ME 450 Final Report

Baja Gear Reduction

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ABSTRACT

The University of Michigan Baja Team designs, builds, tests, and races an off road race vehicle each year. During each season, a custom drivetrain is typically designed as a reduction after the continuously variable transmission. The goal of the project is to develop a lightweight, compact gear reduction that will increase the efficiency, design complexity, and durability of the 2012-2013 vehicle. The Baja Team’s hope is that this system will help them to be more successful during the 2012-2013 SAE Baja season.

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EXECUTIVE SUMMARY

Each year, the University of Michigan SAE Baja Team designs, builds, and tests an off road race vehicle. During their annual design process, a custom drivetrain is designed to follow the continuously variable transmission. In recent years, a number of reduction sizes and types have been chosen in an attempt to increase the reliability and efficiency of the vehicle while minimizing the weight. One of Baja's overall goals this year is to win the Ironman award, which goes to the team that achieves the highest combined score after the season's three competitions. To reach this goal, the Baja Team hopes to earn higher scores in the design aspect of their competitions. While belt and chain reductions receive satisfactory scores for design, judges in the design event have recently expressed a desire to see gear reductions. As a result, Team 6 has been tasked with designing and building a gear reduction system to remedy their design issues, while also increasing the efficiency and durability of their reduction system.

The Michigan Baja team has a number of specific requirements for the gear reduction and housing. The Baja Team requested the drivetrain have a breakaway torque to rotate less than or equal to 1.35 in-oz and that the weight of the drivetrain not exceed 30 lbs. The Baja Team has also requested that Team 6 work closely with them as they solidify the design for their vehicle and that the drivetrain comply with the 2012-2013 Baja SAE Racing rules. Expanding on these original specifications, Team 6 and the Baja Team have agreed that an appropriate total gear ratio can range from 10.5:1 to 11.5:1. The Baja team also requested that Team 6 avoid using keyways within their gear reduction due to high failure rates in previous years.

Team 6 began their project by spending time discussing the specifications with the Baja Team and outlining the design process. With the specifications outlined, Team 6 brainstormed possible concept solutions for both the gear reduction and the gearbox. After choosing five different gear reduction options and four gearbox options, Team 6 used Pugh charts to determine the most effective concepts, which defined an alpha design. Using their alpha design, Team 6 conducted engineering analysis, which provided a variety of outputs used to determine gear specifications, material choices, and final design decisions. Once designs were finalized for both the gear reduction and gearbox, CAD was created of the final design assembly. With the designs solidified, Team 6 executed their fabrication plan which included heat treating, external machining done by outside sponsors in addition to machining done by members of Team 6. With possession of all gearbox components, assembly occurred and the validation plan was executed. Based on the results of each step of validation, Team 6 met all engineering specifications set fourth throughout the project. Upon completion of the project, Team 6 critiqued their design and provided recommendations for improvement of their product if they were provided additional resources and time.

Throughout this process, Team 6 encountered a number of challenges. Material selection became a challenge as Team 6 faced limited resources since their sponsor is a student run team which uses mostly donated materials. Provided the three-month time constraints to finish the project, there was also difficulty getting the gears manufactured by General Motors which required Team 6 to use an alternative sponsor, Vertical Machining, for wire EDM. The purpose of this report is to provide project motivation, background, literature review, customer requirements, engineering specifications, concept generation, alpha design details, engineering analysis, final design description, fabrication, validation and design critiques

PICTORIAL SUMMARY

Right side of finished gearbox including carbon fiber finger guards.

Left side of finished gearbox without carbon fiber finger guards exposing gear reduction

Team photo from the Design Expo

PROBLEM DESCRIPTION

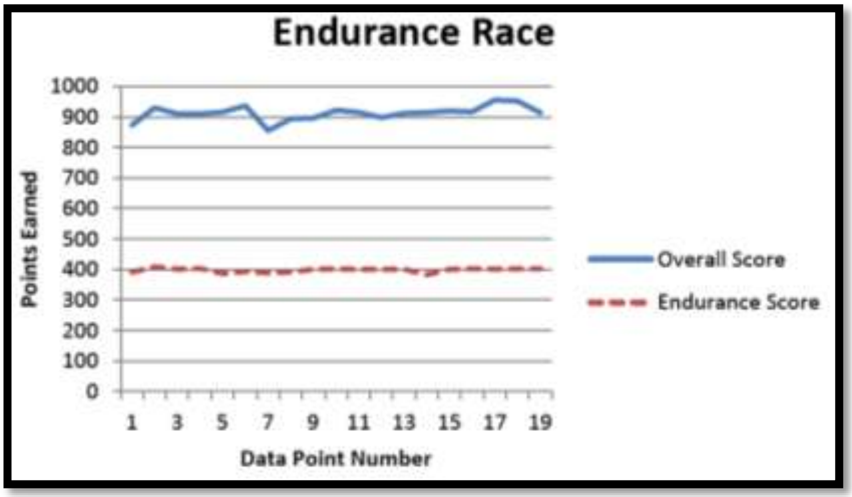
Each year, the Society of Automotive Engineers (SAE) hosts a collegiate Baja design series. The SAE Baja design series consists of three competitions that are held in the spring every year, where approximately 150 teams compete. Each student run team is responsible for designing, building, and testing their off road vehicle for the competitions which consist of three days of events. The first day consists of design and cost judging, as well as a technical inspection. The second day consists of dynamic events including acceleration, land maneuverability, suspension and traction, hill climb, mud bog, and rock crawl. The final day of competition is a four hour endurance race with approximately a hundred vehicles competing.

At the University of Michigan, the SAE Baja Team consists of 20-25 students who work together to be successful at each competition. The 2012-2013 team is made up of 21 undergraduate and 3 graduate students. These students work together to secure funding, organize team meetings and events, and design a Baja vehicle to meet the requirements of the competition. They then build the vehicle to match the design and subsequently test the vehicle to ensure its success at competition; Figure 1 shows the 2011-2012 vehicle.

Figure 1: An example of a University of Michigan Baja vehicle that was built for the 2011-2012 season.

Recently, the Baja Team's results at competition have continued to improve each year. During the 2011-2012 season, the team placed 11th at Auburn and 12th in Oregon. After traveling to all of the competitions, and competing against over 150 other universities, the culmination of all the competitions resulted in a 9th place overall finish in the Ironman competition. Looking to improve upon this placement for the 2012-2013 season, the goals of the Baja Team this year include increasing the vehicle's efficiency without sacrificing weight and durability, as well as increasing the Baja Team's design score. With these goals in mind, the Baja Team has tasked Team 6 with designing, building, and testing a gear reduction and housing, which can be implemented on the 2012-2013 vehicle. It is the hope of the Baja Team that the gears will introduce less failure modes in their reduction, therefore increasing the team's success during the endurance event. Figure 2, below, illustrates the importance of the endurance race. The Baja team has determined that finishing the endurance race is the first step towards earning 400 points in this event, and that a gear reduction will help accomplish this task since the gear reduction will also increase the efficiency of the car, thereby increasing the speed.

Figure 2: The figure shows that the teams which took first place at competition for the past 10 years have averaged 400, out of a maximum of 400, points in the endurance race.



INFORMATION SOURCES

Team 6 has consulted a number of sources in order to be successful in approaching this task. The use of previous Baja Team designs, combined with mechanical design handbooks, will be instrumental in creating a successful product.

Previous Sponsor Designs and Information

Over the past 5 years, the Michigan Baja Team has tried a number of different designs for the final reduction in attempts to increase efficiency, ease of packaging, and serviceability, while simultaneously decreasing weight. In recent history, the team focused on two other types of reductions: chains and belts. In 2010-2011, the Michigan Baja Team designed a reduction box which utilized Gates Carbon Fiber Timing Belts to achieve the desired reduction. By using belts, the team was able to have a lightweight drivetrain, through the use of aluminum pulleys. The Team was also drawn to choose a belt design because Gates advertised the efficiency of their belts as higher than chains. However, the belts performed poorly on the car, breaking multiple times due to shock loading. Baja Team engineers recognized that in designing a reduction that utilizes belts, there is no design parameter to account for shock loading. Due to the multiple belt failures and the inability to compensate for shock loading, the team looked into running chains.

Due to the team's success with chains prior to 2009, and their proven increase in efficiency, chains were chosen as the reduction for the 2011-2012 vehicle. Utilizing aluminum sprockets for the initial reduction, the team was able to minimize the weight impact. One drawback of the chain reduction was the increased rolling resistance of the drivetrain. Nevertheless, testing and competition showed the vehicle to perform well with the chains, taking 3rd place in acceleration. During the endurance race, however, the chains also proved unable to handle some shock loading. This, combined with the theoretically higher efficiency which gears provide, has driven the team to request a new reduction for the 2012-2013 vehicle. In recent years, both team members and design judges have expressed interest in seeing a gear reduction attempt for a new reduction option.

Outside Source Information

Apart from learning from the members of the Michigan Baja Team, Team 6 has examined a number of sources to fully understand the concepts related to the drivetrain. The first source addressed was the Rules and Regulations of the Baja competition. There are a number of rules set forth by SAE Baja that relate directly to the drivetrain. The rules state that all rotating parts must be completely covered, to prevent fingers from being caught. There also needs to be a gear housing made out of either AISI 1010 strength steel at least 0.06 in thick or 6061-T6 strength aluminum at least 0.12 in thick that prevents the driver or bystanders from injury, if a part of the drivetrain becomes separated by centrifugal force. (SAE International)

To create a successful gear reduction, Team 6 also needed to become familiar with gear properties, methods, and equations used to design a gear reduction. Using *Shigley's Mechanical Engineering Design (Eighth Edition),* Team 6 looked into the details of different types of gears and how gear type selection would affect both the design process and the final product. Spur gears, the most common type of gears, are used to transmit motion between parallel shafts. Some of the benefits of choosing spur gears include ease of manufacturability and maintenance and the absence of end thrust. One of the disadvantages in using spur gears is that they are typically used at slower speeds, as they can produce significant noise at higher speeds. Another common gear choice, helical gears, have inclined teeth and can be used for many of the same applications as spur gears. Lowering noise levels is one of the advantages of helical gears over spur gears. The angled helical gears also create bending couples and thrust loads which are not present when spur gears are used. Unfortunately, helical gears are more complicated to machine than spur gears. Bevel gearing is also a viable option for this gear reduction project but is typically more useful for applications where the shafts transmitting motion are intersecting. Other than the provided packaging requirements, the Baja Team requested that the designed gear reduction provide 10.5-11.5:1 final gear ratio. To obtain this ratio, equations and guidance provided by *Shigley's Mechanical Engineering Design (Eighth Edition)* was utilized (Shigley, Nisbett, & Budynas, 2011).

Along with *Shigley's Mechanical Engineering Design*, the team examined a number of papers and books that looked more in depth at gear reduction related equations and design methods. One such book was the *Handbook of Gear Design*, which contained more in-depth equations and detailed theory behind gear design (Maitra, 1997). From this handbook, Team 6 determined that more than one pair of teeth is in contact at any given time and, because of this, the bending stress can be divided by the contact ratio. The team explored gears with higher contact ratio's to help reduce the design failure rate (Sabah & Mohammad, 2008). This concept is further discussed in the Engineering Analysis section on Page 19.

Team 6 also referenced *Manual of Applied Machinery Design* to better understand what mechanisms were required to support the gears. This text also contains information pertaining to bearings used with gear shafts. Team 6 referenced this information extensively to determine what bearings are required for their design. This text also contains a number of interesting gear configurations and more detailed information on the advantages and disadvantages of different configurations (ALVORD, 2012).

The team was considering using aluminum hubs and therefore looked at a patent that referenced the use of aluminum gear hubs with steel outer rings (Premiski & Premiski, 1987). Team 6 would like to use this idea on the larger gears to reduce the weight, however they were only able to find information on aluminum hubs on bicycles (Allen, 2011), (Brown, 2008). Due to the lack of available information, Team 6 derived their own equations based on the equation in *Intermediate Mechanics of Materials* related to press fits (Barber, 2000). These equations are further discussed on Page 21 and Appendix C.

Various sources were also consulted to complete calculations related to splines and polygons as methods to translate torque from the shafts to the gears. The *Machinery's Handbook, 28th Edition* was referenced to determine all equations related to splines (Oberg, Jones, Holbrook, & Ryffel, 2008). Polygon supplier technical information was reviewed to calculate the bending and torsional moments on shafts (Polygon Engineering Date P3 & PC4 Polygon Standars Design of Shafts and Hubs, 2001).

In addition, a number of patents related to All Terrain Vehicle (ATV) drivetrains were explored. One such patent uses a CVT attached to a series of pulleys attached by belts to achieve the necessary reduction (Pestotnik, 2001). Another ATV transmission considers using uses a four stage, spur gear reduction as well as a chain reduction. One ATV patent used manual transmission instead of a CVT which requires a much more complex gear reduction (Davis, Davis, & Davis, 2005).

Finally, Team 6 attempted to examine other SAE Baja teams' gear reduction methods. Due to the fact that SAE Baja is a competition, teams usually choose not to share information regarding their vehicle design and as a result it was hard to uncover much valuable information. Team 6 was able to find that the 2010 the California Polytechnic State University Team used a sequential shift manual transmission by purchasing a 5-speed Kawasaki Bayou gear set for their drivetrain (McCausland, Watkins, Masterson, & Sommer, 2010) and that the 2012 Auburn team used a CVT with a planetary gear reduction system. The Auburn team found that they had a number of reliability issues with their reduction which are outlined in the article in SAE's *Momentum* magazine (ETS Baja Parts Failure, 2012).

PROJECT REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Michigan Baja is an engineering team and therefore gave a very specific set of project requirements to Team 6. The team took the provided requirements and developed the engineering specifications.

Project Requirements

The Michigan Baja Team has a desire to switch their drivetrain reduction from a chain to a gear reduction in order to improve efficiency. The Baja Team recognizes that a gear reduction will increase the weight of the vehicle, but they would like the weight increase to be minimized so that the drivetrain weight does not increase the weight of the vehicle by more than 10% of the weight of the 2011-2012 vehicle. The Baja Team would also like a final gear reduction of 10.5-11.5:1. Because the team expects the finished gear reduction box to be competition ready, the drivetrain must fit within the parameters of the vehicle and also follow all the rules outlined by SAE Baja, stated above. In order to meet the packaging requirements of the vehicle, the drivetrain must work with a 0.75 inch input shaft. Team 6 is also expected to work closely with the Michigan Baja Team throughout their design process to ensure the final product integrates successfully with the 2012-2013 vehicle.

The team also has some additional requirements, which need to be considered and applied to the system, despite not being fundamental to the design. The first requirement is the application of a brake caliper mount. In order to meet the team's needs to reduce the amount of unsprung mass (mass at the wheel) on the vehicle, the team plans on using just one rear brake, which is to be located at the reduction box. The caliper will be attached to the structural siding of the finger guard in order to meet packaging requirements. In addition, the mount will need to be able to support the weight of the caliper and be configured for proper integration with the brakes system. The mount will also need to be able to withstand the loading from the caliper during a full wheel lock up situation. A second requirement is a packaging requirement which influences the distance between the centerline of the input shaft and the centerline of the output shaft. The input shaft will need to integrate with the continuously variable transmission (CVT) that the Baja Team currently runs on the vehicle. The final reduction shaft, or output shaft, will need to mate to a driveline joint. The sizing of the CVT and driveline joint defines a packaging constraint that allows for the best possible vehicle integration. For optimal integration of the reduction box to each system and the vehicle, there is a minimum distance of six inches and maximum distance of eight inches between the centerlines of each shaft.

Engineering Specifications

Having met with the Baja Team, Team 6 has added and revised a number of engineering specifications. Initially, the Baja Team requested a reduction equal to an 11:1 reduction. However, after conversing with powertrain engineers on the Baja Team, they agreed that a range of reduction options was more practical, since determining gear tooth combinations that generate a reduction of exactly 11:1 would be nearly impossible. Team 6 and the Baja Team agreed that a final reduction ratio range of 10.5:1 to 11.5:1 would result in a suitable ratio that would allow the team to be successful in the 2012-2013 season.

As the vehicle CVT and suspension systems were designed, the packaging requirements became more clearly defined. The distance between the shafts became a limiting factor for Team 6, with a minimum length of six inches between the input and output shafts. Due to the packaging requirements, the width of the gear box cannot be greater than four inches. The vehicle is not finished being designed and, therefore, these requirements may still change, this issue is further discussed on Page 38.

Once shaft design began, Team 6 considered using keyways, splines and polygons to transfer motion from the shafts to the gears. However after discussing with the Michigan Baja team, Team 6 was informed that the Baja team had durability issues when using key slots in the past and no longer use any key slots in the primary reduction stages. Because of this, Team 6 only investigated the use of polygons or splines, which can be found on Page 23.

