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EML4551-2

Team 515: Human Lander System Landing Legs with Reusable Shock Absorbers

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Abstract

In the 2024 Artemis mission, NASA is sending a team, including their first woman, to the moon to create a long-term presence. An outpost called Gateway will orbit the moon, allowing travel from the outpost to the moon's surface. A human lander will repeatedly carry the astronauts between Gateway and the surface with little needed maintenance between trips. Extreme space conditions make it challenging to design for moon landings. The moon's surface has a top layer of sharp rocks and dusty material. Motion can turn this into a cloud and cover sensors. Previously, the Apollo-class moon lander crushed a honeycomb cartridge to absorb the impact energy. This design was not reusable, needing a new cartridge for each landing. Because of the back-and-forth nature of our mission, this won't work. Our challenge is to create a reusable design that can withstand the debris and moon's low temperatures.

We have designed a reusable shock absorber that stores the impact energy in a spring, holds it, and later releases it. Our design uses a spiral ratchet and pawl (the lever that blocks movement) to lock the spring after absorbing the impact. It's like if a pogo stick locked rather than bounced. Each ring of the spiral acts as teeth for the end of the lever to hold on to, locking it into place. We chose spiral teeth to have a controlled release of the spring. A motor within the leg slowly rotates the spiral ratchet back to the starting length.

The design is reusable since it loads and then unloads a spring. We picked materials for our design that safely handle the extreme temperatures of the moon. The moving parts will have a cover to protect them from the harsh conditions. Our design will bring down cost, time, and materials to carry out further moon missions.

Keywords: shock absorber, reusable, ratchet screw.

Acknowledgement

We would all like to take a moment to thank our project sponsor NASA for providing us the opportunity to expand our education with this unique and challenging project. We would especially like to thank our contacts at NASA, Rachel McCauley and Richard Knochelmann, for guiding us through the good times and the bad times.

We would also like to thank our project advisor Keith Larson for his support and guidance. Without his input to our brainstorming sessions we would have been lost in a sea of panic. And as much as he does not want to be thanked, we would like to thank Shayne McConomy for his constructive reinforcement, both positive and negative.

We would like to thank Jason at the machine shop for answering all of our less-than-smart questions when it came to fabrication.

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NASA	National Aeronautics and Space Administration
LM	Lunar Module

Chapter One: EML 4551C

1.1 Project Scope

1.1.1 Project Description

The objective of this project is to design a reusable device for the new lunar lander module that will dissipate the impact energy in such a way that it does not damage the vessel or occupants.

1.1.2 Key Goals

The overarching goal of this project is to ensure the safety of human passengers and equipment onboard the lunar lander module. The astronomical cost of launching matter into space requires that the device be as lightweight as possible. The goal is to develop a device that can be used more than once without needing substantial maintenance.

1.1.3 Markets

The primary market for the project is NASA. Secondary markets include other national space agencies, such as the European Space Agency, as well as corporate space programs, such as Space X and Virgin Galactic.

1.1.4 Assumptions

Assumptions are made to help limit the scope of the project. It is assumed that the project will be done using SI units. The device is assumed to be only used on the lunar surface. It is assumed that the device will only operate in the vacuum of space. It is assumed that the attachment points for the legs will be provided by the sponsor. It is assumed that the lunar lander module will have four legs. It is assumed that the mass of the lunar lander will not be more than twice that of the Apollo lunar lander. It is assumed that the maximum landing speed will be 3.048 m/s (10ft/s) (NASA Apollo Lunar Module (LM) News Reference, 1999). It is assumed that the device will be subjected to the full range of lunar surface temperatures, 25K – 400K (NASA, 2014).

1.1.4 Stake Holders

The primary stake holder in this project is the project sponsor, NASA, who is assigning this project through Rachel McCauley. The faculty advisor for the project, Keith Larson, and the teaching faculty in charge of the senior design program, Dr. Shayne McConomy, are also stakeholders in this project. Additional stake holders are the American taxpayer and the FAMU-FSU College of Engineering.

1.2 Customer Needs

To better understand the desired project outcomes, we created a list of questions to ask the sponsor. We then interpreted customer needs based off their responses and presented them in Table 1.

Table 1. Questions, answers, and interpreted needs to customer responses.

Question	Customer Response	Interpreted Need
How many uses will be considered reusable?	As many as possible.	1) The product can be used indefinitely.
What are aspects of the current product that are positive?	The Apollo struts were lightweight.	2) The product is lightweight.
What are aspects of the current product that are negative?	They could only be used once and were left behind on the moon.	3) The product can be sent to the moon and used repeatedly.
Will the project return to Earth?	No.	4) The product will not return to Earth in between trips.
How often should maintenance be performed on the product?	In between landings.	5) No routine maintenance is necessary during remainder of each lunar trip.
What does the project brief mean when it says “hop”?	Module will have smaller landings once already on the surface.	6) Shock absorber dynamic qualities does not change or diminish after an impact.
What tools will be needed for maintenance?	As few tools (light weight) as possible.	7) Multiple components can be fixed by the same tool.
What is the maximum landing speed of the lunar lander?	10 feet per second.	8) The product can handle an impact speed of 10 feet per second.
How many legs are on the module?	4 legs.	9) Each of the four legs will have a shock absorber component.
How massive is the lunar module?	25 metric tonnes.	10) The product can support 25,000 kg.
Will the legs need to be load bearing on the Earth?	Yes,	11) The legs can support the lander under earth’s gravity.
What is the maximum angle that the lander could make with the surface?	10 degrees.	12) The product can land at up to a 10-degree offset from the z-axis.

The fundamental needs of this project have been interpreted as the following: A lightweight product that is reusable in space and can repeatedly withstand an initial impact velocity of 10ft/s.

1.3 Functional Decomposition

1.3.1 Function Determination

To better understand what our product must accomplish, a functional decomposition was performed. A functional decomposition breaks down the overarching function of a design into smaller, basic functions that cannot be broken down further. To gain background information on shock absorbers, we researched how “long travel” automobile suspension works. With this background knowledge, we then thought about what would physically happen, step-by-step, if the lander impacted the lunar surface with a similar type of shock absorber. As we thought about this, we created a list of basic functions that the design must accomplish, then we grouped the basic functions into systems that accomplish a related function. We determined that our project has three systems: support, impact reduction, and reusability. After the basic functions were sorted, we constructed a functional decomposition hierarchy chart, Figure 1, and we were able to identify additional basic functions.

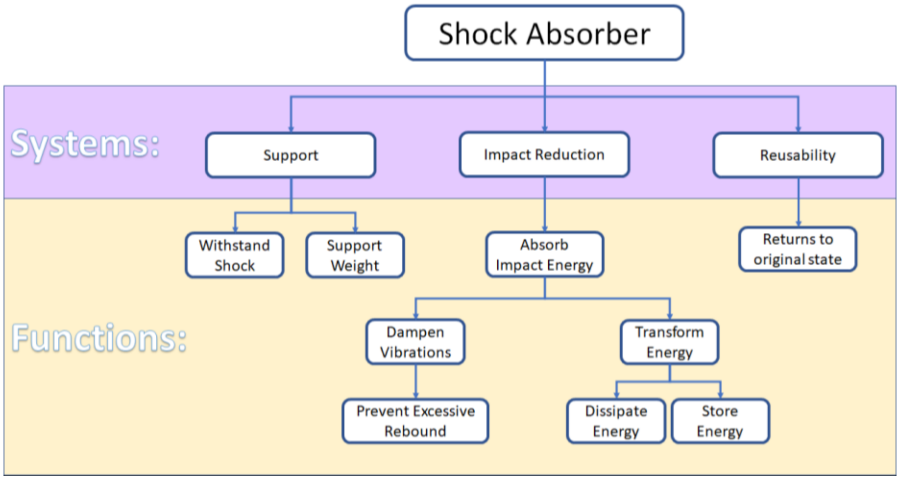
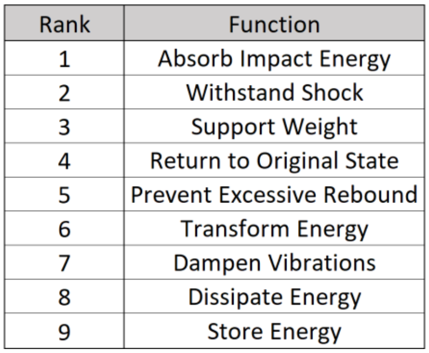


Figure 1. The functional decomposition hierarchy chart.

1.3.2 Function Ranking

After the basic functions were identified we had to determine the priority of the functions, i.e. which functions were the most important. To do this we constructed a cross reference table, Table B-1 in the appendix, and used a bitwise comparison method to compare the function of a row to the function of a column. If the row was deemed a more important function than the column it was given a 1, otherwise it was given a 0. The sum of the rows was taken and the row with the highest tally was deemed the most important function. The priority rank of all the functions is given in Table 2.

Table 2. Ranked priorities of the product functions.



Rank	Function
1	Absorb Impact Energy
2	Withstand Shock
3	Support Weight
4	Return to Original State
5	Prevent Excessive Rebound
6	Transform Energy
7	Dampen Vibrations
8	Dissipate Energy
9	Store Energy

We were somewhat surprised to see that 'return to original state' is the 4th highest priority. Since the project brief centered around the reusable aspect of the design, we assumed that it would rank first, which may realign some of our concept's focus. It is interesting that the highest ranked function and all the lowest ranked functions come from impact reduction. The support system ranks higher than the reusability system, which will most likely affect our design concept focus.

1.3.3 Action and Outcomes

The overall action of the design will be to impact the moon, and the expected outcome is to do it multiple times safely. Absorb impact energy is the highest-ranking function for the design followed by the ability to withstand shock. The absorption of impact energy and ability to withstand shock, will ensure the safety of the contents of the human lander.

1.3.4 Connection to Systems

The three main systems that we determined were support, impact reduction, and reusability. The support and impact reduction are the functions that make the human lander system serve its function of getting to the moon and are therefore required in our design. Reusability is what our sponsor has emphasized and what makes this design unique from previous shock absorbers used for human lander systems.

Generally, functions are combined as much as possible, but we are trying to separate out the many functions of automobile shock absorbers that are accomplished by single parts. The 'store energy' function and 'dissipate energy' function may be integrated like they are in vehicle shock absorbers, but we do not want to assume that they need to be. Both may not be required if energy can be stored in a useful capacity or if the energy can be dissipated quickly enough. The 'absorb impact energy', 'support weight', and 'withstand shock' functions may be combined as well, like in automobile shock absorbers, but we did not want to assume that they needed to be.

1.3.5 Function Resolution

The design will ensure a safe landing on the moon through reusable shock absorbers with the ability to absorb impact energy, withstand shock, and support the weight of the human lander and its cargo. The design will be able to transform energy, dampen vibrations, dissipate energy, and store energy allowing for the safest landing possible.

1.4 Targets and Metrics

1.4.1 Targets

After defining the ultimate goal of this project and decomposing each of the system's functions, the design process was followed by identifying targets. Each of the targets and their respective functions are based directly off of customer needs. Targets are the goal for each function, which then add constraints and conditions to the functions, allowing us to determine possible solutions to the problem.

Following the hierarchy chart created in the functional decomposition, we identified each function that our design should have to satisfy the customer needs. Each function has a respective target defined with it, allowing us to view the relationship with the function goal and how to accomplish it. The targets were chosen through asking questions to our technical contacts at NASA and by standards set by previous missions, such as Apollo, that work well and take customer and users' needs into consideration. Targets are shown in Table 1, including the critical targets which are highlighted in yellow.

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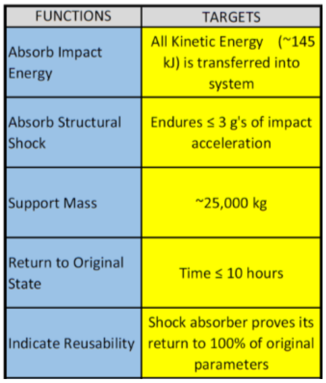
Table 3. Critical functions and defined targets.



FUNCTIONS	TARGETS
Absorb Impact Energy	All Kinetic Energy (~145 kJ) is transferred into system
Absorb Structural Shock	Endures ≤ 3 g's of impact acceleration
Support Mass	~25,000 kg
Return to Original State	Time ≤ 10 hours
Indicate Reusability	Shock absorber proves its return to 100% of original parameters

1.4.1.1 Critical Targets

1.4.1.1.1 Absorb Impact Energy

To land safely without a risk of failure, the system must be able to absorb, store, and then dissipate the energy safely. Therefore, the first critical target for this system is that it must be able to absorb the impact energy, which we calculated our target to be approximately 145 KJ of kinetic energy. This value was calculated by using the simple mass spring damper equation for kinetic energy,

$$KE = \frac{1}{2}mv^2$$

1.4.1.1.2 Absorb Structural Shock

Structural shock is the shock that the system experiences from its own deceleration. The target for this function must be less than or equal to 3 Earth g’s, since this is NASA’s limit for a safe landing for a human. This was chosen because the system must be as safe as possible and prevent the HLS from falling apart upon landing.

1.4.1.1.3 Support Mass

The target for this system to is to support the mass of the HLS, which according to NASA, is expected to be around 25,000 kg. However, this is an estimation and not final mass value because the lander is still in the design process. This estimation includes the mass of the lander, the legs, and all the passengers and equipment on board.

Commented [MP2]: Write about this in metrics

1.4.1.1.4 Return to Original State

For the shock absorber system to be reusable, it must return to its original state that it was in before being used. One of the most crucial functions that makes this problem different from previous shock absorption systems is that it must be reusable. Therefore, it is only a matter of how long it takes for it to be reused. The target time for the system to return to its original state after landing was chosen to be 10 hours. This number was chosen because it is low enough to allow the HLS to hop to another site during the same mission and long enough to allow the system to dissipate energy.

1.4.1.1.5 Indicate Reusability

The target for indicating reusability is that the shock absorber clearly proves to its user(s) that it has completed return to 100% of original parameters. This means it cannot be up to interpretation if the shock is ready to be used again.

Commented [MP3]: Orrrrrrr we can make it so it automatically wont work if its not ready

1.4.1.2 Additional Targets

1.4.1.2.1 Prevent excessive rebound

The target for preventing excessive rebound from the surface was decided to be a rebound height of less than 0.5m. Ideally, the system will have no rebound, but this is limiting. Instead, by restricting the maximum rebound height to 0.5m, it allows for prioritizing other critical targets while keeping the entire system safe.

1.4.1.2.2 Transform and Store Energy

The target for transforming energy of the system is a final kinetic energy of zero. This indicates that all the energy created during landing has been transformed. The target for storing energy is that the system is capable of storing ~145KJ of energy. The target for dissipating energy is that all stored energy can be dissipated within 10 hours.

1.4.1.2.3 Dampen Vibrations

The target for dampening of vibrations is to have a settling time of less than 2 seconds. This is a value that is standard in controls that is used as a starting point for the metrics.

1.4.1.2.4 Withstand Lunar Conditions

The target for withstanding lunar conditions is about 10 years. Mission Artemis is centered around developing and maintaining a human presence on the moon (and eventually Mars) and ultimately the search for water. It is expensive and wasteful to use single-use shocks, such as the crushable shocks from Apollo. Reusability of this device is crucial, not only to be used twice, but to be used for years. The goal is a 10-year lifespan.

1.4.2 Metrics

Metrics can be defined as the methods that we are going to use to test our established targets. Some of our testing is validated with physics, math, and/or engineering equations. Table 2 shows the functions and metrics, with the most important functions highlighted in yellow.

1.4.2.1 Critical Metrics

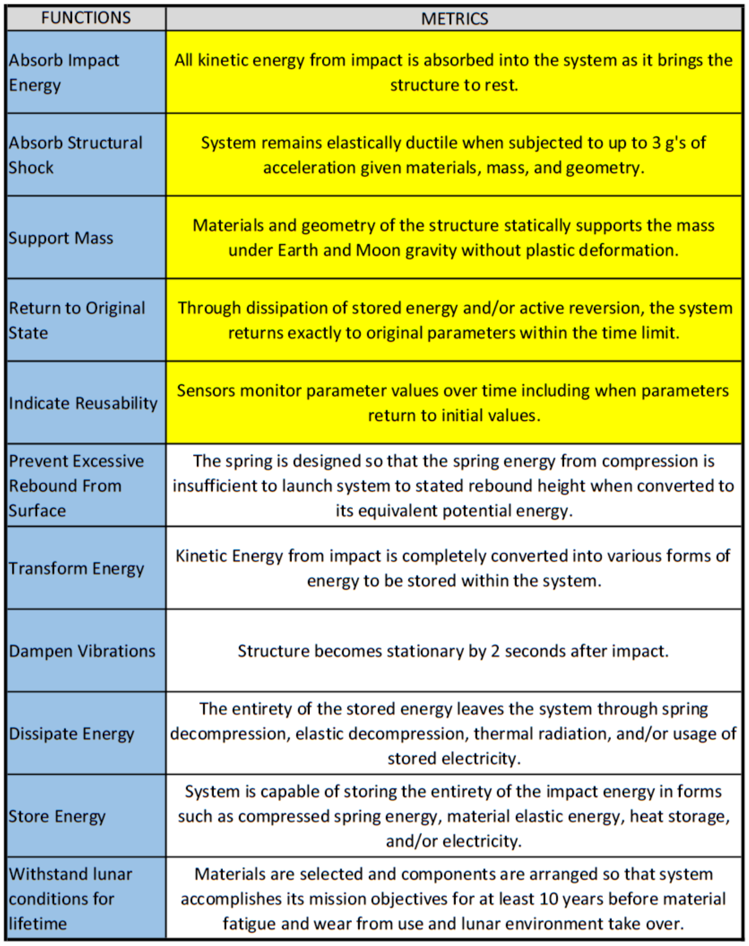
1.4.2.1.1 Absorb Impact Energy

The metric for deriving impact energy and stored energy may be calculated using the equation for kinetic energy. This was the simplest solution for obtaining these metrics and it gave us a clear sense of how we are satisfying one of our critical functions. The value calculated for absorbing impact energy is critical to know because that is the total amount of energy in the system that must be conserved or properly dissipated.

1.4.2.1.2 Absorb Structural Shock

One of the functions is for our system to absorb structural shock upon landing. In order to absorb the structural shock, the system must remain elastically ductile when subjected to up to 3 g’s of acceleration given the materials, mass, and geometry chosen in the final design. This was deemed to be one of our critical functions because if this target is not met, the entire system would catastrophically fall apart.

Table 4. Critical functions and methods of testing.



FUNCTIONS	METRICS
Absorb Impact Energy	All kinetic energy from impact is absorbed into the system as it brings the structure to rest.
Absorb Structural Shock	System remains elastically ductile when subjected to up to 3 g's of acceleration given materials, mass, and geometry.
Support Mass	Materials and geometry of the structure statically supports the mass under Earth and Moon gravity without plastic deformation.
Return to Original State	Through dissipation of stored energy and/or active reversion, the system returns exactly to original parameters within the time limit.
Indicate Reusability	Sensors monitor parameter values over time including when parameters return to initial values.
Prevent Excessive Rebound From Surface	The spring is designed so that the spring energy from compression is insufficient to launch system to stated rebound height when converted to its equivalent potential energy.
Transform Energy	Kinetic Energy from impact is completely converted into various forms of energy to be stored within the system.
Dampen Vibrations	Structure becomes stationary by 2 seconds after impact.
Dissipate Energy	The entirety of the stored energy leaves the system through spring decompression, elastic decompression, thermal radiation, and/or usage of stored electricity.
Store Energy	System is capable of storing the entirety of the impact energy in forms such as compressed spring energy, material elastic energy, heat storage, and/or electricity.
Withstand lunar conditions for lifetime	Materials are selected and components are arranged so that system accomplishes its mission objectives for at least 10 years before material fatigue and wear from use and lunar environment take over.

1.4.2.1.3 Support Mass

To support the mass of the HLS, the materials and geometry of the structure must statically support the mass under Earth and Moon gravity without plastic deformation. This is also deemed to be one of our critical targets and metrics because failure could result in the loss of human life.

1.4.2.1.4 Return to original state

One of the critical functions of the shock absorber system is for it to be able to return to its original state before the module takes off for another landing. This will be verified by comparing the parameters of the shock absorber before and after use. If the parameters are the same, then the function has been satisfied.

1.4.2.1.5 Indicate Reusability

Since the shock absorber must be reused safely, it must prove it has returned to its original parameters. Therefore, the shock absorber must recognize its current state, which would involve the use of sensor. This sensor would monitor parameters over time, including when parameters return to initial values. To achieve this, we may use concepts of mechatronic systems and dynamics to create a system to indicate whether the shock absorber is ready to be used, shows warnings, and shows when it is not ready/safe to be used. It must clearly indicate its status for the safety of the passengers.

1.4.2.2 Additional Metrics

1.4.2.2.1 Prevent excessive rebound

To prevent excessive rebound, the shock absorber system should be designed so that any energy from landing that is not transformed is insufficient to launch the HLS past the target rebound height.

1.4.2.2.2 Transform Energy

Another function of the shock absorber system is to be able to transform the kinetic energy of the module from landing into energy that is either stored or dissipated through the shock absorber system. This will be verified when the module is brought safely to rest and thus its kinetic energy is zero, and the system has reached its steady state value.

1.4.2.2.3 Dampen & moderate vibrations

Commented [MP4]: Idea: modify this target to encompass the resonate frequencies

Another function of the shock absorber system is to dampen any vibrations that may result from landing. The module, if vibrating at all, will settle to its steady state value within 2 seconds. This will be verified through graphing software such as MATLAB that will allow us to see the point in time that the system settles.

Resonate frequencies within the shock absorbing system will be a concern before the lunar module even reaches the moon. The entire launch vehicle will be subjected to many low frequencies as it traverses from the surface of the Earth to the Moon. It is important that the natural frequency of the shock absorber system does not fall in the range of expected launch frequencies, because dangerous vibrations could result. Our project sponsor has advised us that there should be no problems with resonance so long as the shock absorber system's natural frequency is above 50 Hz.

1.4.2.2.4 Store and Dissipate Energy

Dissipating and storing energy are shown as two different functions in the table, but they are inversely related to each other in the sense that whatever is not dissipated must be stored. This is based upon the phenomena that energy cannot be created nor destroyed. The system must be capable of storing all the impact energy in forms such as compressed spring energy, material elastic energy, heat storage, and/or electricity. Then the entirety of the stored energy must leave the system through spring decompression, elastic deformation, thermal radiation, and/or usage of the stored electricity.

1.4.2.2.5 Withstand Lunar Conditions

The LM is planned to be reused for a period of 10 years. To achieve this, we must investigate the material strength properties under lunar and space conditions. Then, we must choose materials that will ensure a long lifespan while still being able to meet the requirements of the other targets. Extreme temperatures and extreme changes in temperatures must be considered because this condition affects material properties.

The shock must be resistant or shielded to regolith, meaning the system must be able to withstand impact of small, glass-like particles, shooting at the HLS at high speeds. We will use material science concepts, such as particulate size and diffusion, to determine the features of the shock absorbing system.

1.5 Concept Generation

For this project 100 design concepts were generated. Each team member generated 10 concepts on their own, then concept generation tools were utilized to assist the team. Biomimicry was the first concept tool used, and was focused on animals that hop, jump, or land. Several animals that were identified were crabs, spiders, insects, and kangaroos.

The anti-problem method was used to help identify concepts that tackled specific problems associated with the shock absorber, such as deceleration displacement, returning to its original state, and energy dissipation. The battle of perspective method was used by dividing the team members into outdoor/indoor preference, like/dislike pumpkin spice, and cats/dog people. The crapshoot method and morphological chart were used to generate the balance of the 100 concepts. The morphological chart used is presented in figure D-1 in appendix D.

Concept 1

The first concept that was generated is 4 accordion/scissor jacks at each corner that extend down before landing. Each joint of the accordion contains a friction disc damper. Upon landing, an electric motor slows down the compression of the 4 jacks. This is a medium-fidelity concept

Concept 2

The next concept that was generated is the use of traditional heavy equipment leaf springs positioned at each corner with a landing pad axel that runs between the opposite springs. Energy is dissipated through frictional forces between the leaves of the springs. This is a high-fidelity concept.

Concept 3

The next concept that was generated is an electromagnetic coil with a magnetic responsive core attached to the footpad part of the leg. Initially starts with large magnetic flux before landing, then a feedback control system regulates power to the coil, which regulates the magnetic field, to bring the core to a slow stop. This is a medium-fidelity concept.

