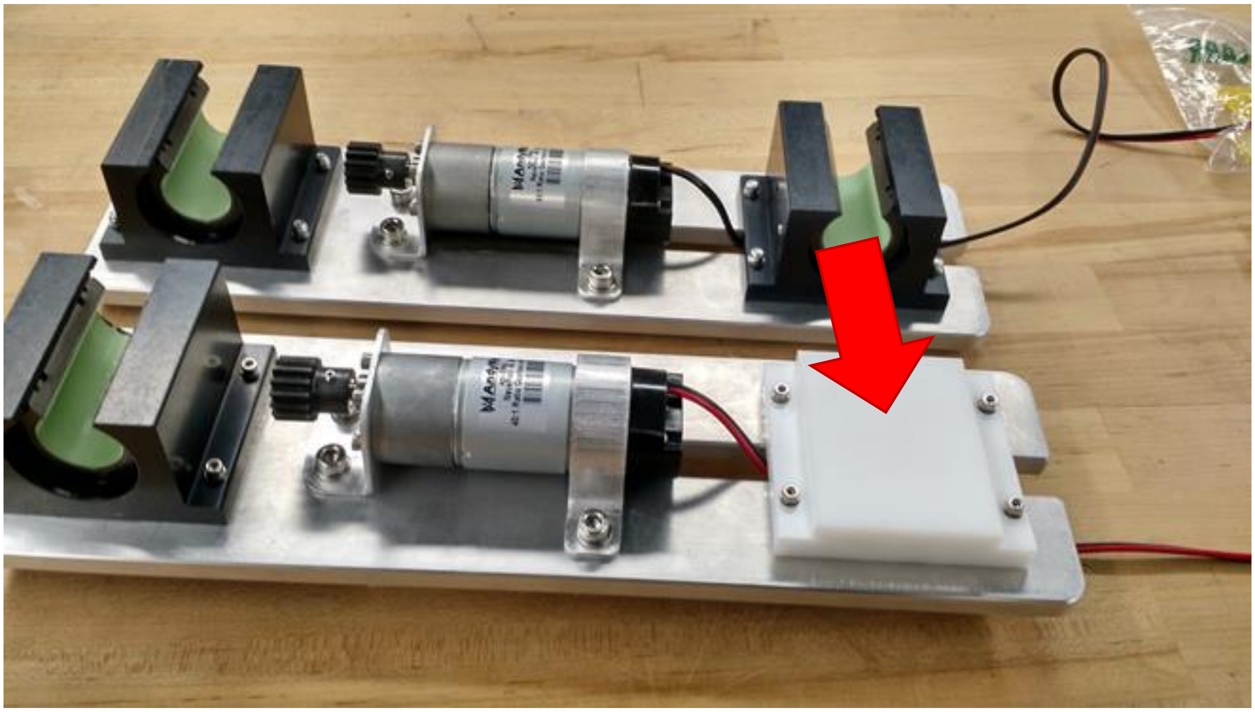

Figure 29-Bath Cart Bearing Modification

# 5.3 Testing

Once the bearings were modified and the carts could be moved smoothly and freely by hand, the vertical and horizontal translation systems were operated together to execute a fiber dipping motion. One bath cart with a 3-D printed model of a heater block was installed on the rails, and a 3-D printed model of the FCT was placed into the FCT cradle. The bath cart was manually controlled by adjusting the current supplied to its motor from a variable DC power supply. The motion of the FCT was controlled by a computer communicating with the Zaber linear stage.

In this preliminary test, the bath cart was started from rest at one side of the A-CHEM. By increasing the current supplied to its motor, the bath cart moved to the center of the machine, where it was stopped smoothly by decreasing current to zero. Once the bath cart had moved the bath into position under the FCT, a LabVIEW script was activated manually. The script ran the Zaber linear stage, moving the model FCT down, then back up after a pause.

After the FCT moved to its home location, the positive and negative motor leads of the bath cart were switched, allowing the bath cart to move in the opposite direction. Once the FCT motion stopped, the bath cart was driven back to its starting location.

To ensure that the baths would not spill their chemicals, a test of the bath cart movement system was executed with water as an analog for acid. One bath cart was wired to an adjustable DC power supply, and its bath was filled with an amount of water approximately equal to the amount of acid that would fill the bath. The current supplied to the bath cart motor was modulated up and down to simulate both normal and aggressive bath movement, and no water spilled from the baths. Additionally, a timed test was done to determine the amount of time needed to wait for the liquid to settle after movement. This settling time, after testing about 10 cases with varying speeds was always less than 20 seconds. When low speeds were used (< 30 cm/s) the settling time was approximately 6 seconds, which does not affect the etching process with a factor of safety of 3.

# 5.4 Final Prototype Build

The revisions listed above were implemented, and incorporated into the A-CHEM. The drawings of the A-CHEM were revised in order to reflect these changes. The Final Prototype is shown in Figure 30 below.


Figure 30- Final Prototype Build of the A-CHEM

# 6. Project Management

## 6.1 Group Safety

The GLOWS CO team will not use or come into close contact with caustic chemicals; all liquids were simulated with water. The machine is motorized and involves a number of moving assemblies. This section will describe and analyze potential safety hazards and the mitigations involved in the manufacturing, assembling, testing, operating, displaying, storing, and disposal of the parts used in this project.

### 6.1.1 Manufacturing

Many parts used in this project were fabricated by a local machine shop and purchased off the shelf. A handful of parts were manufactured in the Santa Clara University machine shop. To mitigate the risks involved in machining, all parts underwent the required vetting procedures before being produced. During the machining process the GLOWS CO team followed all Mechanical Engineering Lab safety guidelines, and after machining the GLOWS CO team ensured that every machined surface is free from burrs or sharp corners.

### 6.1.2 Assembly

Risks in the assembling of the machine could result in pinching of skin, cutting due to sharp corners and edges, or crushing from dropped parts. Pinching can occur when adjacent parts close in on a person causing small cuts or bruises. To prevent injury during the assembling, clear communication between people assembling the machine was enforced. To protect against injury from dropped parts, care was taken to grip the parts securely and heavy parts were moved by groups. All sharp edges were removed before assembling them into the machine. Safety glasses were worn at all times by all team members when in the workshop.

## 6.2 Tests and Operation

Risks in these stages fall under two major categories: physical and electrical.

### 6.2.1 Physical Risks

Moving parts in the A-CHEM pose an increased risk of pinching, entrapment, entanglement, and volatile particulates. Entrapment occurs when any part of a person is stuck between parts of the machine. Entanglement occurs when an article of clothing gets caught in a rotating or moving part and draws the person wearing the clothing into the moving part. With electric motors powering the various subsystems, there is a risk of unexpected movement that could put users at risk of injury. To mitigate the risk of pinching, entrapment and entanglement, the machine was only powered on after everyone had moved away from the machine. To further protect against entanglement, no one wore anything on their lower arms or dangling from their body that could be caught in moving machine such as jewelry or baggy clothing. The moving parts of the machine could potentially throw small pieces of debris into the air. To reduce this risk, the machine's moving parts were thoroughly cleaned before it was powered on and safety glasses were worn at all times in proximity to the machine. Also, the design of the machine incorporates covers and shielding on moving assemblies and motors.

### 6.2.2 Electrical Risks

The power and control subsystems of the machine pose a high voltage shock hazard. In general, GLOWS CO followed the Santa Clara University electrical safety guidelines. Unnecessary electrical components were removed from the electrical system for each test. The system had no batteries, but the various components may include capacitors and inductors that store electrical potential

No live work was conducted on the machine. The wiring insulation of the machine was visually checked before any operations and all other charged parts were protected from accidental contact during normal operation. The baths were only filled with water when it is necessary to test the bath heater or the kinematic response of the water in the moving baths. When water was used, care was taken to ensure no electrical components get wet.

## 6.3 Display

When being displayed, the machine was either disconnected completely from electrical power or was enclosed within a safety box. When not moving, the machine is incapable of causing pinches, entrapment or entanglement. It was placed on a stable table or counter so it did not fall. The machine was not filled with water or chemicals during any display scenario.

## 6.4 Storage

The machine was stored in a dry, room temperature environment. It was placed where it did not present a tripping hazard or impede normal movement. The machine was covered to protect it from dirt and to protect people from any sharp edges.

## 6.5 Disposal

GLOWS CO did not generate any hazardous waste while manufacturing the A-CHEM. All waste that GLOWS CO generated was recycled or disposed of appropriately, like aluminum beams and plastic packaging. All waste generated by the manufacturer of the machine's components has been handled by the manufacturer.

# 7. Engineering Standards and Realistic Constraints

## 7.1 Economics

Economic constraints played a significant role in the development of the A-CHEM due to GLOWS CO's budget and goals. GLOWS CO fulfilled the aforementioned goals and requirements while balancing costs. However, to date, the budget has only eliminated several expensive prebuilt components from consideration. GLOWS CO created an experimental business plan to analyze how successful an automation company working with machines similar to the A-CHEM could be. This plan can be found in Appendix J.

The A-CHEM will have a large impact for Lumentum by decreasing process variation in manufacturing and minimizing the time spent by technicians on this portion of the fiber laser process. The tool's design will also minimize operating costs such as maintenance, part replacement, and electrical power to increase the machine's operational value. Additionally, the machine will have a five-year lifetime which impacts the quality of parts utilized and the cost.

## 7.2 Manufacturability

Designing for manufacturability imposes many constraints on the A-CHEM. The following are examples of methods to increase the manufacturability of the machine:

- Minimize the total number of parts.
- Minimize the variety of highly standard parts like bolts.
- Fabricate large parts from multiple smaller parts.
- Design custom parts to require minimal material removal.
- Design custom parts to be made from the same materials.
- Use standard parts wherever possible.

## 7.3 Ethics

GLOWS CO faces a number of ethical responsibilities: to itself, to Lumentum, and to the technicians who operate the machine and society.

The members of the GLOWS CO team must treat each other ethically as they work on the project. Work must be shared equally, deadlines and requirements must be met, and everyone must be treated with respect.

GLOWS CO has a number of ethical obligations to Lumentum. First, GLOWS CO must deliver a safe and accurate machine to etch fiber optic cables by July of 2016. The safety concerns are addressed above. To meet the deadline, GLOWS CO has created an aggressive schedule to ensure that they have enough time to manufacture, test and refine the machine.
In order to interface with Lumentum's existing technology, Lumentum has provided GLOWS CO with proprietary information that GLOWS CO is contractually obligated to keep confidential. GLOWS CO has developed a peer-check process to minimize the risk of divulging proprietary information, but should any breach occur, GLOWS CO must notify Lumentum. GLOWS CO is also responsible for providing Lumentum with all technical documents, instructions, potential problems and uncertainties relating to the design. The information must be as complete as possible so the machine can be utilized to its full potential.

To facilitate the change in ownership and operation of the machine, GLOWS CO will provide Lumentum with the personal contact information of the design engineers so that future operation problems can be addressed directly by the most knowledgeable people.

Most importantly, GLOWS CO must hold the personal safety of anyone who uses the machine to the highest regard because the machine has the capacity to injure persons who operate or interact with it.

## 7.4 Environmental

GLOWS CO has the ethical responsibility to select materials and manufacturing processes for the A-CHEM that does not harm the environment significantly more than the alternatives. Because the machine will decrease the number of failed fiber etching processes and is using the same amount of chemicals currently used, the net long-term environmental impact will be positive.

# 8. Summary and Conclusion

The design of the current A-CHEM met the key points of safety and accuracy for Lumentum. The use of commercially available parts in the construction of the machine led to a lower overall cost, with the custom parts being responsible for the necessary accuracy of this process. By keeping major aspects of the design simple, the fiber etching process can be streamlined.

# Appendix A: Bibliography


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[2] O'Connor, Michael, and Bill Shiner. *Excerpt: High-power Fiber Lasers for Industry and Defense--Part III*. Rep. UBM Canon, 27 Apr. 2011. Web. 17 Nov. 2015.

[3] Doyon, Pete. "Optical-fiber Window-stripping: Why and How?" *Journal of Lightwave Technology* 19.9 (2002). *Lightwave Online*. IEEE. Web. 26 Oct. 2015.

[4] "Accident and Injury Statistics." Safety in the Use of Industrial Robots. Geneva: International Labour Office, 1989. 15-20. Print.

# Appendix B: Detailed Calculations

# Appendix B. 1 Vibration and Bending Analysis

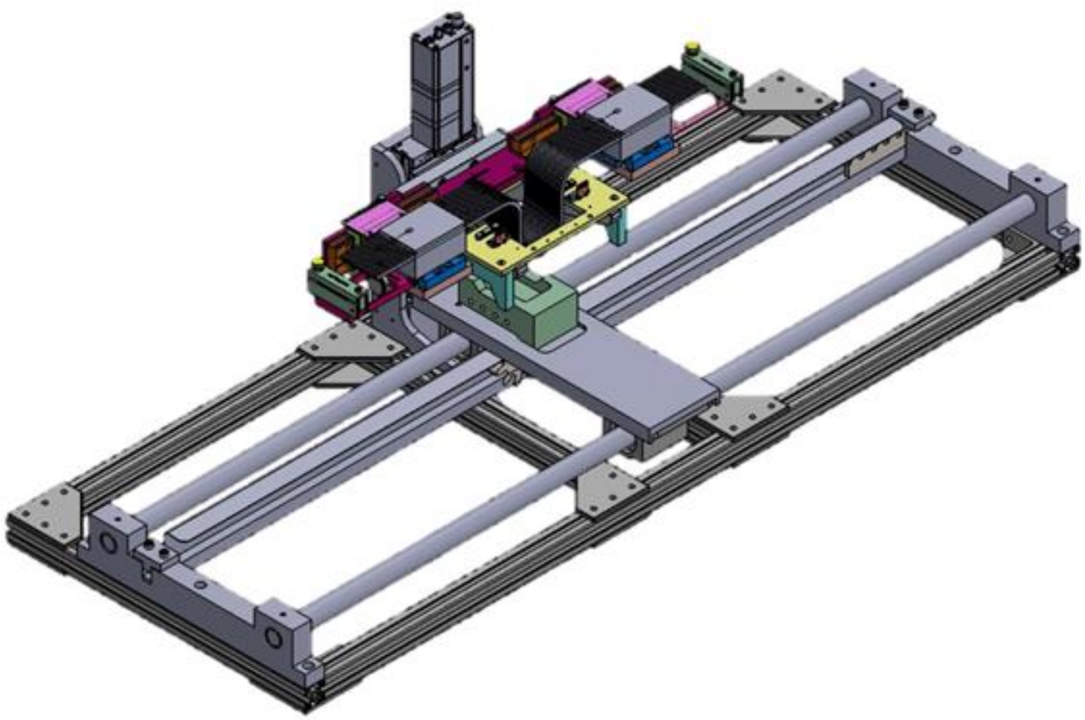


Figure 31- Visual Representation of the A-CHEM for Analysis

**Simplifying Elements and Assumptions**

For all subassemblies, screws, nuts, and washers were removed to reduce meshing constraints and reduce extraneous calculations the software must accomplish. Also, this helped remove solid model overlaps that otherwise would have caused errors while meshing and calculating results. Screw threads typically enter material in holes made within Solidworks due to how it creates and models threads and their associated threaded holes.

Additionally, some larger parts were removed from models because they were not loaded: the rack shield did not attribute a significant rigidity to the sled support system, so it was not factored into the model.  Also, the sled itself was not used in the model for static loading as it was simulated with either a point load or distributed load depending on the situation being tested. Finally, all materials were assumed to be either Aluminum Alloy 6063-T6 or 6061-T6 based on the selection criteria of materials due to caustic chemicals and their availability in pre-fabricated parts.

For hand calculations, beams were assumed to have a pinned-pinned connection which overestimates the bending of parts and allows us to include even more factors of safety.  Most beams can be considered to have a fixed-fixed connection within our assemblies due to the methods chosen to clamp them together.

**Vibrational Analysis**

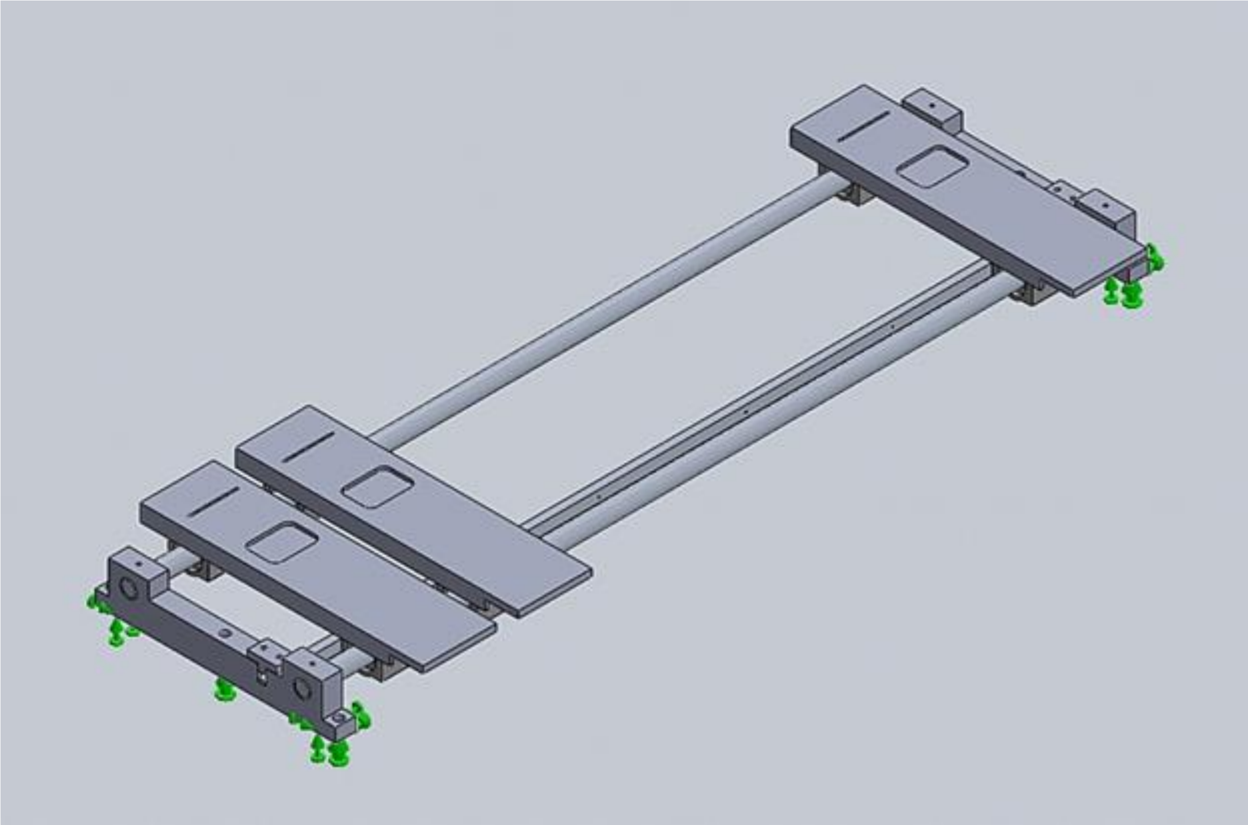


Figure 32- Simplified Sled Assembly Used for Testing

This analysis was used to determine the natural frequencies of the support beams used in this assembly under various configurations.  These configurations are listed below:

1. Support System without sleds

2. Support System with a single sled positioned on a side

3. Support System with a single sled positioned at the center

4. Support System with two sleds positioned on a side

5. Support System with two sleds positioned one on a side one in the center

6. Support System with two sleds positioned one on each side

7. Support System with three slides positioned two on a side one on the opposite side

8. Support System with three slides positioned two on a side on in the center

The model was assumed to be rigidly fixed at the bottom of the end pillow blocks because they would be attached to the frame. For purposes of this analysis, all the parts were assumed to be Aluminum Alloy 6063-T6.

Table A- List of Vibrational Analysis Results

| Configuration | Enclosed Part Numbers | Simulation Material(s) | Natural Frequency (Hz) | | | Notes |
|---|---|---|---|---|---|---|
| | | | Mode 1 | Mode 2 | Mode 3 | |
| Simplified Bath Movement Assembly | C-0010, C-0013, C-0014, C-0026 | 6063-T6 AA | 48.50 | 64.70 | 82.20 | Mode 1 & 2 - Rack Support. Mode 3 - Side Rail. |
| Simplified Bath Movement Assembly + Simple Sled (Side) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 64.80 | 74.50 | 107.70 | Mode 1 - Rack Support. Mode 2 &3 - Side Rails. |
| Simplified Bath Movement Assembly + Simple Sled (Middle) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 46.10 | 64.80 | N/A | Mode 1 - Side Rails. Mode 2 - Rack Support. |
| Simplified Bath Movement Assembly + 2 Simple Sled (Side) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 61.30 | 124.26 | N/A | Mode 1 - Rack Support. Mode 2 - Side Rails. |
| Simplified Bath Movement Assembly + 2 Simple Sled (Side & Middle) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 46.36 | 64.88 | 82.39 | Mode 1 &3 - Side Rails. Mode 2 - Rack Support |
| Simplified Bath Movement Assembly + 2 Simple Sled (Oppo Side) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 83.82 | 115.94 | N/A | Mode 1 & 2 - Side Rails. |
| Simplified Bath Movement Assembly + 3 Simple Sled (2 Side & 1 Side) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 67.61 | 141.20 | N/A | Mode 1 & 2 - Side Rails. |
| Simplified Bath Movement Assembly + 3 Simple Sled (2 Side & Middle) | C-0010, C-0012, C-0013, C-0014, C-0026 | 6063-T6 AA | 48.22 | 89.00 | N/A | Mode 1 & 2 - Side Rails. |

The results for these configurations show that the system must not be loaded around 45 Hz, 60Hz, 75Hz, 90Hz, and over 100Hz. All of these are not very likely to happen in our system due to the very low movement required for stability of the chemicals within the baths, but it is good to be mindful of these results. Additionally, from the models, if these natural frequencies were used during movement, we could excite some of the structural members to oscillate at amplitudes over nearly 5 inches, which would not only damage the assemblies but also spill chemicals on everything.

## Bending Analysis

The three subassemblies detailed before were loaded with realistic values derived from existing part weights and package loads. Table B shows the different loads applied to the subassemblies and their results for displacement, Von Mises stresses and relevant reaction forces.

Table B- Bending Analysis Results

| Subassembly: Bath Movement: Subassembly Part Numbers: C-0013, C-0010, C-0014, C-0026 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Parts Loaded | Type of Load | Magnitude of Load | Result | | | Notes | |
| | | | Displacement (mm) | Von Mises (N/m^2) | Reaction Force (N) | Yield Strength of Testing Material | Load Explanation |
| C-0010 | Distributed Load | 1000 N | 2.94E+00 | 5.90E+07 | 1.48E+02 | 2.15E+08 | Human Weight |
| C-0026 | Distributed Load | 1000 N | 1.11E+01 | 1.64E+08 | 1.66E+02 | 2.15E+08 | Human Weight |
| C-0010<br>C-0026 | Distributed Load<br>Distributed Load | 70 N<br>70 N | 1.94E-01<br>7.77E-01 | 1.92E+06<br>1.15E+07 | 2.03E+01<br>3.48E+01 | 2.15E+08<br>2.15E+08 | Single Sled<br>Single Sled |
| C-0010 | Distributed Load | 210 N | 5.84E-01 | 1.50E+07 | 4.34E+01 | 2.15E+08 | 3 Sled Stacked |
| C-0026 | Distributed Load | 210 N | 2.33E+00 | 3.59E+07 | 8.68E+01 | 2.15E+08 | 3 Sled Stacked |
| | | | | | | | |
| Subassembly: Vertical Movement: Subassembly Part Numbers: B-0004, B-0005 | | | | | | | |
| Parts Loaded | Type of Load | Magnitude of Load | Result | | | Notes | |
| | | | Displacement (mm) | Von Mises (N/m^2) | Reaction Force (N) | Yield Strength of Testing Material | Load Explanation |
| B-0004 | Split Load - 2 | 44.48 N (10 lb) | 1.34E-02 | 2.37E+06 | 4.58E+00 | 2.15E+08 | FCT Loading |
| B-0004 | Split Load - 2 | 1000 N | 3.00E-01 | 4.00E+07 | 1.03E+02 | 2.15E+08 | Human Weight |
| | | | | | | | |
| Subassembly: : Frame: Subassembly Part Numbers: C-0030, C-0032 | | | | | | | |
| Parts Loaded | Type of Load | Magnitude of Load | Result | | | Notes | |
| | | | Displacement (mm) | Von Mises (N/m^2) | Reaction Force (N) | Yield Strength of Testing Material | Load Explanation |
| C-0030, C-0032 | Split Load - 4 | 444.8 N (100 lb) | 4.75E-01 | 7.91E+06 | 6.23E+01 | 2.75E+08 | Estimated Full Assembly Load |
| C-0030, C-0032 | Split Load - 4 | 4448 N | 4.75E+00 | 1.06E+08 | 6.23E+02 | 2.75E+08 | 4 People Sitting on Frame |

This model looked at various cases of loading based on how many carts were being simulated. Initially, one cart's weight was applied on the three supporting beam's center which is roughly 70 Newtons. Figures 33 and 34 show the load's orientation, locations, and resulting maximum displacements of the beam. With the same model, a worst case simulation was considered where one of our members could accidentally fall onto the beams, thus loading them with roughly 1000N which can be seen in Figures 35 and 36.