After speaking with the team's gear manufacturing sponsor, General Motors, a new requirement was developed. While General Motors is able to manufacture gears with almost any dimensions and specifications, they are only able to cut gears with a 14.5 degree pressure angle. Because of this manufacturing constraint, Team 6 has added an engineering specification that the gears use a 14.5 degree pressure angle. With the new 14.5 degree pressure angle requirement, and the strength requirements previously discussed, Team 6 also added a requirement that the gears be hardened. This requirement is necessary in order to ensure proper strength of the gears. The strength requirements are further discussed in the gear engineering analysis on Page 19.

Benchmarking

Looking at the requirements for the gear reduction, the most readily available benchmarking tool is the 2011-2012 vehicle. One of the provided requirements is that the gear reduction assembly must not increase the weight of the vehicle by more than 10%. Placing the 2011-2012 vehicle on corner scales, a vehicle weight of 307 lbs. was measured. Therefore, the gear reduction assembly must not weigh more than 30 lbs.

Baja has also specified that the friction of the drivetrain must be decreased by 10%, when measured by using breakaway torque to rotate, as the friction causes a loss of power. Because competition rules specify the stock engine the Baja Team must use, efficiencies in the drivetrain are a significant factor in the Baja Team’s success in acceleration and top speed. In order to measure the frictional losses of the drivetrain, an industry standard of utilizing torque to rotate was implemented. Using a torque wrench, the torque to rotate of the 2011-2012 vehicle was measured as 1.5±0.0625 in-oz.

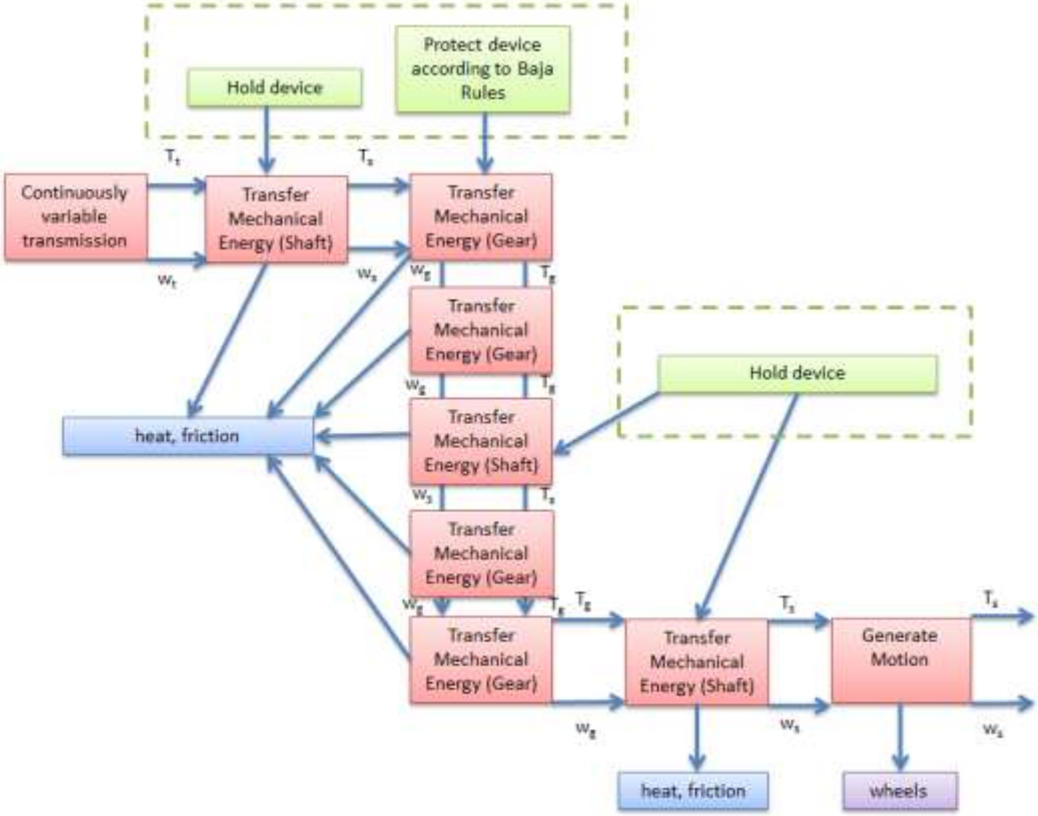
CONCEPT GENERATION

In order to generate concepts, the team performed the initial steps of the design process. The first step was to complete a functional decomposition of the system, in order to understand the necessary functional requirements of the design. Members of Team 6 then individually developed design concepts for the gear reduction and housing. The functional decomposition, top gear reduction concepts, and the top housing concepts are described below.

Functional Analysis

A functional decomposition provides a general overview of the project purpose and the expected components. Its’ simple format helps to easily depict what the project must accomplish and then helps outline viable design solutions. The auxiliary functions are the components outside of the immediate design that will help integrate the alpha design with the Baja vehicle. Adding these auxiliary requirements to the visual showed Team 6 which gear reduction components will need to be supported by the gearbox design. In addition, the arrows throughout the analysis are labeled to show Team 6 which components have an applied torque or an angular velocity. Because of these labels, Team 6 was able to get an idea of which components will need to be supported by bearings and which components will need to have force analysis conducted on them. The functional decomposition also accounts for the energy outputs as a result of the movement of our design components, highlighting which areas of the design will affect efficiency. Based on the alpha design, the functional decomposition is now equipped to also represent the transfer of mechanical energy from the input shaft to the first gear reduction, to the intermediate shaft, to the second gear reduction, and finally to the output shaft to power the vehicles wheels. In summary, the functional decomposition shows that the project system includes an input shaft equipped to rotate following the continuously variable transmission, the alpha design gear reduction as it transfers mechanical energy, and the rotating output shaft that will power the wheels, as shown in Figure 3.

Figure 3: The functional analysis below shows the transfer of mechanical energy from the input shaft to the first gear reduction, to the intermediate shaft, to the second gear reduction, and finally to the output shaft to power the vehicles wheels while also pointing out where rotation accommodating supports are necessary and where efficiency will be lost.



Brainstorming

With a deeper understanding of what the system would need to include, members of Team 6 worked independently on creating a number of unique design concepts. After the concepts had been generated, the team met to review them, to elaborate on existing ideas, and to brainstorm new ideas. While meeting, Team 6 quickly realized that the designs for the gear reductions and the designs for the gear housing were two separate entities with different design criteria and should be examined separately.

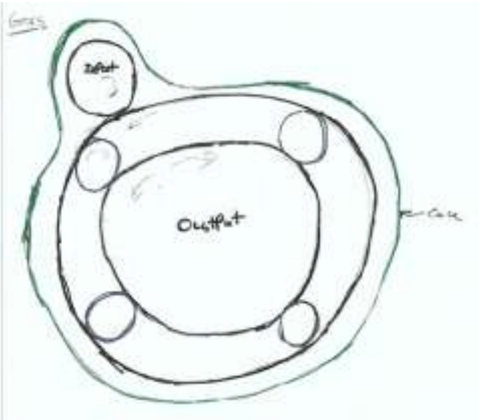
Gear Reductions

All of the gear designs conceived fit into one of the following categories: spur, helical, planetary, bevel, or combinations of the previous categories. The designs ranged from single stage gear reductions up to four stage reductions. Below are descriptions of five main gear reduction concepts along with their main advantages and disadvantages. A number of the concepts were eliminated without use of a scoring matrix, because they were either very similar to other concepts generated, or had obvious flaws; there were also some concepts that were combined to produce other concepts. All of the concepts selected for the design matrix had the correct output shaft rotational direction.

Concept 1: Planetary Gears

Multiple team members created concepts using planetary gears and, after much discussion, the following design was developed. This design uses planetary gears and an individual spur gear as the gear input, which rotates the outer planetary gear. This outer gear rotates four smaller inner gears, which transfer the motion to the sun gear which acts as the drivetrain output, shown in Figure 4. Other planetary gear designs are located in Appendix A.1. One advantage of this gear reduction is that it is light-weight. Some disadvantages of this design are that it may be difficult to manufacture and assemble and also consumes a large amount of raw material during the manufacturing process. Another disadvantage is the increase in friction due to the number of meshing gears. Also, due to the large space requirements of a planetary gear reduction, there could be packaging conflicts when integrating the design into the Baja vehicle.

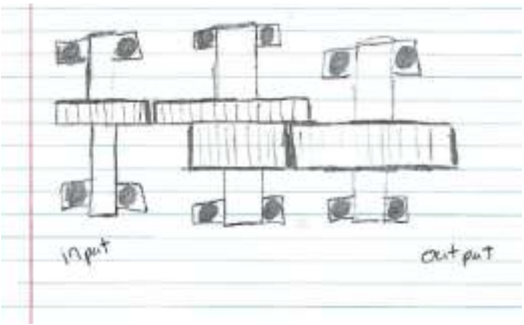
Figure 4: The illustration below show the front view of gear reduction Concept 1, which uses planetary gears.



Concept 2: Spur Gears

Team 6 investigated spur gears with multiple stage reductions, considering using between one and four stage reductions to create an 11:1 gear ratio. All of the spur gear concepts can be found in Appendix A.2. The final decision was a three stage gear reduction, shown in Figure 5. A three stage reduction was chosen because having the input and the output shaft rotate in the same direction was a necessity, and only an odd stage reduction would accomplish this. In order to minimize the weight of the system, a three stage, rather than a five stage, reduction was chosen. In this concept, the input gear will mesh with an intermediate gear. This gear will be on the same shaft as the second intermediate gear so they rotate at the same speed. The second intermediate gear then meshes with the output gear. There are many advantages of spur gears, including ease of manufacturing, low friction properties, and weight savings opportunities. It will be easier for GM to manufacture spur gears due to the ease of cutting. Spur gears also allow for the possibility of hubs, which can allow the system to use a lighter material. For packaging on the vehicle, the spur gears would be preferred since the long narrow box will integrate well with the current vehicle being designed. One disadvantage is that the design is fairly simple in that it only uses two stages of very basic spur gears. In competition, design judges are constantly looking for ways that teams could increase their design complexity regardless of the efficiency of their design and may prefer a more complex reduction Also, at high speeds, spur gears are known to produce loud sounds, a disadvantage in many applications.

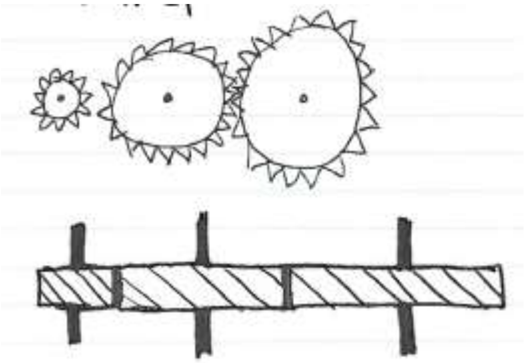
Figure 5: This illustration shows the top and front view of Concept 2, which show a gear reduction using spur gears.



Concept 3: Helical Gears

Concept 3 uses at a number of helical gears in series, as shown in Figure 6, on the next page. Team 6 decided on a three stage reduction which could create the correct reduction and ensure the output shaft will spin the in the correct direction. The input gear will rotate an intermediate gear, which then turns the output gear. Each gear will have a larger diameter than the previous gear. Appendix A.3 contains more designs with helical gears. Concept three will have similar advantages as concept two, including ease of assembly, lightweight, and low drivetrain friction. Compared to spur gears, helical gears are also inherently quieter at high speeds. Helical gears would be harder to have a sponsor manufacture due to the complexity of the shape and time to machine each part. Furthermore, the volume may be unnecessarily large due to the need for a large output gear in order to achieve the correct final reduction.

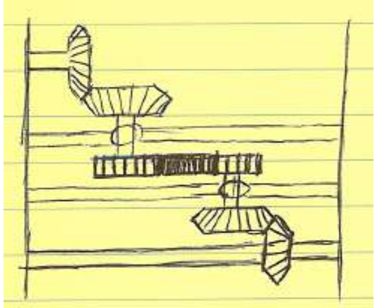
Figure 6: The illustration shows the front and top view of Concept 3, which uses a series of helical gears.



Concept 4: Bevel and Spur Gears

The team examined using a combination of bevel and spur gears to create the desired reduction. In this design concept, the input shaft would go to a set of bevel gears. The secondary bevel gear would be on the same shaft as a spur gear. This spur gear goes to two additional spur gears, the second of which is on the same shaft as a bevel gear which then meshes with an output bevel gear. This reduction sequence is best shown in Figure 7. Similar concepts are given in Appendix A.4. Though bevel gear reductions are ideal for intersecting shafts, Baja's vehicle does not require any intersecting shafts, making bevel gears unnecessary. Bevel gears are also difficult to manufacture and having perpendicular shafts would make this concept hard to assemble. Also, bevel gears create torques on the system that may cause the need for extra support on the system.

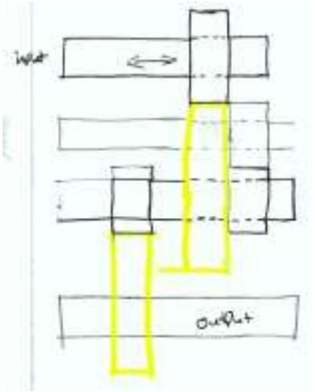
Figure 7: This illustration shows a top view of Concept 4, which uses bevel and spur gears.



Concept 5: Forward and Reverse

Team 6 also looked at adding additional functionality to the gear box by adding reverse to the drivetrain. This gear reduction uses spur gears and a movable shaft in order to facilitate reverse, as shown in Figure 8, on the next page. To create a drivetrain with reverse, there is additional gear in the reduction, which, when engaged, will reverse the direction of the final drive. During forward movement the gear reduction functions similarly to Concept 2. To switch to reverse, the input shaft translates horizontally and engages with a different set of gears, causing the output shaft to spin in the opposite direction. Bedsides increasing the functionality, this would also increase the complexity of the gear design which would in turn increase the Baja's design scores at competition. There are a number of disadvantages associated with this added functionality. The weight and volume would increase and the manufacturability and assembly would be more difficult. Also, the team has not asked for this increased functionality.

Figure 8: The illustration below shows a top view of Concept 5, which has the added functionality of reverse.



Gear Reduction-Evaluation Matrix

To effectively compare the chosen concepts, Team 6 determined what criteria were necessary for a successful gear reduction. Subsequently, the chosen concepts were evaluated on their ability to satisfy each criterion. Items that were absolutely necessary for a successful product for the Baja Team took first priority, which included the correct output direction and the minimum center to center. The friction was also ranked highly due to the overall goal of increasing the efficiency of the system. Next, weight, volume, manufacturability, ease of assembly, amount of material and complexity are ranked to help the team achieve the goals of the sponsor and to optimize the system. The center-to-center, manufacturability, and ease of assembly were the criteria with the largest spread of scores and ultimately were the deciding factors. The advantages and disadvantages, listed in the sections above with each concept were used to create the scoring matrix, shown in Figure 9.

Figure 9: The table shows the evaluation matrix for gear reduction concepts 1-5.

Criteria	**Weight**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
Output Direction	30	2	2	2	2	2
Center to Center	30	0	2	1	-1	0
Drivetrain Friction	25	-1	1	1	0	-1
Weight	20	1	1	1	0	-2
Volume	15	1	0	0	-1	-1
Manufacturability	10	-1	1	0	-2	-2
Ease of Assembly	10	-2	1	2	-2	-2
Amount of Raw Material	5	-1	0	1	0	-2
Design Complexity (for higher scoring in design competition)	5	1	0	-1	0	2
Total		15	185	155	-25	-60

From the scoring matrix it was determined that Concept 2 best meets the criteria and will be combined with a housing concept in the alpha design.

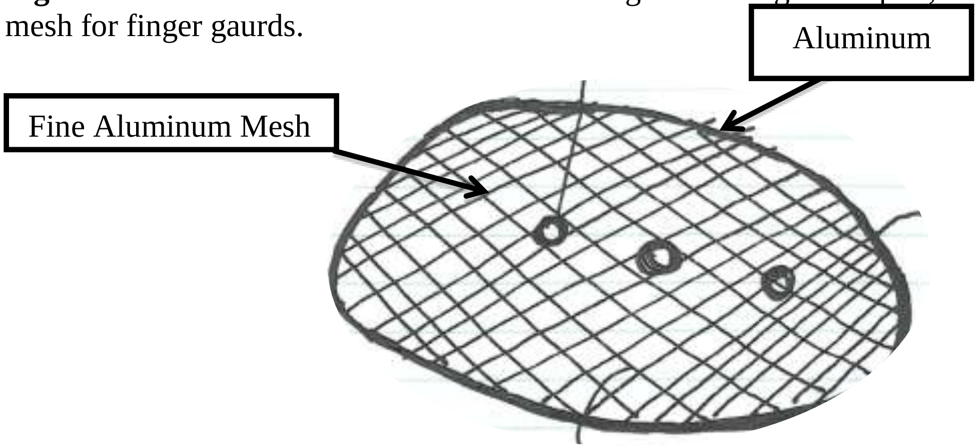
Gear Housing

Once gear reductions concepts were discussed and a concept was agreed upon, the team individually developed housing concepts. There was little variation in housing concepts, partially because there are a number of SAE Baja rules that relate to the gear housing and partially because the housing is affected by the gear reductions that is chosen. Per Baja rules, a surround is similar in all concepts. A total of eight housing concepts were generated. Most housing variations differed in the material used for the finger guards or the geometry of the shaft supports. There were four main categories: metal mesh, metal with cut-outs, metal with composites, and completely metal. A design for each category is described below, the remaining designs are shown in Appendix B.