Concept 4

The next concept that was generated is the use of battery powered motors to move spring mounted weights up and down to damp the vibration out. This is a high-fidelity concept.

Concept 5

The next concept that was generated is the use of compliant joint mesh filled with foam in empty spaces. The joint mesh would deform elastically upon impact and the foam would dampen the return motion of the mesh. This is a medium-fidelity concept.

Concept 6

The next concept that was generated is the use of spider style legs that would absorb shock through the leg joints (trampoline type effect). Rotational friction dampers used at each joint, and springs attached between each leg link. This is a medium-fidelity concept.

Concept 7

The next concept that was generated is the use of torsion springs within joints that can be locked at different angles to prevent bounce. The joints can be released mechanically until the load is equal to the spring force. This is a high-fidelity concept.

Concept 8

The last concept generated was an inverted tripod with internal viscous fluid resisting motion. The legs of the inverted tripod would be filled with a viscous fluid with ferritic particles suspended in it. As the legs deflect, the fluid is ported between the legs, and the rate at which the fluid flows can be controlled by varying the electromagnetic field around the flow orifices. As the magnetic field is intensified more magnetic particles stick to and clog the orifice, restriction flow and dampening the return rate of the deflected legs. This is a medium fidelity concept.

1.6 Concept Selection

The final concept was selected by utilizing a Pugh chart and House of Quality (HoQ). Our selection was validated by use of the Analytical Hierarchy Process (AHP). The design that was chosen based off concept selection tools was concept # 7: a spring that locks at maximum compression.

1.6.1 House of Quality

To select a final concept, we first had to determine which selection criteria were the most important. The HoQ used is presented in figure E-1. First, we weighted the customer needs based on discussions with our sponsor and the overall goal of the project. We then compared each customer need with a functional characteristic. Each functional characteristic was given a score of 1, 2, or 3 corresponding to a low, medium, or high impact each function had on the customer need. If a function did not impact the customer need it was left blank. The score for each box was then multiplied by the weight factor of each row, and then each column was summed down to produce a raw score. This raw score allowed us to rank each functional characteristic in order of importance. The top 11 functional characteristics were chosen to be used in the Pugh chart.

1.6.2 Pugh Chart

The Pugh chart allowed us to choose our top three concepts, and then ultimately our final concept. Before the Pugh chart could be used, we first had to pick our top eight ideas. We did this by having each group member pick their two favorite concepts from the list while taking mass, power consumption, and physical feasibility into consideration. This gave us our top 10 concepts. Two concepts were eliminated from that list of 10 through group deliberations.

With the top concepts and functional characteristics selected we constructed the first Pugh chart, presented in Figure E-2. The datum used in the first Pugh chart was the crushable shock absorbers used on the Apollo lander. Each concept was compared to the Apollo shock absorbers for each functional characteristic. If the concept performed better it was given a '+', if it performed worse it was given a '-' and if it was judged to be about as effective it was given a 's'. The total numbers of '+' and '-' were summed down and the scores for each concept were compared. The top three concepts were #2, #7, and #4. Concept #6 was decided to be used as the datum in the next Pugh chart because it was a medium performer.

The second Pugh chart was constructed and is presented in figure E-3. The same procedure was followed for the first Pugh chart, except now only the top three concepts were being compared to concept #6, dubbed 'Spider Legs'. The outcome of the second Pugh chart indicated that the best concept was #7, dubbed 'Locking Spring'.

1.6.3 Analytical Hierarchy Process (AHP)

The first step in the AHP is to create a matrix of customer needs vs. customer needs. The diagonal of the matrix is given a value of 1, then rows are compared against columns and given a score. If the row is more important than the column it is given an integer score greater than one, with higher importance items given a higher integer score. The scores are then reflected and inverted across the diagonal, to give a fractional value to boxes with columns that are valued as more important than rows.

Columns were then summed down to get a cumulative score, and then a normalized matrix was form. The normalized matrix divided each element of a column by the sum of that column. Rows were then summed to the right and divided by the number of elements in each row to form the criteria weight vector. The criteria comparison matrix was then multiplied by the criteria weight vector to form the weighted sum vector. The weighted sum vector was then divided by the criteria weight vector to form the consistency vector. The average consistency, λ, was calculated from the consistency vector, the random index value was pulled from a table provided in the EDM lecture slides, and finally we were able to calculate our consistency ratio.

Our final consistency ratio was found to be 0.12, which is above the expected 0.1. However, in talking with our sponsor about our selected design concept we feel confident in our choice and stand by our decision.

1.6.4 Final Selection

Concept #7, the locking springs, was chosen based off findings from the concept selection tools. First in the HoQ, we found that absorbing impact energy, absorbing structural shock and supporting mass were our most important engineering functions.

Next, in the Pugh chart we found that compared to the Apollo shock absorbers, the top designs would be concepts #7, #4, and #2. We compared all of these to a moderately rated design, #6. Concept #7 did the best, with a total of 10'+'s and only one '-'. #2 and #4 tied at five '+'s and two '-'s.

We followed the AHP to determine which customer needs were most valuable and from here we found that the results from our analytical hierarchy chart are consistent with the concept #7. The most important need was found to be "handle impact speed of 10 ft/s" with a weight of 0.3140. This need would be met by concept #7 because it is a spring damper system designed to specifically handle that. The runner-up need was “can support 32800 kg” at a weight of 0.21. The part that makes the springs unique is that they will lock and that will provide great stability rather than the spring continuing to bounce. It was not surprising to see that consistent tooling was not a top need, but it would not be difficult to implement with our design. The surprising part was the runner-up least important was lightweight, but after speaking to our sponsor we realize that lightweight is much more important to the design which we would have to work on.

We still have some choices to make regarding the execution of the selected concept. The locking mechanism could either be mechanical, magnetic, electrical, or any combination of the three types. The spring would ideally be released upon take off to assist in launch from the lunar surface, however the springs could also be released in flight if conditions require. The type of spring can also be modified moving forward, a torsional spring was presented in the original concept, but a helical compression spring may also be used. A sketch of the concept is presented in figure 2.

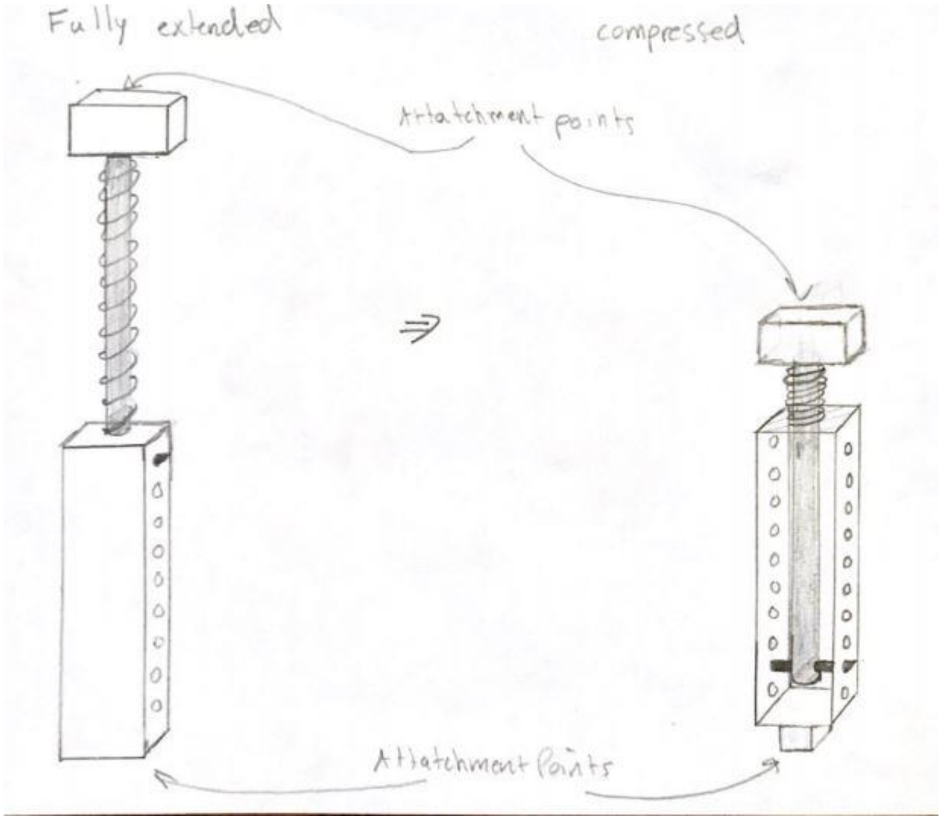


Figure 2. Locking spring sketch.

1.8 Spring Project Plan

Our spring project plan is to have the design complete enough to design a prototype and start ordering parts by the beginning of February. Then we will use the remaining months to test and redesign.

Chapter Two: EML 4552C

2.1 Restated Project Definition and Scope

The scope of the project has been reduced from an entire shock absorbing leg system to a shock absorber that can be integrated into a leg system. The project description, key goals, markets, assumptions, and stake holders are otherwise unchanged.

2.2 Prototypes

2.2.1 Prototype Scaling

The prototypes for this project were dynamically scaled according to *Dynamic similarity and scaling for the design of dynamical legged robots* (Miller & Clark), and the relevant scaling factors are presented in Table 5.

Table 5. A tabulation of relevant scaling factors and their relationship to each other.

Parameter	Scaling Factor	Relationship
Length	α_L	α_L
Mass	α_m	α_F
Stiffness	α_k	$\alpha_F \alpha_L$
Touch-Down Velocity	α_v	$\alpha_L^{1/2}$

The prototypes were scaled around a preformed spring. The prototype spring was chosen from a catalogue and was selected because it had a similar scaling factor to the designed spring in both the radial and axial directions. The overall length scaling factor was taken as the average between the radial and axial scaling factors of the prototype spring. The stiffness scaling factor was taken as the ratio between the designed spring and the prototype spring. From there, the scaling factors for mass and velocity were found using the relationships listed in Table 5.

The scaling factors and various test parameters are listed in Table 6. The deflection was calculated in two ways. The first way was the use of the spring energy equation, listed in the table, using the scaled spring stiffness and scaled impact energy. The second was by applying the length scaling factor to the expected real spring deflection. The fact that both calculated deflections are the same proves that the dynamic scaling was performed properly.

Table 6: Various parameter values for the spring prototype.

Spring Prototype Calculations				
Stiffness Scaler	5.530E-03		180.8	
Length Scaler	0.280		3.567	
Time Scaler	0.5294651		1.889	
Force/Mass scaler	0.0015503		645.0	
Mass	38.76	kg	85.45	lbs
Drop height	0.1659265	m	0.544	ft
Impact Energy	63.088426	J		
Scaled speed	1.8042941	m/s		
Deflection calc	0.1852268	m	0.608	ft
KE = 0.5*k*x^2				
Deflection from scale	0.1852268	m	0.608	ft

2.2.2 Spring Prototype

The spring prototype tested a spring under a dynamically scaled impact to measure deflection. A weight of 90 lbs. was dropped from a height of six inches to simulate the maximum expected impact force.

2.2.3 Locking Prototype

The locking prototype was designed to test the inward ratcheting motion of the ratchet screw and the ability of the eighth nuts/pawl arms to lock the ratchet screw under maximum load. Due to fabrication limitations at the university machine shop the locking prototype was designed with pawl arms with integrated threaded teeth.

A weight of 141 lbs. would have been hung from the yellow eyebolt to test the locking action. The eyebolt would have been replaced with the strike plate from the spring prototype to test the inward ratcheting motion of the ratchet screw.

2.2.4 Unlocking Prototype

The unlocking prototype would have been designed to test that the motor could unscrew the ratchet screw under maximum load. The unlocking prototype would have been the same as the locking prototype with the addition of the motor and mounting systems. Due to time constraints the unlocking prototype was not fully designed.

2.3 Experimental Procedure

2.3.1 Spring Prototype

A paper scale was attached next to the viewing slot in the spring prototype, see Figure 3. The spring prototype inside of the 55-gallon drum.. The spring prototype was mounted inside of a 55-gallon steel drum to protect the feet of the testers. A line was scribed into the inside of the barrel 6 inches above the prototype strike plate. Two 2-inch diameter holes were cut into the side of the barrel to provide viewing access. The first hole allowed

Figure 3. The spring prototype inside of the 55-gallon drum.

viewing and recording of the plunger scale, and the second was used to position the weights the correct height above the prototype strike plate.

A group member started a slow-motion video recording prior to the test. Two group members held two 45-lbs. gym plates above the strike plate while a fourth group member directed the weights up or down in reference to the previously scribed line. The weights were dropped onto the strike plate after a countdown. The test was performed 5 times, until the strike plate broke off the test rig.

2.3.2 Locking Prototype Model

A real locking prototype was not able to be fabricated, however a same size geometric model was 3D printed. The model only had two pawl arms and used half nuts instead of eighth nuts. The ratcheting motion of the model was tested by firmly holding the main cylinder and slamming the ratchet screw onto a flat surface.

The locking action of the model was tested by hanging the model from a pull up bar and attaching a weight of 10-lbs. to the ratchet screw. The ratchet screw was rotated in the outward direction while the weight was attached. It was noticed that once the rotation was started the amount of force needed to continue rotation drastically decreased.

2.4 Results

2.4.1 Spring Prototype

The results of the tests are shown in Table 7.

Table 7. Spring prototype test data

Test number	Deflection
Anticipated	7.87 in
Weighted Equilibrium	4.29 in
Test 1	Bottomed Out ~5.25 in
Test 2	4.08 in
Test 3	3.26 in
Test 4	3.64 in
Test 5	4.21 in

The most important thing to notice is that no test produced the expected deflection. The second thing to notice is that the prototype bottomed out before the anticipated deflection was reached.

The reason the rig bottomed out is that the rig was designed around a much stiffer spring with an anticipated deflection of around 4 inches. The spring was changed out for a less stiff spring to lower the weight and height that the weight was dropped from, but the viewing slot and the length of the plunger was not updated.

Despite the design oversight, there is still qualitative data that can be analyzed. Since the plunger was stopped before the rig bottomed out for 4/5 tests it is apparent that a non-negligible amount of energy was absorbed in the frictional forces between the plunger and the cylinder wall. The reason for large spread in displacements is most likely due to dropping the weights off center, which caused a variable amount of binding between the plunger and the cylinder wall.

2.4.2 Locking Prototype Model

The inward motion of the ratchet screw worked as expected, which verifies the geometry of the ratchet components. Since the stiffness of the model pawl arms and the actual pawl arms is different the entire design is not verified.

The ability of the design to lock under load was not verified, since the tested weight was only 10/141 lbs. However, the model test at least shows that the geometry performs as expects under a load. The outward rotation test suggests that the motor may not need to be as powerful as originally thought.

2.5 Conclusion

Humanity is going back to the moon, but unlike the Apollo missions we plan on staying on the moon for extended periods of time. Humanity will need to solve sustainability issues associated with traversing space, and shock absorber are a small facet of that problem. This paper presented a shock absorbing method that could be integrated into a larger shock absorbing leg system that could help solve the sustainability problems of space travel, but there is a lot of work that still needs to be done to bring this design to fruition.

2.6 Future Work

2.6.1 Test Components at Temperature

To verify if this concept is even possible the components should be tested at the most extreme temperature condition. The limiting temperature condition will occur during landing, where one side of each leg will face the hot exhaust of the landing rocket and the other side of each leg could potential face cold deep space. There are two specific aspects of the design that should be tested in this situation: material failure and thermal expansion.

The main spring and pawl arms are expected to function as designed at the high end of the expected temperature band, but material failure upon impact is not unexpected at -280ºF. From our research, 304 SS is widely used in the cryogenic industry because it resists brittle fracture even at low temperature, but we were unable to find any situation where it was used for impact or spring applications at cryogenic temperatures. The main spring and pawl arms should be tested at temperature to verify they retain their elastic properties, and the ratchet screw and eighth nuts should be tested to verify they won't shear upon impact.

Thermal expansion and contraction in the pawl arms would change the length of each pawl arm, which would change the axial location of each eighth nut in relation to each other and could result in partial thread engagement. This may be mitigated by the regolith shield acting as a heat shield. The regolith shield should help distribute incoming heat around the entire shock absorber, but further testing is needed to verify.

2.6.2 Cam-esque Tooth Profile

While discussing the use of eighth nuts instead of pawl arms with integrated pawl teeth, it was noticed that only the tooth closest to the pawl arm mount would be in contact with the ratchet screw during the inward ratcheting motion; all other teeth would be deflected out of contact with the ratchet screw.

In other words, even though all teeth of the eighth nuts would be used to lock the ratchet screw in place, only one tooth would be involved in the ratcheting motion. This realization led to the possibility of specializing one of the eighth nut teeth for ratcheting, and one possible way is to give the tooth a cam profile. This would be very difficult to accomplish but could reduce the surface stresses associated with the ratcheting motion.

2.6.3 Regolith Shields

The regolith shields are a necessary component to protect the shock absorber during landing, and possibly distribute heat evenly around the shock absorber. Since the design of the regolith shields depend on final geometry of the shock absorber they were saved until the shock absorber design is finalized.

2.6.4 Parabolic Pawl Arms

The current pawl arms are designed as straight beams for simplicity, geometric, and mass concerns. However, if the pawl arms were designed as parabolic leaf springs they may be able to provide more clamping force onto the ratchet screw and dissipate impact energy as friction between the leaves. This design characteristic is not necessary but could optimize the design and should be investigated further.

2.6.5 Motor Equipment

The motor, motor housing, and thrust bearing still need to designed. Although all three components were within the scope of this project, time constraints directed the design teams efforts toward the spring locking mechanism. The motor needs to provide roughly 20 kN-m of torque, which is no small feat, but the qualitative data from the locking prototype model suggests that number may be much lower.

2.6.6 Lightweight Geometry

Since mass is the prime consideration in any spacecraft design, lightweighting the geometry is a prime concern. One area that could potentially be lightweighted is the pawl arms. The pawls arms could potentially be designed with a truss structure, instead of as solid beams as they are now.

2.6.7 Integrate Shock Absorber into Leg System

The Apollo lunar lander used three separate shock absorbers: a primary one that absorbed the forces in the vertical direction and two secondary ones that absorbed forces in the horizontal direction. The ratchet screw shock absorber described in this paper was designed to replace the main shock absorber of the Apollo lunar lander. In order to make our design functional it will need to be integrated into a leg system.

References

Miller, B. D., & Clark, J. E. (n.d.). Dynamic similarity and scaling for the design of dynamical legged robots. Tallahassee, FL, USA: Department of Mechanical Engineering, Florida State University.

NASA. (2014, May 27). *NASA.gov*. Retrieved from LUNAR RECONNAISSANCE ORBITER: Temperature Variation on the Moon: https://lunar.gsfc.nasa.gov/images/lithos/LROlitho7temperaturevariation27May2014.pdf

NASA Apollo Lunar Module (LM) News Reference. (1999, Feb 7). NASA Apollo Lunar Module (LM) News Reference. 21-40. Grumman Aircraft Engineering Corporation. Retrieved from LUNAR MODULE LANDING GEAR STRUT CRUSHABLE HONEYCOMB: http://webapp1.dlib.indiana.edu/virtual_disk_library/index.cgi/5894299/FID1008/pdf/lmnr2.pdf

Appendices

Appendix A: Code of Conduct

Mission Statement

The mission of team 515 is to help each other grow professionally and interpersonally as we design the reusable shock absorber for the Human Lander System. We will do this by working together and effectively communicating with each other, our advisor, and our Sponsor.

Decision Making

For decision making purposes “the group” refers to at least 3 members of the group acting together in agreeance. The exception being document revision, which requires at least 4 group members to agree.

Team Roles

Team roles will evolve over the course of the project. As new duties emerge the group will assign them to members that accept the responsibility of a new duty.

Josh Blank: Design Engineer.

Responsible for pushing the design process, CAD modeling, and background research. Also ensures that assignments are submitted on time and correctly.

Melanie Porter: Dynamics Engineer.

Focus on the mechanics of the design and the dynamics of the shock absorber. Additional responsibilities include effective and efficient communication both within the group and with third parties such as advisors or sponsors. Formal Point of Contact (PoC).

Matt Fowler: Systems Engineer.

Ensures all aspects of the project work together in concert. Focuses on how the components integrate successfully with the rest of the project. Sets and manages timelines for tasks.

Tristan Jenkins: Design Engineer.

Tasked with implementing innovative ideas into the design of the requested product. Deals with CAD modeling, Static and Dynamic Systems calculations, and hand drawn sketches and drafts.

Alex Noll: Mechanical Engineer.

Focuses on the mechanical aspects of the shock absorber and the design. Additional responsibilities include helping research and design different shock absorbers that meet the requested needs of the product.

Communication

Group Chat.

The group chat will be the primary mode of communication between group members. Group members should check the group chat at least once each day, and should respond within 24 hours if tagged by name.

University Email.

University email will be the formal mode of communication between group members and should be used whenever documentation of communication is desired. University email can be used to send files between members, but files that pertain to the project should be uploaded to the group folder so that each member has access. Each group member should check their university email at least once per day. Group members are expected to respond to emails within 24 hours.

University email will be the primary mode of communication between the group and the sponsor, advisor, TA's and Dr. McConomy. The Point of Contact (PoC) should be the person sending and receiving all group emails from the sponsor, advisor, TA's and Dr. McConomy. However, any other group member may send emails on behalf of the group if the situation requires it. All emails sent on behalf of the group, by the PoC or other members, should CC the other group members. If a group member receives an email that pertains to the group, but the rest of group is not CC'd by the sender, then the receiving group member should forward that email to the rest of the group as soon as possible.

Basecamp.

Basecamp will be used primarily for managing the group schedule, managing To-Do lists, and having formal group discussions in the message board.

To-Do Lists.

No one person will be assigned to create the To-Do lists, but the group should ensure that To-Do lists are created as specified in this section and as deemed necessary by the group. The group will assign the responsibility of a To-Do task after a member volunteers for it, or after a member is notified that they will be assigned and positively confirms that they are aware. No member should be assigned a To-Do task without their knowledge, except for tasks that apply to the whole group.

Each assignment will receive its own To-Do list, which will contain a list of tasks required to complete the assignment. The group should ensure that To-Do lists are created promptly after an assignment is released. Each task should be as specific as possible (e.g. For the Project Scope To-Do list, make “*Find competitor products. Research competitor products. Make benchmarking excel spread sheet.”* separate tasks instead of just “*Benchmarking”*). Each assignment will have the following tasks:

- “Submit <name of assignment> “on the due date.
- “Finish <name of assignment>” the day before the due date, to allow for typo checking and formatting.

Schedule.

No one person will be assigned to update the schedule, but the group should ensure that the schedule is updated. When creating a new event the group availability tracker in the Group Folder should be referenced. Group meetings should be added to the schedule as soon as possible after the group decides to hold a meeting. When a group meeting time is changed, a message should be sent to all group members.

Message Board.

The message board is a formal communication method and should be used as an extension of group meetings. It should primarily serve to introduce topics that would be covered in a group meeting or ask project related questions to the group that do not require a timely answer.

Post Lecture Zoom meeting.

A mandatory zoom session will be held after each lecture. The group should try to conclude the meeting by 8 pm if class ends early, but meetings should not go past 9pm. The duration may be brief, but it is important to establish an understanding of the path forward after each lecture. The focus of the post lecture meeting is to digest any new information that was put out and to check in with group members. If an assignment is released during a lecture, the To-Do list should be created during the post lecture meeting.

Friday Meeting.

The Friday meeting will occur from 10am to 3pm, unless the group decides otherwise. The duration is subject to change and will be based on the amount of work remaining.

Dress Code

Team Meetings.

Team meeting do not require formal dress. Any clothing that would be appropriate to wear to class is acceptable.

Professional Meetings.

Meetings with the sponsor, advisor, or other professional should be conducted in business casual attire. The outfits do not need to be coordinated beforehand.

Presentations.

Presentations will be conducted in business formal attire. Outfits should be coordinated beforehand.

Attendance and Participation Policy

The Attendance Log.

An attendance log will be maintained in an Excel document in the team folder. The keeper of the log will lock the cells of all past days to ensure group members cannot modify their past attendance. The attendance log will be used to track team member attendance at:

- The two post-lecture Zoom sessions.