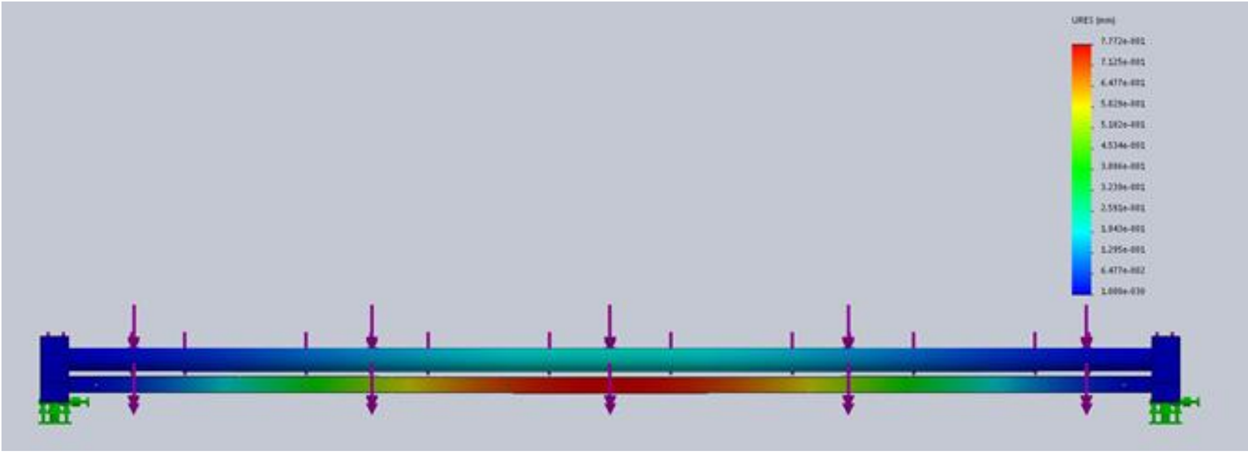


Figure 33- Bath Movement Subassembly Bending Analysis Side View (70N)

Red Zones 7.78E-1 mm, Green Zones 3.89E-1 mm, Blue Zones 0 mm defelection

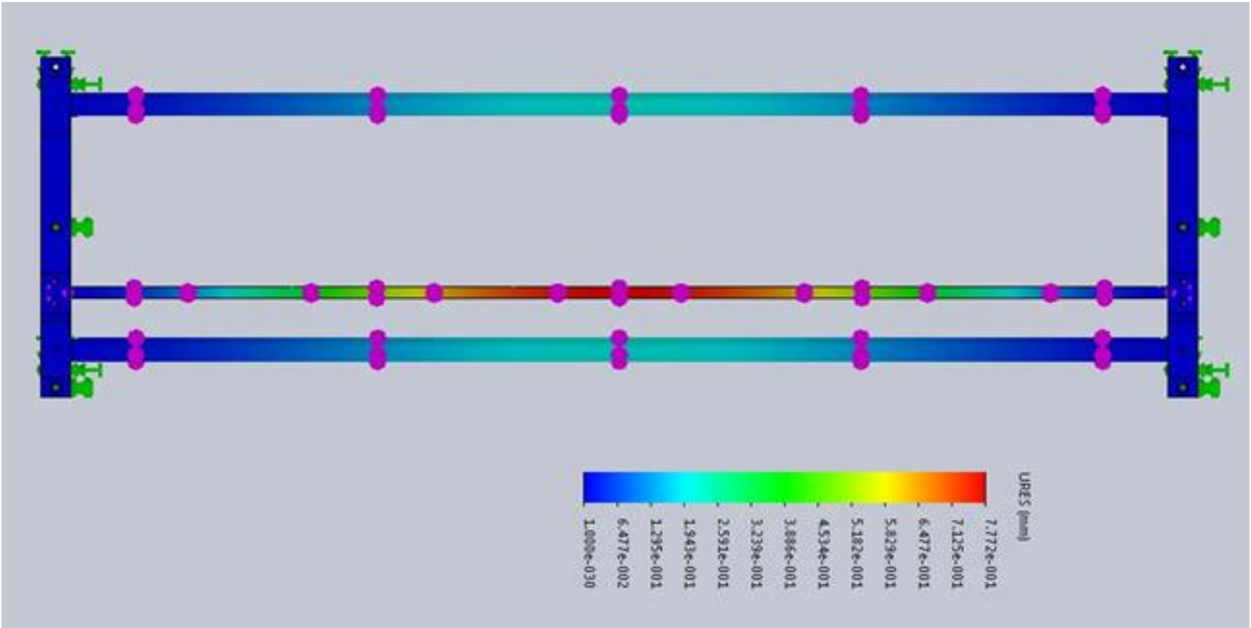


Figure 34- Bath Movement Subassembly Bending Analysis Top View (70N)

Red Zones 7.78E-1 mm, Green Zones 3.89E-1 mm, Blue Zones 0 mm defelection

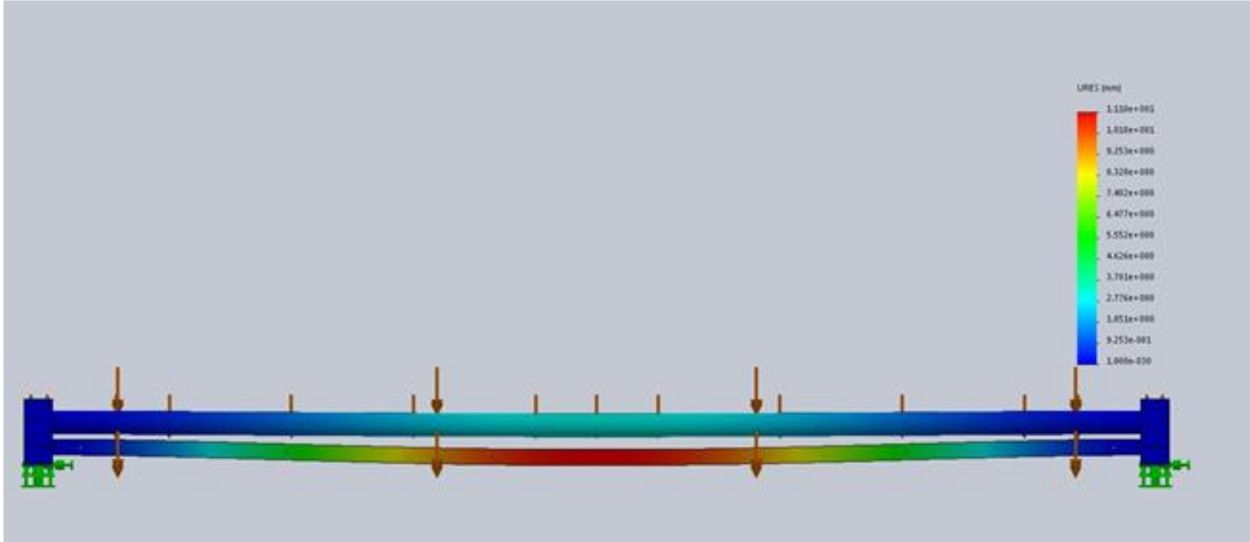


Figure 35- Bath Movement Subassembly Bending Analysis Side View (1000N)

Red Zones 1.12E+1 mm, Green Zones 5.55E0 mm, Blue Zones 0 mm defelection

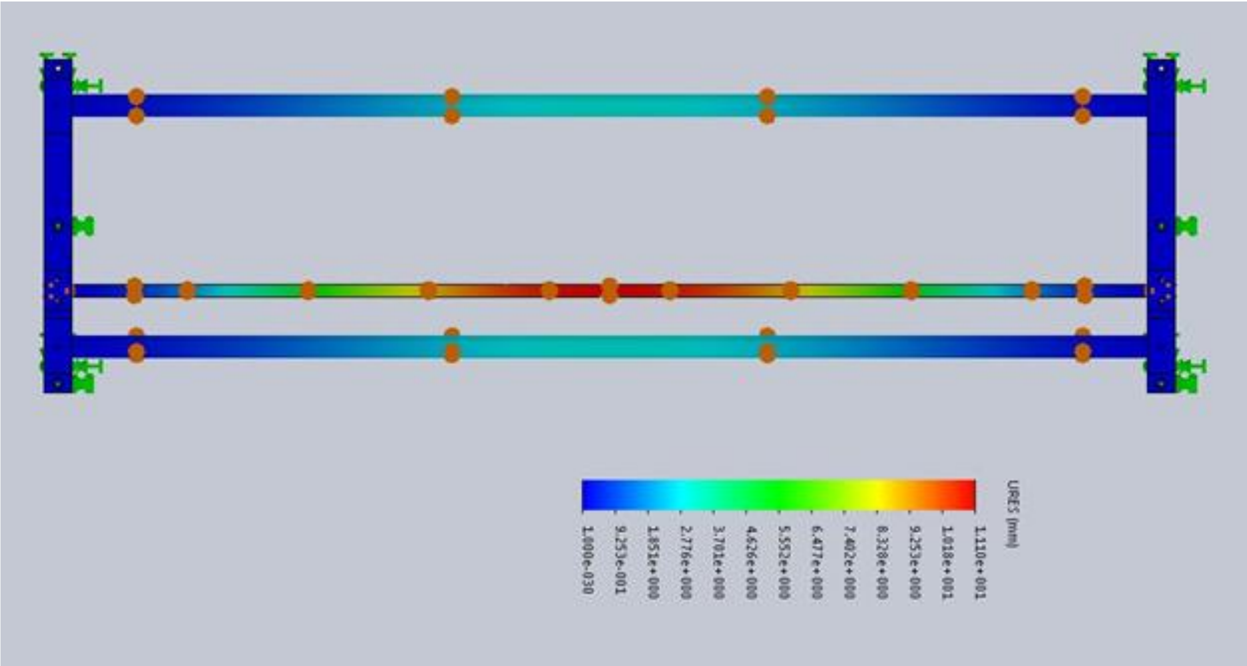


Figure 36- Bath Movement Subassembly Bendng Analysis Top View (1000N)

Red Zones 1.12E+1 mm, Green Zones 5.55E0 mm, Blue Zones 0 mm defelection

After the loading simulations for the bath subassembly was completed, the FCT support assembly was examined. Lumentum has specified the FCT will be approximately 10Lbs, so we used this value in our analysis.  Figures 37 and 38 show the orientations and location of the forces used in this model.  The load is split between the two side brackets because that is how it would be loaded physically.  To take this to a worst case scenario, we assumed a maximum load of 1000N to simulate a person putting their full weight on the support bracket with the FCT in place. The results of this test can be seen in Figures 39 and 40.

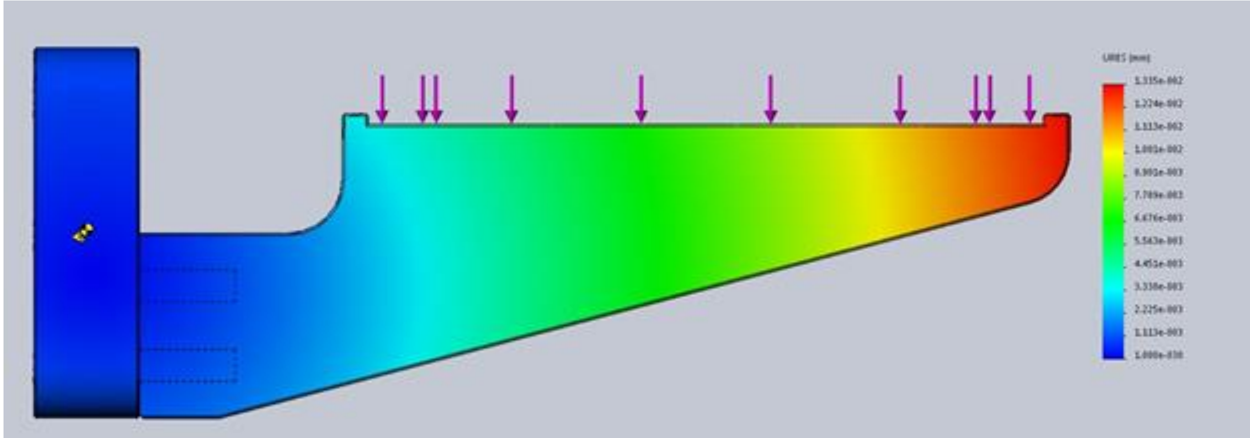


Figure 37- FCT Support Subassembly Bending Analysis Side View (10 lbs., 44.48 N)

Red Zones 1.34E-2 mm, Green Zones 6.68E-3 mm, Blue Zones 0 mm defelection

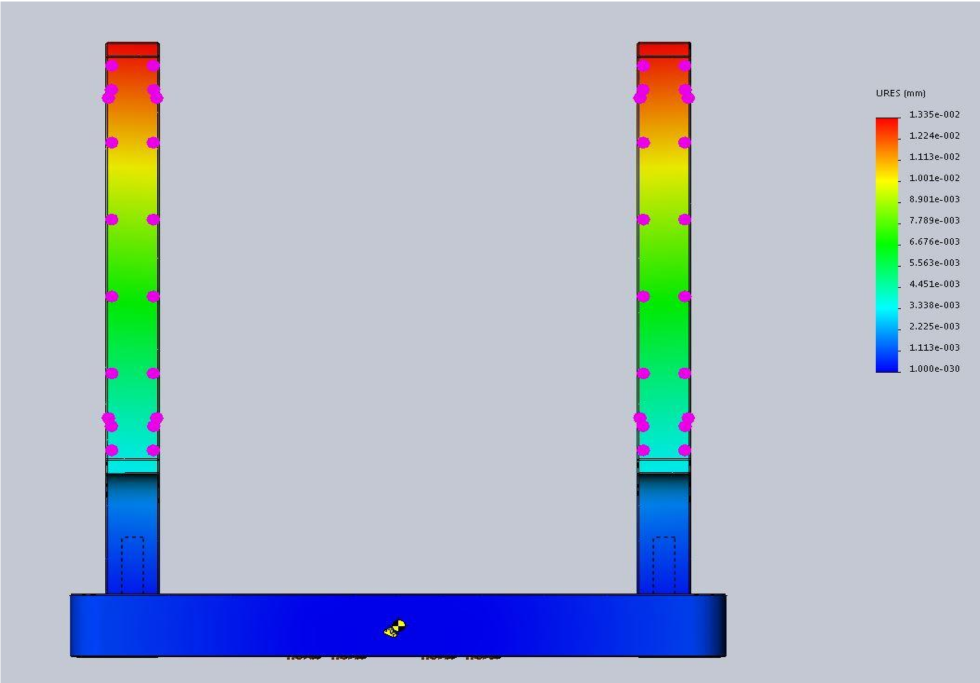



Figure 38- FCT Support Subassembly Bending Analysis Top View (10 lbs., 44.48 N)

Red Zones 1.34E-2 mm, Green Zones 6.68E-3 mm, Blue Zones 0 mm defelection

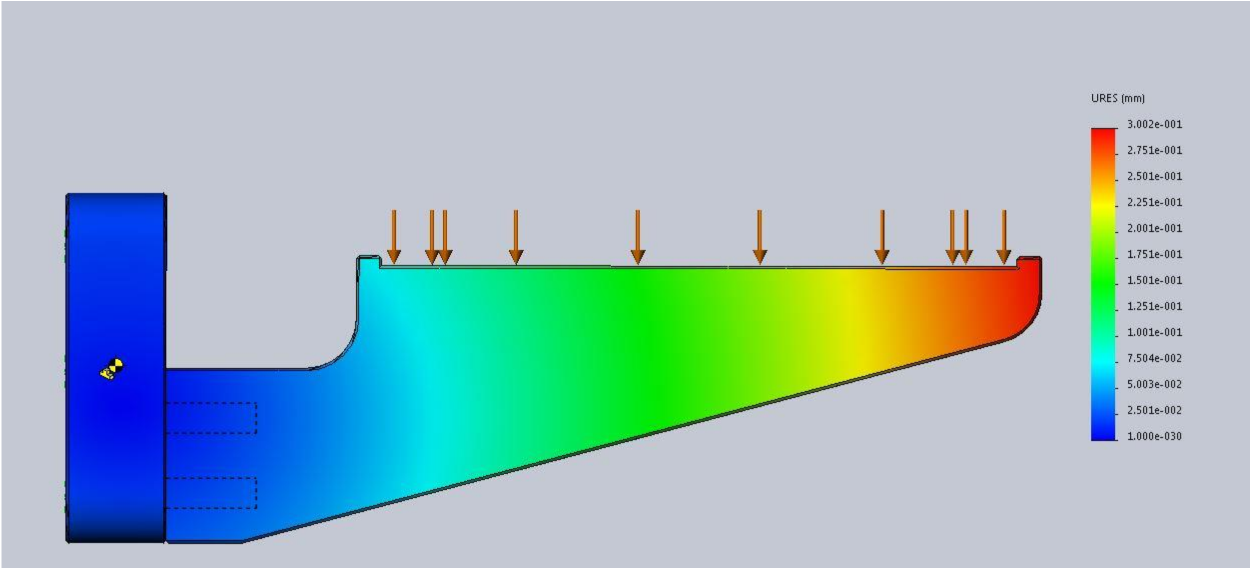



Figure 39- FCT Support Subassembly Bending Analysis Side View (1000 N)

Red Zones 3.00E-1 mm, Green Zones 1.50E-1 mm, Blue Zones 0 mm defelection

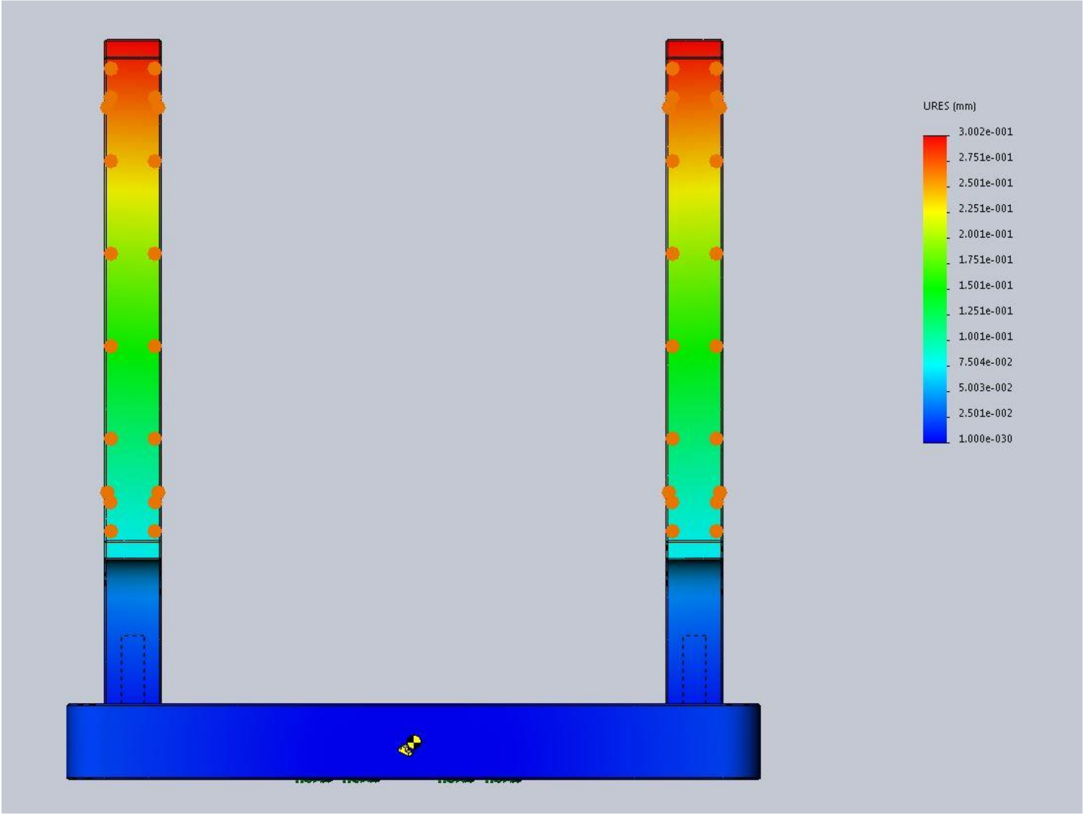



Figure 40- FCT Support Subassembly Bending Analysis Top View (1000 N)

Red Zones 3.00E-1 mm, Green Zones 1.50E-1 mm, Blue Zones 0 mm defelection

After the testing of the FCT support assembly, the frame assembly was analyzed. To determine the load applied to the frame, a simple addition of the weights of all the systems besides the frame was calculated and determined to be 404 N (~90 lbs.). We chose to increase this weight to 444.8 N (100 lbs.) to account for the parts not included in the model and for future parts that could be added. This analysis for bending can be seen in Figures 41 and 42. For a worst case scenario, we hypothesized most of our members would rest their weight on the frame, even if it is not permitted. This hypothesis means that roughly 4448N (1000lbs) would be applied to the frame. This situation can be seen in Figures 43 and 44.

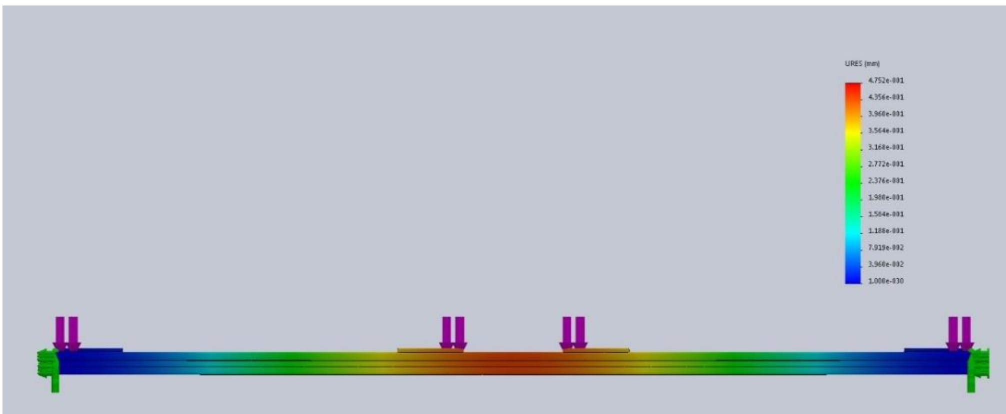



Figure 41- Frame Assembly Bending Analysis Side View (444.8 N, 100 lbs.)

Red Zones 4.75E-1 mm, Green Zones 2.38E-1 mm, Blue Zones 0 mm defelection

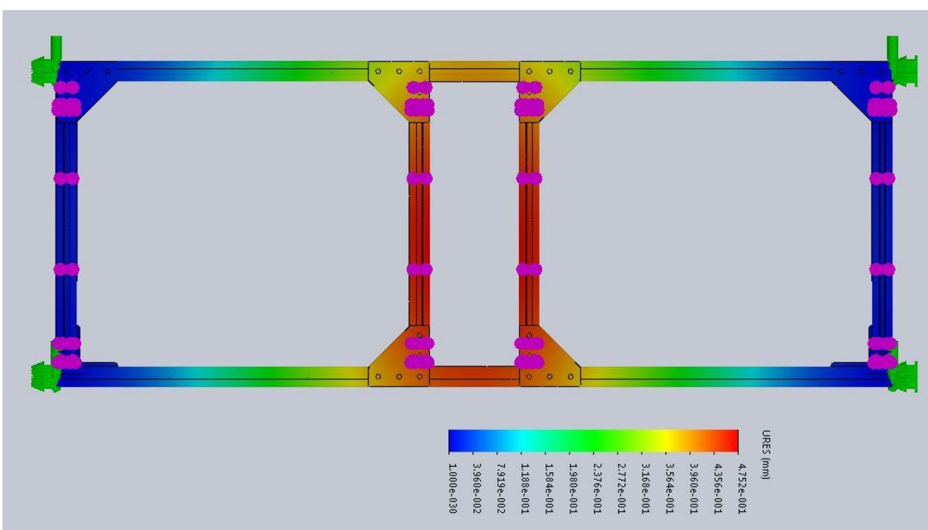



Figure 42- Frame Assembly Bending Analysis Top View (444.8N, 100 lbs.)