Concept 1: Metal Mesh

Concept 1 uses finger guards made out of a fine aluminum mesh. This mesh would also serve as the shaft support, shown below in Figure 10. The material surrounding the gears radially would be made out of aluminum in conjunction with the Baja SAE rules. This would make the housing lighter and it would be easy to manufacture. However, it would still need a large sheet of meshing for the raw material. The meshing may also have difficulties supporting the gear shafts effectively and it would not contain the gear lubricant.

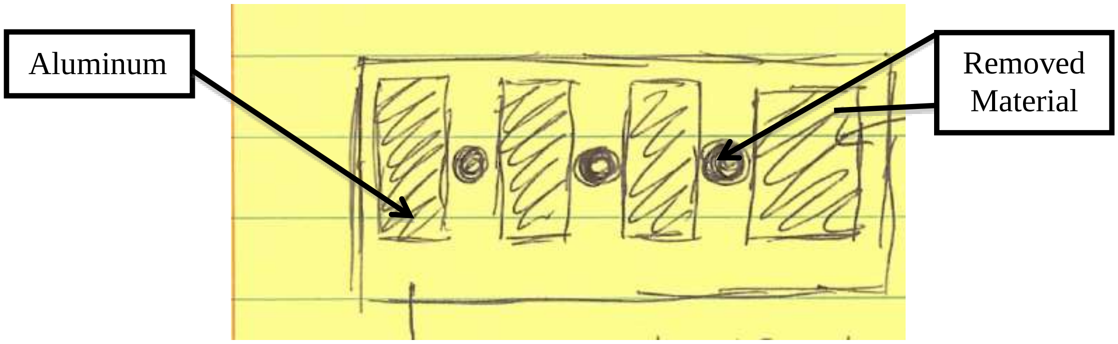
Figure 10:This illustration shows the front veiw gear housing Concept 1, which uses aluminum mesh for finger gaurds.



Concept 2: Metal with Cut Outs

Concept 2 is similar to Concept 1 because the housing could also be an aluminum sheet with a number of sections removed, which would reduce the weight while still supporting the gear shafts. A drawing of Concept 2 is shown in Figure 11. The benefits of Concept 2 include a low amount of raw material and reduced weight. One major disadvantage of this concept is the lack of finger guard, which is required by SAE Baja rules, in the areas with cut out material. Also, if a lubricant was deemed necessary, Team 6 would need to fully close the box which would require redesign.

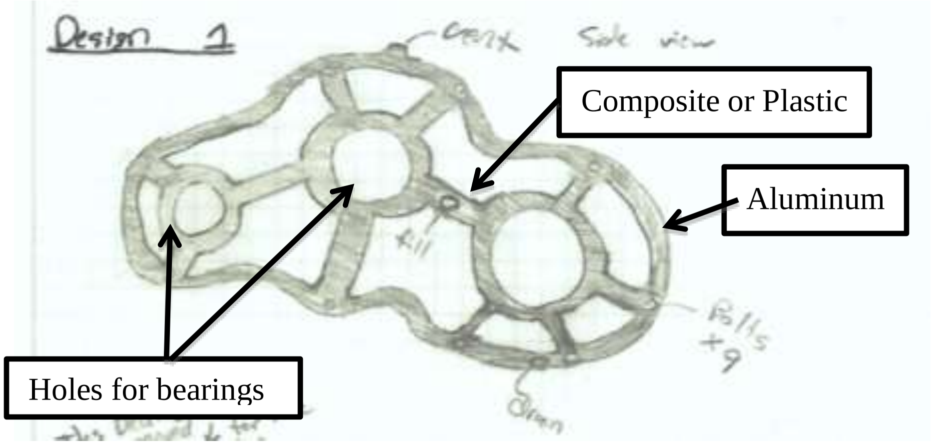
Figure 11: The illustration below is a front view of Concept 2, which removes material from the housing to reduce weight.



Concept 3: Metal with Composites or plastic

Concept 3 solves the guarding problems of Concept 2 by using carbon fiber or plastic as finger guards, as well as a sealing gel to contain the gear lubricant if necessary. A shaft support structure could be fabricated out of aluminum and used in conjunction with the finger guard. This concept is displayed in Figure 12. This material combination would support the shafts and still avoid adding unnecessary metal to the housing design. Unfortunately, there could potentially be challenges sealing the finger guard materials to the housing and two or more materials would need to be purchased.

Figure 12: This illustration shows a front view of Concept 3, which uses a combination of metal and composites or plastic.

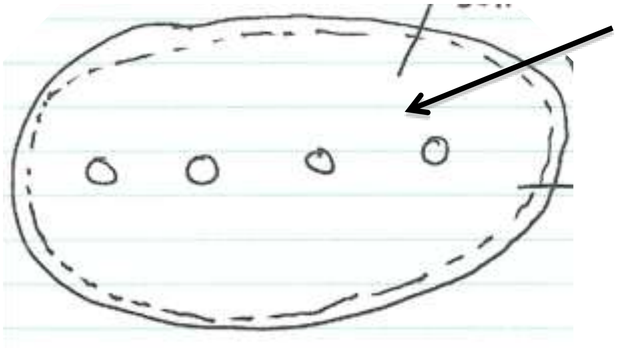


Concept 4: Solid Metal

Concept 4 uses a solid flat metal plate to support the gear shafts, to serve as figure guards, and to contain lubricant. This design is shown below in Figure 13. The advantages of this design include its ease of manufacturability and its ability to support the gear shafts properly. Unfortunately, this design would require a large piece of material and it would be relatively heavy.

Figure 13: The illustration below shows the front view of Concept 4, which is a solid metal housing.

Aluminum



Gear-Housing Evaluation Matrix

Similar to the gear shafts, the four gear housing concepts were also compared using a scoring matrix. Because the gear reduction and housing combine to make our product, multiple criterion for success can be seen in both scoring matrices. However, the housing is different because it must to be able to support the gear shafts to be successful. Also, adherence to Baja SAE rules affects the housing of the drivetrain and must be considered in the scoring. The criterion that had the largest difference in scoring was ability to support shafts, overall weight, and total volume. The scoring matrix is shown below in Figure 14.

Figure 14: The table shows the evaluation matrix for gear housing concepts 1-4.

Criteria	**Weight**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**
Shaft Support Strength	30	-2	1	1	2
Follow SAE Rules	25	1	1	1	1
Weight	20	1	0	2	-2
Volume	10	0	0	2	-2
Manufacturability	10	1	1	0	2
Ease of Assembly	10	2	1	0	1
Amount of Raw Material	5	1	0	0	-1
Ease of lubrication	5	0	0	1	1
Total		20	75	110	55

Based on the evaluation matrix, gear housing Concept 3 was chosen.

ALPHA DESIGN DESCRIPTION

Team 6’s chosen alpha design is based on the combination of Concept 2 from the gear reduction concept generation and Concept 3 from the gear housing designs. The input gear receives the power from the CVT via the input shaft. The input gear then meshes with the first intermediate gear creating the first reduction. A shared shaft supports both intermediate gears; therefore, the motion from the first intermediate gear is transferred to the second intermediate gear without the need of additional meshing gears or added weight. The second intermediate gear then meshes with the output gear, creating the second and final gear reduction. The output gear's rotation turns the output shaft which transfers mechanical energy to the rear wheels as well as a brake rotor. Figure 15, shows the completed alpha design model. Team 6 has also considered using aluminum hubs for the gears to help reduce the weight and moment of inertia of the system, without sacrificing the wear or strength benefits of steel for the gear teeth. In addition, Team 6 expects that all of the shafts will have splines or polygons to ensure that gears and shafts rotate together and will be supported by the gear housing. The gear housing will require bearings fitted in bearing carriers that will support the shafts and reduce friction. There will also be finger guards made out of carbon fiber or another, readily available, lightweight composite or plastic, which will help with sealing and follow all SAE Baja rules. The use of liquid sealant will ensure the system is leakproof.

Prototype Creation

To help evaluate their alpha design, Team 6 created a prototype to demonstrate both form and function. Based on their alpha design calculations, the team was able to determine a rough idea of the sizing of the gears. The team was able to place this rough idea in CAD without tooth details. However, when placing the dimensions in the software, the team realized that the first stage's intermediate gear was too large and went through the output shaft, which would not work for an actual design. This allowed the team to determine another equation that needed to be satisfied to produce a feasible gear reduction. After correcting for the error in overlap of the output shaft and intermediate gear, the team completed the CAD model. After completing the model, they were able to place the design into GibbsCam and create the G-Code for the CNC router, located in the Wilson Student Project Team Center. Using the router, Team 6 was able to cut the design out of tooling board, as the Baja Team has tooling board readily available. A safety report for this process is located in Appendix G. After the shapes were created, the team adhered the steel shafts to the tooling board gears. To allow the gears to be able to rotate, the team applied grip tape to the system; this increased the friction and allowed the gears to turn when enough torque is applied. A photograph of the prototype is shown in Figure 16, on the next page.

Figure 15: The illustration below is a preliminary CAD model of Team 6's alpha design.

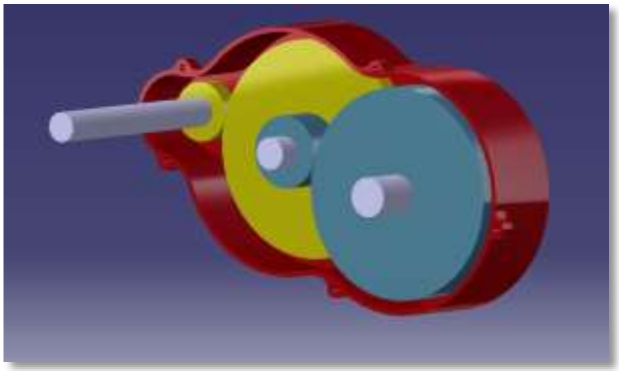


Figure 16: This picture shows the prototype created of the alpha design.

The creation of their proof of concept prototype helped Team 6 complete extensive design analysis.

ENGINEERING DESIGN PARAMETER ANALYSIS

The engineering analysis necessary to take the alpha design to a final design involved solid mechanics and dynamics, along with gear calculations. Tools that Team 6 used to complete this project include Excel, Catia and Hypermesh FEA software. The team's first step was completing the calculations described below. They then created CAD models and conducted Finite Element Analysis (FEA). This allowed the team to determine their final design.

Gears

As previously mentioned, extensive gear calculations were completed to determine the gear geometries. The main components of these equations include material strength, pressure angle, gear reduction ratio, center-to-center distance, pitch, face width, and the number of teeth on each gear. The material, and subsequently the material strength, was determined based on the materials the Baja Team has available. The pressure angle for the gears has become a specification after discussions with GM concerning their gear manufacturing capabilities. The Michigan Baja Team specified the gear reduction ratio and minimum center-to-center distance. Once possible designs are determined, Team 6 determined the optimum dimensions to minimize the amount of mass and moment of inertia. Also note that all equations are in English units per the Baja Team's request.

The first part of analysis Team 6 completed was the loading parameters on the gears. To determine these parameters, the team determined the equations for pitch line velocity, v, tangential load ,W, and applied torque, T. The pitch line velocity was determined using the maximum rpm, S_{rpm}, coming from the CVT, and the first gear diameter, D_1, as seen in Equation 1.

$$\frac{\pi * D_1 * S_{rpm}}{12} = v \qquad \text{Equation 1}$$

This allowed the team to account for the maximum pitch line velocity possible. Team 6 then applied the pitch line velocity to calculate tangential load, *W* (Equation 2). By applying the peak power and pitch line velocity, Team 6 can account for the maximum tangential load on the system. The tangential load can then be used to determine the applied torque on the gear, as seen in Equation 3.

$$W = \frac{33000 * Power}{v} \quad T = \frac{D_2 * W}{2 * 12} \qquad \text{Equations 2, 3}$$

After determining these parameters, Team 6 needed to calculate the bending stress on each gear tooth. This was necessary to ensure the material selected was strong enough to support the calculated stresses. The bending stress, σ, is calculated using the maximum tangential load, the module, *m* (as determined in Equation 4), the Lewis Factor, *Y*, and the face width, *B*. These variables are used to calculate the maximum stress in Equation 5. The Lewis Factor was determined using the pressure angle of the gear along with the number of teeth per the gear. The safety factor includes multiple conditions such as the form factor, application factor, size factor, load distribution factor, rim thickness factor and dynamic factor.

$$m = \frac{Pitch\ diameter}{number\ of\ teeth} \quad \sigma = \frac{W * K}{B * Y * m} \qquad \text{Equation 4, 5}$$

Once the diameters, pitches and module were determined, the team could then calculate the number of teeth in mesh, shown in Equation 6. This equation determined how many teeth share the stress, which lowers the stress on a single tooth. Once the team determined multiple values that follow all of the guidelines, they optimized the system by calculating which values give the lowest mass, *M*, moment of inertia, *I*, and volume, *V*. Equations 7 and 8 were used for total volume and mass, while Equation 9 was used to calculate moment of inertia.

$$\frac{\sqrt{D_{2o}{}^2 - D_{2B}{}^2} + \sqrt{D_{1O}{}^2 - D_{1B}{}^2} - \frac{D_{1B}}{2} - \frac{P_1 + P_2}{2} * \sin(\frac{Angle * \pi}{180})}{\pi * \cos\left(\pi * \frac{Angle}{180}\right) * m} = Teeth\ in\ Mesh \qquad \text{Equation 6}$$

$$V = \sum \pi (\frac{D}{2})^2 B \quad M = d * V \quad I = \sum \frac{1}{2} M \frac{D^2}{4} \qquad \text{Equations 7, 8, 9}$$

Hub Design

In order to decrease the weight and rotating inertia of the system, Team 6 determined that press-fit aluminum hubs were the optimal method to transmit torque between the gear teeth and the shafts. While bolt-on hubs were also considered, press-fit hubs reduced the weight of the assembly by removing the need for steel bolts. By using aluminum hubs instead of a solid steel gear, the team can reduce the weight by 2 lbs. Using methods taught in advanced statics and described in James Barber's *Intermediate Mechanics* textbook, the torque at which an aluminum hub press fit into a steel gear could transmit before slip was determined. This torque was determined through the derivation of a number of equations; a full copy of the Maple code used in this derivation is attached in Appendix C.

In summary, the code takes in a hub width, interface radius, gear outer radius, hub inner radius, and radial interference and returns the maximum torque which can be transmitted and the maximum stresses induced on the aluminum due to the interference fit. The results of the calculations are given on Page 33.

Shafts

After the gear design was complete, the team worked on calculations regarding the shafts. They first looked at the bending and torsion stresses the shafts will experience. They then investigated different options for transferring torque including splines and polygons. The team did not look at using keyways per the Michigan Baja Teams request, which is described on Page 10. All calculations completed are described below.