- The Friday meeting.
- Any full group meeting the group decides is necessary.

Excused Absences.

If a group member notifies the other group members that they will be absent at a group meeting, the member's absence will be marked excused in the attendance log. The group must be notified at least 24 hours in advance, unless the situation is an emergency. The group should be notified through either the group chat or a group email to ensure all group members are aware, and to maintain a log of excused absences. The group member does not need to provide a reason for their absence and the group will not demand a reason.

Participation.

The group will not require anyone to participate. Participation must be derived from a desire to contribute and cannot be forced on a group member. If a group member cannot complete a task that has been assigned to them it is the group's responsibility to ensure the task is completed. No animosity will be held against someone who does not complete an assigned task. The group will not punish anyone for not completing a task.

Correcting Group Member Issues.

Problems should be resolved at the lowest level possible. If a group member is consistently missing meetings, or if the group is concerned about a member's wellbeing, or if the group is not satisfied with a member's participation, the group will attempt to hold an intervention to assist the member. If the intervention does not assist the group member, or if an intervention cannot be held, the group may seek guidance from the TA's and Dr. McConomy.

Group File Folder

All team files will be saved in our SharePoint folder. This allows all team members to see any file at any point in time, and allows for multiple team members to simultaneously edit files. The link to the SharePoint folder can be found on the Basecamp message board.

Revision Process

When revisions to group documents, including this Code of Conduct, become necessary, a draft of the revised section will be proposed to the group. The draft will be voted on by the group and a 4/5 majority is needed to legitimize the revision. A PDF copy of the document will be made before the revision is applied and will be saved in the group folder for future reference. Revision bars will be added to the section that is revised.

Privacy Clause

All group members will respect the privacy of all other group members. Group members will not share personal information about other group members to any outside party.

Statement of Understanding

Signing below indicates that the group member is committed to our mission statement and accepts the stipulations listed in this Code of Conduct:

Joshua Blank: ____________________ Date: 9/10/2020

Melanie Porter: ____________________ Date: 9/10/2020

Matt Fowler: Matthew Fowler Date: 9/10/2020

Tristan Jenkins: ____________________ Date: 9/10/2020

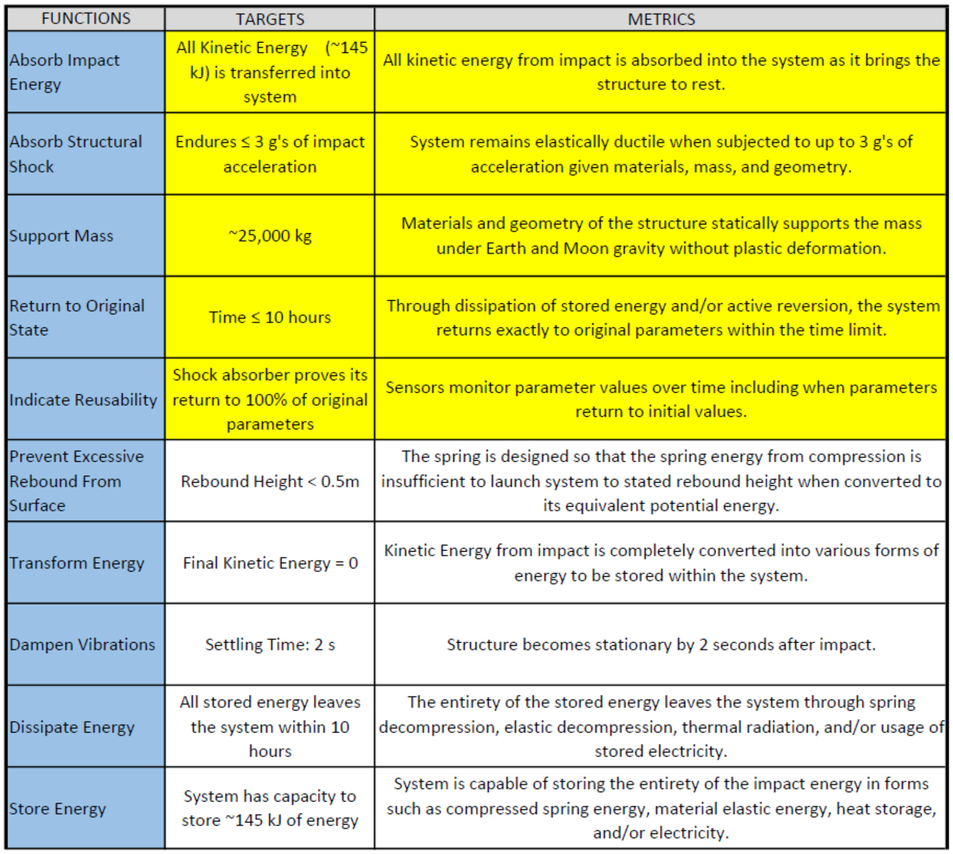
Alexander Noll: ____________________ Date: 9/10/2020

Appendix B: Functional Decomposition

	Withstand Shock	Support Weight	Absorb Impact Energy	Dampen Vibrations	Prevent Excessive Rebound	Transform Energy	Dissipate Energy	Store Energy	Return to Original State	Sum
Withstand Shock	-	1	0	1	1	1	1	1	1	7
Support Weight	0	-	0	1	1	1	1	1	1	6
Absorb Impact Energy	1	1	-	1	1	1	1	1	1	8
Dampen Vibrations	0	0	0	-	0	0	1	1	0	2
Prevent Excessive Rebound	0	0	0	1	-	1	1	1	0	4
Transform Energy	0	0	0	1	0	-	1	1	0	3
Dissipate Energy	0	0	0	0	0	0	-	1	0	1
Store Energy	0	0	0	0	0	0	0	-	0	0
Return to Original State	0	0	0	1	1	1	1	1	-	5
Rank	2	3	1	7	5	6	8	9	4	

Table B-1. The functional decomposition cross reference table used to determine the priority of project functions.

Appendix C: Targets and Metrics



FUNCTIONS	TARGETS	METRICS
Absorb Impact Energy	All Kinetic Energy (~145 kJ) is transferred into system	All kinetic energy from impact is absorbed into the system as it brings the structure to rest.
Absorb Structural Shock	Endures ≤ 3 g's of impact acceleration	System remains elastically ductile when subjected to up to 3 g's of acceleration given materials, mass, and geometry.
Support Mass	~25,000 kg	Materials and geometry of the structure statically supports the mass under Earth and Moon gravity without plastic deformation.
Return to Original State	Time ≤ 10 hours	Through dissipation of stored energy and/or active reversion, the system returns exactly to original parameters within the time limit.
Indicate Reusability	Shock absorber proves its return to 100% of original parameters	Sensors monitor parameter values over time including when parameters return to initial values.
Prevent Excessive Rebound From Surface	Rebound Height < 0.5m	The spring is designed so that the spring energy from compression is insufficient to launch system to stated rebound height when converted to its equivalent potential energy.
Transform Energy	Final Kinetic Energy = 0	Kinetic Energy from impact is completely converted into various forms of energy to be stored within the system.
Dampen Vibrations	Settling Time: 2 s	Structure becomes stationary by 2 seconds after impact.
Dissipate Energy	All stored energy leaves the system within 10 hours	The entirety of the stored energy leaves the system through spring decompression, elastic decompression, thermal radiation, and/or usage of stored electricity.
Store Energy	System has capacity to store ~145 kJ of energy	System is capable of storing the entirety of the impact energy in forms such as compressed spring energy, material elastic energy, heat storage, and/or electricity.

Figure C-1. Full targets and metrics

Appendix D: List of Concepts

1. Electromagnetic particles in the working fluid.
2. Inverted tripod with internal viscous fluid resisting motion.
3. Inverted tripod with electromagnetic particles resisting motion.
4. Inverted tripod with large magnets pushing each other apart to dampen the impact.
5. 4 legs with a motor that pushes the legs up during impact.
6. A crushable shock that has elastic deformation as opposed to plastic deformation.
7. Inverted tripod with internal viscous fluid resisting motion as a result of springs at each end.
8. Skid type mechanism that is spring loaded.
9. Landing skids to land like a plane.
10. Hydraulic solenoids that compress upon impact.
11. Giant crab legs with a rotational motor at each joint that opposes collapsing. Legs can fold up into each other.
12. 4 accordion/scissor jacks at each corner that extend down before landing and an electric motor slows their compression as it lands.
13. Electromagnet attached to the moving part of the leg interacts with a magnetic piston that compresses fluid in a regular hydraulic cylinder.
14. As the spring is compressed a ratchet pawl is rotated and locks the spring at max compression.
15. Conical helical springs that expand radially as the springs are compressed to interact frictionally with the walls.
16. Springs with empty space filled with a memory foam type polymer that expands slower than it compresses.
17. 4 traditional heavy equipment leaf springs at each corner with a landing pad axel that runs between opposite springs.
18. Helical leaf springs, basically two springs sandwiched together that rub together as the springs are compressed.
19. A chain of short springs, double helical springs with frictional rotation pads in between springs that rub against each other as the spring compression creates a rotational output.
20. A combination compression spring and extension spring. As the compression spring is compresses, the extension spring ratches up and locks into position when the compression spring is at maximum compression. Then as the compression spring expands, the extension spring extends and resists the expansion of the compression spring.
21. An electromagnetic coil as the whole leg with a magnetic responsive core attached to the footpad part of the leg. Initially starts with large magnetic flux before landing, then a feedback control system regulates power to the coil, which regulates the magnetic field, to bring the core to a slow stop.

22. A landing pad that compresses a fluid and uses a turbine to regenerate energy.
23. Replaceable aluminum honeycomb cartridges.
24. Nitrogen gas springs that compress the gas and reclaim it.
25. Nitrogen loaded cylinders that bleed off compressed nitrogen above a certain pressure to the aether. Basically, a compressed gas cylinder attached to a plunger with a relief valve that vents to atmosphere. Just bring a lot of nitrogen.
26. Really long extendable stiff legs that allow for the rocket to be on for the complete decent and rocket control accounts for shock absorption.
27. Really long stiff legs that are attached after the HLS is in space, and then the rocket decent engine control accounts for the shock absorption. The legs are sent up with, but detached from, the HLS and are attached in space during a spacewalk, or with the Canadarm, at the ISS or in transit to the moon.
28. Put a superconducting landing pad down before the HLS is set to arrive, wait for the lunar night, then when the HLS nears the landing pad supercurrents are formed that repel the HLS and levitate it.
29. Very high tolerance pneumatic shocks with helium as the working fluid because the properties are probably pretty constant across the temperature range.
30. Hydraulic shocks with electrical heater temperature control to ensure relatively constant viscosity across the full external temperature range.
31. Long, low angle legs that deflect a lot as the HLS approaches the surface.
32. Gas filled (He) copper bellows that plastically deform upon impact but once back up in 0g heaters heat the bellows to annealing temperature and the bellows are stretched back to the original length.
33. Use a skycrane like with the Curiosity rover on Mars.
34. Rotary friction damped insect legs. 2+ link legs with rotational friction pad assembly at each joint and a mechanical compression spring between links to resist crumpling and reposition legs once off the surface.
35. use battery-powered motors to move spring mounted weights up and down to damp the vibration out.” source
36. Spring damper with shielding and temperature regulation attached to each leg that absorbs all the shock.
37. Spring dampener attached to each leg that stores energy and uses it to bounce a couple of times before finally landing.
38. Airbags that deploy when landing.
39. Crushable shocks that can be decompressed.
40. Spider-like legs that absorb shock through the leg joints (like a trampoline type effect).
41. Trampoline type thing that it lands into with assistance of thrusters.
42. Sealed strut type suspension (Orion).
43. Absorb shock and store it as heat to fuel the next trip.

44. “spring-loaded ring that would detune the stack by softening the interface between the first and upper stages while preserving lateral stability”. source
45. Pour a liquid that works like water on earth into a moon crater and then land in that.
46. Seismic inspired shock absorber, like the pendulum form. source
47. Shock absorber that uses oobleck as the fluid.
48. Spring in a retractable beam that locks into notches and is slowly released mechanically.
49. Electromagnetic shock absorber using ferrofluid to vary the viscosity and thus the damping.
50. Base unit filled with compressed air that is released upon impact at a rate that reduces the impact energy.
51. Base unit filled with oobleck or other non newtonian fluid.
52. Thrusters that are on the side of the module so they can be used all the way to the ground.
53. Wave spring with damper.
54. Torsion spring to act as knees.
55. Rubber bands inside of a temperate container to keep properties constant.
56. Compliant joints that lock at different angles.
57. Electromagnetic resistance with force proportional to velocity (Pure Electromagnet).
58. Stiff yet flexible compliant joint mesh.
59. Compliant joint mesh filled with foam in empty areas.
60. Airbag with folding skeleton to retract.
61. Thruster usage to reduce speed.
62. Telescopic piston.
63. Locking the Springs.
64. Separate Landing Pad.
65. Momentum transfer mechanism.
66. Rubber Bands.
67. Excite Regolith for softer landing area.
68. Give astronauts pogo sticks.
69. Steal pillows from Russian space agency and use them.
70. Dry friction damper. (perhaps with leaf springs)

Concepts 70-100 were created using the morphological chart in figure D-1.

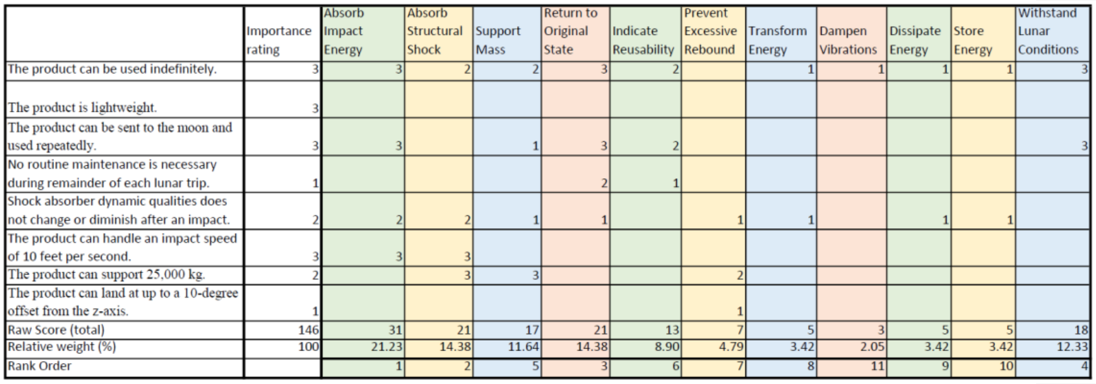
Control vibrations (main type)	Return to original state	Energy absorption	Energy Dissipation/ storage	Indicate reusability	Withstand lunar conditions
Electromagnetic	Natural return	Pressure increase	Heat	Red, yellow, green light	Regolith shielding/ sealing
Electric motor	Forced return	Elastic deformation	Electricity	Position indicator	Avoid open parts
Mechanical springs	Manual return	Plastic Deformation	Kinetic Energy	Percentage indicator (like phone battery)	Temperature controlled casing
Fluid based					

Figure D-1. Morphological chart used to generate concepts.

71. Electromagnetic, natural return, pressure increase, heat, RGB lights, regolith shielding
72. Electromagnetic, natural return, pressure increase, heat, RGB lights, avoid open parts
73. Electromagnetic, natural return, pressure increase, heat, RGB lights, temp controlled casing
74. Electromagnetic, natural return, pressure increase, heat, Position indicator, regolith shielding
75. Electromagnetic, natural return, pressure increase, heat, Position indicator, avoid open parts
76. Electromagnetic, natural return, pressure increase, heat, Position indicator, temp controlled casing
77. Electromagnetic, natural return, pressure increase, heat, percentage, regolith shielding
78. Electromagnetic, natural return, pressure increase, heat, percentage, avoid open parts
79. Electromagnetic, natural return, pressure increase, heat, percentage, temp controlled casing
80. Electromagnetic, natural return, pressure increase, electricity, RGB lights, regolith shielding
81. Electromagnetic, natural return, pressure increase, electricity, Position indicator, avoid open parts
82. Electromagnetic, natural return, pressure increase, electricity, percentage, temp controlled casing
83. Electromagnetic, natural return, pressure increase, kinetic energy, RGB lights, regolith shielding
84. Electromagnetic, natural return, pressure increase, kinetic energy, Position indicator, avoid open parts
85. Electromagnetic, natural return, pressure increase, kinetic energy, percentage, temp controlled casing

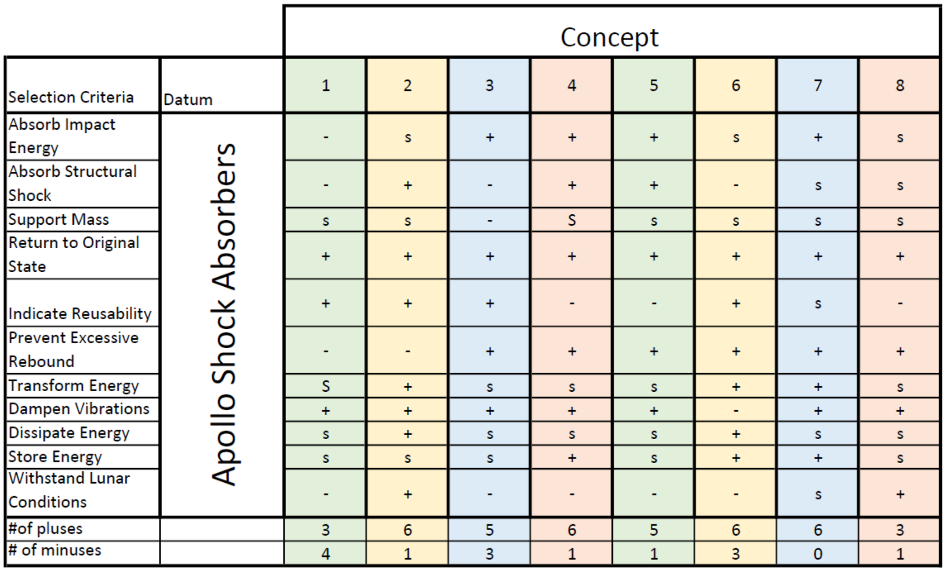
86. Electromagnetic, natural return, elastic deformation, electricity, Position indicator, avoid open parts
87. Electromagnetic, natural return, elastic deformation, Electromagnetic, natural return, pressure increase, kinetic energy, Position indicator, avoid open parts
88. Electromagnetic, natural return, elastic deformation, heat, percentage, temp controlled casing
89. Electromagnetic, forced return, plastic deformation, electricity, Position indicator, avoid open parts
90. Electromagnetic, forced return, plastic deformation, kinetic energy, percentage, temp controlled casing
91. Electromagnetic, forced return, plastic deformation, heat, percentage, temp controlled casing
92. Electromagnetic, manual return, pressure increase, heat, percentage, temp controlled casing
93. Electromagnetic, manual return, pressure increase, heat, percentage, temp controlled casing
94. Electromagnetic, manual return, pressure increase, heat, percentage, temp controlled casing
95. Mechanical springs, natural return, pressure increase, heat, Position indicator, regolith shielding
96. Mechanical springs, natural return, pressure increase, heat, Position indicator, regolith shielding
97. Mechanical springs, natural return, pressure increase, heat, Position indicator, regolith shielding
98. Fluid-based, natural return, pressure increase, heat, RGB lights, regolith shielding
99. Fluid-based, natural return, pressure increase, heat, RGB lights, avoid open parts
100. Fluid-based, natural return, pressure increase, heat, RGB lights, temp controlled casing
101. Fluid-based, natural return, pressure increase, heat, percentage, temp controlled casing

Appendix E: Concept Selection Supplement



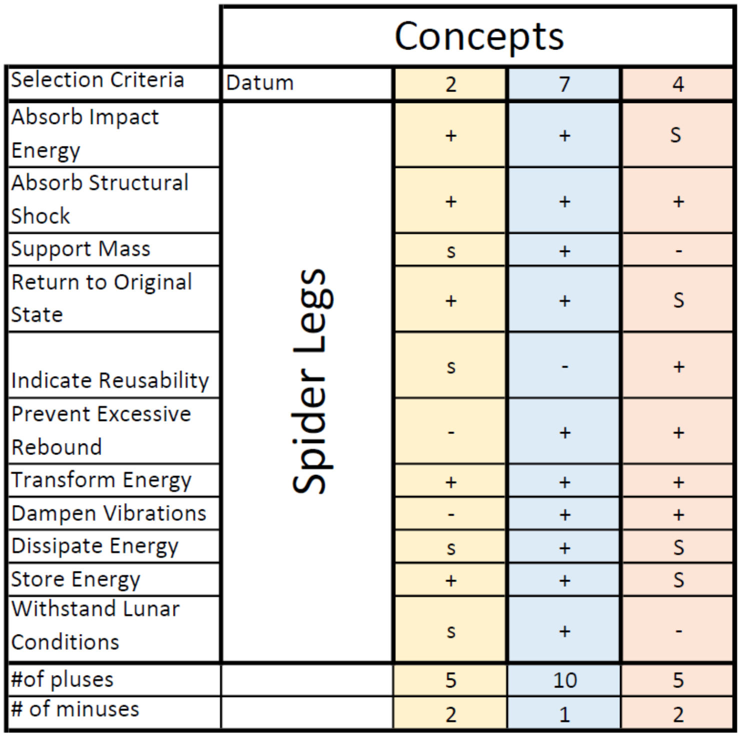
	Importance rating	Absorb Impact Energy	Absorb Structural Shock	Support Mass	Return to Original State	Indicate Reusability	Prevent Excessive Rebound	Transform Energy	Dampen Vibrations	Dissipate Energy	Store Energy	Withstand Lunar Conditions
The product can be used indefinitely.	3	3	2	2	3	2		1	1	1	1	3
The product is lightweight.	3											
The product can be sent to the moon and used repeatedly.	3	3		1	3	2						3
No routine maintenance is necessary during remainder of each lunar trip.	1				2	1						
Shock absorber dynamic qualities does not change or diminish after an impact.	2	2	2	1	1		1	1		1	1	
The product can handle an impact speed of 10 feet per second.	3	3	3									
The product can support 25,000 kg.	2		3	3			2					
The product can land at up to a 10-degree offset from the z-axis.	1						1					
Raw Score (total)	146	31	21	17	21	13	7	5	3	5	5	18
Relative weight (%)	100	21.23	14.38	11.64	14.38	8.90	4.79	3.42	2.05	3.42	3.42	12.33
Rank Order		1	2	5	3	6	7	8	11	9	10	4

Figure E-1. HoQ used to determine most important qualities for the Pugh charts.



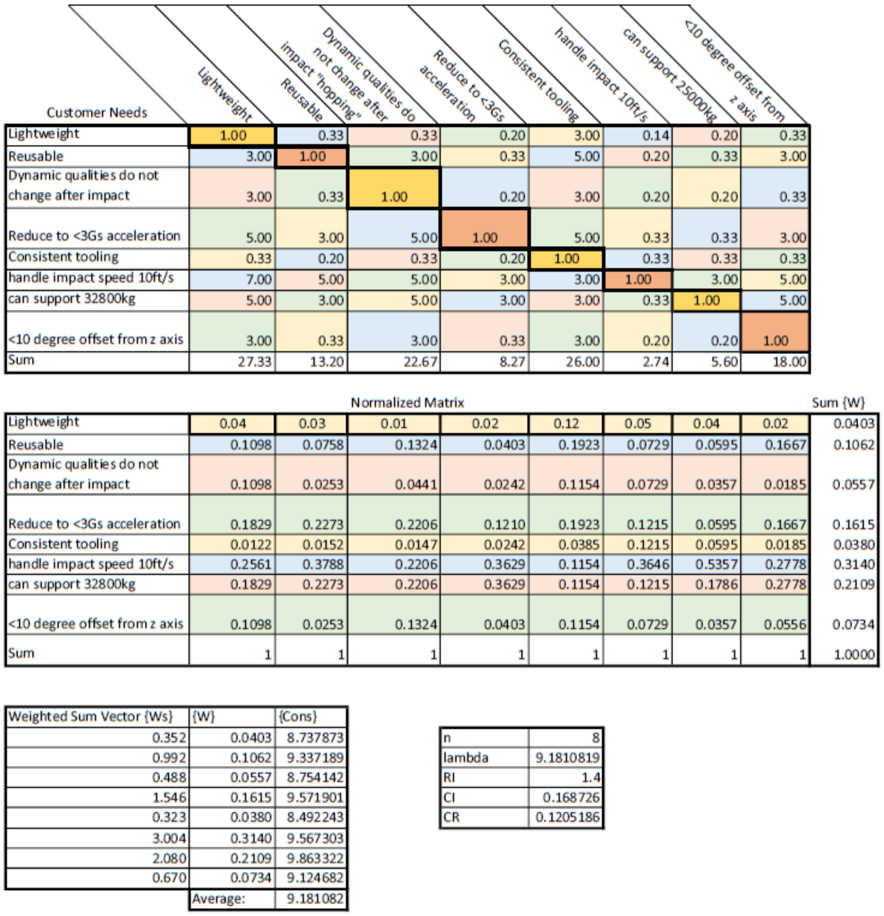
		Concept							
Selection Criteria	Datum	1	2	3	4	5	6	7	8
Absorb Impact Energy	Apollo Shock Absorbers	-	s	+	+	+	s	+	s
Absorb Structural Shock		-	+	-	+	+	-	s	s
Support Mass		s	s	-	S	s	s	s	s
Return to Original State		+	+	+	+	+	+	+	+
Indicate Reusability		+	+	+	-	-	+	s	-
Prevent Excessive Rebound		-	-	+	+	+	+	+	+
Transform Energy		S	+	s	s	s	+	+	s
Dampen Vibrations		+	+	+	+	+	-	+	+
Dissipate Energy		s	+	s	s	s	+	s	s
Store Energy		s	s	s	+	s	+	+	s
Withstand Lunar Conditions		-	+	-	-	-	-	s	+
#of pluses		3	6	5	6	5	6	6	3
# of minuses		4	1	3	1	1	3	0	1

Figure E-2. First Pugh chart used to select final 3 concepts.



