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Team 501: Psyche Sample Acquisition

Author1 Name: Michael B. Gregory;Author2 Name: Conner J Holmes;Author3 Name: Claudia A. Irausquin;Author4 Name: Jake L. Marcus;Author5 Name: Janna L. Rhodes; Author6 Name: Jerry M. Richardson
FAMU-FSU College of Engineering 2525 Pottsdamer St. Tallahassee, FL. 32310

Abstract

We are designing a system to collect metal and rock samples from the surface of asteroid Psyche. This work supports NASA's Psyche mission, which studies a rare, metal-rich asteroid that may be the exposed core of an early planetesimal. Learning about Psyche can help scientists understand how planets form and evolve. Our goal is to gather useful samples from different surfaces and keep them clean and secure. We work with Senior Design Team 502 which focuses on bringing the samples back to Earth. Because of this, our system must pass each sample safely and reliably to the return system. Our system collects samples, stores them, and prepares them for transfer. We are designing a tool that breaks loose surface material, captures it, and places it into a sealed container. The system must also work in space, where there is almost no gravity, extreme cold, and no air. To meet these challenges, we studied past missions such as OSIRIS-REx and the Mars rover sampling systems. We then adapt the methods in these missions to a metal-rich surface. We build and test a prototype on Earth using materials and setups that match what we expect to find on Psyche. This prototype is made up of a tool that combines drilling with a short gas release that can collect both loose dust and solid pieces. Using this method limits sample loss and reduces mixing between sites. The design stores several samples, keeps each one sealed, and measures how much material is collected. The project shows a small, automated system that can support future missions to metal-rich asteroids. The system provides a clear path for collecting clean, well-preserved samples that can help scientists learn how planets form and change over time.

Keywords: Sample Collection, Storage, Psyche

Disclaimer

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We would also like to thank our advisor, Dr. Shreyas Balachandran. Dr. Balachandran has provided us with guidance on material and tool selection, continuously reviewed our progress, gave helpful feedback for many of our deliverables, and assisted us in obtaining samples that accurately act as a Psyche surface simulant. He played an essential role in developing our sampling system in the right direction, as well as pointing out research topics that helped us advance along the way. His mentorship and support were instrumental in shaping both the technical direction and overall success of this project.

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Notation

NASA	National Aeronautics ans Space Administration
OSIRIS-Rex	Reference NASA mission
ASU	Arizona State University
501	Sampling and Caching Team
502	Transfer Team
JPL	Jet Propulsion Laboratory
M-Type	Metallic asteroid composed of primarily iron-nickel
EDL	Entry Descent Landing
SCAMPER	Substitute Combine Adapt Modify Put to use Eliminate Reverse
HoQ	House of Quality
AHP	Analytic Hierarchy Process
CR	Consistency Ratio
VDR	Virtual Design Review
CAD	Computer Aided Design
FAMU-FSU COE	FAMU-FSU College of Engineering
COMSOL	Flow Simulation Software
ABAQUS	FEA Software
TA	Teaching Assistant
PI	Primary Investigator/Instructor
PHA	Project Hazard Assessment
FEA	Finite Element Analysis

Chapter One: EML 4551C

1.1 Project Scope

1.1.1 Project Description

The objective of this project is to acquire and cache samples across multiple surface types on asteroid (16) Psyche. This effort is coordinated with Team 502, who focuses on sample retrieval and Earth return.

Psyche is a large, metal-rich asteroid in the main belt and the target of NASA's Psyche mission; the spacecraft on route to study it. This capstone project is part of the NASA Psyche Capstone program at Arizona State University (ASU), sponsored by Dr. Cassie Bowman. The Psyche mission is led by ASU, with NASA's Jet Propulsion Laboratory (JPL) responsible for mission management, operations, and management.

Psyche may be the remnant of a differentiated body's exposed core. Sampling its surface can test hypotheses about planetary differentiation, space weathering of metals, and metal-silicate mixing. These science goals drive our design toward multi-terrain sampling in low gravity with clean, cache ready sample handing.

1.1.2 Key Goals

Team 501 has five key goals, listed below:

1. Develop a Sampling System
    - Design and prototype a sampling mechanism capable of collecting material from the range of hypothesized Psyche surfaces. These include flat metallic surfaces, mixed metal/rock debris fields, rough or high-relief terrain, and metallic crater walls.
2. Develop a Caching System
    - Create a secure caching system that can safely contain collected samples in compliance with NASA planetary protection and contamination-prevention guidelines.
3. Enable Sample Transfer for Retrieval
    - Cached samples shall be retrievable by Team 502 while minimizing the risk of damage or contamination.

4. Ensure a variety of samples can be collected
    - Samples may differ in chemical composition; ideally samples will be various types of metals as opposed to multiple samples of the same metal.
5. Develop and Demonstrate a Scalable Prototype
    - Build a scale model of the integrated sampling and caching system. Conduct simulations and physical testing under conditions analogous to Psyche's low-gravity, metallic surface environment to validate functionality and scalability.

1.1.3 Market

The primary market for this project is planetary small-body acquisition teams planning metal-rich (Psyche-class) asteroid missions (ASU/NASA/JPL mission concept teams) - including payload leads, sampling PI's, and system engineers who specify, evaluate, and integrate sampling hardware.

The secondary market for this project includes spacefaring operations and some industries on Earth. This includes any future missions by NASA or other companies like SpaceX to celestial bodies where sampling is required. The Psyche asteroid is categorized as an M-type asteroid, meaning that it is primarily made of metals. As of this writing, no sampling missions to type-M asteroids have been conducted, making the challenges this project faces to be unique. While the field is still underdeveloped, the metal content of the Psyche asteroid makes it one of the prime targets for asteroid mining. Missions conducted by Space Forge or other similar asteroid mining companies to the Psyche asteroid and other M-type asteroids will be greatly influenced by the challenges and successes of this project.

The storage system for Psyche samples taken could influence other storage-related companies on Earth. After extraction, the samples need to stay as close to their original state as possible when returning to Earth. Storage-related companies may use the performance of the conservation of Psyche samples as inspiration for the creation of extreme condition storage.

Sampling the Psyche asteroid may impact the mining industry as well. Any technological innovations to assist in sampling may inspire the development and optimization of mining tools. This could be in the form of a mining tool that operates in extremely cold environments or a reduction in the energy consumption of current tools.

1.1.4 Assumptions

- Psyche has a density of ~3400-4000kg/m^3.
- Psyche has a mass of ~2.28x10^19 kg.
- Psyche is ~279 x 232 x 189 kilometers in size.
- Psyche is composed of 30 to 60% metal by volume.
- Assume the sampler is already delivered to Psyche and mounted on a host; EDL (entry-descent-landing), mobility, and delivery to Psyche are out of scope.
- Assume very low gravity ~0.144m/s^2 and vacuum (no atmosphere).
- All specifications and data in SI units.
- The materials sampled will vary from iron-nickel metal to silicate rich materials and can include gold or platinum.
- Given a lack of atmosphere, assume wide thermal swings and abrasive metallic/rocky particulates.
- Mechanism/design will have necessary power.
- Command-level sequences with onboard checks; no real-time teleoperation.

1.1.5 Stakeholders

Table 1 ***Stakeholder Breakdown***

	Investors	Decision- Makers	Advisors	Receivers
Cassie Bowman		X	X	X
Shreyas Balachandran			X	
Dr. McConomy			X	
Arizona State University	X		X	X
NASA	X			X

1.2 Customer Needs

1.2.1 Customer Needs Table

The following table summarizes the discussion with Dr. Cassie Bowman that provided a clearer understanding of the project objective. Customer statements were discussed and interpreted to find key requirements, constraints, and expectations for what was needed for system operation:

Table 2 ***Customer Needs***

Question	Customer Statement	Interpreted Need
Will we be creating a rover with the extraction system?	You can use a rover from previous missions as a base for the sampling.	The system operates as a hosted payload already on the asteroid.
What are the current estimates of seasonal and diurnal temperature variations on the surface of the asteroid?	For this question, please take a look at the Bierson 2022 paper in the Psyche Research Papers folder.	Estimate for Seasonal is >100K. The estimate for is Diurnal <10K. The system survives large temperature swings.
Can we assume a specific season for the mission? Can we assume a specific region?	Yes, you can determine this. Yes.	The mission can take place in any season we choose; also, any specific region of the asteroid.
Are we assuming that the sampling system is already on the asteroid?	Yes, assume the sample is delivered and mounted on host. Operations are command-level sequences.	The system operates as a hosted payload already on the asteroid.
What sample type (metal, metal-silicate, regolith, sub surface) should take priority?	You should collect a variety of samples to accurately reflect the composition of the asteroid.	The system collects a variety of materials across distinct surface types.

Do we have to follow NASA's current planetary protection provisions for robotic extraterrestrial missions?	It is a good idea, though Psyche is not in the most restrictive category.	The system follows the planetary protection requirements that are defined by the mission type.
How much sample should we extract from Psyche?	Benchmark quantity of material collected based on similar missions. Use volume as a measurement.	The quantity of samples to extract is close to that of similar missions with respect to volume.
What is the size limit of our prototype?	Up to design team, this will be something to be decided upon with T502.	The size of the system is compatible with T502's device.
What is the weight limit of our prototype?	Up to design team, use benchmarking and justify your decision.	The weight of the system is compatible with T502's device.
Does our prototype simulation need to function with both Earth's gravity and Psyche's gravity?	A physical prototype should only use Earth's gravity. A simulation should ideally be in Psyche's gravity.	The physical prototype functions with Earth's gravity, and any system simulations function with Psyche's gravity.
How many samples should the device extract? Continuous extraction or a max number of extractions per mission?	Use benchmarking with previous missions to decide this.	Sample extraction requirements are like those of previous missions.
Will the device need to collect data while extracting samples?	That would be ideal, but likely outside of your scope.	The device can collect extracting data.

Should our prototype take samples from multiple locations?	It is up to you, justify your answer.	The system collects samples across distinct surface types, which vary with location.
As we plan to build a prototype, which surface types should we prioritize for testing? There is a document in the Psyche research folder outlining the construction of simulated test surfaces—should we use this as our reference?	Yes, the document identifies easy-to-access materials for what we might expect to find at Psyche.	The surface types for prototype testing match similarly to the referenced Psyche research document.
How deep into Psyche should we take samples from? (Surface level, subsurface?)	Benchmark off current rover sampling operations on similar surfaces.	The system acquires surface material and subsurface material.

1.2.2 Explanation of Results

The resulting customer statements were obtained from the sponsor via direct communication through Slack. This is the sponsor's preferred method of communication. Additionally, we communicated with team 502 to gather different customer statements. The interpreted needs were refined for the purpose of simplifying the project to prevent scope creep. These needs will impact the targets and metrics for the project, as well as influence the team's ideas during concept generation.

1.3 Functional Decomposition

1.3.1 Functional Decomposition Introduction

Functional decomposition is employed to break down a complex problem into smaller, manageable elements. By examining the purpose of each function, it becomes evident which functions most directly influence the overall success of the project.

To complete this process, a hierarchical tree will be developed to visualize relationships, clarifying how specific subsystems connect to broader functions. This structure enables the reconstruction of the overall function from its constituent parts. In addition, interaction between functions and systems will be examined, allowing the team to identify the most crucial functions within the system.

1.3.2 Data Generation

To break the main system into functions, T501 first analyzed the mission statement and the customer's needs. These shaped the scope of the project, allowing for the creation of sub-systems for the functions to fit into. Using other missions as reference, such as the Perseverance rover and the Philae lander, T501 learned steps necessary for successful sample extraction as well as benchmarks that their project can follow. To relate these steps to the Psyche asteroid, further research was carried out into the properties of the Psyche asteroid's interior makeup as well as its atmosphere. In combining the information from other missions and the research, functions that could achieve the goals of their respective subsystems were created. In addition, the sponsor was contacted to clarify any doubts and prevent out-of-scope functions and subsystems.

1.3.3 Hierarchy Chart and Cross Reference Table

Figure 1 shows a hierarchy chart of the function decomposition. The customer needs were used to develop the primary breakdown of the system.

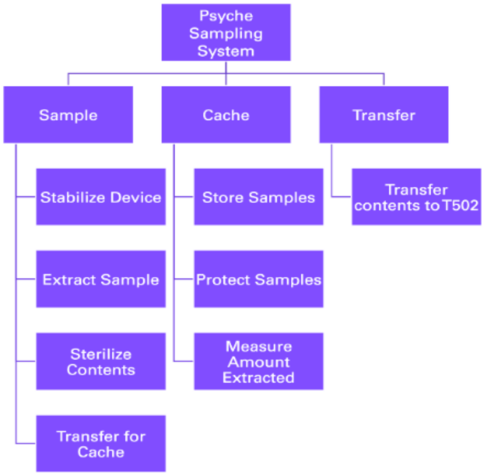


Figure 1 Hierarchy Chart of Functional Decomposition

The hierarchy chart was then used to develop the cross-reference table, shown in Table 1. The primary systems are shown across the second row of the table. The subfunctions are then listed in the first column of the table. By cross-referencing the systems to the breakdown of functions, the most important functions of the overall system can be determined. While each function was placed into a category in the hierarchy chart, there are functions that can fit into multiple systems, and marks on the table represent this. Caching and Sampling were determined to be the most important systems, while the transfer only covered 2 functions of the system.

Table 3 ***Cross-Reference of Functional Decomposition***

Systems				
Functions	Cache	Sample	Transfer	Sum
Store Sample	X	X	X	3
Measure Amount Extracted	X	X		2
Protect Sample	X	X	X	3
Transfer Contents to T502	X		X	2
Stabilize Device		X		1
Extract Sample		X		1
Transfer Sample for Cache	X		X	2

Sterilize Contents	X	X		2
Sum	6	6	4	14

1.3.4 Connection to Systems

The Psyche Caching and Sampling System is divided into three main subsystems which are Sample, Cache, and Transfer. Each subsystem plays an integral role in the overall performance of the system. In a sequential process, Sample is independent of the other two subsystems as Cache depends on the successful completion of Sample, and Transfer depends on the successful completion of Cache.

The first main subsystem is Sample, which covers the system's ability to obtain specimens from the surface of the asteroid Psyche. Sampling handles the processes required to extract a physical sample and is broken down into four smaller functions that include stabilizing the extraction device, extracting the sample, sterilizing the sample, and transferring the sample to the Cache.

The second main subsystem is Cache, which manages the secure storage of the extracted samples in accordance with NASA's Planetary Protection policies. To ensure this process is carried out correctly, the Cache system includes three functions which are storing the collected sample, protecting the sample, and measuring the volume of extracted material.

The final main subsystem is Transfer, which handles the secure delivery of protected samples to Team 502. Transfer has only one function, which is to manage the exchange of collected samples with Team 502.

The order of the subsystems is purposeful, as each subsystem subsequently follows one another. Obtaining the sample if followed by the caching of the sample and thereafter the transfer of the sample. Due to their equal number of relationships to functions, the cross-reference table ranks caching and sampling as equal importance. However, the order of system priority also accounts for the sequence the system follows during execution, leaving Sample as the highest priority. If the system cannot extract samples following the functions, then subsequently, the system will not be able to cache samples. This puts Cache as the second highest priority. Due to it being the final subsystem in the sequence and relating to the least number of functions, Transfer is the lowest priority subsystem in the project.

1.3.5 Smart Integration

The Sample subsystem holds the highest priority rank, but many other functions can affect the success of other system's functions as well. For example, the storage of the sample fits into all three subsystems and are dependent on each other. The size of the sample can change how the sample is stored, measured and transferred, ultimately altering the cache and transfer subsystems. The number of samples extracted can also have the same effect. The subsystems will also have physical means connecting them together, so having a successful method of transferring the samples between each subsystem is key to successful integration of each system.

One of the most critical subsystems of the project is sample protection, as it ensures integrity of the collected material. As shown in Table 1, this function spans across the sample, cache, and transfer subsystems. At every stage of the process, it is essential to preserve the sample's condition, since any contamination or damage could compromise the reliability of future analysis. Closely related is the sterilization of the extraction system. Because the system is intended to sample multiple surfaces, strict sterilization protocols will be required to prevent any cross-contamination at the point of extraction.

Mass flow will need to be accounted for when connecting the subsystems as well. From the extraction of a material, to storing, and later transferring to the sample return team, a mass will need to be held in each step. Conservation of mass when transferring between subsystems, especially after the mass measurement function, will also be factored in, to prevent loss and maintain the integrity of the sample. Preventing contamination after sample extraction can also help maintain the sample through its course of transfer. Energy transfer and energy loss will also be a large factor when powering the overall system and ensuring the system function connections can take place.

The opportunities for innovation are limited due to sampling systems on foreign bodies being a very theorized subject. The mechanics of breaking materials and securing them are well understood. However, there are opportunities for innovation in the ways those operations are executed such as minimizing recoil in microgravity, new drilling techniques, and contamination prevention. The Psyche asteroid, being an untested environment could require innovative techniques in collecting and securing samples as a result.

1.3.6 Actions and Outcomes

The main purpose of this project is to collect and store samples from the surface of the Psyche asteroid that operates within microgravity and near absolute zero temperatures. This is accomplished through the collection mechanism and storage design. A controlled mechanical force dislodges the materials from the metallic and regolith surface while countering the opposing force due to the low gravity to prevent de-stabilization of the sampling system. The materials freed from the asteroid due to the mechanical force are guided to a storage chamber where they are placed into a sealed capsule. The sealed capsule is protected from contamination and ready for pickup by the return system.

1.3.7 Functional Resolution

The smallest element the design system needed is the transfer implementation. While the overall system expands more on the collection of samples on the Psyche asteroid, the transfer of samples to Team 502 ultimately determines the success of the mission. Transfer is the final step that will allow the Psyche team to move onto the next step sample return for the future successful data acquisition. In the end, the simplest possible design must collect a sample from the Psyche asteroid and have it ready for transfer to Team 502.

1.4 Target Summary

1.4.1 Targets and Metrics

Targets and metrics serve as standards for evaluating the success of a design. To validate a design using them, one must first link each function to an appropriate metric that measures its performance and then establish a target value for that metric based on benchmarking, industry research, or other reliable sources of information. Metrics can be objective, such as size, temperature, or pressure; or psychological, based on opinions or feelings.

1.4.2 Critical Targets/Metrics

Based on the functional decomposition and cross reference table completed, the critical systems are sample and cache. As such, Table 1 has been made to summarize the critical targets and metrics for each function. The function actions are to extract samples, store samples, measure amount extracted, protect samples, transfer contents to T502, transfer samples to cache, and sterilize contents (prevent cross-contamination).

Table 4 *Metrics and Targets for Critical Functions*

Function	Metric	Target
Extract Samples	Quantity (samples) Volume (cm^3)	8 samples 6 -10 cm^3 per sample
Store Samples	Quantity (samples)	8 samples
Protect Samples	Failure Rate (%)	12.5% or 1 sample
Measure Amount Extracted	Accuracy (%)	±10.0%
Transfer Contents to T502	Pass/Fail	Pass
Transfer Samples to Cache	Failure Rate	12.5%
Prevent Cross-Contamination	Carryover (%)	<1%
Withstandable Temperatures	Kelvin (K)	100 K - 200 K
Capability of Collecting Varied Samples	Pass/Fail (Metallic vs Non-Metallic)	Pass
Stabilize Device	Pass/Fail	Pass
Automated Process	Pass/Fail	Pass

1.4.3 Derivation of Targets and Metrics

1.4.3.1 Extract Sample

The system's primary objective is to extract and store samples from the surface of Psyche. Accordingly, the metric for evaluating the extraction function will be the number of samples successfully obtained from the surface. To establish a reasonable target, benchmarking was conducted against NASA's Perseverance Mars Rover, which has the capacity to extract and store up to 43 sample tubes, including 4 witness tubes for contamination assessment [1]. Given that the Perseverance sampling system underwent over seven years of development, this capacity was scaled down to reflect Psyche's mission constraints and timeline. Furthermore, Psyche's heterogeneous surface composition justifies a target of 8, more than 5 but fewer than 15 samples, balancing the representation of collected materials with practical feasibility. To validate this metric, the total number of samples extracted will be counted upon return to Earth and during ground testing of the system. In a test environment, engineers can replicate Psyche-like surface conditions to assess how many samples are successfully extracted and verify that the requirement is achievable.

Going off the needs identified through discussions with the sponsor, the system should collect a minimum amount of material per extraction. As such, the selected metric for this function is volume, since an anticipated constraint would relate to the amount of space the samples take up. Benchmarking against previous missions informed this choice: NASA's Perseverance mission collected an average sample size of roughly 7.96 cm^3 [4] per vial. Each vial could also fill samples to a maximum of 10.08 cm^3 [5]. Based upon this precedent and the similar nature of this mission, a minimum of 6 cm^3 and maximum of 10 cm^3 per sample is a reasonable goal for the Psyche mission. This range ensures sufficient scientific value while remaining feasible for the system's design. To validate this metric, the primary method will be post-return analysis on Earth, where each sampler container is removed from the cache, and sample volumes are measured.

1.4.3.2 Extract Sample Store Sample

The metric for evaluating the storage function is the total number of samples retained in the cache. Using the same benchmarking approach as the previous section, the cache will be sized to hold two more samples than the number targeted for extraction, one witness for contamination assessment and one redundant for reliability. The design target is eight (8) intact science samples in cache at the mission end. Validation is determined by counting samples upon insertion to T502's device during recovery operations and again in lab receiving; the final count of intact, sealed containers is compared to the target to verify compliance.

1.4.3.3 Extract Sample Protect Sample

The cache must protect each sealed sample throughout stowage, cruise, and recovery. The metric is given by equation 1, with a target ≤ 12.5% and an absolute cap of one (1) failed sample over the mission.

$$Cache\ Failure\ Rate = \frac{Lost\ or\ Compromised\ Samples}{Total\ stored\ Samples} \quad \textbf{Equation 1.}$$

A sample is compromised if (a) contamination exceeds limits derived from a matched witness tube baseline for that site, or (b) mechanical damage renders the sample unfit for intended analyses. Validation of metrics includes visual/mechanical inspection and contamination assessment.

In the design of the device, the total number of stored samples will be treated as a key parameter influencing critical design decisions. To validate this metric, the samples will be counted upon insertion to T502's device. The number of intact samples remaining in the cache system will then be compared against the defined target of eight, thereby providing verification that the requirement has been met.

1.4.3.4 Extract Sample Measure Amount Extracted

This function evaluates how well the system measures the amount collected per extraction; therefore, the selected metric is volume-measurement accuracy (error between the measured and true value), not the volume itself. Given Psyche's metal-rich, heterogeneous surface and variable density, we specify an accuracy target of ±10% per container. Validation will be performed primarily on Earth by measuring recovered samples and comparing this value to in-flight estimates.

1.4.3.5 Extract Sample Prevent Cross-Contamination

Materials extracted must represent the composition of the area they are sampled from. This function aims to prevent the mixing of material from multiple sample sites. During extraction, parts of the sample may get stuck on the sampling and storage system. These parts have the possibility of carrying over to the next sample and mixing in with their contents. This function aims to minimize the amount of outside carryover mixed into each sample. The percentage of carryover material in a sample will be measured. Due to the importance of preserving the integrity of each sample, a maximum of 1% total volume can be composed of carryover material. Validation will be performed on Earth by analyzing trace elements from previous samples to see how much material was carried over.

1.4.3.6 Withstand able Temperatures

Beyond high temperatures, the system needs to be able to withstand low temperatures as well. This is due to the variation of material properties at low temperatures compared to high temperatures. Therefore, the target range of temperatures the system needs to withstand is from

100K-200K. This range will be validated based on materials calculations and known material properties.

1.4.3.7 Capability of Collecting Varied Samples

The sponsor mentioned that they wanted to get a variety of sample types. As such, the sampling device cannot limit methods to solely extract metals or silicates. Hence, the method of extraction needs to be able to get metallic and non-metallic material. This will be validated on a pass or fail basis.

1.4.3.8 Stabilize Device

To avoid failure, the sampling device must be in a stabilized position before starting the extraction process. This may be done by setting the extraction device in its optimal positioning before movement. Due to the nature of this function, it will be evaluated on a pass or fail basis. The capacity of this will be validated based on whether the extraction device can extract material.

1.4.3.9 Automated Process

Real time control of any device in outer space is extremely difficult and complicated. As such, the device needs to have some form of automation to ensure the sampling/storing process can be done without real-time human control. A small, basic automated system should be good enough to allow for collecting and storing samples. The metric will be validated by its ability to incorporate such a system with a pass or fail.

1.5 Concept Generation

Team 501 utilized a variety of structured ideation tools—including the Crap Shoot, SCAMPER, Biomimicry, Anti-Problem, Battle of Perspectives, and general brainstorming techniques—to develop a total of 100 concepts for the Psyche sampling and catching system. Each ideation method is shown in action and explained in the Appendix E.

After the full set of concepts was generated, the team evaluated each idea based on how they encompassed the entire problem. From this evaluation, five medium-fidelity concepts and three high-fidelity concepts were selected for further development and visualization. The medium-fidelity concepts represented promising yet unrefined solutions, while the high-fidelity concepts were mature, testable designs demonstrating strong potential for practical implementation.

1.5.1 Medium Fidelity Concepts

Conically Rotating Drill Bit (Concept 69)

This concept features a drill bit that rotates in a conical pattern, extracting a cone-shaped core sample from the surface. Before drilling begins, an initial gas blast removes loose surface material to ensure a clean starting point. Once drilling is complete, a containment tube lowers and securely latches onto the detached sample, lifting it into the collection chamber. The sample is then sealed and stored alongside previously collected specimens for further analysis.

Grinding Capsules (Concept 38)

This concept was considered a medium fidelity for gathering samples. The idea behind this is that a canister can attach to the surface of Psyche and begin spinning with something like a diamond polishing paper to grind away material from the surface to which it's attached. The grinded material flows upward inside the canister, which self-seals to hold the material. The secondary seal detaches from the main canister, allowing it to be collected. The design for this concept is very simplistic and can be better seen in the picture. The reason this concept was chosen for fidelity was its simplistic design, replicability, and applicable to different types of surfaces.

Rotating Cone Grinder (Concept 60):

Concept number 60 contains an angle grinder that is positioned at an angle relative to the surface. The grinder rotates 360° around a single extraction point, cutting a circular trench and leaving behind a loose conical section. The cone is then collected and stored as a sample. Having a continuous conical drill path avoids having heat concentrated in one location, which can help with overheating.

Corer with Gas Blast (Concept 101):

This concept integrates the mechanisms of a rotary corer and a gas-blast sampling system used in earlier missions, allowing flexible operation depending on surface conditions. To collect loose regolith, the system can release a controlled gas blast beneath a cover to capture airborne particles within a defined area. If the surface is more compact or solid, a rotary corer can instead be deployed to extract an intact core sample. By enabling the use of either or both methods as needed, this design maximizes sampling efficiency across varying terrain types. The concept was developed using the “C” (Combine) element of the SCAMPER technique, merging two complementary approaches to meet diverse mission requirements.

Laser Coring Method (Concept 74):

Lasers are used to core out area. Rotating on a 360-degree track, the lasers will vaporize materials until a core of chosen volume is created. Core is stored in a vial and extracted. The properties around the edges of the core may change, but the direct center of the sample should be representative of its original nature.

1.5.2 High Fidelity Concepts

Auger Corer (Concept 68)

This concept was considered high fidelity due to its ability to collect both a cored sample and surface regolith from Psyche. The device is designed to lower onto the surface, where a coring drill initiates rotation to penetrate the material. The rotational motion of the coring drill simultaneously drives an auger profile, which gathers loose regolith from the surface. Once the desired depth is reached, a percussive mechanism activates to separate the core sample from the host material. The retrieved core is then transported upward through the drill and deposited into a sealed collection tube, while the regolith collected by the auger is directed into a separate containment chamber.

Semi-Portable Trepanner (Concept 46)

This concept was considered a high-fidelity concept because it could obtain a solid, more intact sample instead of a grinded one. Trepanning additionally seems less risky than the use of a traditional drill, which contains a pointed surface that can break unexpectedly. A possible trade-off to this may be that weight may become a limiting factor; however, a more intact sample bey also be more beneficial. This concept was chosen because it is applicable to thick metallic surfaces, has the potential for a simple automated procedure, and can provide a solid sample.

Ultrasonic Auger Drill (Concept 78):

A nitrogen blast will push away all regolith from the direct surface. An ultrasonic drill that is surrounded by an auger drill is pushed normal to the surface. Ultrasonic drill makes small percussions into surface, creating a powder. The powder is carried up to the surface with the use of the auger drill. Surrounding the two drills is a small tube that will act as a barrier and guide for the powder's transport to a vial that will self-seal after a certain volume of material is collected.

1.6 Concept Selection

Selecting the most promising solution from a set of medium- and high-fidelity concepts requires more than a single broad decision. To ensure an objective and well-supported choice, it is important to evaluate concepts through multiple structured decision-making methods. The House of Quality (HoQ) translates customer needs into engineering requirements, guiding the team toward designs that best satisfy stakeholder expectations. The Pugh Chart allows for direct comparison of concepts against a baseline, highlighting relative strengths and weaknesses. Finally, the Analytical Hierarchy Process (AHP) provides a quantitative, criteria-based ranking by assigning weighted priorities to each requirement.

Together, these methods break the decision process into informed, evidence-based steps, enabling the team to confidently select the concept that most effectively meets customer needs and offers strong potential for successful implementation.

1.6.1 Binary Pairwise Comparison

A Binary Pairwise Comparison is a numerical method used to determine the relative importance of customer needs by comparing them two at a time. Each comparison identifies which need holds greater priority, producing weighted scores (Table 6) that ensure the concept selection process reflects the true voice of the customer.

Table 5 ***Customer Needs Legend***

1. Compatible with T502 for handoff
2. Acquire multiple samples
3. Acquire surface and subsurface material
4. Maintain sample integrity

5. Withstand large temperature swing
6. Automated

This comparison is carried out using a matrix in which the customer needs shown above (Table 5) are listed across the top row and down the left column (Table 6). For each paired comparison, a 1 is assigned if the customer need in the column is more important than the need in the row; otherwise, a 0 is assigned. The diagonal is marked with dashes, as a need is not compared against itself. Once all comparisons are complete, the row totals are calculated, producing an importance score for each customer need. These scores serve as weighting factors for the subsequent House of Quality (HoQ) analysis.

Table 6 ***Binary Pairwise Comparison***

Binary Pairwise Matrix							
	1	2	3	4	5	6	**Total**
1. Compatible for handoff with Team 502 system.	-	0	0	0	0	1	**1**
2. Takes multiple samples.	1	-	0	1	1	1	**4**
3. Acquires surface and subsurface material.	1	1	-	0	1	1	**4**
4. Keeps integrity of each sample.	1	0	1	-	1	1	**4**
5. Withstands large temperature swings.	1	0	0	0	-	0	**1**
6. Automated	0	0	0	0	1	-	**1**
Total	**4**	**1**	**1**	**1**	**4**	**4**	

1.6.2 House of Quality

Once the weighting factors are established through the Binary Pairwise Comparison, the next step is to complete the House of Quality (HoQ). The HoQ supports Quality Function Deployment by ensuring that the voice of the customer is directly incorporated into the engineering decision-making process. To do this, each engineering characteristic is evaluated against the customer needs, and a value of 1, 3, or 9 is assigned to each cell to indicate a weak, moderate, or strong relationship, respectively (Table 9). After all relationships are assigned and the scores are totaled, the HoQ calculates the relative importance of each engineering characteristic. Characteristics that were identified as constraints rather than true engineering criteria were removed to ensure the remaining characteristics actively guide design decision-making.

Table 7 *House of Quality*

		Engineering Characteristics													
Improvement Direction		↑	↑	↑	↑	↓	↓	↓	↑	↓	↓	↓	↑	Pass	↑
Units		Units	Units	Units	%	kg	cm^3	N	K	Units	%	s	%	l	mm
Customer Requirements	Importance Weight Factor	Quantity of extracted sample	Quantity of sample types	Quantity of stored samples	Accuracy of sample measurements	Mass of completed cache	Size of completed cache	Required counter force supplied by rover	Material functionality	Steps taken to move sample into storage	Amount of cross-contamination	Time of Sampling Process	Reliability of Sampling System	Sample Stratigraphy	Depth of Sample Taken from Surface
1. Compatible for handoff	4			1		9	9		3						
2. Multiple samples	1	9	9	3	1	3	1		3				9	1	3
3. Surface & Subsurface Material	1	1	9	1	1	1			3			3	3	9	9
4. Sample Integrity	1						3	3	9	3	9	1	3	9	1
5. Withstand temp swings	4								9				1		3
6. Automation	4	1	1	1			1	3		9		3			
Raw Score	339	14	22	12	2	40	44	15	63	39	9	16	19	19	25
Relative Weight %		4.13	6.49	3.54	0.59	11.7994	12.9794	4.42478	18.5841	11.5	2.65487	4.72	5.60471976	5.60472	7.374631
Rank Order		11	6	12	14	3	2	10	1	4	13	9	8	7	5

The HoQ chart identifies the key engineering characteristics that will be critical to the final design. Material Functionality emerged as the highest-priority characteristic, emphasizing the need for durable, mission-ready materials that maintain performance in extreme environments. The second-ranked characteristic, Mass of Completed Cache, reflects the importance of collecting sufficient material for examination on return to Earth. Quantity of Stored Samples ranked third, reinforcing the requirement to store multiple samples within a single mission.

In fourth place, Accuracy of Sample Measurements tied with Size of Completed Cache, indicating that precise characterization and compact storage are equally important to mission success. The fifth-ranked characteristic, Depth of Sample Taken from Surface, highlights the value of obtaining both surface and subsurface material to enhance scientific return.