Red Zones 4.75E-1 mm, Green Zones 2.38E-1 mm, Blue Zones 0 mm defelection

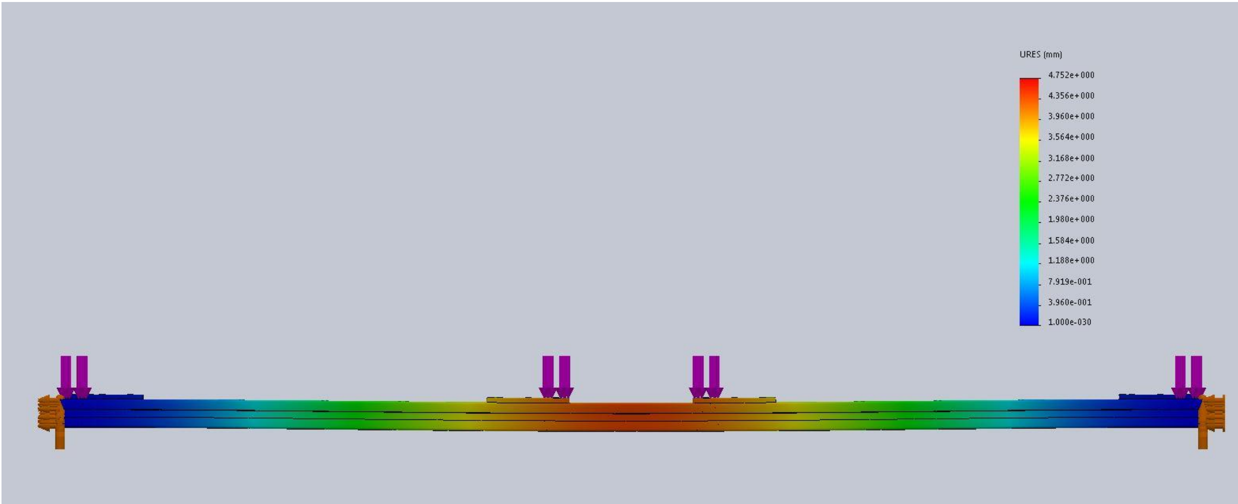



Figure 43- Frame Assembly Bending Analysis Side View (4448N, 1000 lbs.)

Red Zones 4.75E0 mm, Green Zones 2.38E0 mm, Blue Zones 0 mm defelection

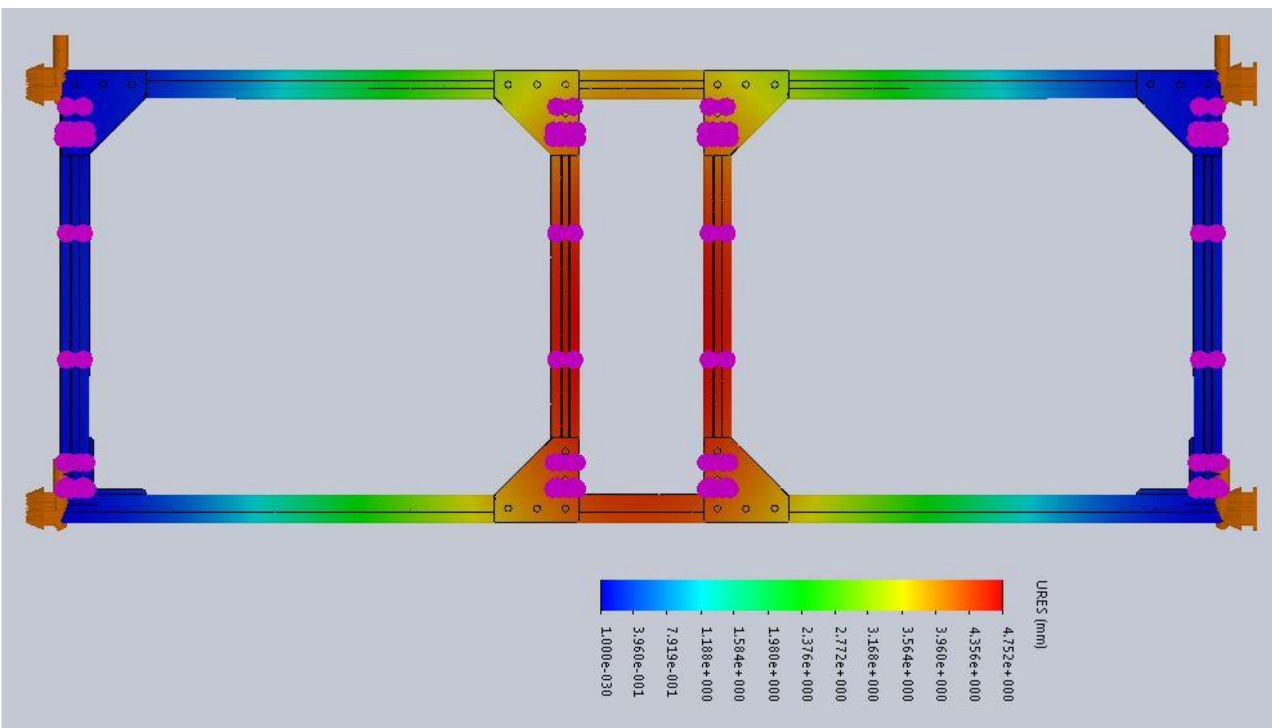


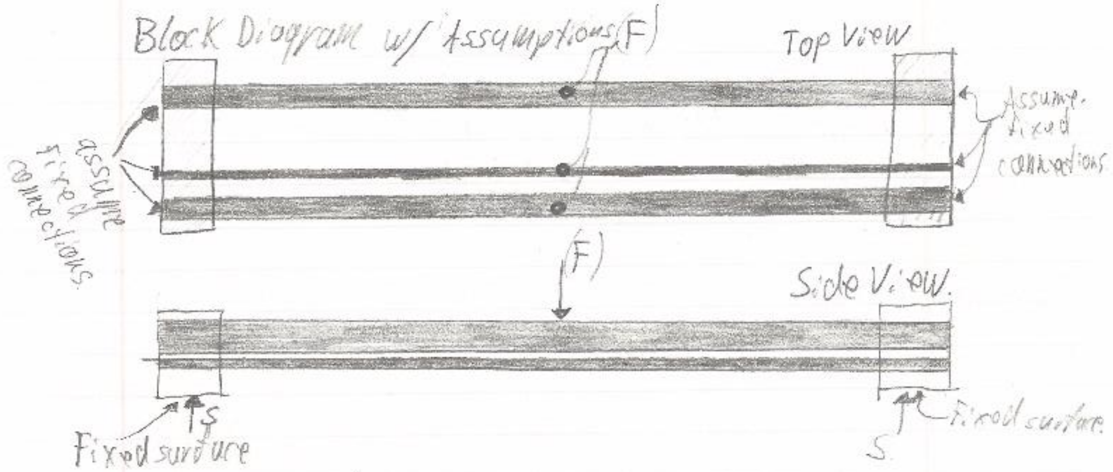

Figure 44- Frame Assembly Bending Analysis Top View (4448N, 1000 lbs.)

Red Zones 4.75E0 mm, Green Zones 2.38E0 mm, Blue Zones 0 mm defelection

Hand calculations were also done for this analysis; they most corresponded with the analysis done in Figures 33 and 34, where they model the single sled on the beams. The values were very close so we knew that the program had not grossly overestimated our loads. Additionally, we had found that there were no displacements, due to loading, greater than 3mm in the bath movement subassembly. This is good because the maximum valuable allowed for this assembly to displace is 5mm to maintain proper gear/rack meshing. These hand calculated values are shown on the following 3 pages, in Figure 45, 46, and 47.

Mishan Golshan

Sled Support Assembly.




F, applied at center of beams.
S, Reaction forces at Support Pillow Blocks

- All materials used are assumed to be ASM 6063-T6 Aluminum Alloy.

$E = 68.9\ GPa$
$UTS = 241\ MPa$
$\nu = 0.33$

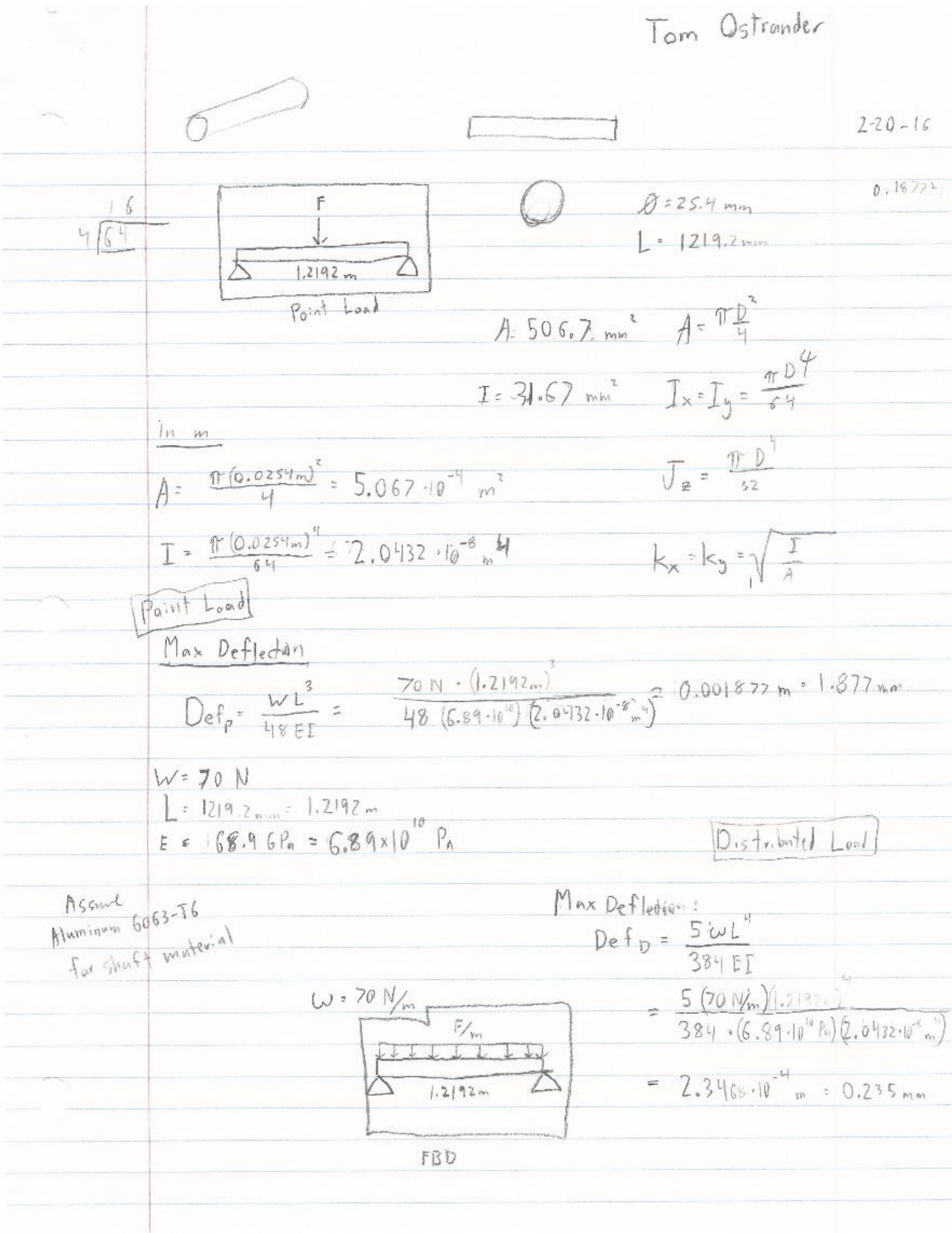
- Simplifications: Screws from model ignored In hand calculations, model assumed to be pin-pinned supports.
- Solidworks simulation, fixed-fixed used. All beams are solid with no chamfers or complex geometry.

Figure 45- Bending Analysis Hand Calcuations Page 1

Failures are: Exceeding 4 mm of displacement.
Source: Maximum distance allowable for gears and rack not to mesh.
Failure: Maximum stress must not exceed Yield Strength.

Identification of parts that should fail: small cross beam used for supporting our rack. Reason: smaller beam and is much weaker due to its smaller moment of inertia

Figure 46- Bending Analysis Hand Calculations Page 2



Tom Ostrander

2-20-16

0.18772

Point Load

1.2192 m

$\varnothing = 25.4$ mm

L = 1219.2 mm

$A = 506.7\ mm^2$ $\quad A = \frac{\pi D^2}{4}$

$I = 31.67\ mm^2$ $\quad I_x = I_y = \frac{\pi D^4}{64}$

in m

$A = \frac{\pi (0.0254 m)^2}{4} = 5.067 \cdot 10^{-4}\ m^2$ $\quad J_z = \frac{\pi D^4}{32}$

$I = \frac{\pi (0.0254 m)^4}{64} = 2.0432 \cdot 10^{-8}\ m^4$ $\quad k_x = k_y = \sqrt{\frac{I}{A}}$

Point Load

Max Deflection

$Def_p = \frac{WL^3}{48EI} = \frac{70 N \cdot (1.2192 m)^3}{48 (6.89 \cdot 10^{10}) (2.0432 \cdot 10^{-8} m^4)} = 0.001877\ m = 1.877\ mm$

W = 70 N

L = 1219.2 mm = 1.2192 m

$E = 68.9\ GPa = 6.89 \times 10^{10}\ Pa$

Distributed Load

Assume Aluminum 6063-T6 for shaft material

Max Deflection:

$Def_D = \frac{5 \omega L^4}{384 EI}$

$= \frac{5 (70 N/m)(1.2192 m)^4}{384 \cdot (6.89 \cdot 10^{10} Pa)(2.0432 \cdot 10^{-8} m^4)}$

$= 2.3468 \cdot 10^{-4}\ m = 0.235\ mm$

$\omega = 70\ N/m$

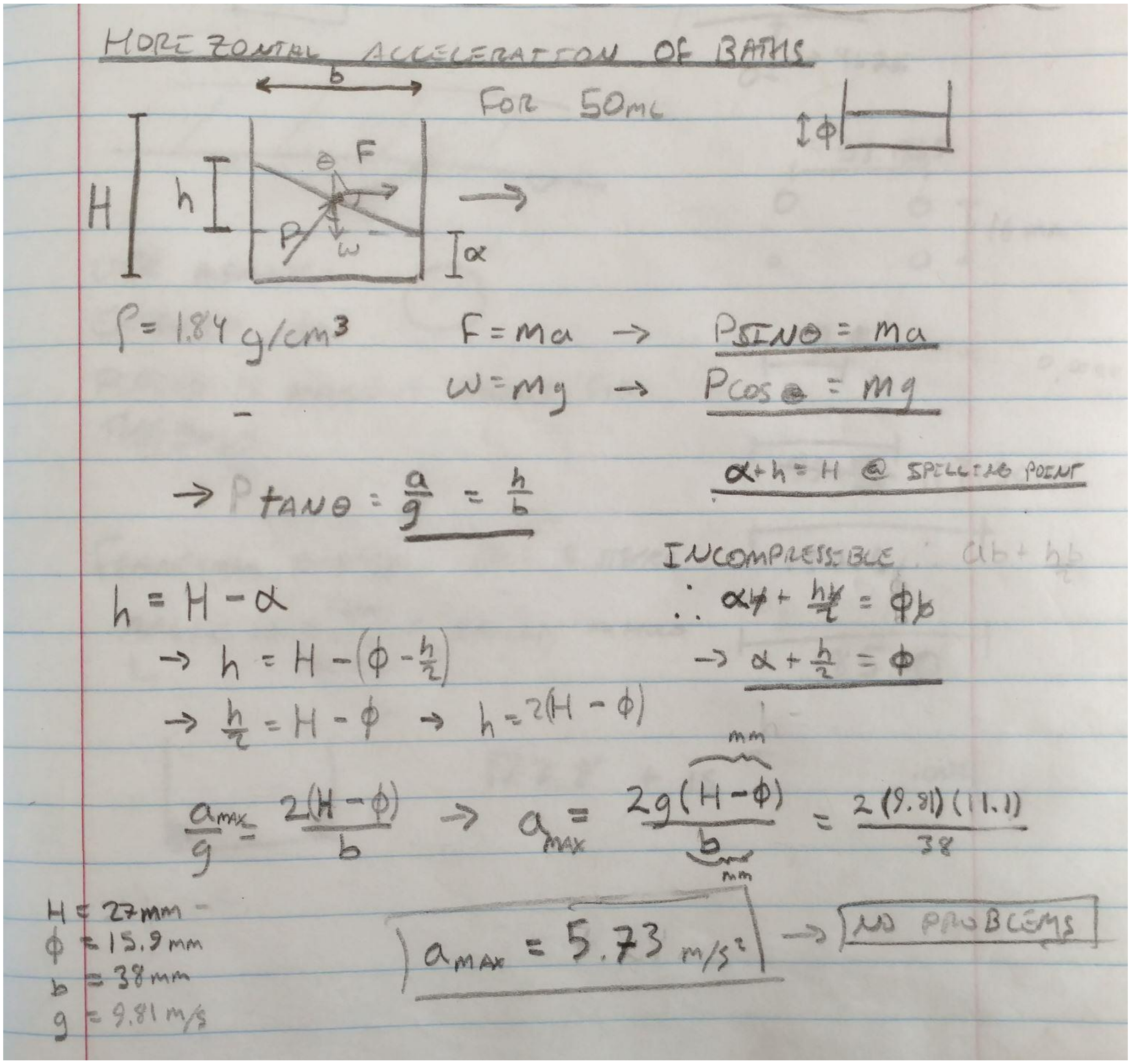
F/m

1.2192 m

FBD

Figure 47- Bending Analysis Hand Calculations Page 3

# Appendix B. 2 Bath Sloshing Analysis



DOUBLE CHECK ON NEARLY FULL CLEANING BATH

$g = 9.81\ m/s^2$

$H = 27\ mm$

$\phi = 25\ mm$

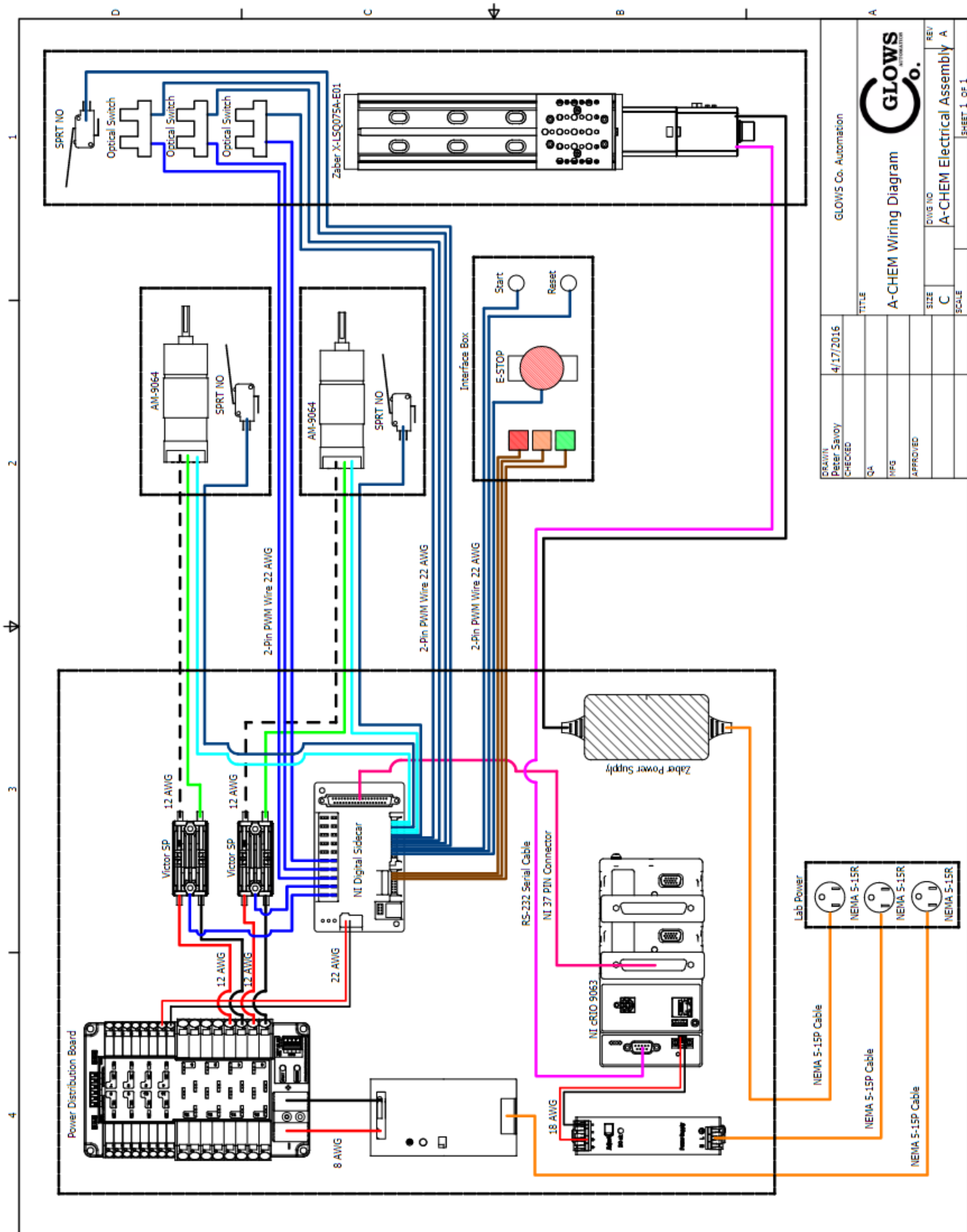
$b = 38\ mm$

$$a_{MAX} = \frac{2g(H-\phi)}{b} = 1.03\ m/s^2$$

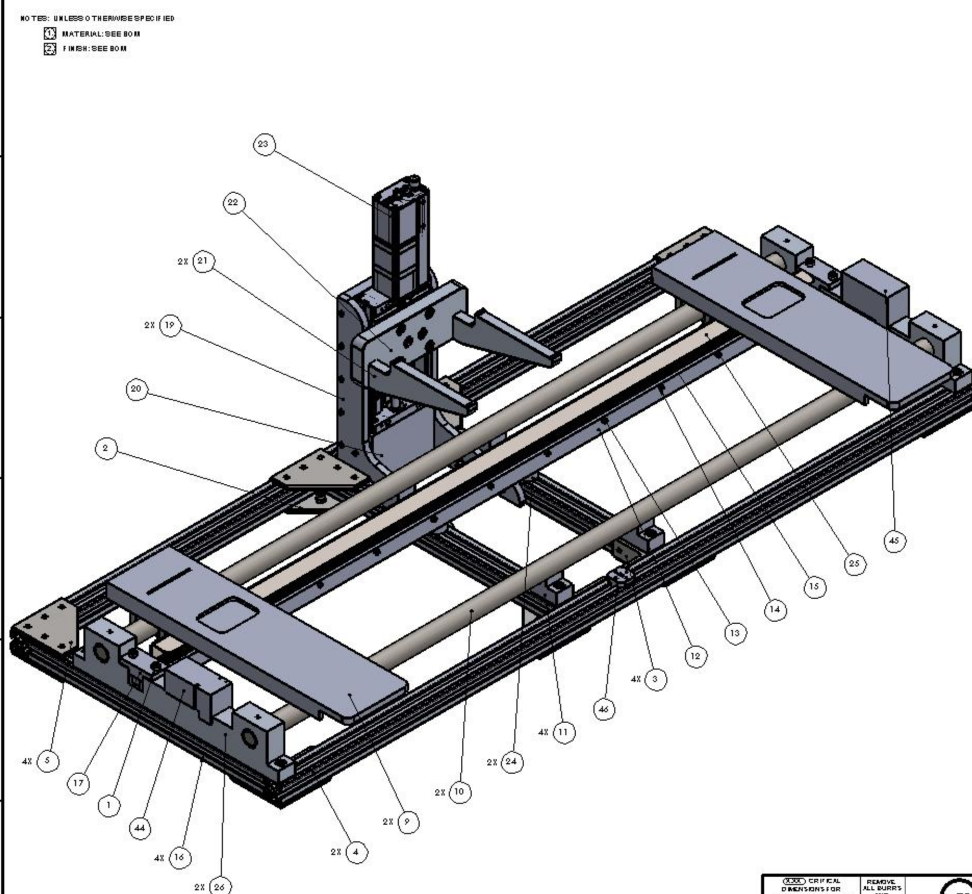
→ FINE

# Appendix C: Detail and Assembly Drawings

| Page Number | Part Designation | Part Name |
|---|---|---|
| **75** | A-CHEM Electrical Assembly | A-CHEM Wiring Diagram |
| **76** | A-CHEM Assembly Drawings | A-CHEM |
| **81** | B-0004 | FCT Cradle Arm |
| **82** | B-0005 | FCT Cradle Base |
| **83** | B-0006 | Vertical L Support |
| **84** | B-0007 | Vertical Support Block |
| **85** | C-0010 | Ceramic-Coated Aluminum Rail |
| **86** | C-0027 | Rack Shield |
| **87** | C-0021 | Reworked Rack |
| **88** | C-0023 | Motor Bracket Cradle |
| **89** | C-0024 | Motor Bracket Shaft Side |
| **90** | C-0001 | Bath Sled Base |
| **91** | C-0028 | Sled Shield |
| **92** | C-0033 | Gear Shaft Sleeve |
| **93** | C-0035 | Rail Support Pillar |
| **94** | C-0036 | Rack Support Beam |
| **95** | C-0037 | Rack Support Pillar |
| **96** | C-0038 | Rod and Rack Holder |
| **97** | C-0040 | Rail Frame Rack Lock |
| **98** | C-0041 | T-Slot Triangle Foot |