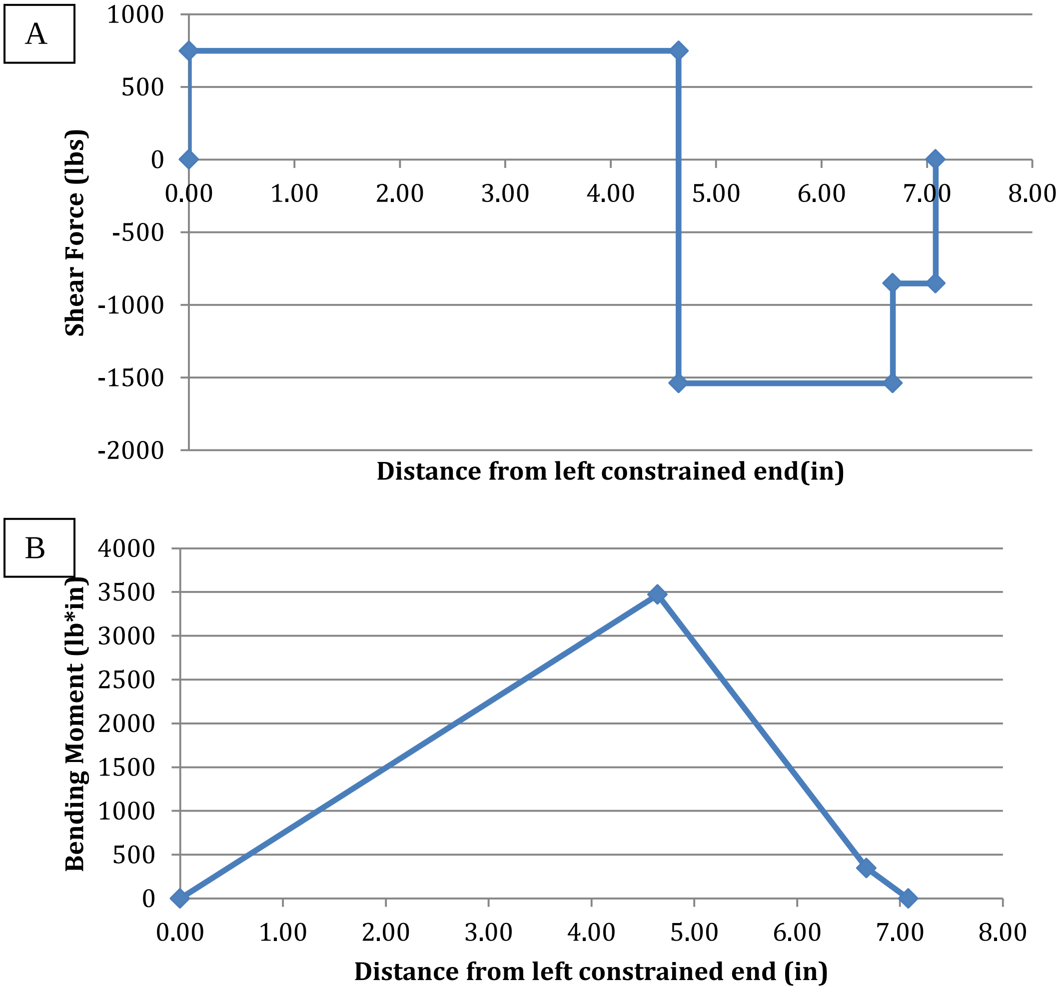
Bending Stresses

To conduct an analysis of the bending stress on each of the shaft, Team 6 first identified the direction and magnitude of each of the forces on the shafts. Because of the alignment of the shafts, Team 6 was able to assume that all of the forces were in the horizontal direction. Using this assumption and the assumption, that all of the forces were point forces, Team 6 began by calculating shear force from left to right across each shaft. Shear diagrams were then used to visually represent the force across each shaft, as shown in Figure 17, on the next page. Using the shear forces and the distance each force is from the static ends, bending moments were calculated. The area beneath the shear diagram line at each point force location also visually represents the bending moment. To determine the maximum bending stress , σ_b, in each shaft, Equation 10 was used to determine the bending stress at each point force. In this equation, *M* is the moment at the location and *Z* is the section modulus. In Equation 11, R_o, is the outer diameter of the shaft, which has been specified to appropriately integrate the drivetrain with the vehicle, and, R_i, is the inner diameter of the shaft which can be chosen to optimize for strength and weight. The stresses determined from this analysis aided Team 6 in selecting a shaft wall thickness, as well as ensuring the design is strong enough to resist deformation from bending stresses given the properties of their selected material.

$$\sigma_b = M/Z \qquad \text{Equation 10}$$

$$Z = \pi * \frac{(R_o^4 - R_i^4)}{(32 * R_o)} \qquad \text{Equation 11}$$

Figure 17: Below are the diagrams to represent the shear force (A) and bending moments (B) along the input shaft. Diagrams to accompany the intermediate shaft and output shaft can be found in Appendix D.



Torsional Stresses

In addition to bending stresses, Team 6 needed to account for the stresses that will occur as a result of torsion on each of the shafts. Knowing the torque on each shaft, *T*, the team calculated the shear force, τ, caused by torsion using Equation 12, which also required the pitch diameter, *D*, and the second moment of area, *J*. The second moment of area could be calculated using Equation 13, which accounts for both the inner, R_i and outer, R_o, diameter of the shaft in question. Once the team had calculated shear force, τ, for the various shafts, they used Equation 14 to determine the torsional stress on each shaft and whether or not it satisfied the criteria for the selected shaft material yield stress.

$$\tau = \frac{T(^{D}/_{2})}{J} \qquad \text{Equation 12}$$

$$J = \frac{\pi({R_o}^4 - {R_i}^4)}{2} \qquad \sigma_H = \sqrt{3\tau^2} \qquad \text{Equation 13, 14}$$

Splines

When determining the spline design for the external shafts, the first step was to determine the parameters that can be manufactured by the Baja Team's spline sponsor, Modified Gear and Machine. One of the first limitations was the pressure angle at which the splines could be cut. Common spline pressure angles are 30, 40 and 45 degrees, however, the sponsor could only do a pressure angle of 30 degrees, limiting design options. Team 6 then determined the number of teeth, *N*, and pitch, *P*, of the splines. This produced the pitch diameter, *D*, as seen in Equation 15.

$$D = N/P \qquad \text{Equation 15}$$

Based on the equations in the *Machinist's Handbook*, the team was then able to calculate the major, D_o, and minor, D_{re}, diameters of the splines, using Equations 16 and 17.

$$D_o = \frac{(N+1)}{P} \qquad D_{re} = \frac{(N-1.35)}{P} \qquad \text{Equation 16, 17}$$

The team then determined the maximum effective tooth thickness, t_v, in order to determine the shear stress at the pitch diameter, $\tau_{pd}$where L_e is the length of the spine, *T* is the torque seen by the shaft and *K* is the multiple safety factors, as seen in Equations 18 and 19.

$$t_v = \frac{\pi}{2P} \qquad \tau_{pd} = \frac{4TK_aK_m}{DNL_etK_f} \qquad \text{Equation 18, 19}$$

Team 6 also checked the shear stress under the roots of the external teeth, τ_{un}, and the compressive stress on the sides of the spline teeth, σ_c, as seen in Equation 20. This allowed the team to compare the stresses throughout the spline and determine if either the tooth thickness, length of spline, or material needed to be changed in order to prevent shearing at any point along the shape.

$$\sigma_c = \frac{2TK_mK_a}{DNL_ehK_w} \qquad \text{Equation 20}$$

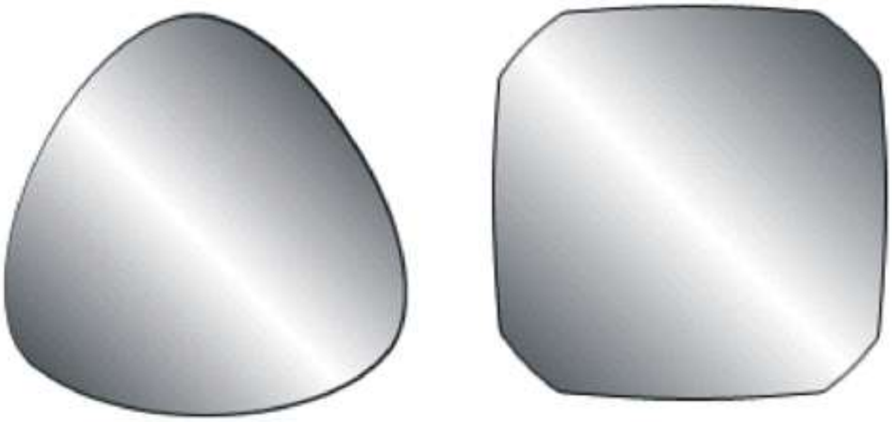
Team 6 then determined the depth of tooth engagement of the splines, h, as seen in Equation 21. This allowed the team to determine if they could use square splines, which can be adapted for aluminum hubs.

$$h = .9/P \qquad \text{Equation 21}$$

Polygons

Polygon shafts were also investigated as an alternative to splines. There are two main shapes of polygon standards, P3 and PC4, shown in Figure 18, on the next page. Both shapes were examined for load feasibility.

Figure 18: Common shapes of polygon shafts.



P3

PC4

Image Source: http://www.homebuiltairplanes.com/forums/firewall-forward-props-fuel-system/3623-help-me-source-psru-project-2.html

First, Team 6 examined the torsional, M_T, and bending, M_B, moments on the shafts for both polygon shapes. The torsional moments are dependent on the admissible torsion, T, the mean diameter profile, D_M, diameter of profile circumscribed circle, D_a, and the diameter of the profile inscribed circle, D_i, shown in Equation 22 and 23. The bending moments are affected by the admissible bending stress (O_B) along with geometric properties, shown in Equation 24 and 25.

$$M_{T,PC3} = T(\frac{\pi D_M{}^4}{16D_a}) \qquad M_{T,PC4} = T(\frac{\pi D_i{}^3}{16}) \qquad \text{Equations 22, 23}$$

$$M_{B,PC3} = O_B\left(\frac{\pi D_M{}^4}{32D_i}\right) \qquad M_{B,PC4} = 0.15(O_B D_i{}^3) \qquad \text{Equations 24, 25}$$

The team then examined the minimum thickness of the hub. The hub calculations, shown in Equations 26 and 27 are affected by the, O, b, and M_t calculated above. The maximum stresses, S, were also calculated for each shape and are shown below in Equations 26 and 27.

$$S_{PC3} = 1.44\sqrt{\frac{M_t}{O*b}} \qquad S_{PC4} = 0.7\sqrt{\frac{M_t}{O*b}} \qquad \text{Equations 26, 27}$$

Bearings

The information calculated in the bending stresses, combined with the Baja Team's previous successes, determined the bearings which were used in the design. NSK is a sponsor of the Michigan Baja Team, therefore all the bearings used in the gearbox were NSK bearings.

In order to determine the number of revolutions the bearing would see, the team used the Baja Team's common practice, which is to calculate for 25 mph for 10 hours. This requires the vehicle's bearings to be designed for 250 miles of vehicle travel. Speaking with the Michigan Baja Team, wheel data was determined to calculate the number of wheel revolutions necessary to achieve this distance. Equation 28, on the next page, shows the equation used to calculate the number of revolutions the input shaft sees after 10 hours of driving. In this equation, *R* is the number of revolutions, *W* is the distance the wheels travel in one revolution, in feet, and *m* is the number of miles the vehicle is expected to travel, and *r* is the final drive reduction, in this case 10.6.

$$R = \frac{(5280*m)}{W*r} \qquad \text{Equation 28}$$

Using this information and the reduction at each shaft, the number of revolutions each shaft will complete was calculated. The input shaft will see 2,561,030 revolutions within the lifetime of the vehicle, the intermediate shaft will see 698,462 revolutions, and the output shaft will see 240,096 revolutions. Next, the radial load was considered, F_r, in accordance with NSK's Bearing selection guide, p. A29 (Motion & Control - NSK, 2005). As specified in the selection guide, F_r is calculated as the radial load on the bearing, and was found in the section on shaft loading, Pages 23. With this information, the basic load rating, C_r can be found using Equation 29 below, where *P* is the radial force on the bearing and f_h and f_n are lifetime factors, available in the NSK selection guide (Motion & Control - NSK, 2005) .

$$C_r \geq \frac{P*f_h}{f_n} \qquad \text{Equation 29}$$

The critical load rating for each bearing was then used in the tables in the selection guide to determine which bearings met this criterion. With a lifetime of only 10 hours, a number of bearings were available. In order to narrow the selection, Team 6 consulted the Baja Team regarding which bearings have been successful during the life of the vehicle in the past, influencing the final selection.

Housing

Based on the Baja SAE rules, the housing needed to be fabricated from 6061 strength aluminum, or 1018 steel. The team looked at both materials' density and the approximate volume of the housing and determined that using aluminum would be the lightest option and sufficiently strong. Once this was decided, CAD of the housing was created and FEA was completed using CATIA's Finite Element Package in order to aide in optimization of the housing. When completing this analysis, the team examined the housing's stresses and displacement. A number of iterations were created, with analysis done on each result to determine where material should be removed or added, based on concentration of stresses or displacement. Figure 19, on the following pages, shows the displacement of the housing after the first iteration. Blue indicates 0 inches of displacement and red indicates 0.00125 inches of displacement. Figure 20, on the next page, shows the stresses on the housing. In this figure, blue indicates negligible and red indicates 157 MPa.

Figure 19: Displacement of the housing after the first iteration of optimization. The right side of the housing is on top and the left side of the housing is below.

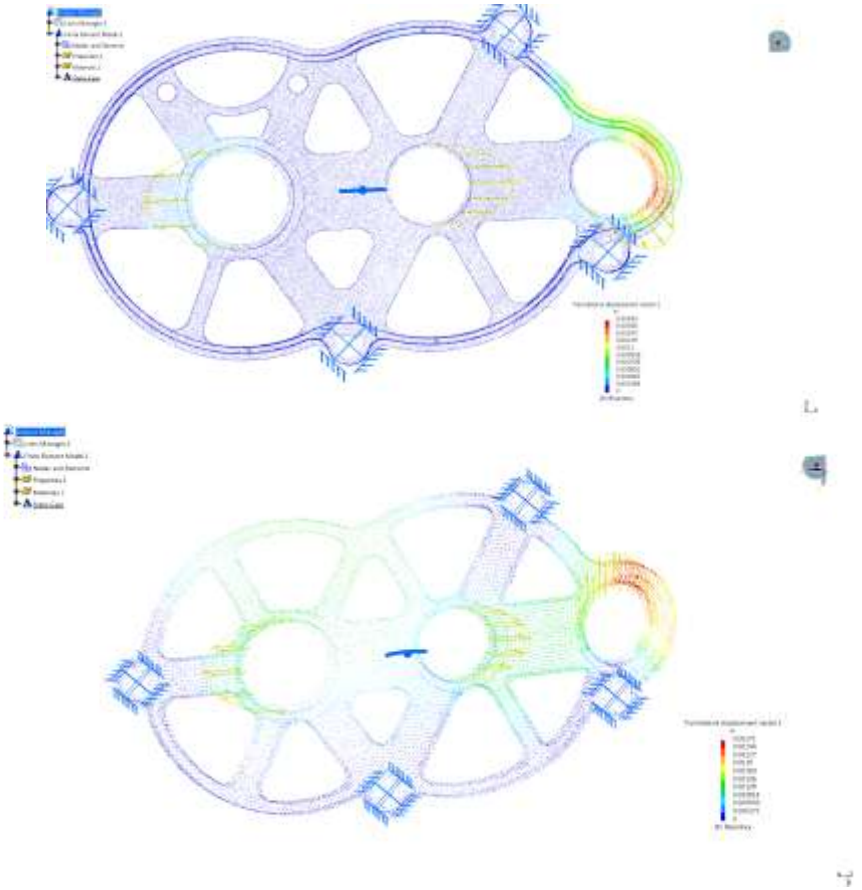
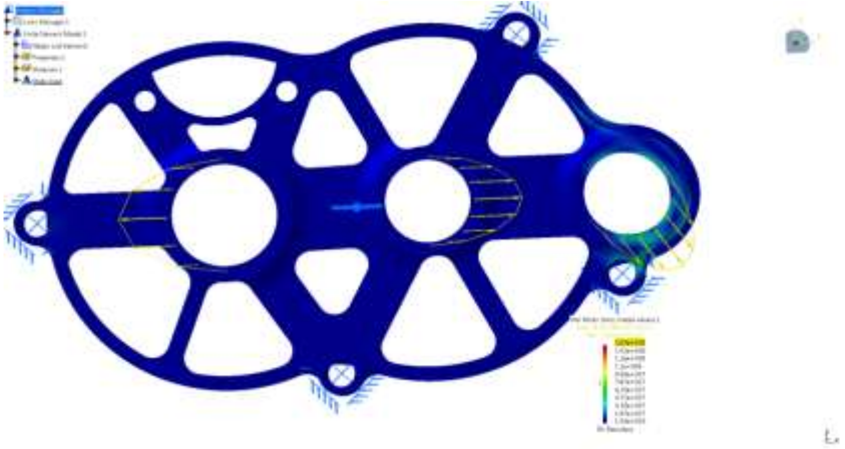
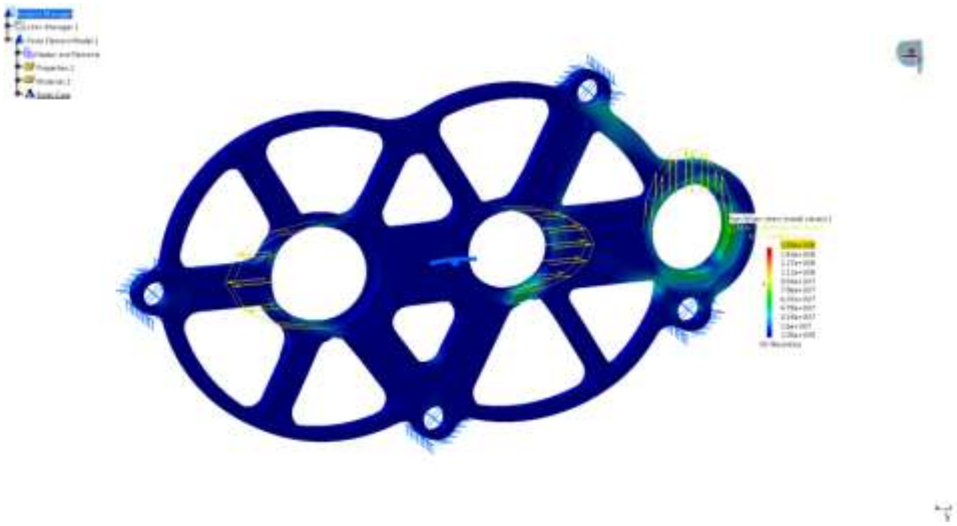


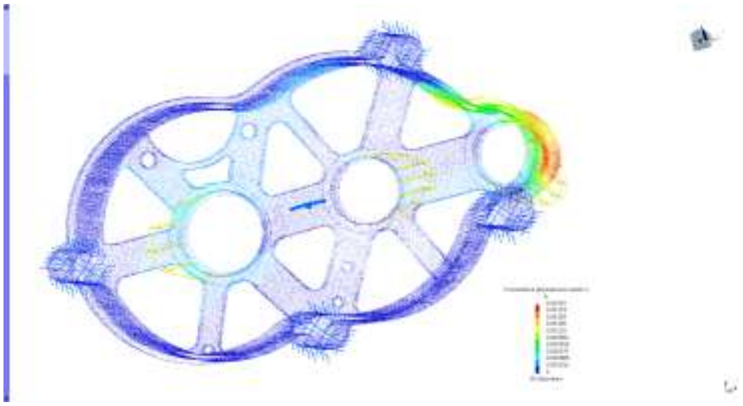
Figure 20: Stresses on the housing after the first iteration of optimization. The right side of the housing is on top and the left side of the housing is on the next page.