To reiterate, characteristics identified as constraints were not carried forward into the selection criteria and therefore were not used in the rating of concepts during the Pugh chart evaluations. By establishing these priorities, the HoQ ensures that engineering decisions remain closely aligned with customer needs and mission goals, guiding the concept selection process toward solutions that maximize scientific value, operational efficiency, and performance reliability.

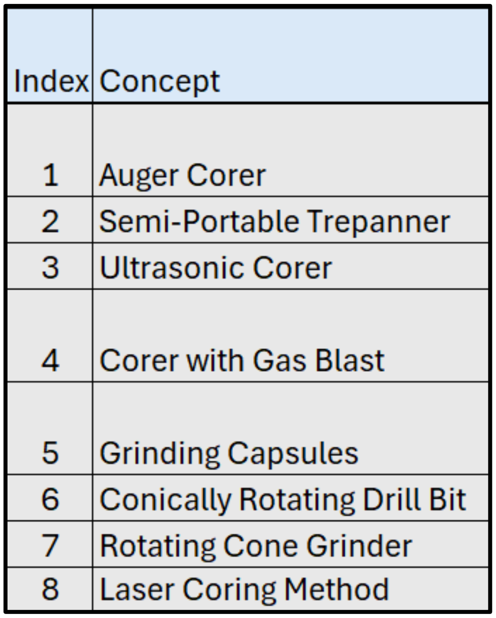
1.6.3 Pugh Chart

The Pugh Chart uses the highest-priority engineering characteristics identified in the HoQ to compare concepts and determine which option best meets customer needs. The process begins by selecting a datum, which serves as a baseline for comparison. The datum represents a current or established solution that fulfills the mission requirements but does not necessarily reflect the optimal design. In this evaluation, the Perseverance Rover sampling system was selected as the baseline.

Each concept (Table 8) is then assessed against the datum for every engineering characteristic and rated as better (+), the same (S), or worse (–). This structured comparison allows strengths and weaknesses to be identified objectively, enabling the team to determine which concepts most effectively satisfy customer needs and should progress further in the design process.

The chosen datum is NASA’s Perseverance rover. The Perseverance rover took multiple samples from the surface of mars using a coring system. It was specifically proficient in its speed, reliability, and its ability to keep the stratigraphy of its samples.

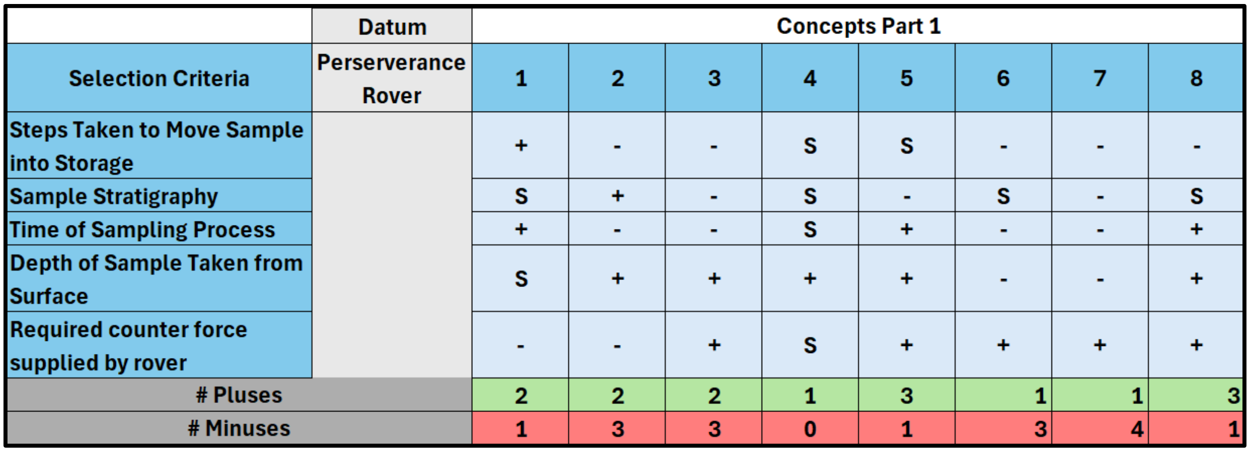
Table 8 ***Concepts***



Index	Concept
1	Auger Corer
2	Semi-Portable Trepanner
3	Ultrasonic Corer
4	Corer with Gas Blast
5	Grinding Capsules
6	Conically Rotating Drill Bit
7	Rotating Cone Grinder
8	Laser Coring Method

Once the first iteration of the Pugh chart is complete, the total number of +/- are summed and presented at the bottom.

Table 9 ***Pugh Chart 1***



	Datum	Concepts Part 1							
Selection Criteria	Perserverance Rover	1	2	3	4	5	6	7	8
Steps Taken to Move Sample into Storage		+	-	-	S	S	-	-	-
Sample Stratigraphy		S	+	-	S	-	S	-	S
Time of Sampling Process		+	-	-	S	+	-	-	+
Depth of Sample Taken from Surface		S	+	+	+	+	-	-	+
Required counter force supplied by rover		-	-	+	S	+	+	+	+
# Pluses		2	2	2	1	3	1	1	3
# Minuses		1	3	3	0	1	3	4	1

By reviewing the plus and minus counts for each concept, the team identifies which design performs most favorably relative to the datum. The concept with the strongest overall

performance—or one that closely approaches the top performer—is then selected as the new datum for the next comparison round. Concepts that show weak performance, indicated by a high number of "–" ratings or results like the datum, are removed from further consideration.
This iterative approach ensures that customer priorities remain central to the decision-making process, as each new comparison is made against a progressively stronger benchmark. The cycle continues until one concept consistently emerges as the preferred solution and is selected as the final datum (Table 9).

Table 10 ***Pugh Chart 3***

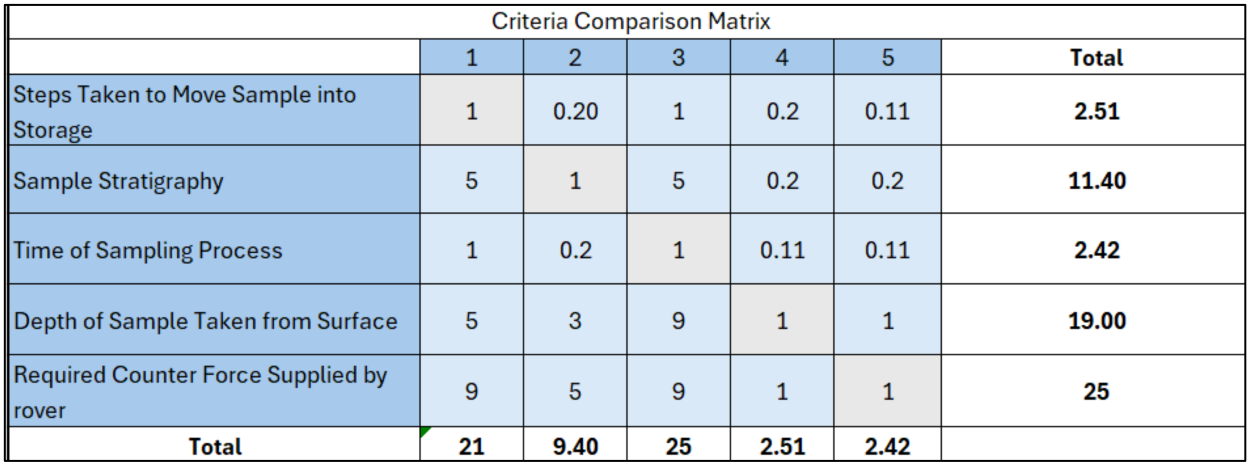
	Datum	Concepts Part 3		
Selection Criteria	**8**	**3**	**4**	**5**
Steps Taken to Move Sample into Storage		+	S	+
Sample Stratigraphy		S	+	-
Time of Sampling Process		-	+	-
Depth of Sample Taken from Surface		+	+	-
Required counter force supplied by rover		-	-	-
# Pluses		**2**	**3**	**1**
# Minuses		**2**	**1**	**4**

The third Pugh chart created (Table 9) used concept 8 as the datum because it resulted in one plus and one minus in the second iteration, indicating an average performance compared to the other concepts. Compared to concept 8, concepts 3 and 4 received similar ratings; however, Concept 4 had a plus in Sample Stratigraphy, which was the second-highest ranked selection criterion.

1.6.4 AHP

The Analytical Hierarchy Process (AHP) provides a structured and quantitative approach to decision-making by prioritizing the engineering characteristics selected for evaluation. In this method, matrices are used to conduct pairwise comparisons between criteria, assigning a value of 1, 3, 5, or 9 to indicate the relative importance of one criterion over another. The first matrix establishes these comparisons across all selected characteristics in hierarchical order (Table 11). The resulting AHP tables generate weighted values for each engineering characteristic, offering clear insight into which features should have the greatest influence on the final design. To ensure the reliability of these results, AHP incorporates a consistency check, confirming that the judgments made during comparison are logically aligned. Our process achieved a consistency ratio of 0.03, indicating strong internal consistency and validating the objectivity of the weighting outcomes.

Table 11 ***Criteria Comparison Matrix***



Criteria Comparison Matrix

	1	2	3	4	5	**Total**
Steps Taken to Move Sample into Storage	1	0.20	1	0.2	0.11	**2.51**
Sample Stratigraphy	5	1	5	0.2	0.2	**11.40**
Time of Sampling Process	1	0.2	1	0.11	0.11	**2.42**
Depth of Sample Taken from Surface	5	3	9	1	1	**19.00**
Required Counter Force Supplied by rover	9	5	9	1	1	**25**
Total	**21**	**9.40**	**25**	**2.51**	**2.42**	

After summing each column of the pairwise comparison matrix (Table 11), a normalized criteria matrix is generated to calculate the weight of each criterion.

Table 12 ***Normalized Criteria Comparison Matrix***

Normalized Comparison Matrix						
	1	2	3	4	5	**Criteria Weights**
Steps Taken to Move Sample into Storage	0.048	0.021	0.040	0.080	0.046	**0.047**
Sample Stratigraphy	0.238	0.106	0.200	0.080	0.083	**0.141**
Time of Sampling Process	0.048	0.021	0.040	0.044	0.046	**0.040**
Depth of Sample Taken from Surface	0.238	0.319	0.360	0.398	0.413	**0.346**
Required Counter Force Supplied by rover	0.429	0.532	0.360	0.398	0.413	**0.426**
Sum	**1**	**1**	**1**	**1**	**1**	**1.000**

This normalization converts the comparison values into proportional importance scores, resulting in a weighted priority for each engineering characteristic. For example, sample stratigraphy received a higher normalized score than time of sampling process, indicating that preserving sample integrity and orientation is more important than the time it takes to acquire the sample (Table 12).

Table 13 ***Consistency Check for Criteria Matrix***

Consistency Check		
Weigted Sum Vector	Criteria Weights	Consistency Vector
0.231	0.047	4.937
0.729	0.141	5.159
0.201	0.040	5.043
1.789	0.346	5.174
2.259	0.426	5.299

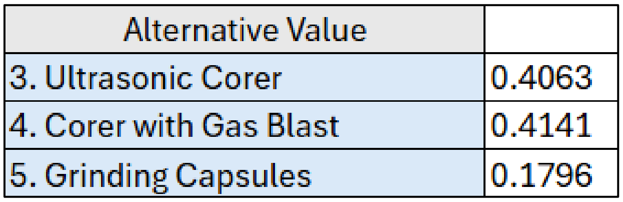
To ensure the pairwise comparison judgments were reliable, a consistency check was performed (Table 13). The Weighted Sum Vector was calculated and divided by each corresponding Criteria Weight to form the Consistency Vector. The average of this vector was then used to compute the Consistency Ratio (CR). Since the CR was below the accepted 0.10 threshold, the results were considered consistent and valid.

Table 14 ***AHP Consistency Rate for Criteria Matrix***

Consistency Index (CI)	Random Index (RI = 5)	Consistency Ratio (CR)
0.03	1.11	0.03

The average of the Consistency Vector is used to calculate the Consistency Index (CI) and Consistency Ratio (CR). Since the CR fell below the 0.10 threshold (Table 14), the comparisons were considered consistent and valid. With this confirmed, the AHP process was repeated six times—once per criterion—using the three remaining concepts to support the final concept selection.

Table 15 ***Alternative Values for Final Concepts***



Alternative Value	
3. Ultrasonic Corer	0.4063
4. Corer with Gas Blast	0.4141
5. Grinding Capsules	0.1796

Once the Consistency Ratio was verified, the priority values were combined with the criteria weights through matrix multiplication to determine the Alternative Values for each concept. These values represent how well each concept satisfies the selected engineering criteria. The AHP results indicate that the Corer with Gas Blast offers the strongest overall performance across the criteria, followed closely by the Ultrasonic Corer. The Grinding Capsules concept ranked third, demonstrating a noticeably lower fit to the prioritized requirements (Table 15).

1.6.5 Final Selection

Figure 2 AI example of corer with blast

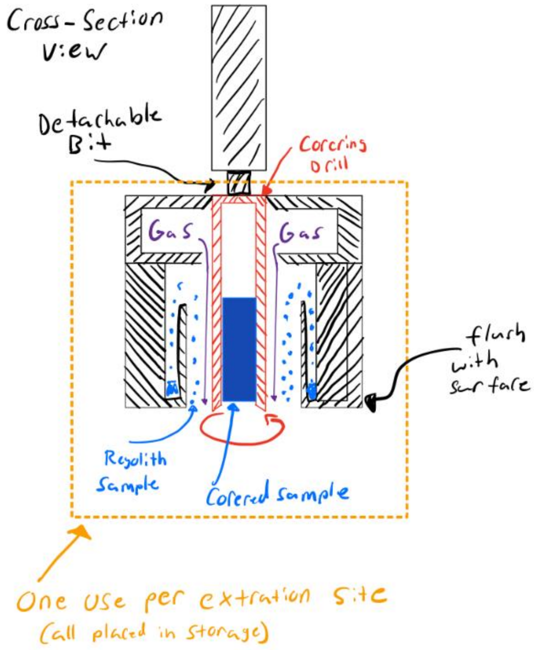


Figure 3 Cross-sectional view of final selection

Based on the alternative values, the corer with gas blast meets the selected criteria best. This design has a hub containing a gas-blasting mechanism and coring bits that are attached to the rover arm. Upon approaching the site, the hub will be lowered to the surface, and a series of gas blasts will commence. These blasts will push regolith toward the outer edges of the hub, where sample collection compartments are located. The blasts also clear the surface, allowing the rover to use the coring bit for drilling. A percussive element will be required to free the sample from the host material. Once drilling is complete, the rover will move the hub to a storage compartment. A new hub will be used for each extraction site.

1.7 Spring Project Plan

Table 16 ***Spring Project Plan***

Course Week	Task	Notes	Date

Week 1 **01/04 - 01/10**			
1	Spring Semester Initial Meeting	First meeting post-Christmas break.	6-Jan
	Full Size Prototype	Print the full-size prototype.	6-Jan
	Gas Blast Integration	Integrate the gas blast system into the prototype.	7-Jan
	Bi-Weekly Team 501 and 502 Meeting	1st meeting back from break to ensure both teams scheduling for the semester is on track and discuss project's progression.	7-Jan
	Code Update 1	Begin code for gas blast, drill motor, and linear actuator operation.	7-Jan
	Sponsor Meeting	First sponsor meeting in the Spring to establish expectations and schedule.	7-Jan
	Week 1 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	9-Jan
Week 2 **01/11 - 01/17**			
2	Start VDR4	Initial VDR4 development	12-Jan
	Finalize Component List	Complete list of all required components	13-Jan
	Absolute Positioning	Finalize method for determining absolute positioning of inner rotating body.	13-Jan
	Drill Motor/Linear Actuator Integration	Integrate the drill motor and linear actuator into the prototype.	14-Jan
	Current Sensor Operation	Install current sensors to motors to monitor current and prevent overheating in space.	14-Jan

	Code Update 2	Finalize code for drill motor and linear actuator.	14-Jan
	Apply for Graduation	Apply for graduation within application window ending Jan 25	14-Jan
	Week 2 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	16-Jan
Week 3 **01/18 - 01/24**			
3	Sponsor Meeting	Second sponsor meeting.	21-Jan
	Finalize CAD Model	At this point, CAD models should be complete, showing components and movements.	21-Jan
	Code Update 3	Finalize code for gas blast system.	22-Jan
	Bi-Weekly Team 501 and 502 Meeting	Discuss CAD parts and ensure final designs are compatible. Review each team VDR4 for improvements.	22-Jan
	VDR4 Draft	VDR4 final changes and begin practicing for VDR4 Presentation	22-Jan
	Week 3 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	23-Jan
Week 4 **01/25 - 01/31**			
4	Machine CAD parts	Send CAD and materials to machine shop to be manufactured.	26-Jan
	Code Update 4	Integrate previous subsystems into master algorithms.	28-Jan
	Flap Integration	Integrate flaps into assembly	29-Jan

	VDR4 Final	VDR4 is ready to present on initial design phase and early prototyping with CAD supporting a fully functioning exhibit in the future.	30-Jan
	Week 4 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	30-Jan
Week 5 **02/01 - 02/07**			
5	Start VDR5	Initial VDR5 development	2-Feb
	Code Update 5	Develop code to release cache.	4-Feb
	Bi-Weekly Team 501 and 502 Meeting	Discuss VDR5 development. Ensure both teams are on same page and discuss progress with coding implementation.	4-Feb
	Sponsor Meeting	Third sponsor meeting.	4-Feb
	Week 5 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	6-Feb
Week 6 **02/08 - 02/14**			
6	Engineering Job and Internship Fair	Event for organizations to scout out talent within engineering fields.	10-Feb
	Code Update 6	Develop control algorithms to monitor current outputs and create failsafe to ensure safe motor operation.	11-Feb
	VDR5 Draft	VDR5 final changes and begin practicing for presentation	12-Feb
	Week 6 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	13-Feb

Week 7 - Spring Break (No Class) **02/15 - 02/21**			
7	Sponsor Meeting	Fourth sponsor meeting	18-Feb
	Code Update 7	Final Testing of Code	19-Feb
	Bi-Weekly Team 501 and 502 Meeting	Begin preliminary testing with T502 for sample transfer. Discuss updates for the week and plan next meeting.	19-Feb
	Week 7 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	20-Feb
Week 8 **02/22 - 02/28**			
8	VDR5 Final	VDR5 ready to present on final modeled design overview and budget spent	25-Feb
	Rehearse VDR5	Initial VDR5 rehearsal	25-Feb
	Preliminary Integration	Assemble all components on body, integrate code, and test. This is a good time to identify issues and troubleshoots.	26-Feb
	Week 8 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	27-Feb
Week 9 **03/01 - 03/07**			
9	Start VDR6	Initial VDR6 development	1-Mar
	Sponsor Meeting	Fifth sponsor meeting	3-Mar
	Bi-Weekly Team 501 and 502 Meeting	Meet with T502 to discuss integration, testing, and update progress on VDR.	3-Mar
	Integration and Testing	Begin integrating final hardware, software, and electrical components with prototype.	4-Mar

	Week 9 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	5-Mar
Week 10 **03/08 - 03/14**			
10	Final Integration and Testing	Finalize integrate hardware, software, and electrical components with prototype.	9-Mar
	VDR6 Continuation Work	Continue to work on VDR6, including relevant design information and iteration changes. The VDR should be nearing completion around this point.	10-Mar
	Week 10 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	13-Mar
Week 11 **03/15 - 03/21**			
11	Sponsor Meeting	Last sponsor meeting before presenting final project.	18-Mar
	Bi-Weekly Team 501 and 502 Meeting	Meeting with T502 to discuss VDR, design, and clear up any questions before presentations.	19-Mar
	VDR6 Draft	VDR6 final changes and begin practicing for presentation.	19-Mar
	Week 11 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	20-Mar
	Assembly of Final Prototype	Final prototype assembled and functioning begin testing under different environments.	20-Mar
Week 12 **03/22 - 03/28**			

12	VDR6 Final	VDR6 ready to present in-depth design iterations and in-depth testing data and analysis.	25-Mar
	Week 12 Lab Cleaning	Clean weekly assigned section of Senior Design Lab.	27-Mar
	Documentation and Tutorial Development	Final documentation and tutorials developed with troubleshooting information and FAQ's	27-Mar
Week 13 **03/29 - 04/04**			
13	Rehearse Presentation	Run through presentation, addressing potential questions and concerns.	1-Apr
	Bi-Weekly Team 501 and 502 Meeting	Rehearse final project with collaboration team to ensure consistent information and proper discussion of concepts and designs.	2-Apr
	Engineering Design Day	Showcase final project	3-Apr
Week 17 **04/26 - 05/02**			
17	Final Exam Week Starts	Final exams scheduled Monday through Friday	27-Apr
	FSU-FAMU COE Graduation	Graduate (Some of us).	1-May

Chapter Two: EML 4552C

2.2 Restated Project Charter and Scope

2.2.1 Restated Project Description

The objective of this project is to acquire and cache samples across multiple surface types on asteroid (16) Psyche. This effort is coordinated with Team 502, who focuses on sample retrieval. Psyche is a large, metal-rich asteroid in the main belt and the target of NASA's Psyche mission; the spacecraft on route to study it. This capstone project is part of the NASA Psyche Capstone program at Arizona State University (ASU), sponsored by Dr. Cassie Bowman. The Psyche mission is led by ASU, with NASA's Jet Propulsion Laboratory (JPL) responsible for mission management, operations, and management.

Psyche may be the remnant of a differentiated body's exposed core. Sampling its surface can test hypotheses about planetary differentiation, space weathering of metals, and metal-silicate mixing. These science goals drive our design toward multi-terrain sampling in low gravity with clean, cache ready sample handing.

2.2.2 Restated Key Goals

Team 501 has five key goals, listed below:

- Design and develop a sampling system prototype capable of collecting material from multiple hypothesized Psyche surfaces. These include flat metallic surfaces, mixed metal/rock debris fields, rough or high-relief terrain, and metallic crater walls.
- Design and develop a secure caching system that can safely contain collected samples in compliance with NASA planetary protection and contamination-prevention guidelines.
- Enable sample retrieval by Team 502 while minimizing the risk of damage or contamination.
- Ensure a variety of samples can be collected. Samples may differ in chemical composition, ideally samples will be various types of metals as opposed to multiple samples of the same metal.

- Build a scale model of the integrated sampling and caching system. Conduct simulations and physical testing under conditions analogous to Psyche's low-gravity, metallic surface environment to validate functionality and scalability.

2.2.3 Restated Market

The primary market for this project is planetary small-body acquisition teams planning metal-rich (Psyche-class) asteroid missions (ASU/NASA/JPL mission concept teams) - including payload leads, sampling PI's, and system engineers who specify, evaluate, and integrate sampling hardware.

The secondary market for this project includes spacefaring operations and some industries on Earth. This includes any future missions by NASA or other companies like SpaceX to celestial bodies where sampling is required. The Psyche asteroid is categorized as an M-type asteroid, meaning that it is primarily made of metals. As of this writing, no sampling missions to type-M asteroids have been conducted, making the challenges this project faces to be unique. While the field is still underdeveloped, the metal content of the Psyche asteroid makes it one of the prime targets for asteroid mining. Missions conducted by Space Forge or other similar asteroid mining companies to the Psyche asteroid and other M-type asteroids will be greatly influenced by the challenges and successes of this project.

The storage system for Psyche samples taken could influence other storage-related companies on Earth. After extraction, the samples need to stay as close to their original state as possible when returning to Earth. Storage-related companies may use the performance of the conservation of Psyche samples as inspiration for the creation of extreme condition storage.

Sampling the Psyche asteroid may impact the mining industry as well. Any technological innovations to assist in sampling may inspire the development and optimization of mining tools. This could be in the form of a mining tool that operates in extremely cold environments or a reduction in the energy consumption of current tools.

2.2.4 Restated Assumptions

- The seasonal and diurnal cycles, as well as the locations of each extraction point, are predetermined.

- The sampler is delivered to Psyche and electrically and mechanically mounted to a host vehicle prior to Entry, Descent, and Landing (EDL).
- The host vehicle and the sampling/ caching system are capable of reliable two-way communication.
- The system is capable of operating in microgravity and in a near-vacuum environment; however, the prototype will be tested at 1 atm.
- The host vehicle can safely and precisely traverse the surface of Psyche and position the sampler at designated regions of interest.
- The host vehicle supplies all required electrical power to the sampling and caching system.
- Information regarding surface composition is provided to the sampling and caching system prior to extraction.
- The devices developed by Team 501 and Team 502 are capable of inter-system communication.
- The host vehicle is capable of transporting collected samples to a designated retrieval location.
- The host vehicle is capable of autonomously or remotely swapping drill bits and end-effectors as required for different sampling operations.
- The host rover has an approximate mass of 1500 kg. Under Psyche's gravitational acceleration (~0.1 m/s^2), this results in an effective downforce of approximately 150 N available for maintaining contact and helping counter reaction forces during drilling and sampling operations.
- Assume the composition of the surface matches NASA's predictions. (Mix of silicates and metals).

2.2.4 Restated Stakeholders

Table 17 ***Restated Stakeholder Breakdown***

	Investors	Decision- Makers	Advisors	Receivers
Cassie Bowman		X	X	X

Shreyas Balachandran			X	
Arizona State University	X		X	X
NASA	X			X

SPLI

2.3 Results

2.3.1 Goals for Results Evaluation

Successful sample acquisition is critical for the study of the asteroid, as system reliability heavily impacts mission success. The primary goals of this study are to:

1. Quantify the effectiveness of the sampling system in terms of material collection
2. Evaluate the flow behavior using simulation tools
3. Assess system repeatability across multiple trials
4. Analyze performance across varying material simulant sizes
5. Identify limitations and areas of improvement based on observations

These goals provide structure in determining the success of the proposed sampling system for the metal asteroid.

2.3.2 Sample Collection Performance

A key target for sample collection is to collect at least 9 cm^3 of material per sample. To quantify system performance, the apparatus was tested using one cup of simulated loose regolith. The regolith simulant consisted of foam spheres selected to approximate the average particle size and mass expected on 16 Psyche. Experimental testing demonstrated that the system could consistently collect regolith that met the minimum sample volume. Minor variation in collected volume was observed between trials.

2.3.3 Regolith Sample Collection

Table 18 ***Regolith Sampling vs. Volume Collected***

Trial #	Volume (cm^3)
1	10
2	10

3	10
4	11
5	10
6	15
7	9
8	10

Across 8 regolith samples collected, the system achieved:

- Mean collected volume: 10.63 cm^3
- Standard deviation: 1.85 cm^3
- Success rate: 100%

The low standard deviation indicates consistent regolith collection. Collection variation was also dependent on material distribution on the surface, and the type of material collected.

2.3.4 Subsurface Sample Collection

Drilling was selected as the method for subsurface material extraction. This led the team to evaluate two drilling operations: single entry drilling and peck drilling. Single entry drilling was quickly eliminated as a viable option due to consistent stalling of the drill motor and a required downforce exceeding 25 lbs. The most significant constraint encountered was the 25 lb downforce limitation imposed on all drilling operations. This limitation was established to simulate the downforce available under Psyche's gravitational acceleration of approximately 0.144 m/s^2.

Peck drilling proved to be advantageous for several reasons: it eliminated stall torque issues, allowed control over heat generation, and enabled management of chip size. A feed rate controller was implemented to maintain drill rig stability under the 25 lb load constraint. The following results were obtained from tests conducted both in the drill rig (Fig. 3) and in the assembled housing capsule (Fig. 4).

Drill Testing Overview

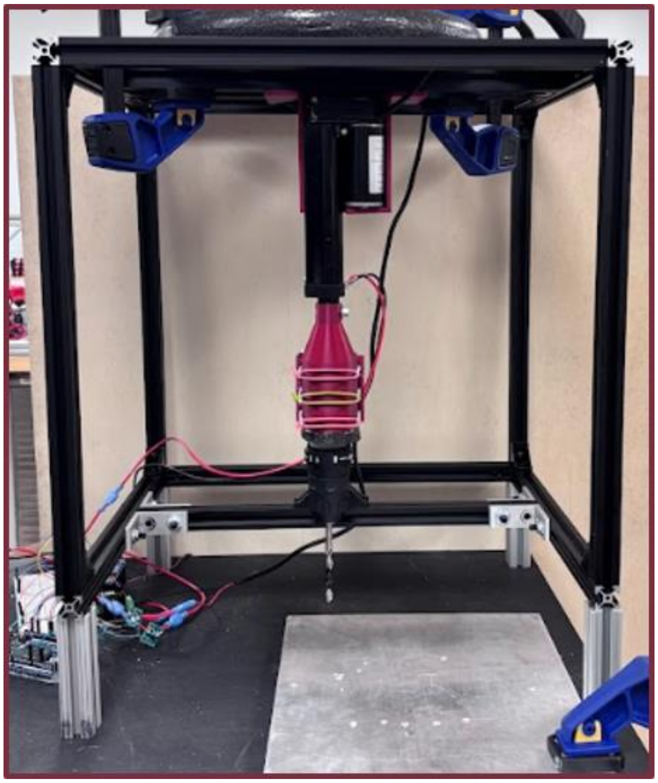


Figure 4 Drill Fixture Setup

The drill fixture consists of a linear actuator providing 1,000 N of downforce at a feed rate of 14 mm/s. Mounted to the linear actuator is a 12V drill motor capable of 700 RPM, equipped with a planetary gearbox to increase output torque. The drill is guided perpendicular to the surface via a vertical piece of extruded aluminum, stabilized by a surrounding extruded aluminum frame structure.

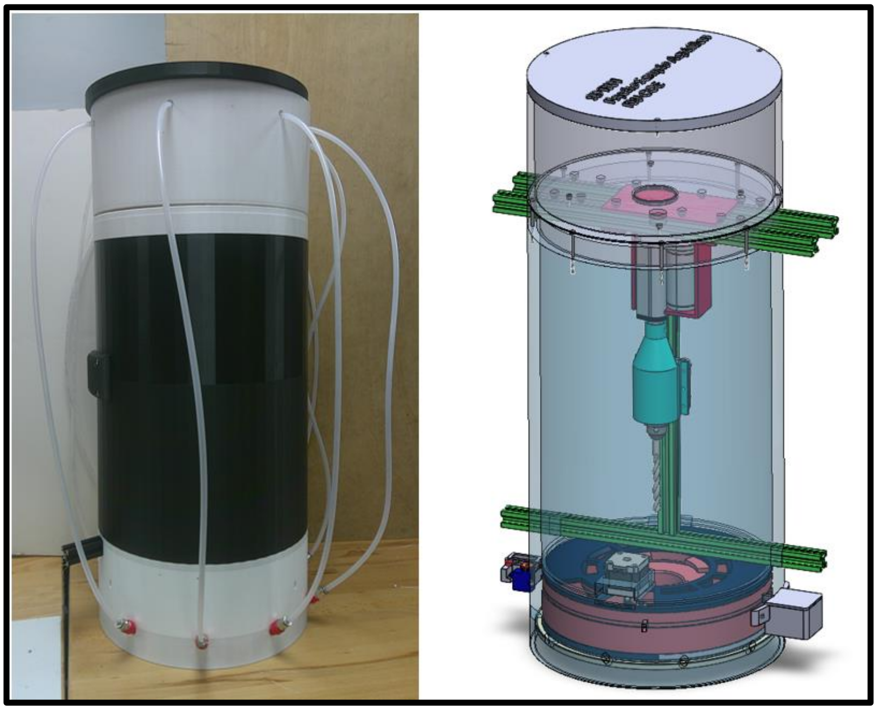


Figure 5 Drill Secured in Housing Capsule

Figure 5 illustrates the complete construction of the sampling system and how the drill fits within the housing capsule. The drill is mounted to a vertical piece of extruded aluminum that constrains its motion to a linear path normal to the surface. Feed force is supplied by the same linear actuator configuration used in the drill fixture. In both assemblies a 25lb weight was placed on top to supply the allotted downforce. Testing of the steel samples was conducted inside the assembled system to simulate full system capability and provide a more realistic operational scenario. Sample size constraints limit the number of trials that could be performed on these materials.

Fixed Test Conditions

The following parameters remained constant across all trials, as they were determined by the operation limits of the linear actuator used in the test apparatus:

Parameter	Value

Drill bit diameter	5/16" (7.94 mm)
Spindle speed	700 RPM
Feed force	1,000 N
Feed rate	6 mm/s

Drilling Test Results

For 304 stainless steel and C250 maraging steel, drilling was stopped at approximately 2 minutes. As the primary objective was to confirm chip generation and subsurface material collection rather than achieve a set depth, trials on harder materials were concluded once successful chip collection was observed, and to conserve the limited available sample stock.

#	Material	Avg. Drill Time	Hole Depth	Chips Generated	Subsurface Collected	Chip type/ Notes	Notes
		Aluminum — 5 Trials					
1	Aluminum	~390 s	10 mm	Yes	Yes	Long curly strands were generated. Depending on time drill spent in contact with surface determined the length of the chip.	5 trials were conducted due to the limit of the Al sample size.
2	Aluminum	~380 s	10 mm	Yes	Yes		
3	Aluminum	~370 s	10 mm	Yes	Yes		
4	Aluminum	~392 s	10 mm	Yes	Yes		
5	Aluminum	~400 s	10 mm	Yes	Yes		
		304 Stainless Steel — 1 Trial					
6	304 Stainless Steel	~120 s	2 mm	Yes	Yes	Small filings and short strands	Drilling stopped at 2 min once chip collection confirmed; limited sample stock
		C250 Maraging Steel — 1 Trial					
7	C250 Maraging Steel	~120 s	4 mm	Yes	Yes	Small filings and short strands	Drilling stopped at 2 min once chip collection confirmed; limited sample stock

The drilling trials successfully generated chips across all three materials tested. In the aluminum trials, long curly strands were produced, with chip length varying as a function of the time the drill remained in contact with the surface. For the 304 stainless steel and C250 maraging steel trials, smaller filings and short strands were generated, consistent with the higher hardness and work hardening behavior of these materials.