SPRT NO
Optical Switch
Optical Switch
Optical Switch
Zaber X-LSQ075A-E01
AM-9064
SPRT NO
AM-9064
SPRT NO
Interface Box
Start
Reset
E-STOP
2-Pin PWM Wire 22 AWG
2-Pin PWM Wire 22 AWG
2-Pin PWM Wire 22 AWG
Zaber Power Supply
12 AWG
12 AWG
Victor SP
Victor SP
NI Digital Sidecar
RS-232 Serial Cable
NI 37 PIN Connector
NI cRIO 9063
12 AWG
12 AWG
22 AWG
Power Distribution Board
8 AWG
18 AWG
Lab Power
NEMA 5-15R
NEMA 5-15R
NEMA 5-15R
NEMA 5-15P Cable
NEMA 5-15P Cable
NEMA 5-15P Cable
GLOWS Co. Automation
GLOWS Co.
DRAWN
Peter Savoy
4/17/2016
CHECKED
QA
MFG
APPROVED
TITLE
A-CHEM Wiring Diagram
SIZE
C
DWG NO
A-CHEM Electrical Assembly
REV
A
SCALE
SHEET 1 OF 1



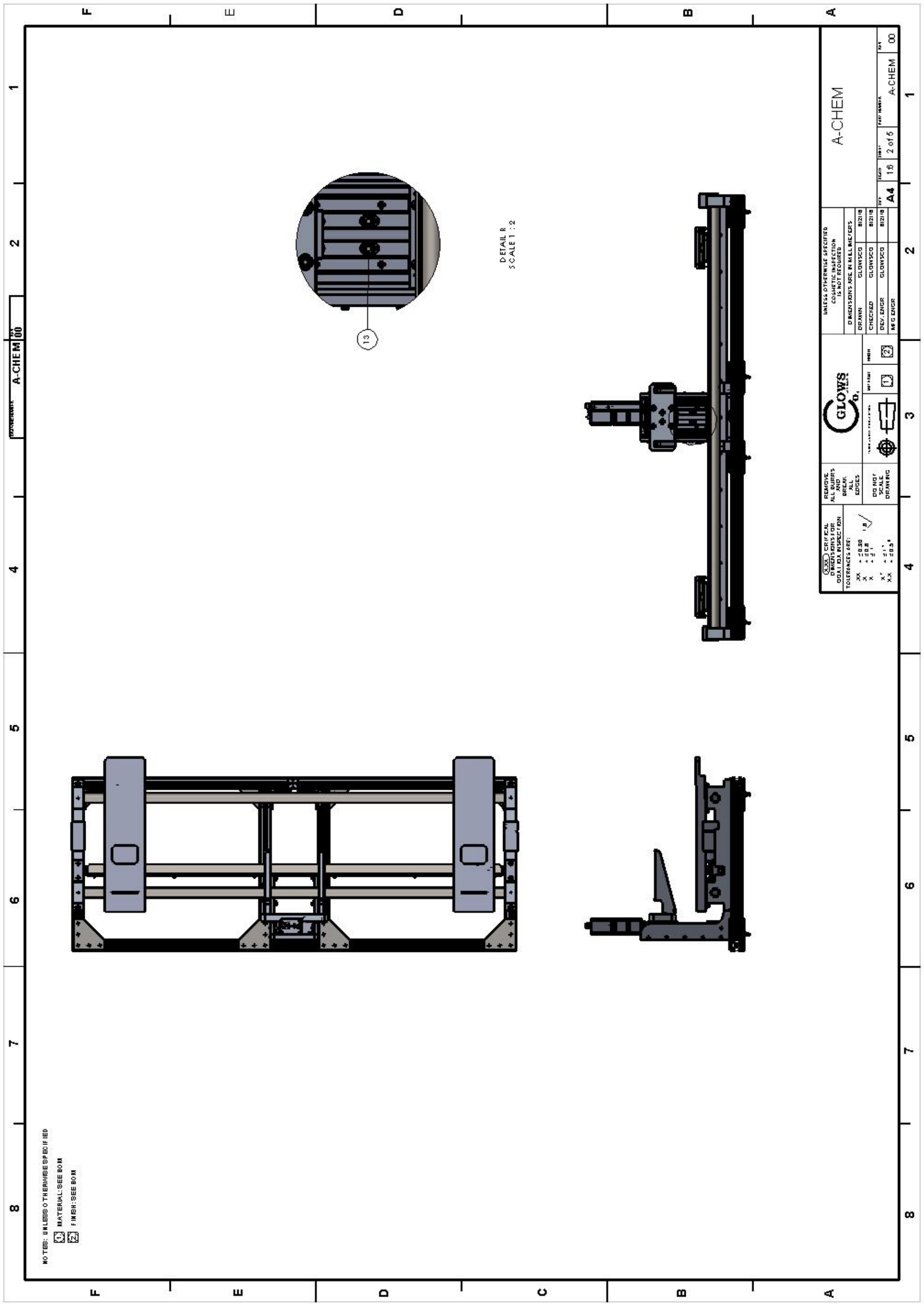

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | A-0006 | M6 18MM LENGTH SOCKET HEAD CAP SCREW | 38 |
| 2 | C-0041 | T-SLOT TRIANGLE FOOT | 8 |
| 3 | C-0025 | T SLOT L BRACKET | 4 |
| 4 | C-0030 | FRAME X SUPPORT BEAM | 2 |
| 5 | C-0029 | T SLOT TRIANGLE BRACKET | 4 |
| 6 | A-0003 | M6 25MM LENGTH SOCKET HEAD CAP SCREW | 14 |
| 7 | A-0014 | M3 20MM LENGTH SOCKET HEAD CAP SCREW | 12 |
| 8 | C-0034 | LINEAR SLEEVE BEARING | 2 |
| 9 | C-0028 | SLED SHIELD | 2 |
| 10 | C-0010 | CERAMIC COATED ALUMINUM RAIL | 2 |
| 11 | C-0035 | RAIL SUPPORT PILLAR | 4 |
| 12 | C-0036 | RACK SUPPORT BEAM | 1 |
| 13 | A-0007 | M3 SOCKET HEAD CAP 25MM LONG | 27 |
| 14 | A-0013 | M3 WASHER STEEL | 63 |
| 15 | C-0039 | RACK | 1 |
| 16 | C-0032 | FRAME Y SUPPORT BEAM | 4 |
| 17 | C-0040 | RAIL FRAME RACK LOCK | 2 |
| 18 | A-0009 | M6X1 HEX NUT | 24 |
| 19 | B-0006 | VERTICAL L SUPPORT | 2 |
| 20 | B-0007 | VERTICAL SUPPORT BLOCK | 1 |
| 21 | B-0004 | FCT CRADLE ARM | 2 |
| 22 | B-0005 | FCT CRADLE BASE | 1 |
| 23 | B-0001 | VERTICAL LIFTING STAGE | 1 |
| 24 | C-0037 | RACK SUPPORT PILLAR | 2 |
| 25 | C-0027 | RACK SHIELD | 1 |
| 26 | C-0038 | ROD AND RACK HOLDER | 2 |
| 27 | A-0004 | M6 WASHER STEEL | 46 |
| 28 | A-0005 | M6 SPLIT WASHER | 24 |
| 29 | A-0011 | M3 PLASTIC WASHER | 12 |
| 30 | A-0012 | T-SLOT NUT M6 THREAD 8MM SLOT | 24 |
| 31 | A-0015 | M3 6MM LENGTH SOCKET HEAD CAP SCREW | 14 |
| 32 | A-0016 | M3 SPLIT WASHER | 8 |
| 33 | A-0017 | M3 HEX NUT | 24 |
| 34 | A-0018 | M6 20MM SOCKET HEAD CAP SCREW | 8 |
| 35 | A-0020 | M6 30MM SOCKET HEAD CAP SCREW | 4 |
| 36 | C-0001 | BATH SLED BASE | 2 |
| 37 | C-0002 | ANDY MARK NEVERREST AM-2964A | 2 |
| 38 | C-0022 | SPUR GEAR | 2 |
| 39 | C-0023 | MOTOR BRACKET CRADLE | 2 |
| 40 | C-0024 | MOTOR BRACKET SHAFT SIDE | 2 |
| 41 | C-0033 | GEAR SHAFT SLEEVE | 2 |
| 42 | C-0042 | FLAT BEARING | 2 |
| 43 | A-0021 | GEAR SET SCREW | 2 |
| 44 | C-0048 | LIMIT SWITCH MOUNT | 1 |
| 45 | C-0049 | LIMIT SWITCH TRIGGER | 1 |
| 46 | C-0050 | OPTICAL SWITCH MOUNT | 1 |

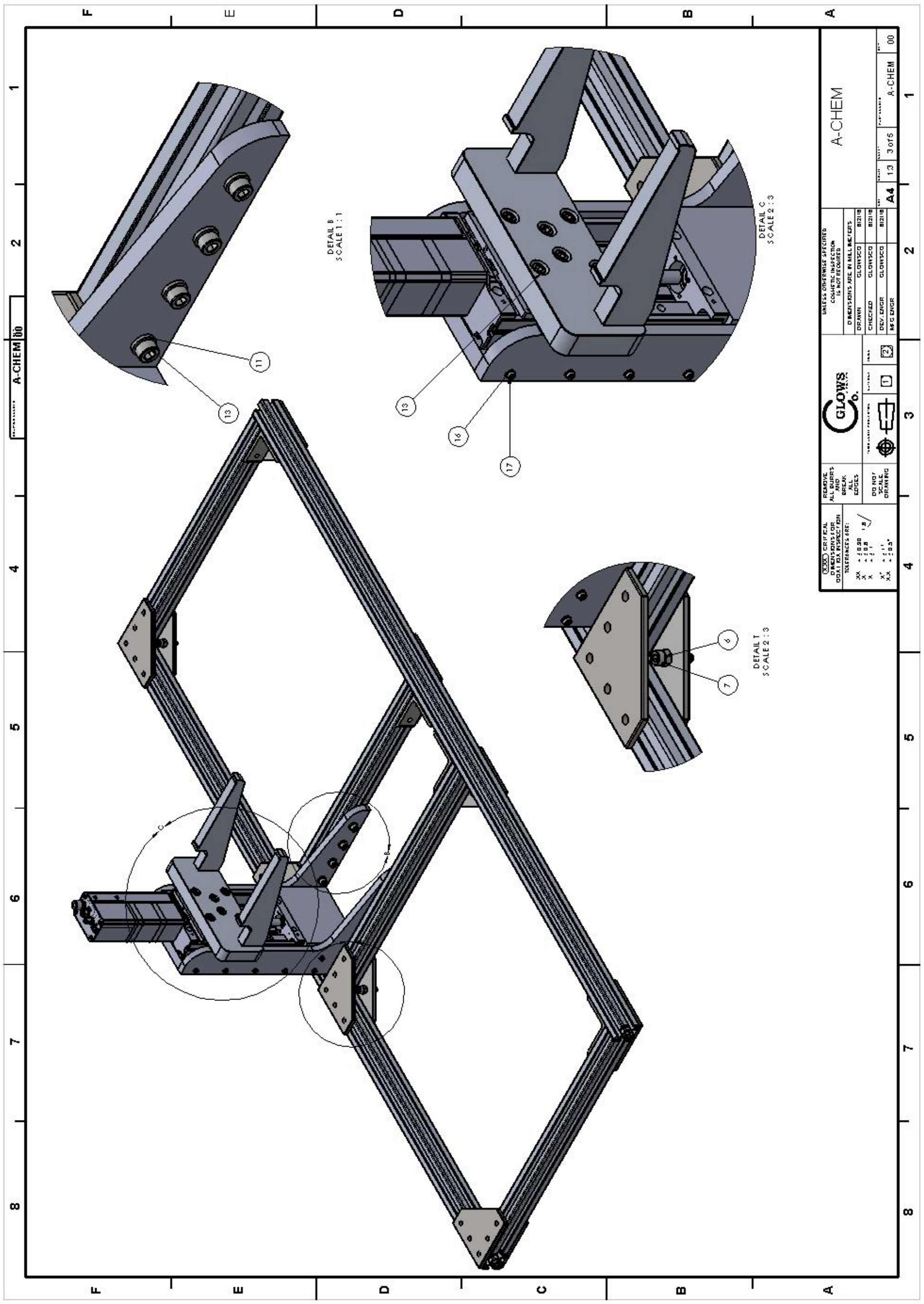
GLOWS Co.

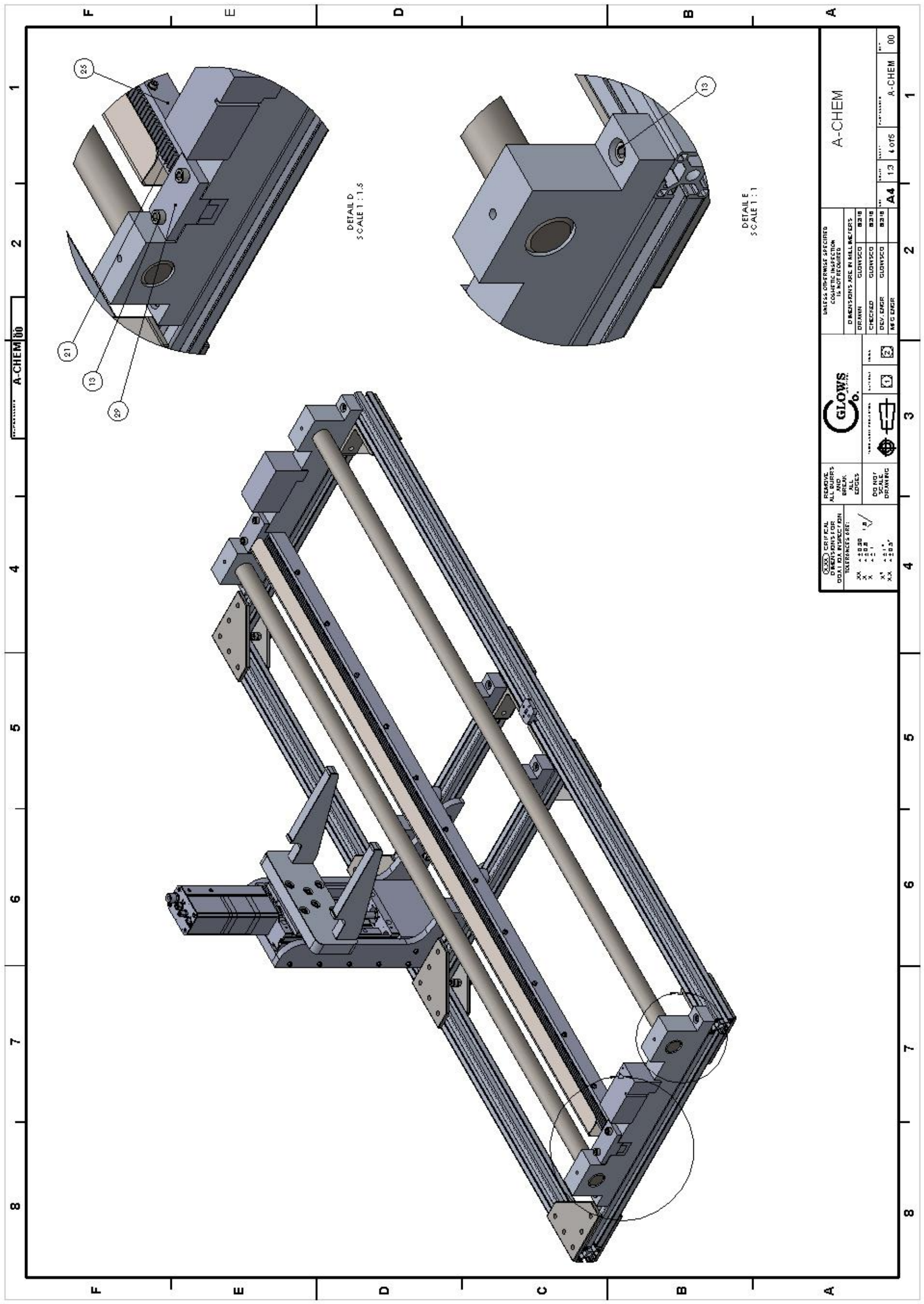
UNLESS OTHERWISE SPECIFIED
COSMETIC INSPECTION IS NOT REQUIRED
DIMENSIONS ARE IN MILLIMETERS