After the first FEA iteration, the team made a number of changes to the housing design including: 1. Removing material near the final reduction to decrease the weight 2. Adding material near the front to decrease the stress and displacement 3. On the right side, thinning the supports axially and adding holes for lubricant. They then conducted additional FEA and the results are shown in Figure 21 and 22 on the following pages.

Figure 21: Displacement of the housing after the second iteration of optimization. The right side of the housing is on top and the left side of the housing is below, the same displacement scale is used on these figures as was previously described, in order to facilitate comparison between designs.



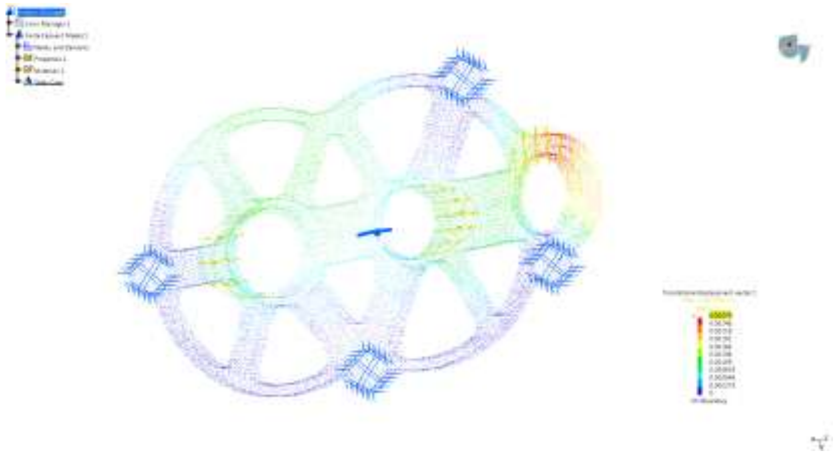
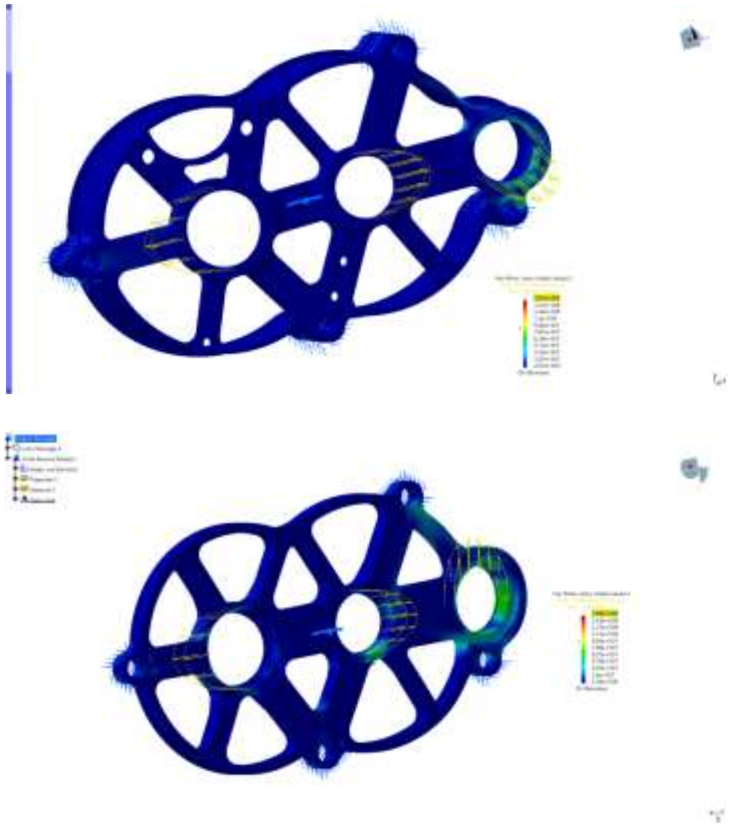


Figure 22: Stresses on the housing after the first iteration of optimization. The right side of the housing is on top and the left side of the housing is on the next page. The scale of the stress in the figure matches that of the first iteration.



SAFETY

After completing the design of the components, safety analysis was performed to ensure a safe design and that safe assembly could be performed. A safety concern arose when looking at the creation of the carbon-fiber finger guards. However, the risk was mitigated through the use of proper OSEH personal protective equipment. The assembled gearbox also poses a safety risk, as the gear interface is a pinch point if the finger guards are not present, or improperly installed. This risk was mitigated by ensuring that everyone was clear of the box before any rotation of the shafts occurred, and a maximum rotation rate of 100 rpm was maintained at all times. For a full list of safety concerns and the mitigation steps, see Appendix E.

ENVIROMENT

Team 6 addressed environmental concerns by examining the materials used for the gearbox in Simapro. When picking the materials, the aluminum alloys were much worse for the environment than steel or cast iron, due to the aluminum production process. In Appendix F, the team examined two materials for three main components and how these materials affect the environment.

FINAL DESIGN DESCRIPTION

Based on all of the analysis described above, a final design was determined; final design details are described in the following sections. Drawings for all parts can be found in Appendix G.

Materials

As previously mentioned, Team 6 was asked by their sponsor to only use materials that the Baja Team had available. Even with this restriction, the team had multiple material options to consider. A summary of the materials chosen can be found in Figure 23, Page 32. For most of the components, the team was looking into metals to ensure durability and loading parameters were accounted for. Since the gears and shafts needed to have a high wear resistance, they were made out of a steel. The steel materials available in the necessary sizes to the Baja Team are 9310, 4340, and 8620. Looking at material properties and hardenability, Team 6 determined 9310 would be the best choice. The shafts were required to be steel in order to support the bending loads previously described. The most logical choice for the team was 300M, due to the high hardenability and the material’s wear characteristics. The team needed a material that was not susceptible to deformation during torsion and numerous bending cycles, and 300M fit these requirements.

For the gear hubs, Team 6 knew they would need a material with a lower density than steel in order to minimize the total weight. Looking at multiple aluminum alloys, it was determined that 7075-T6/T651 would be best suited for the hubs, due to its ability to withstand the stresses from the splines. Also, it had the required modulus of elasticity for the press-fit hubs. The team considered the negatives to having the stress concentrations in the aluminum due to the spline interface. To account for this, exterior splines with a rounded fillet were designed. All of the spacers were made out of 6061 aluminum since it had the necessary strength and weight properties for that of a spacer, and is much less expensive than 7075 T6/T651.

The team looked at multiple materials, such as Plexiglas and carbon fiber, to be used for the finger guards. From material research it was determined, Plexiglas had a density of 31,823 oz./yd^3 while the carbon fiber the team would use, 2x2 3K twill, would have a density of 17,117 oz./yd^3.This significant difference in density was the driving factor behind using carbon fiber over any plastic material. The team researched different weave patterns before choosing the twill pattern. The basic weaves are plain, twill, and satin. When researching the three weaves, the team discovered a pattern in which satin was the strongest weave, followed closely by twill. However, satin is also very thin. Since satin is so thin, there would be minimal material present unless they applied multiple layers to keep the lubricant sealed in. If multiple layers were needed, the weight of the piece would go up, therefore supporting the decision to use carbon fiber futile. As a result, the team decided to use the pattern already available to them, 2x2 3K twill. Carbon fiber also has some ability to take on loads in the direction of the fibers. The displacement caused by the bearing loads on the gearbox will be decreased by the over lapping weave directions of carbon fiber. The carbon fiber will also seal in the lubricant without the fear of the lubricant corroding the composite. The adhesive for the carbon fiber to the aluminum will be Loctite 9430 Structural Adhesive. The gearbox sealer from aluminum to aluminum was a gasket sealer known as RTV. Due to the lower temperatures the gearbox will see, the team chose the blue series. All of these materials were available to the Baja Team therefore ensuring the team does not have to account for material transit time or any budget issues.

Team 6 used CES and Simapro to analyze the material selection, manufacturing processes, and environmental impacts of the shafts, gearbox and finger guards. Based on CES and the Ashby Material selection, high carbon steel was determined to be the ideal material for the shafts, aluminum alloys were best for the gearbox and fiberglass composite was chosen for the finger guards. Simapro was then used to determine the environmental impact of two materials for each component assuming. From this analysis the shafts should be made from steel, the gearbox from aluminum, and the finger guards from PVC plastic. CES was then used to determine the machining process of the components. If the gear reduction was to be mass produced, then the gearbox would have finger guards made out of the same material as the rest of the gear box. Therefore, for the manufacturing processes, only the shafts and gearbox were analyzed. Team 6 determined that conventional machining was the best method of making the shafts and low-pressure casting should be used to create the gearbox. A complete analysis is located in Appendix F.

Figure 23: The advantages and disadvantages of the materials chosen for each part in the assembly.

Part	**Material**	**Advantage**	**Disadvantage**
Shaft	300M	-Easily ground for splines -Already available	-Heavy -Expensive
Hubs	7075 Aluminum	-Higher shear strength for splines (than 6061) -Lightweight	-Expensive
Gears	9310 Steel	-Higher shear strength for splines -Lightweight	-Needs to be hardened
Gearbox	7075 Aluminum	-Lightweight -Strong	-Expensive -Not readily available
Spacers	6061 Aluminum	-Durable	-Heavy compared to plastics
Finger Guards	Carbon Fiber	-Lightweight material -High load capabilities	-Expensive

Metal Sealer	Blue RVT Silicone Gasket Sealer	-Low cost	-Need to be reapplied after every use
Carbon to Metal Adhesive	Loctite 9430 Epoxy Structural Adhesive	-Previous experience with the product -Able to seal in the lubricant	-Expensive

Gears

From the gear calculations and material availability, Team 6 determined that all gears should be made from 9310 steel, a common gear steel. The pressure angle is 14.5^{o} and the pitch is 12 for all gears. The reduction ratio is 3.66 for the first reduction and 2.91 for the second reduction. In addition, the face width is 0.5 inches for the first reduction and 1 inch for the second reduction. The team also determined the number of teeth, pitch diameter and, face width for each gear, which is summarized below in Figure 24.

Figure 24: Summary of gear features for final design

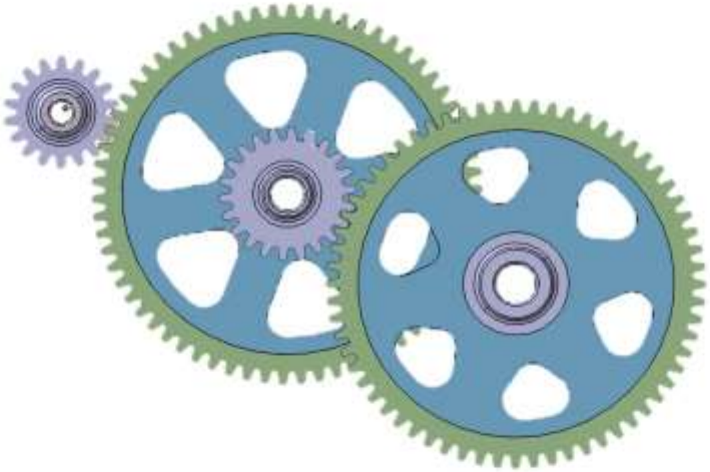
Gear	Number of teeth	Pitch Diameter (in)
Input	18	1.5
Intermediate 1	66	5.5
Intermediate 2	22	1.8
Output	64	5.3

The final reduction ratio is 10.65:1 and the center-to-center distance between the input and output shaft is seven inches. Both of these details fulfill the engineering specifications described on Page 9. The final gear reduction is shown in Figure 25, on the next page.

Hubs

Using the calculations described in previous sections, along with the Maple Code in Appendix C, the final dimensions of the press-fit aluminum hubs were determined. For both the intermediate and output gear, the aluminum hub will be the width of the gear, 0.5 inches and 1 inch, respectively. For the intermediate gear, in order to obtain a safety factor of 5 against slip, a diametric press fit of 0.005 inches was used at an interface diameter of 4.8 inches. A safety factor of 5 was given per Baja's press-fit standards. For the output gear, a similar safety factor was used, giving a 0.006 inch press-fit at a diameter of 4.6 inches. The stresses were also analyzed, as shown in the Maple Code, to ensure that the pressure on the aluminum hub was well below the maximum hoop stress 7075-T6/T651 could withstand before yield. Figure 25, below, illustrates the hub design, shown in in turquoise.

Figure 25: Final gear reduction



Shafts

For the input shaft, the shaft diameter was the driving factor, as a 0.75 inch shaft is necessary for vehicle integration to the CVT. For the intermediate shaft, loading information determined that the shaft could also be 0.75 inches, which will aid in ease of manufacturing. The output shaft has an outer diameter of 1.05 inches, so it can be easily integrated with the driveshaft. Team 6 decided to have hollow shafts in order to reduce the weight of the drivetrain. The input and intermediate shaft wall thickness is 0.125 inches based on calculations. The output shaft wall thickness is 0.15 inches, as it experiences larger forces.

Spacers

In order to properly constrain the distance between the gears, spacers have been designed. These spacers will be manufactured out of 6061 aluminum because they will see minimal axial compressive force.

Splines

Team 6 determined that both splines and polygons could adequately support the gears. However, the Baja Team has a spline sponsor that could grind the splines in approximately a week, and Team 6 already has a tight manufacturing timeline, while polygons require a longer machine time. As a result the team decided to use splines. For serviceability, the input and intermediate shaft each have the same splines. The splines will have a 30° pressure angle, a pitch of 16, and a total of 14 teeth. This will give an outer diameter of 0.9375 inches, and provides the strength necessary to prevent tooth shear. Because of its higher loading and larger outer diameter, the output shaft has a pitch of 20 and a total of 26 teeth. These parameters give an outer diameter of 1.35 inches, and again provide the strength necessary to prevent shearing of spline teeth.

Bearing Selection

Performing the bearing calculations described previously, consulting NSK’s bearing selection book, and researching the Michigan Baja Team’s history, bearing selections were made. All information on the input shaft resulted in a selection of NSK R12V bearings. When speaking with the Michigan Baja Team, they encouraged similarities between the input and intermediate shafts for ease of manufacturability and assembly. Because of this request, and seeing that it would meet the lifetime requirements, a NSK R12V was selected for the intermediate shaft's bearings as well. On the output shaft, a number of bearings were available which were large enough for the shaft, while keeping a minimum weight and meeting lifetime requirements. With this information in mind, a bearing selection of NSK 60/28 VV was made for the output shaft.