Drilling on stainless steel and maraging steel samples was intentionally stopped at approximately 2 minutes and 2 to 4 mm of depth. This decision was guided by two primary considerations. First, the principal objective of these trials was to demonstrate the feasibility of chip generation and subsurface material collection, which was achieved in both cases. Second, research into space weathering on airless planetary bodies indicates that surface contamination from micrometeorite impacts and solar wind implantation is largely confined to the uppermost 2 to 4 mm of material [6]. Drilling beyond this depth would therefore be sufficient to access uncontaminated subsurface material, meaning extended drilling was unnecessary to validate the collection concept. Together, these factors justified the conservative drill duration used for the harder material samples.

Vicker’s hardness Testing C250 Maraging Steel

Vickers hardness testing was performed on the C250 maraging steel sample at a load of HV0.5 to characterize its mechanical properties relative to the proposed iron nickel composition of asteroid 16 Psyche. Iron nickel meteorites, considered analog materials for the Psyche surface, typically exhibit hardness values in the range of approximately 250 to 350 HV [7]. The C250 sample falls within this range, supporting its suitability as a test analog.

Table 19 Vicker's Hardness Table

Measurement	HV0.5 Value	Notes

1	312.9	Within iron-nickel meteorite range (~250-350 HV)
2	312.0	
3	299.6	
4	317.1	
Average	**310.4**	

2.3.5 Flow Behavior and Simulation Results

The primary method of transporting samples uses a gas blast mechanism, where a solenoid-controlled pressurized gas flow mobilizes particles into collection chambers.

Early experimental results showed that the system required:

- High exit flow velocity to initiate particle motion
- Low mass flow rate to conserve pressurized fluid resources

Using compressible flow relations, exit velocities were determined to be:

- 259 m/s at 200K
- 313 m/s at 293K

COMSOL simulations were used to analyze internal flow fields to analyze the internal geometry of the system before experimental testing. Streamline results showed:

- Predominant flow paths directed toward collection chambers
- Localized recirculation zones within the cylindrical region

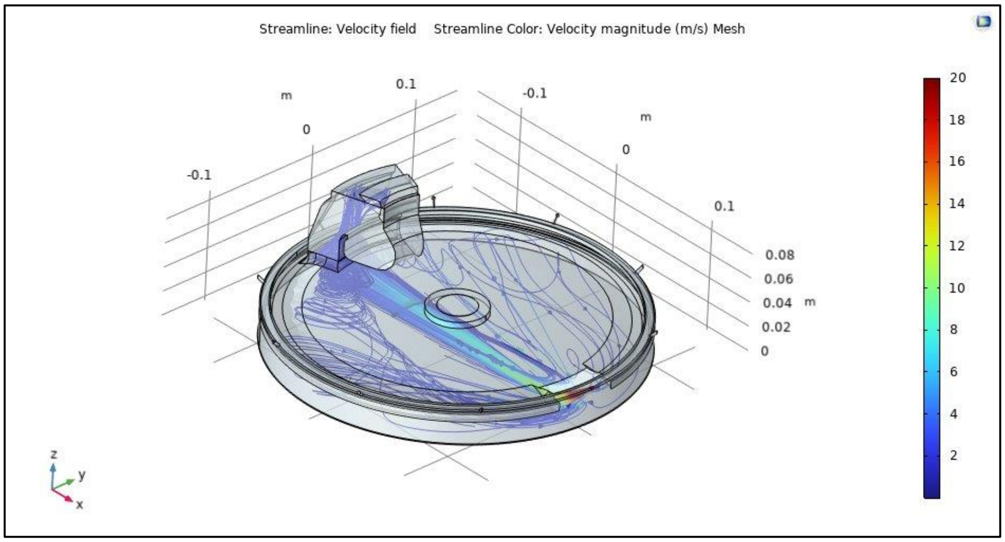


Figure 6 COMSOL Gas Blast Flow into One Chamber

While these effects did not prevent successful sample collection, it did reduce overall efficiency of the system. These flow characteristics are attributed to the rotating mechanism integrated into the system, which allows for indexing between all the collection chambers built into the system. As a result, the cylindrical internal geometry introduces complex flow behavior which ultimately prevents the material from being uniformly directed into the collection chambers. This behavior was identified during simulation and determined to be acceptable, as the system still met the required sample collection threshold, as verified through experimental testing.

2.3.6 Gas Blast Valve Opening Duration

Gas blast timing was evaluated to determine the solenoid open duration required to achieve sufficient material transport while also minimizing gas usage. The resulting collected volumes were recorded for each actuation time, using the simulant regolith:

Trial #	Regolith on Surface (mL)	Actuation Time (s)	Collected Volume (cm³)
1	473	0.25	20
2	237	0.20	7
3	237	0.25	10
4	237	0.25	10

Results showed that increasing the solenoid actuation time by 0.05 seconds improved sample collection by successfully collecting the target of 9 cm^3. The amount of regolith on the surface under the surround cylindrical space also increased the volume collected by double. An actuation time of 0.25 seconds was used for all future tests to decrease gas usage while consistently collecting the target volume of material.

2.3.7 Drilling Performance Analysis

Drilling performance was evaluated using material properties closely representing materials predicted to make up the Psyche asteroid. The material was approximated as an Fe-Ni alloy with mechanical behaviors like austenitic stainless steel which helps provide estimates for material cutting.

Assumptions made:

- Machine efficiency: 0.75
- Drill diameter: 7.94 mm
- Cutting speed range: 10-20 m/min

Calculated performance:

- Spindle speed range: 401-802 rpm
- Average operating speed: 601.5 rpm
- Feed rate: 60 mm/min
- Material removal rate: 2970.86 mm^3/min

These values indicated that the drilling system operates in a range acceptable for subsurface penetration.

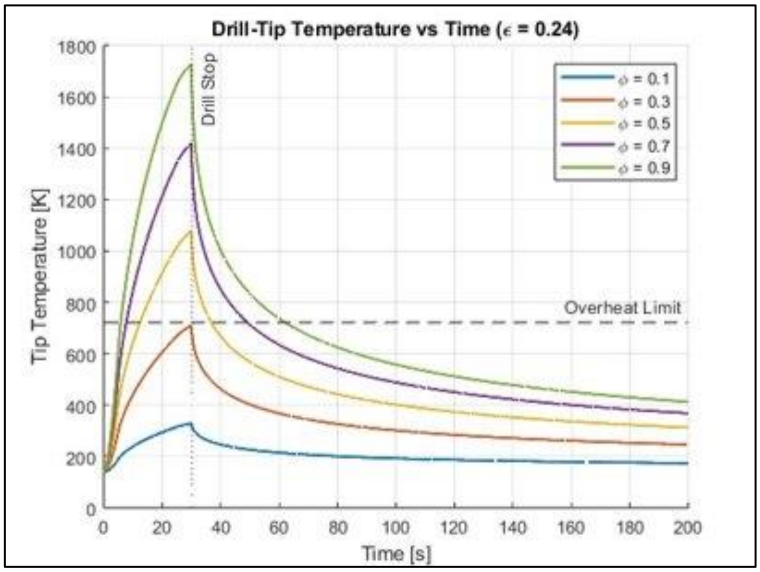


Figure 7 Effect of Operational Intensity on Drill-Tip Temperature

Figure 5 shows the effect of operational intensity on drill-tip temperature over time. As operational intensity increases, the peak temperature of the drill tip increases significantly. These results highlight the dependence of drilling operations on thermal properties of the drill-tip and surrounding system, especially important in Psyche's space vacuum.

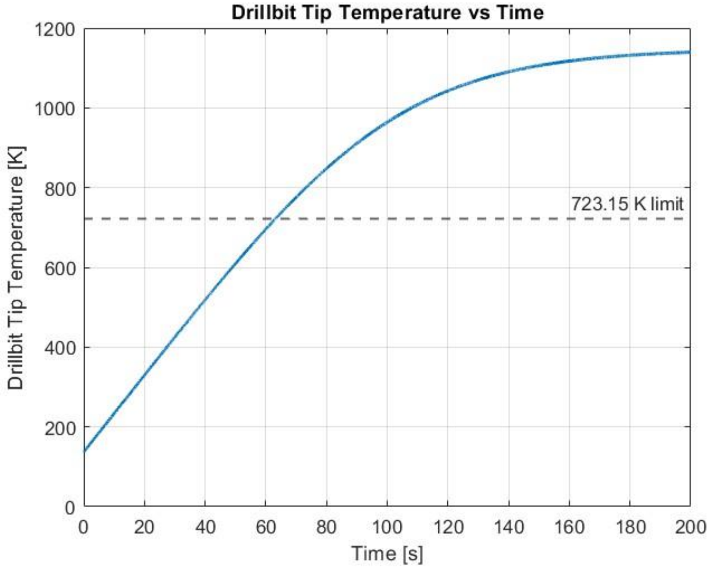


Figure 8 Drillbit Temperature vs Time

The thermal environment on Psyche is extreme. The drill bit may start at cryogenic temperatures around 137 Kelvin, while the surrounding vacuum of space acts as a heat sink at approximately 3 Kelvin. The maximum allowable temperature for the drill bit material is about 723 Kelvin before beginning to undergo potential damage due to heat. This plot shows the predicted drill temperature over time during operation. We defined heat input as a constant entering the drill. The key takeaway from this plot is how sensitive the drill temperature is to the assumed heat input. The drill heats quickly at first because radiation is weak at low temperatures, but as temperature increases, radiation becomes more significant and begins to limit the rate of temperature rise. This plot demonstrates that even modest heat input can lead to rapid heating in a vacuum environment, highlighting the importance of thermal management in the drill design.

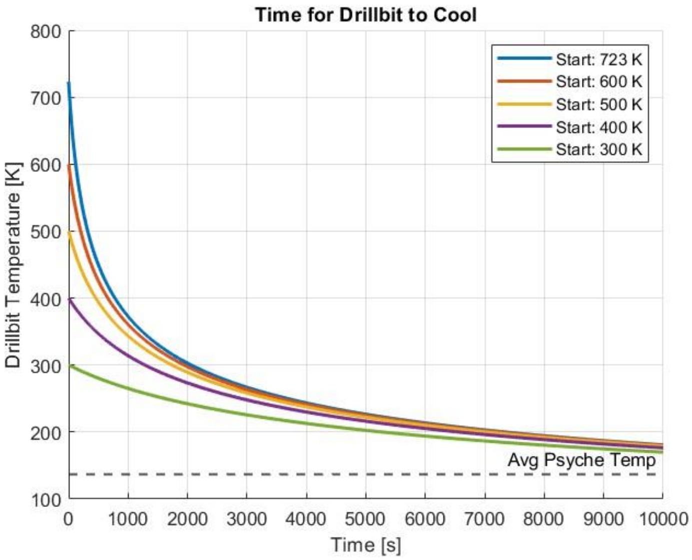


Figure 9 Time for Drill bit to Cool

This plot shows how the drill cools down after operation, assuming no additional heat input and only radiation to a 3 Kelvin vacuum environment. Multiple starting temperatures were evaluated, and each curve shows how long it takes for the drill to return to 137 Kelvin, which represents the ambient temperature of asteroid Psyche. The drill cools quickly at high temperatures but slows significantly as it approaches the ambient temperature. Overall, this plot shows that in a vacuum environment, cooling is highly temperature-dependent and becomes increasingly inefficient at lower temperatures.

2.3.7 Drilling Simulation

Drilling performance was additionally evaluated with FEA using ABAQUS to determine structural integrity of the drill during the operation. The drill bit material used was M42 Cobalt alloy and the material to simulate Psyche surface was FeNi36. Using the material properties of these, a simulation was made to show the stress of the drill to ensure there’s be no breakage or catastrophic failure.

Shown below in Figure 7 is the first initial step and assembly cross-section of the drilling simulation. The stress is shown in the upper-left corner and will be in megapascals.

Figure 7 ABAQUS First Step & Initial Assembly

An important exception to note however was that the Johnson-Cooke parameters and constants were not able to be calculated for the M42 Cobalt Alloy and FeNi36. Due to lack of time, resources, and expertise, these values regularly obtained through testing were instead substituted with those of other materials. The surrogate materials used were S-7 Tool Steel for the M42 cobalt alloy and 52100 Steel for the FeNi36. These surrogates had a close enough yield and fracture stress to their respective material, and thus their values for Johnson-Cooke parameters and constants were input into the material properties. These values help determine deformation behavior in ABAQUS, so they had to be input.

With this, the simulation had many iterations due to the learning curve of new software that is not generally taught at the FAMU-FSU COE. The final step of the simulation shown in Figure 8 displays the drill going into the surface and removing material from the surface.

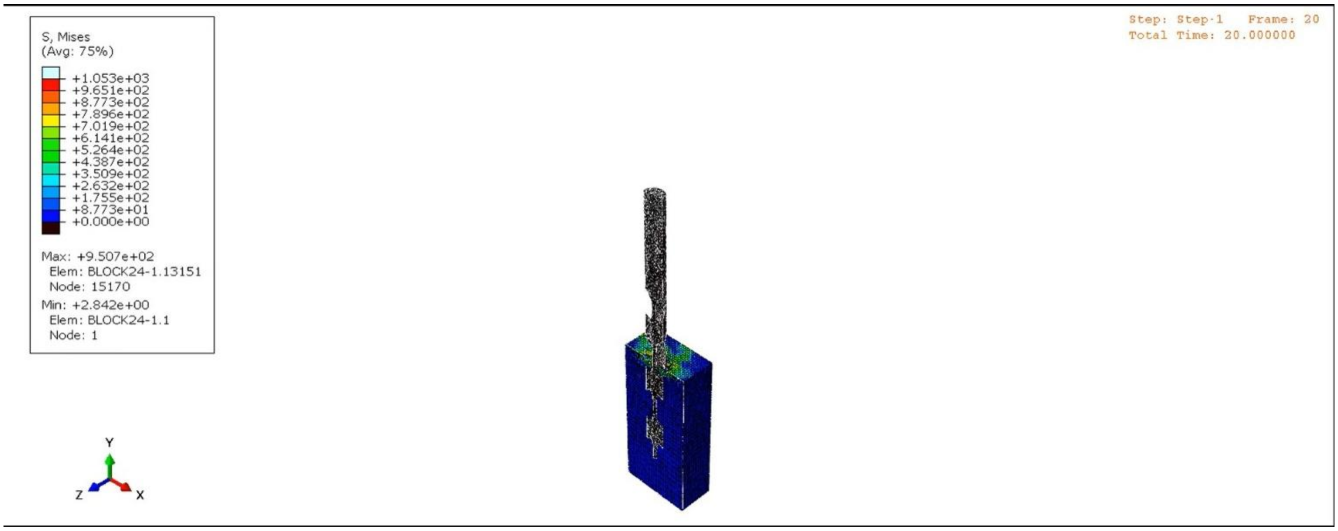


Figure 8 Final Step of ABAQUS Simulation

The resulting simulation obtained in ABAQUS showed no critical failure for the drilling at 20 seconds. This simulation helps as proof of concept of drilling on Psyche surface with a minor exception in temperature. Temperature could not be properly integrated into the simulation, however the simulation is applicable to the Earth operation.

2.3.8 System Repeatability

Repeatability testing confirms consistent system operation through multiple autonomous sampling system trials. Repetitive subsystem tests were conducted for the gas blast system, drill system, detachment mechanism, and indexing functions. After subsystems were confirmed to function as desired, fully integrated system tests were performed to verify the collection abilities and transfer tasks of the Psyche sampling system.

Through repetition of the subsystems, errors in the mechanics of the sampler were found early on and adjusted before full system integration. Some noticeable changes were the adjustments of electromagnetic actuators to servo motors in the detachment mechanism, as well as the location change of ventilation for the gas blast to exit the collection chambers. After full system integration and autonomous initiation cycle were completed repetitively, no major failures were observed.

2.3.9 Material Simulant Size Performance

Due to the difference in simulants for the regolith and subsurface materials, different particle sizes were used to replicate more realistic conditions of the differences. The regolith particles were collected more efficiently due to their smaller and more uniform size, while the subsurface particles had more trouble collecting, since they consisted of metal scraps and spiral chips since they were surfaced using a drill bit. The smaller scraps were less likely to become stuck in the entrance of the collection chambers. Larger scraps were less responsive to the gas blast and had a decreased chance of being captured, so implementing peck drilling was necessary to produce shorter, broken chips.

2.3.10 Limitations and Improvements

Several limitations were identified through initial design, testing, and analysis. One large limitation was the maximum height that the transfer cache could be, severely limiting design choices involved with motor attachments and rotating flap adjustments. Previously discussed was the cylindrical air space that the gas blast would enter and push material across and up into the collection chamber; if the height requirement was higher, a more tunneled and direct flow could have been implemented which would have improved overall flow and reduce recirculation. Additionally, the performance of the system was impacted by the size of particle being transferred, showing that the regolith collection is more successful than subsurface material.

Future improvements focus on improving the internal geometry to reduce recirculation regions to promote more uniform flow and increase the volume of collected samples. A further study of inlet orientations was well as geometry improvements to guide flow are future improvements to do this. Improving the subsurface collection chambers by widening the inlets and reducing the curves that the scraps must travel through would help to reduce jamming with larger particles. These modifications would increase system performance by maintaining the previously demonstrated reliability of the Psyche sampling system.

2.4 Discussion

2.4.1 Sample Collection Performance

The results showed that the Psyche sampling system met its primary goal of collecting at least 9 cm^3 of material for 4 regolith samples and 4 subsurface samples. The system performed best with the collection of regolith material due to a more uniform particle size.

Subsurface sampling presented greater challenges, due to the required drilling of surface material before gas blasting. Thermal limits and material hardness of Psyche metals meant that drill holes needed to be kept shallow to reduce the chance of the drill bit breaking, as well as limit thermal conduction to other system parts which could compromise functionality if overheating occurred. To overcome this, the transition from single-entry to multi-entry drilling allowed to shallow holes that still surfaced the required amount of material to collect at least 9 cm^3.

Flow analysis revealed that internal geometry of the system played a dominant role in overall efficiency of the system. Recirculation zones were confirmed through simulation that showed reduced flow in the outside portions of the cylindrical flow region. These effects did not prevent successful sample capture, as experimental testing showed successful material collection, given that many of the streamlines still entered the chamber. This highlights how important internal geometry is in optimizing future designs.

Evaluation of the gas blast valve opening duration defined an important timing parameter that maximized material collection while minimizing pressurized gas usage. Excessive durations were unnecessary as the collection chambers still had a limit of how much material they could hold. An optimal actuation window allowed for the smallest loss of gas. This also improved sample collection consistency and resource usage.

Drilling analysis indicated feasible ranges for drilling within the system. Since Psyche is in a vacuum environment with no convection, the heat transfer study is important to prevent overheating of the system. This defines a drill cycle that prevents tool wear and overheating throughout the system.

The repeatability testing of the subsystems allowed for iterative prototyping that improved reliability of the whole system.

Overall, the system demonstrates a successful Earth prototype of future Psyche sampling that can be implemented on M-type asteroids for material collection and drilling.

2.5 Conclusion

This work presented the design, development, and testing of an Earth prototype for a sample acquisition and caching system intended for asteroid (16) Psyche. The system integrates a combined gas-blast and peck-drilling mechanism to collect both surface regolith and subsurface material, addressing the unique challenges of operating in a metallic, low-gravity environment. All major subsystems, including the gas blast mechanism, drill assembly, detachment mechanism, and indexing system were individually tested and verified to function as intended prior to full system integration. Regolith collection trials achieved a 100% success rate across eight samples, with a mean collected volume of 10.63 cm^3 and a standard deviation of 1.85 cm^3, meeting and exceeding the 9 cm^3 target. Subsurface sampling was validated across three materials aluminum, 304 stainless steel, and C250 maraging steel with successful chip generation and subsurface material collection confirmed in all trials. Vickers hardness testing confirmed that C250 maraging steel, with an average hardness of 310.4 HV, falls within the iron-nickel meteorite analog range of 250-350 HV, supporting its suitability as a Psyche surface simulant.

COMSOL flow simulations revealed localized recirculation zones within the cylindrical collection region, an expected consequence of the system's rotating indexing geometry. While these zones reduced overall flow uniformity, they did not prevent successful sample collection, as experimental results confirmed that sufficient material still entered the collection chambers. Optimization of the solenoid actuation timing to 0.25 seconds was found to reliably meet the volume target while minimizing pressurized gas consumption. Peck drilling was demonstrated to be the viable drilling strategy, overcoming the stall-torque limitations encountered in single-entry drilling and enabling sample collection within the 25 lb downforce constraint imposed to simulate Psyche's gravitational environment.

Several complications arose during the development process. The height limitation of the transfer cache constrained the internal flow geometry, preventing a more direct and efficient flow path from being implemented. Additionally, larger subsurface chips produced by the drill were less responsive to the gas blast and more prone to jamming at collection chamber inlets, reducing subsurface collection efficiency relative to regolith collection. A transition from electromagnetic actuators to servo motors in the detachment mechanism was also required after initial integration testing revealed reliability concerns. These challenges were identified and addressed through iterative subsystem testing prior to full system integration, with no major failures observed during fully integrated autonomous operation.

Overall, the prototype demonstrates the feasibility of a combined gas-blast and peck-drilling approach for acquiring diverse samples from a metal-rich asteroid surface, providing a validated foundation for future mission-level development.

2.6 Future Work

Several areas have been identified for continued development and improvement of the Psyche sampling system.

The internal flow geometry of the gas-blast mechanism remains the most significant opportunity for performance improvement. Future work should investigate alternative inlet orientations and internal channel geometries designed to reduce recirculation zones and promote more uniform particle transport toward collection chambers. A more direct, tunneled flow path would improve collection efficiency and reduce dependence on surface material distribution, which was found to influence collected volume across trials.

Subsurface collection performance should also be a focus of continued development. Widening the collection chamber inlets and reducing the curvature of the material transport path would decrease the likelihood of larger drill chips jamming before reaching the collection volume. Further optimization of peck drilling parameters — including depth per peck, retraction speed, and cycle count — could improve chip geometry consistency and reduce the proportion of large fragments that are unresponsive to the gas blast.

The current prototype was tested under Earth's atmospheric pressure and gravity. Future testing should incorporate a vacuum chamber environment to better replicate Psyche's operating conditions. As the gas-blast thrust calculations indicate, total thrust increases significantly in vacuum, and the absence of atmospheric drag will affect particle trajectories during collection. Characterizing system performance under vacuum conditions is a critical step toward validating the design for spaceflight application.

Thermal management of the drill system requires further study. The drill-tip temperature analysis indicated a strong dependence of peak temperature on operational intensity, and because Psyche's vacuum environment eliminates convective cooling, thermal accumulation during extended drilling cycles poses a risk to tool integrity and system reliability. Development of an optimized drill duty cycle that limits peak temperature while maintaining adequate material removal rates should be pursued.

Finally, coordination with Team 502 on full inter-system integration testing should be prioritized. Validating the sample transfer interface under representative conditions — including repeated handoff cycles and compatibility checks under both nominal and off-nominal scenarios — will be essential for ensuring end-to-end mission success.

References

[1] NASA. (2023, September 20). *The extraordinary sample-gathering system of NASA's perseverance mars rover*. NASA. https://www.nasa.gov/centers-and-facilities/jpl/the-extraordinary-sample-gathering-system-of-nasas-perseverance-mars-rover/

[2] NASA. (2025, March 31). *NASA announces OSIRIS-Rex bulk sample mass - NASA science*. NASA. https://science.nasa.gov/blogs/osiris-rex/2024/02/15/nasa-announces-osiris-rex-bulk-sample-mass

[3] Japan Aerospace Exploration Agency. (n.d.). *Asteroid explorer "hayabusa2."* JAXA. https://global.jaxa.jp/projects/sas/hayabusa2

[4] NASA. (2024, November 10) *"Perseverance's Rock Core From 'Berea' Outcrop"*. NASA. https://science.nasa.gov/resource/perseverances-rock-core-from-berea-outcrop

[5] Moeller, R.C., Jandura, L., Rosette, K. et al. (2021, December 21) *"The Sampling and Caching Subsystem (SCS) for the Scientific Exploration of Jezero Crater by the Mars 2020 Perseverance Rover"*. Space Sci Rev 217, 5. https://doi.org/10.1007/s11214-020-00783-7

[6] Anand, M., Taylor, L. A., Nazarov, M. A., Shu, J., Mao, H.-K., & Hemley, R. J. (2004). Space weathering on airless planetary bodies: Clues from the lunar mineral hapkeite. *Proceedings of the National Academy of Sciences, 101*(18), 6847–6851.

[7] Ahles, A. A., Emery, J. D., & Dunand, D. C. (2021). Mechanical properties of meteoritic Fe-Ni alloys for in-situ extraterrestrial structures. *Acta Astronautica*, 189, 465–475.

[8] **[3]** Burks, M., Friedrich, S., Goldsten, J., Heffern, L., Hines, N., Kim, G.-B., Lawrence, D. J., Mozin, V., & Peplowski, P. (2024). *Measuring the surface abundance of iron and nickel on the asteroid (16) Psyche in the presence of large solar particle events*. Planetary and Space Science, 240, 105832. https://doi.org/10.1016/j.pss.2023.105832

[9] Kalpakjian, S., & Schmid, S. R. (2006). *Manufacturing engineering and technology* (5th ed.). Pearson Prentice Hall.

[10] Cui, J., Hou, X., Wen, G., & Liang, Z. (2019). Thermal simulation of drilling into lunar rock simulant by discrete element method. *Acta Astronautica, 160*, 378–387. https://doi.org/10.1016/j.actaastro.2019.05.002

[11] Suhner Machining. Machining formulas calculator. https://www.suhner-machining.com/fileadmin/user_upload/Machining-Spindeln/MACH-Formeln-Kalkulator_EN.pdf

[12] Colaprete, A., et al. (2015). Impact of drilling operations on lunar volatiles capture. NASA Technical Reports Server (NTRS). https://ntrs.nasa.gov/api/citations/20150011440/downloads/20150011440.pdf

Appendices

Appendix A: Code of Conduct

Mission Statement

Design with rigor, act with integrity, communicate early and often, meet deadlines, protect intellectual property, and support each other as we work together to deepen understanding of the Psyche asteroid.

Outside Obligations

Weekly commitments for each member have been documented and shared via Outlook and When2meet. Team members are required to notify the entire group if their availability changes. Regular meetings will be held every Tuesday or Thursday from 5–7 pm. In addition, Team 501 will meet with Team 502 every Tuesday or Thursday from 5–7 pm. Any additional meetings will be scheduled outside of class hours; members who are unable to attend due to scheduling conflicts (within reason) will not be penalized.

Team Roles

Members will ultimately be responsible for a different task depending on the assignment, ideally based on their expertise. The members are not solely responsible for completing the task, as all assignments should be assisted and reviewed by the entire group; however, there will be a clear distinction between duties and responsibilities. Of the group, one will be designated to submit the assignment, with the responsibility to be determined when the task is assigned.

Dress Code

The dress code for class and team meetings is straightforward and casual. When meeting with the sponsor, the goal is to dress business casual; no uncovered tank tops or novelty shirts. When doing presentations, the dress code will be business to business formal; no jeans, sweatpants, or flip flops. It is important to dress appropriately during meetings.

How to Respond to People in Professional Meeting

When responding to people in a professional meeting, it is important to maintain a positive tone, give kind answers, and speak honestly. Members of the meeting should avoid interrupting each other during responses and should hear the full question/statement before replying. Take moments to consider responses so clear and concise answers are given.

Communication

Communication with team members will be through Microsoft Teams, Slack, Discord, email, text group chat, and in-person group meetings. Scheduling is done through when2meet polling and group discussion with at least 24 hours of notice given before the decided upon meeting time. Any time conflicts will be addressed within the communication methods mentioned. Group members are expected to respond to inquiries within 24 hours.

How to Notify Group

Group members must notify the entire group when there is a change of plans. The location to notify other members is the Team 501 text message group. For absences, notification must be received 24 hours in advance, and not by word of mouth. For other updates or breakthroughs, the group should be notified as soon as possible. Members being notified should react or respond to the message they received within 24 hours to acknowledge that they have read it. Failing to notify the group twice will result in a warning. Three failures will result in the other team members reaching out to the TAs and potentially Dr. McConomy.

Attendance Policy

Meeting times are agreed upon by all members. Meetings that require the presence of all members are scheduled at least one week in advance. If a member needs to miss a meeting, the team will be notified 24 hours in advance. If an emergency occurs, the team must be notified of their absence as soon as possible. Failing to contact the team before or after an absence will not be tolerated. Two missed meetings with failed contact will result in the other team members reaching out to the TAs and potentially Dr. McConomy.

What do we do before Dr. McConomy or TAs

Before reaching out to Dr. McConomy or TAs with respect to behavior or team member shortcomings, the group will collectively talk to the said member. It is important to be blunt yet politically correct in these conversations. It is understandable that sometimes things happen, but this is an important project that relies on team effort and everyone doing their part. Regarding questions about the project or class, any team member can reach out at any time to Dr. McConomy or the TAs.

At what point do we contact Dr. McConomy

It is important that communication is always prompt and constant within the group. As such, if a member fails to contact the group for a whole week or doesn't have their respective work done by Fridays at 2:00pm, this is grounds for contacting Dr. McConomy.

What do you want Dr. McConomy to do when you come

Providing that a group member violates the code of conduct, we would like Dr. McConomy to review our situation and provide us with further guidance.

How to amend

With quorums, amendments pass by four (4) of six (6) votes. 3 to 3 votes are decided by a single coin toss — heads adopt, tails reject — the result is final, amended in the Code of Conduct, and effective immediately unless a later date is specified.

Statement of Understanding

I acknowledge that I have read, understand, and agree to comply with this Code of Conduct. I understand that violations may result in corrective action, and I will seek clarification when it is uncertain.