	Concepts			
Selection Criteria	Datum	2	7	4
Absorb Impact Energy	Spider Legs	+	+	S
Absorb Structural Shock		+	+	+
Support Mass		s	+	-
Return to Original State		+	+	S
Indicate Reusability		s	-	+
Prevent Excessive Rebound		-	+	+
Transform Energy		+	+	+
Dampen Vibrations		-	+	+
Dissipate Energy		s	+	S
Store Energy		+	+	S
Withstand Lunar Conditions		s	+	-
#of pluses		5	10	5
# of minuses		2	1	2

Figure E-3. Second Pugh chart used to determine final concept.



Customer Needs	Lightweight	Reusable	Dynamic qualities do not change after impact "hopping"	Reduce to <3Gs acceleration	Consistent tooling	handle impact 10ft/s	can support 25000kg	<10 degree offset from z axis
Lightweight	1.00	0.33	0.33	0.20	3.00	0.14	0.20	0.33
Reusable	3.00	1.00	3.00	0.33	5.00	0.20	0.33	3.00
Dynamic qualities do not change after impact	3.00	0.33	1.00	0.20	3.00	0.20	0.20	0.33
Reduce to <3Gs acceleration	5.00	3.00	5.00	1.00	5.00	0.33	0.33	3.00
Consistent tooling	0.33	0.20	0.33	0.20	1.00	0.33	0.33	0.33
handle impact speed 10ft/s	7.00	5.00	5.00	3.00	3.00	1.00	3.00	5.00
can support 32800kg	5.00	3.00	5.00	3.00	3.00	0.33	1.00	5.00
<10 degree offset from z axis	3.00	0.33	3.00	0.33	3.00	0.20	0.20	1.00
Sum	27.33	13.20	22.67	8.27	26.00	2.74	5.60	18.00

Normalized Matrix

									Sum {W}
Lightweight	0.04	0.03	0.01	0.02	0.12	0.05	0.04	0.02	0.0403
Reusable	0.1098	0.0758	0.1324	0.0403	0.1923	0.0729	0.0595	0.1667	0.1062
Dynamic qualities do not change after impact	0.1098	0.0253	0.0441	0.0242	0.1154	0.0729	0.0357	0.0185	0.0557
Reduce to <3Gs acceleration	0.1829	0.2273	0.2206	0.1210	0.1923	0.1215	0.0595	0.1667	0.1615
Consistent tooling	0.0122	0.0152	0.0147	0.0242	0.0385	0.1215	0.0595	0.0185	0.0380
handle impact speed 10ft/s	0.2561	0.3788	0.2206	0.3629	0.1154	0.3646	0.5357	0.2778	0.3140
can support 32800kg	0.1829	0.2273	0.2206	0.3629	0.1154	0.1215	0.1786	0.2778	0.2109
<10 degree offset from z axis	0.1098	0.0253	0.1324	0.0403	0.1154	0.0729	0.0357	0.0556	0.0734
Sum	1	1	1	1	1	1	1	1	1.0000

Weighted Sum Vector {Ws}	{W}	{Cons}
0.352	0.0403	8.737873
0.992	0.1062	9.337189
0.488	0.0557	8.754142
1.546	0.1615	9.571901
0.323	0.0380	8.492243
3.004	0.3140	9.567303
2.080	0.2109	9.863322
0.670	0.0734	9.124682
	Average:	9.181082

n	8
lambda	9.1810819
RI	1.4
CI	0.168726
CR	0.1205186

Figure E-4. AHP matrices.

Appendix F: Operations Manual

This section explains how the full-scale design and each of the prototypes is operated.

F.1 Full Scale Design

The full-scale design operation is purely hypothetical and not all applicable prototype tests have been performed at the time of writing. The following procedure is a sequential list of expected interactions between the various components and any steps that need to be taken by the user.

1) The ratchet screw is impacted by a force.
2) The impact force is transferred from the ratchet screw to the thrust bearing, which transfers the force to the motor housing, which transfers the force to the main spring.
3) The main spring is compressed as the ratchet screw moves inward.
4) A sensor delivers information to the user that the spring has compressed.
5) The angled surface of the ratchet screw helix profile encounters the angled surface of the pawl teeth.
6) The ratchet screw deflects the end of the pawls outward as the ratchet screw moves inward.
7) The pawl tooth eventually slides over the top of the ratchet tooth that it was in contact with and falls down into the cavity created behind the ratchet tooth.
8) Steps 4-6 repeat until all the impact energy has been absorbed by the main spring and the inward movement of the ratchet screw stops.
9) The main spring attempts to expand, which pushes the motor housing, thrust bearing, and ratchet screw out of the main cylinder.
10) The ratchet screw moves outward until the load bearing face of the helix profile interacts with the load bearing surface of the pawl tooth. The force of the main spring, acting through the motor housing, thrust bearing, and ratchet screw, is now held completely by the pawl arms.
11) The sensor notifies the user that the spring is fully compressed.
12) At this point all the impact energy is stored in the main spring. The system can remain in this state indefinitely. The rest of the procedure must be performed before the shock absorber is ready to be used again.
13) To unload the main spring the user must activate the motor.
14) The motor creates a twisting force between the main cylinder and the thrust bearing, which turns rotates the ratchet screw.

15) The ratchet screw is unthreaded from the pawl teeth until the main spring is completely decompressed.
16) The user deactivates the motor, the sensor shows that the spring is not compressed, and the system is ready for use again.

F.2 Spring Prototype

The spring prototype is designed to test the main spring component of the design. The spring should not fail under the load resulting from an impact force or compress far enough that the strike plate bottoms out. The following procedure is a sequential list of expected interactions between the various components and any steps that need to be taken by the user.

1) The base plate is fastened to a surface to provide stability. A 55-gallon steel drum provides stability and prevents the weights from sliding off the strike plate after the drop.
2) A displacement measurement system is established. Paper rulers can be taped near the viewing slot on the spring pipe. Slow motion video capture can be used to analyze each drop test afterwards.
3) The strike plate is impacted by a 90lb weight that is dropped from a fixed height of 6 inches. This produces the dynamically scaled impact energy expected during a worst-case scenario lunar landing. The scaled impact energy is 63 Joules.
4) The stroke length is recorded, preferably with slow motion video capture. The stroke length is the max distance the plunger travels before reversing direction from the spring's opposing force.
5) Multiple weight drops should be performed to collect a list of data.
6) The spring will be determined fit or unfit for the design based on the stroke length.

F.3 Locking Mechanism Prototype

The locking mechanism prototype is tested in two ways. The first is a ratcheting motion test, which tests that the ratchet screw deflects the pawls outward as designed. The second is a locking mechanism test, which tests whether the locking mechanism will be able to hold the spring/ratchet helix in place when it has all the energy stored from the landing.

F.3.1 Ratcheting Motion Test

1) The eyebolt is removed from the ratchet screw and the strike plate is inserted.
2) The locking mechanism prototype is mounted in such a way that the strike plate can be impacted.
3) The ratchet screw is positioned such that most or all of the ratchet screw is extended out through the pawl arms.
4) Impact the strike plate by dropping 90lbs. from a height of 6 inches onto

F.3.2 Locking Mechanism Test

1) The strike plate is removed from the ratchet screw and the eye bolt is inserted.
2) The locking mechanism prototype is mounted in such a way that the weight, 144 lbs., can safely be hung from the eyebolt.
3) The ratchet screw is positioned such that at least half of the ratchet screw is inside of the main cylinder.
4) The weight is hung from the eyebolt and any movements are noted. The weight should be hung for enough time to note any slow changes or deformations. The ratchet screw may slowly unscrew under load. If this occurs the speed of the rotation should be noted, and calculations should be performed to determine if the rotation would pose a threat to the safety of the landing craft on the full-size design.
5) Remove the weight from the eyebolt.

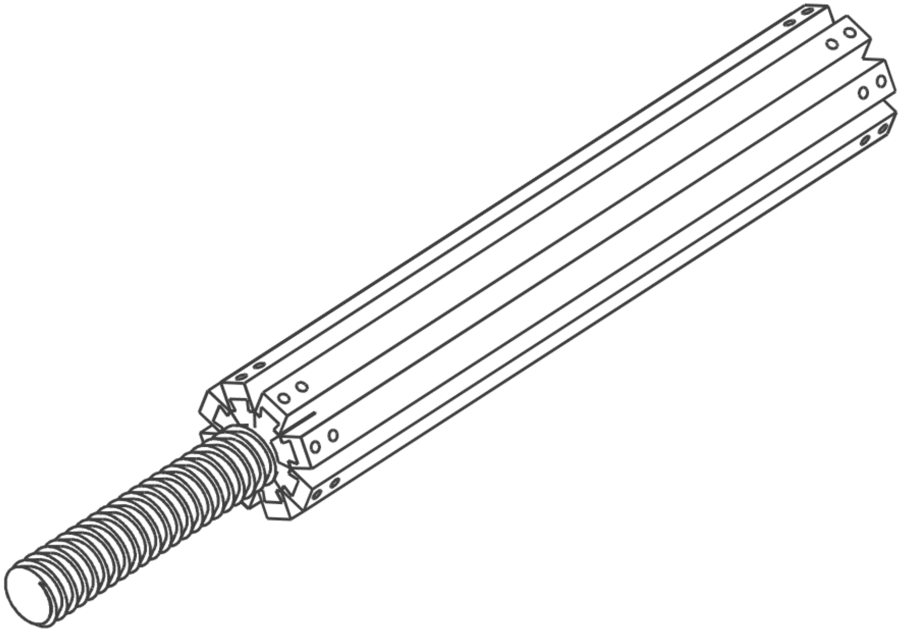
F.4 Unlocking Mechanism Prototype

The unlocking mechanism prototype is designed to test the ability of the ratchet screw to unthread under maximum loading.

1) The prototype is mounted in such a way that the proper amount of weight, 144lbs, can be hung from the eyebolt on the ratchet screw.
2) The ratchet screw is positioned in the pawl teeth such that half of the ratchet screw is within the main cylinder.
3) The weight is attached to the eyebolt.
4) The motor is activated to unthread the ratchet screw through the pawl teeth.
5) When the screw is fully unthreaded and the slider block is interfering with the pawl teeth, turn off the motor and remove the weight from the eyebolt.

Appendix G: Drawings

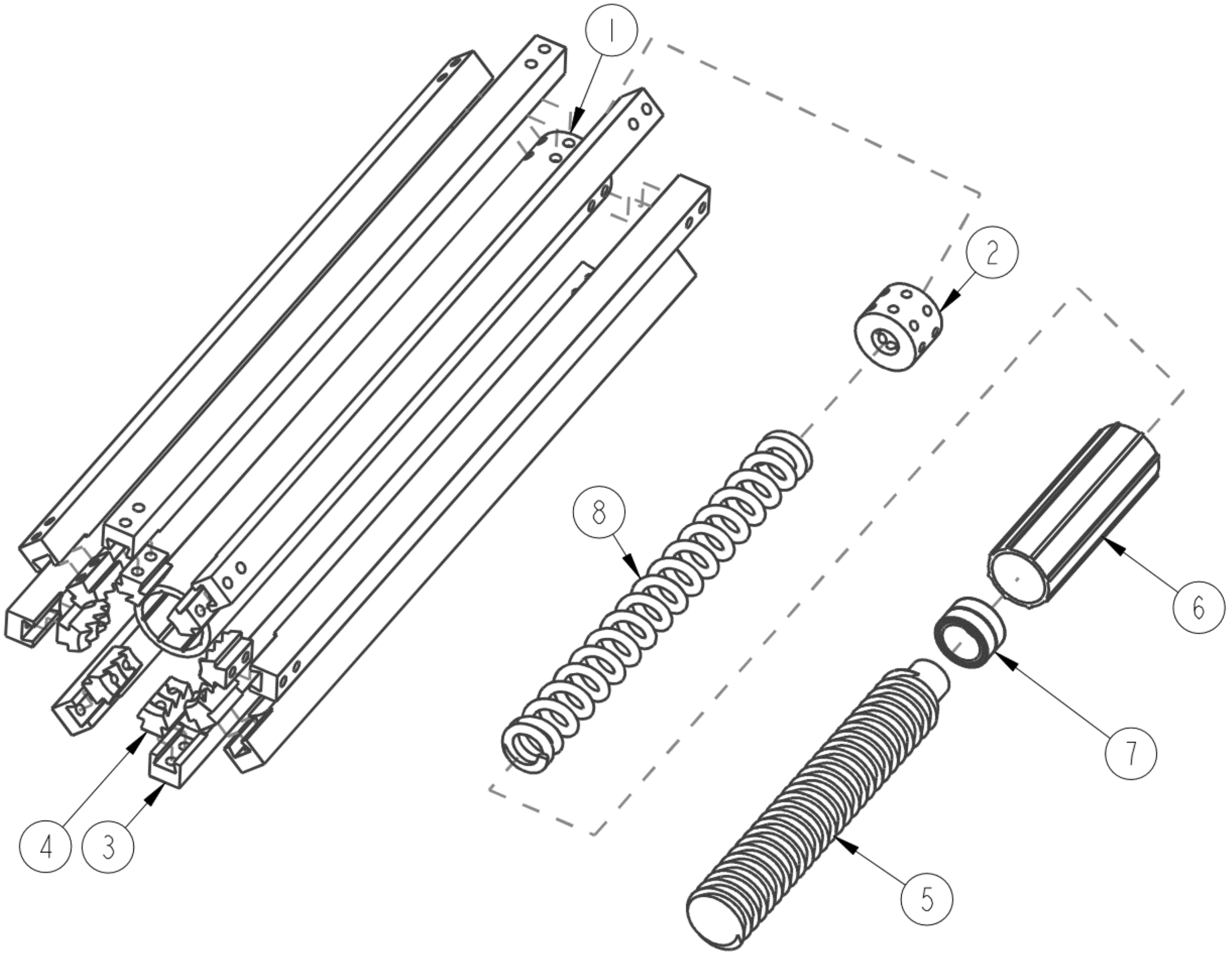
This appendix contains the drawings of the full-scale design, the spring prototype, and the locking mechanism prototype. The unlocking mechanism prototype has not been designed yet at the time of writing.



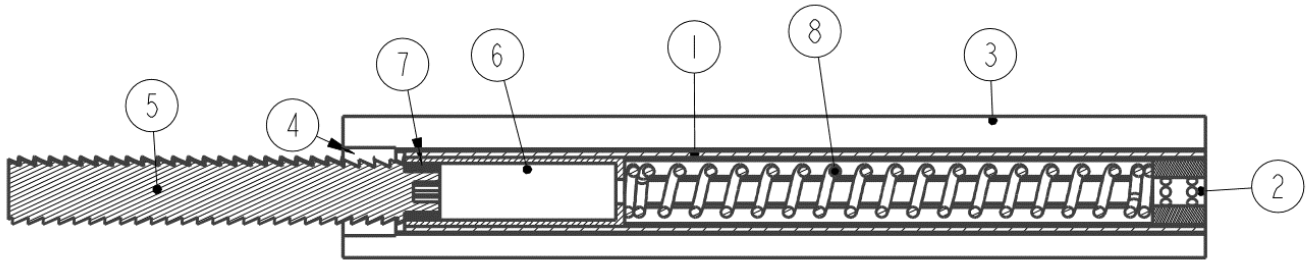
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: ASSEMBLY		PROJECT NAME: SHOCK ABSORBER		
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: VARIOUS	
SCALE: 0.060	REV: 0	SHEET NUMBER: 1 OF 3	PART NUMBER: SA-21-009	



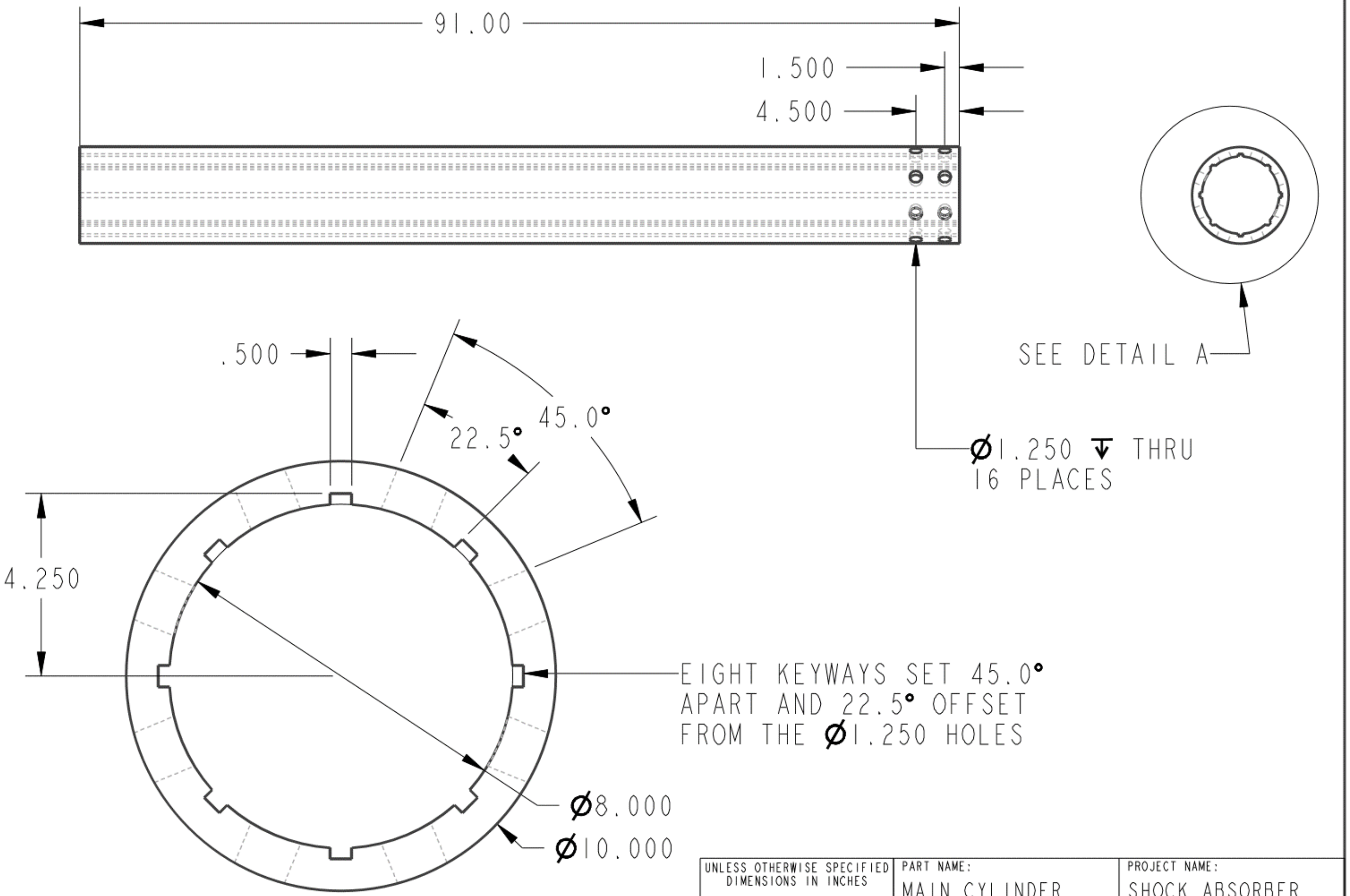
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES	PART NAME: ASSEMBLY		PROJECT NAME: SHOCK ABSORBER	
TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: VARIOUS
	SCALE: 0.060	REV: 0	SHEET NUMBER: 2 OF 3	PART NUMBER: SA-21-009



#	PART NAME	QTY	MATERIAL
1	MAIN CYLINDER	1	AL-7178
2	END CAP	1	AL-7178
3	PAWL ARM	8	304 SS
4	EIGTH NUT	8	304 SS
5	RATCHET SCREW	1	304 SS
6	MOTOR HOUSING	1	AL-7178
7	THRUST BEARING	1	304 SS
8	MAIN SPRING	1	304 SS

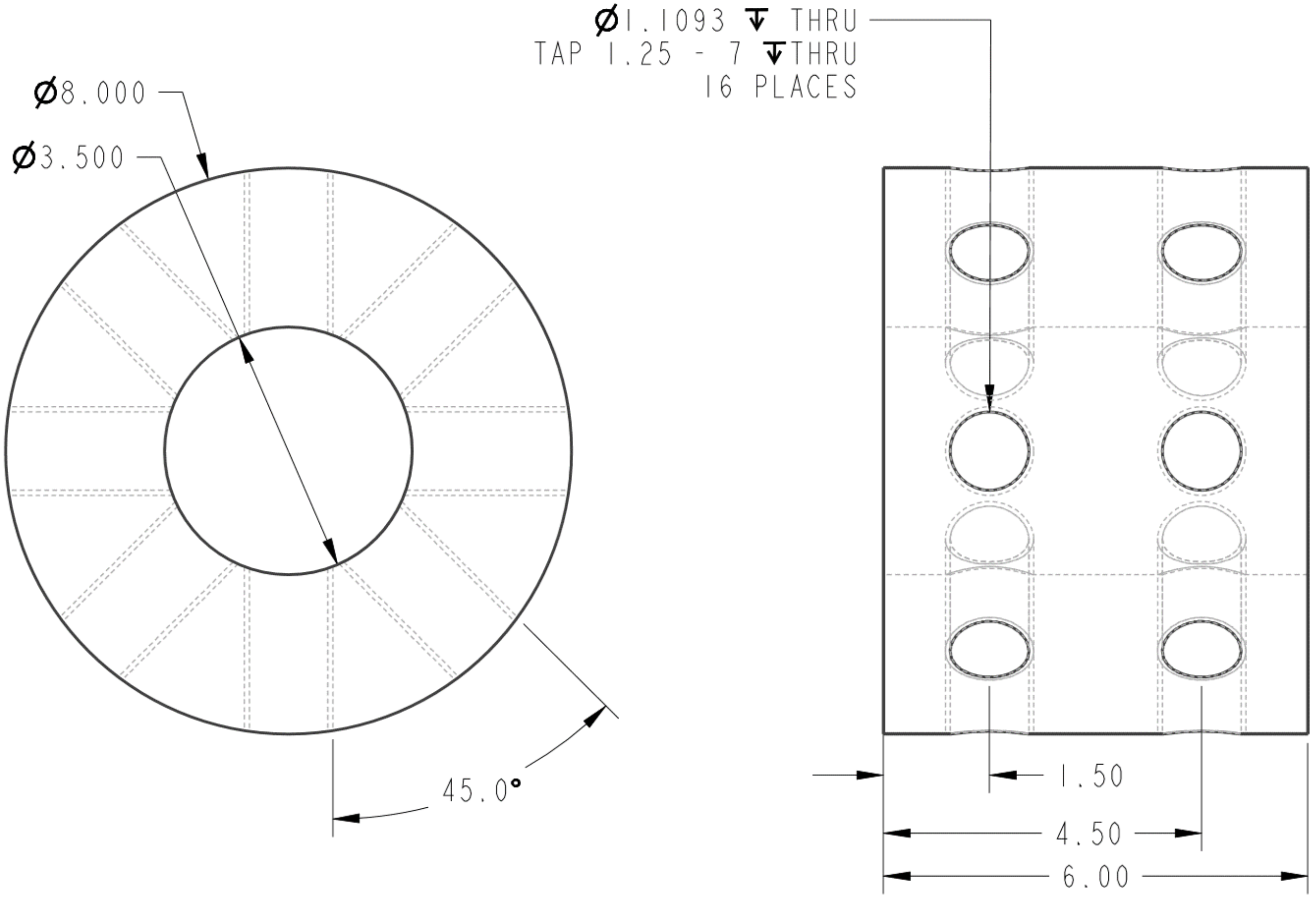
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: ASSEMBLY
PROJECT NAME: SHOCK ABSORBER
DRAWN BY: JOSH BLANK
DATE: 3/18/21
SIZE: A
MATERIAL: VARIOUS
SCALE: 0.060
REV: 0
SHEET NUMBER: 3 OF 3
PART NUMBER: SA-21-009