Housing

The housing was optimized using FEA software, and the amount of material at specific locations will help accommodate the bearings and properly support the loads imposed by the gears. The final design has an area to attach a brake caliper so that the braking system can be integrated with the drivetrain, as requested by the Baja Team. The final housing also has holes where a lubricant can be added and drained from. The two halves of the housing will be held together using eight bolts and seven dowel pins. At the interface, a small groove was machined to allow for the application of RTV blue series, allowing the case to be properly sealed. The housing is shown below in Figure 26, 27 and 28.

Figure 26: The right side of the housing without finger guards.

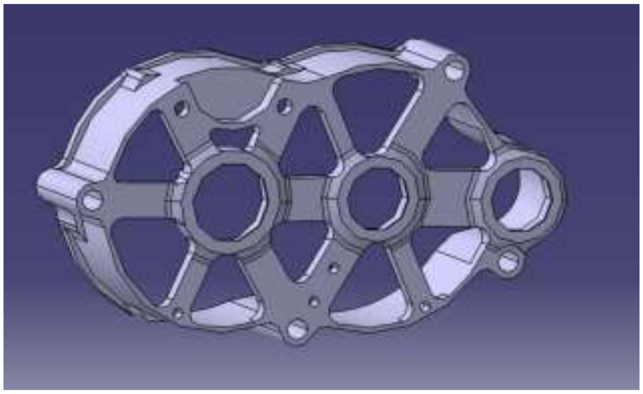


Figure 27: The left side of the housing without finger guards.

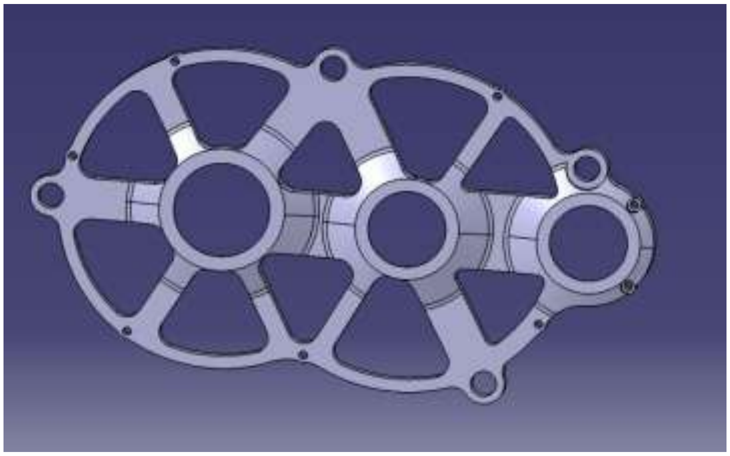
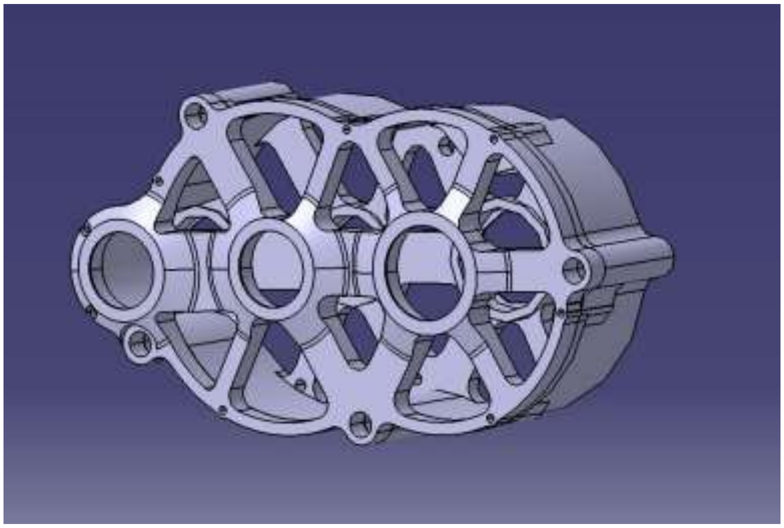


Figure 28: Assembled housing without finger guards.



Complete Assembly

The completed final design met all engineering specifications and is shown in Figure 29. Using CAD, the final weight for the system was approximated as 9.8lbs, but there was some disconnect between this weight and the final weight due to modeling errors, such as the bearing and finger guard weights. In addition, it will be able to be integrated with the rest of the vehicle, shown in Figure 30.

Figure 29: Complete assembled isometric view of final design.

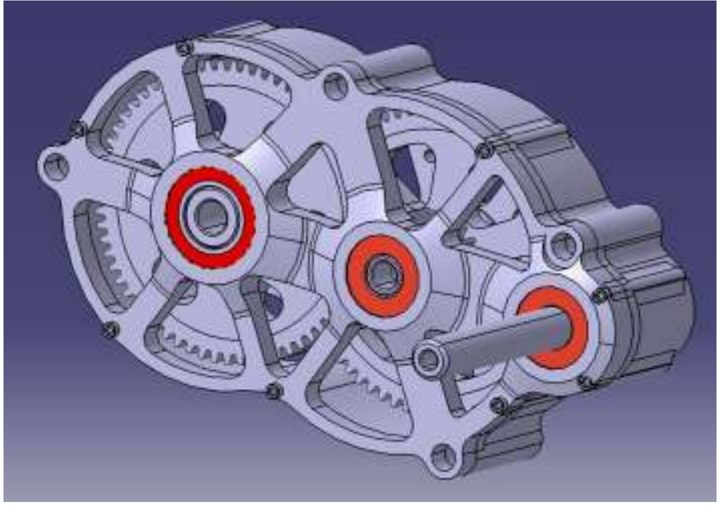
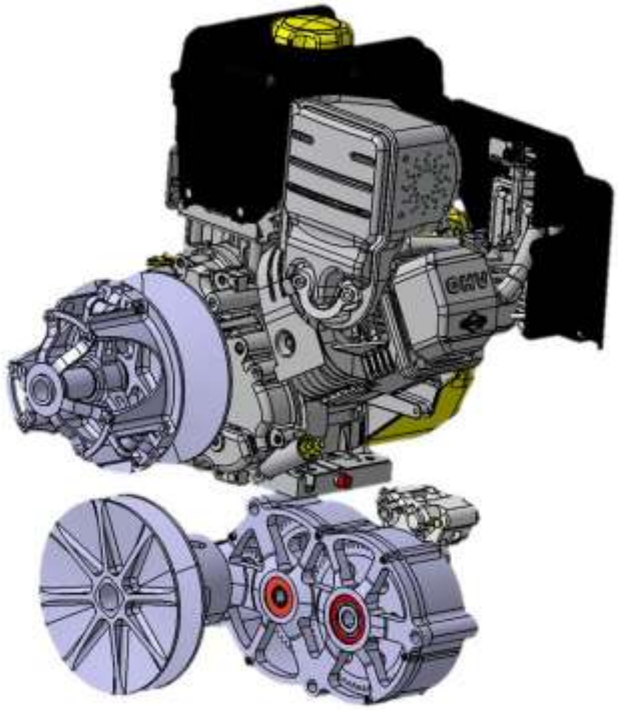


Figure 30: Gear housing integrated with the rest of the vehicle.



FABRICATION PLAN

The gear teeth and splines were sent out to be manufactured, while the gear hubs, gearbox, and finger guards were completely fabricated by Team 6. The detailed fabrication plan for each component, as well as the final assembly, is described below. All CNC millwork was completed using a HAAS VF2 SS, as it has the capabilities to perform the necessary operations and hold the necessary tolerances. A variety of lathes were utilized in order to complete any turning operations. Tooling for the operations were provided by the Michigan Baja Team. A full description of parts, tools, feeds, and speeds that were used is listed in Appendix I. All related safety reports are located in Appendix E.

Gear Teeth

The gears were beyond the capabilities of the machine shops at U of M; therefore, the gear teeth were cut by Vertical Machining, a wire EDM company. Since heat-treating affects the material shape, the heat treating process occurred before the shape was machined. The gears were heat treated to 36 Rockwell C. Vertical Machining then EDM'ed the gear teeth. The tolerances on the gear teeth were very important, as this would affect how well the gear teeth would mesh together and how much torque was required.

Gear Hubs

With possession of the gears, the team then removed the center of the larger intermediate and output gears on a CNC Mill, so that a ring with teeth remains. These tolerances are very important for the press fit with the aluminum hubs to transfer the appropriate torques. The aluminum hubs were initially turned down with a lathe and final machining was done using the same CNC mill to ensure the appropriate tolerances were met. The teeth were then placed in the oven while the hubs were placed in a dry ice and acetone mixture. The gear teeth and aluminum hubs were then pressed together for the larger intermediate gear and output gears.

Splines

All four gear assemblies were then given to Vertical Machining, the Baja Team's wire EDM sponsor, to have the internal splines wire EDM'ed. The shafts were turned to length and to the correct outer diameter. After hardening, the final diameter of the shafts was turned, and the shafts were given to Modified Gear and Machine in order for the external splines to be ground.

Gearbox

The gear housing's machining was completed on a CNC Mill. Using a number of tools and fixtures, the outer casing was machined. The tolerances were critical for the bearings to be press fitted and to ensure that the shafts had the correct spacing. Therefore, these surfaces were bored.

Finger Guards

The finger guards were created using a carbon fiber molding process. First, a mold was created out of tooling board using a router. Release wax was applied to the mold four times and the carbon fiber was cut to shape. The team mixed the epoxy and hardener in a 5:1 volume ratio. This mixture was then applied to the carbon fiber and spread out with paddles. Two layers of carbon fiber were then placed in the mold with peel ply placed on top of carbon fiber. A breather was placed on top of the peel ply and sealer tap was applied to the mold. A vacuum bag was attached to the sealer tape and a vacuum hose was attached to the vacuum bag to prevent air from escaping. The vacuum was turned on and the epoxy was allowed six hours to cure. Finally, the composite was removed from the mold and trimmed using a Dremel.

Final Assembly

First, the finger guards were glued in place within the case using Loctite 9430 Epoxy Structural Adhesive. The bearings were then press fit into both sides of the housing. The gears and spacers were placed on their respective shaft and inserted into right side of the housing. Gear lubricant was placed in the housing and liquid gasket was placed in the groove around the edge of the right side of the housing. Finally, the left side of the housing was bolted to the right side. During the assembly, Team 6 realized that some changes needed to be made. All changes were recorded in Engineering Changes Notices, located in Appendix J.

PROTOTYPE DESCRIPTION

The gearbox that Team 6 designed and fabricated is the final gearbox that Michigan Baja will be using on their 2013 competition vehicle. Therefore, this gearbox is not a prototype and needs to be fully functional and competition ready. This gearbox must also be easily integrated with the rest of the Baja vehicle.

VALIDATION PLAN

For final testing, the team weighed the assembled drivetrain using a scale to determine if it weighted less than 30 lbs. They used a torque wrench to determine the torque required to rotate the gears. Team 6 then used calipers to measure the thickness of the housing to ensure that it was thick enough to meet Baja SAE rules. Safety reports for both preliminary and final testing are located in Appendix E.

VALIDATION RESULTS

The primary method of validation of the final assembly was performed by measuring the breakaway torque required to rotate the input shaft, using a dial torque wrench with a scale from 0 to 8in-oz and a minimum reading of 0.125in-oz. Using this wrench on the input shaft, three measurements were taken and averaged to determine the torque to rotate of the gearbox. Using this method, a torque to rotate of 0.75 in-oz. ±0.0625 in-oz. was measured. With an engineering requirement of 1.35±0.0625in-oz, the measured torque to rotate meets the requirements.

In order to validate the weight requirement of the project, Team 6 placed the fully assembled gearbox on a scale. Using a scale, a total weight of 10.75±0.50lbs was measured. This meets the requirement set forth by the Michigan Baja Team, which limited the box to a maximum weight of 30 lbs. This low weight and low torque to rotate will help ensure the Michigan Baja Team's success at competition for the 2012-2013 season. Team 6 then used calipers to measure the thickness of the housing to ensure that it was thick enough to meet Baja SAE rules, and it met all of the specifications.

DISCUSSION

If the team were to remanufacture the project, or had more manufacturing time, they would have approached certain project components differently. First, when designing the molds for the carbon fiber pieces, the team would add a radius onto the mold. This would make the parts come out of the mold easier and ensure epoxy can fill every crevasse easier. Second, the team would add some post machining steps to ensure the gearbox would fit correctly in the car. This would be done by placing the gearbox back on the jig and machining some of the surfaces in the CNC mill. The team would also like to validate the durability of the design, however this was impossible because a completed Baja car will not be ready until March. Therefore, if there were more time or an available car, Team 6 would conduct full durability testing, with multiple shock loads. Another aspect to improve upon, if there was more time, is integration of the differential. At the time of design the Baja Team did not know if they were going to have the differential on the car, therefore Team 6 did not design for it. However with more time and completed vehicle CAD, Team 6 could have integrated the differential into the gearbox.

RECCOMENDATIONS

For the future, Team 6 would recommend a multispeed gearbox as a design upgrade to maximize drivetrain efficiency for all aspects of the competition. This gearbox could have a setting for high speed and low torque for areas of the competition such as acceleration and maneuverability. It could then have another setting with low speed and high torque for parts of the competition including: the tractor pull, rock climb and hill climb. Having two-speed settings would optimize the gearbox for each aspect of the competition.

ACKNOWLEDGEMENTS

Team 6 would like to thank our sponsor the Michigan Baja Team for their willingness to meet with us and their continuous support throughout the semester. The team would also like to thank Vertical Machining for cutting the gear teeth and internal splines as well as Modified Gear and Machine for grinding the external splines. They appreciate Temprite Steel Treating taking the time to heat-treat the gears.

PRODUCT PLAN

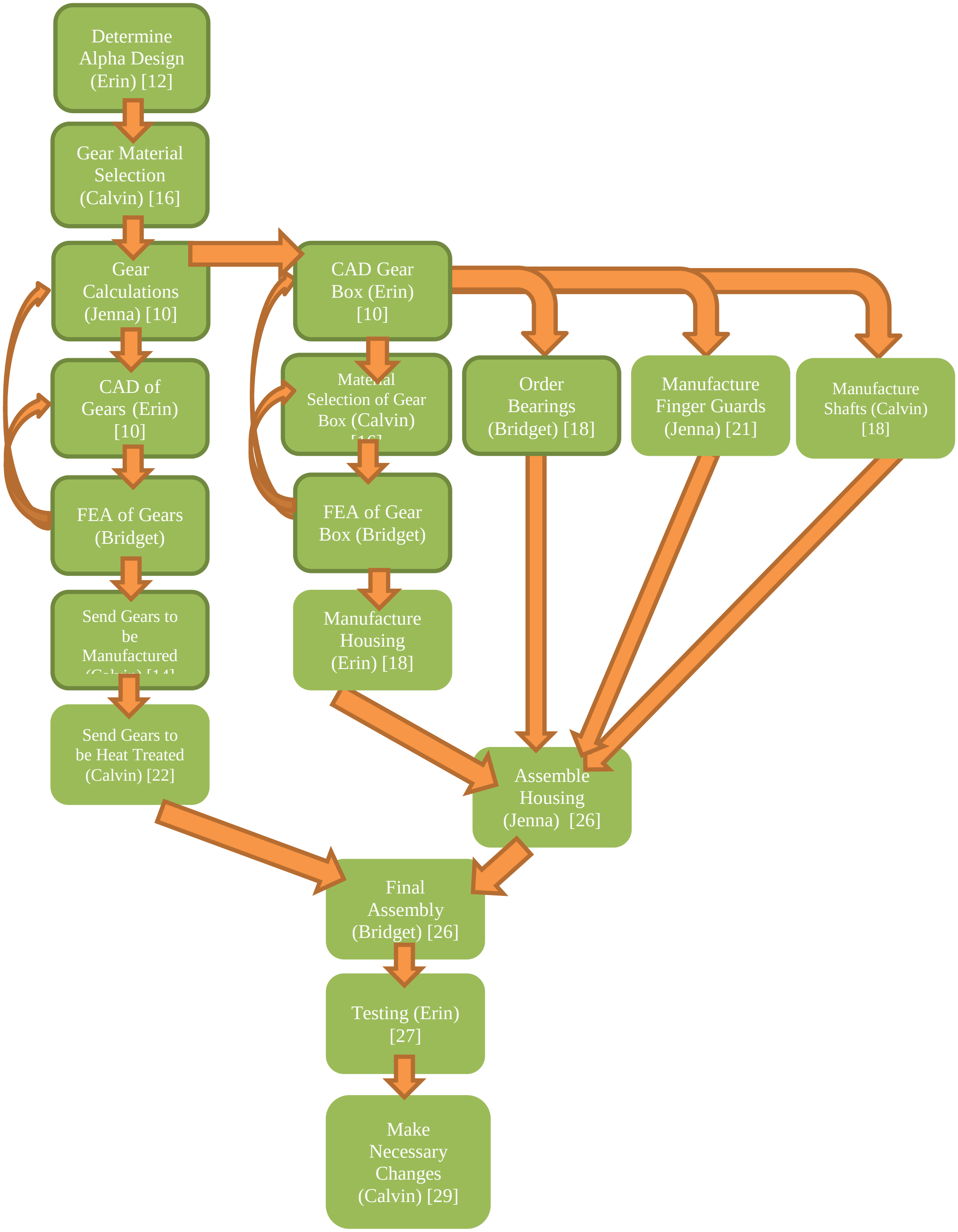
The team was able to successfully complete the project by following the Gantt chart in Appendix K. The team did miss some internal deadlines set forth in their Gantt chart due to the some of the issues outlined in the specific challenges, on Page 41. However, working closely together as a team and with their sponsor, Team 6 was then able to overcome these challenges and create a successful project.