Michael Gregory	Michael Gregory	9/11/2025
Conner Holmes	Conner Holmes	9/11/2025
Claudia Irausquin	Claudia Irausquin	9/11/2025
Jake Marcus	Jake Marcus	9/11/2025
Janna Rhodes	Janna Rhodes	9/11/2025
Jerry Richardson	Jerry Richardson	9/11/2025

Appendix B: Work Breakdown Schedule

Milestone	Task	Notes	Assigned	Status	Due Date
Code of Conduct				Complete	9/12/2025
	Mission Statement	Define mission statement	Jake	Complete	
	Outside Obligations	Define obligation priority	Michael	Complete	
	Team Roles	Designate team roles	Claudia	Complete	
	Communication	Define how the group will communicate	Jake	Complete	
	Dress Code	Determine appropriate dress code	Conner	Complete	
	Attendance Policy	Draft policy for attendance	Michael	Complete	
	How to notify group	Draft procedure for notifying others	Janna	Complete	
	Respond in Meeting	Responding to people in professional meeting	Jake	Complete	
	Statement of Understanding	Sign statement of understanding	All	Complete	
	Before Dr. McConomy	What do we do before Dr. McConomy	Jake	Complete	
	Contacting Dr. McConomy	At what point do we contact Dr. McConomy	Jake	Complete	
	Dr. McConomy Response	What do you want Dr. McConomy to do	Michael	Complete	
	How to amend	Define procedure to amend code of conduct	Janna	Complete	
	Submit Document	Submission & Update Evidence Manual	Claudia	Complete	
Project Scope					9/19/2025

	Project Description	Describe the project	Claudia	Complete	
	Key Goals	Determine objectives of the project	Claudia	Complete	

	Market		Claudia	Complete	
	Assumptions	Explain any assumptions	Jake	Complete	
	Stakeholders	Who has a say in the project?	Jake	Complete	
	Submit Document	Submission & Update Evidence Manual	Claudia	Complete	
Work Breakdown Structure					9/19/2025
	Define Milestones	Include milestones defined in evidence manual	Michael	Complete	
	Describe Tasks	Break down tasks into enough detail	Claudia	Complete	
	Select Assignees	Assign milestones to individuals/ self-selection	Jake	Complete	
	Submit Document	Submission & Update Evidence Manual	Michael	Complete	
Customer Needs					9/26/2025
	Customer Statement	Provide customers’ statements and questions to customer	Jake	Complete	
	Interpreted Need	Interpret 50% of customer statements	Jake	Complete	
	Explanation of Results	Synthesis information for reader	Jake	Complete	
	Revision and Editing	Revise and edit for final submission	Jerry	Complete	
	Submit Document	Submission & Update Evidence Manual	Conner	Complete	
Function Decomposition					10/3/2025
	Graphics	Generate graphics	Jerry	Complete	
	Explanation of Results	Describe results and their significance	Conner	Complete	
	Connection to Systems	Explain how the results are connected to	Claudia	Complete	
	Smart Integration	Break down each system into subsystems	Claudia	Complete	

	Action and Outcome	Describe the physical action of the outcome	Jake	Complete	
	Function Resolution	How each system and subsystem will work together	Michael	Complete	
	Revision and Editing	Revise and edit for final submission	Claudia	Complete	
	Submit Document	Submission & Update Evidence Manual	Jake	Complete	
VDR1					10/6/2025
	Project Brief Summary	Summarize project brief	Jerry	Complete	
	Project Scope	Summarize project scope	Jake	Complete	
	Customer Background	Summarize customer background	Jake	Complete	
	Customer Needs	Summarize customer needs	Jake	Complete	
	Functional Decomposition	Summarize functional decomposition	Janna	Complete	
	Future Work	Explain future work	Conner	Complete	
	Revision and Editing	All slides should be cohesive. Check for errors.	Conner	Complete	
	Submit Document	Submission & Update Evidence Manual	Janna	Complete	
Targets					10/10/2025
	Functions	List all functions of device.	Conner	Complete	
	Targets to Functions	Connect each function to a target/metric.	Jake	Complete	
	Beyond Targets	Targets address more than just function.	Conner	Complete	
	Method of Validation	Define method(s) for validating targets	Claudia	Complete	
	Derivation of Targets/Metrics	Explain how the targets/metrics were derived	Jake	Complete	
	Discussion of Measurements	Describe what, how, and why we measured	Janna	Complete	
	Critical Targets/Metrics	What is critical to the project	Janna	Complete	
	Summary and Catalog	Overview of targets and metrics	Conner	Complete	
	Revision and Editing	Revise and edit for final submission	Conner	Complete	

	Submit Document	Submission & Update Evidence Manual	Michael	Complete	
VDR1 Corrections					10/14/2025
	Discussion of VDR1 Errors	Discuss and analyze errors, implement fix	Jake	Complete	
	Project Brief Summary	Correct errors	Michael	Complete	
	Project Scope	Correct errors	Claudia	Complete	
	Customer Background	Correct errors	Conner	Complete	
	Customer Needs	Correct errors	Claudia	Complete	
	Functional Decomposition	Correct errors	Claudia	Complete	
	Future Work	Define future work	Conner	Complete	
	Revision and Editing	Revise and edit for final submission	Jerry	Complete	
	Submit Document	Submission & Update Evidence Manual	Jake	Complete	
Concept Generation					10/17/2025
	100 Concepts	Create 100 device concepts	Jake	Complete	
	5 Medium Fidelity Concepts	Explain in detail the 5 medium fidelity concepts	Janna	Complete	
	3 High Fidelity Concepts	Explain in detail the 3 high fidelity concepts	Janna	Complete	
	Concept Generation Tools	Ensure evidence of tools used is in document	Janna	Complete	
	Revision and Editing	Revise and edit for final submission	Jerry	Complete	
	Submit Document	Submission & Update Evidence Manual	Janna	Complete	
Concept Selection					10/24/2025
	House of Quality	Complete and discuss outcomes	Jerry	Complete	
	Pugh Charts	Ensure outcomes of the chart(s) are discussed	Claudia	Complete	
	AHP	Ensure outcome(s) of the chart(s) are discussed	Janna	Complete	
	Final Selection	Select final concept, provide justification	Michael	Complete	
	Revision and Editing	Revise and edit for final submission	Jake	Complete	

	Submit Document	Submission & Update Evidence Manual	Janna	Complete	
VDR2					11/13/2025
	Create PowerPoint		Janna	Complete	
	Time Duration	Rehearse and time presentation	Michael	Complete	
	Revision and Editing	Revise and edit for final submission	Michael	Complete	
	Submit Document	Submission & Update Evidence Manual	Jake	Complete	
Bill of Materials					11/14/2025
	Fill Out Line Items	Define materials and items needed	Claudia	Complete	
	Identify Vendors	Source parts and identify vendors	Jake	Complete	
	Quantify Unit Costs	Document unit costs	Michael	Complete	
	Quantify Labor Costs	Document labor costs	Michael	Complete	
	Revision and Editing	Revise and edit for final submission	Jerry	Complete	
	Submit Document	Submission & Update Evidence Manual	Claudia	Complete	
Technology Demonstration of Prototype					12/2/2025
	Physical Prototype	Construct prototype and validate functions	Conner	Complete	
	Report	Write report describing the prototype	Jerry	Complete	
	Mock Presentation	Run through a rehearsal to prepare	Jake	Complete	
Spring Project Plan					12/5/2025
	Project Progress Timeline	Timeline of future deliverables	Michael	Complete	
	Final Design	Final design selection and why	Jerry	Complete	
	Submit Report	Submission & Update Evidence Manual	Jake	Complete	
Poster					12/5/2025
	Design Poster	Create poster describing final design	Conner	Complete	
	Submit Document	Submission & Update Evidence Manual	Jake	Complete	

Appendix C: Stakeholders and Customer Needs

Table 1. ***Stakeholder Breakdown***

	Investors	Decision- Makers	Advisors	Receivers
Cassie Bowman		X	X	X
Shreyas Balachandran			X	
Dr. McConomy			X	
Arizona State University	X		X	X
NASA	X			X

Table 2. ***Customer Needs***

Question	Customer Statement	Interpreted Need
Will we be creating a rover with the extraction system?	You can use a rover from previous missions as a base for the sampling.	The system operates as a hosted payload already on the asteroid.
What are the current estimates of seasonal and diurnal temperature variations on the surface of the asteroid?	For this question, please take a look at the Bierson 2022 paper in the Psyche Research Papers folder.	Estimate for Seasonal is >100K. The estimate for is Diurnal <10K. The system survives large temperature swings.
Can we assume a specific season for the mission? Can we assume a specific region?	Yes, you can determine this. Yes.	The mission can take place in any season we choose; also, any specific region of the asteroid.
Are we assuming that the sampling system is already on the asteroid?	Yes, assume the sample is delivered and mounted on host. Operations are command-level sequences.	The system operates as a hosted payload already on the asteroid.
What sample type (metal, metal-silicate, regolith, sub surface) should take priority?	You should collect a variety of samples to accurately reflect the composition of the asteroid.	The system collects a variety of materials across distinct surface types.
Do we have to follow NASA's current planetary protection provisions for robotic extraterrestrial missions?	It is a good idea, though Psyche is not in the most restrictive category.	The system follows the planetary protection requirements that are defined by the mission type.
How much sample should we extract from Psyche?	Benchmark quantity of material collected based on	The quantity of samples to extract is close to that of similar missions with respect to volume.

	similar missions. Use volume as a measurement.	
What is the size limit of our prototype?	Up to design team, this will be something to be decided upon with T502.	The size of the system is compatible with T502’s device.
What is the weight limit of our prototype?	Up to design team, use benchmarking and justify your decision.	The weight of the system is compatible with T502’s device.
Does our prototype simulation need to function with both Earth’s gravity and Psyche's gravity?	A physical prototype should only use Earth’s gravity. A simulation should ideally be in Psyche’s gravity.	The physical prototype functions with Earth’s gravity, and any system simulations function with Psyche’s gravity.
How many samples should the device extract? Continuous extraction or a max number of extractions per mission?	Use benchmarking with previous missions to decide this.	Sample extraction requirements are like those of previous missions.
Will the device need to collect data while extracting samples?	That would be ideal, but likely outside of your scope.	The device can collect extracting data.
Should our prototype take samples from multiple locations?	It is up to you, justify your answer.	The system collects samples across distinct surface types, which vary with location.
As we plan to build a prototype, which surface types should we prioritize for testing? There is a document in the Psyche research folder outlining the construction of simulated test surfaces—should we use this as our reference?	Yes, the document identifies easy-to-access materials for what we might expect to find at Psyche.	The surface types for prototype testing match similarly to the referenced Psyche research document.
How deep into Psyche should we take samples from? (Surface level, subsurface?)	Benchmark off current rover sampling operations on similar surfaces.	The system acquires surface material and subsurface material.

Appendix D: Functional Decomposition

Table 3 ***Cross-Reference of Functional Decomposition***

Systems				
Functions	Cache	Sample	Transfer	Sum
Store Sample	X	X	X	3
Measure Amount Extracted	X	X		2
Protect Sample	X	X	X	3
Transfer Contents to T502	X		X	2
Stabilize Device		X		1
Extract Sample		X		1
Transfer Sample for Cache	X		X	2
Sterilize Contents	X	X		2
Sum	6	6	4	14

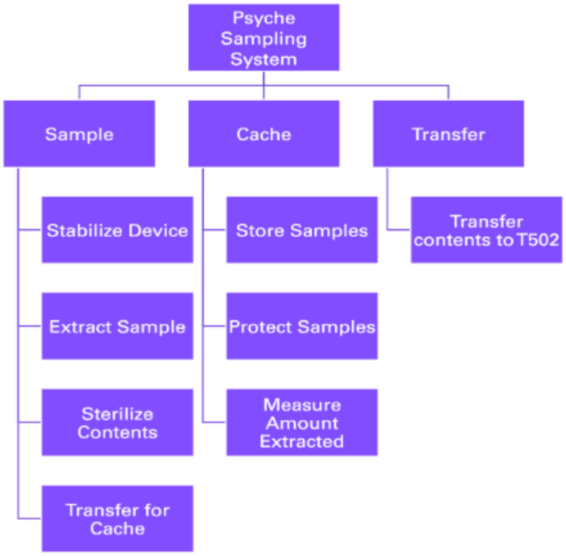


Figure 1 Hierarchy Chart of Functional Decomposition

Appendix E: Target Catalog

Table 4 *Metrics and Targets for Critical Functions*

Function	Metric	Target
Extract Samples	Quantity (samples) Volume (cm^3)	8 samples 6 -10 cm^3 per sample
Store Samples	Quantity (samples)	10 samples
Protect Samples	Failure Rate (%)	12.5% or 1 sample
Measure Amount Extracted	Accuracy (%)	±10.0%
Transfer Contents to T502	Pass/Fail	Pass
Transfer Samples to Cache	Failure Rate	12.5%
Prevent Cross-Contamination	Carryover (%)	<1%
Withstandable Temperatures	Kelvin (K)	100 K - 200 K
Capability of Collecting Varied Samples	Pass/Fail (Metallic vs Non-Metallic)	Pass
Stabilize Device	Pass/Fail	Pass
Automated Process	Pass/Fail	Pass

Appendix F: Concept Generation

F.1 Concept Generation Table

#	Name	Method of Generation	Description
1	Rotary Core Drill	Ideation	A drill with a hollow coring bit penetrates the surface and captures a sample inside the collection tube.
2	Percussive Drilling with Auger System	Ideation	A percussive drill slams Psyche's surface to loosen materials, then an auger feeder rotates materials up to the collection system.
3	Percussive Drilling with Gas Guiding System	Ideation	After the percussive drill slams the surface to loosen materials, gas is used to guide materials to the collection chamber.
4	Raking/Sweeping Mechanism	Ideation	An arm with a rake sweeps surface debris into sample containment.
5	Laser-Based Sampling	Ideation	A pulsed laser targets a spot, vaporizing the material into a collection bin.
6	Projectile and Collection Arm	Ideation	A projectile is shot into the surface; debris loosened from impact is collected via a collection arm and stored in rotating tubes.
7	Harpoon	Ideation	A tethered harpoon shot into the surface dislodges materials and traps them in ridged edges as it is pulled back.
8	Adhesive Pad	Ideation	An adhesive pad attached to an arm presses into the surface to collect materials, then drops the pad into the collection chamber.
9	Claw Arm	Ideation	A claw is used to grab material from the surface and place it into a collection bin.
10	Explode and Collect	Ideation	An explosive detonates on the surface, and the rover drives into the floating debris to collect materials in a bin.
11	Magnetic Collection	Ideation	Uses magnets on magnetic materials to collect metallic particles from Psyche's surface.

12	Traditional Excavator	Ideation	A small rover design similar to an excavator uses raking and bucketing techniques to gather materials.
13	Bucket Wheel Excavator	Ideation	A jagged-edged wheel spins to dislodge and collect materials, dropping them into a collection bin behind the wheel.
14	Cryogenic Freezing and Shattering	Ideation	Uses cryogenics to freeze materials to extremely low temperatures, then a percussive device shatters them for collection.
15	Tethered Hooks	Ideation	Multiple hooks tethered to the rover are deployed into the surface to dislodge materials as the rover moves forward.
16	High-Powered Explosive	Anti-Problem	High-power explosives eject materials into space; concept used to define limits of destructive sampling.
17	Collection Dome	Anti-Problem	A dome placed over an explosive site to contain and capture debris ejected by a high-powered explosion.
18	Spinning Mechanism Failure	Anti-Problem	A spinning tool flings materials away due to microgravity; illustrates instability problem.
19	Spinning Collection System	Anti-Problem	A solution using barriers and tuned rotation speeds to prevent material loss during spinning collection.
20	Electrostatic Repulsion	Anti-Problem	A device that unintentionally repels desired materials due to charge mismatch.
21	Electrostatic Attraction	Anti-Problem	A device that uses charge attraction to collect metallic dust and particles.
22	Slippery Mechanism	Anti-Problem	A surface too smooth to retain collected material, causing it to slip away in microgravity.
23	Sticky Mechanism	Anti-Problem	A surface engineered with adhesive material to ensure captured particles stay attached until stored.
24	Gas Ejection System Failure	Anti-Problem	A gas burst dislodges materials uncontrollably, sending them into space.

25	Guided Gas Mechanism	Anti-Problem	Uses angled gas bursts to guide loosened materials into a controlled collection path.
26	Adaptive Extraction System	Crap Shoot	System determines terrain viability and chooses whether extraction should occur to prevent tool damage.
27	Replaceable Extraction Drills	Crap Shoot	System has changeable one-use drill heads that can be swapped when damaged by unexpected terrain.
28	Folding Thermal Processing System	Crap Shoot	A thermal management unit unfolds from the main rover to prevent overheating during extraction and transfer.
29	Insulated Sample Capsules	Crap Shoot	Compact insulated capsules protect newly extracted samples from heat transfer and contamination.
30	Regolith Brush Pre-Cleaner	Crap Shoot	System brushes away regolith before extraction to prevent contamination of the drill and sample.
31	Regolith as Sample	Crap Shoot	System collects surface regolith directly and seals it as a sample without further drilling.
32	Mechanical Pulsed Drill	Ideation	A drill that uses pulsed impacts to avoid overheating in a vacuum while coring the surface.
33	Thermal Control Drill System	Ideation	Transfers heat away from both drill and asteroid metal to allow continuous operation without overheating.
34	Perimeter Drilling Core Extraction	Ideation	Small drill makes circular holes around a region so the center core can be pulled out as a single sample.
35	Drill-as-Containment	Ideation	Drill bit doubles as the containment chamber; the bit seals at the bottom after extraction.
36	Percussive Funnel Sampler	Ideation	A conical percussive bit surrounded by a funnel collects loose fragments directly into containment.
37	Wedge-Blade Scraper	Ideation	A wedged blade runs at an angle to scrape thin surface layers, pushing shavings into a vacuum chute.

38	Tube Corer with Detachable Sleeve	Ideation	A coring tube with an inner sleeve that detaches and seals the sample for reuse of the outer housing.
39	Ultrasonic Surface Sampler	Ideation	A vibrating probe loosens nearby material, which is drawn into a small collector.
40	Helical Drill Bit Sampler	Ideation	Helical drill shards are retained as samples; the bit may be left attached if fragments jam in grooves.
41	Drag Net Collection System	Ideation	A rover drags a durable net behind it to gather surface regolith and later drop it for pickup.
42	Grinding Capsules	Ideation	Small capsules attach to the surface and grind material away, self-sealing after a set time.
43	Cryogenic Jet Cutter	Ideation	Uses a “water-jet”-like stream of cryogenic liquid to cut and dislodge surface material.
44	Electric Discharge Machining (EDM) Cutter	Ideation	A portable EDM arc cuts metallic material using controlled electrical discharges.
45	Explosive Containment Net	Ideation	A net secured around a surface region contains debris after an explosive charge detonates inside.
46	Frequency-Assisted Drill	Ideation	Applies natural resonance frequencies of materials to reduce drilling resistance and energy cost.
47	Hydraulic Breaker with Magnet Mount	Ideation	A hydraulic hammer anchored by a magnet pulverizes surface sections for collection.
48	Ionizing Radiation Pre-Treatment	Ideation	Uses radiation pulses to embrittle metal, making it easier to fracture for sampling.
49	Multi-Drill Sander Array	Ideation	Multiple short drills mounted on a rotating platform work like a sander to abrade the surface.
50	Portable Trepanning Device	Ideation	A compact coring device extracts intact circular samples, separating collection and drilling operations.
51	Laser Firing Mechanism	Ideation	Uses multiple high-energy laser pulses to break material loose from the surface for collection.

52	Thermal Heater Cutter	Ideation	Applies directed heat (like a flamethrower) to soften and separate surface material for sampling.
53	Sticky Hand Collector	Ideation	A sticky pad or “hand” is launched onto the surface to grab loose debris and retracts with samples attached.
54	Diamond Chain Saw	Ideation	A rotating chain embedded with diamond teeth cuts into metallic rock for later collection.
55	Adhesive Wheel Collector	Ideation	A tank-like wheel coated with adhesive gathers fine regolith while rolling over the surface.
56	Chemical Etching Sampler	Ideation	Uses chemical agents to dissolve or weaken metal, producing larger sample volumes with fewer extractions.
57	Wire EDM Cutter	Ideation	A precision wire EDM system slices through surface metal, producing clean sample cross-sections.
58	Grinder Sampling System	Ideation	A grinder mounted on a robotic arm abrades the surface; a hood collects ejected material into a sealed compartment.
59	Percussive Drill Sampling System	Ideation	A jackhammer-style percussive drill fractures the surface, and loosened material is collected from debris.
60	Adhesive Collection Arm	Ideation	A rover arm with an adhesive tip lifts loose regolith and deposits it into a sample tube for storage.
61	Timed Explosive Sampling	Ideation	Controlled explosives loosen material at predetermined sites; the rover later returns to collect debris.
62	Magnetic Tube Collection	Ideation	A magnetized tube lowers to the surface to attract and seal magnetic particles for storage.
63	Dual Trepanning Drill System	Ideation	Two trepanning drills at opposing angles cut and extract a core for secure collection.
64	Rotating Cone Grinder	Ideation	An angled grinder rotates 360° to carve out a conical section of material that is later stored.

65	Horizontal Coring and Vertical Cutting Arm	Ideation	A dual-tool arm drills horizontally and cuts vertically to free and collect cylindrical samples.
66	Electromagnetic Hover Collector	Ideation	A hovering electromagnet sweeps above the surface to pick up metallic dust and particles.
67	Percussive Hammer and Retrieval System	Ideation	A hammer fractures surface material; a second arm retrieves fragments for storage.
68	Auger Corer	Ideation	An auger collects loose regolith while a nested coring bit retrieves an intact core.
69	Conically Rotating Drill Bit	Ideation	A small angled drill rotates to carve a cone; a tube then captures the freed piece.
70	Laser Cone Sampler	Ideation	Uses an angled rotating laser to cut a conical section, which is collected by a retractable tube.
71	Dredging Net Collector	Ideation	A deployable net trails the rover to capture dislodged debris as it moves past sampling sites.
72	Non-Physical Data Collection	Ideation	Collects only spectral data using LIBS analysis rather than physical samples.
73	Ultrasonic Drill with Funnel	Ideation	An ultrasonic impactor loosens material into a surrounding funnel for isolation and storage.
74	Auger-Drill Funnel Collector	Ideation	Auger motion lifts regolith into a funnel that directs material into sealed vials.
75	Aerogel Funnel with Air Blast	Ideation	Air blasts lift particles that become embedded in an aerogel-lined funnel for capture.
76	Large-Impact Funnel System	Ideation	A high-velocity conical impactor fractures material; a funnel above collects flying fragments.
77	Coring Drill with Diamond Bit	Ideation	A crown-shaped bit with diamonds bores into metal, feeding loosened material into storage.
78	Ultrasonic + Auger System	Ideation	Ultrasonic drill loosens particles while a surrounding auger lifts them into storage.

79	Auger + Small Funnel	Ideation	An auger spins within a small surface funnel to push loosened material into sealed vials.
80	Scoop Method	Ideation	A 45-degree angled bit continuously impacts the surface, propelling fragments into a collection funnel.
81	Dual Scoop Method	Ideation	Two angled bits strike alternately to loosen material from multiple directions for capture.
82	Ultrasonic + Air Blast	Ideation	Air jets remove regolith as ultrasonic impacts break up material, directing it into a small funnel.
83	Compaction Storage System	Ideation	Collected regolith is compressed in sealed tubes for high-density storage and minimal volume.
84	Octo-Grab	Biomimicry	Tentacle-like arms scoop material using a central beak; inspired by octopus motion and grip.
85	Trunc	Biomimicry	A trunk-like extension suctions material from the ground through a central vacuum tube.
86	Klaw	Biomimicry	Claw mechanism inspired by burrowing mammals digs and lifts metallic regolith.
87	Hammar	Biomimicry	A hammer tool mimics chimpanzees cracking shells; used to break tough metallic crusts.
88	Sharp	Biomimicry	A beak-like percussive tool inspired by hummingbirds removes small bits of hard material.
89	Electro-Gel Scoop	SCAMPER	A flexible electro-gel scoop stiffens under charge, conforming to surface texture for efficient pickup.
90	Dry Ice Sampler	SCAMPER	Uses sublimating CO_2 pellets to fracture surface layers through expansion.
91	Laser-Vacuum Hybrid	SCAMPER	Combines a pulsed laser to loosen debris with a synchronized vacuum cone for instant collection.
92	Magneto-Adhesive Arm	SCAMPER	Blends magnetic claws and adhesive pads to collect both ferrous and non-ferrous materials.

93	Honeybee Collector	SCAMPER	Oscillating charged bristles sweep metallic dust into micro-cells, inspired by bee pollen gathering.
94	Sandfish Burrower	SCAMPER	A tapered oscillating probe “swims” into regolith like a sandfish lizard, drawing samples backward.
95	Expandable Corer	SCAMPER	A coring bit that expands radially once inserted to retrieve a larger sample with minimal entry.
96	Micro-Impact Array	SCAMPER	Cluster of micro-hammers produces distributed low-force strikes to prevent ejecta escape.
97	Thermal Regolith Shield Reuse	SCAMPER	Repurposes thermal shields as domes to trap ejecta during drilling operations.
98	Thruster Exhaust Sampler	SCAMPER	Reverses attitude thrusters to blow loosened material toward an intake port for collection.
99	Inverted Air-Blast Collector	SCAMPER	Uses suction instead of blowing to pull particles upward from the impact site.
100	Back-Mounted Hammer	SCAMPER	Anchors the tool tip first, then pulls backward to shear off samples instead of striking down.

F.2 Concept Generation Tools

<u>Crap Shoot</u>

The crap shoot method was used to derive six generated concepts. Three dice were rolled and the numbers obtained from each dice correlate to the chart below. If a six was rolled, the dice was rolled again, since the chart contains five parts for each die. Mixing environmental constraints, device activities, and other important factors allowed concepts to be generated from ideas that were not combined previously.

	Die 1 Environmental Constraint	Die 2 Activity	Die 3 Important Factor
1	Lots of Regolith	Extract	Fast Sampling
2	Extreme Temps	Protect	Prevent Contamination

3	Microgravity	Measure	Compact Design
4	Unexpected Terrain	Transfer	Precision Sample Collection
5	High Radiation	Sample Collection	Repeatable Collection

Roll 1 – Unexpected Terrain – Extract – Repeatable Collection

Resulting Idea 1: System determines viability of extraction surface and chooses to extract based on if the terrain surface will damage the extraction tool.

Resulting Idea 2: System has changeable, 1-use extraction drills in case of damage when extracting on unexpected terrain.

Roll 2 – Extreme Temps – Transfer – Compact Design

Resulting Idea 1: Thermal processing system that can unfold from main rover to prevent overheating in system and sample and avoid damage when transferring

Resulting Idea 2: Insulation built into compact transfer capsules to protect the system when holding newly extracted samples.

Roll 3 – Lots of Regolith – Extract – Prevent Contamination

Resulting Idea 1: System brushes away regolith before extracting to avoid regolith particles contaminating drill and system

Resulting Idea 2: System scoops regolith and uses the regolith as the sample, making sure to contain it

Biomimicry

Five ideas were generated using biomimicry. Characteristics of animals and nature were developed into mechanical designs that mimic natural processes to solve the problem of extracting samples on the Psyche asteroid.

Octo-Grab: Body with tentacle-like arms that extend to scoop up material with a sharp beak to break up harder metallic areas. The idea comes from biomimicry of how octopus use their arms and beak to manipulate and maneuver their environment.

Trunc: Trunk-like extension that grabs material from the ground, with a suction device in the center

Klaw: Claw at the end of an arm to break up tightly packed materials. Inspiration comes from many mammals which use their claws to dig material. Material storage could be done via vacuum, or scoop as many animals do. Examples on animals which do this include badger, sloth, jaguar, eagle, etc.

Hammar: Hardened hammer that swings down to smash material in order to break it up for removal. Material collection is then done with a robotic hand. Inspiration comes from the chimpanzees which used stone hammers to break open nuts and other tough objects.

Sharp: Beak-like tip used to percussively impact hard surfaces, material to then be collected by robotic claw/scoop. Inspiration comes from hummingbirds and how they use their beaks to remove material from the tough outsides of trees.

Battle of Perspectives

Battle of perspectives was one of the methods used to generate concepts. Some comparisons were rock vs metal and cutting vs braking. Psyche's surface is speculated to be more metallic than rocky. However, most sampling data for outer space is dependent on missions that took place on rocky surfaces. Hence, some concepts were made with these two competing surfaces in mind. For example, a concept using trepanning was created with "metallic" in mind, while a concept with a form of grinder was made with "rocky" in mind. Cutting out material from the surface would be a method of sampling as opposed to breaking it and obtaining smaller broken pieces. Using "breaking" contributed to generating the idea of freezing a surface on Psyche and generating a force to shatter it to gather specimens. The opposing perspective of "cutting" helped in generating the idea of using a metallic cutter to gather material.

SCAMPER

The SCAMPER concept generation technique is a structured method used to inspire creativity in concept generation. The name SCAMPER is an acronym that stands for Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse. Each prompt serves as a different lens for creative exploration: substituting materials or components to improve performance, combining elements to create new functions, adapting designs for different uses, modifying size or shape to enhance usability, finding alternative applications, eliminating unnecessary parts to simplify, and reversing or rearranging elements to reveal fresh possibilities. By systematically applying these seven approaches, SCAMPER allowed T501 to generate a wide range of innovative ideas and improvements, making it a valuable tool in design, engineering, and problem-solving.

Electro-gel scoop – Replace rigid scoops with a soft electro-gel that stiffens when charged, conforming to surface texture to collect material efficiently. S from SCAMPER

Dry ice sampler – Substitute mechanical impact with sublimating CO_2 pellets that fracture the surface as they expand. S from SCAMPER

Laser-vac hybrid – Combine a pulsed laser to loosen particles with a synchronized vacuum cone that collects debris instantly. C from SCAMPER.

Magneto-adhesive arm – Merge a magnetized claw with adhesive micro-pads so both ferrous and non-ferrous materials can be retrieved. C from SCAMPER

Honeybee collector – Adapt the honeybee's pollen-brush system: oscillating micro-bristles coated with static charge sweep metallic dust into micro-cells. A from SCAMPER.

Sandfish burrower – Adapt the motion of sandfish lizards; a tapered oscillating probe that "swims" into regolith, drawing samples backward as it vibrates. C from SCAMPER.

Expandable corer – Modify the coring bit to expand radially once inside the surface, retrieving larger samples with minimal entry hole. M from SCAMPER.

Micro-impact array – Miniaturize the impact concept: a cluster of micro-hammers creating distributed low-force strikes to reduce risk of ejecta escape. M from SCAMPER.

Thermal regolith shield reuse – Repurpose thermal shields as temporary collection domes post-landing to trap ejecta during drilling. M from SCAMPER.

Thruster exhaust sampler – Use the lander's attitude-control thrusters in reverse bursts to blow loosened particles toward an open intake port. M from SCAMPER.

Inverted air-blast – Instead of blowing air at the surface, create suction above the impact site that pulls released particles upward. R from SCAMPER.

Back-mounted hammer – Reverse the hammer placement: anchor the tip to surface first, then use a rear actuator to pull backward, shearing off a sample instead of striking down.

Anti Problems:

High-powered explosive – Explosives of such high power used that materials shot into space, out of reach to be collected.

Solution: Collection Dome

Reasoning: Microgravity is the cause of the problem as the materials fly into space after explosive detonation, so collection method over explosive area is solution.

Spinning Mechanisms – Mechanism spins too fast causing materials to fly off mechanism due to centrifugal forces and microgravity.

Solution: Spinning Collection method with barriers and attuned speeds

Reasoning: Spinning methods can be used as long as barriers to prevent materials from flying off at the edges and speeds attuned to the local gravity.

Electrostatic Repulsion – Device that repels desired materials due to charge repulsion.

Solution: Electrostatic Attraction

Reasoning: Device that attracts desired materials due to charge attraction.

Slippery Mechanism – Device with materials too slippery that grabbing materials is and holding them as guided to collection is too difficult as they slip off.

Solution: Sticky Mechanism

Reasoning: Device that materials stick to after grabbed so they do not fall off due to microgravity and slippery surfaces allowing the materials to be brought to collection bin.

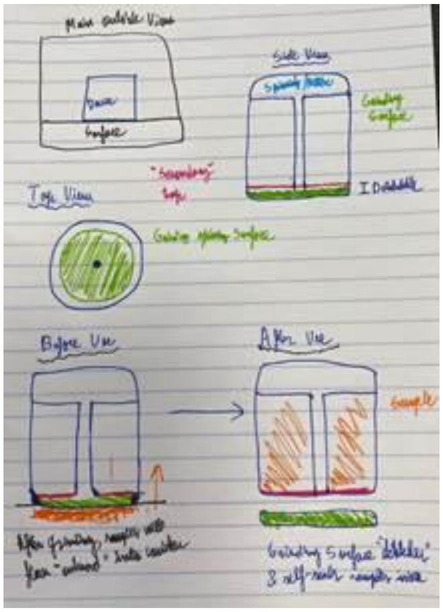
Gas Mechanism – A gas mechanism that flows bursts into the surface that causes the materials to float away into space.

Solution: Gas Mechanism with Guidance

Reasoning: A gas mechanism that bursts gas into the surface at an angle that guides the materials into a engineered collection path that leads to the collection chamber.

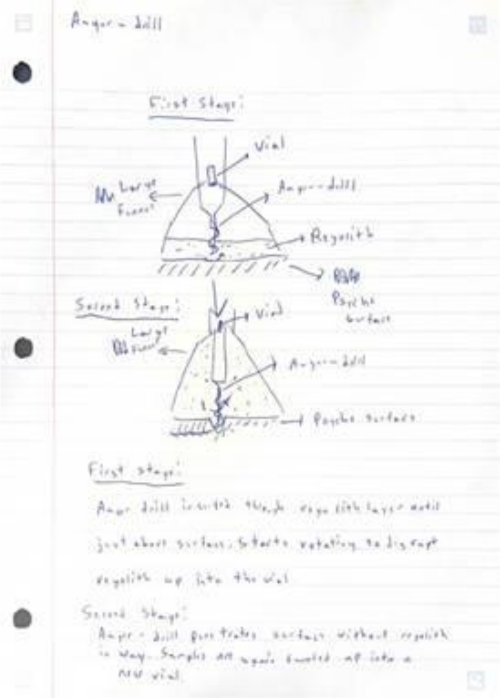
F.3 Images for generated concepts

Idea #38



Idea #48

Idea #58



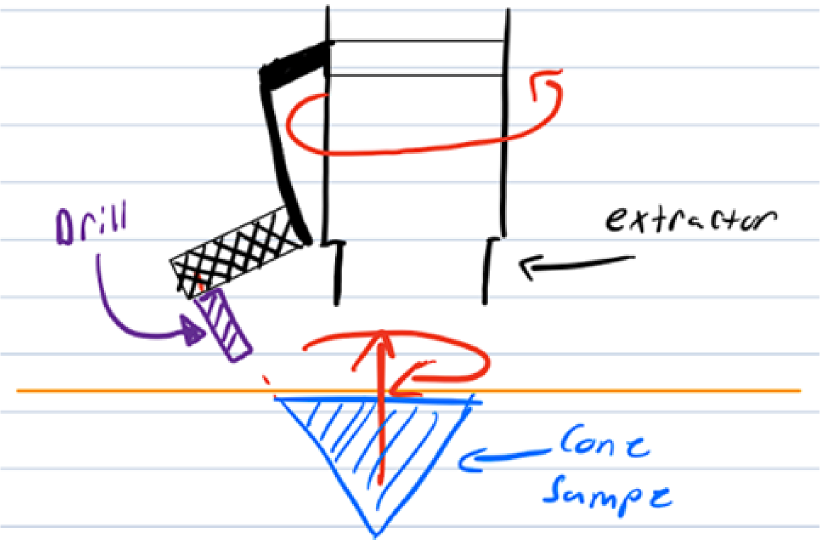
First stage:

Auger drill inserted through regolith layer until just about surface; starts rotating to disrupt regolith up into the vial

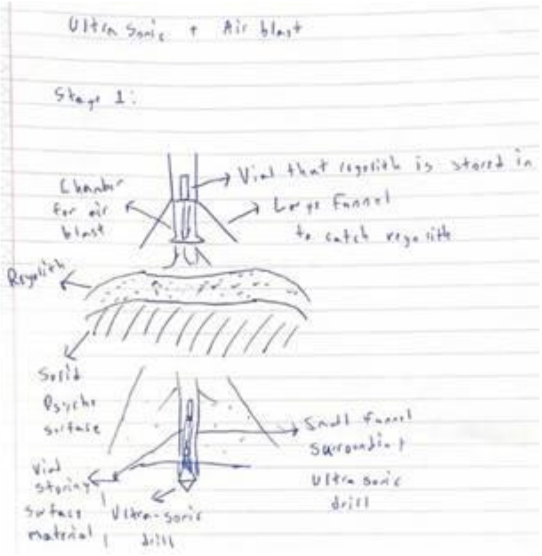
Second Stage:

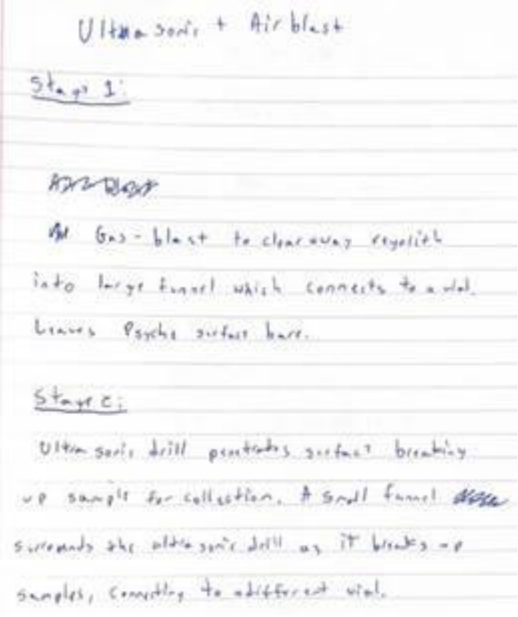
Auger-drill penetrates surface without regolith in way. Samples are again funneled up into a new vial

Idea #69



Idea #70





Ultra sonic + Air blast

Stage 1:

~~Air Blast~~

~~Ai~~ Gas - blast to clear away regolith into large funnel which connects to a vial. Leaves Psyche surface bare.