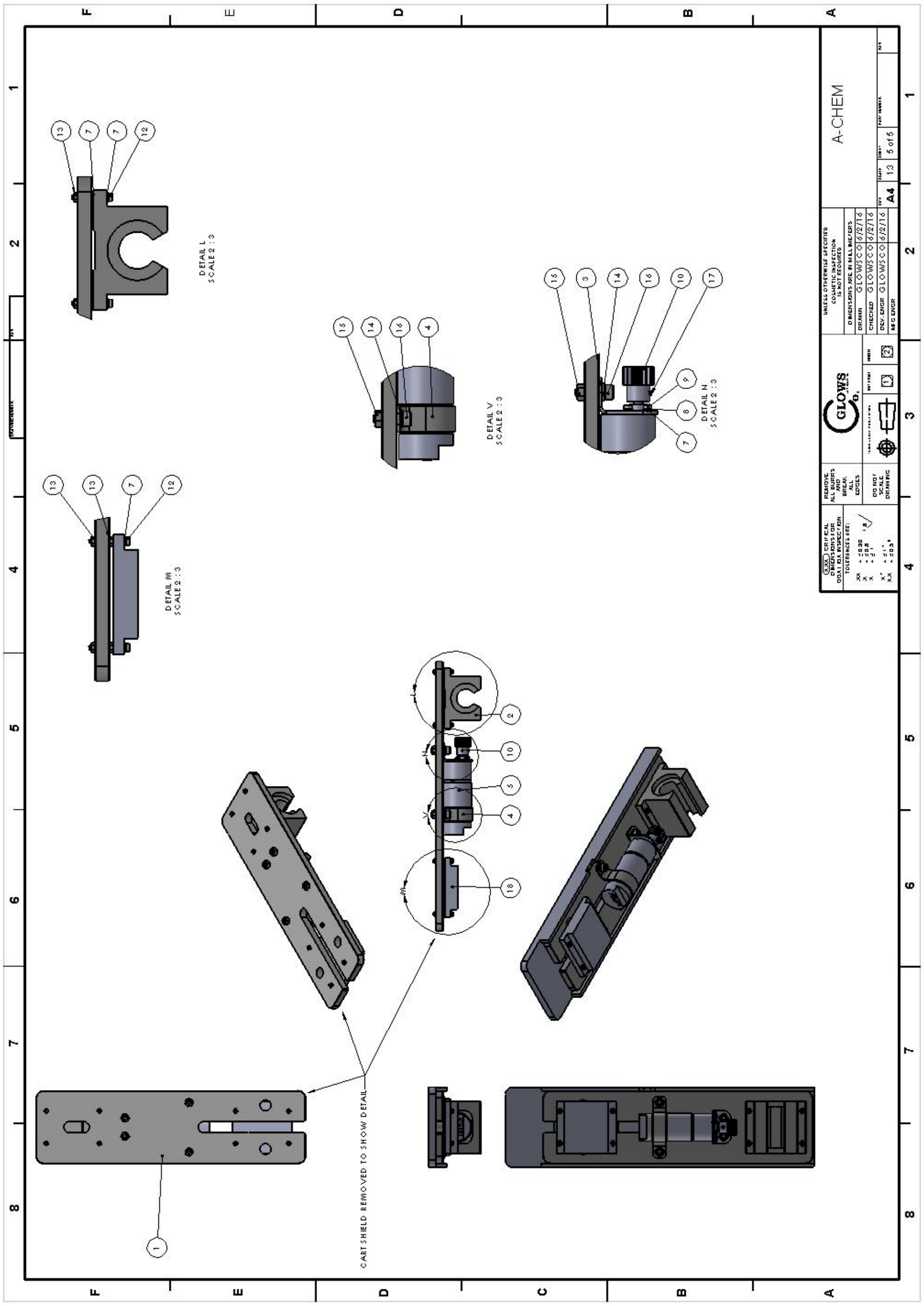
A-CHEM

A4 | 1:3 | 1 of 5 | A-CHEM | 00

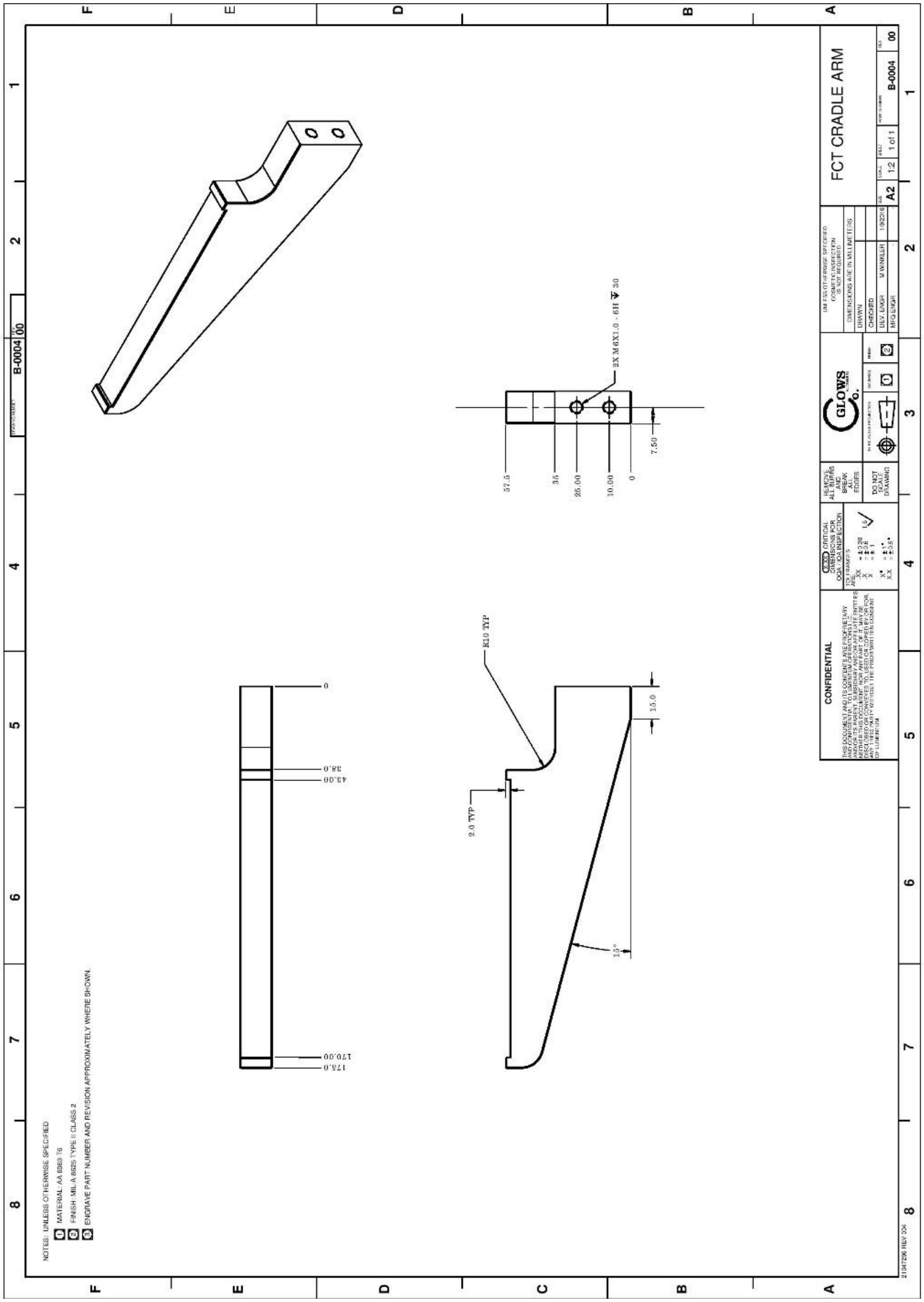

A-CHEM
DETAIL R
SCALE 1 : 2

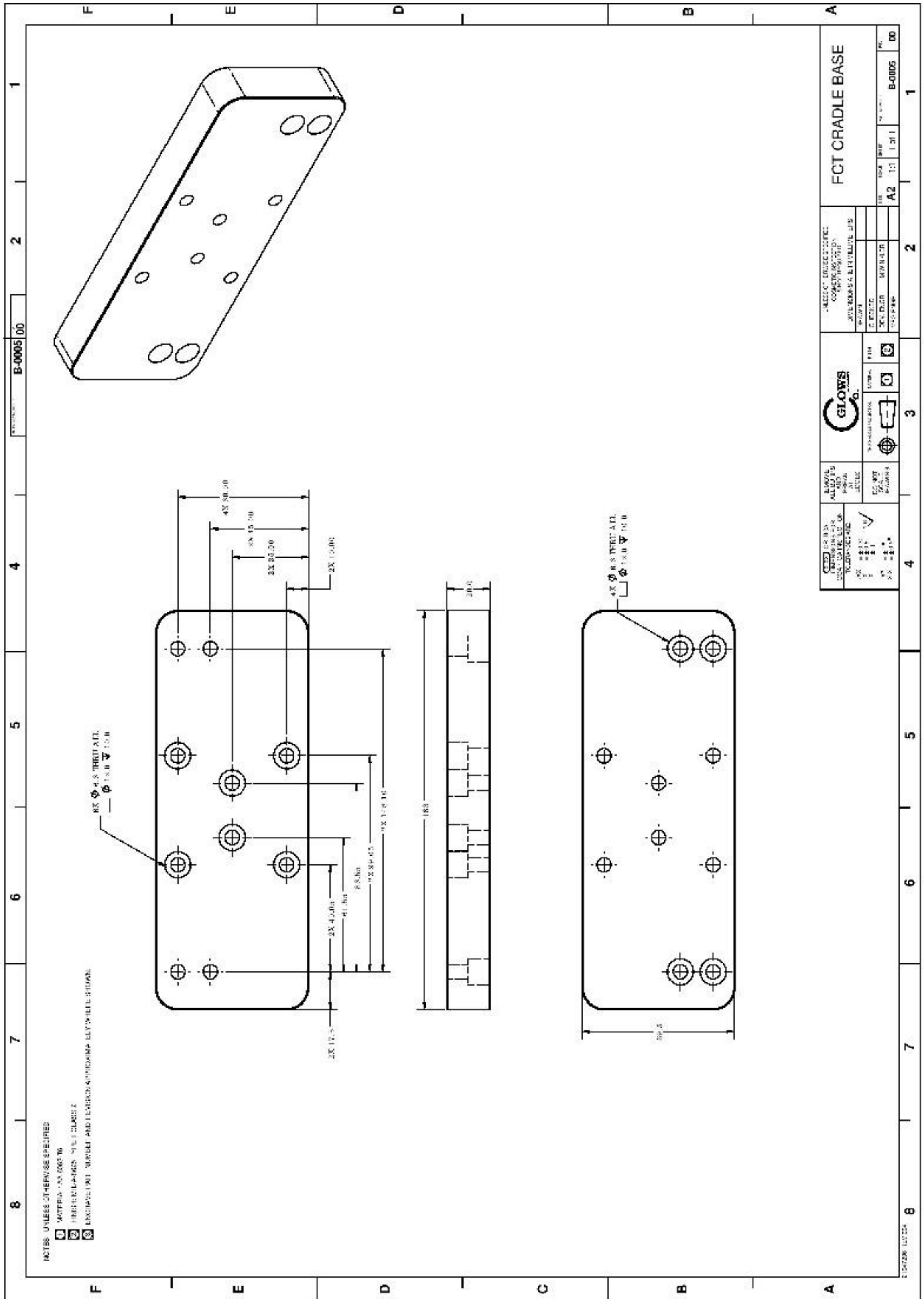

A-CHEM
DETAIL B
SCALE 1 : 1
DETAIL C
SCALE 2 : 3
DETAIL T
SCALE 2 : 3
GLOWS

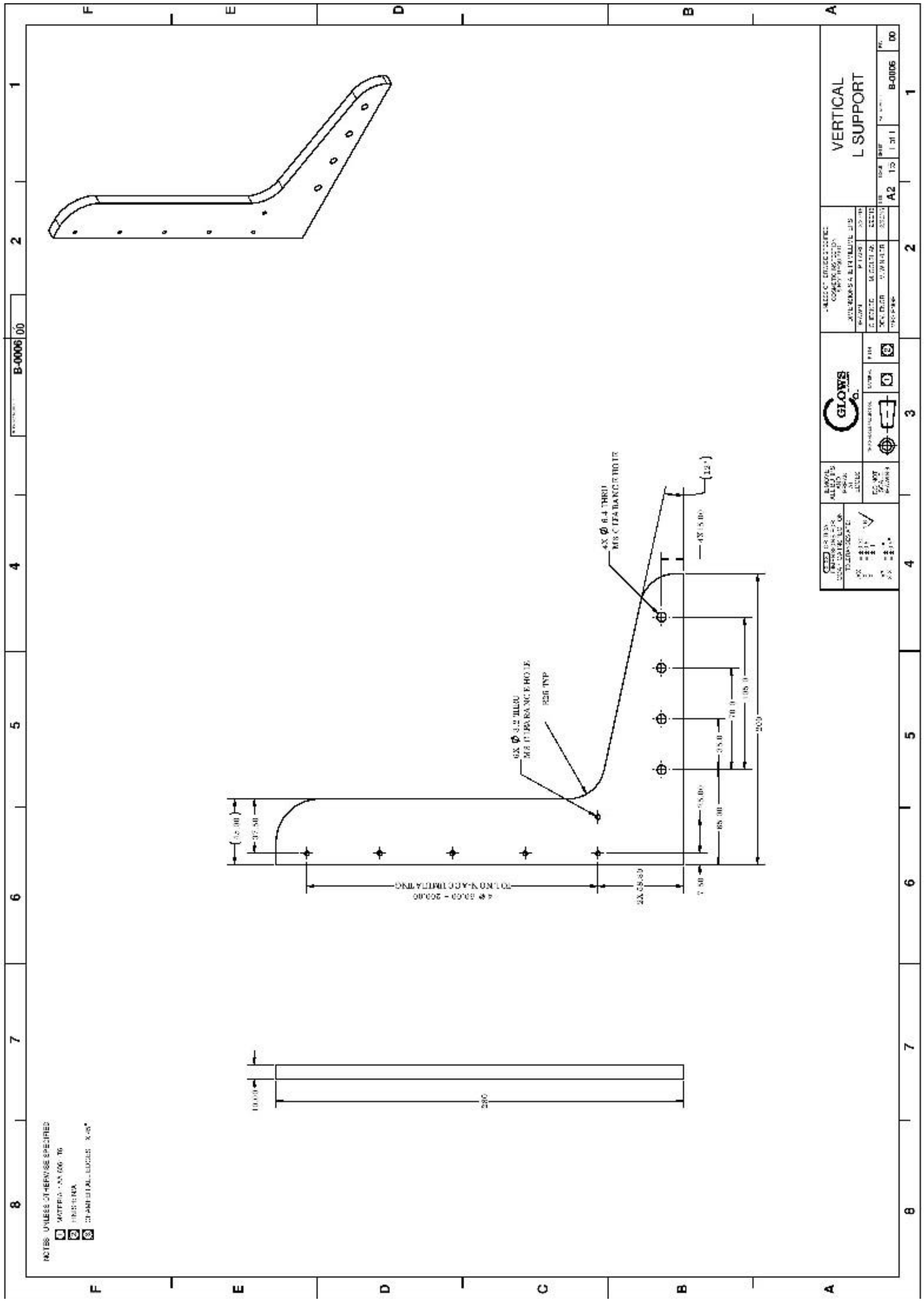

DETAIL D
SCALE 1 : 1.5
DETAIL E
SCALE 1 : 1
A-CHEM
00
GLOWS CO.
A4
1:3
4 of 5

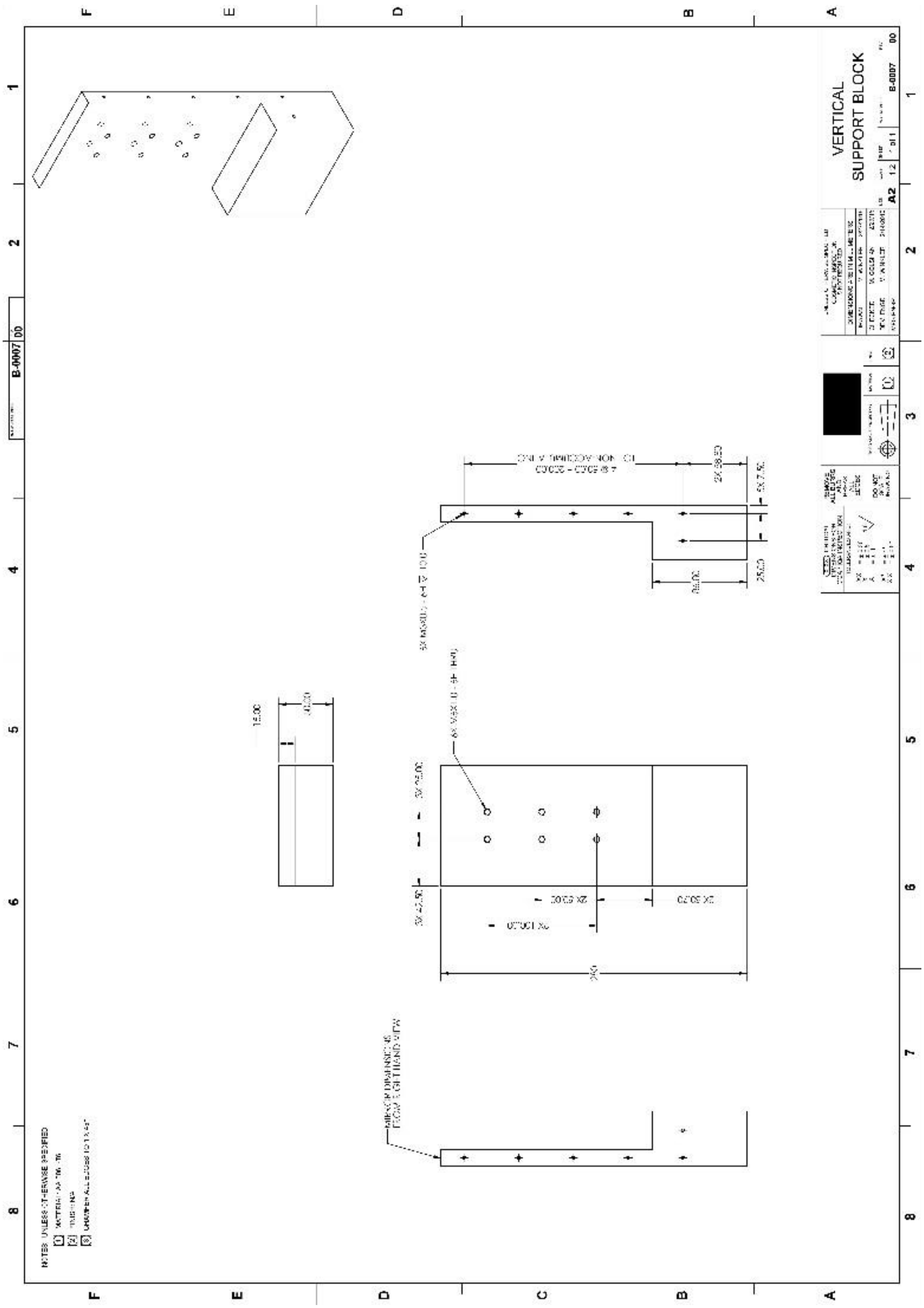


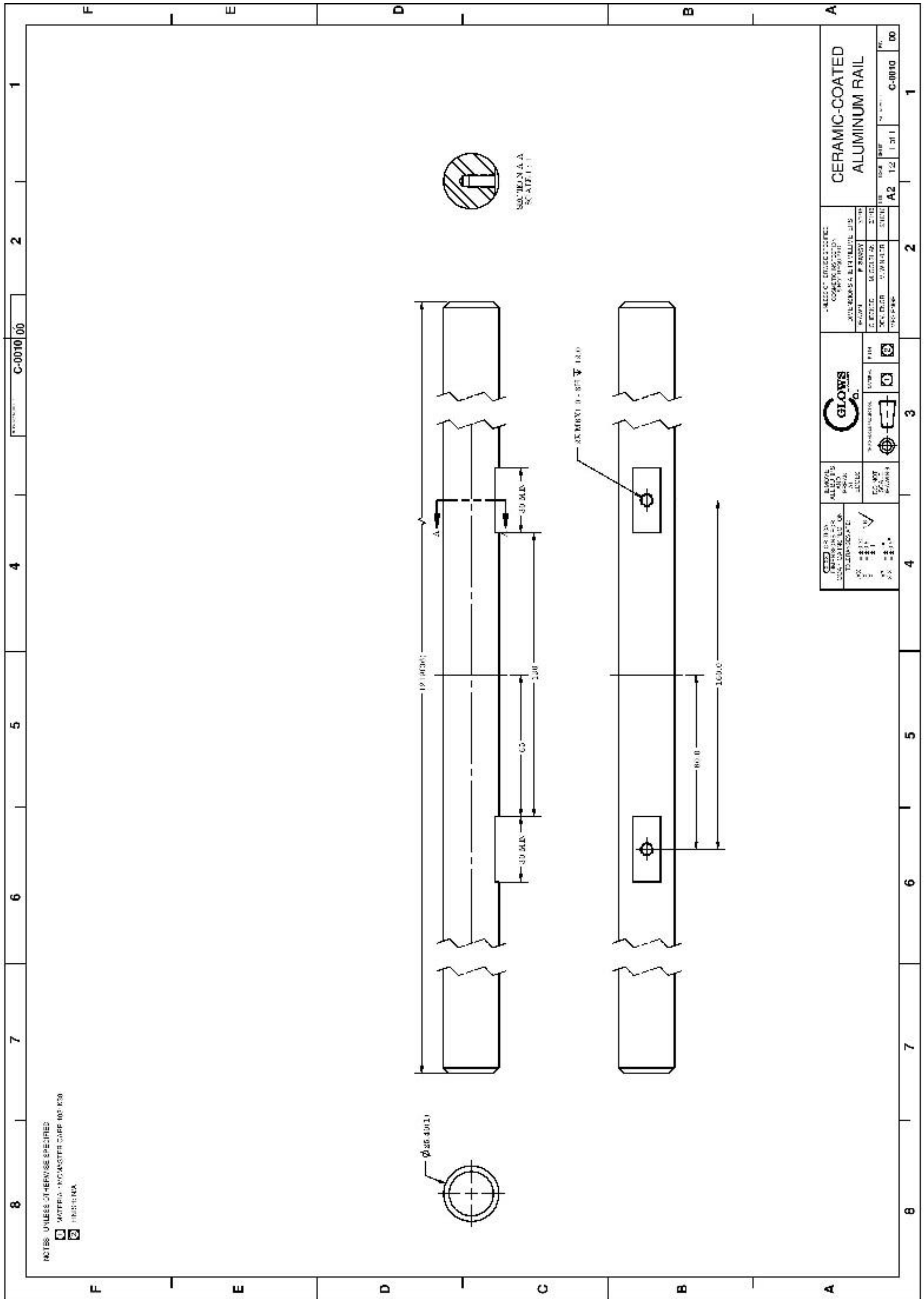
A-CHEM
DETAIL L
SCALE 2 : 3
DETAIL M
SCALE 2 : 3
DETAIL V
SCALE 2 : 3
DETAIL N
SCALE 2 : 3
CART SHIELD REMOVED TO SHOW DETAIL

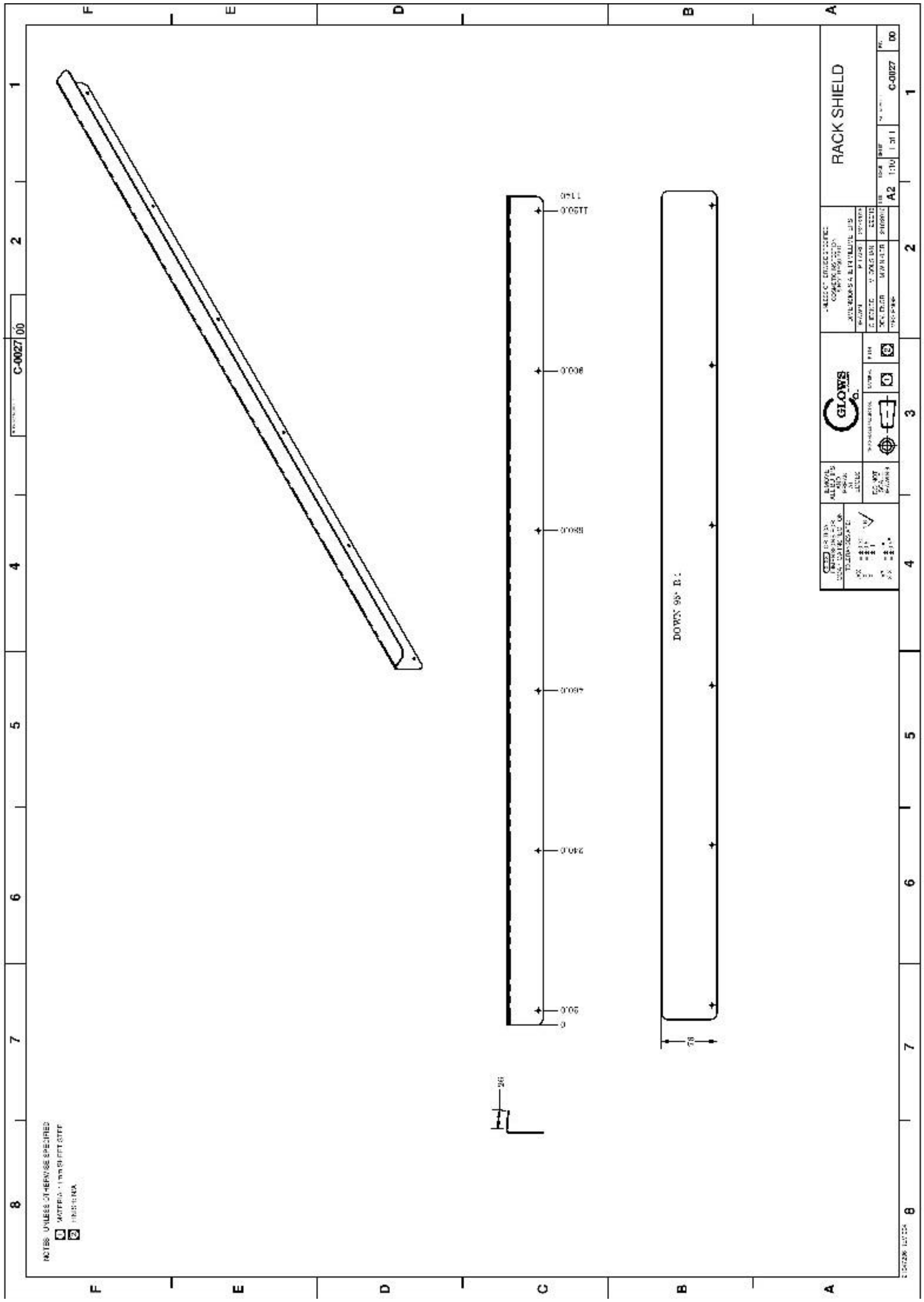

FCT CRADLE ARM
B-0004
00
A2
1:2
1 of 1
CONFIDENTIAL
NOTES: UNLESS OTHERWISE SPECIFIED
MATERIAL: AA 6063 T6
FINISH: MIL-A-8625 TYPE II CLASS 2
ENGRAVE PART NUMBER AND REVISION APPROXIMATELY WHERE SHOWN
2X M6X1.0 - 6H ↧ 30
R10 TYP
2.0 TYP
15.0
15°
7.50
57.5
35
25.00
10.00
38.0
43.00
170.00
175.0
REMOVE ALL BURRS AND BREAK ALL EDGES
DO NOT SCALE DRAWING
DRAWN
CHECKED
DEV ENGR
MFG ENGR
M WINKLER
DIMENSIONS ARE IN MILLIMETERS