SPECIFIC CHALLENGES

The project sponsor, SAE Baja Racing, is a student project team with limited resources and materials. The Baja Team receives support from sponsors in materials and manufacturing; the Michigan Baja Team also has a cash budget for any items not received by sponsors. The sponsor support the Baja team relies on only provides certain materials, which limited the materials Team 6 has access to. As a result, material availability became the driving factor behind some engineering decisions.

Due to the complexity of the manufacturing processes involved, the gear design was intended to be sent to General Motors to be machined. Unfortunately, after design review three, GM informed Team 6 that they would not be able to finish the gears until January. Because of this, Team 6 needed to find another sponsor to manufacture the gears. They were able to have Vertical Machining wire EDM the gears. Though this method is not ideal for creating gears, it is becoming a more accepted method in industry.

Figure 31: This diagram shows the steps Team 6 took to successfully create a drivetrain for the Baja Team. The person responsible for each task is shown in parentheses. The numbers correlate to the task number in the Gantt Chart.



CONCLUSION

Team 6 has been tasked with designing a gear reduction system to remedy the Baja Team's design issues, while also increasing the efficiency and durability of the reduction system. To increase efficiency, the Baja Team has requested that the new reduction design provide a measured breakaway torque less than or equal to 1.35 in-oz. Because the Baja Team is aware that a gear reduction is inherently heavier than a chain reduction, they have asked that the weight of the entire reduction and the surrounding gearbox be less than 30 lbs. in order to be considered for competition use. Expanding on the original specifications, Team 6 and the Baja Team have agreed that an appropriate total gear ratio can range from 10.5:1 to 11.5:1. In order to produce a competition ready reduction assembly, Team 6 must work closely with the Baja Team as they solidify the design for the 2012-2013 vehicle and also ensure that the reduction and gearbox design fully comply with the 2012-2013 SAE Baja Racing rules.

After design review one, the next step within the project was to determine viable concepts. Using the specifications outlined, Team 6 first created a functional decomposition to describe the operation of the desired product and used this as a reference to brainstorm possible concept solutions for both the gear reduction and the gearbox. After narrowing the concepts to five different gear reduction options and four gearbox options, Team 6 created Pugh Charts to determine the most effective concepts. Using the results of the Pugh Charts, Team 6 chose an alpha design that combines a two-stage spur gear reduction with an aluminum skeleton gearbox that utilizes a composite material wherever aluminum is unnecessary.

After design review two, the next step was to complete the necessary engineering analysis in order to make the final design decisions. Using methods from *Shigley's Mechanical Engineering Design* and other outside sources, the team chose a pressure angle of 14.5° with a pitch of 12 for all gears. From their calculations, Team 6 was also able to determine face width, number of teeth and pitch diameter for all of the gears, which produced a total reduction of 10.65:1. Accounting for material constraints, the Baja Team's past knowledge of materials and stress calculations, Team 6 determined that all gears should be made from 9310 steel, a standard gear steel. Team 6 also conducted engineering analysis to investigate shaft bending and torsion, press-fit verus bolt-on hubs, bearings options, and spline versus polygon interfaces. Using these calculations, Team 6 was able to collect a variety of outputs that helped to define final material selection and design choices. Once designs were finalized for both the gear reduction and gearbox, CAD was created of the final designs and the CAD gear housing was analyzed using finite element analysis, which summarized the stresses and displacement. The finalized design was expected to meet all of the engineering specifications.

After design review three, the next step towards completion of the project was to execute the fabrication plan and, lastly, validate our assembled prototype. Blanks milled to an appropriate size for each gear, along with shafts turned to length and outer diameter, were sent to the Baja Team's heat treatment sponsor to be hardened. After the shafts were hardened, the final diameter was turned, and the shafts were given to Modified Gear and Machine in order for the splines to be ground. After the splines were ground, the hardened gear blanks and shafts were sent to Vertical Machining to have the gear teeth and internal splines wire EDM'ed. While outside source machining and heat-treating occurred, Team 6 fabricated the gear hubs, gearbox, spacers, and finger guards using tooling and resources provided by the Michigan Baja Team. Once all components were completed, final assembly occurred and validation was conducted as planned. A torque to rotate of 0.75 in-oz. ±0.0625 in-oz. was measured and a total weight of 10.75±0.50lbs was measured. It was also confirmed that the gear reduction satisfied the required total reduction range and abided by Baja SAE rules. Based on these results, Team 6 met all engineering specifications set fourth throughout the project.

Throughout this process, Team 6 encountered a number of challenges. Material selection became a challenge as Team 6 faced limited resources since their sponsor is a student run team which uses mostly donated materials. Provided the three-month time constraints to finish the project, there was also difficulty getting the gears manufactured by General Motors which required Team 6 to use an alternative sponsor, Vertical Machining, for wire EDM.

Calvin O’Brien

Calvin O’Brien is studying to be a mechanical engineer at the University of Michigan. Born in Washington D.C. in 1991, Calvin then moved to Atlanta, Georgia, where his younger brother, Christopher O’Brien, was born. After moving to Georgia, Calvin and his family moved to Denver, Colorado, before finally settling in Boca Raton, Florida, where Calvin lived from age 5 until attending Michigan at age 18. As a freshman at the University of Michigan, Calvin joined the Michigan Baja Team. As a new member on the team in 2009, Calvin worked hard to ensure the team’s success at competition, contributing in any way possible, despite his lack of prior experience. For the past three years on the team, Calvin has worked to be the main CNC Mill Machinist for the team, learning GCODE and CAM to manufacture a number of complicated parts using the Wilson Center’s 4 axis HAAS. Last year, Calvin worked as the drivetrain lead to design the chain reduction for the vehicle. He attended all three competitions with the team, and got the chance to drive the majority of the endurance race at competition. For the 2012-2013 season, Calvin has been elected to be the team captain, and is working to ensure the team’s success. On his career path, Calvin’s first internship was between his sophomore and junior year with American Axle and Manufacturing. After a summer in the Automotive Industry, Calvin chose to change his field of work, and spent the summer after junior year as an onshore mechanical engineer for BP. Calvin intends to return to BP as a full time engineer following a successful completion of senior year.

Bridget Quick

Bridget Quick is a fourth year Mechanical Engineering student from Mequon, Wisconsin. Her interest in mechanical engineering stemmed from her desire to find a field that could combine her passion for creativity, design and art with her interest in math, science and how mechanical systems function. For the past two summers, Bridget has interned for General Motors at Flint Truck Assembly, specifically working in Body Shop Maintenance. She is interested in staying within the automotive industry and hopes to find a career where she could be an asset as a connection between an automotive company’s industrial designers and vehicle design engineers. She has also taken college level drawing classes, as studying a field within the College of Art and Design was another option she considered before college. During the fall of her freshman year at the University of Michigan she became a member of the engineering social sorority, Phi Sigma Rho, and since has held the offices of Recruitment Chair, VP of Programming, and Associate Member Educator. Bridget has also been employed by the University’s

Office of Undergraduate Admissions for over a year as a Campus Tour Guide and enjoys sharing her passion for the University of Michigan with prospective students and their families.

Erin Ebsch

Erin is from Gibraltar, Michigan and is a senior in Mechanical Engineering. Her parents own a machine shop that is a contractor for heavy industry. Exposer to large mechanical equipment is what originally sparked her interest in mechanical engineering. She started at the University of Michigan through Michigan's Science Technology Engineering and Math Academy. After her freshmen year she started working at the advanced life support laboratory where she completed research on the fabrication of artificial lungs. Beginning her sophomore year she became involved in the Society of Women Engineers and served as the Elementary Outreach Officer as well as becoming a Mentor to incoming freshmen through the Multicultural Engineering Programs Office. Erin continued working in the same research lab but worked on building and programming a total liquid ventilation system. After her sophomore year Erin studied aboard at Shanghai Jiao Tong University, in China for two months where she took an engineering course as well as Chinese language and culture classes. Upon her return to the U.S. she continued to work on liquid ventilation. Her junior year she became the SWE Middle School Outreach officer and was a chair on the logistics committee for the Career Fair. The winter semester of her third year she completed a co-op at SC Johnson working on new product development for Ziploc in Bay City, Michigan. That summer she moved to Allentown, Pennsylvania to do and internship at Air Products where she worked as a Customer Engineering intern, working on safety systems of industrial hydrogen tanks. Following this internship she returned to U of M, continued doing research and began working with new SWE members as well as working on the operations committee for Career Fair. After her fourth year she spent the summer working with Schlumberger as a measurement while drilling engineer on an oil rig. She is currently completing her final year of school.

Jenna Kudla

Jenna Kudla is a mechanical engineer born in Plymouth, Michigan. Born and raised in Rochester Hill, Michigan and an automotive family, Jenna always knew she wanted to work in the car industry. During her second year at the University of Michigan, she joined the Formula SAE team, MRacing. On this team she became the leader of carbon fiber manufacturing. She creates molds for each carbon fiber part on the car and manufactures them in very involved multi step process that uses NX CAD software, a CNC router, many hours of preparation, and the application of carbon fiber. She will lead the team again this year and will prepare for much more work with the addition of a carbon fiber aero package. She accompanies the team as they travel to Michigan International Speedway and Hockenheim, Germany to compete and defend their ranking of 10th in the world out of 500 teams. Jenna is also involved in the Society of Women Engineers (SWE). Besides being an elevated member, she is also is a chair on the SWE/TBP career fair board, last year as a logistics chair and this year as the volunteer chair. Jenna interned at Chrysler LLC after sophomore and junior year in supplier quality and corporate quality respectively. She will be working at Meritor a then end of the school year.

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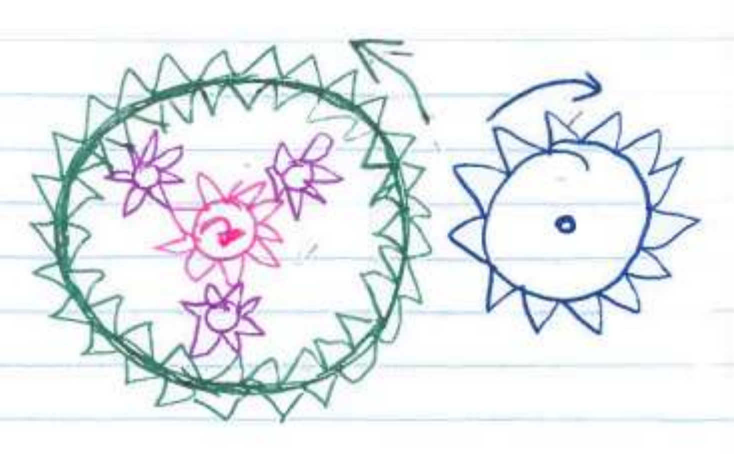
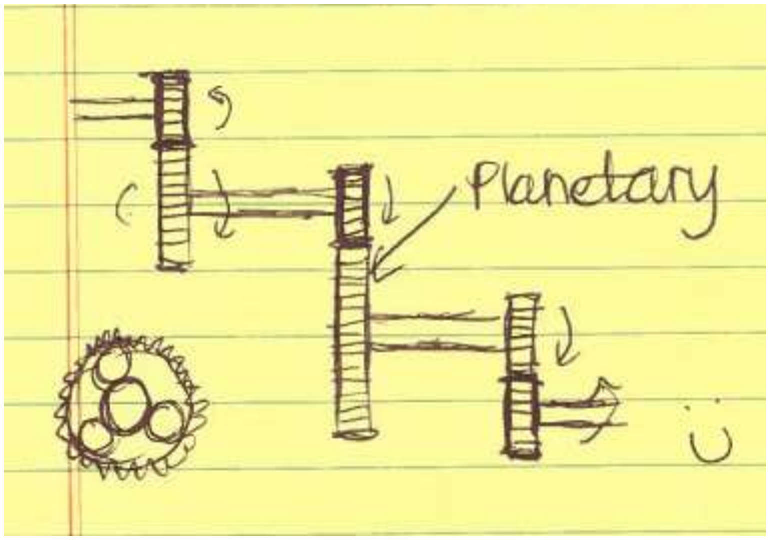
APPENDIX A-Gear Reduction Concepts

Appendix A.1-Planatary Gears

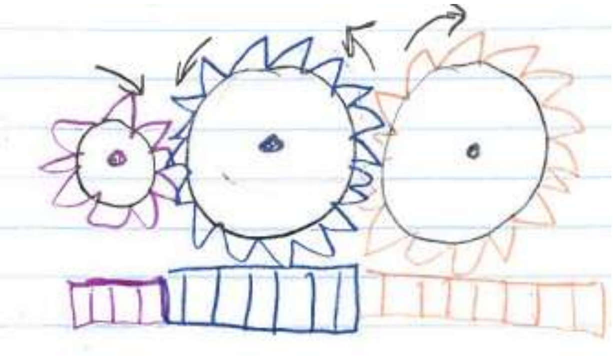


In this design the sun gear is the input gear and the blue spur gear is the output. The main benefits is that this design is very compact and would be easy to machine. The disadvantages include the amount of raw material needed and the difficulty of assembly.

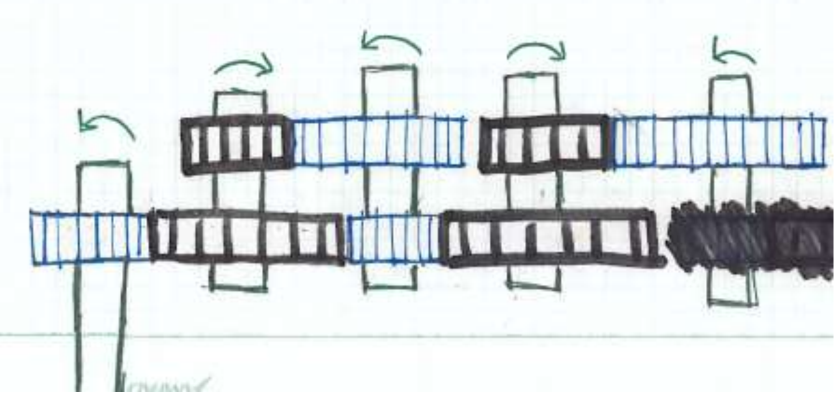


For this reduction there are a series of spur gears in combination with planetary gears.
The benefits of this design include correct output direction and parallel shafts though this reduction would require large amounts of material resulting in a heavy design.

Appendix A.2-Spur Gears

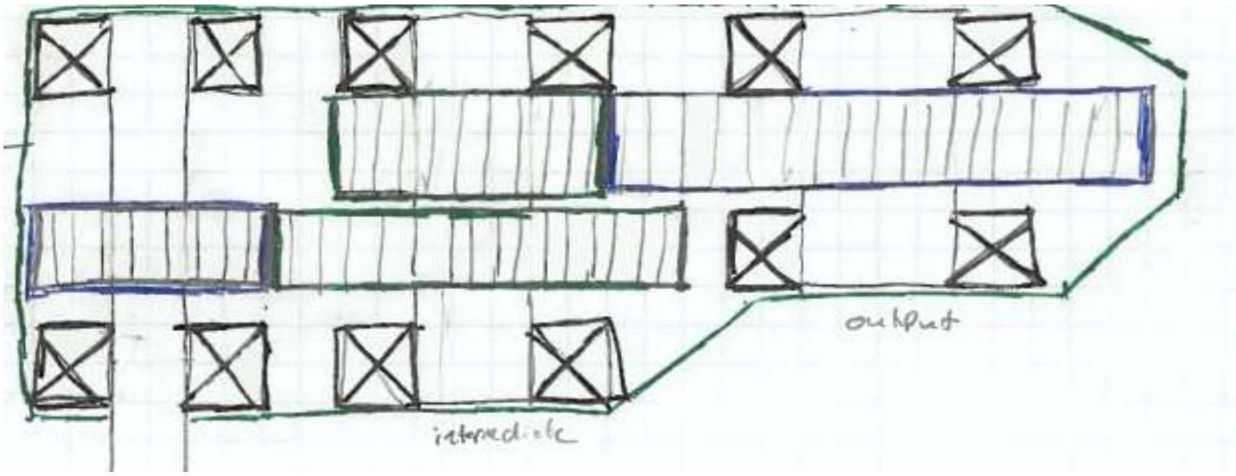


There are three spur gears with increasingly large diameters to create an 11:1 reduction. This design would be easy to manufacture and assemble however this design would have a very large volume and would be quite heavy.