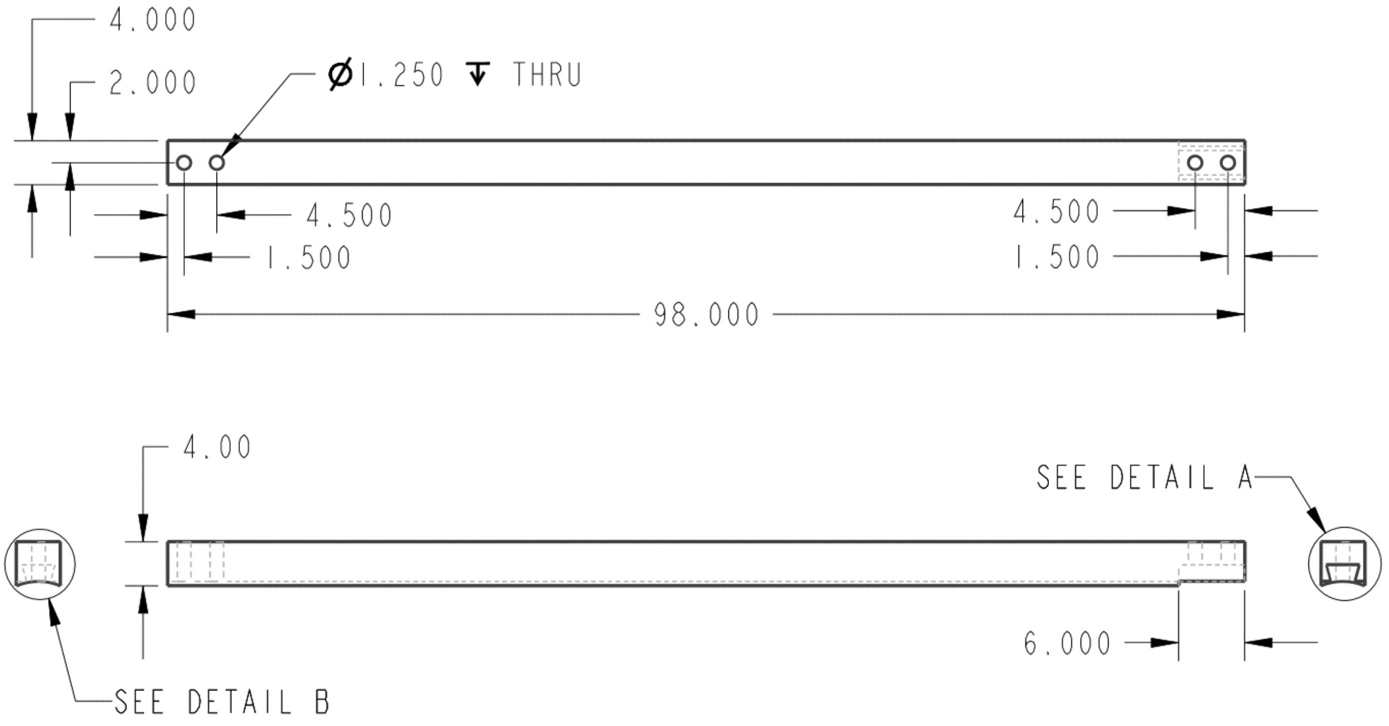
DETAIL A
SCALE 0.333

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: MAIN CYLINDER			PROJECT NAME: SHOCK ABSORBER	
	DRAWN BY: JOSH BLANK		DATE: 3/18/21	SIZE: A	MATERIAL: AL-7178
	SCALE: 0.075	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SA-21-001	



TWO ROWS OF 8 1.25-7 TAPPED
HOLES SET 45° APART

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: END CAP		PROJECT NAME: SHOCK ABSORBER	
	DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: AL-7178
	SCALE: 0.500	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SA-21-002

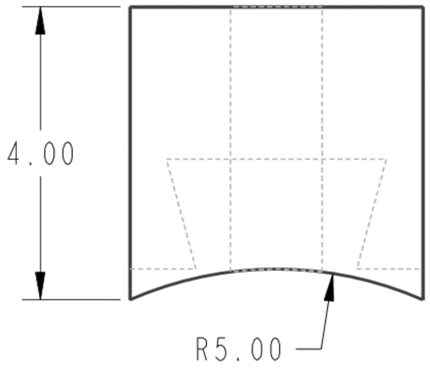


UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

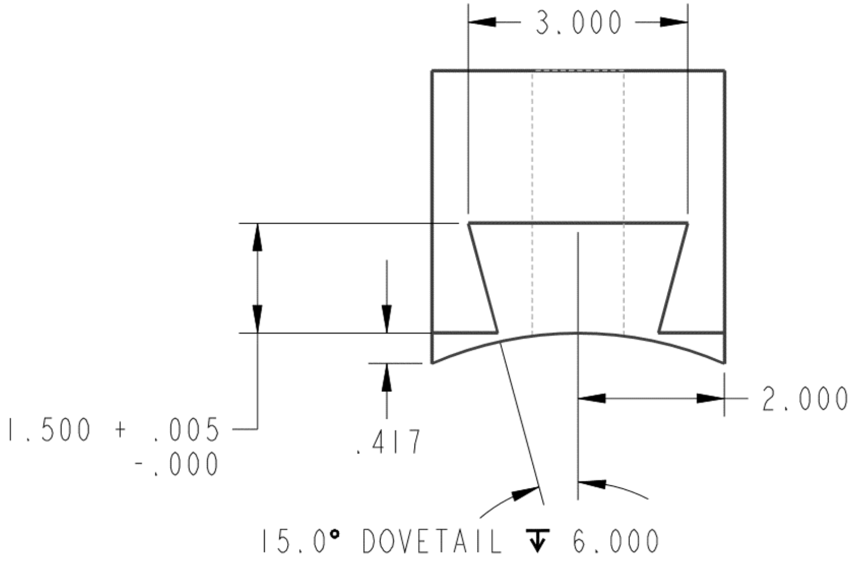
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: PAWL ARM
PROJECT NAME: SHOCK ABSORBER
DRAWN BY: JOSH BLANK
DATE: 3/18/21
SIZE: A
MATERIAL: 304 SS
SCALE: 0.075
REV: 0
SHEET NUMBER: 1 OF 1
PART NUMBER: SA-21-003

DETAIL B
SCALE 0.500

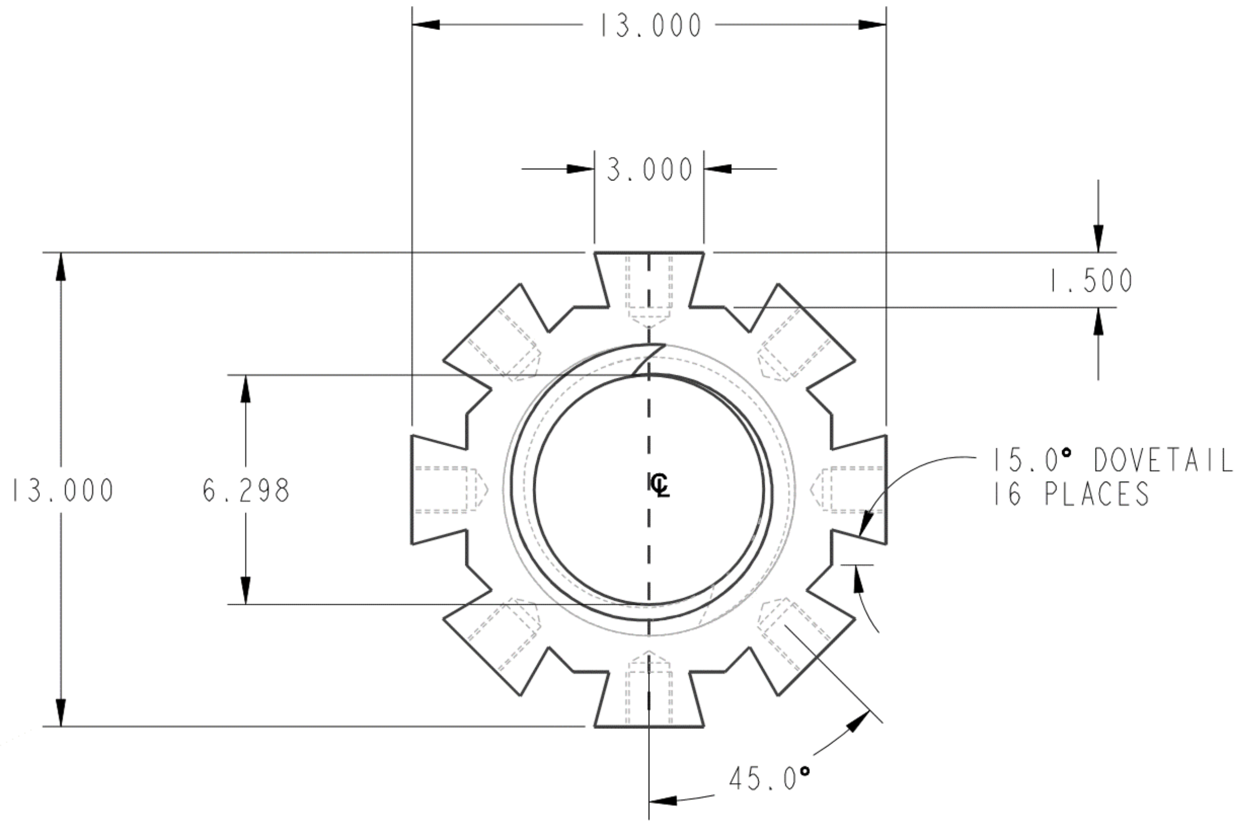


DETAIL A
SCALE 0.500

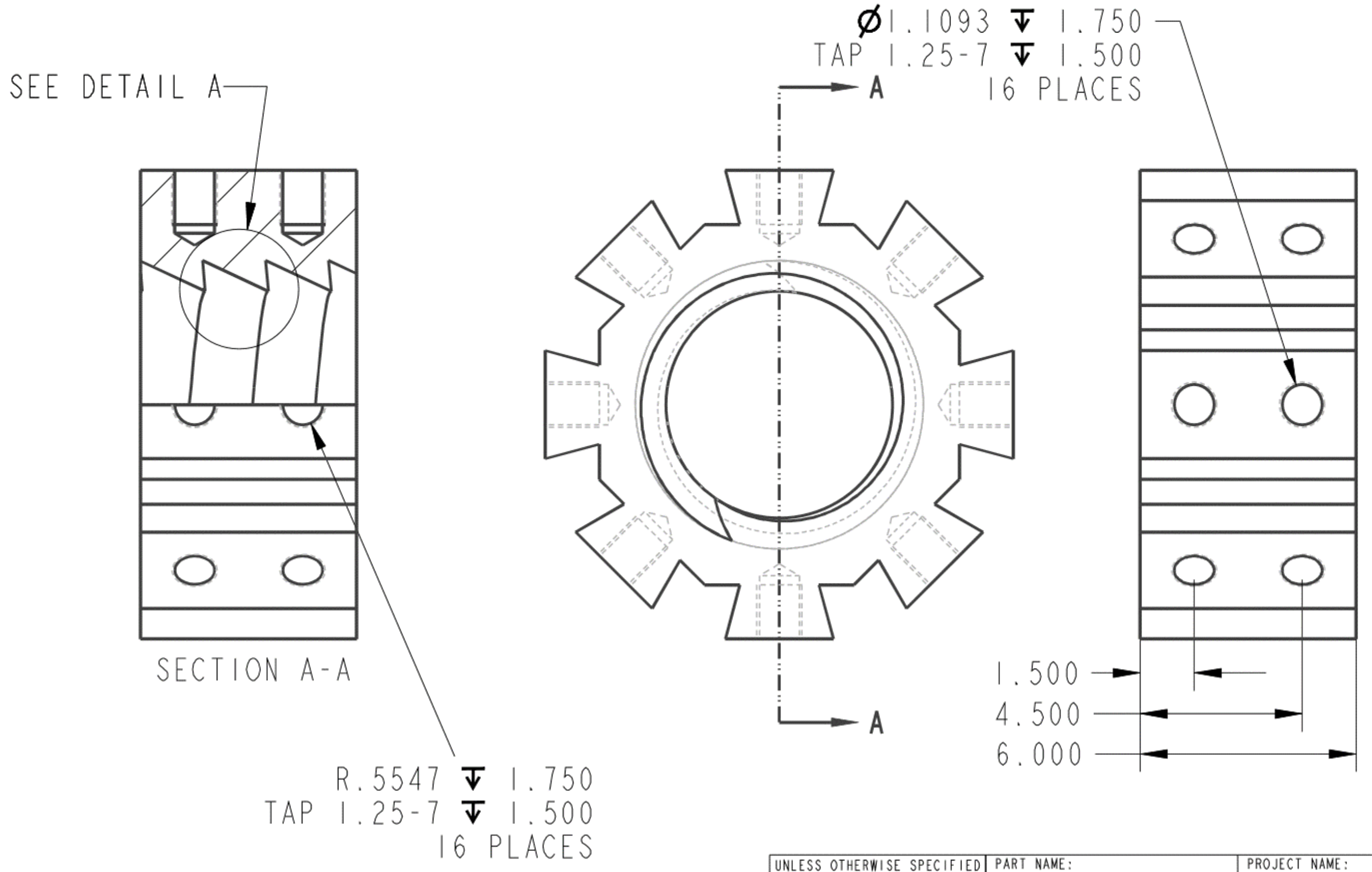


UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: PAWL ARM		PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: 304 SS
SCALE: 0.075	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SA-21-003



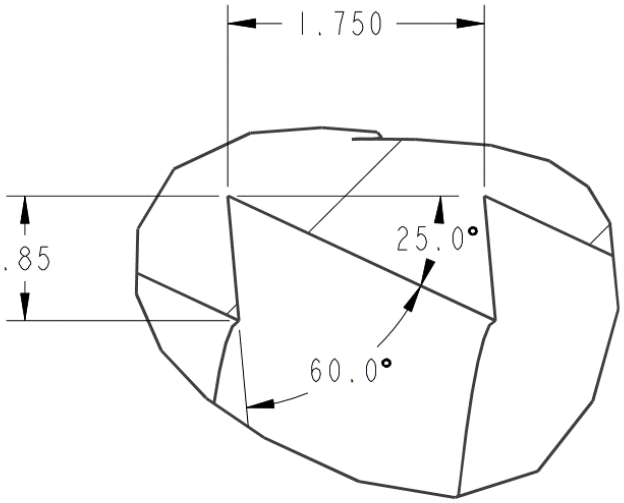
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: EIGHTH NUTS		PROJECT NAME: SHOCK ABSORBER	
	DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: 304 SS
	SCALE: 0.250	REV: 0	SHEET NUMBER: 1 OF 4	PART NUMBER: SA-21-004



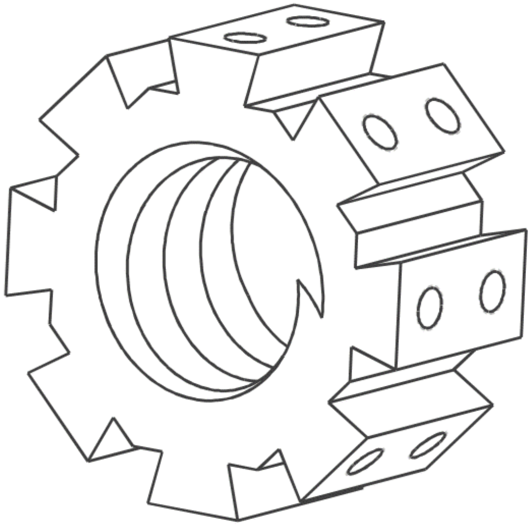
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: EIGHTH NUTS			PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK		DATE: 3/18/21	SIZE: A	MATERIAL: 304 SS
SCALE: 0.250	REV: 0	SHEET NUMBER: 2 OF 4	PART NUMBER: SA-21-004	



DETAIL A
SCALE 1.000

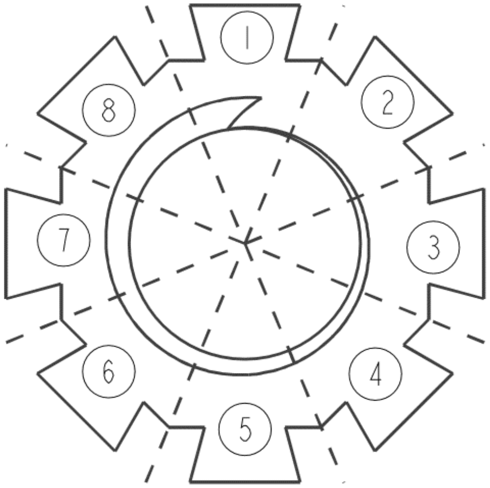


CONCEPTUAL VIEW

SCREW INFOMATION	
MINOR ID	6.298
MAJOR ID	8.00
PITCH	1.750
DEPTH	.851

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: EIGHTH NUTS		PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: 304 SS
SCALE: 0.250	REV: 0	SHEET NUMBER: 3 OF 4	PART NUMBER: SA-21-004

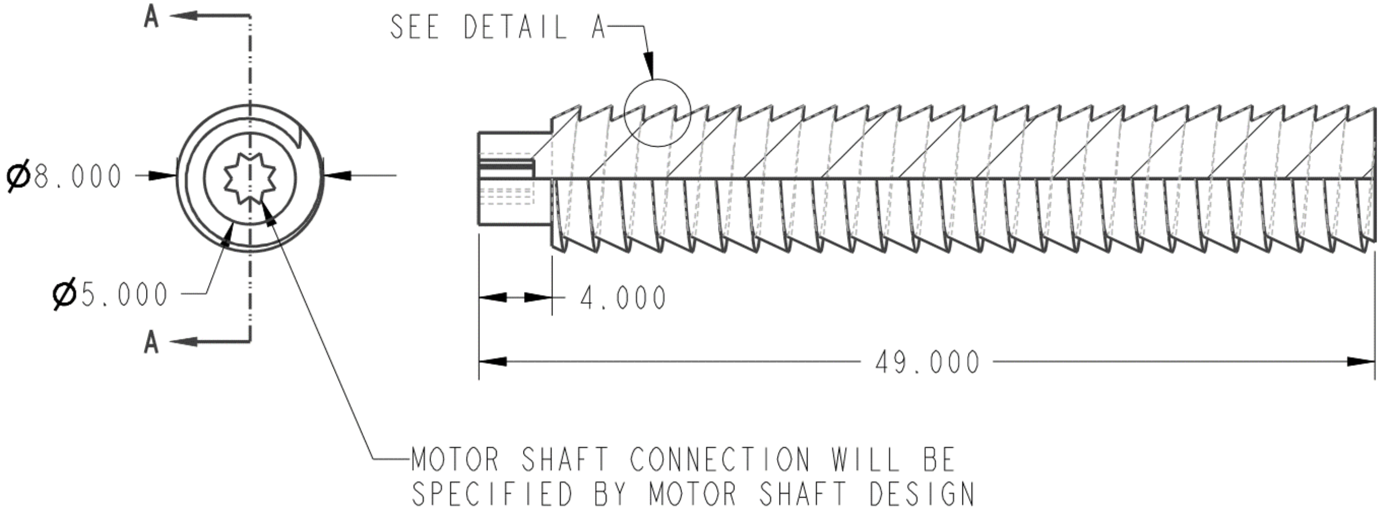


AFTER FABRICATION, CUT NUT INTO EIGHT SECTIONS ALONG DASHED LINES
MARK EACH SECTION 1-8 CLOCKWISE AS NOTED BY BALLOONS

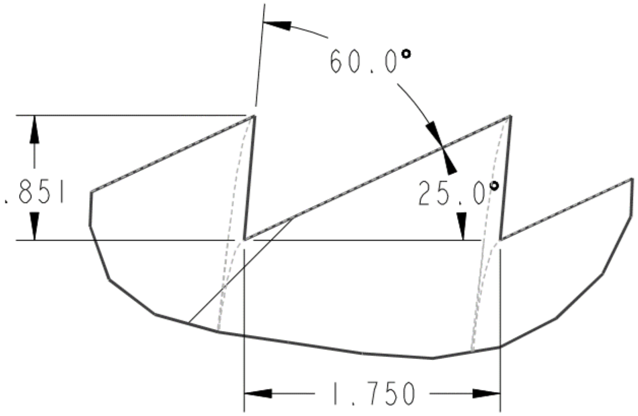
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: EIGHTH NUTS		PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: 304 SS
SCALE: 0.250	REV: 0	SHEET NUMBER: 4 OF 4	PART NUMBER: SA-21-004