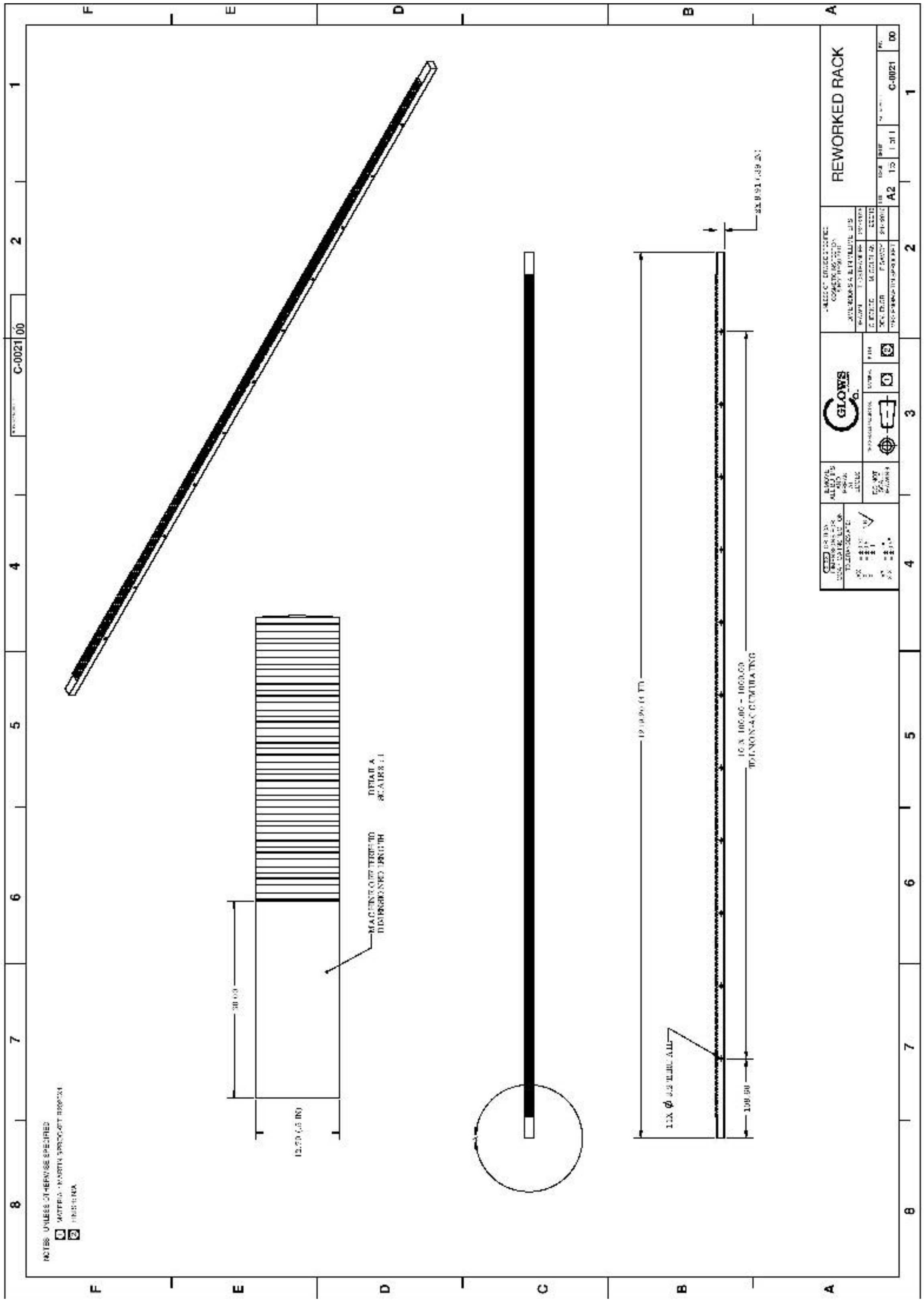

FCT CRADLE BASE
B-0005
A2
GLOWS

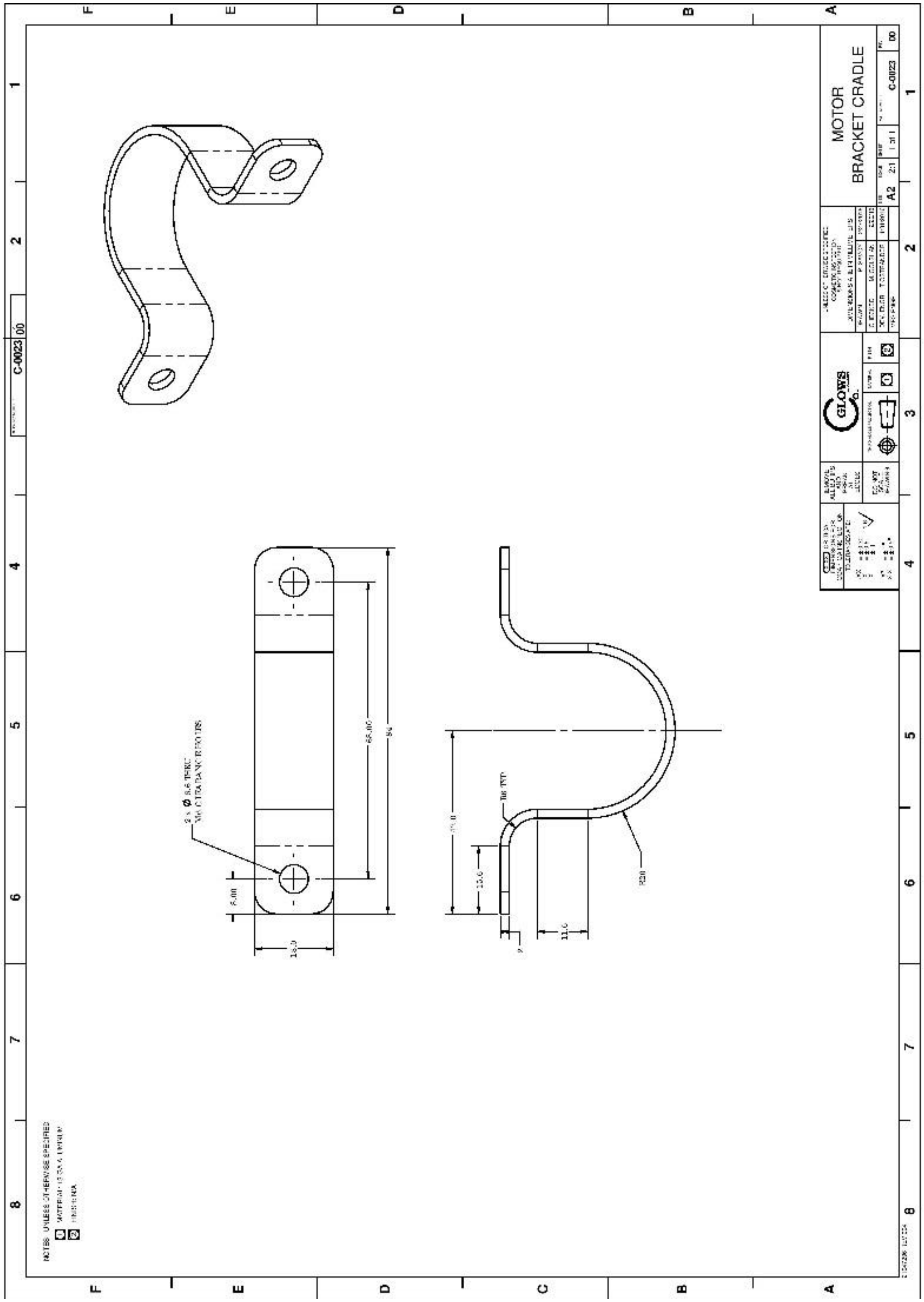

VERTICAL
L SUPPORT
B-0006
GLOWS
A2
6X Ø 3.2 THRU
4X Ø 6.4 THRU
280


VERTICAL
SUPPORT BLOCK
B-0007
00
A2

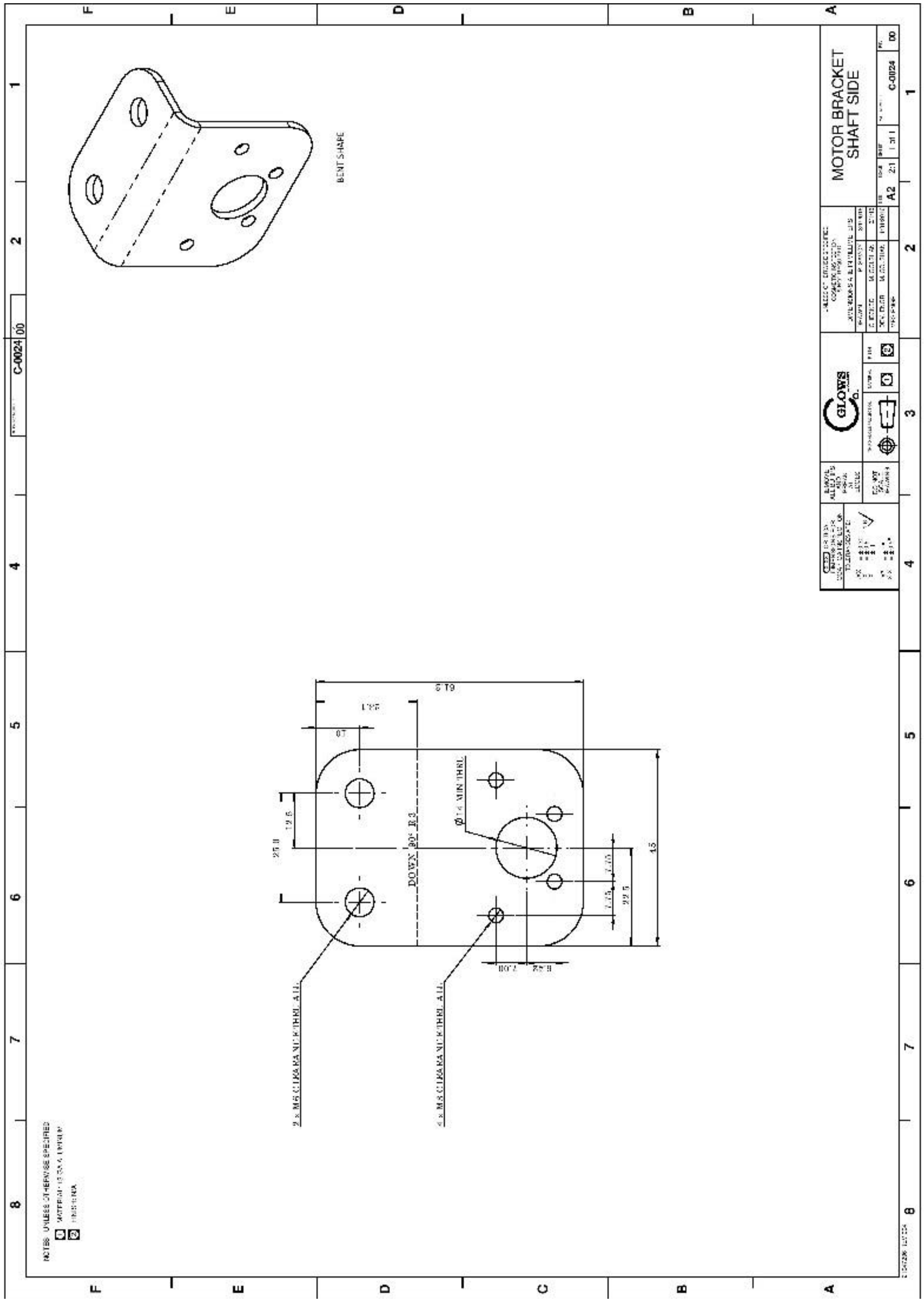

CERAMIC-COATED
ALUMINUM RAIL
C-0010
A2
1:2
00

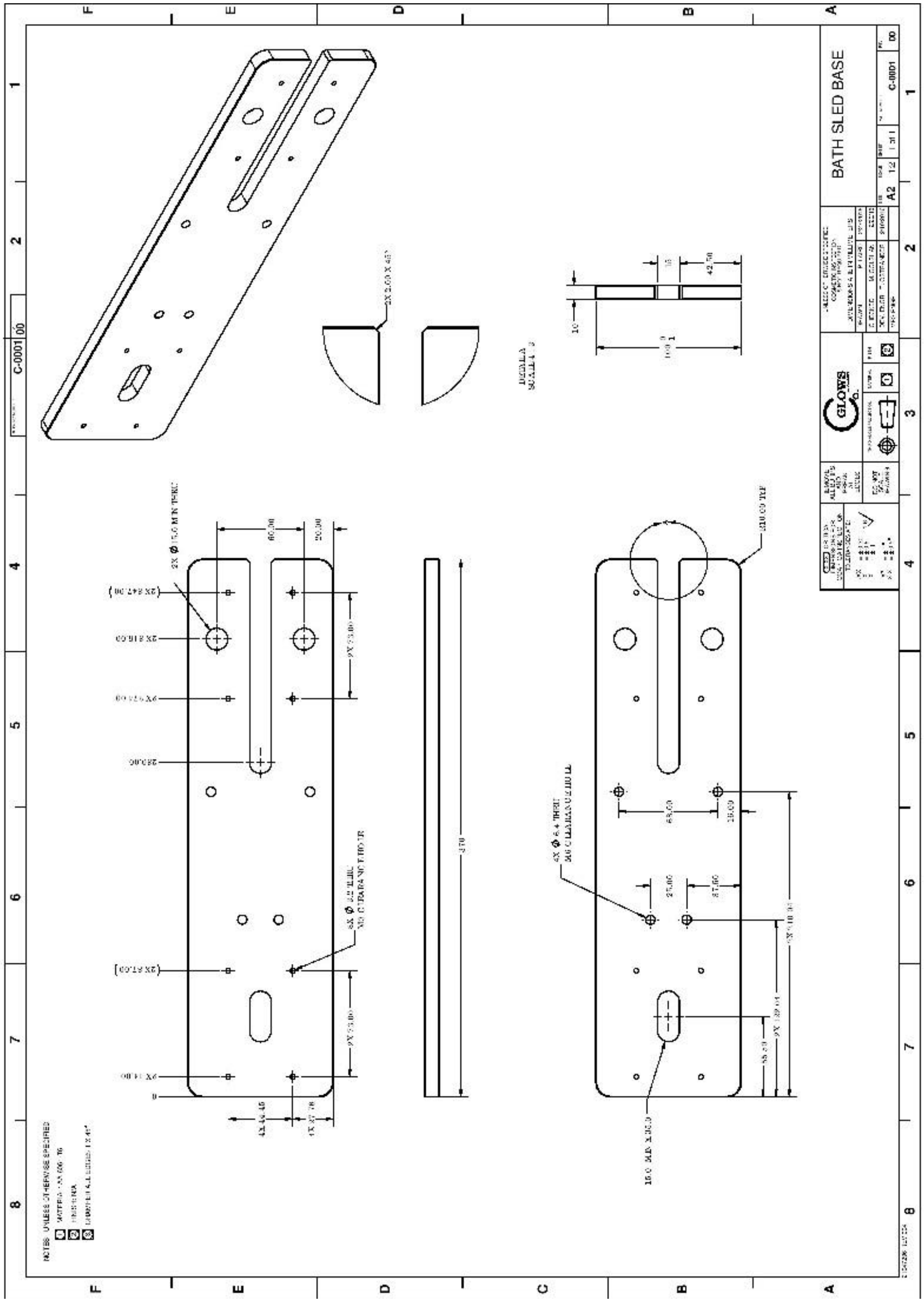

RACK SHIELD
C-0027
00
A2

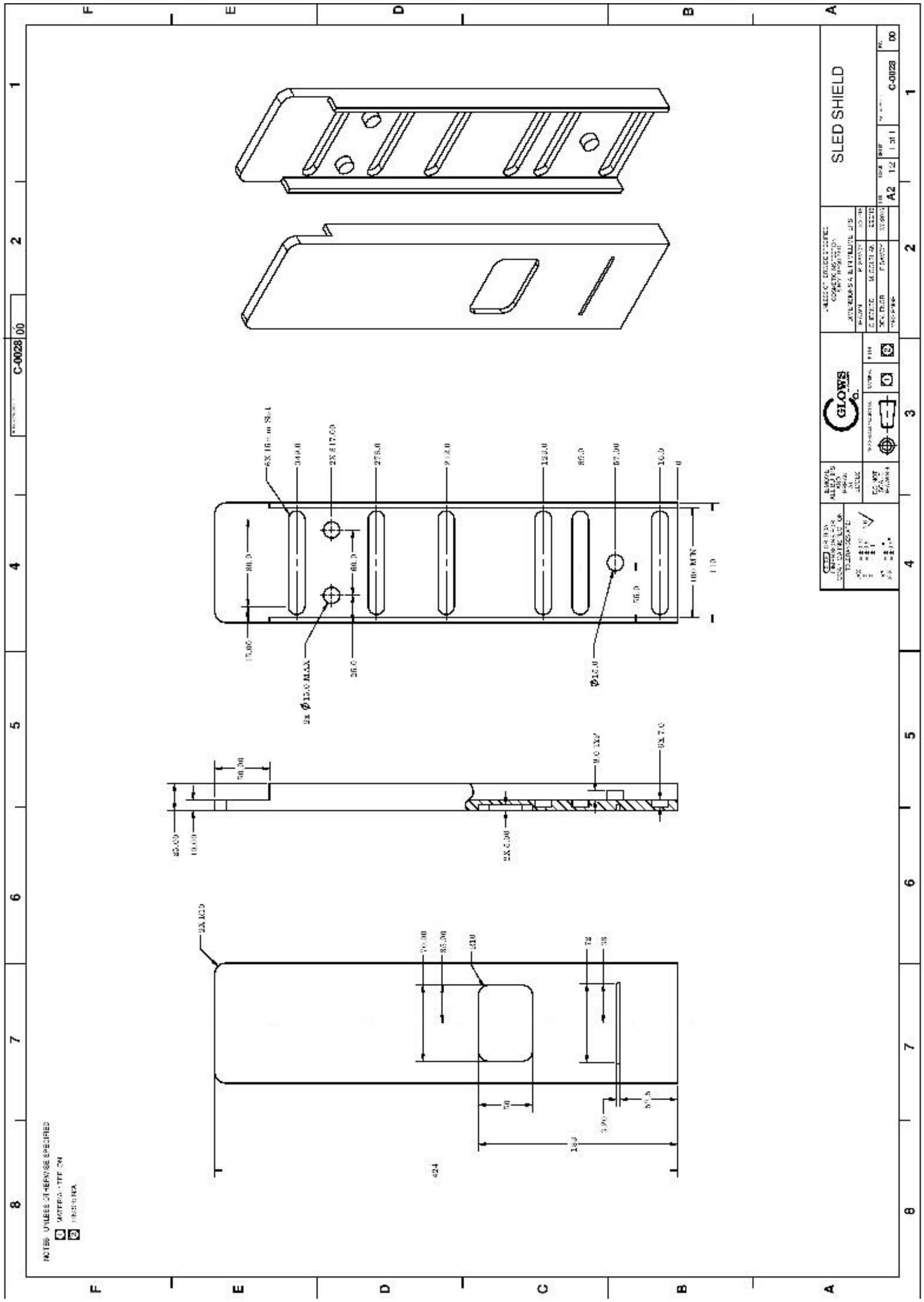

REWORKED RACK
C-0021
A2
GLOWS

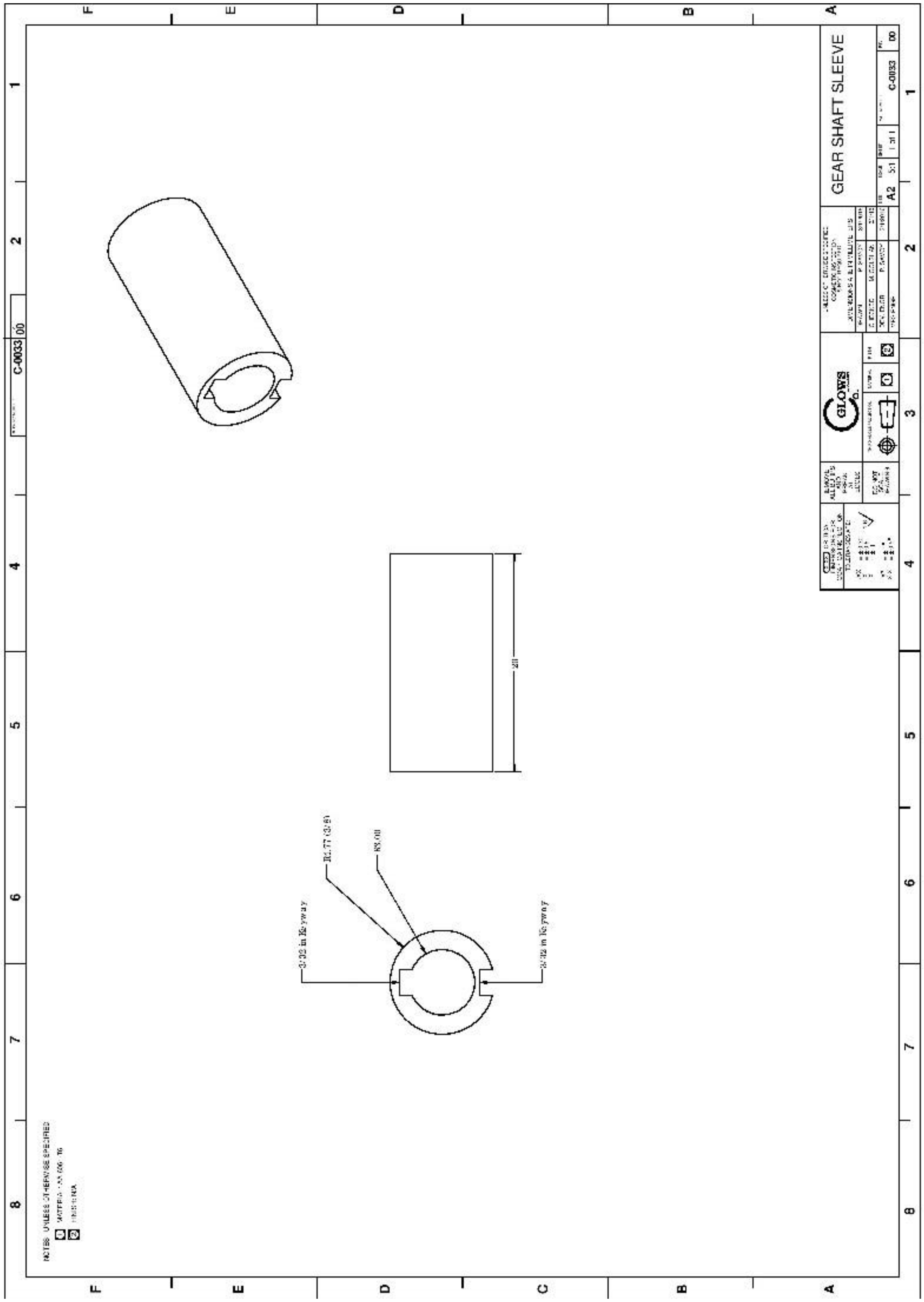


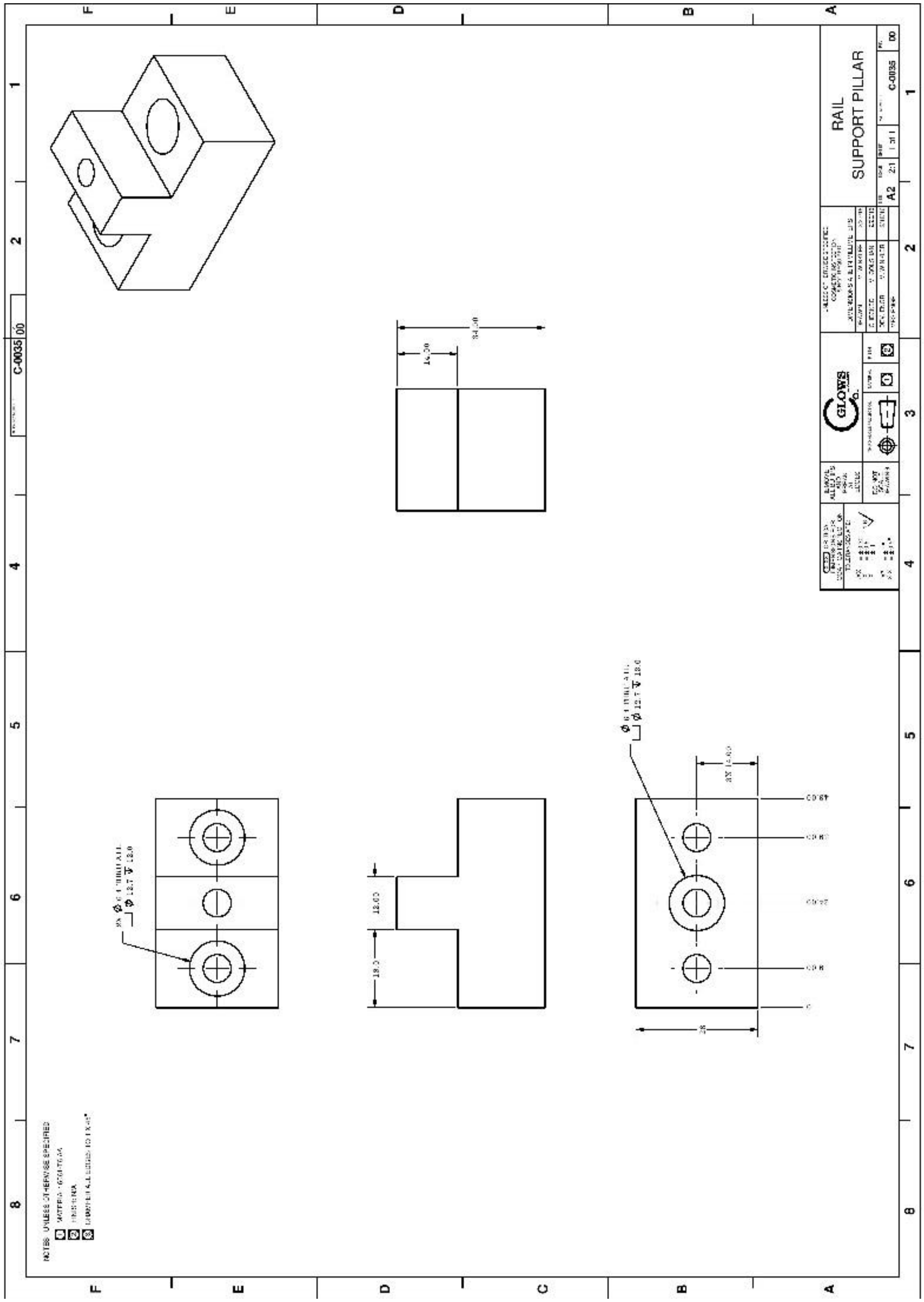
MOTOR
BRACKET CRADLE
C-0023
00
A2
2:1
GLOWS
R20
11.0
15.0