Stage 2:

Ultra sonic drill penetrates surface breaking up sample for collection. A small funnel surrounds the ultra sonic drill as it breaks up samples, connecting to a different vial.

Appendix G: Concept Generation Tables

Table 1-G. House of Quality Chart

		Engineering Characteristics													
Improvement Direction		↑	↑	↑	↑	↓	↓	↓	↑	↓	↓	↓	↑	Pass	↑
Units		Units	Units	Units	%	kg	cm^3	N	K	Units	%	s	%	Pass/Fail	mm
Customer Requirements	Importance Weight Factor	Quantity of extracted sample	Quantity of sample types	Quantity of stored samples	Accuracy of sample measurements	Mass of completed cache	Size of completed cache	Required counter force supplied by rover	Material functionality	Steps taken to move sample into storage	Amount of cross-contamination	Time of Sampling Process	Reliability of Sampling System	Sample Stratigraphy	Depth of Sample Taken from Surface
1. Compatible for handoff	4			1		9	9		3						
2. Multiple samples	1	9	9	3	1	3	1		3				9	1	3
3. Surface & Subsurface Material	1	1	9	1	1	1			3			3	3	9	9
4. Sample Integrity	1						3	3	9	3	9	1	3	9	1
5. Withstand temp swings	4								9				1		3
6. Automation	4	1	1	1			1	3		9		3			
Raw Score	339	14	22	12	2	40	44	15	63	39	9	16	19	19	25
Relative Weight %		4.13	6.4897	3.54	0.59	11.8	12.98	4.425	19	11.5	2.65	4.72	5.605	5.60472	7.375
Rank Order		11	6	12	14	3	2	10	1	4	13	9	8	7	5

Table 2-G. Binary Pairwise

Binary Pairwise Matrix							
	1	2	3	4	5	6	**Total**
1. Compatible for handoff with Team 502 system.	-	0	0	0	0	1	**1**
2. Takes multiple samples.	1	-	0	1	1	1	**4**
3. Acquires surface and subsurface material.	1	1	-	0	1	1	**4**
4. Keeps integrity of each sample.	1	0	1	-	1	1	**4**
5. Withstands large temperature swings.	1	0	0	0	-	0	**1**
6. Automated	0	0	0	0	1	-	**1**
Total	**4**	**1**	**1**	**1**	**4**	**4**	

Table G-3. First Iteration of Pugh Chart

	Datum	**Concepts Part 1**							
Selection Criteria	**Perserverance Rover**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Steps Taken to Move Sample into Storage		+	-	-	S	S	-	-	-
Sample Stratigraphy		S	+	-	S	-	S	-	S
Time of Sampling Process		+	-	-	S	+	-	-	+
Depth of Sample Taken from Surface		S	+	+	+	+	-	-	+
Required counter force supplied by rover		-	-	+	S	+	+	+	+
# Pluses		2	2	2	1	3	1	1	3
# Minuses		1	3	3	0	1	3	4	1

Table G-4 Second Iteration of Pugh Chart

	Datum	Concepts Part 2				
Selection Criteria	1	3	4	5	6	8
Steps Taken to Move Sample into Storage		S	-	+	-	S
Sample Stratigraphy		S	S	-	-	S
Time of Sampling Process		-	-	-	-	-
Depth of Sample Taken from Surface		-	S	-	-	S
Required counter force supplied by rover		+	S	+	+	+
# Pluses		1	0	2	1	1
# Minuses		2	2	3	4	1

Table G-5 Final Iteration of Pugh Chart

	Datum	Concepts Part 3		
Selection Criteria	8	3	4	5
Steps Taken to Move Sample into Storage		+	S	+
Sample Stratigraphy		S	+	-
Time of Sampling Process		-	+	-
Depth of Sample Taken from Surface		+	+	-
Required counter force supplied by rover		-	-	-
# Pluses		2	3	1
# Minuses		2	1	4

Table G-6. General Criteria Comparison Matrix

Criteria Comparison Matrix						
	1	2	3	4	5	**Total**
Steps Taken to Move Sample into Storage	1	0.20	1	0.2	0.11	**2.51**
Sample Stratigraphy	5	1	5	0.2	0.2	**11.40**
Time of Sampling Process	1	0.2	1	0.11	0.11	**2.42**
Depth of Sample Taken from Surface	5	3	9	1	1	**19.00**
Required Counter Force Supplied by rover	9	5	9	1	1	**25**
Total	**21**	**9.40**	**25**	**2.51**	**2.42**	

Table G-7. General Normal Comparison Matrix

Normalized Comparison Matrix						
	1	2	3	4	5	**Criteria Weights**
Steps Taken to Move Sample into Storage	0.048	0.021	0.040	0.080	0.046	**0.047**
Sample Stratigraphy	0.238	0.106	0.200	0.080	0.083	**0.141**
Time of Sampling Process	0.048	0.021	0.040	0.044	0.046	**0.040**
Depth of Sample Taken from Surface	0.238	0.319	0.360	0.398	0.413	**0.346**
Required Counter Force Supplied by rover	0.429	0.532	0.360	0.398	0.413	**0.426**
Sum	**1**	**1**	**1**	**1**	**1**	**1.000**

Table G-8. General Consistency Check Table

Consistency Check		
Weighted Sum Vector	Criteria Weights	Consistency Vector
0.231	0.047	4.937
0.729	0.141	5.159
0.201	0.040	5.043
1.789	0.346	5.174
2.259	0.426	5.299

Table G-9. AHP for Steps Taken to Move Sample into Storage

Steps Taken to Move Sample into Storage			
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules
Ultrasonic Corer	1	1	0.143
Corer with Gas Blast	1	1	0.111
Grinding Capsules	7	9	1
Sum	9	11.000	1.254

Table G-10. Normalized AHP for Steps Taken to Move Sample into Storage

Normalized Steps Taken to Move Sample into Storage [NormC]				
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules	Design Alternative Priorities {Pi}
Ultrasonic Corer	0.111	0.091	0.114	0.105
Corer with Gas Blast	0.111	0.091	0.089	0.097
Grinding Capsules	0.778	0.818	0.797	0.798
Sum	1	1	1	1

Table G-11. Consistency Check for Steps Taken to Move Sample into Storage

Consistency Check				
Weighted Sum Vector	Consistency Vector		λ	3.007
0.316	3.002		n	3
0.291	3.002		CI	0.004
2.407	3.017		RI	0.52
			CR	0.007

Table G-12. AHP for Sample Stratigraphy

Sample Stratigraphy			
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules
Ultrasonic Corer	1	1	9.000
Corer with Gas Blast	1	1	9.000
Grinding Capsules	0.111	0.111	1
Sum	2.111	2.111	19.000

Table G-13. Normalized AHP for Sample Stratigraphy

Sample Stratigraphy [NormC]				
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules	Design Alternative Priorities {Pi}
Ultrasonic Corer	0.474	0.474	0.474	0.474
Corer with Gas Blast	0.474	0.474	0.474	0.474
Grinding Capsules	0.053	0.053	0.053	0.053
Sum	1	1	1	1

Table G-14. Consistency Check for Sample Stratigraphy

Consistency Check				
Weighted Sum Vector	Consistency Vector		λ	3.000
1.421	3.000		n	3
1.421	3.000		CI	0.000
0.158	3.000		RI	0.52
			CR	0.000

Table G-15. AHP for Time of Sampling Process

Time of Sampling Process			
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules
Ultrasonic Corer	1	0.2	1.000
Corer with Gas Blast	5	1	3.000
Grinding Capsules	1	0.333	1
Sum	7	1.533	5.000

Table G-16. Normalized AHP for Time of Sampling Process

Time of Sampling Process [NormC]				
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules	Design Alternative Priorities {Pi}
Ultrasonic Corer	0.143	0.130	0.200	0.158
Corer with Gas Blast	0.714	0.652	0.600	0.655
Grinding Capsules	0.143	0.217	0.200	0.187
Sum	1	1	1	1

Table G-17. Consistency Check for Time of Sampling Process

Consistency Check				
Weighted Sum Vector	Consistency Vector		λ	3.029
0.476	3.015		n	3
2.005	3.058		CI	0.015
0.563	3.015		RI	0.52
			CR	0.028

Table G-18. AHP for Time of Sampling Process

Depth of Sample Taken from Surface			
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules
Ultrasonic Corer	1	0.143	3.000
Corer with Gas Blast	7	1	9.000
Grinding Capsules	0.333	0.111	1
Sum	8.333	1.254	13.000

Table G-19. Normalized AHP for Time of Sampling Process

Depth of Sample Taken from Surface [NormC]				
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules	Design Alternative Priorities {Pi}
Ultrasonic Corer	0.120	0.114	0.231	0.155
Corer with Gas Blast	0.840	0.797	0.692	0.777
Grinding Capsules	0.040	0.089	0.077	0.069
Sum	1	1	1	1

Table G-20. Consistency Check for Depth of Sample

Consistency Check				
Weighted Sum Vector	Consistency Vector		λ	3.082
0.471	3.043		n	3
2.477	3.190		CI	0.041
0.206	3.013		RI	0.52
			CR	0.079

Table G-21. AHP for Counter Force Supplied by Rover

Required counter force supplied by rover			
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules
Ultrasonic Corer	1	3	5.000
Corer with Gas Blast	0.2	1	0.333
Grinding Capsules	0.2	3	1
Sum	1.4	7.000	6.333

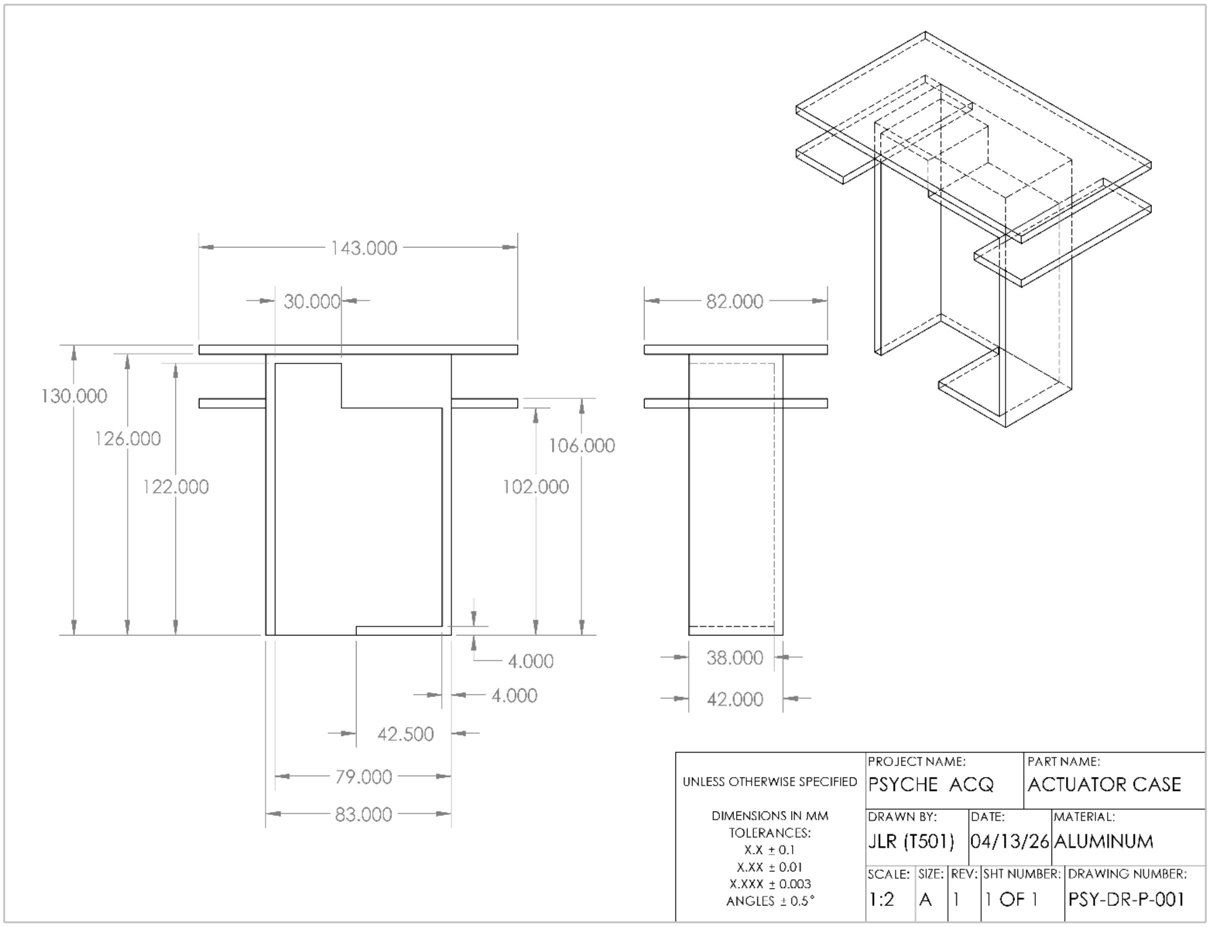
Table G-22. Normalized AHP for Counter Force Supplied by Rover

Required counter force supplied by rover [NormC]				
	Ultrasonic Corer	Corer with Gas Blast	Grinding Capsules	Design Alternative Priorities {Pi}
Ultrasonic Corer	0.714	0.429	0.789	0.644
Corer with Gas Blast	0.143	0.143	0.053	0.113
Grinding Capsules	0.143	0.429	0.158	0.243
Sum	1	1	1	1

Table G-23. Consistency Check for Counter Force Supplied by Rover

Consistency Check				
Weighted Sum Vector	Consistency Vector		λ	3.065
2.198	3.412		n	3
0.323	2.861		CI	0.032
0.710	2.922		RI	0.52
			CR	0.062

Appendix H: Engineering Drawings



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ		PART NAME: ACTUATOR CASE	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)	DATE: 04/13/26	MATERIAL: ALUMINUM	
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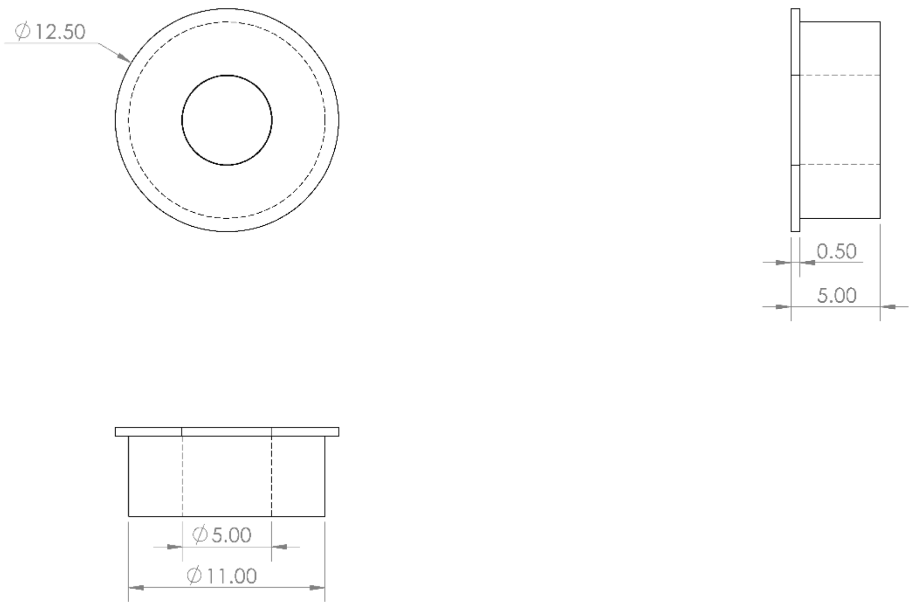
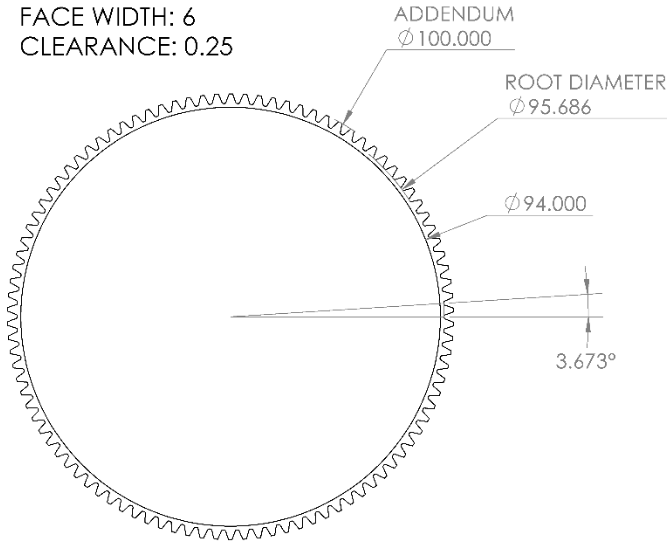


UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ			PART NAME: BEARING	
DRAWN BY: CJH (T501)	DATE: 04/14/26	MATERIAL: GCr15		
SCALE: 4:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GS-P-008

GEAR SPECIFICATIONS:
1. DIAMETRAL PITCH: 98
2. NO. TEETH: 98
3. PRESSURE ANGLE: 20 DEG
4. FACE WIDTH: 6
5. CLEARANCE: 0.25



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DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)		DATE: 04/14/26	MATERIAL: PLA	
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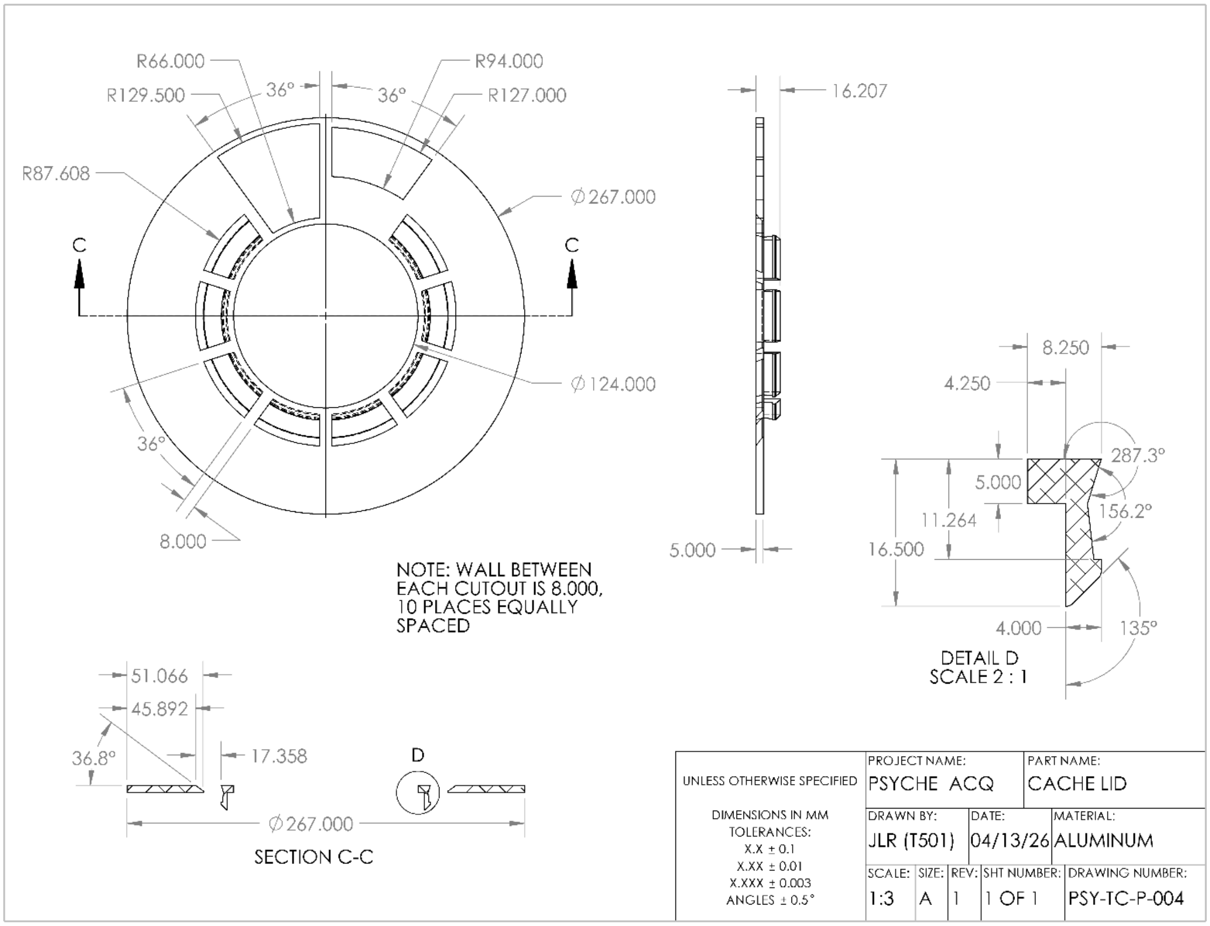
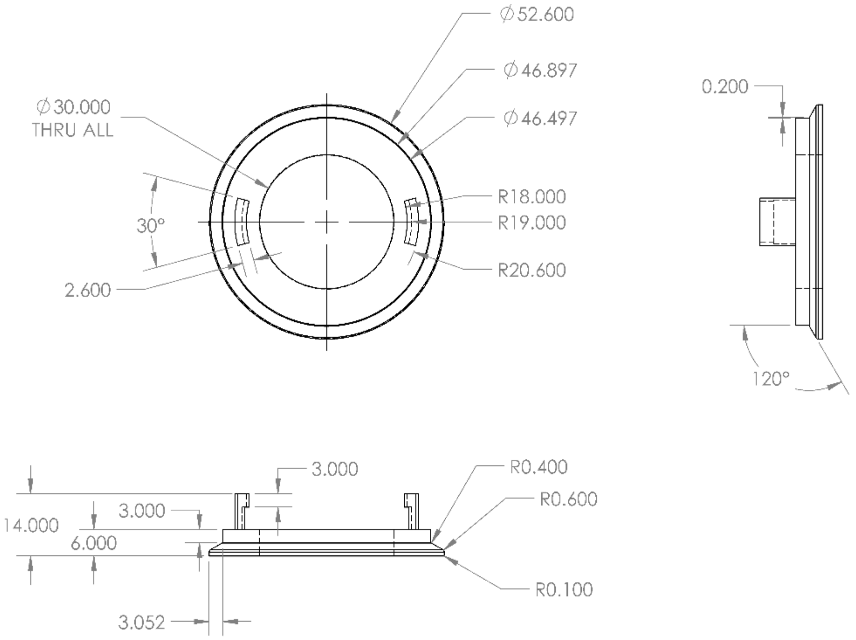


NOTE: WALL BETWEEN EACH CUTOUT IS 8.000, 10 PLACES EQUALLY SPACED

UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ			PART NAME: CACHE LID	
DRAWN BY: JLR (T501)	DATE: 04/13/26		MATERIAL: ALUMINUM	
SCALE: 1:3	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-TC-P-004



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DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)		DATE: 04/13/26		MATERIAL: ALUMINUM	
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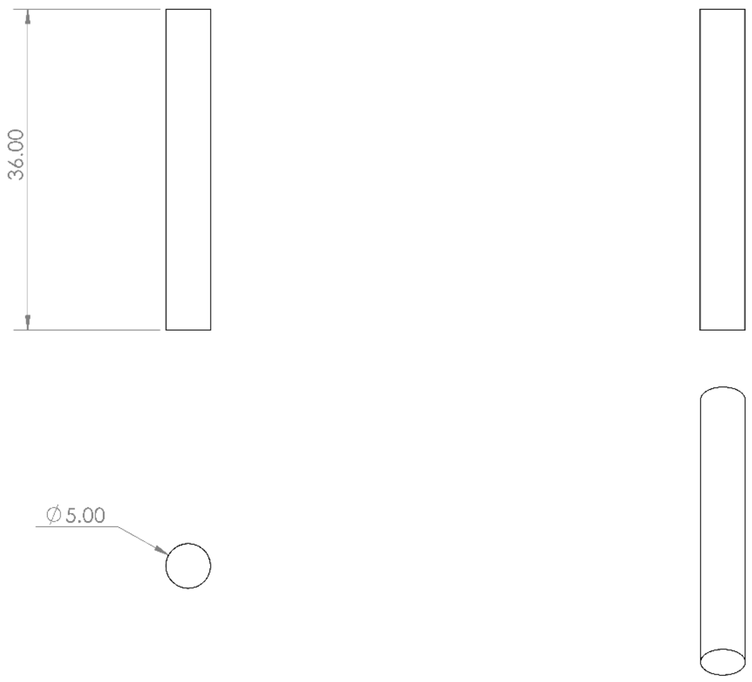

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ		PART NAME: CONNECTING GEAR SHAFT		
	DRAWN BY: CJH (T501)	DATE: 04/14/26	MATERIAL: HSS		
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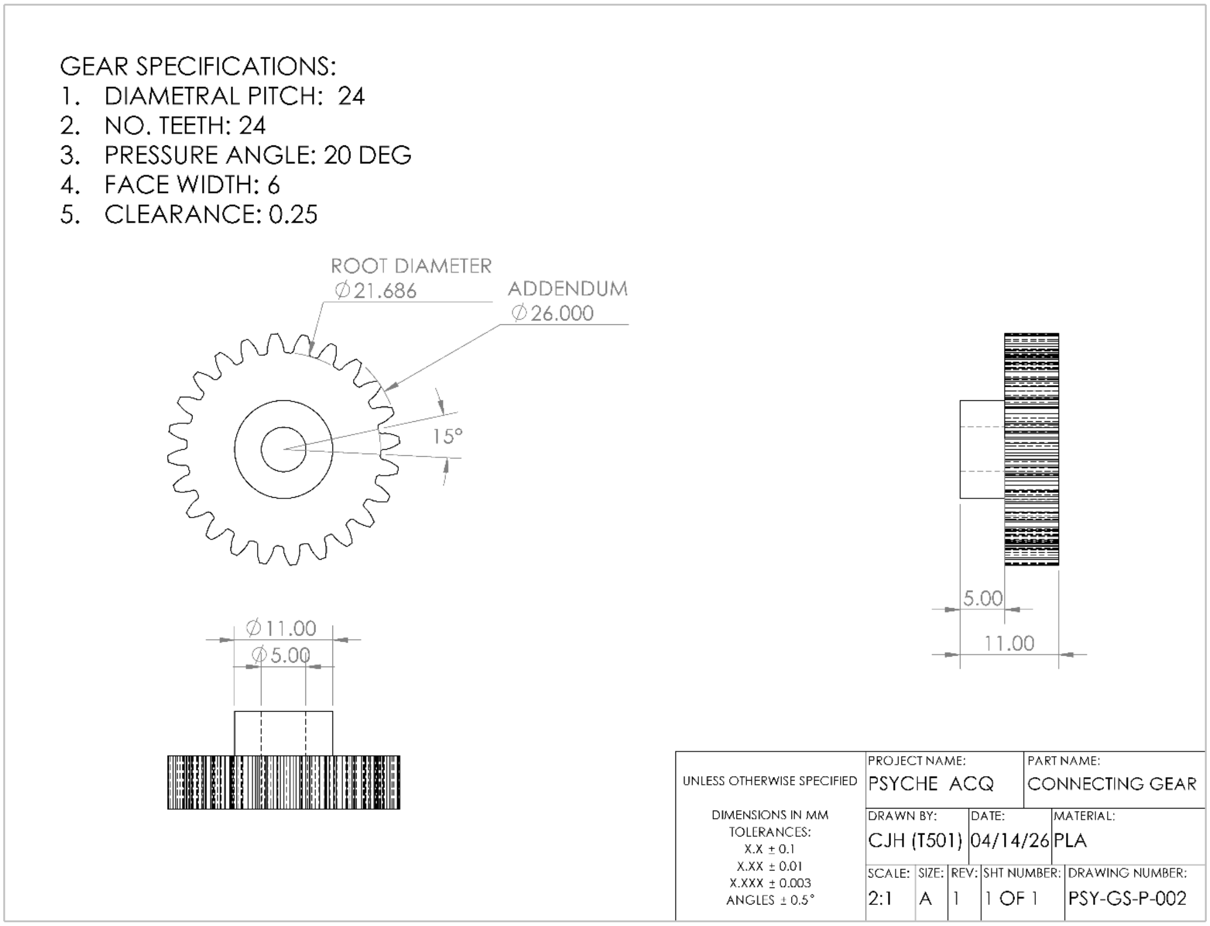
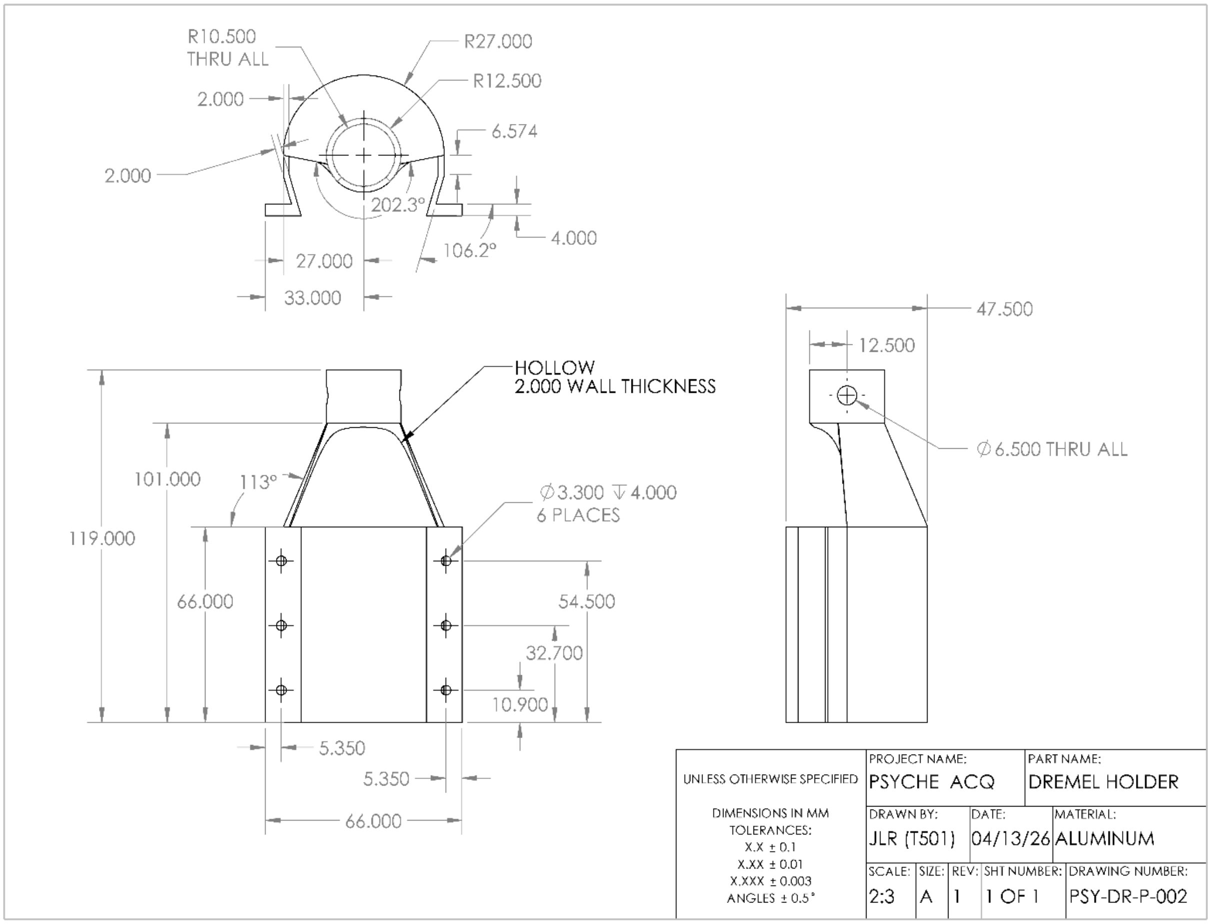