MOTOR SHAFT CONNECTION WILL BE SPECIFIED BY MOTOR SHAFT DESIGN



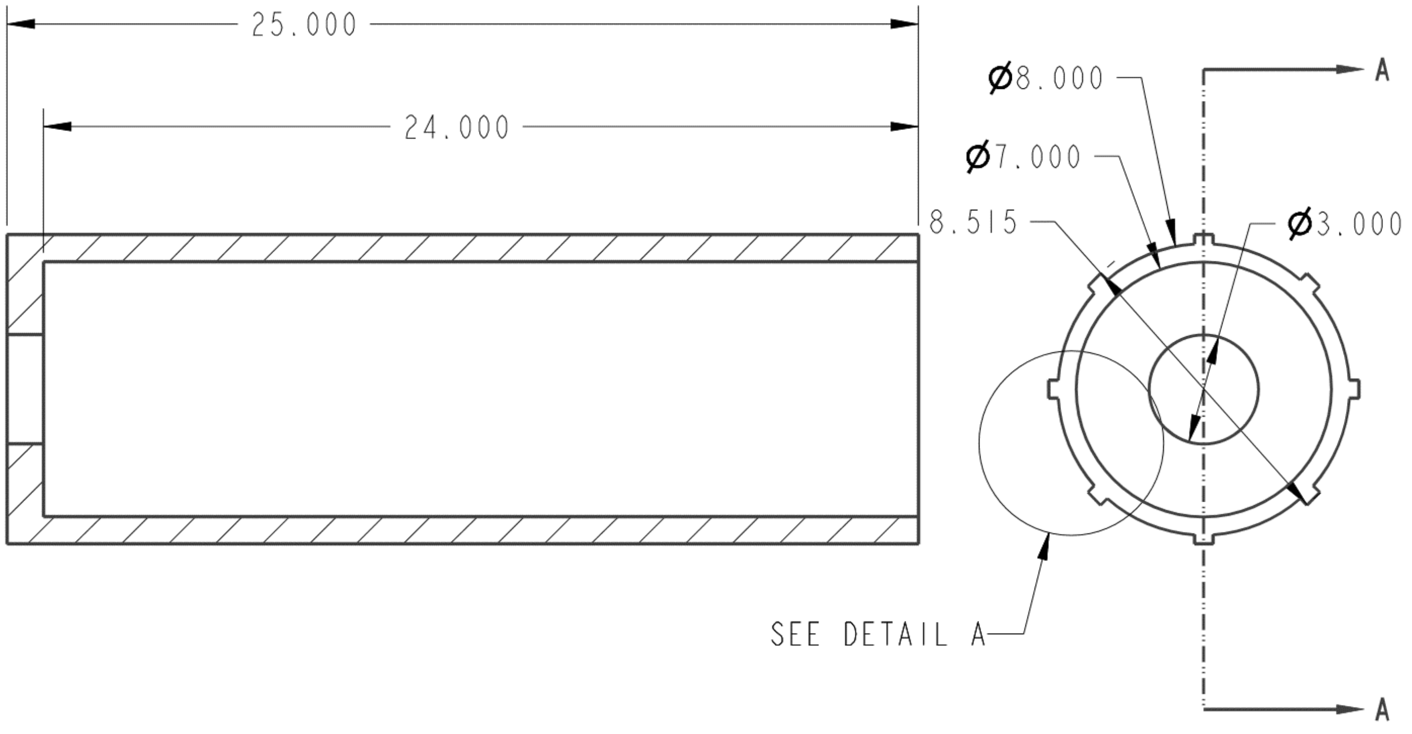
DETAIL A
SCALE 1.000

SCREW INFORMATION	
MAJOR OD	8.000
MINOR OD	6.30
PITCH	1.750
DEPTH	.851

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

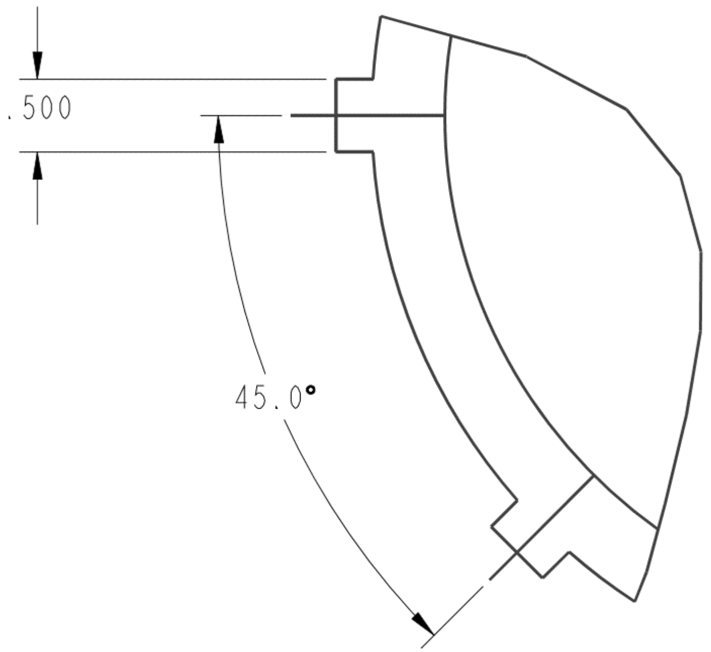
PART NAME: RATCHET SCREW		PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: 304 SS
SCALE: 1.000	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SA-21-005



UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: MOTOR HOUSING		PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: AL-7178
SCALE: 0.250	REV: 0	SHEET NUMBER: 1 OF 2	PART NUMBER: SA-21-006



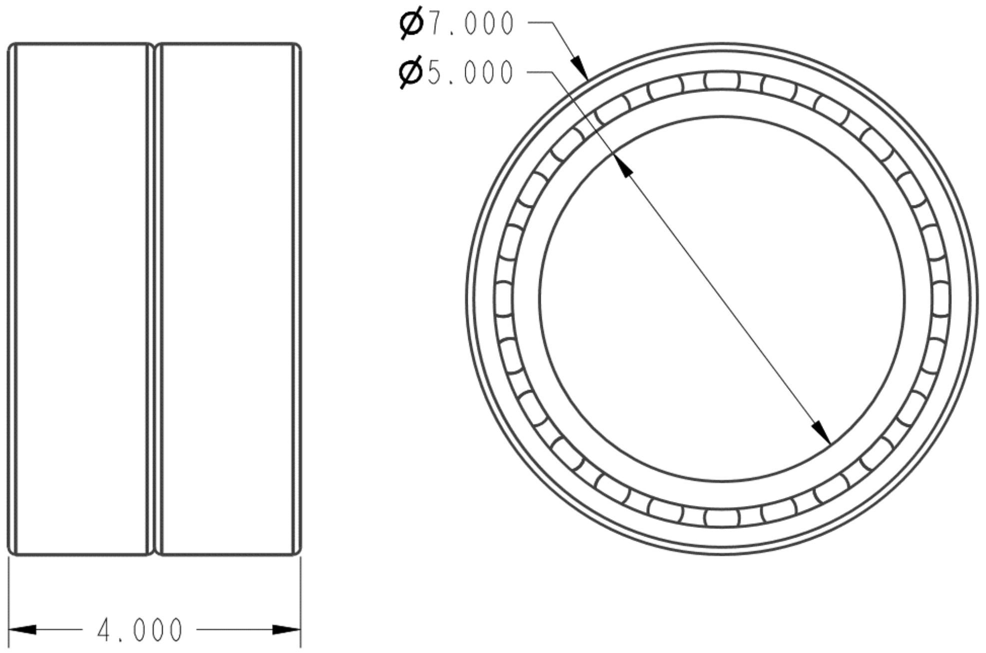
DETAIL A
SCALE 1.000

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

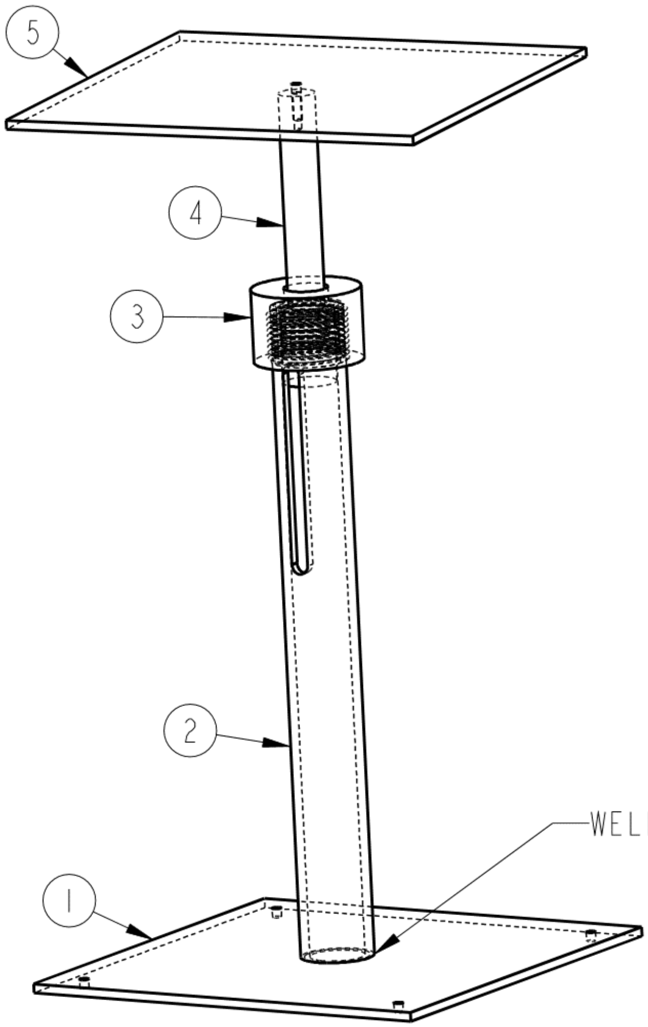
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: MOTOR HOUSING		PROJECT NAME: SHOCK ABSORBER	
DRAWN BY: JOSH BLANK	DATE: 3/18/21	SIZE: A	MATERIAL: AL-7178
SCALE: 0.250	REV: 0	SHEET NUMBER: 2 OF 2	PART NUMBER: SA-21-006

THE THUST BEARING HAS NOT BEEN DESIGNED YET
THE LISTED OD, ID AND LENGTH ARE WORKING VALUES



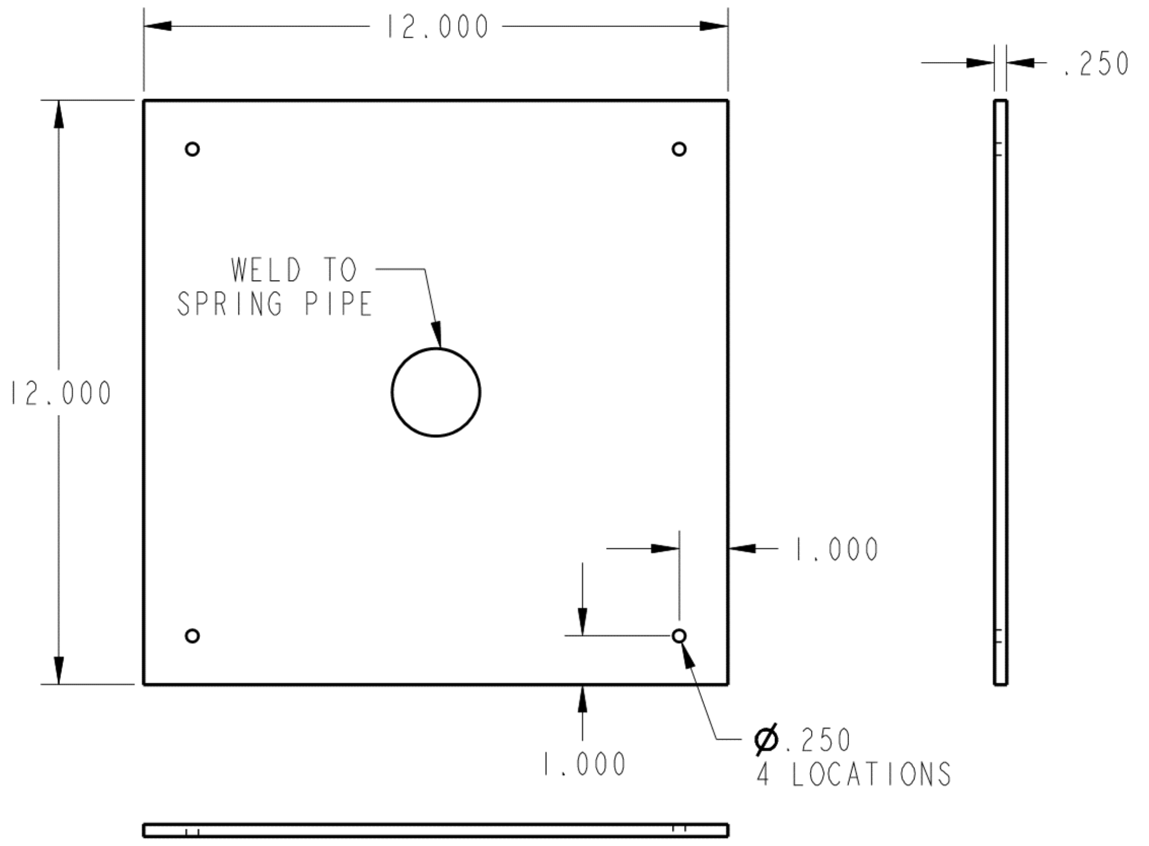
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES	PART NAME:				PROJECT NAME:	
TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	THRUST BEARING				SHOCK ABSORBER	
	DRAWN BY: JOSH BLANK		DATE: 3/18/21		SIZE: A	MATERIAL: 304 SS
	SCALE: 0.500	REV: 0	SHEET NUMBER: 1 OF 1		PART NUMBER: SA-21-007	



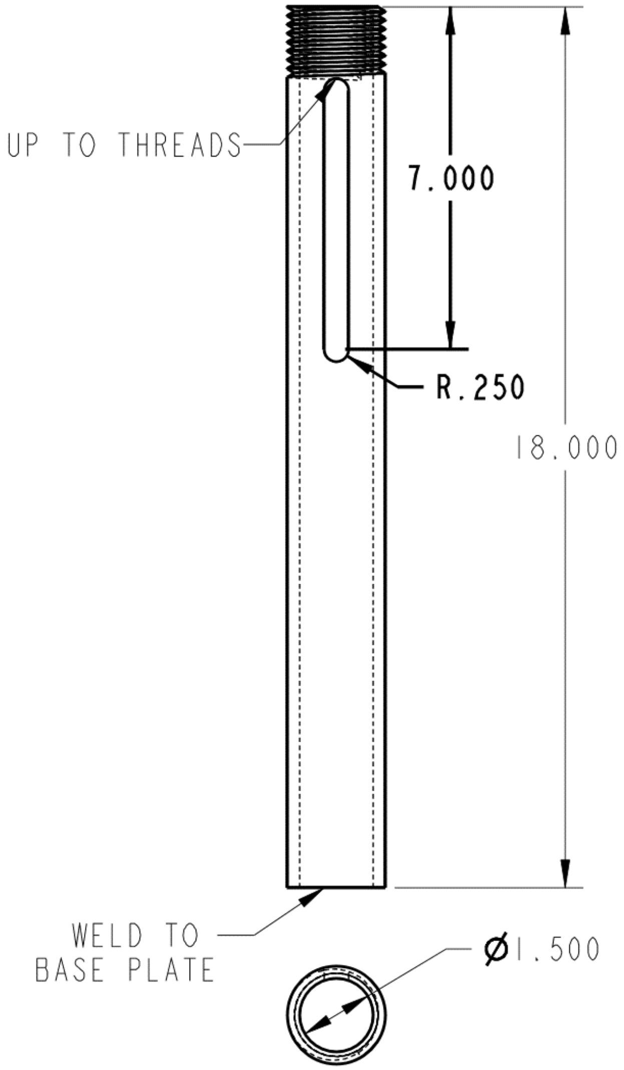
WELD BASE PLATE TO SPRING PIPE

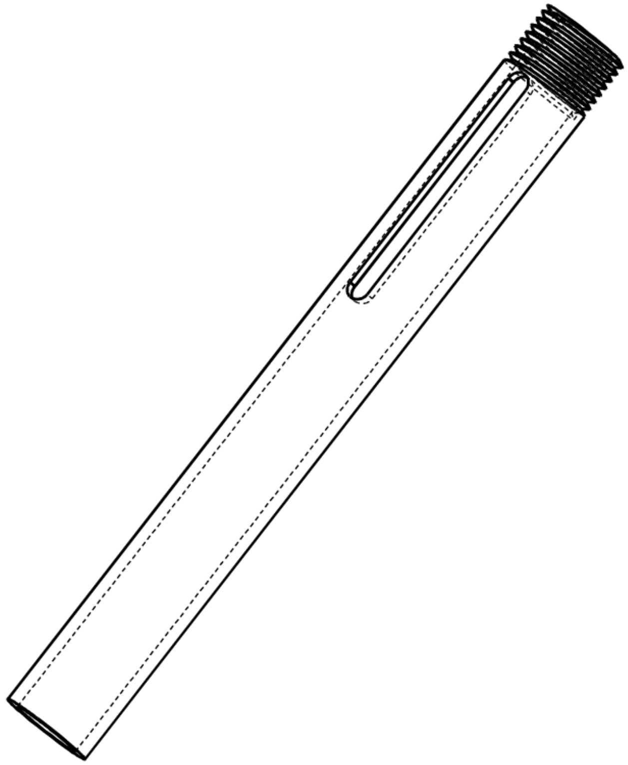
#	PART NAME	PART NUMBER
1	BASE PLATE	SP-21-001
2	SPRING PIPE	SP-21-002
3	CAP	SP-21-003
4	PLUNGER	SP-21-004
5	STRIKE PLATE	SP-21-005

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: ASSEMBLY VIEW			PROJECT NAME: SPRING PROTOTYPE	
	DRAWN BY: JOSH BLANK		DATE: 2/3/21	SIZE: A	MATERIAL: VARIOUS
	SCALE: 0.500	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP-21-006	



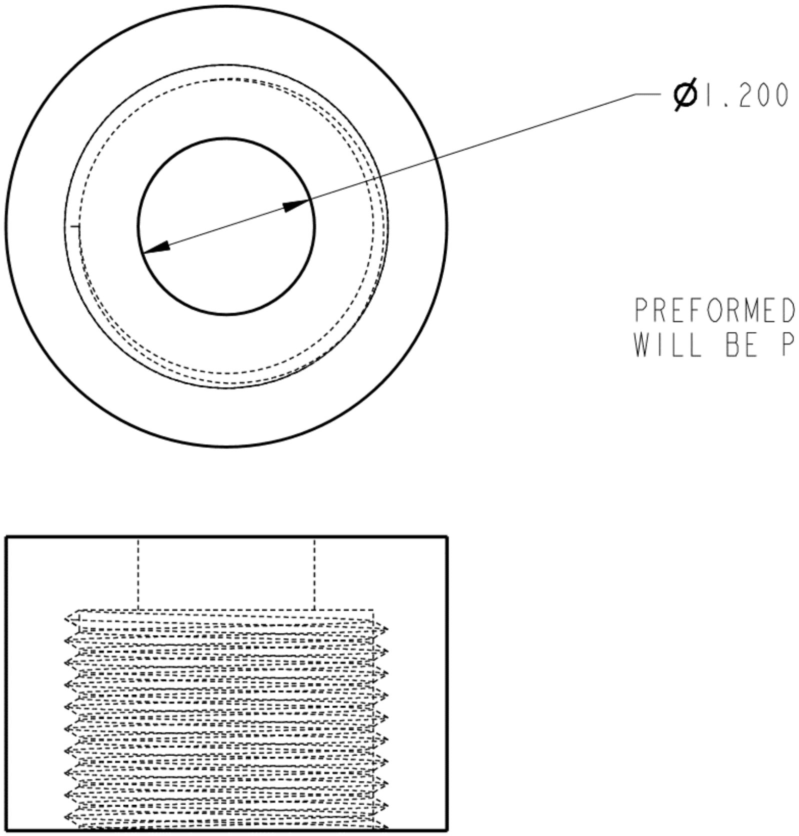
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: BASE PLATE			PROJECT NAME: SPRING PROTOTYPE	
	DRAWN BY: JOSH BLANK		DATE: 2/3/21	SIZE: A	MATERIAL: STEEL PLATE
	SCALE: 0.333	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP-21-001	





PERSPECTIVE VIEW FOR VISUALIZATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES	PART NAME: SPRING PIPE			PROJECT NAME: SPRING PROTOTYPE	
TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JOSH BLANK		DATE: 2/3/21	SIZE: A	MATERIAL: BLACK PIPE
	SCALE: 0.333	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP-21-002	

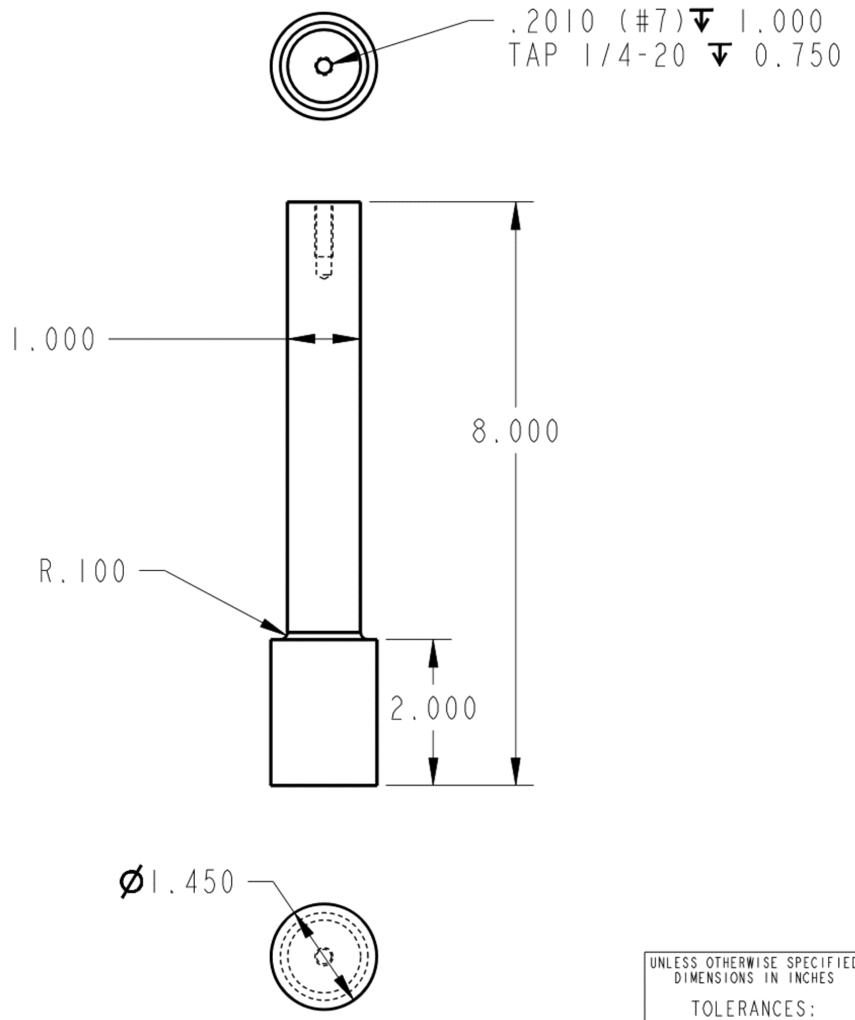


PREFORMED PIPE CAP WITH FNPT
WILL BE PROVIDED

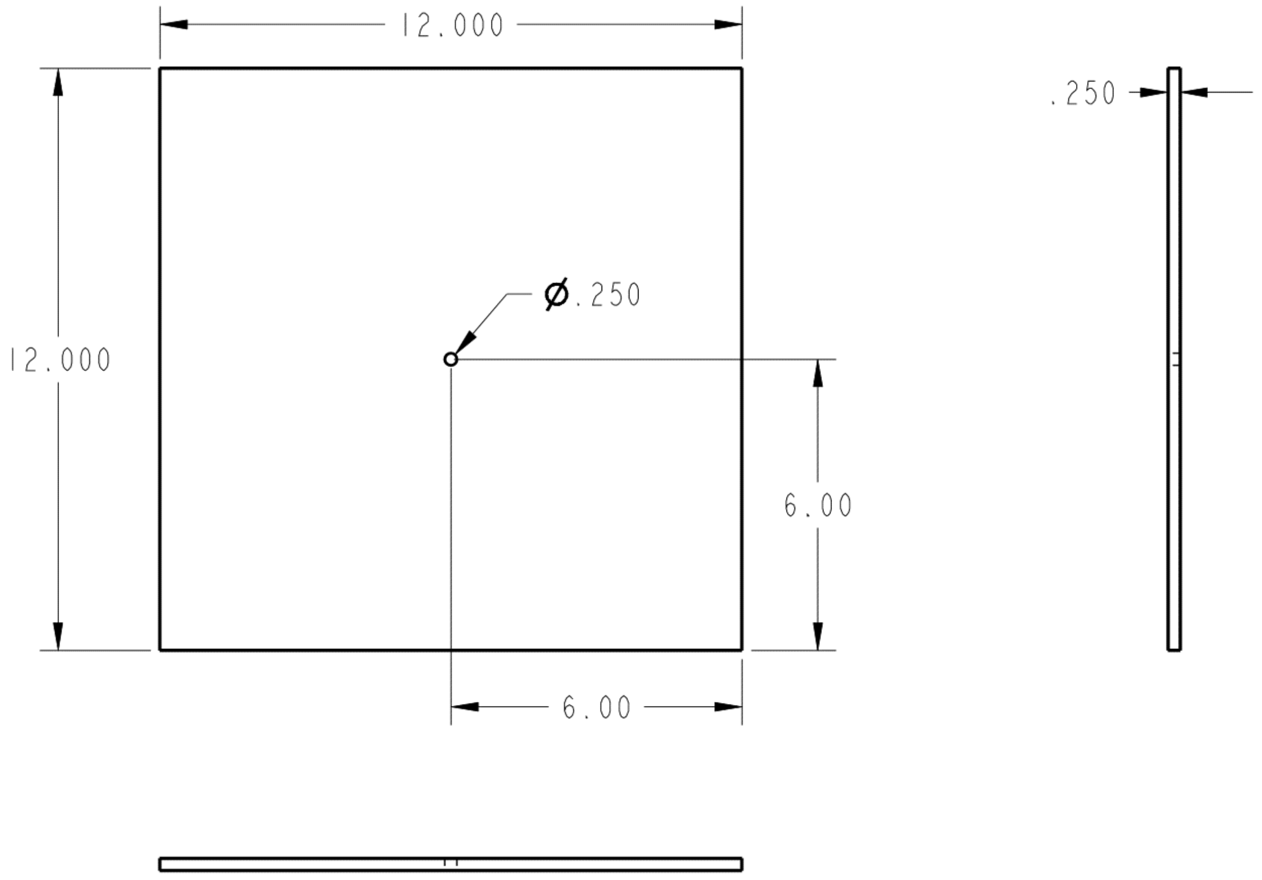
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: CAP		PROJECT NAME: SPRING PROTOTYPE	
DRAWN BY: JOSH BLANK	DATE: 2/3/21	SIZE: A	MATERIAL: STEEL CAP
SCALE: 1.000	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP-21-003