MOTOR BRACKET
SHAFT SIDE
C-0024
BENT SHAPE
DOWN 90° R3
GLOWS

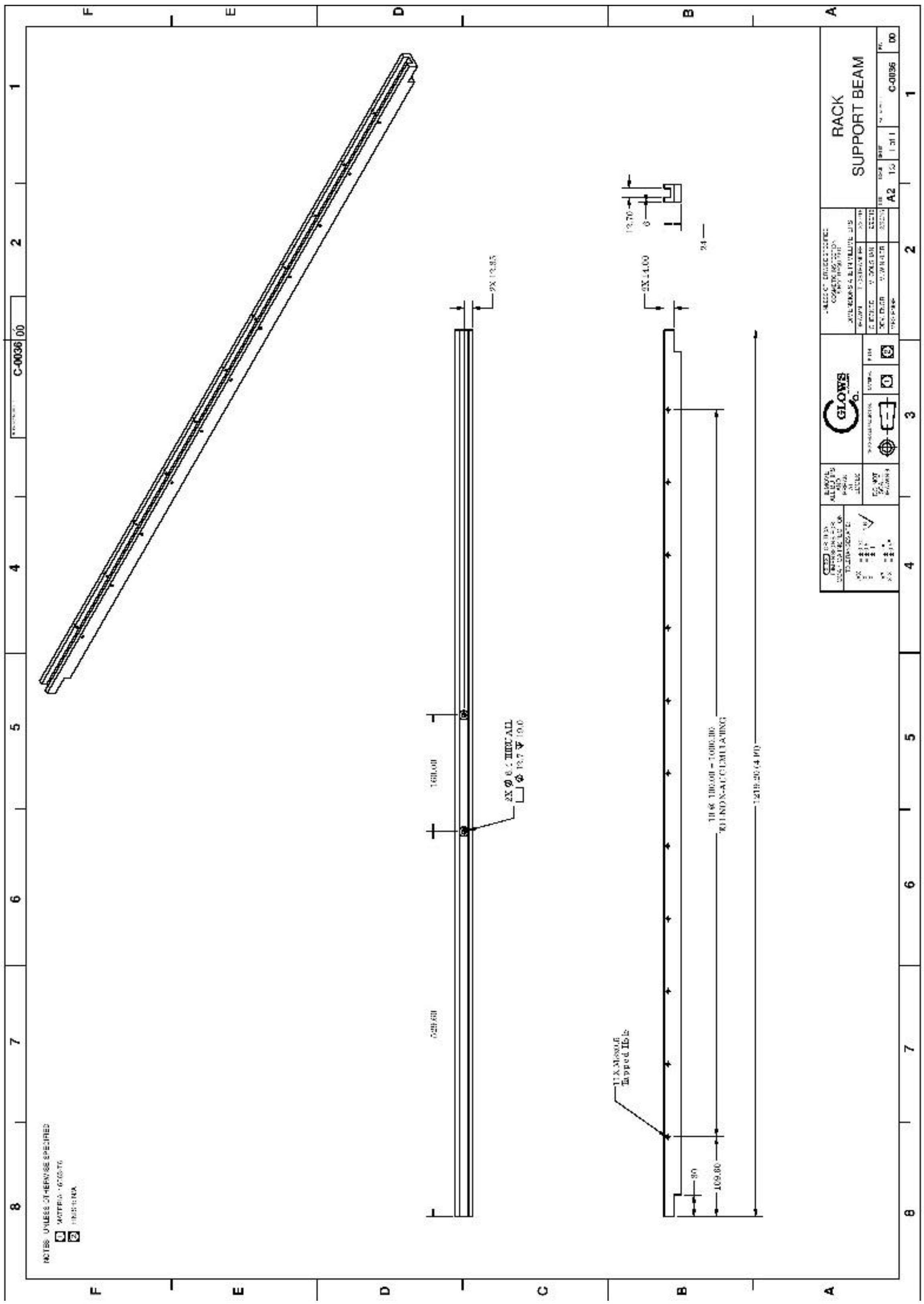

BATH SLED BASE
C-0001
A2
GLOWS

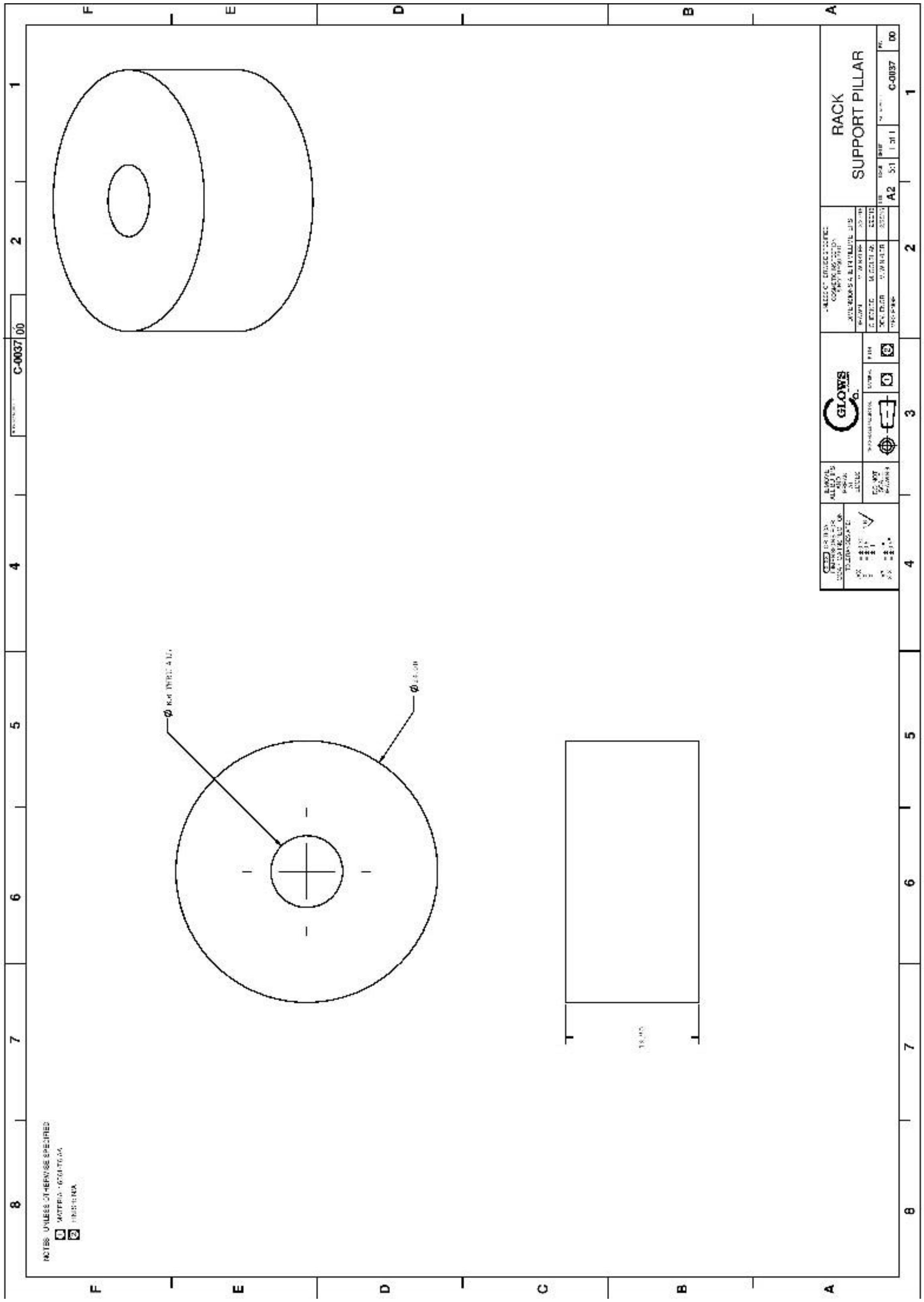

SLED SHIELD
C-0028

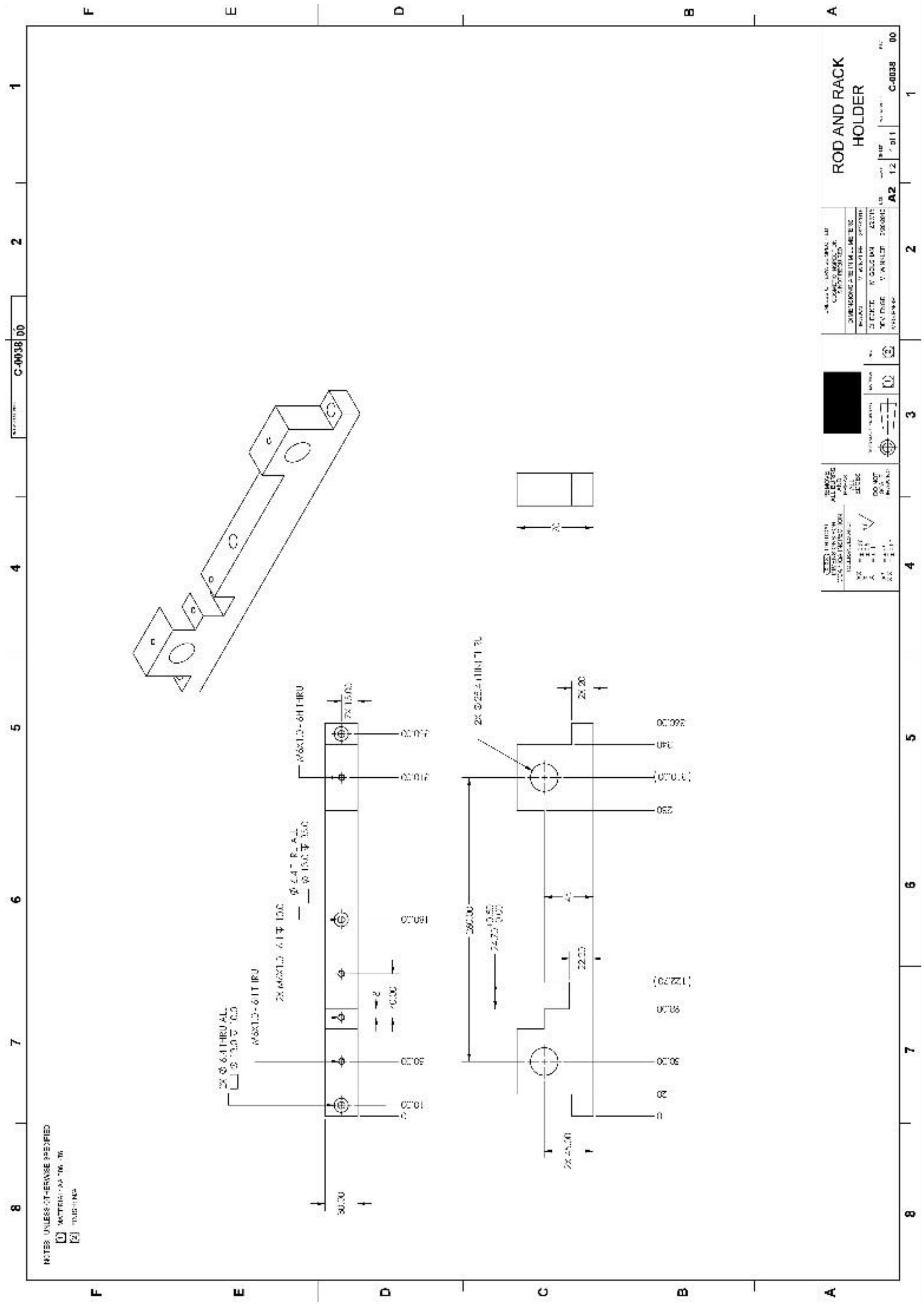

GEAR SHAFT SLEEVE
C-0033
00
A2
3/32 in Keyway
3/32 in Keyway

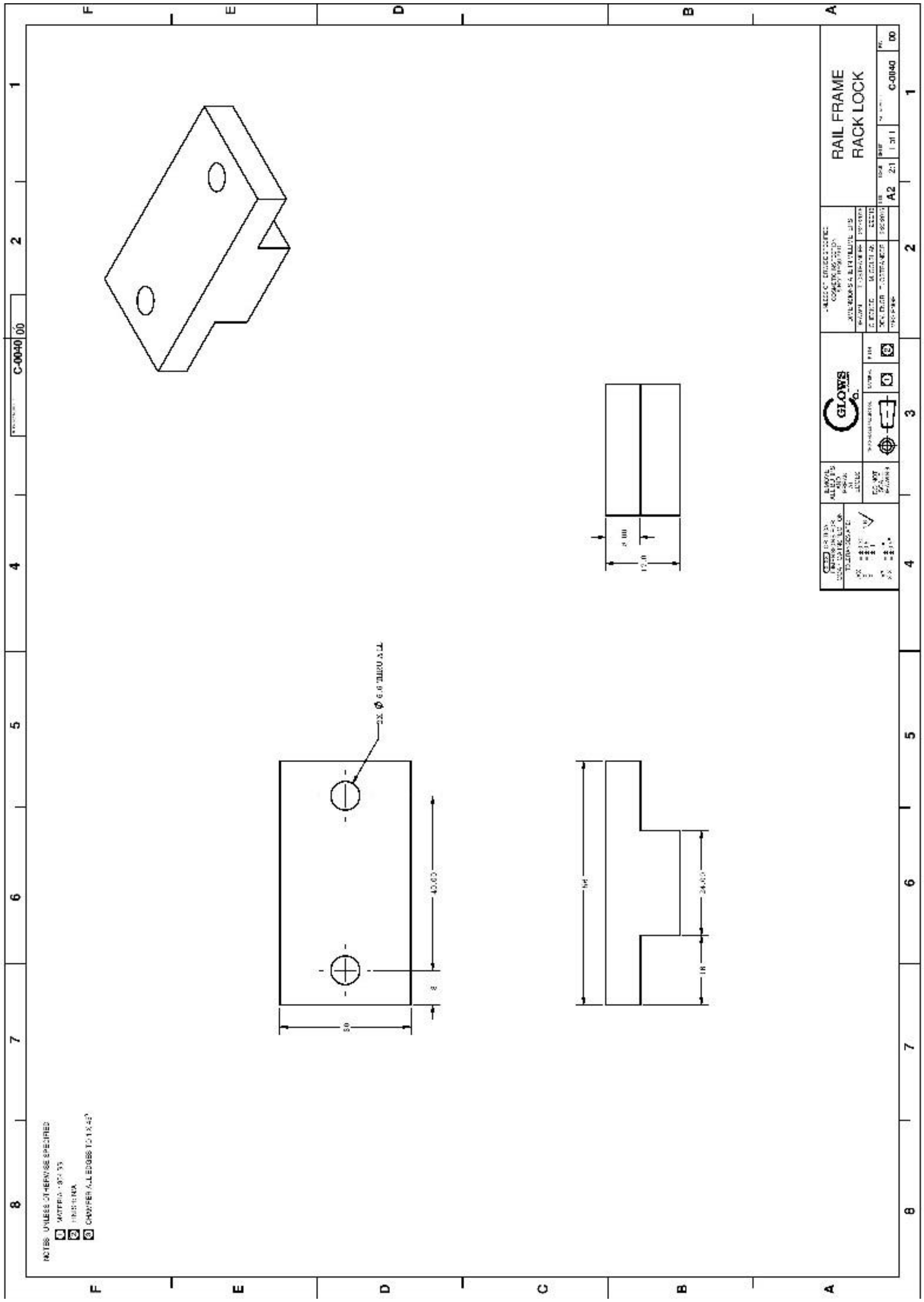


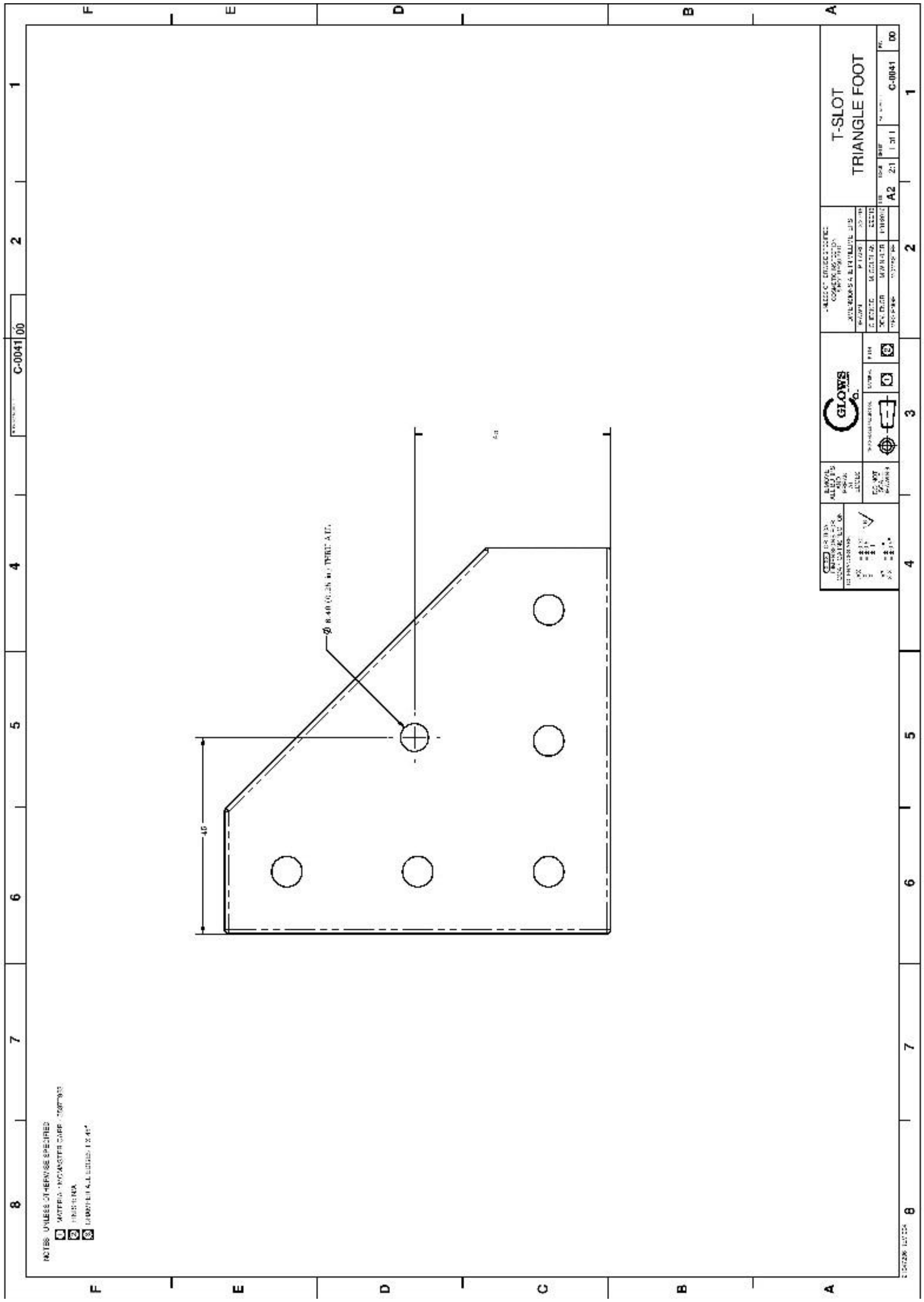
RAIL
SUPPORT PILLAR
C-0035
00
A2
2:1


RACK
SUPPORT BEAM
C-0036
00
A2
GLOWS


RACK
SUPPORT PILLAR
C-0037
A2
GLOWS


ROD AND RACK HOLDER
C-0038


RAIL FRAME
RACK LOCK
C-0040
00
A2
2X Ø 6.6 THRU ALL
40.00
24.00
12.0
50
8
18


T-SLOT
TRIANGLE FOOT
C-0041
A2
2:1
GLOWS
NOTES: UNLESS OTHERWISE SPECIFIED

# Appendix D: PDS

Datum description: Lumentum's current manual process which is manually performed using Lumentum's equipment.

| Elements/Requirements | Units | Datum | Target Range |
|---|---|---|---|
| **Process** | | | |
| Bath Side-Side Accuracy | mm | 5 | 2.0 |
| Bath Maximum Velocity | mm/s | N/A | 50.0 |
| FCT Vertical Accuracy | mm | 2 | 1.0 |
| Fiber Dip Time Accuracy | s | 15 | 1.0 |
| Maximum Vertical Acceleration | $m/s^2$ | N/A | 0.05 |
| Fiber Table Max Acceleration | $m/s^2$ | N/A | 0.1 |
| Fiber Table Max Velocity | mm/s | N/A | 30.0 |
| Heats Acid Baths | Yes/No | Yes | Yes |
| Heater Block Control On/Off | Yes/No | Yes | Yes |
| Does Not Excite Natural Frequencies | Yes/No | N/A | Yes |
| Time Between Baths | s | 45 | 20-30 |
| Has Reset Function? | Yes/No | N/A | Yes |
| Only Operates When Fume Hood Closed | Yes/No | No | Yes |
| Class XXXX Clean Room | Yes/No | Yes | Yes |
| **Physical Requirements** | | | |
| Max Depth | m | N/A | 0.6 |
| Max Width | m | N/A | 1.8 |
| Max Height | m | N/A | 1.0 |
| Interfaces With Lumentum Tool FCT | Yes/No | Yes | Yes |
| Dynamic Loading Yielding | FOS | N/A | >5 |
| Operating Temperature | C | 10-30 | 10-30 |
| **Safety** | | | |
| Human Interface Start/Stop Only | Yes/No | No | Yes |
| E-Stop Reliability | % | N/A | 100 |
| Movement Components Shielded? | Yes/No | N/A | Yes |
| Must Be Easy To Load and Unload Baths | Yes/No | N/A | Yes |
| No Heat Leaking | Yes/No | N/A | Yes |
| Power Supply | N/A | N/A | Single Phase 110V |
| No Sharp Corners | Yes/No | Yes | Yes |

| | | | |
|---|---|---|---|
| **Maintenance** | | | |
| Surface Wear | Yes/No | N/A | No |
| Sulfuric Acid Resistance | Yes/No | N/A | Yes |
| Lifespan | Years | N/A | 5 |
| Cycles Before Human Calibration | Cycles | N/A | 500 |
| Parts Removable? | Yes/No | N/A | Yes |
| **Other** | | | |
| Delivery Date | Date | N/A | 7/29/2016 |
| Total Cost of Final Tool | $ | N/A | 12000 |

Other Project Requirements

-machine must interact with existing fiber-holding tool
-etched section of fibers must never touch each other
-machine must be easily serviceable
-machine must thermally insulate bath heaters from rest of machine
-baths should be easy to remove from the machine
-machine controls should be simple to use

# Appendix E: Manufactured Parts Quote

| Item | Drawing# Part# | Description | Qty | Unit Price ($) | Sub Total ($) |
|---|---|---|---|---|---|
| 1 | B-0004 REV 00 | FCT CRADLE ARM (AL 6061) | 2 | $ 185.00 | $ 370.00 |
| 2 | B-0005 REV 00 | FCT CRADLE BASE (AL 6061) | 1 | $ 215.00 | $ 215.00 |
| 3 | B-0006 REV 00 | VERTICAL L SUPPORT | 2 | $ 145.00 | $ 290.00 |
| 4 | B-0007 REV 00 | VERTICAL L SUPPORT BLOCK | 1 | $ 275.00 | $ 275.00 |
| 5 | C-0001 REV 00 | BATH SLED BASE | 3 | $ 145.00 | $ 435.00 |
| 6 | C-0010 REV 00 | CERAMIC-COATED ALUMINUM RAIL (MODIFY ONLY) | 2 | $ 165.00 | $ 330.00 |
| 7 | C-0021 REV 00 | REWORKED RACK (MATERIAL: MARTIN SPROCKET R2020X4) | 1 | $ 335.00 | $ 335.00 |
| 8 | C-0023 REV 00 | MOTOR BRACKET CRADLE | 3 | $ 58.00 | $ 174.00 |
| 9 | C-0024 REV 00 | MOTOR BRACKET SHAFT SIDE | 3 | $ 52.00 | $ 156.00 |
| 10 | C-0027 REV 00 | RACK SHIELD | 1 | $ 150.00 | $ 150.00 |
| 11 | C-0028 REV 00 | SLED SHIELD | 3 | $ 325.00 | $ 975.00 |
| 12 | C-0035 REV 00 | RAIL SUPPORT PILLAR | 4 | $ 75.00 | $ 300.00 |
| 13 | C-0036 REV 00 | RACK SUPPORT BEAM (AL 6061) | 1 | $ 475.00 | $ 475.00 |
| 14 | C-0037 REV 00 | RACK SUPPORT PILLAR | 2 | $ 18.00 | $ 36.00 |
| 15 | C-0038 REV 00 | ROD AND RACK HOLDER | 2 | $ 285.00 | $ 570.00 |
| 16 | C-0040 REV 00 | RAIL FRAME RACK LOCK | 2 | $ 105.00 | $ 210.00 |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | **TOTAL:** | **$ 5,296.00** |