GEAR SPECIFICATIONS:

1. DIAMETRAL PITCH: 24
2. NO. TEETH: 24
3. PRESSURE ANGLE: 20 DEG
4. FACE WIDTH: 6
5. CLEARANCE: 0.25

UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: CONNECTING GEAR	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)		DATE: 04/14/26	MATERIAL: PLA	
	SCALE: 2:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GS-P-002



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: DREMEL HOLDER	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)		DATE: 04/13/26	MATERIAL: ALUMINUM	
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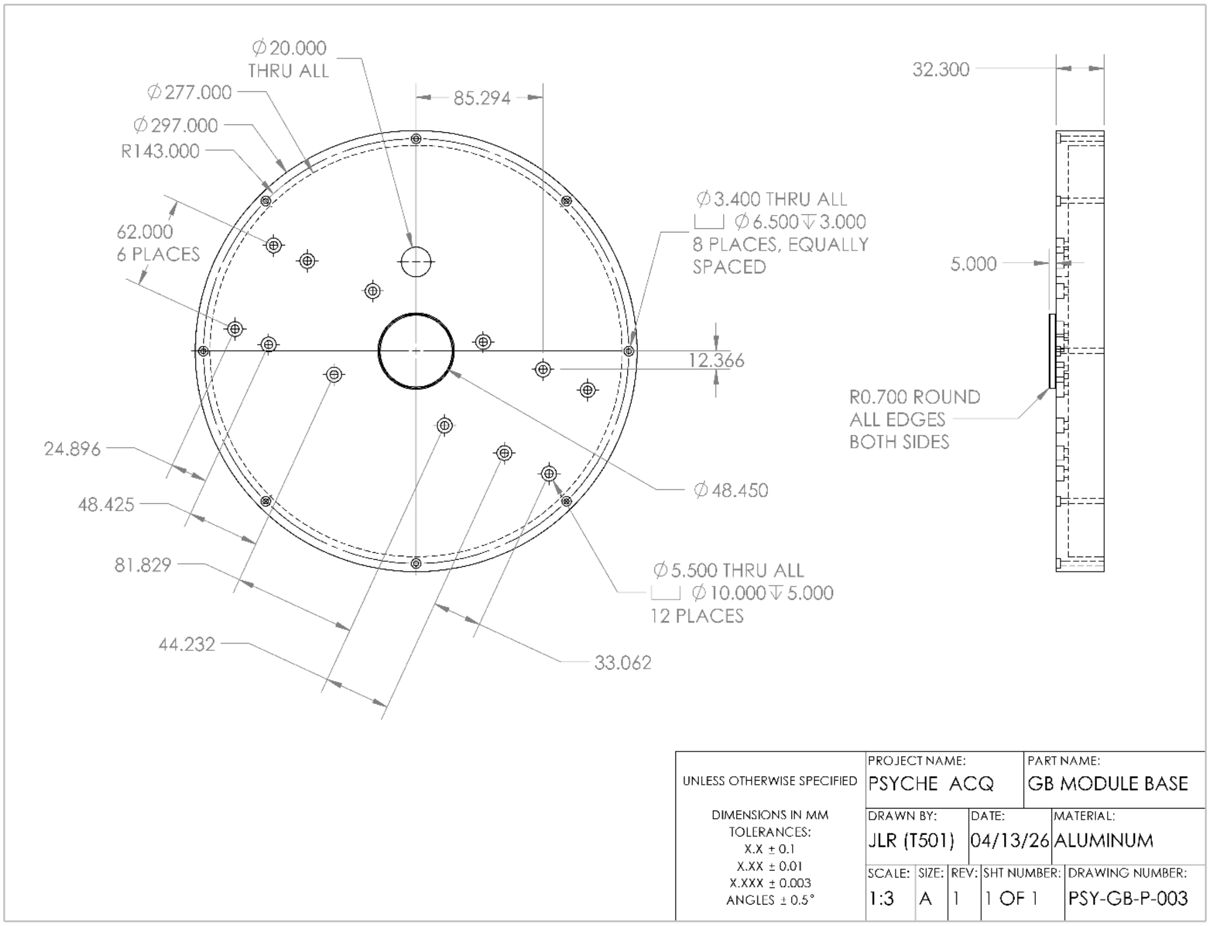
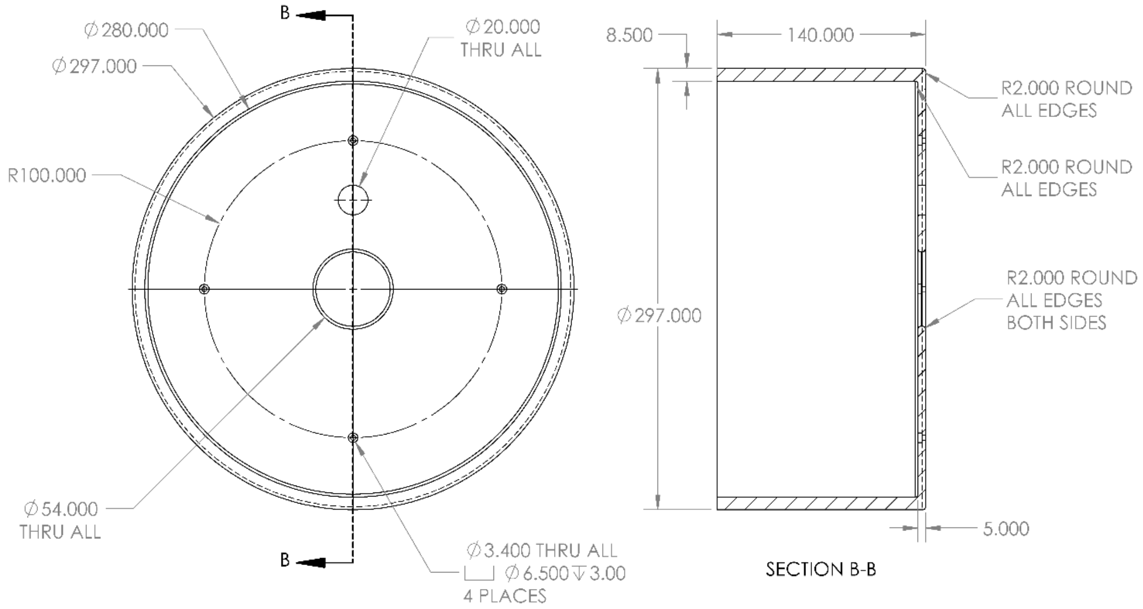
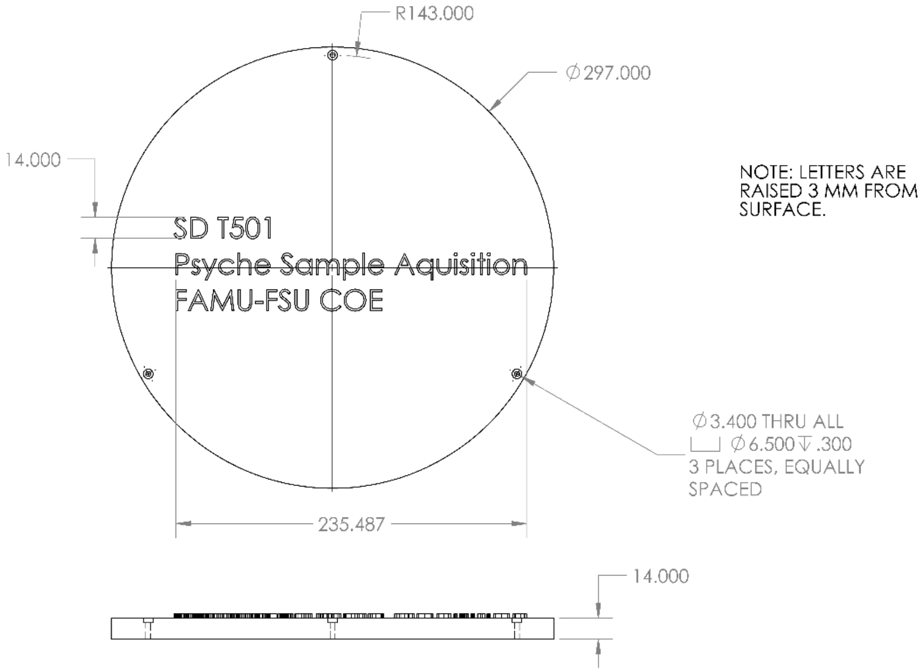


UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ		PART NAME: GB MODULE BASE		
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)	DATE: 04/13/26	MATERIAL: ALUMINUM		
	SCALE: 1:3	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GB-P-003

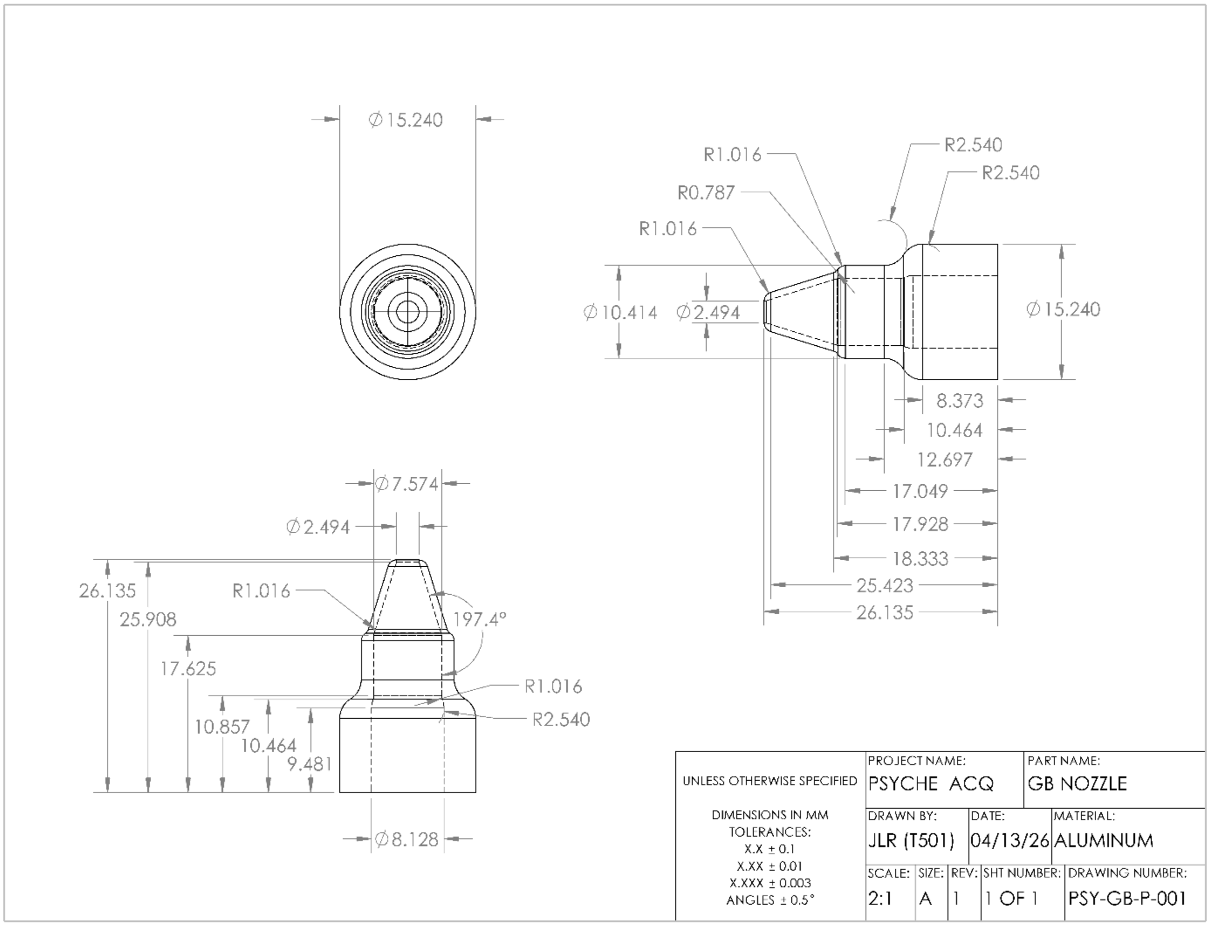


UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: GB MODULE	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)		DATE: 04/13/26	MATERIAL: ALUMINUM	
	SCALE: 1:3	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GB-P-002

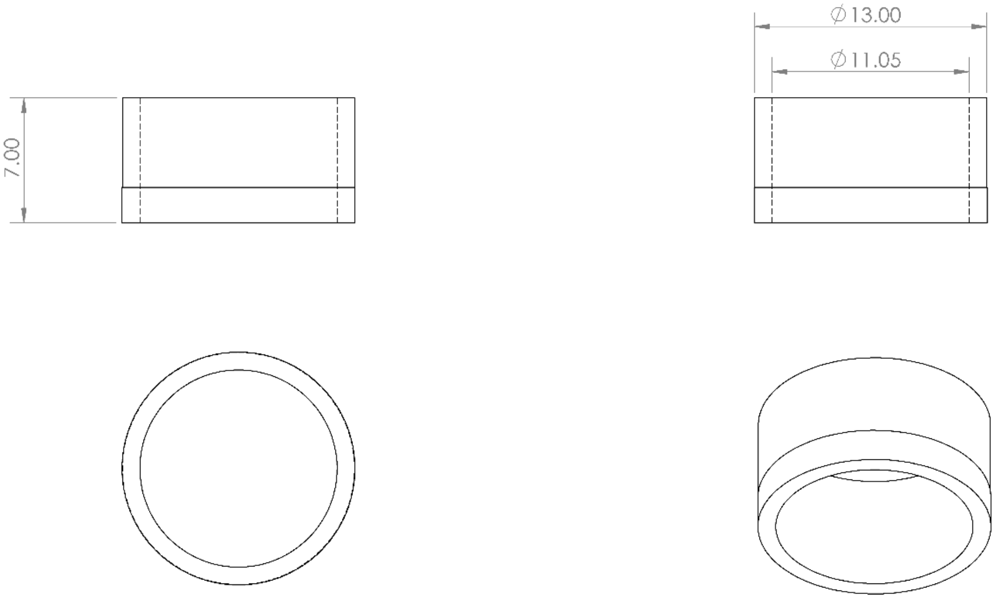


NOTE: LETTERS ARE RAISED 3 MM FROM SURFACE.

UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: GB MODULE LID	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)		DATE: 04/13/26	MATERIAL: ALUMINUM	
	SCALE: 1:3	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GB-P-004



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ				PART NAME: GB NOZZLE
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)		DATE: 04/13/26		MATERIAL: ALUMINUM
	SCALE: 2:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GB-P-001



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: LOWER BEARING HOUSING	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)		DATE: 04/14/26	MATERIAL: PLA	
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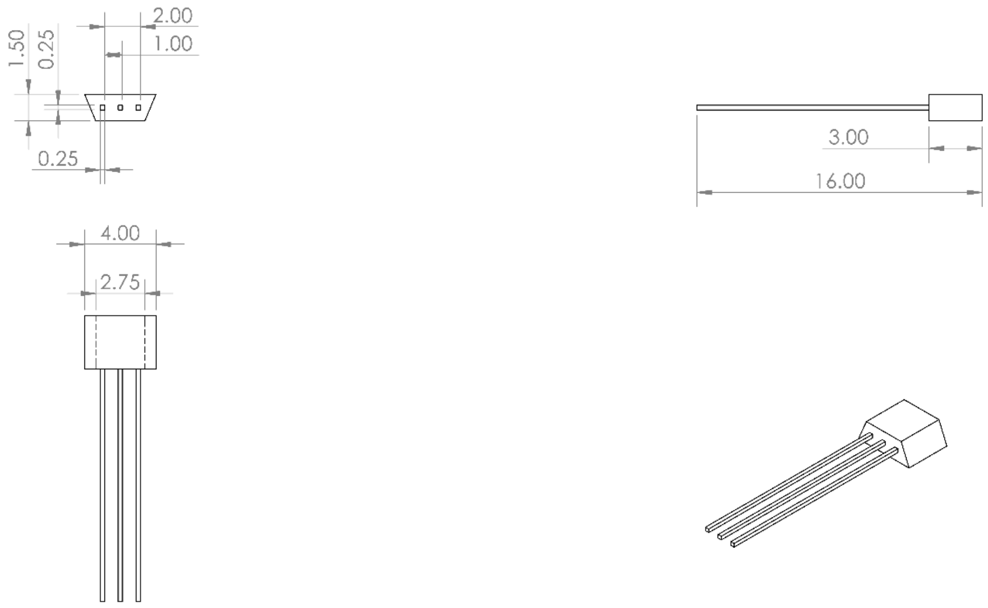
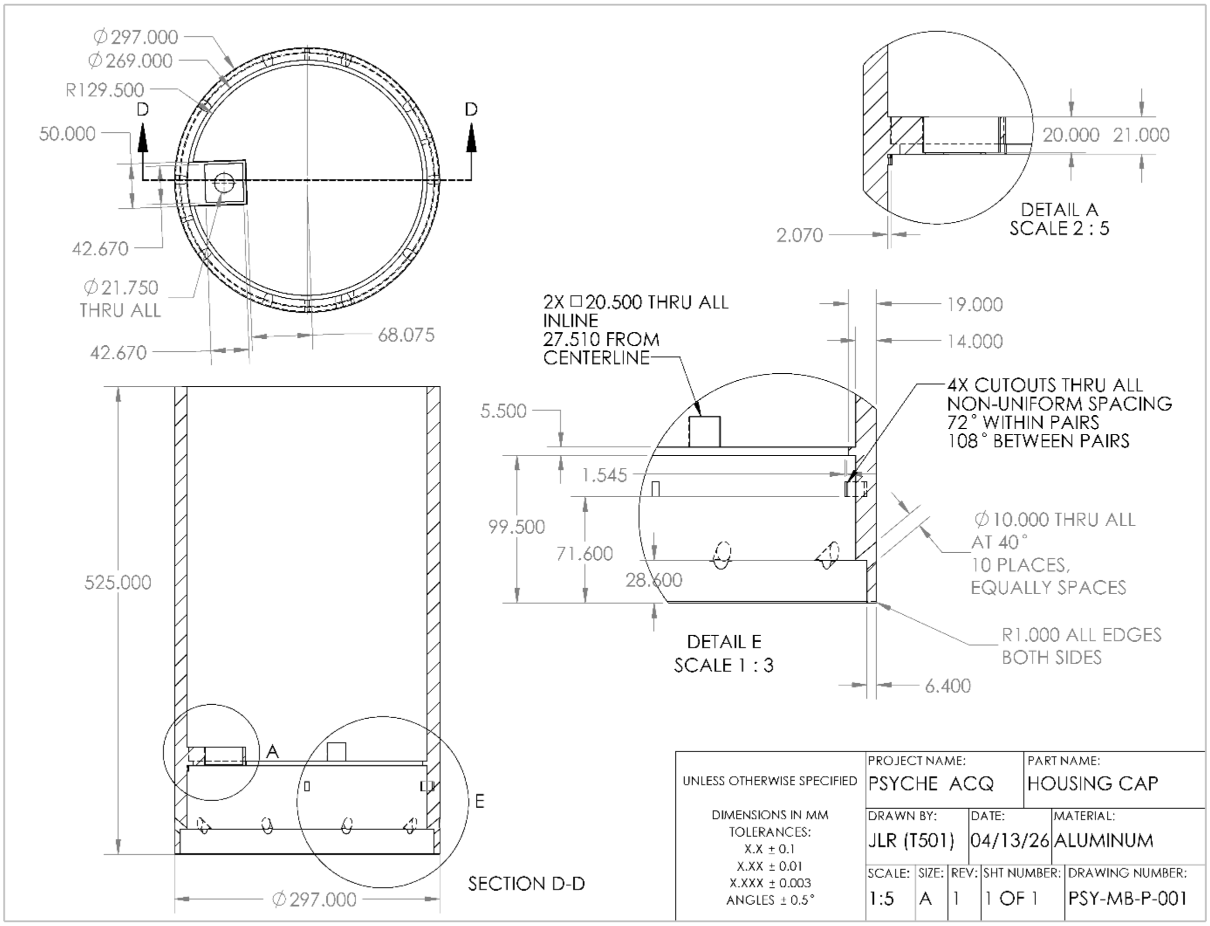


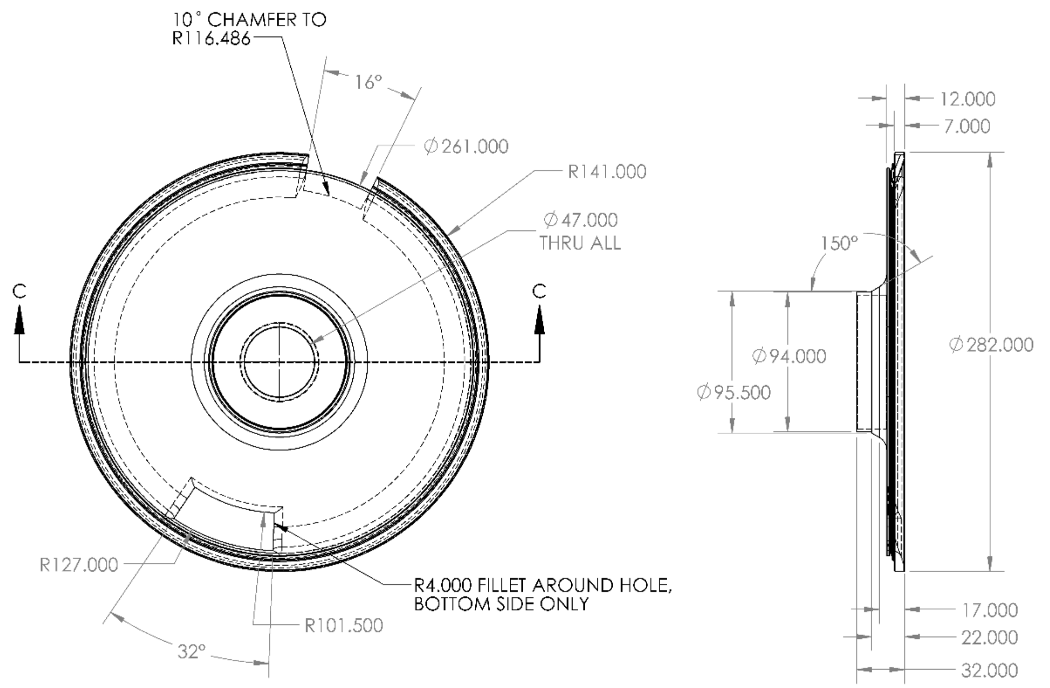
UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ				PART NAME: HALL EFFECT SENSOR	
	DRAWN BY: CJH (T501)		DATE: 04/14/26		MATERIAL: NPN SILICON TRANSISTOR	
	SCALE: 4:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GS-P-011	



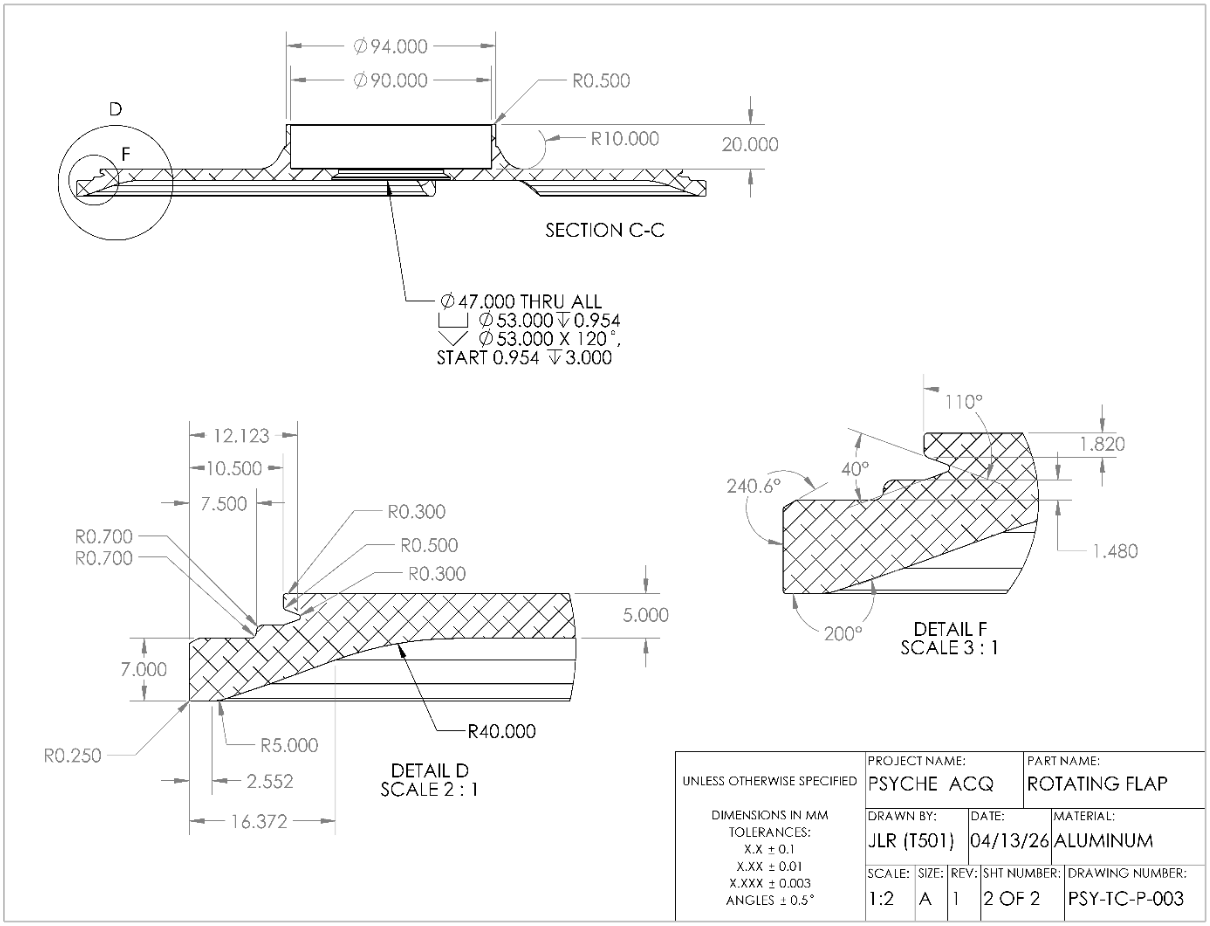
UNLESS OTHERWISE SPECIFIED

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

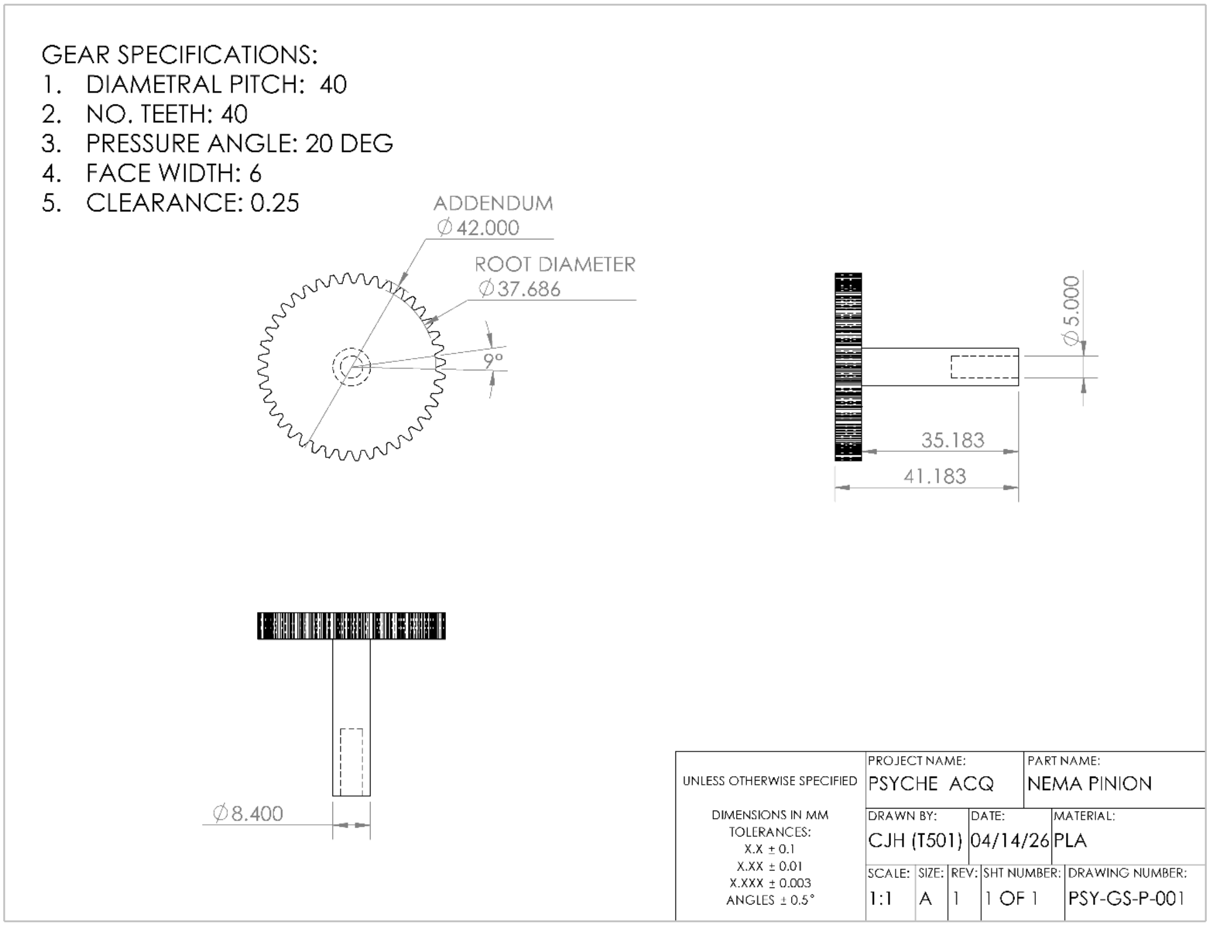
PROJECT NAME: PSYCHE ACQ
PART NAME: HOUSING CAP
DRAWN BY: JLR (T501)
DATE: 04/13/26
MATERIAL: ALUMINUM
SCALE: 1:5
SIZE: A
REV: 1
SHT NUMBER: 1 OF 1
DRAWING NUMBER: PSY-MB-P-001



UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ			PART NAME: ROTATING FLAP	
	DRAWN BY: JLR (T501)	DATE: 04/13/26		MATERIAL: ALUMINUM	
	SCALE: 1:3	SIZE: A	REV: 1	SHT NUMBER: 1 OF 2	DRAWING NUMBER: PSY-TC-P-003



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: ROTATING FLAP	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)	DATE: 04/13/26		MATERIAL: ALUMINUM	
	SCALE: 1:2	SIZE: A	REV: 1	SHT NUMBER: 2 OF 2	DRAWING NUMBER: PSY-TC-P-003

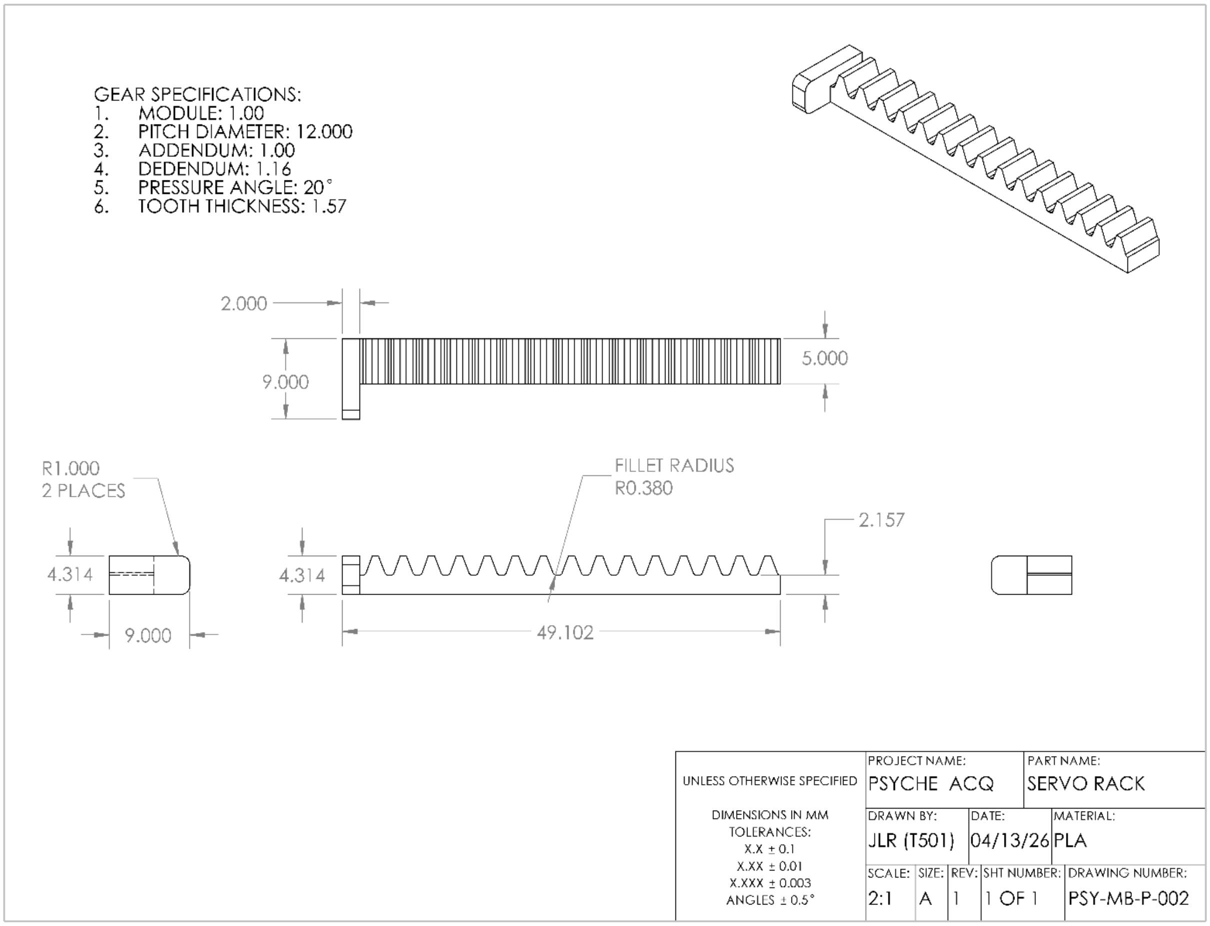

GEAR SPECIFICATIONS:

1. DIAMETRAL PITCH: 40
2. NO. TEETH: 40
3. PRESSURE ANGLE: 20 DEG
4. FACE WIDTH: 6
5. CLEARANCE: 0.25

UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ		PART NAME: NEMA PINION		
DRAWN BY: CJH (T501)	DATE: 04/14/26	MATERIAL: PLA		
SCALE: 1:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GS-P-001

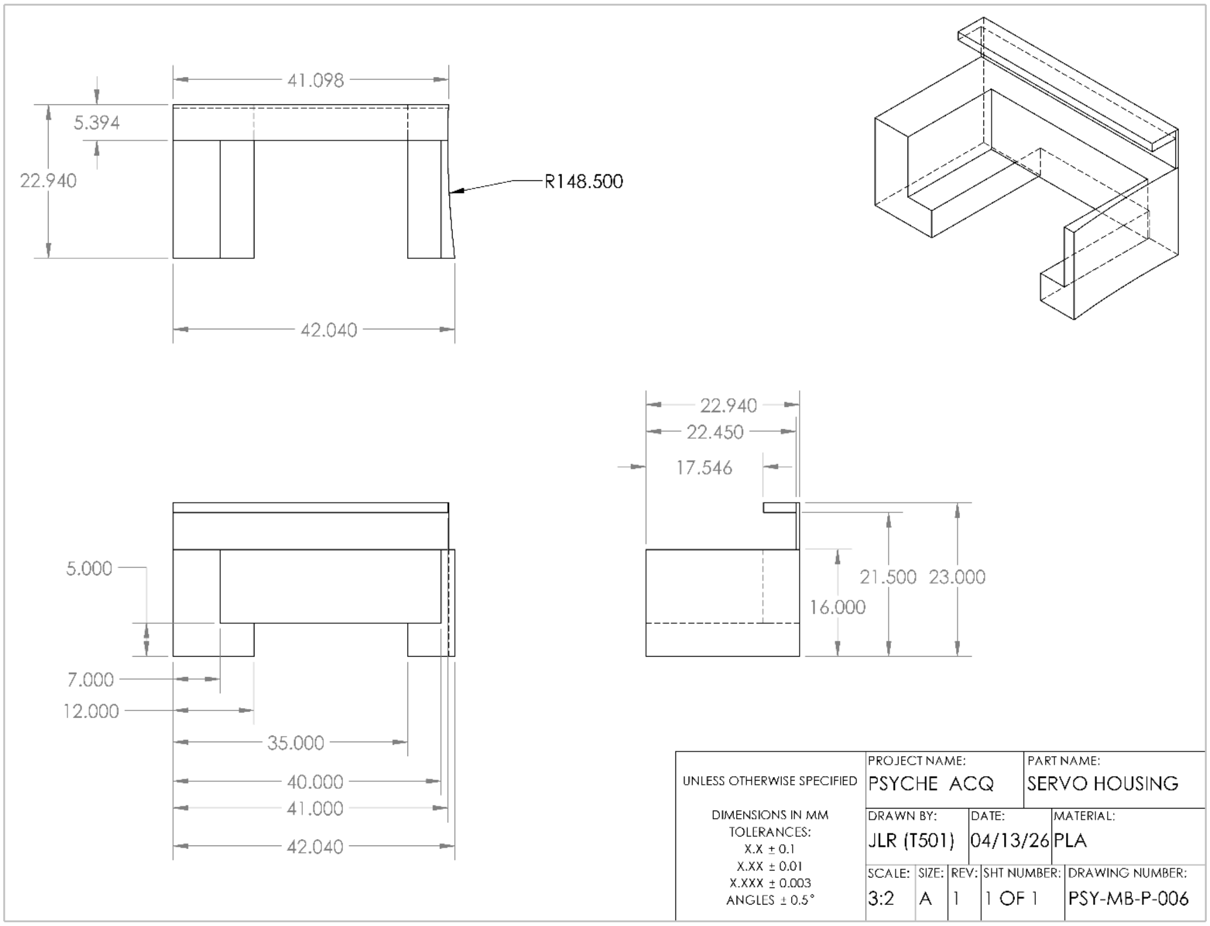


GEAR SPECIFICATIONS:
1. MODULE: 1.00
2. PITCH DIAMETER: 12.000
3. ADDENDUM: 1.00
4. DEDENDUM: 1.16
5. PRESSURE ANGLE: 20°
6. TOOTH THICKNESS: 1.57

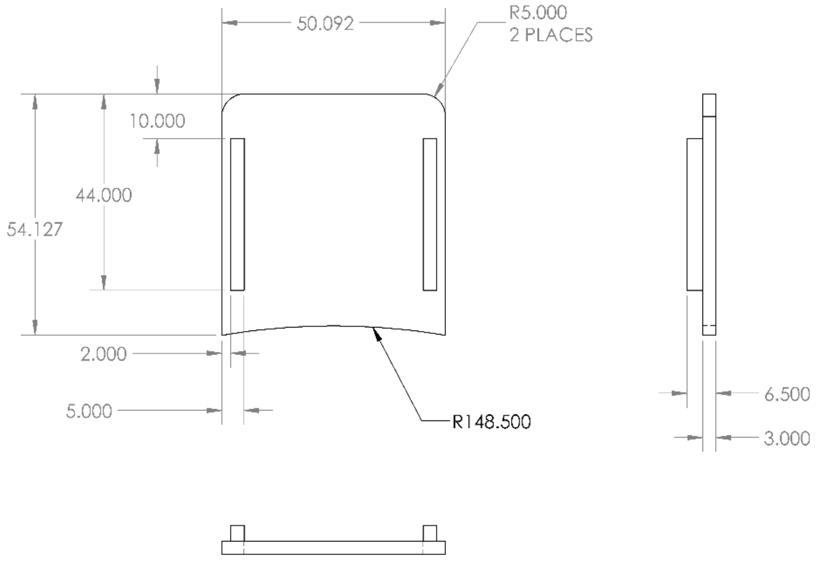
UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ
PART NAME: SERVO RACK
DRAWN BY: JLR (T501)
DATE: 04/13/26
MATERIAL: PLA
SCALE: 2:1
SIZE: A
REV: 1
SHT NUMBER: 1 OF 1
DRAWING NUMBER: PSY-MB-P-002



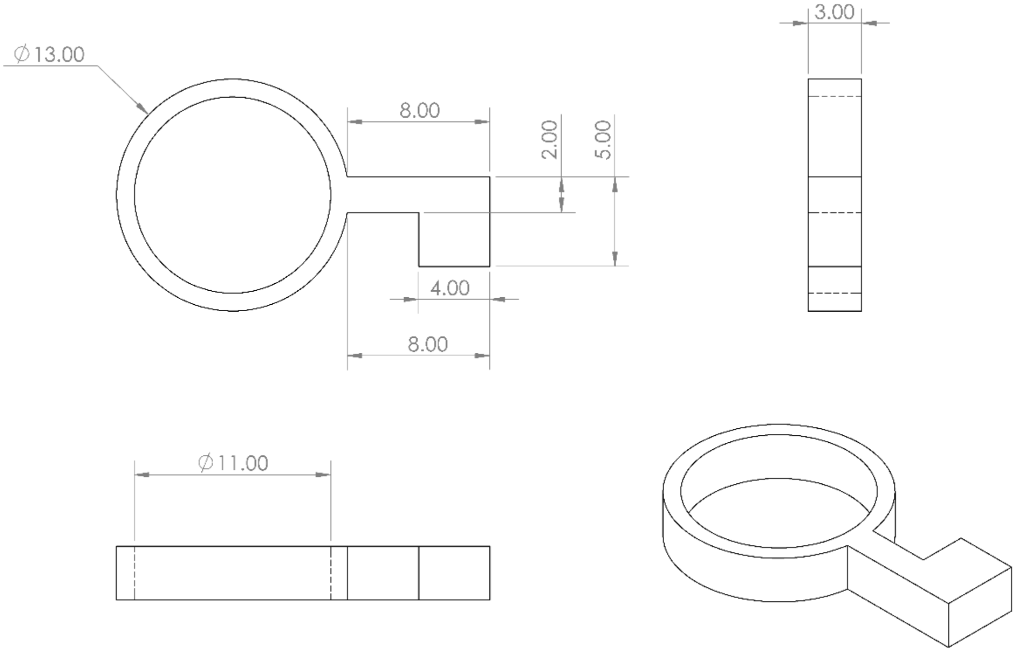
UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: SERVO HOUSING	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)		DATE: 04/13/26	MATERIAL: PLA	
	SCALE: 3:2	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-MB-P-006



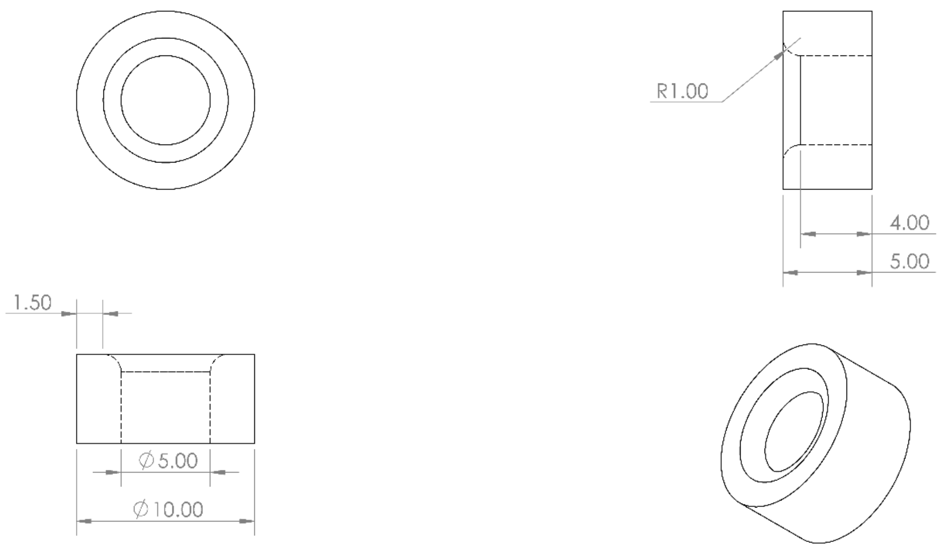
UNLESS OTHERWISE SPECIFIED

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

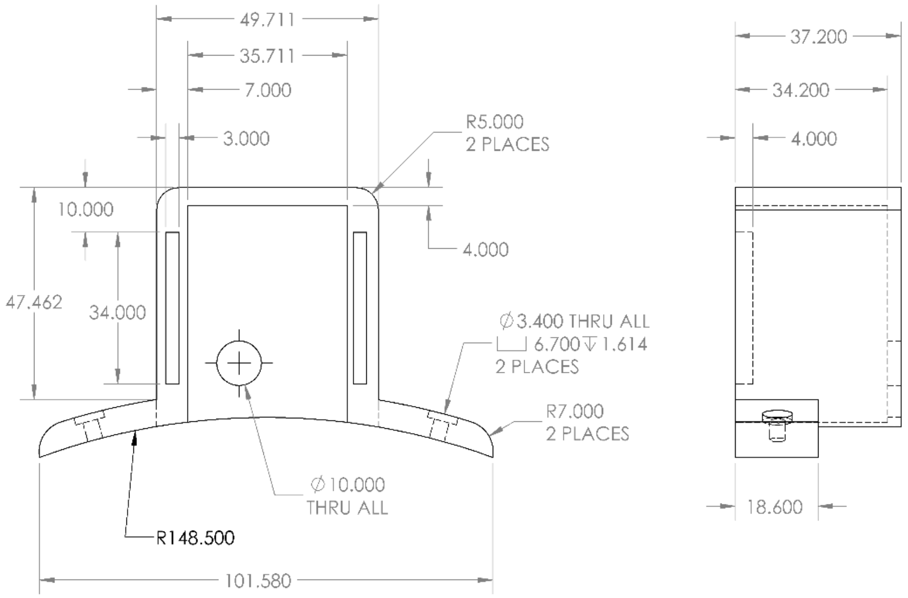
PROJECT NAME: PSYCHE ACQ
PART NAME: SERVO CAP
DRAWN BY: JLR (T501)
DATE: 04/13/26
MATERIAL: ALUMINUM
SCALE: 1:1
SIZE: A
REV: 1
SHT NUMBER: 1 OF 1
DRAWING NUMBER: PSY-MB-P-004



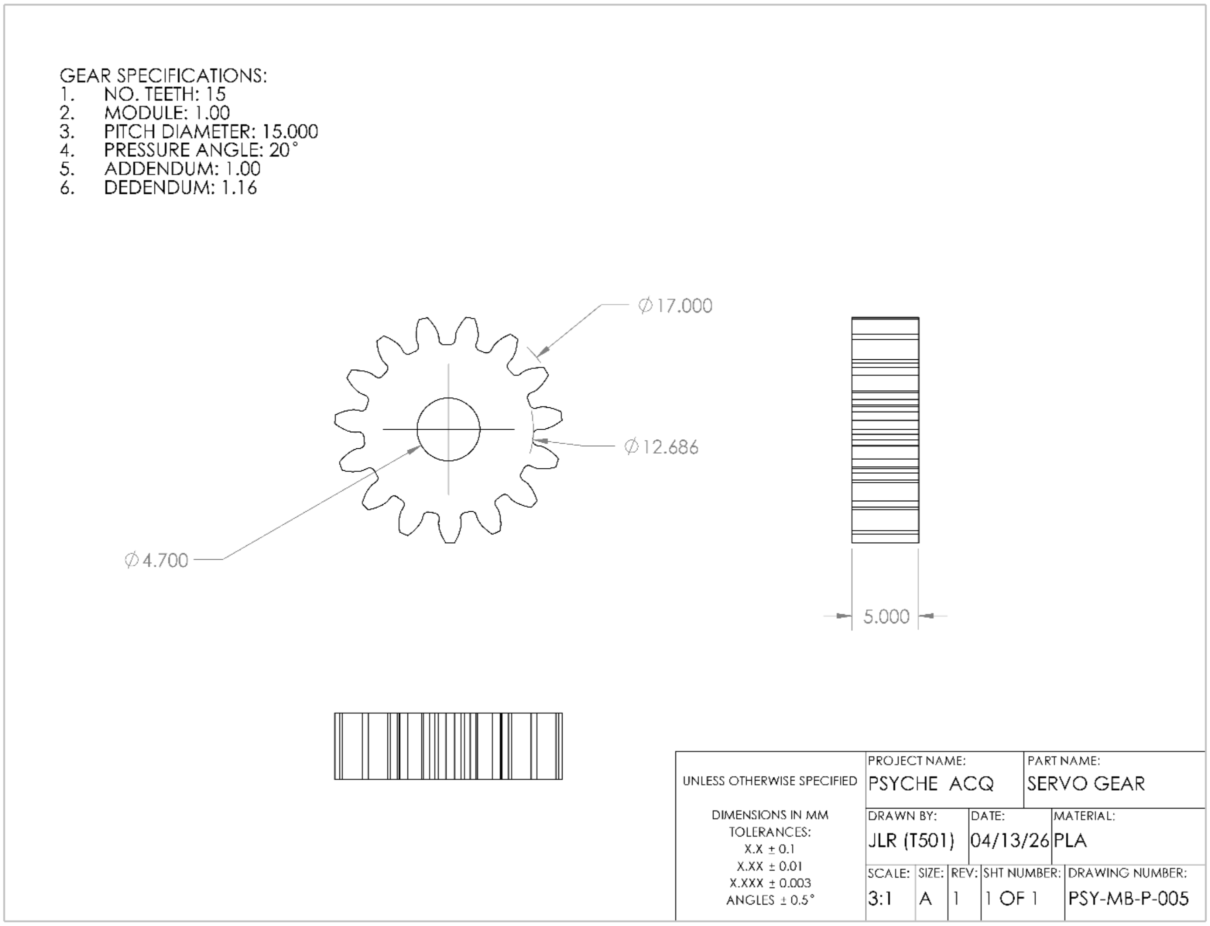
UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ				PART NAME: UPPER BEARING HOUSING	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)			DATE: 04/14/26	MATERIAL: PLA	
	SCALE: 4:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GS-P-006	



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: TOP BEARING CLAMP	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)	DATE: 04/14/26		MATERIAL: PLA	
	SCALE: 4:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-GS-P-005



UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: SERVO HOUSING	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)	DATE: 04/13/26		MATERIAL: ALUMINUM	
	SCALE: 1:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-MB-P-003

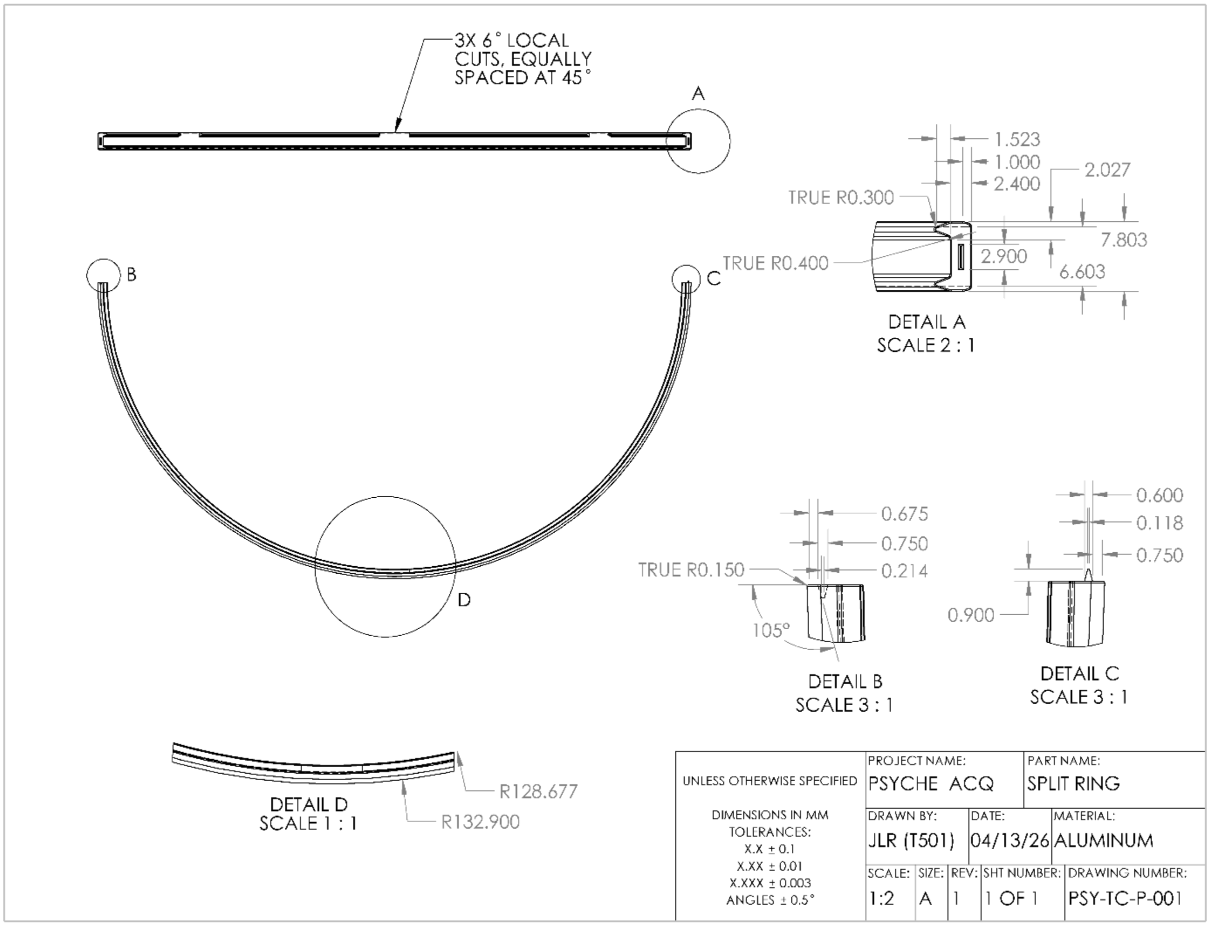


GEAR SPECIFICATIONS:
1. NO. TEETH: 15
2. MODULE: 1.00
3. PITCH DIAMETER: 15.000
4. PRESSURE ANGLE: 20°
5. ADDENDUM: 1.00
6. DEDENDUM: 1.16

UNLESS OTHERWISE SPECIFIED

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

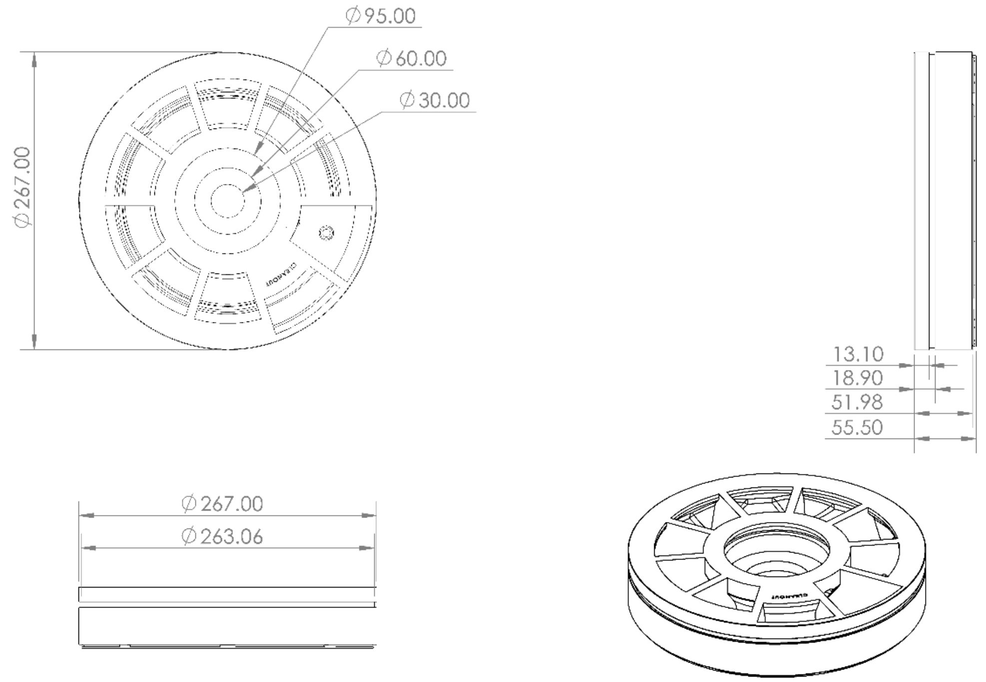
PROJECT NAME: PSYCHE ACQ			PART NAME: SERVO GEAR	
DRAWN BY: JLR (T501)		DATE: 04/13/26	MATERIAL: PLA	
SCALE: 3:1	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-MB-P-005



UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ
PART NAME: SPLIT RING
DRAWN BY: JLR (T501)
DATE: 04/13/26
MATERIAL: ALUMINUM
SCALE: 1:2
SIZE: A
REV: 1
SHT NUMBER: 1 OF 1
DRAWING NUMBER: PSY-TC-P-001

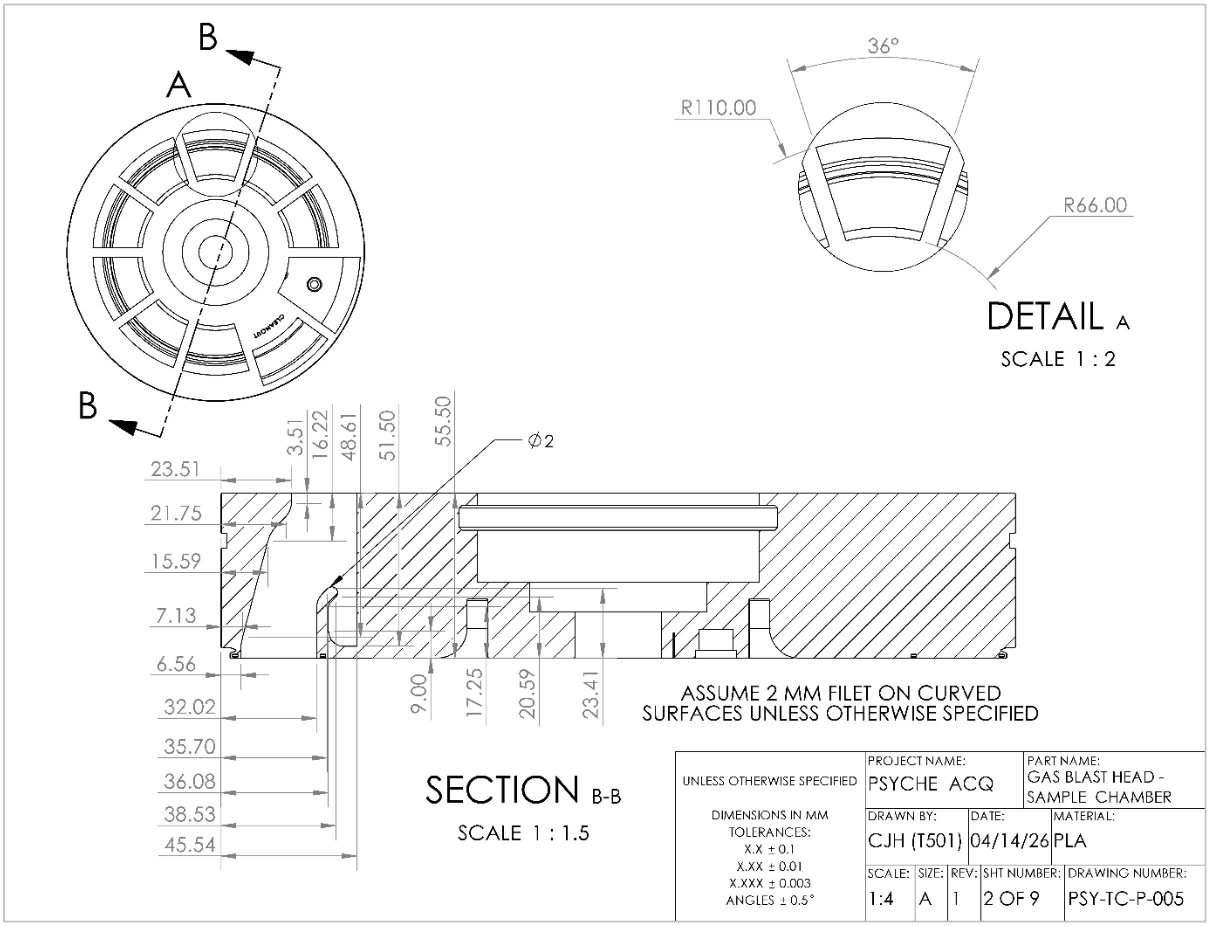


UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ
PART NAME: GAS BLAST HEAD - MAIN
DRAWN BY: CJH (T501)
DATE: 04/14/26
MATERIAL: PLA

SCALE:	SIZE:	REV:	SHT NUMBER:	DRAWING NUMBER:
1:4	A	1	1 OF 9	PSY-TC-P-005

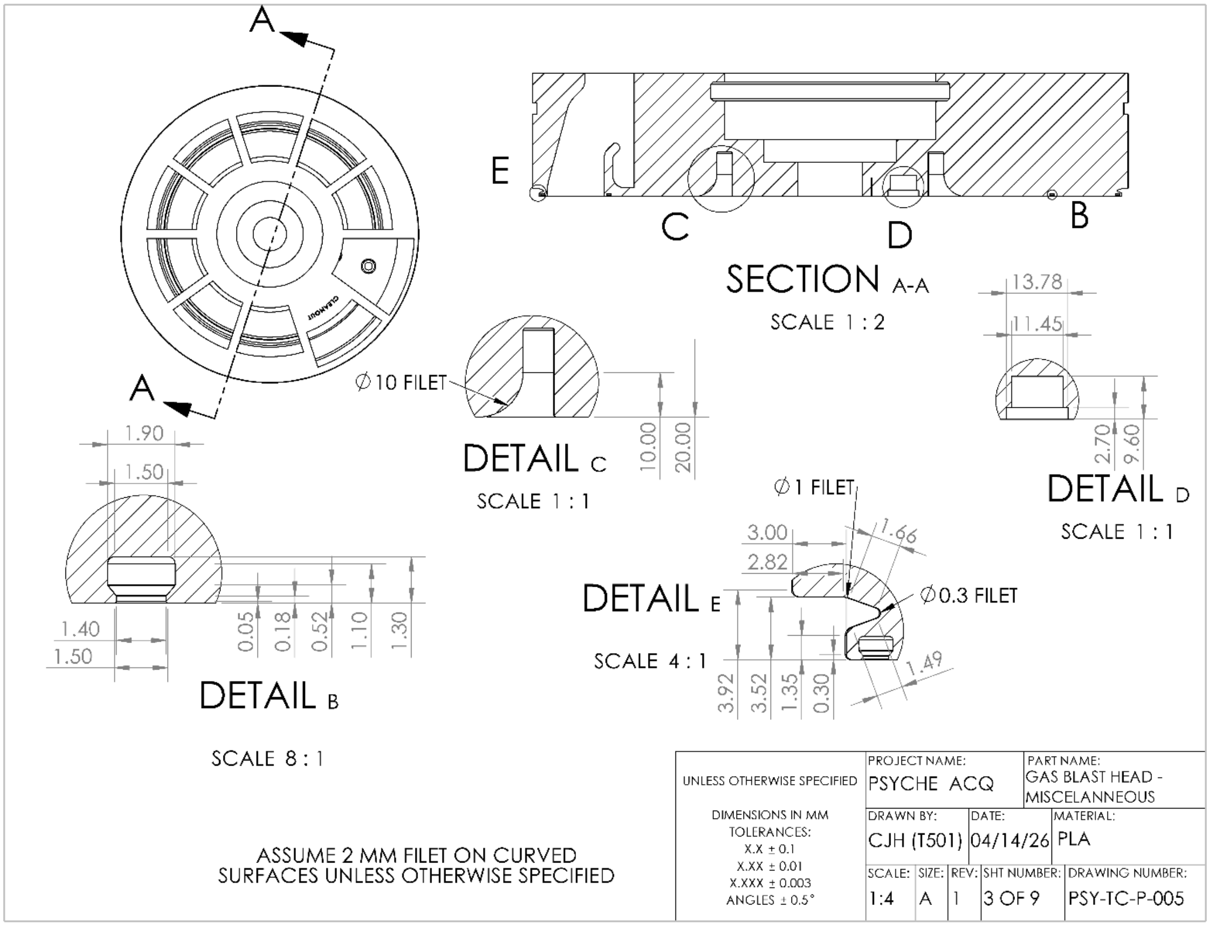


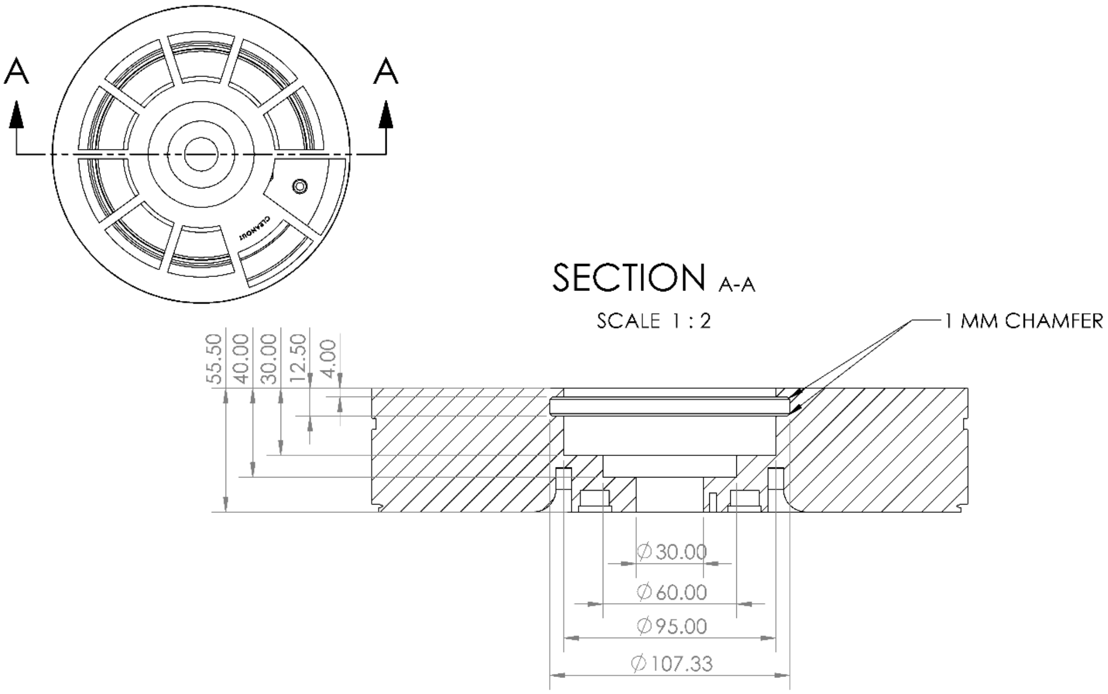
ASSUME 2 MM FILET ON CURVED SURFACES UNLESS OTHERWISE SPECIFIED

UNLESS OTHERWISE SPECIFIED

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

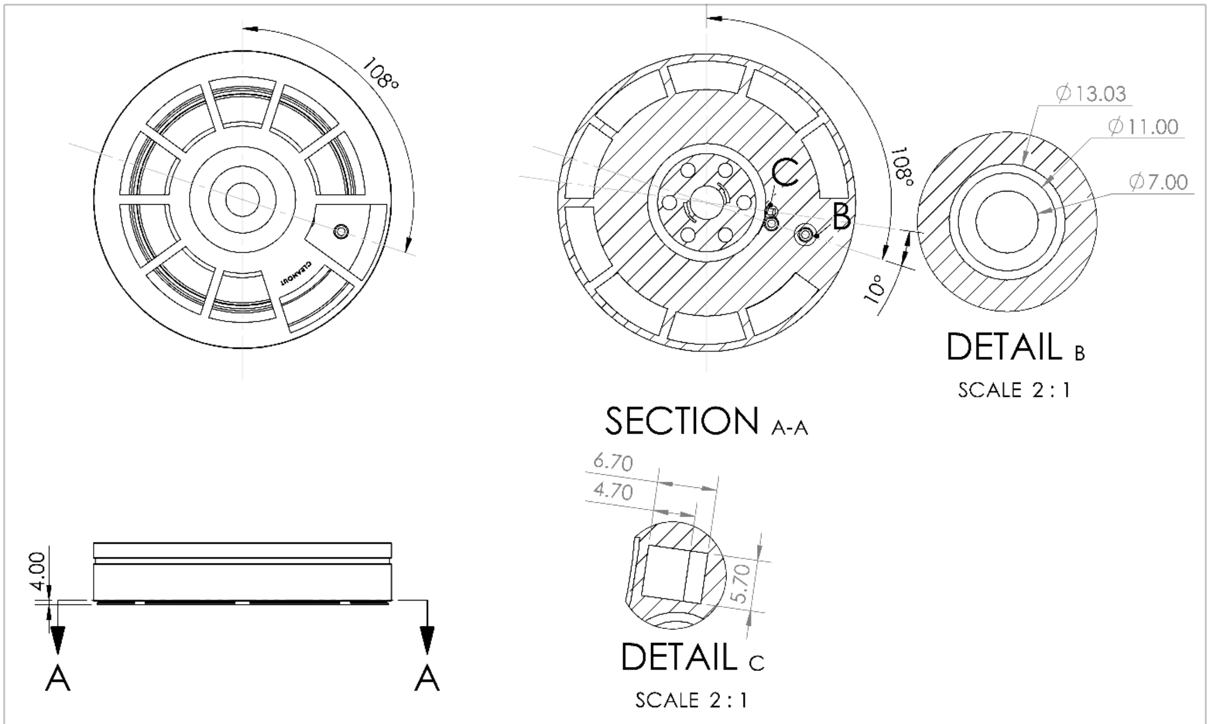
PROJECT NAME: PSYCHE ACQ
PART NAME: GAS BLAST HEAD - SAMPLE CHAMBER
DRAWN BY: CJH (T501)
DATE: 04/14/26
MATERIAL: PLA
SCALE: 1:4
SIZE: A
REV: 1
SHT NUMBER: 2 OF 9
DRAWING NUMBER: PSY-TC-P-005