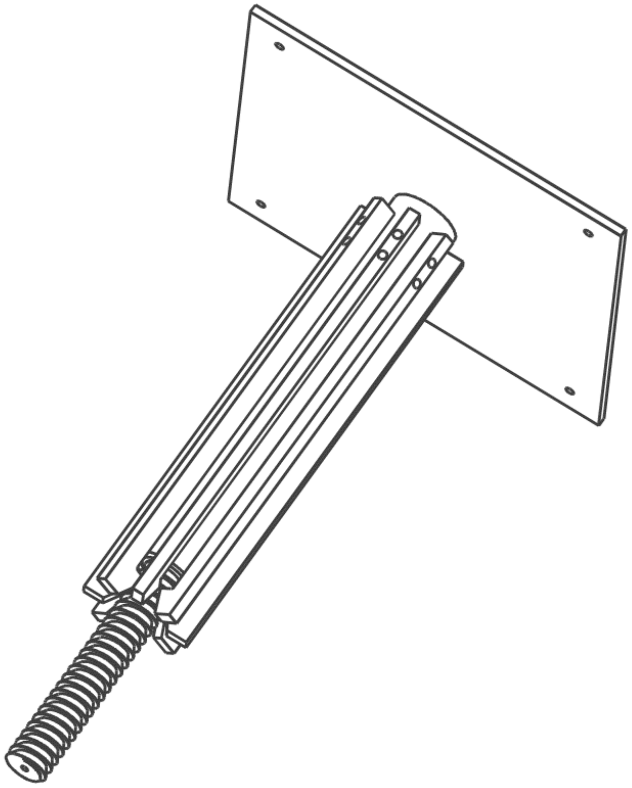
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES	PART NAME: PLUNGER		PROJECT NAME: SPRING PROTOTYPE	
TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JOSH BLANK	DATE: 2/3/21	SIZE: A	MATERIAL: STEEL ROD
	SCALE: 0.500	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP-21-004



UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: STRIKE PLATE		PROJECT NAME: SPRING PROTOTYPE	
DRAWN BY: JOSH BLANK	DATE: 2/3/21	SIZE: A	MATERIAL: STEEL PLATE
SCALE: 0.333	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: SP-21-005

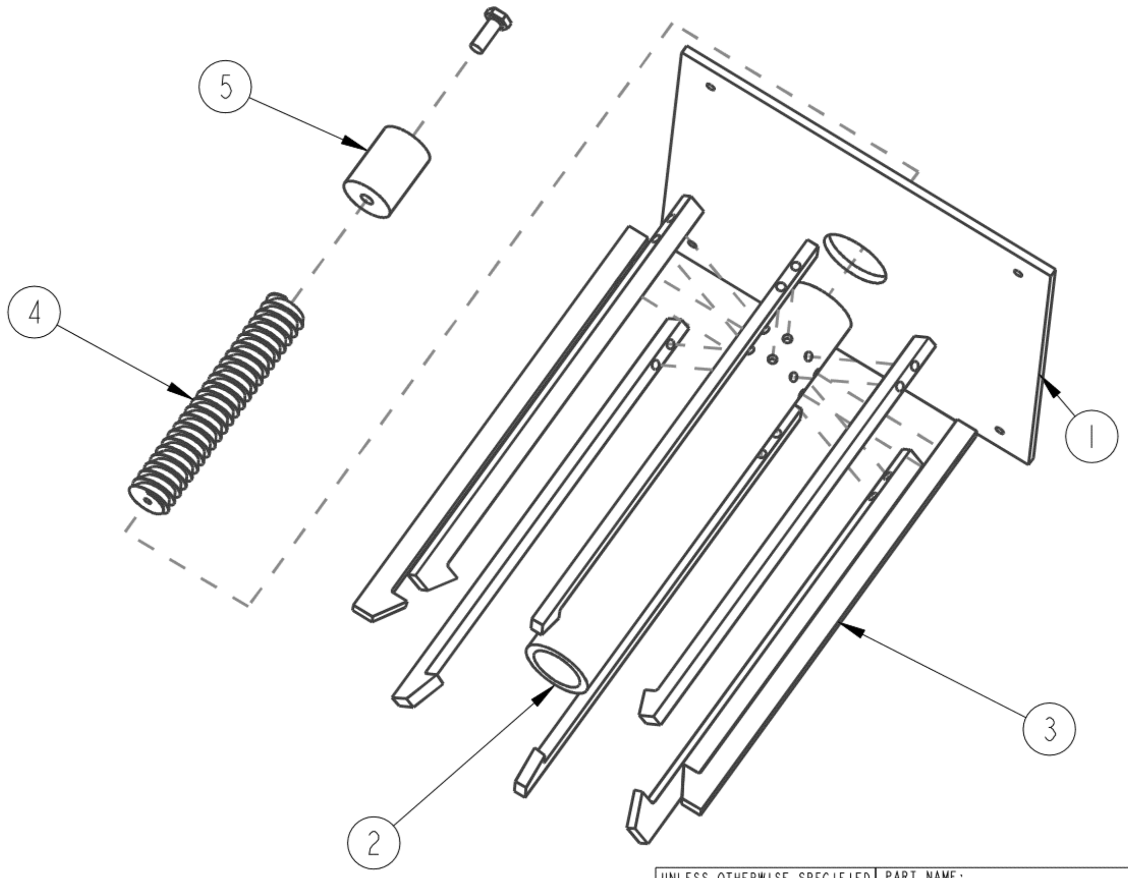


PART #	PART NAME	QTY	MATERIAL
1	BACK PLATE	1	STEEL
2	MAIN CYLINDER	1	STEEL
3	PAWL ARM	8	STEEL
4	SCREW	1	STEEL
5	SLIDER BLOCK	1	STEEL
	3/8-16 x 1.5 BOLT	1	
	1/4-20 x 1.25 BOLT	17	
	1/4-20 NUT	17	

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

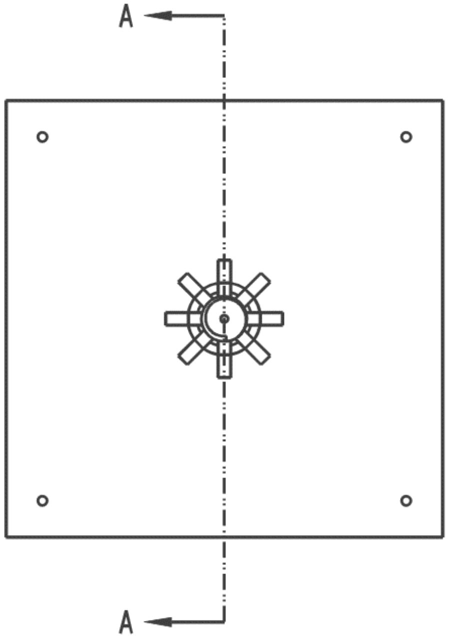
PART NAME: ASSEMBLY			PROJECT NAME: LOCKING PROTOTYPE	
DRAWN BY: JOSH BLANK		DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
SCALE: 0.250	REV: 0	SHEET NUMBER: 1 OF 3	PART NUMBER: LP-21-006	

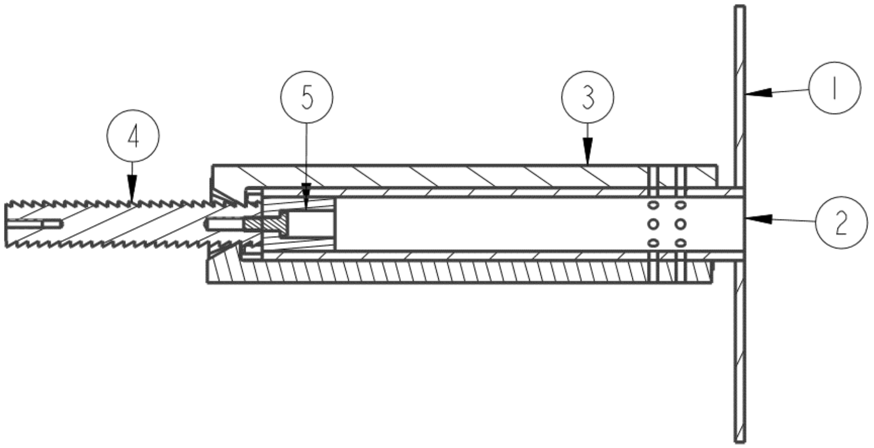


UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

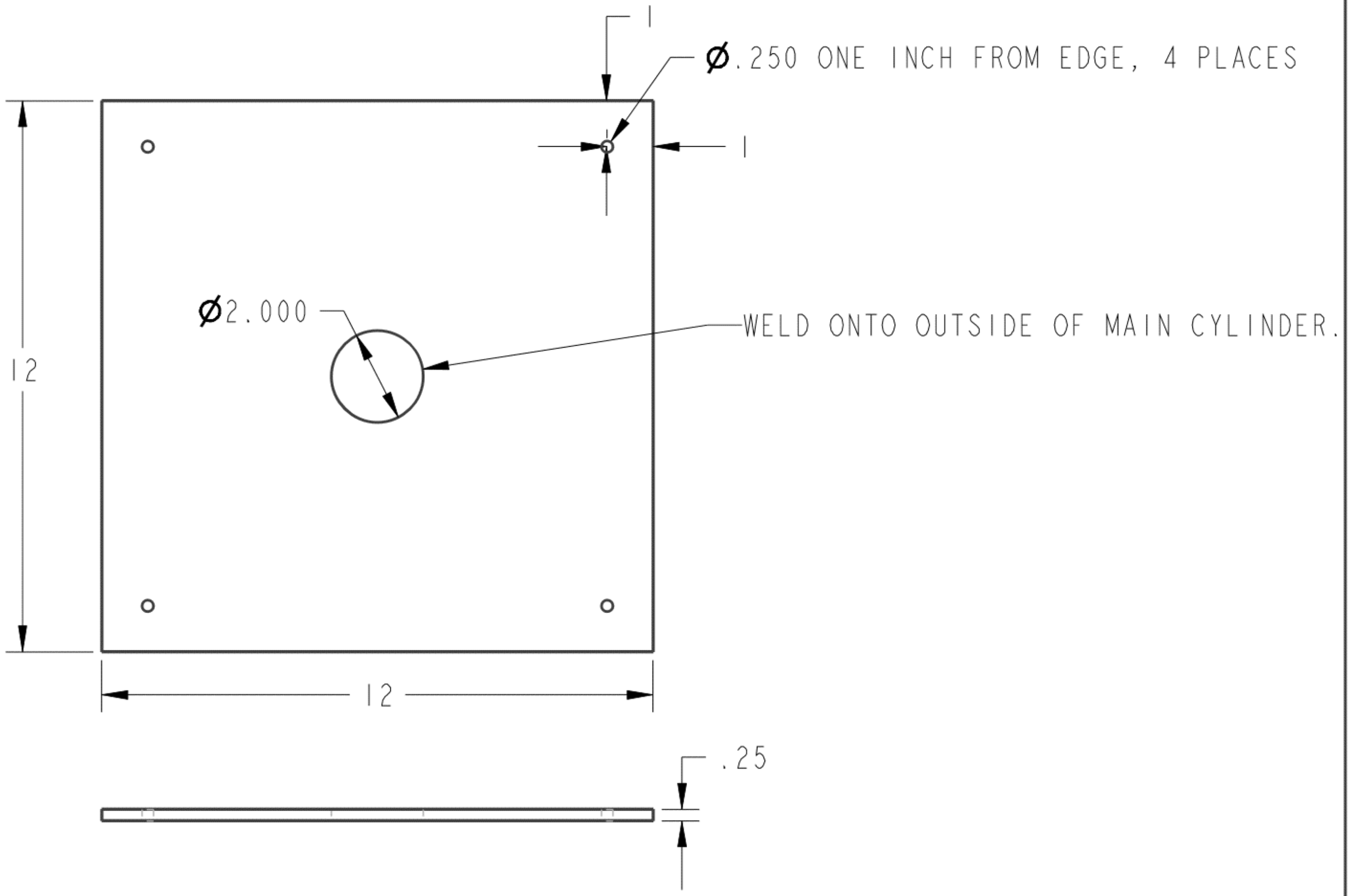
PART NAME: ASSEMBLY		PROJECT NAME: LOCKING PROTOTYPE		
DRAWN BY: JOSH BLANK		DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
SCALE: 0.250	REV: 0	SHEET NUMBER: 2 OF 3	PART NUMBER: LP-21-006	





SECTION A-A
SCALE 0.250

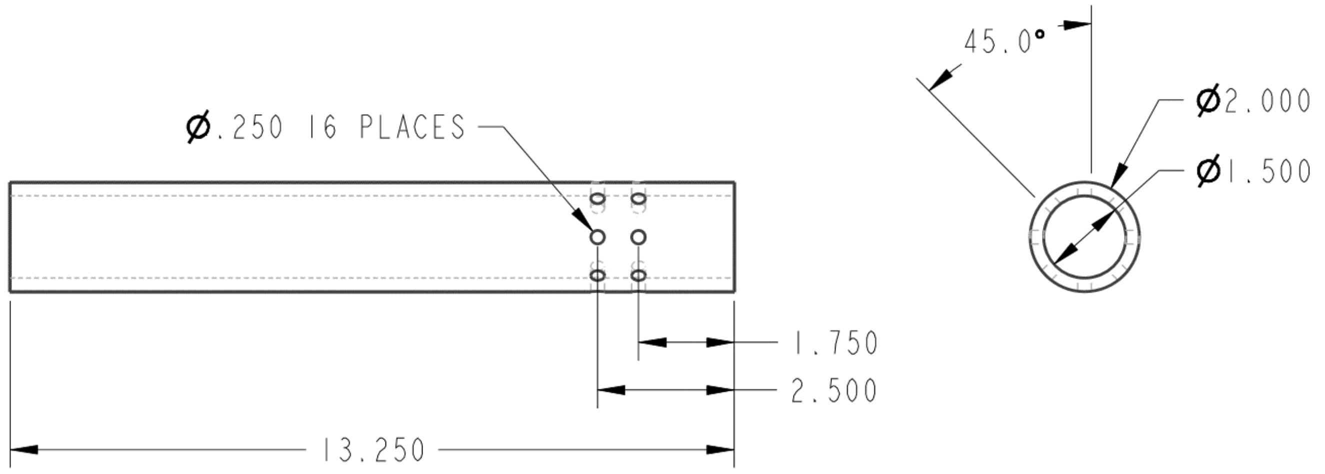
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: ASSEMBLY		PROJECT NAME: LOCKING PROTOTYPE	
	DRAWN BY: JOSH BLANK	DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
	SCALE: 0.250	REV: 0	SHEET NUMBER: 3 OF 3	PART NUMBER: LP-21-006



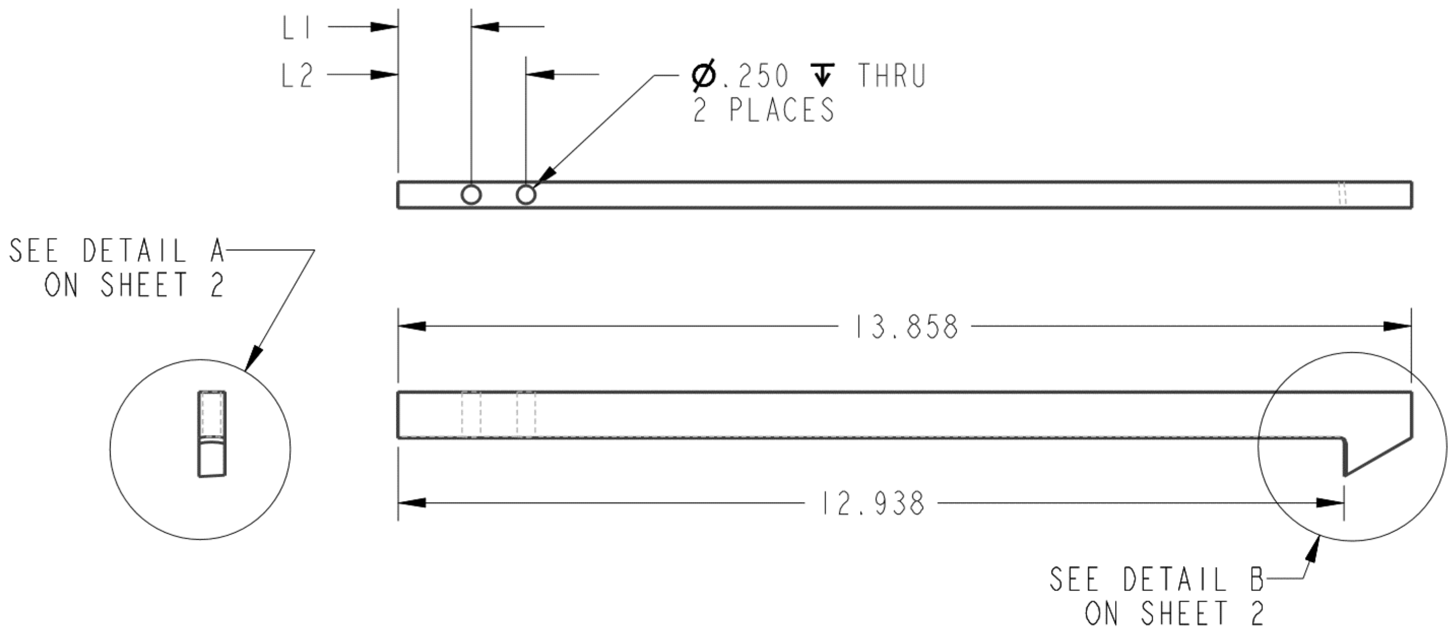
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: BACK PLATE		PROJECT NAME: LOCKING PROTOTYPE	
DRAWN BY: JOSH BLANK	DATE: 3/3/21	SIZE: A	MATERIAL: STEEL PLATE
SCALE: 0.333	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: LP-21-001

CLYINDER HAS 2 ROWS OF Ø.250 HOLES,
AT 45° FROM EACH OTHER FOR A TOTAL
OF 16 HOLES



UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES	PART NAME: MAIN CYLINDER			PROJECT NAME: LOCKING PROTOTYPE	
TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JOSH BLANK		DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
	SCALE: 0.375	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: LP-21-002	



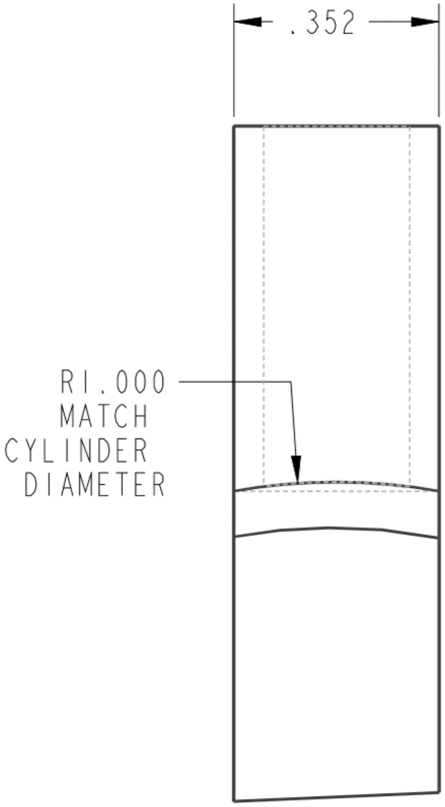
PAWL #	L1	L2
1	1.000	1.750
2	0.963	1.713
3	0.926	1.676
4	0.889	1.639
5	0.852	1.602
6	0.815	1.565
7	0.778	1.528
8	0.741	1.491

FABRICATE EIGHT PAWL
ARMS WITH STAGGARED
MOUNTING HOLES
ACCORDING TO TABLE

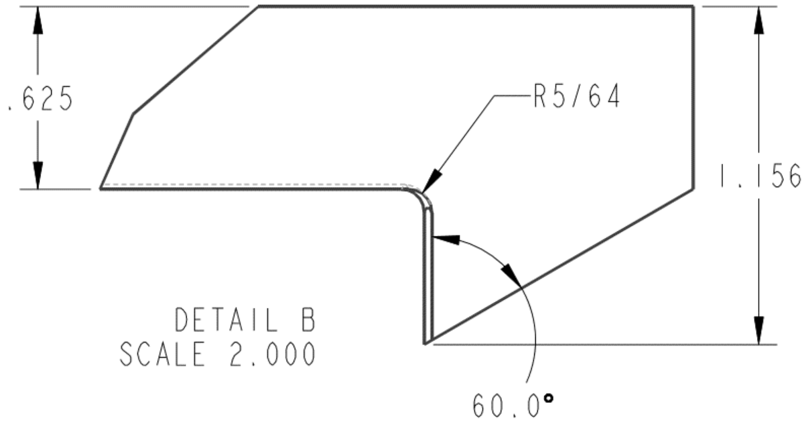
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: PAWL ARM			PROJECT NAME: LOCKING PROTOTYPE	
DRAWN BY: JOSH BLANK		DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
SCALE: 0.500	REV: 0	SHEET NUMBER: 1 OF 3	PART NUMBER: LP-21-003	



DETAIL A
SCALE 4.000

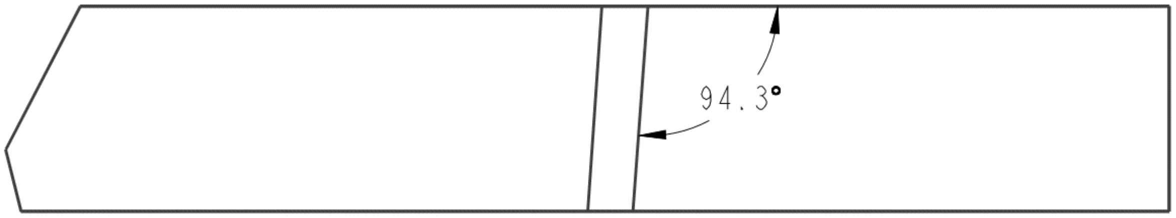


DETAIL B
SCALE 2.000

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: PAWL ARM			PROJECT NAME: LOCKING PROTOTYPE	
DRAWN BY: JOSH BLANK		DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
SCALE: 0.500	REV: 0	SHEET NUMBER: 2 OF 3	PART NUMBER: LP-21-003	



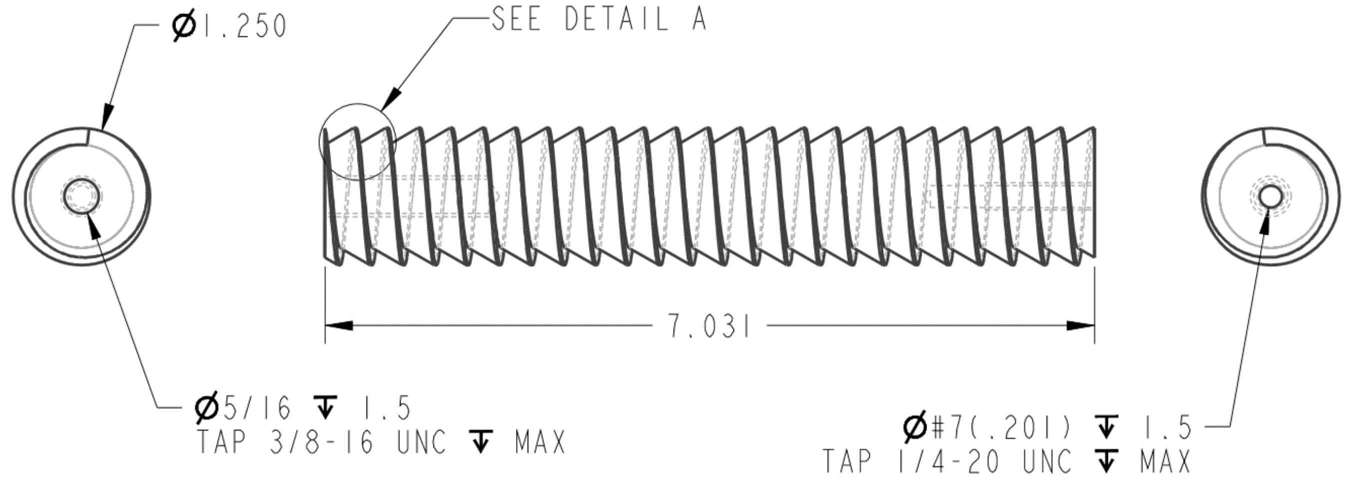
DETAIL C
SCALE 4.000

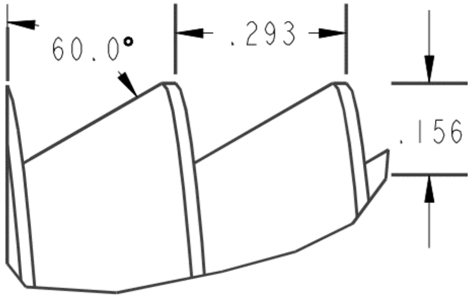
TOOTH FLAT ON PAWL ARM IS ANGLED TO MATCH THE PITCH OF THE SCREW

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: PAWL ARM		PROJECT NAME: LOCKING PROTOTYPE	
DRAWN BY: JOSH BLANK	DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
SCALE: 0.500	REV: 0	SHEET NUMBER: 3 OF 3	PART NUMBER: LP-21-003