# Appendix F: Projected Cost

Table C- Expected Final Product Cost

| Item: | Cost: |
|---|---|
| **Purchased Parts - Accessories** | $3,904 |
| Screws-Hardware | $180 |
| Frame Support Material | $104 |
| Lifting Mechanism | $3,420 |
| Linear Slide Rails | $200 |
| **Processing Board/Controller** | $1,799 |
| NI CompactRIO-9063 | $1,299 |
| Controlling Modules | $500 |
| **Machined Parts** | $1,200 |
| FCT Cradle | $800 |
| Bath Assembly Support Beams | $400 |
| **Motors and Controllers** | $1,980 |
| Stepper Motor + Controller Combo | $1,000 |
| Motor Driver Board | $980 |
| **Total:** | $8,883 |

| System | Description | Original Manufacturer | Manufacturer Part Number | Part Number | Cost/ Part | Qty. | Total |
|---|---|---|---|---|---|---|---|
| General | M3 Thread, 16mm Length, .5mm Pitch | McMaster Carr | 92290A120 | A-0001 | $0.20 | 100 | $20.00 |
| General | M6 Thread, 25mm Length, 1mm Pitch | McMaster Carr | 92290A330 | A-0003 | $0.47 | 100 | $47.00 |
| General | Type 316 Stainless Steel Flat Washer, M6 Screw Size | McMaster Carr | 90965A170 | A-0004 | $0.07 | 100 | $7.00 |
| General | Type 316 Stainless Steel Split Lock Washer, M6 Screw Size | McMaster Carr | 92153A426 | A-0005 | $0.06 | 100 | $6.00 |
| General | M6 Thread, 18mm Length, 1mm Pitch | McMaster Carr | 92290A323 | A-0006 | $0.42 | 100 | $42.00 |
| General | M3 Thread, 25mm Length, .5mm Pitch | McMaster Carr | 92290A124 | A-0007 | $0.27 | 50 | $13.44 |
| General | M6x1 Thread Size, 10mm Wide, 5mm High Hex Nut | McMaster Carr | 94150A345 | A-0009 | $0.19 | 50 | $9.58 |
| General | T-slot Nut 8mm Slot M6 Thread | McMaster Carr | T9FB797274 | A-0012 | $1.76 | 14 | $24.64 |
| General | M3 Washer, 316 Steel | McMaster Carr | 90965A130 | A-0013 | $0.03 | 100 | $2.68 |
| General | M3 Thread, 20mm Length, .5 pitch | McMaster Carr | 92290A122 | A-0014 | $0.23 | 50 | $11.44 |
| General | m3 thread 6mm length .5mm pitch | McMaster Carr | 92290A111 | A-0015 | | 50 | $9.44 |
| General | M6 Split Lock Washer, 316 Steel | McMaster Carr | 92153A426 | A-0019 | $0.06 | 200 | $11.00 |
| General | m6 thread 30mm length | McMaster Carr | 92290A332 | A-0020 | $0.52 | 25 | |
| General | 6-32 thread 1/4" set screq, 316 stainless | McMaster Carr | 92158A167 | A-0021 | N/A | 3 | N/A |

| System | Description | Original Manufacturer | Manufacturer Part Number | Part Number | Cost/ Part | Qty. | Total |
|---|---|---|---|---|---|---|---|
| FCT System | Prebuilt Vertical screw Lift | Zaber | X-LRQ075BL-E01-KX13C | B-0001 | $2,672.00 | 1 | $2,672.00 |
| FCT System | FCT Cradle Arm | GLOWS CO | N/A | B-0004 | $185.00 | 2 | $370.00 |
| FCT System | FCT Cradle Base | GLOWS CO | N/A | B-0005 | $215.00 | 1 | $215.00 |
| FCT System | Vertical L Support | GLOWS CO | N/A | B-0006 | $145.00 | 2 | $290.00 |
| FCT System | Vertical Support Block | GLOWS CO | N/A | B-0007 | $275.00 | 1 | $275.00 |
| Sled System | Chemical Bath Sled | GLOWS CO | N/A | C-0001 | $145.00 | 3 | $435.00 |
| Sled System | NeverRest40 Motor w/ Built in Encoder | AndyMark | AM-2964A | C-0002 | $33.00 | 3 | $99.00 |
| Frame | Precision Ceramic-Coated Aluminum Shaft | McMaster Carr | 1031K38 | C-0010 | $165.00 | 2 | $330.00 |
| Sled System | 20 Pitch, 20 Degree PA, 4 ft. Rack | Martin Sprocket | R2020X4 | C-0021 | 79.37 (raw cost) | 1 | $335.00 |
| Sled System | 20 Pitch. 20 Degree PA, 15 Tooth Gear | Martin Sprocket | TS2015BS | C-0022 | $23.97 | 3 | $71.91 |
| Sled System | Cradle Motor Bracket | GLOWS CO | N/A | C-0023 | $58.00 | 3 | $174.00 |
| Sled System | Shaft Motor Bracket | GLOWS CO | N/A | C-0024 | $52.00 | 3 | $156.00 |

| System | Description | Original Manufacturer | Manufacturer Part Number | Part Number | Cost/ Part | Qty. | Total |
|---|---|---|---|---|---|---|---|
| Frame | T-slot L angle bracket | McMaster Carr | 5537T345 | C-0025 | $8.40 | 3 | $25.20 |
| Sled System | Rack Shield | GLOWS CO | N/A | C-0027 | $150.00 | 1 | $150.00 |
| Sled System | Sled Shield | GLOWS CO | N/A | C-0028 | $325.00 | 3 | $975.00 |
| Frame | T Slot Triangle Bracket | McMaster Carr | 5537T963 | C-0029 | $12.11 | 6 | $72.66 |
| Frame | T Slot Frame Front/Back 1828.8mm (6ft) | McMaster Carr | 5537T97 | C-0030 | $23.98 | 2 | $47.96 |
| Frame | T Slot Frame Middle, 914.4mm (3ft) | McMaster Carr | 5537T97 | C-0032 | $13.09 | 1 | $13.09 |
| Sled System | Gear Shaft Sleeve | GLOWS CO | N/A | C-0033 | 0 | 3 | 0 |
| Sled System | Mounted Linear Bearing w/ gap | McMaster Carr | 8649T16 | C-0034 | $99.73 | 3 | $299.19 |
| Sled System | Rail Support Pillar | GLOWS CO | N/A | C-0035 | $75.00 | 4 | $300.00 |
| Sled System | Rack Support Beam | GLOWS CO | N/A | C-0036 | $475.00 | 1 | $475.00 |
| Sled System | Rack Support Pillar | GLOWS CO | N/A | C-0037 | $18.00 | 2 | $36.00 |
| Sled System | Rail and Rack Holder | GLOWS CO | N/A | C-0038 | $285.00 | 2 | $570.00 |
| Frame | Rail Frame Rack Lock | GLOWS CO | N/A | C-0040 | $105.00 | 2 | $210.00 |
| Frame | T-Slot Triangle Bracket W/ Feet | McMaster Carr | 5537T963 | C-0041 | $12.11 | 8 | 0 |

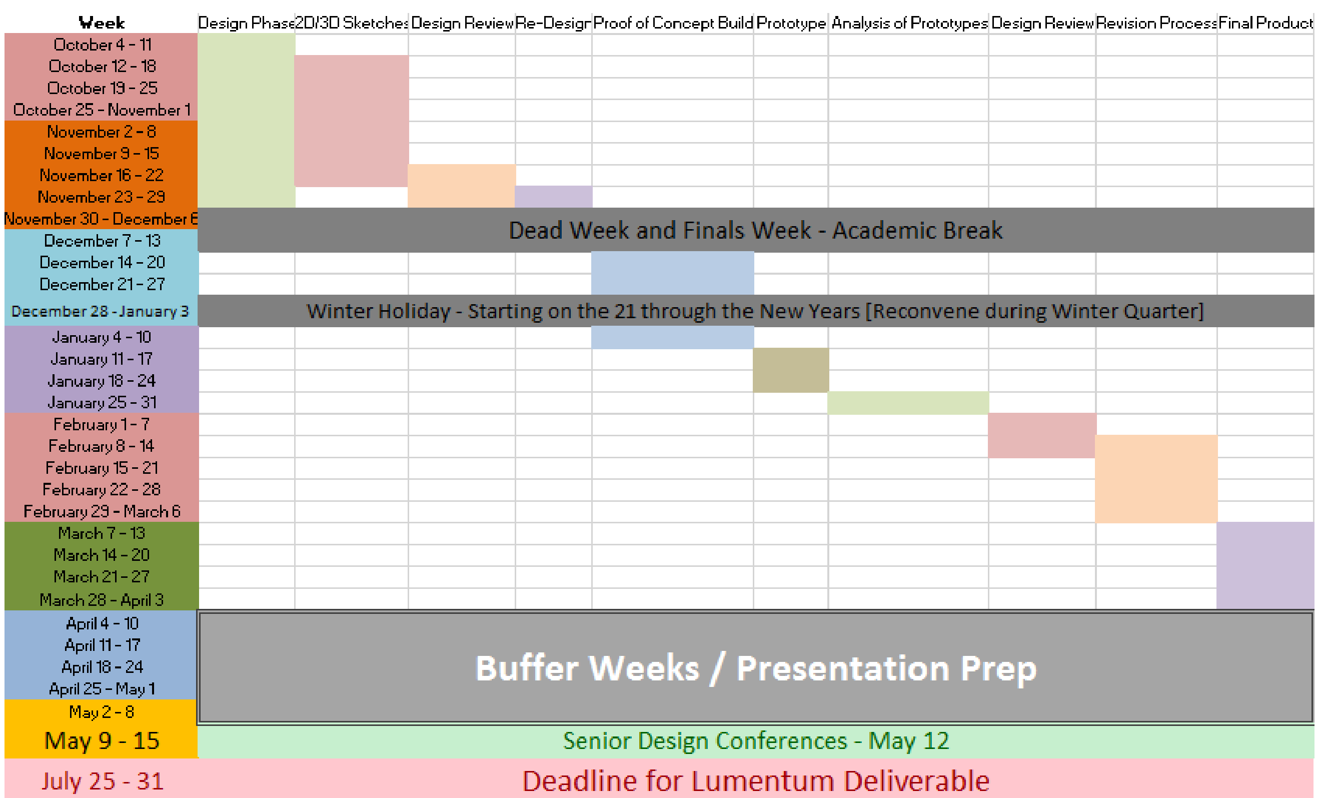
| System | Description | Original Manufacturer | Manufacturer Part Number | Part Number | Cost/ Part | Qty. | Total |
|---|---|---|---|---|---|---|---|
| Sled System | Flat Bearing | GLOWS CO | N/A | C-0042 | $1.28 | 3 | $3.84 |
| SLED System | Limit Switch Mount | GLOWS CO | N/A | C-0048 | 0 | 1 | 0 |
| SLED System | Limit Switch Trigger | GLOWS CO | N/A | C-0049 | 0 | 1 | 0 |
| SLED System | Optical Switch Mount | GLOWS CO | N/A | C-0050 | 0 | 1 | 0 |
| Control System | cRIO | National Instruments | cRIO-9063 | D-0001 | $1,299.00 | 1 | $1,299.00 |
| Control System | Buttons | N/A | Assorted | D-0002 | $12.00 | 1 | $12.00 |
| Control System | E-STOP BUTTON | Walmart | NA | D-0003 | $5.19 | 1 | $5.19 |
| Control System | Power Distribution Panel | AndyMark | AM-2856 | D-0008 | $200.00 | 1 | $200.00 |
| Control System | Fuses | Goliath | N/A | D-0009 | $11.99 | 1 | $11.99 |
| Control System | cRIO Digital IO Module | National Instruments | NI-9401 | D-0010 | $70.00 | 1 | $70.00 |
| Control System | cRIO Digital IO Module | National Instruments | NI-9381 | D-0012 | $541.00 | 0 | $0.00 |

| System | Description | Original Manufacturer | Manufacturer Part Number | Part Number | Cost/ Part | Qty. | Total |
|---|---|---|---|---|---|---|---|
| Control System | Optical Switch | Jameco | 114091 | D-0013 | $2.85 | 1 | $2.85 |
| Control System | Power Supply: Din Rail 12VDC 10A | CDI | DR-120-12 | D-0015 | $38.70 | 1 | $38.70 |
| Control System | Limit Switch | Jameco | 2204015 | D-0016 | $1.19 | 4 | $4.76 |
| Control System | Victor SP | VEX Robotics | 217-9090 | D-0017 | $59.99 | 3 | $179.97 |
| Control System | cRIO Digital Sidecar | AndyMark | AM-0866 | D-0018 | $70.00 | 1 | $70.00 |
| Control System | Industrial Safety Lights | Wolf Automation | PTE-A-202-RG-B | D-0019 | $5.00 | 1 | $5.00 |
| | | | | | | TOTAL COST: | $10,704.53 |

# Appendix G: Project Timeline

Table D- A-CHEM Project Timeline

| Autonomous Fiber Etching Tool Timeline | | | | |
|---|---|---|---|---|
| Main Goals | Weeks Required | Start Date | Estimated End Date | notes |
| Design Phases | 8 | 4-Oct | 30-Nov | |
| 2D/3D Sketches | 4-5 | 15-Oct | 20-Nov | |
| Design Review | 2 | 20-Nov | 3-Dec | |
| Re-Design | 1 | 30-Nov | 4-Dec | |
| Proof of Concept Build | 2 | 14-Dec | 8-Jan | |
| Prototype | 2 - 3 | 11-Jan | 25-Jan | |
| Analysis of Prototypes | 1-2 | 25-Jan | 31-Jan | |
| Design Review | 2 | 1-Feb | 12-Feb | |
| Revision Process | 3 - 4 | 8-Feb | 6-Mar | Includes Redesign of Prototype |
| Final Product | 3 | 7-Mar | 31-Mar | |



# Appendix H:    Selection Criteria

Table E- Selection Criteria Used in Design Process

| Elements/ Specifications | Importance | | Parameters | | |
|---|---|---|---|---|---|
| Performance/Requirements | Yes? | No? | Reason | Units | Datum |
| Corrosion Resistance | x | | Required by Lumentum | years | 5 |
| Time of x-Travel to bath | x | | | s | |
| Maxiumum Velocity of Fiber Table | x | | | m/s | |
| Maxium Acceleration of Fiber Table | x | | | m/s^2 | |
| Accuracy of x-Travel | x | | | % | 1% |
| Accuracy of dip time in baths | x | | Required by Lumentum | % | 1% |
| Dip time for acid baths | x | | Required by Lumentum | s | |
| dip time for sonicated baths | x | | Required by Lumentum | s | |
| System Power Consumption | | x | | W-hr | |
| Emergency Stop Response Time | x | | Required by Lumentum | s | |
| Repeatability | x | | Required by Lumentum | | |
| Fits inside fume hood | x | | Required by Lumentum | | |
| minimal human interaction | x | | Required by Lumentum | | |
| class 100 safe room | x | | Required by Lumentum | | |
| product cost | x | | Required by Lumentum | $USD | 7000 |
| selling price | | x | Commisioned NFS | | |
| time scale | x | | Commit Date | Date | Jul-16 |
| customer | x | | | | Lumentum LLC |
| manufacturing processes | | x | Pre-fabricated | | |
| size | x | | Must fit in Fume Hood | m | 1.7 |
| shipping | | x | Built at SCU/moved to Lumentum | | |
| company constraints | x | | See above | | |
| disposal | | x | Recyclable electronic/metals | | |
| manufacturing facility | | x | N/A | | |
| politics | | x | External Company | | |
| market constraints | | x | Lumentum Sole Customer | | |
| weight | x | | High Weight Improves Stability | kg | |
| maintenance | x | | Must be easily serviceable and repairable | | |
| competition | | x | others exist, but not as cheaply | | |
| packing | | x | Comes in parts and asembled in lab | | |
| quality and reliability | x | | 5 year lifespan and accuracy listed above | | |
| shelf life storage | | x | Not being stored/ no perishables | | |
| patents | | x | not new IP | | |
| environment | x | | Clean Room | | |
| testing | x | | Must be repeatable | | |

| Elements/ Specifications | Importance | | Parameters | | |
|---|---|---|---|---|---|
| Performance/Requirements | Yes? | No? | Reason | Units | Datum |
| legal | x | | Yes, owned by company | | |
| documentation | x | | yes, needs work instructions upon completion | | |
| quantity | | x | Only one being made | | |
| product life span | x | | Must last through production of lasers | years | 5 |
| materials | x | | must be corrosion resistant | | steel/al/Teflon |
| ergonomics | x | | must be easily interface able | | |
| standards/specifications | x | | Using standards parts, makes documentation easier | | |
| aesthetics | | x | Used in a fume hood, needs to be functional | | |
| installation | x | | easily installable by technicians | | |

# Appendix I: Alternative Products

http://www.3sae.com/fiber-strippers.php
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=1388

# Appendix J: Experimental Business Plan

**Background**

GLOWS CO will make small automated machines for the high tech manufacturing companies of Silicon Valley. The machines will automatically execute precise actions, like movements or thermal regulation, to fabricate small devices.

GLOWS CO will employ 5 engineers, one secretary, and one part time intern.

**Company Goals and Objectives**

GLOWS CO strives to become the leading provider of small bespoke automated manufacturing machines in the Bay Area over the next 10 years.

**Product Description**

GLOWS CO will design and assemble application-specific machines to automate small, delicate manufacturing processes. GLOWS CO's flagship machine, the Automated Chemical Etching Machine, or A-CHEM, was designed and assembled in house to automate Lumentum LLC's window etching process. The A-CHEM precisely dips fiber optic cables into chemical baths to remove the plastic cladding from the fiber's glass core. The A-CHEM represents GLOWS CO's expertise at designing machines to satisfy a number of requirements, including chemical resistance, clean room compatibility, and ease of use.

The GLOWS CO team brings its experience to market to create bespoke automated solutions for Silicon Valley's cutting edge manufacturing companies. GLOWS CO automated manufacturing machines have a proven track record of increasing user safety, improving process repeatability and accuracy, and streamlining the user experience when replacing a manual manufacturing process. Integrating a GLOWS CO machine into a manufacturing process means lower risk of injury and fewer botched parts, saving considerable money in dangerous and high precision applications.

### Potential Markets

Many large companies purchase specialized manufacturing solutions from small automation companies.  Production Robotics, an automation engineering firm located near the Oakland airport, employs 30 people, yet is able to furnish huge companies with automated solutions. Their clients include: Intel, Lifetime Products, Skurka Aerospace and Tesla Motors.

To begin selling, GLOWS CO will pursue additional contracts with Lumentum, their first contractor. GLOWS CO will grow by providing automation services to an increasing number of companies, and developing their expertise into new fields, like biomedical devices.

### Competition

Cubatic Technology and Production Robotics both offer automation services similar to those offered by GLOWS CO  Both companies are larger than GLOWS CO, allowing them to work on more projects simultaneously.  However, GLOWS CO's small size allows them to dedicate all of their efforts to every project.

Due to the proprietary nature of the work that automation companies do, the number of machines and cost per machine they sell is not made public.

### Sales and Marketing Strategy

GLOWS CO will develop its image and name recognition through word of mouth, light online advertising, and presence at trade shows.  Most importantly, GLOWS CO will grow by expanding the scope of work it performs for each customer, providing them with automated solutions for more of their manufacturing process.

Finished products will be delivered and installed by GLOWS CO engineers for local customers, or shipped via commercial shipping companies and installed by GLOWS CO engineers for remote clients.

### Manufacturing Plans

GLOWS CO will not maintain any inventory because all of their products will be designed and built for each customer's specific application. All of the components of the machine, including standard parts like nuts and bolts, will be ordered after the design is finalized. Custom parts will be manufactured by a local machine shop, but the machine will be assembled in house.

GLOWS CO will have a small on-site machine shop, furnished with a mill and lathe, to make prototypes and to make adjustments to its products.

### Product Cost and Price

The complexity, size and scope of each project will dictate its cost and price. The average cost of off the shelf parts is projected at $10,000 per unit and machined parts are $10,000.  The estimated average price of each machine is $90,000, for a profit of $70,000 per unit. GLOWS CO anticipates selling 12 units per year.

### Service and Warranties

To maintain strong relationships with their clients, GLOWS CO will provide free 10 year warranties for all of their machines. Because GLOWS CO designs and builds their machines, they have the most experience and most complete knowledge of the machines, so it makes economic sense for GLOWS CO to maintain the machines.

Due to the rapidly developing nature of Silicon Valley's high tech industry, products and the processes that manufacture them change quickly. As such, many of GLOWS CO's machines will not need to operate for more than about 5 years. However, the same fast paced industry demands high reliability and minimal down time, dictating that GLOWS CO's machines will be robust enough to exceed the 5 year expected service life. GLOWS CO's engineers will service the machines.

## Financing Plans

GLOWS CO becomes profitable in its $5^{th}$ month. GLOWS CO requires $210,000 to purchase all of its capital assets and to pay for two months of operating expenses. GLOWS CO's ROI exceeds 1 after 25 months, and is 1.9 at 3 years, and 2.9 in 4 years.

Table F- List of GLOWS CO Expenditures

| **Capital Expenses** | | | |
|---|---|---|---|
| Item | Number | Unit Cost | Subtotal |
| Design Computers | 5 | 2500 | 12500 |
| Office Computers | 3 | 500 | 1500 |
| Hand Tools | 1 | 10000 | 10000 |
| Bridgeport Mill | 1 | 20000 | 20000 |
| Lathe | 1 | 8000 | 8000 |
| Prototyping Hardware | 1 | 20000 | 20000 |
| Office Equipment | 1 | 15000 | 15000 |
| Service Truck | 1 | 25000 | 25000 |
| **Total Capital** | | | **112000** |
| **Annual Operating Costs** | | | |
| Engineer Salary | 5 | 90000 | 450000 |
| Secretary Salary | 1 | 50000 | 50000 |
| Intern Wages | 1 | 10000 | 10000 |
| Rent | 1 | 42000 | 42000 |
| Utilities | 1 | 5000 | 5000 |
| Business Services | 1 | 20000 | 20000 |
| Insurance | 1 | 10000 | 10000 |
| **Total Operating Cost** | | | **587000** |
| **Projects** | | | |
| Projects per Year | 12 | | |
| Price | 90000 | | |
| Machining Cost | 10000 | | |
| OTS Part Cost | 10000 | | |
| Profit | 70000 | | |
| Total Project Profit | 840000 | | |

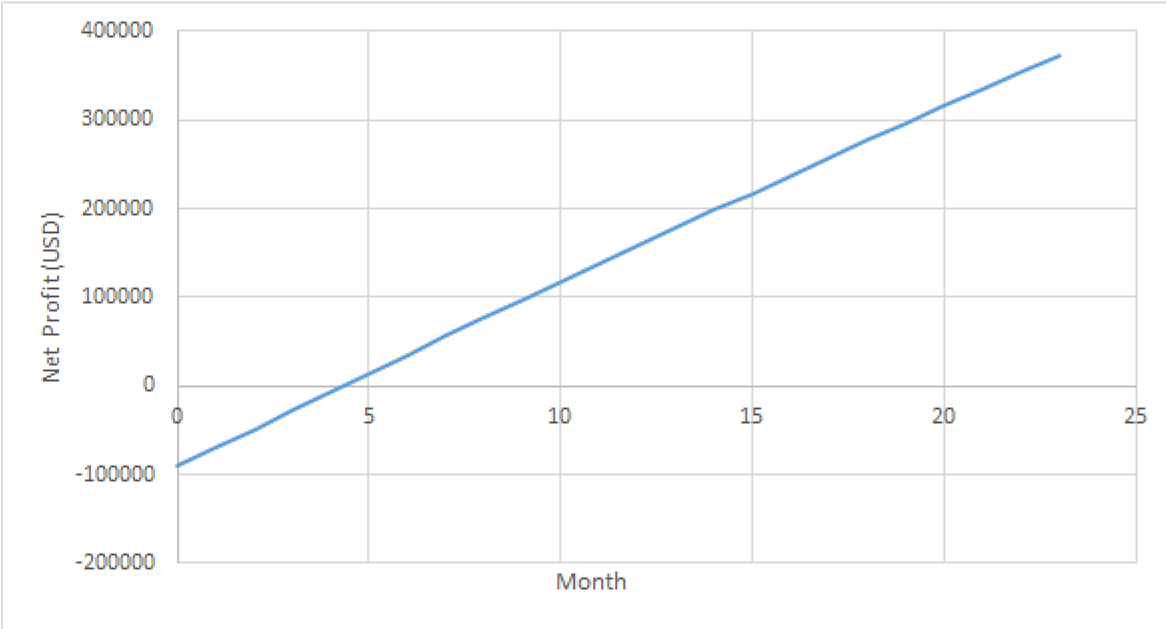



Figure 48- Projected Profit of GLOWS CO Over Time