A
A
E
C
D
B
SECTION A-A
SCALE 1 : 2
CLEANOUT
∅10 FILET
DETAIL C
SCALE 1 : 1
10.00
20.00
13.78
11.45
2.70
9.60
DETAIL D
SCALE 1 : 1
1.90
1.50
1.40
1.50
0.05
0.18
0.52
1.10
1.30
DETAIL B
SCALE 8 : 1
∅1 FILET
3.00
2.82
1.66
∅0.3 FILET
DETAIL E
SCALE 4 : 1
3.92
3.52
1.35
0.30
1.49
ASSUME 2 MM FILET ON CURVED SURFACES UNLESS OTHERWISE SPECIFIED
UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN MM
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°
PROJECT NAME:
PSYCHE ACQ
PART NAME:
GAS BLAST HEAD - MISCELANNEOUS
DRAWN BY:
CJH (T501)
DATE:
04/14/26
MATERIAL:
PLA
SCALE:
1:4
SIZE:
A
REV:
1
SHT NUMBER:
3 OF 9
DRAWING NUMBER:
PSY-TC-P-005



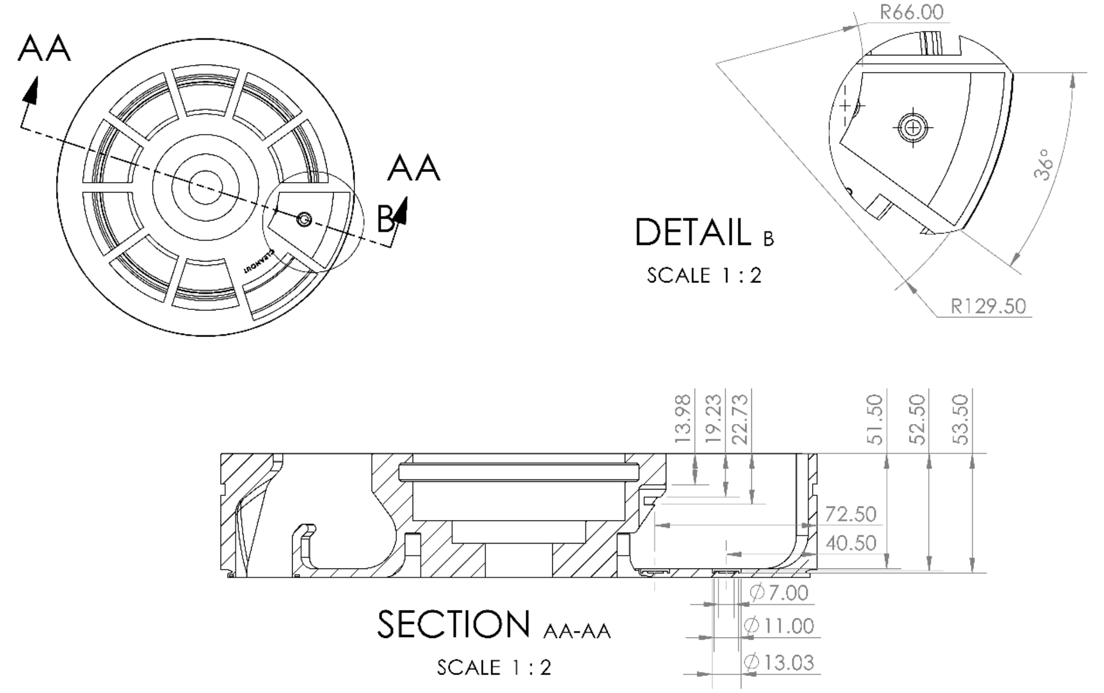
ASSUME 2 MM FILET ON CURVED
SURFACES UNLESS OTHERWISE SPECIFIED

UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ		PART NAME: GAS BLAST HEAD - T502 INTERFACE	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)	DATE: 04/14/26	MATERIAL: PLA	
	SCALE: 1:4	SIZE: A	REV: 1	SHT NUMBER: 4 OF 9
	DRAWING NUMBER: PSY-TC-P-005			



ASSUME 2 MM FILET ON CURVED
SURFACES UNLESS OTHERWISE SPECIFIED

UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ			PART NAME: GAS BLAST HEAD - GEAR CHAMBER FLOOR	
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: CJH (T501)		DATE: 04/14/26	MATERIAL: PLA	
	SCALE: 1:4	SIZE: A	REV: 1	SHT NUMBER: 5 OF 9	DRAWING NUMBER: PSY-TC-P-005



UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ			PART NAME: GAS BLAST HEAD - GEAR CHAMBER	
	DRAWN BY: CJH (T501)	DATE: 04/14/26		MATERIAL: PLA	
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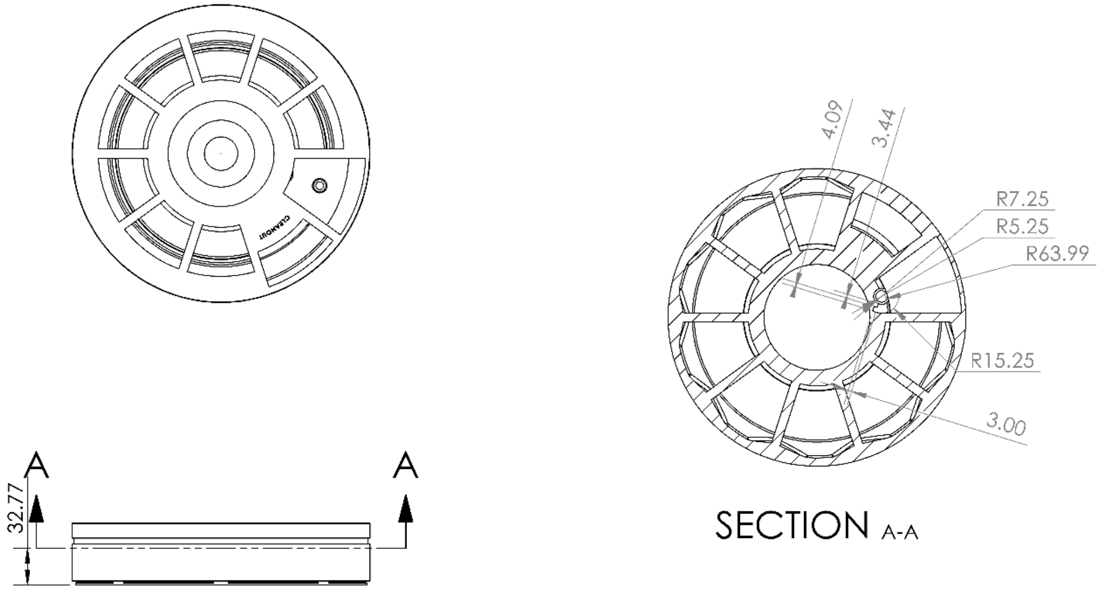
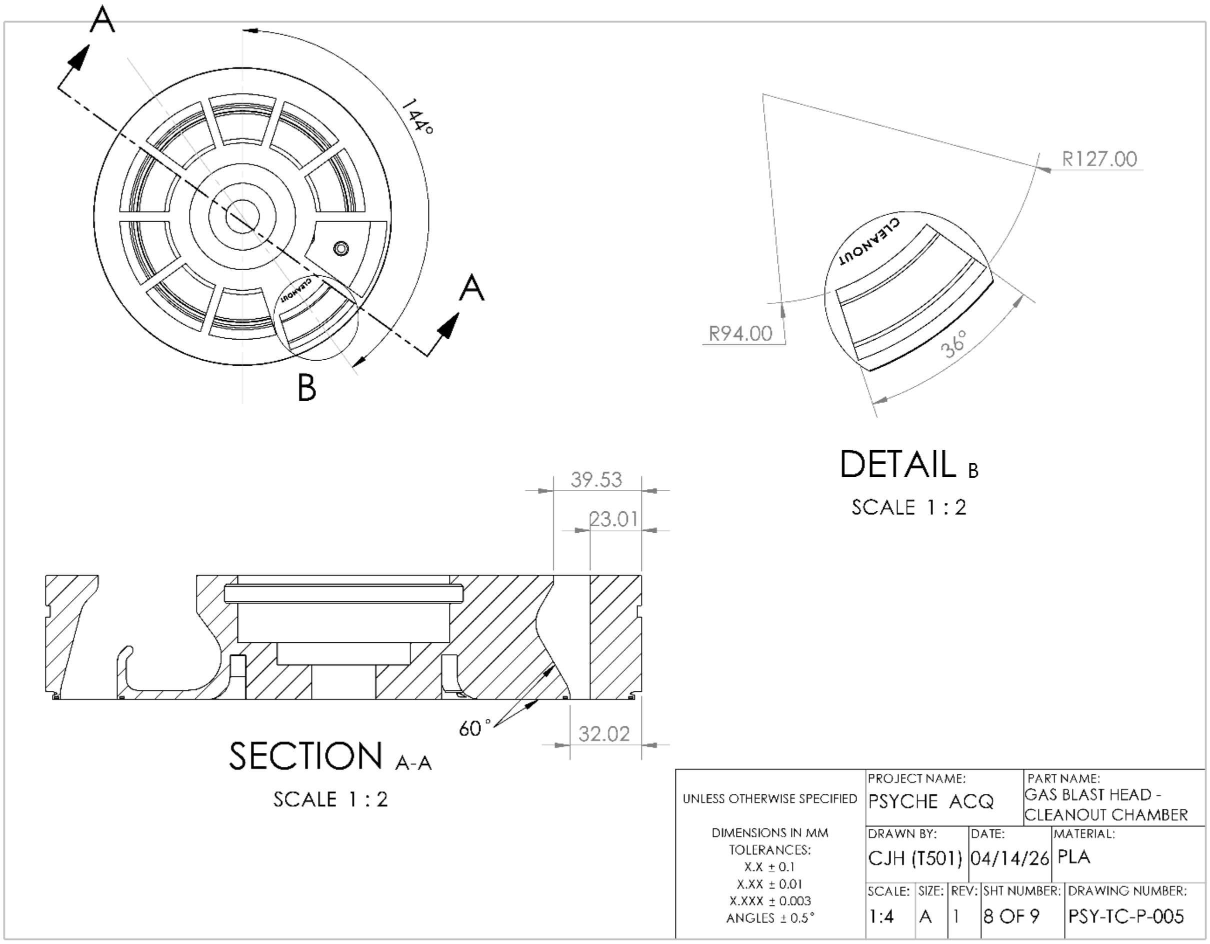


SECTION A-A

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ			PART NAME: GAS BLAST HEAD - GEAR CHAMBER KEY	
	DRAWN BY: CJH (T501)		DATE: 04/14/26	MATERIAL: PLA	
	SCALE: 1:4	SIZE: A	REV: 1	SHT NUMBER: 7 OF 9	DRAWING NUMBER: PSY-TC-P-005

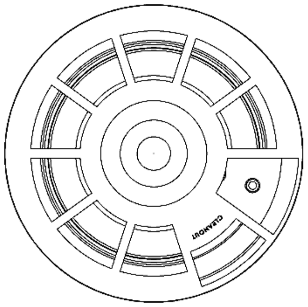


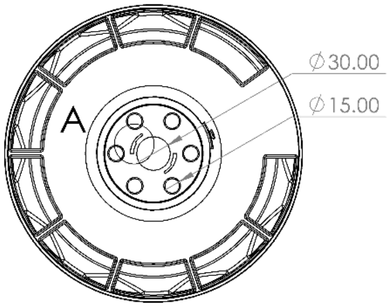
UNLESS OTHERWISE SPECIFIED

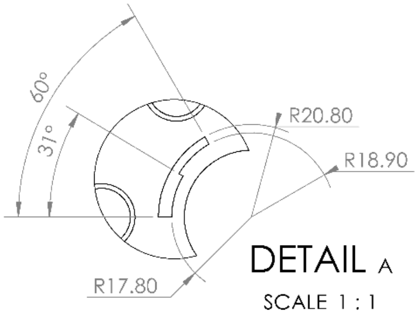
DIMENSIONS IN MM
TOLERANCES:
X.X ± 0.1
X.XX ± 0.01
X.XXX ± 0.003
ANGLES ± 0.5°

PROJECT NAME:		PART NAME:	
PSYCHE ACQ		GAS BLAST HEAD - CLEANOUT CHAMBER	
DRAWN BY:	DATE:	MATERIAL:	
CJH (T501)	04/14/26	PLA	

SCALE:	SIZE:	REV:	SHT NUMBER:	DRAWING NUMBER:
1:4	A	1	8 OF 9	PSY-TC-P-005



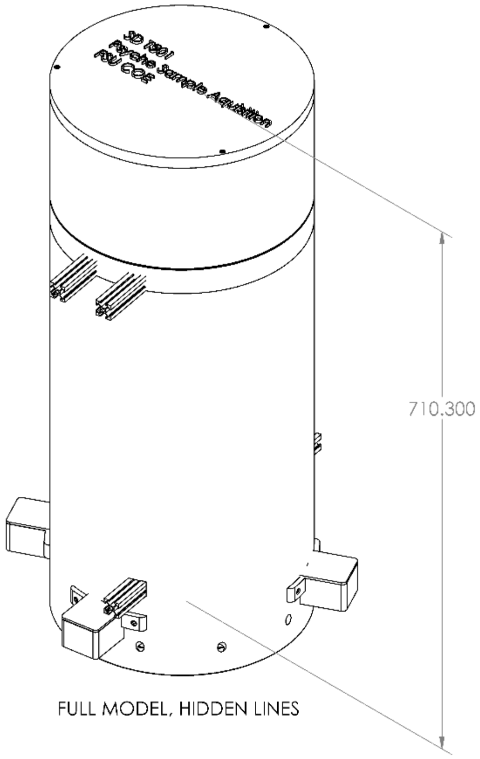




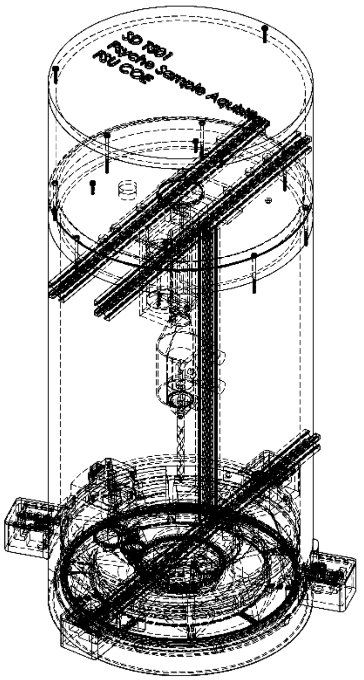
DETAIL A

SCALE 1 : 1

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ			PART NAME: GAS BLAST HEAD - BOTTOM	
	DRAWN BY: CJH (T501)		DATE: 04/14/26	MATERIAL: PLA	
	SCALE: 1:4	SIZE: A	REV: 1	SHT NUMBER: 9 OF 9	DRAWING NUMBER: PSY-TC-P-005

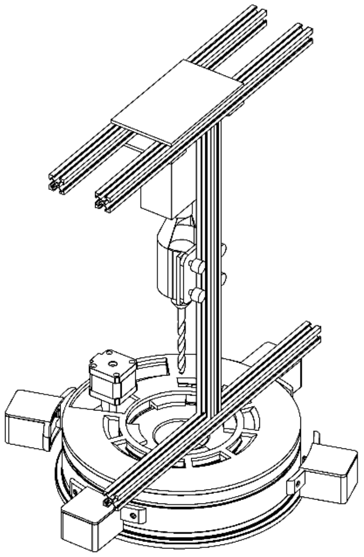


FULL MODEL, HIDDEN LINES

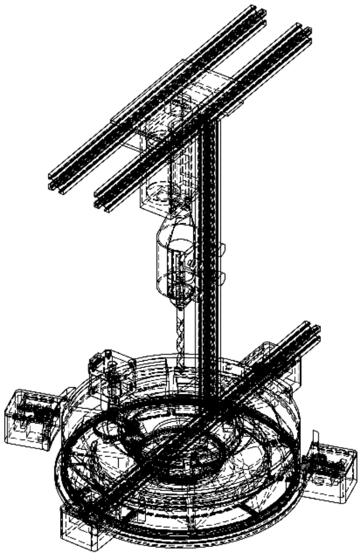


FULL MODEL, NO HIDDEN LINES

UNLESS OTHERWISE SPECIFIED	PROJECT NAME: PSYCHE ACQ		PART NAME: ACQ ASSEMBLY		
DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	DRAWN BY: JLR (T501)	DATE: 04/15/26	MATERIAL:		
	SCALE: 1:5	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-A-001



INSIDE OF MODULAR HOUSING COMPONENT



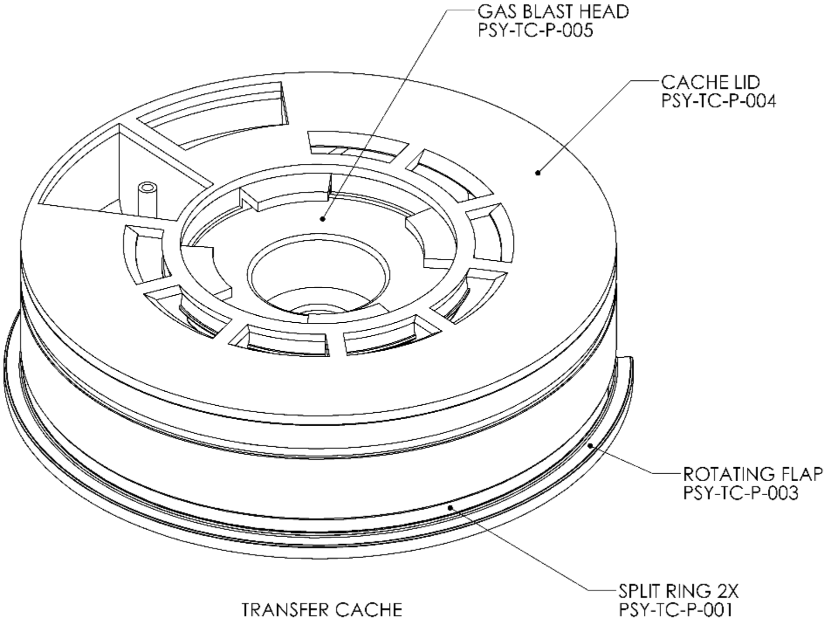
INSIDE OF MODULAR HOUSING COMPONENT, HIDDEN LINES SHOWN

UNLESS OTHERWISE SPECIFIED

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

PROJECT NAME: PSYCHE ACQ
PART NAME: ACQ ASSEMBLY
DRAWN BY: JLR (T501)
DATE: 04/15/26
MATERIAL:
SCALE: 1:5
SIZE: A
REV: 1
SHT NUMBER: 1 OF 1
DRAWING NUMBER: PSY-A-002

NOTE: TOTAL TRANSFER
CACHE HEIGHT IS 73.250



TRANSFER CACHE

NOTE: PARTS INCLUDED IN TRANSFER
BUT NOT VISIBLE FROM VIEW:

HALL EFFECT SENSOR
ROTATING GEAR SYSTEM
MAIN BODY ATTACHMENT
ROLLER BEARINGS

UNLESS OTHERWISE SPECIFIED DIMENSIONS IN MM TOLERANCES: X.X ± 0.1 X.XX ± 0.01 X.XXX ± 0.003 ANGLES ± 0.5°	PROJECT NAME: PSYCHE ACQ			PART NAME: ACQ ASSEMBLY	
	DRAWN BY: JLR (T501)	DATE: 04/15/26	MATERIAL:		
	SCALE: 1:2	SIZE: A	REV: 1	SHT NUMBER: 1 OF 1	DRAWING NUMBER: PSY-A-003

Appendix I: Calculations

I.1 Gas Blast Flow Calculations

Exit Velocity

$$V_e = \sqrt{\gamma R T_0}$$

$$T_0 = 293K \longrightarrow V_e = 313 m/s$$

$$T_0 = 200K \longrightarrow V_e = 259 m/s$$

Mass Flow Rate (Choked Flow)

$$\dot{m} = AP_0 \sqrt{\frac{\gamma}{RT_0}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}}$$

$$T_0 = 293\,K \longrightarrow \dot{m} = 3.15\,g/s$$

$$T_0 = 200\,K \longrightarrow \dot{m} = 3.81\,g/s$$

Momentum Thrust

$$F_m = \dot{m} V_e$$

$$T_0 = 293\,K \longrightarrow F_m = 0.986\,N$$

$$T_0 = 200\,K \longrightarrow F_m = 0.986\,N$$

$$F_{m,avg} \approx 1.0\,N$$

Case A: Earth Conditions

$$P_{amb} = 14.7\,psia = 101.3\,kPa$$

$$F_p = (P_e - P_{amb})A_e$$

$$F_p = 0.221\,N$$

$$F_{tot} = F_m + F_p = 1.2\,N$$

$$F_{tot} = 0.27\,lbf$$

Case B: Psyche (Vacuum)

$$P_{back} \approx 0$$

$$F_p = P_e A_e$$

$$F_p = (144.6 \times 10^3)(4.87 \times 10^{-6}) = 0.704\, N$$

$$F_{tot} = F_m + F_p = 1.69\, N$$

$$F_{tot} = 0.38\, lbf$$

I.2 Drilling and Thermal Calculations

1.2.1 Invar 36 Low End Surrogate Material: Austenitic Stainless Steel

Spindle Speed

$$n = \frac{V_c * 1000}{D_c * pi}$$

$$n_{low} = \frac{1000 * 10}{pi * 7.94} = 401\, rpm$$

$$n_{high} = \frac{1000 * 20}{pi * 7.94} = 802\, rpm$$

Feed Per Revolution

$$f = f_z * z$$

$$f = 2 * 0.05 = 0.10\, mm$$

Feed Rate

$$V_f = f * n$$

$$V_f = 0.10 * 600 = 60 \frac{mm}{min}$$

Material Removal Rate

$$Q = \frac{V_f * pi * D_c^2}{4}$$

$$Q = \frac{60 * pi * (7.94)^2}{4} = 2970.86 \frac{mm^3}{min}$$

Specific Cutting Force

$$k\_c = \frac{k_{c1.1}}{h^m}$$

$$k_c = \frac{2000}{0.05^{0}.21} = 3752 \frac{N}{mm^2}$$

Chip Thickness

$$h = f_z * \sin(K)$$

$$h = 0.05 * \sin(90°) = 0.05\, mm$$

Power Requirement

$$P = \frac{Q * k_c}{60000 * eta}$$

$$P = \frac{2970.86 * 3752}{60000 * 0.75} = 247.70\, W$$

Torque

$$M_c = \frac{D_c^2 * k_c * f}{8000}$$

$$M_c = \frac{(7.94)^2 * 3752 * 0.10}{8000} = 2.957\, Nm$$

Feed Force

$$F_f = \frac{f * D_c * k_c}{2}$$

$$F_f = \frac{0.10 * 7.94 * 3752}{2} = 1490\, N$$

Machining Time

$$t = \frac{L}{V_f}$$

$$t = \frac{30}{60} = 0.5 min = 30\, s$$

1.2.2 Invar 36 High End Surrogate Material: 52100 Steel

Spindle Speed

$$n = \frac{1000 * 25}{pi * 7.94} = 1002\, rpm$$

Feed Rate

$$v_f = 0.10 * 1000 = 100 \frac{mm}{min}$$

Material Removal Rate

$$Q = \frac{100 * pi * 7.94^2}{4} = 4951.43 \frac{mm^3}{min}$$

Specific Cutting Force

$$k_c = \frac{1410}{0.05^{0.39}} = 4535 \frac{N}{mm^2}$$

Power Requirement

$$P = \frac{4951.43 * 4535}{60000 * 0.75} = 499\, W$$

Torque

$$M = \frac{7.94^2 * 4535 * 0.10}{8000} = 3.57\, N * m$$

Feed Force

$$F_f = \left(\frac{1}{2}\right) * 0.10 * 7.94 * 4535 = 1800\, N$$

1.2.3 Thermal Calculations

Heat Flow into Drill

$$q = k_e * P$$
$$q = (0.713) * (374.6\, W) = 267.1\, W$$

Effective Mass Heat of Drill Bit

$$V_{full} = \frac{pi\, d^2 L}{4}$$
$$V_{full} = \frac{pi * (0.00794\, m)^2 * (0.030\, m)}{4} = 1.485E - 6\, m^3$$
$$V_{eff} = 0.65 * (1.485E - 6\, m^3) = 9.66E - 7\, m^3$$
$$m = rho\, V_{eff}$$
$$m = \left(7806 \frac{kg}{m^3}\right) * (9.66E - 7\, m^3) = 0.00754\, kg$$

Radiating Area of Heated Section

$$A_{rad} = pi * D * L + \frac{pi * D^2}{2}$$

$$A_{rad} = pi * (0.00794\, m) * (0.030\, m) + \frac{pi * (0.00794\, m)^2}{2} = 8.47E - 4\, m^2$$

Initial Radiative Heat Loss

$$Q_{rad}, 0 = \varepsilon\, \sigma\, A\, (T_D^4 - T_\infty^4)$$

$$\sigma = 5.67 \times \frac{10^{-8} W}{m^2 \cdot K^4}$$

$$T_D = 137\, K$$

$$T_\infty = 3\, K$$

$$Q_{rad}, 0 = (0.24)\left(5.67 \times \frac{10^{-8} W}{m^2 \cdot K^4}\right)(8.47 \times 10^{-4} m^2)((137\, K)^4 - (3\, K)^4)$$

$$= 0.0081\, W$$

Ratio of Heat Input to Radiative Loss

$$\frac{q}{Q_{rad}, 0} = \frac{267.1\, W}{0.0081\, W}$$

$$\frac{q}{Q_{rad}, 0} = 3.30 \times 10^4$$

Appendix J: Risk Assessment

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.: Mech Eng	Start Date: March 06, 2026	Revision number: 1A
Project: Psyche Mission Sample Acquisition from Hypothesized Surfaces			Location(s): Senior Design Lab	
Team member(s):			Phone #:	Email:
Michael Gregory			386-249-4525	mbg21d@fsu.edu
Conner Holmes			904-510-4876	cjh22d@fsu.edu
Claudia Irausquin			954-778-0382	cai21@fsu.edu
Jake Marcus			609-627-9715	jlm22k@fsu.edu
Janna Rhodes			850-866-7611	jlr22a@fsu.edu
Jerry Richardson			561-660-0996	jmr22f@fsu.edu

Experiment Steps	Location	Person assigned	Identify hazards or potential	Control method	PPE	List proper method of hazardous	Residual Risk	Specific rules based on

			failure points			waste disposal, if any.		the residual risk
1. Setup drill apparatus and secure steel plate	Senior Design Lab	Team 501	Plate may shift or slip during drilling. Pinch points while mounting	Secure plate using clamps. Verify that all mounting bolts are tightened. Keep hands clear during setup	Safety glasses, closed-toe shoes.	No hazardous waste generated.	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.
2. Connect power supply	Senior Design Lab	Team 501	Electrical hazard or accidental startup	Ensure power is OFF before beginning. Inspect cables for damage. Use grounded outlet.	Safety glasses, closed-toe shoes.	No hazardous waste generated.	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.
3. Lower drill toward steel plate	Senior Design Lab	Team 501	Pinch points between drill and plate. Unintended contact with rotating bit	Lower drill slowly using controlled mechanism. Keep hands away from	Safety glasses, closed-toe shoes.	No hazardous waste generated.	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.

				drill path				
4. Activate drill and begin drilling	Senior Design Lab	Team 501	Rotating drill bit may cause entanglement. Metal chips may eject. Drill bit breakage possible	Secure loose clothing/ hair. Ensure proper drill speed. Maintain safe distance.	Safety glasses, closed-toe shoes, face mask.	Metal shavings collected in container	HAZARD: 1 CONSEQ: Minor Residual: Low	Normal lab procedures are sufficient.
5. Metal shavings produced during drilling	Senior Design Lab	Team 501	Sharp metal fragments may eject and cause cuts or eye injury	Use containment tray. Stop drill before clearing any debris	Safety glasses, closed-toe shoes, face mask.	Collect uncontained metal shavings in labeled scrap metal container	HAZARD: 1 CONSEQ: Minor Residual: Low	Normal lab procedures are sufficient.
6. Retract drill after drilling	Senior Design Lab	Team 501	Sharp hot drill bit and chips. Moving mechanical components	Turn drill OFF before retracting fully. Allow drill bit to cool before handling	Safety glasses, closed-toe shoes, face mask.	Collect uncontained metal shavings in labeled scrap metal container	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.
7. Activate gas blast sequence	Senior Design Lab	Team 501	Metal shavings blown airborne from the gas blast where they can be	Ensure retaining body around the gas blast vessel.	Safety glasses, closed-toe shoes, face mask.	Collect uncontained metal shavings in labeled scrap metal container	HAZARD: 2 CONSEQ: Moderate Residual: Low Med	Normal lab procedures are sufficient.

			breathed in or enter eyes.					
8. Remove drilled material and clean work area	Senior Design Lab	Team 501	Cuts from sharp metal shavings. Inhalation of metal dust	Use brush or magnet to collect chips. Do not use hands. Clean surface after experiment	Safety glasses, closed-toe shoes, face mask.	Dispose metal chips in designated metal recycling container	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.
9. Remove & measure extracted/ contained material	Senior Design Lab	Team 501	Cuts from sharp metal shavings. Inhalation of metal dust.	Use brush or magnet to collect chips. Do not use hands. Store metal shavings in plastic container.	Safety glasses, closed-toe shoes, face mask.	Stray metal shavings are collected and disposed in scrap metal container. Measured metal shavings are disposed in scrap metal container.	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.
10. Shutdown and store appropriate equipment	Senior Design Lab	Team 501	Residual sharp debris or electrical hazard	Disconnect power supply. Inspect area for debris	Safety glasses, closed-toe shoes.	Scrap metal disposed in proper container	HAZARD: 1 CONSEQ: Negligible Residual: Low	Normal lab procedures are sufficient.

				before leaving				