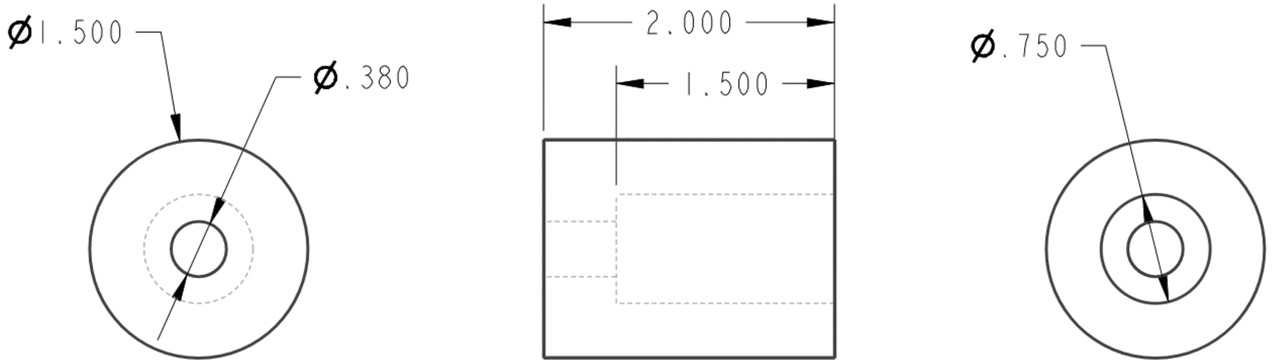




DETAIL A
SCALE 4.000

SCREW HAS A RIGHT TRIANGULAR PROFILE,
A PITCH OF 0.293 AND A DEPTH OF 0.156

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN INCHES TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PART NAME: SCREW			PROJECT NAME: LOCKING PROTOTYPE
	DRAWN BY: JOSH BLANK	DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
	SCALE: 0.750	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: LP-21-004



UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES

TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PART NAME: SLIDER BLOCK		PROJECT NAME: LOCKING PROTOTYPE	
DRAWN BY: JOSH BLANK	DATE: 3/3/21	SIZE: A	MATERIAL: STEEL
SCALE: 1.000	REV: 0	SHEET NUMBER: 1 OF 1	PART NUMBER: LP-21-005

Appendix H: Calculations

Given variables:

Lander mass (m): 25,000 kg

Max impact speed (v): 3.408 m/s

Screw Coefficient of Friction (μ_s): 0.6

Designed Variables:

Spring Stiffness (k): 6.65e5 N/m

Ratchet Tooth Area (A_t): 0.00145 m^2

Screw Radius (r): 0.102 m

Number of Pawl Arms (n): 8

Calculated Values:

Max Impact energy (KE): 1.45e5 J, Eqn. 1.

$$KE = 0.5*m*v^\wedge 2 \tag{1}$$

Max Spring Deflection (x): 0.661 m, Eqn. 2.

$$x = \sqrt{\frac{2 * KE}{k}} \tag{2}$$

Max Spring Force (F_{main}): 4.39e5 N, Eqn. 3.

$$F_{main} = k * x \tag{3}$$

Ratchet Tooth Stress (σ_t): 151 MPa, Eqn. 4.

$$\sigma_t = \frac{\mathrm{F}_{\mathrm{main}}}{A_t} \tag{4}$$

Motor Torque (τ_m): 1.79e4 Nm, Eqn. 5.

$$\tau_{\mathrm{m}} = \mathrm{F}_{\mathrm{main}} * \mu_s * r \tag{5}$$

FEA Analyses

FEA analyses were done for the pawl arm during the inward ratcheting motion, Figure H-1, and while the pawl arm is locking the main spring at maximum compression, Figure H-2. The maximum stress during the inward motion nears the yield strength of the material, but this assumes the pawl arm is being deflected over 2 inches which will not be the case. The pawl arms will only be deflected 0.851 inches outward during the ratcheting motion. The maximum stress for the locking action is well below the yield strength of the material.

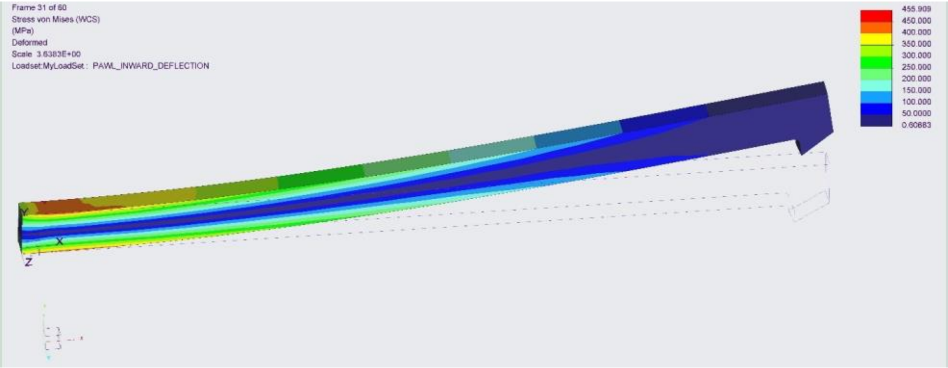


Figure H-1. The Von Mises stresses for the pawl arm during the inward ratcheting motion.

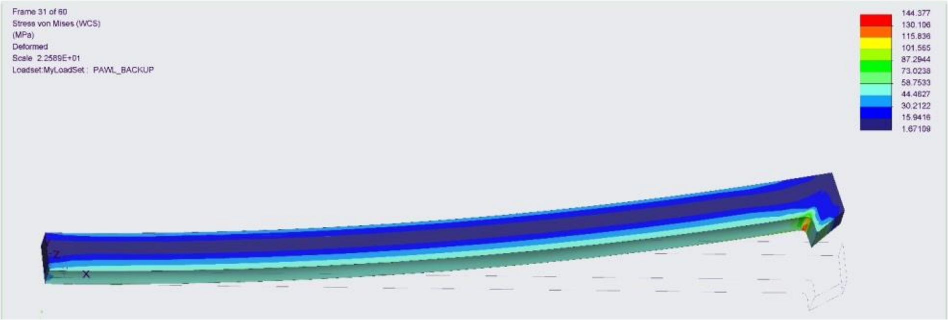


Figure H-2. The Von Mises stresses for the pawl arm during the locking action.

Appendix I: Risk Assessment

The following pages contain the risk assessment that was performed in the fall semester. Not all tests were carried out.

FAMU-FSU College of Engineering
Project Hazard Assessment Policy and Procedures

INTRODUCTION

University laboratories are not without safety hazards. Those circumstances or conditions that might go wrong must be predicted and reasonable control methods must be determined to prevent incident and injury. The FAMU-FSU College of Engineering is committed to achieving and maintaining safety in all levels of work activities.

PROJECT HAZARD ASSESSMENT POLICY

Principal investigator (PI)/instructor are responsible and accountable for safety in the research and teaching laboratory. Prior to starting an experiment, laboratory workers must conduct a project hazard assessment (PHA) to identify health, environmental and property hazards and the proper control methods to eliminate, reduce or control those hazards. PI/instructor must review, approve, and sign the written PHA and provide the identified hazard control measures. PI/instructor continually monitor projects to ensure proper controls and safety measures are available, implemented, and followed. PI/instructor are required to reevaluate a project anytime there is a change in scope or scale of a project and at least annually after the initial review.

PROJECT HAZARD ASSESSMENT PROCEDURES

It is FAMU-FSU College of Engineering policy to implement followings:

1. Laboratory workers (i.e. graduate students, undergraduate students, postdoctoral, volunteers, etc.) performing a research in FAMU-FSU College of Engineering are required to conduct PHA prior to commencement of an experiment or any project change in order to identify existing or potential hazards and to determine proper measures to control those hazards.
2. PI/instructor must review, approve and sign the written PHA.
3. PI/instructor must ensure all the control methods identified in PHA are available and implemented in the laboratory.
4. In the event laboratory personnel are not following the safety precautions, PI/instructor must take firm actions (e.g. stop the work, set a meeting to discuss potential hazards and consequences, ask personnel to review the safety rules, etc.) to clarify the safety expectations.
5. PI/instructor must document all the incidents/accidents happened in the laboratory along with the PHA document to ensure that PHA is reviewed/modified to prevent reoccurrence. In the event of PHA modification a revision number should be given to the PHA, so project members know the latest PHA revision they should follow.
6. PI/instructor must ensure that those findings in PHA are communicated with other students working in the same laboratory (affected users).

7. PI/instructor must ensure that approved methods and precautions are being followed by :
    a. Performing periodic laboratory visits to prevent the development of unsafe practice.
    b. Quick reviewing of the safety rules and precautions in the laboratory members meetings.
    c. Assigning a safety representative to assist in implementing the expectations.
    d. Etc.
8. A copy of this PHA must be kept in a binder inside the laboratory or PI/instructor’s office (if experiment steps are confidential).

Project Hazard Assessment Worksheet

PI/instructor: Shayne McConomy	Phone #: (850)-410-6624	Dept.: ME	Start Date:	Revision number: 0
Project: 515: Reusable Shock Absorber For The New Lunar Lander			Location(s): CoE	
Team member(s):Josh Blank, Melanie Porter, Tristan Jenkins, Matt Fowler, Alex Noll			Phone #:	Email:

Experiment Steps	**Location**	**Person assigned**	**Identify hazards or potential failure points**	**Control method**	**PPE**	**List proper method of hazardous waste disposal, if any.**	**Residual Risk**	**Specific rules based on the residual risk**
Installing/removing springs	C.O.E.	Alex Noll	Struck by hazard when compressing / extending springs	1,3	Work gloves, eye protection, close toed shoes	N/A	HAZARD: 3 CONSEQ: significant Residual: medium high	Stand clear of spring trajectory. Only handle unstretched springs[2]
Testing	C.O.E.	Alex Noll	Struck by hazard with swinging weight.	1		N/A	HAZARD: 1 CONSEQ: Significant Residual: Low-medium	Stand clear of swing area, do not approach until pendulum is at rest. [1] [2] [3]
	C.O.E.	Josh Blank	Entanglement hazard with moving parts	1,3	Work gloves	N/A	HAZARD: 2 CONSEQ: Significant Residual: Medium	Stand clear of prototype during testing. [1] [2]
	C.O.E.	Alex Noll	Impact from spring release	1,3	Eye protection, testing barrier	N/A	HAZARD: 2 CONSEQ: Significant Residual: Medium	Stand clear of prototype during testing[1] [2]

Testing (continued)	C.O.E.	Matt Fowler	Noise hazard from impact / releasing spring	3	Plugs and/or muffs	N/A	HAZARD: 1 CONSEQ: Minor Negligible Residual: Low	Wear hearing protection at all times while testing.
	C.O.E.	Matt Fowler	Electric shock	1,2,3	Rubber gloves	N/A	HAZARD: 2 CONSEQ: Moderate Residual: Low Med	Use low voltage <30VDC, turn off power before touching wires [6]
	C.O.E.	Melanie Porter	Struck by hazard caused by high magnetic field	1,3		N/A	HAZARD: 4 CONSEQ: Significant Residual: Med-High	Remove piercings, clear area of loose ferritic material.
Welding assembly	C.O.E.	Josh Blank	Radiation / burn hazards associated with welding	2,3	Welding shades / masks, welding gloves, long sleeve shirts	N/A	HAZARD: 5 CONSEQ: Significant Residual: High	Let the machine shop do the welding when possible. [4] [5]
Machining materials	C.O.E.	Melanie Porter	Struck by, entanglement, sharp surfaces	2,3	Safety glasses, appropriate clothing	N/A	HAZARD: 3 CONSEQ: Significant Residual: Med High	Let the machine shop do the machining when possible[1] [2]

All	C.O.E.	Tristan Jenkins	Drop hazard associated with heavy components	2,3	Closed toe/steel toe shoes	N/A	HAZARD: 4 CONSEQ: Significant Residual: Med-high	At least two people required when handling prototype[3]
	C.O.E.	Tristan Jenkins	Physical, associated with poor posture and sitting for long periods of time	2		N/A	HAZARD: 1 CONSEQ: Minor Residual: Low	Short sessions and break times

Principal investigator(s)/ instructor PHA: I have reviewed and approved the PHA worksheet.

Name	**Signature**	**Date**	**Name**	**Signature**	**Date**

Team members: I certify that I have reviewed the PHA worksheet, am aware of the hazards, and will ensure the control measures are followed.

Name	**Signature**	**Date**	**Name**	**Signature**	**Date**
Josh Blank	Josh Blank	12/3/2020	Alex Noll	Alex Noll	12/3/2020
Matthew Fowler	Matthew Fowler	12/3/2020	Melanie Porter	Melanie Porter	12/3/2020
Tristan Jenkins	Tristan Jenkins	12/3/2020			

Copy this page if more space is needed.

References

[1] OSHA Standard 1910.212, *General requirements for all machines.* United States Department of Labor. Accessed on 12/3/20 https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.212

[2] OSHA Standard 1910.133, *Eye and face protection.* United States Department of Labor. Accessed on 12/3/20 https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.133

[3] OSHA Standard 1910.136, *Foot protection.* United States Department of Labor. Accessed on 12/3/20 https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.136

[4] OSHA Standard 1910.252, *Welding General requirements.* United States Department of Labor. Accessed on 12/3/20 https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.252

[5] OSHA Standard 1910.254, *Arc welding and cutting.* United States Department of Labor. Accessed on 12/3/20 https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.254

[6] OSHA Standard 1910.303, *Electrical General requirements.* United States Department of Labor. Accessed on 12/3/20 https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.303

DEFINITIONS:

Hazard: Any situation, object, or behavior that exists, or that can potentially cause ill health, injury, loss or property damage e.g. electricity, chemicals, biohazard materials, sharp objects, noise, wet floor, etc. OSHA defines hazards as "*any source of potential damage, harm or adverse health effects on something or someone*". A list of hazard types and examples are provided in appendix A.

Hazard control: Hazard control refers to workplace measures to eliminate/minimize adverse health effects, injury, loss, and property damage. Hazard control practices are often categorized into following three groups (priority as listed):

1. **Engineering control:** physical modifications to a process, equipment, or installation of a barrier into a system to minimize worker exposure to a hazard. Examples are ventilation (fume hood, biological safety cabinet), containment (glove box, sealed containers, barriers), substitution/elimination (consider less hazardous alternative materials), process controls (safety valves, gauges, temperature sensor, regulators, alarms, monitors, electrical grounding and bonding), etc.
2. **Administrative control:** changes in work procedures to reduce exposure and mitigate hazards. Examples are reducing scale of process (micro-scale experiments), reducing time of personal exposure to process, providing training on proper techniques, writing safety policies, supervision, requesting experts to perform the task, etc.
3. **Personal protective equipment (PPE):** equipment worn to minimize exposure to hazards. Examples are gloves, safety glasses, goggles, steel toe shoes, earplugs or muffs, hard hats, respirators, vests, full body suits, laboratory coats, etc.

Team member(s): Everyone who works on the project (i.e. grads, undergrads, postdocs, etc.). The primary contact must be listed first and provide phone number and email for contact.

Safety representative: Each laboratory is encouraged to have a safety representative, preferably a graduate student, in order to facilitate the implementation of the safety expectations in the laboratory. Duties include (but are not limited to):

- Act as a point of contact between the laboratory members and the college safety committee members.
- Ensure laboratory members are following the safety rules.
- Conduct periodic safety inspection of the laboratory.
- Schedule laboratory clean up dates with the laboratory members.
- Request for hazardous waste pick up.

Residual risk: Residual Risk Assessment Matrix are used to determine project's risk level. The hazard assessment matrix (table 1) and the residual risk assessment matrix (table2) are used to identify the residual risk category.

The instructions to use hazard assessment matrix (table 1) are listed below:

1. Define the workers familiarity level to perform the task and the complexity of the task.
2. Find the value associated with familiarity/complexity (1 – 5) and enter value next to: HAZARD on the PHA worksheet.

Table 1. Hazard assessment matrix.

		Complexity		
		Simple	Moderate	Difficult
Familiarity Level	Very Familiar	1	2	3
	Somewhat Familiar	2	3	4
	Unfamiliar	3	4	5

The instructions to use residual risk assessment matrix (table 2) are listed below:

1. Identify the row associated with the familiarity/complexity value (1 – 5).
2. Identify the consequences and enter value next to: CONSEQ on the PHA worksheet. Consequences are determined by defining what would happen in a worst case scenario if controls fail.
    a. Negligible: minor injury resulting in basic first aid treatment that can be provided on site.
    b. Minor: minor injury resulting in advanced first aid treatment administered by a physician.
    c. Moderate: injuries that require treatment above first aid but do not require hospitalization.
    d. Significant: severe injuries requiring hospitalization.
    e. Severe: death or permanent disability.
3. Find the residual risk value associated with assessed hazard/consequences: Low –Low Med – Med– Med High – High.
4. Enter value next to: RESIDUAL on the PHA worksheet.

Table 2. Residual risk assessment matrix.

Assessed Hazard Level	**Consequences**				
	Negligible	Minor	Moderate	Significant	Severe
5	Low Med	Medium	Med High	High	High
4	Low	Low Med	Medium	Med High	High
3	Low	Low Med	Medium	Med High	Med High
2	Low	Low Med	Low Med	Medium	Medium
1	Low	Low	Low Med	Low Med	Medium

Specific rules for each category of the residual risk:

Low:

- Safety controls are planned by both the worker and supervisor.

- Proceed with supervisor authorization.

Low Med:
- Safety controls are planned by both the worker and supervisor.
- A second worker must be in place before work can proceed (buddy system).
- Proceed with supervisor authorization.

Med:
- After approval by the PI, a copy must be sent to the Safety Committee.
- A written Project Hazard Control is required and must be approved by the PI before proceeding. A copy must be sent to the Safety Committee.
- A second worker must be in place before work can proceed (buddy system).
- Limit the number of authorized workers in the hazard area.

Med High:
- After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
- A written Project Hazard Control is required and must be approved by the PI and the Safety Committee before proceeding.
- Two qualified workers must be in place before work can proceed.
- Limit the number of authorized workers in the hazard area.

High:
- The activity will not be performed. The activity must be redesigned to fall in a lower hazard category.

Appendix A: Hazard types and examples

Types of Hazard	**Example**
Physical hazards	Wet floors, loose electrical cables objects protruding in walkways or doorways
Ergonomic hazards	Lifting heavy objects Stretching the body Twisting the body Poor desk seating
Psychological hazards	Heights, loud sounds, tunnels, bright lights
Environmental hazards	Room temperature, ventilation contaminated air, photocopiers, some office plants acids
Hazardous substances	Alkalis solvents

Biological hazards	Hepatitis B, new strain influenza
Radiation hazards	Electric welding flashes Sunburn
Chemical hazards	Effects on central nervous system, lungs, digestive system, circulatory system, skin, reproductive system. Short term (acute) effects such as burns, rashes, irritation, feeling unwell, coma and death. Long term (chronic) effects such as mutagenic (affects cell structure), carcinogenic (cancer), teratogenic (reproductive effect), dermatitis of the skin, and occupational asthma and lung damage.
Noise	High levels of industrial noise will cause irritation in the short term, and industrial deafness in the long term.
Temperature	Personal comfort is best between temperatures of 16°C and 30°C, better between 21°C and 26°C. Working outside these temperature ranges: may lead to becoming chilled, even hypothermia (deep body cooling) in the colder temperatures, and may lead to dehydration, cramps, heat exhaustion, and hyperthermia (heat stroke) in the warmer temperatures.
Being struck by	This hazard could be a projectile, moving object or material. The health effect could be lacerations, bruising, breaks, eye injuries, and possibly death.
Crushed by	A typical example of this hazard is tractor rollover. Death is usually the result
Entangled by	Becoming entangled in machinery. Effects could be crushing, lacerations, bruising, breaks amputation and death.
High energy sources	Explosions, high pressure gases, liquids and dusts, fires, electricity and sources such as lasers can all have serious effects on the body, even death.
Vibration	Vibration can affect the human body in the hand arm with `white-finger' or Raynaud's Syndrome, and the whole body with motion sickness, giddiness, damage to bones and audits, blood pressure and nervous system problems.
Slips, trips and falls	A very common workplace hazard from tripping on floors, falling off structures or down stairs, and slipping on spills.
Radiation	Radiation can have serious health effects. Skin cancer, other cancers, sterility, birth deformities, blood changes, skin burns and eye damage are examples.
Physical	Excessive effort, poor posture and repetition can all lead to muscular pain, tendon damage and deterioration to bones and related structures
Psychological	Stress, anxiety, tiredness, poor concentration, headaches, back pain and heart disease can be the health effects
Biological	More common in the health, food and agricultural industries. Effects such as infectious disease, rashes and allergic response.

Project Hazard Control- For Projects with Medium and Higher Risks

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Melanie Porter	954-330-7735	map17c@my.fsu.edu
Faculty Mentor	**Phone number**	**e-mail**
Keith Larson	850-410-6108	larson@eng.famu.fsu.edu

Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

Installing/Removing Springs: Work gloves, eye protection, and closed toed shoes will be worn by all team members. Spring will only be handled when unstretched. The spring will be activated remotely. No team members will stand within a 180-degree arc around the direction of the spring's trajectory. Outside of this arc, team members will not get within 3 ft of the device while the spring is compressed.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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Safety review signatures

Team member	**Date**	**Faculty mentor**	**Date**
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Tristan Jenkins	12/03/20		
Melanie Porter	12/03/20		
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Testing, Entanglement with Moving Parts: Team members must stand clear of prototype during testing. Only those with an active duty in the testing process should be close only to perform that duty. Others must be behind a protective barrier or behind a three-foot radius mark from the test subject. Team members must remove dangling piercings and avoid loose clothing.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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Testing, Impact from Spring Release: Eye protection will be worn by all team members. Team members must stand behind a testing barrier.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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Testing, Struck By Hazard caused by magnetic field: Ferric materials not part of the project will be moved to a minimum of 6 ft away from the device when it is powered. In addition, team members will wear no jewelry and place their watches and other personal electronics at least 6 ft away from the powered device.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

Welding Assembly: Professionals within the machine shop will complete this process and take all necessary safety precautions within the scope of their job.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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Rewrite the project steps to include all safety measures taken for each step or combination of steps. Be specific (don't just state "be careful").

Machining Materials: Professionals within the machine shop will complete this process and take all necessary safety precautions within the scope of their job.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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All Times, drop hazard: Whenever the prototype will be moved at least two people should handle it. Care should be taken to evenly balance the weight between the two members and be cognizant of the area within the fall radius. Close toed shoes and leather gloves should be worn at all times when moving the prototype.

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

If there is an emergency, the rest of the team will contact Mr. Larson or Dr. McConomy, and if need be, 911. If an accident incapacitates a team member, their emergency contact will be called, and any medical decisions will be made by their emergency contact. In this scenario, the incapacitated team member will not be left alone while Mr. Larson and Dr. McConomy will be called immediately after the emergency contact has been called.

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