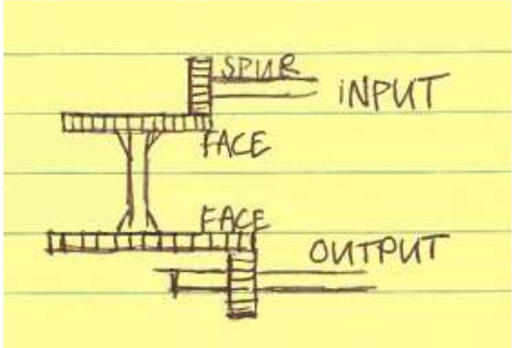
In this design there are three shafts with two gears of different dimensions. On the input and output shafts there is only on gear. The advantages of this design include easy of manufacturability and assembly. Similar to the design above, it would have a very large volume and would be quite heavy.

Appendix A.3-Helical Gears

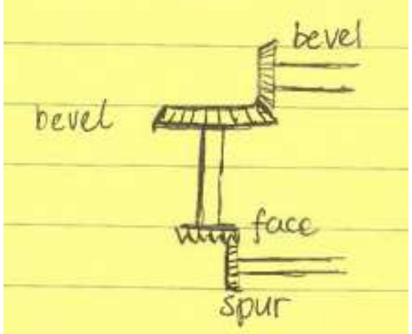


This is a two stage gear reduction, with all helical gears. This design would be easy to assemble however it would be difficult to manufacture the helical gears.

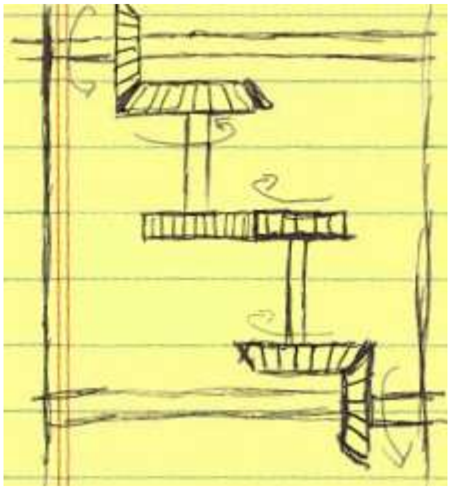
Appendix A.4-Bevel Gears



In this design, the input gear goes to two face gears on the same shaft which then meshes the output gear. While this design would be a challenge to package because of the intersecting shafts, it would be both lightweight and efficient because of the limited reductions.

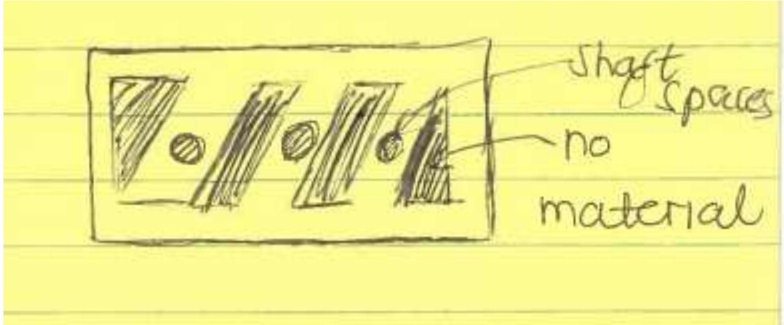


This reduction uses a combination of two bevel gears with one face gear and a spur gear. Similar to the previous design, this design would be a challenge to package because of the intersecting shafts; it would be both lightweight and quiet because of the use of bevel gears instead of spur gears.

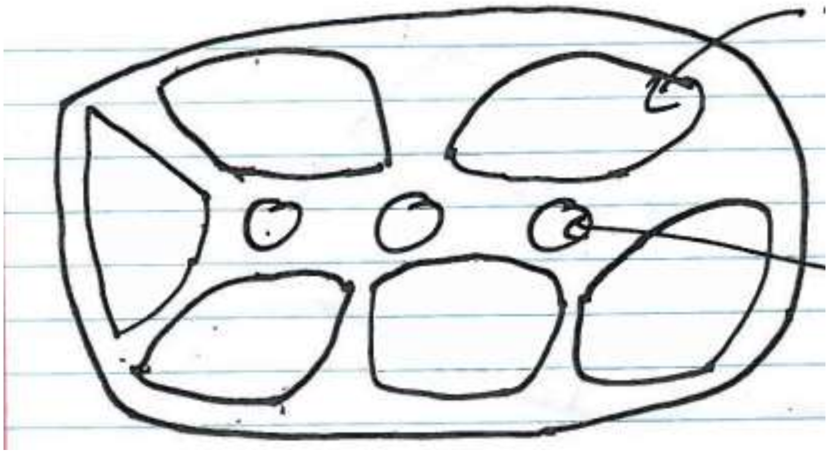


There are two pairs of bevel gears and one pair of spur gears. Both the input and output gears have bevel gears. This design would not be feasible as the output shaft would rotate in the wrong direction.

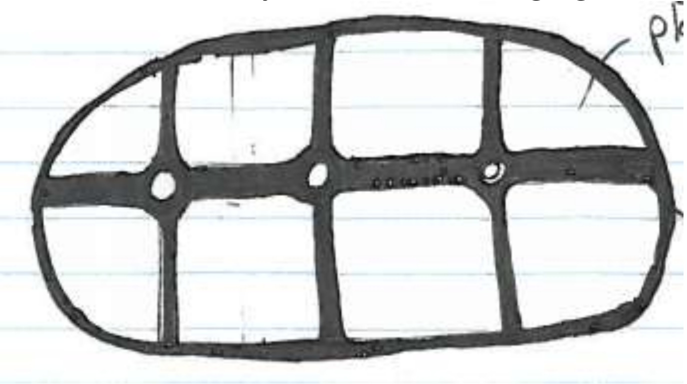
APPENDIX B-Housing Design Concepts



This housing would be comprised of aluminum with some portions of material removed to reduce the weight of the housing. While the cutouts would reduce the weight of the box, the box would require additional design work if lubricant was deemed necessary.



In this drawing the shaft supports would also be made out aluminum and any area with removed material would have fabric to serve as finger guards. The material removal would help with the weight of the box however the fabric may not work well for finger guards.



This housing is created from steel with a lightweight plastic for finger guards. This design is very similar to the chosen design however; the steel housing would make it heavier.

APPENDIX C – Maple Code

> *#Proof for the Equation of Torque for a press fit of aluminum in steel*

>

> *restart* :

> *with*(*DETools*) :

> *with*(*plots*) :

> *#Inch, Pounds, Seconds*

> *#Material 1 is the inner material, in this case, Aluminum 7075-T6\T651*

> $E_1 := 10400 \cdot 10^3$

$$E_1 := 10400000$$

> $v_1 := 0.330$

$$v_1 := 0.330$$

> *#a is the inner radius of the inner circle, currently defined using a "wal thickness" before the spoke like structure*

> #a:=c−.25

> ***#c is the outer diameter of the aluminum, or the inner diameter of the steel, less the interference***

> *#c:=4.5*

> *#assume no inner pressure*

> $P_i := 0$

$$P_i := 0$$

> *#delta is the RADIALnterfernce parameter*

> *#delta:=0.005*

> *#Material 2 is the outer material, in this case, steel, 8620 because 931 properties were not available*

> $E_2 := 29700 \cdot 10^3$

$$E_2 := 29700000$$

> $v_2 := 0.290$

$$v_2 := 0.290$$

> *#b is the outer radius of the steel, in this case, assume the base diameter of the gear, as it will give a lower max torque, so it is the safer assumption*

> *#b:=* $\frac{5.6}{2}$

>

> ***#for now, let l be the face width of the gear***

> *#l:=0.5*

> *#using google, the mu between steel and aluminum was found*

> **mu := 0.61**

$$\mu := 0.61$$

>

>

> *#Radial displacement of the inner material due to a pressure*

> $$u_{1\,R} := \frac{(1-v_1)}{E_1}\cdot\left(\frac{\left(a^2\cdot P_i-(c+\mathrm{delta})^2\cdot P_{charlie}\right)}{(c+\mathrm{delta})^2-a^2}\right)\cdot R + \frac{(1+v_1)}{E_1}\cdot\frac{\left(a^2\cdot(c+\mathrm{delta})^2\cdot\left(P_i-P_{charlie}\right)\right)}{\left((c+\mathrm{delta})^2-a^2\right)\cdot R}$$

$$u_R := -\frac{6.442307692\,10^{-8}\,(c+\delta)^2\,P_{charlie}\,R}{(c+\delta)^2-a^2} - \frac{1.278846154\,10^{-7}\,a^2\,(c+\delta)^2\,P_{charlie}}{\left((c+\delta)^2-a^2\right)\,R}$$

> $u_1 := subs\left(R=(c+\mathrm{delta}),\,u_{1\,R}\right)$

$$u_1 := -\frac{6.442307692\,10^{-8}\,(c+\delta)^3\,P_{charlie}}{(c+\delta)^2-a^2} - \frac{1.278846154\,10^{-7}\,a^2\,(c+\delta)\,P_{charlie}}{(c+\delta)^2-a^2}$$

> *#Radial displacement of the outer material due to a pressure*

> $$u_{2\,R} := \frac{(1-v_2)}{E_2}\cdot\left(\frac{c^2\cdot P_{charlie}}{b^2-c^2}\right)\cdot R + \frac{(1+v_2)}{E_2}\cdot\frac{c^2\cdot b^2\cdot P_{charlie}}{\left(b^2-c^2\right)\cdot R}$$

$$u_{2\,R} := \frac{2.390572391\,10^{-8}\,c^2\,P_{charlie}\,R}{b^2-c^2} + \frac{4.343434343\,10^{-8}\,c^2\,b^2\,P_{charlie}}{\left(b^2-c^2\right)\,R}$$

> $u_2 := subs\left(R=c,\,u_{2\,R}\right)$

$$u_2 := \frac{2.390572391\,10^{-8}\,c^3\,P_{charlie}}{b^2-c^2} + \frac{4.343434343\,10^{-8}\,c\,b^2\,P_{charlie}}{b^2-c^2}$$

> *#Subtracting* u_1 **from** u_1 *gives the interference amount,* delta

> $eq1 := u_2 - u_1 = \mathrm{delta}$

$$eq1 := \frac{2.390572391\,10^{-8}\,c^3\,P_{charlie}}{b^2 - c^2} + \frac{4.343434343\,10^{-8}\,c\,b^2\,P_{charlie}}{b^2 - c^2} + \frac{6.442307692\,10^{-8}\,(c+\delta)^3\,P_{charlie}}{(c+\delta)^2 - a^2} + \frac{1.278846154\,10^{-7}\,a^2\,(c+\delta)\,P_{charlie}}{(c+\delta)^2 - a^2} = \delta$$

> *#Check if algebra matches notes*

> *#eq2:=subs*$\left(\text{delta} = 0, E_1 = E, E_2 = E, eq1\right)$

> *#This check was performed the first time through. The book by James Barber perfomred this analysis assuming E1=E2, so this check wa performed to ensure correctness up until this point*

> *#Pressure is required for the torsion measurements, so this line solves equation 1 in tems of pressure*

> $Pressure := solve\left(eq1, P_{charlie}\right)$

$$Pressure := -\left(1.000000000\,10^{17}\,\delta\,(b^2 - 1.\,c^2)\,(-1.\,c^2 - 2.\,c\,\delta - 1.\,\delta^2 + a^2)\right) \Big/ \left(-4.051735301\,10^{9}\,c^5 - 1.454577829\,10^{10}\,c^4\,\delta - 1.693635068\,10^{10}\,c^3\,\delta^2 - 1.517903393\,10^{10}\,c^3\,a^2 + 1.078574204\,10^{10}\,c^3\,b^2 + 2.801379176\,10^{10}\,c^2\,b^2\,\delta + 2.367035742\,10^{10}\,c\,b^2\,\delta^2 + 8.445027197\,10^{9}\,c\,b^2\,a^2 + 6.442307692\,10^{9}\,\delta^3\,b^2 - 6.442307692\,10^{9}\,\delta^3\,c^2 + 1.278846154\,10^{10}\,a^2\,\delta\,b^2 - 1.278846154\,10^{10}\,a^2\,c^2\,\delta\right)$$

> *#The shear stress at the interface is due to the pressure times the coefficient of friction*

> $shear := Pressure \cdot \text{mu}$

$$shear := -\left(6.100000000\,10^{16}\,\delta\,(b^2 - 1.\,c^2)\,(-1.\,c^2 - 2.\,c\,\delta - 1.\,\delta^2 + a^2)\right) \Big/ \left(-4.051735301\,10^{9}\,c^5 - 1.454577829\,10^{10}\,c^4\,\delta - 1.693635068\,10^{10}\,c^3\,\delta^2 - 1.517903393\,10^{10}\,c^3\,a^2 + 1.078574204\,10^{10}\,c^3\,b^2 + 2.801379176\,10^{10}\,c^2\,b^2\,\delta + 2.367035742\,10^{10}\,c\,b^2\,\delta^2 + 8.445027197\,10^{9}\,c\,b^2\,a^2 + 6.442307692\,10^{9}\,\delta^3\,b^2 - 6.442307692\,10^{9}\,\delta^3\,c^2 + 1.278846154\,10^{10}\,a^2\,\delta\,b^2 - 1.278846154\,10^{10}\,a^2\,c^2\,\delta\right)$$

> *#The torque which can be transmitted is a function of the diamter the interface occurs at, the width* (l) *of the interface,* **and** *the shear force calculated above*

> $Torque := c \cdot shear \cdot c \cdot 2 \cdot \mathrm{Pi} \cdot l$

$$
\begin{aligned}
Torque := -\big(&1.220000000\,10^{17}\,c^2\,\delta\,(b^2 - 1.\,c^2)\,(-1.\,c^2 - 2.\,c\,\delta \\
&- 1.\,\delta^2 + a^2)\,\pi\,l\big) \big/ \big(-4.051735301\,10^{9}\,c^5 \\
&- 1.454577829\,10^{10}\,c^4\,\delta - 1.693635068\,10^{10}\,c^3\,\delta^2 \\
&- 1.517903393\,10^{10}\,c^3\,a^2 + 1.078574204\,10^{10}\,c^3\,b^2 \\
&+ 2.801379176\,10^{10}\,c^2\,b^2\,\delta + 2.367035742\,10^{10}\,c\,b^2\,\delta^2 \\
&+ 8.445027197\,10^{9}\,c\,b^2\,a^2 + 6.442307692\,10^{9}\,\delta^3\,b^2 \\
&- 6.442307692\,10^{9}\,\delta^3\,c^2 + 1.278846154\,10^{10}\,a^2\,\delta\,b^2 \\
&- 1.278846154\,10^{10}\,a^2\,c^2\,\delta\big)
\end{aligned}
$$

> *#evalf(Torque)*

> *#The initial Torque was in inch-lbs, and foot-lbs is a more ideal number to compare with the system requirements*

> $\mathrm{FTorque} := \dfrac{\mathrm{Torque}}{12}$:

>

>

> *#Finding Stresses, assume no internal pressure*

> $\sigma_{radial,\,inner} := -\dfrac{Pressure \cdot c^2}{\left((c + \mathrm{delta})^2 - a^2\right)} \cdot \left(1 - \dfrac{a^2}{(c + \mathrm{delta})^2}\right)$:

> $\sigma_{hoop,\,inner} := -\dfrac{Pressure \cdot c^2}{\left((c + \mathrm{delta})^2 - a^2\right)} \cdot \left(1 + \dfrac{a^2}{(c + \mathrm{delta})^2}\right)$:

>

> *FTorque* :

> *#A series of plots was performed, and this data was input for the plots and was varied so analysis could be performed to develop a relationship between stress, torque, interference, and interface diamter. An example is shown below, as the trend is similar for various setups*

> $l := 0.5$

$$l := 0.5$$

> $a := c - .25$

$$a := c - 0.25$$

> $b := \dfrac{5.6}{2}$

$$b := 2.800000000$$

> *#plot*$(Torque, \mathrm{delta} = 0\,..0.01)$

> $\mathrm{delta} := 0.001$

$$\delta := 0.001$$

> $p1 := plot(FTorque, c = 1.5\,..2.4, color = green)$

$$p1 := PLOT(\ldots)$$

> $s1 := plot(\sigma_{radial,\ inner}, c = 1.5\ ..2.4, color = green)$

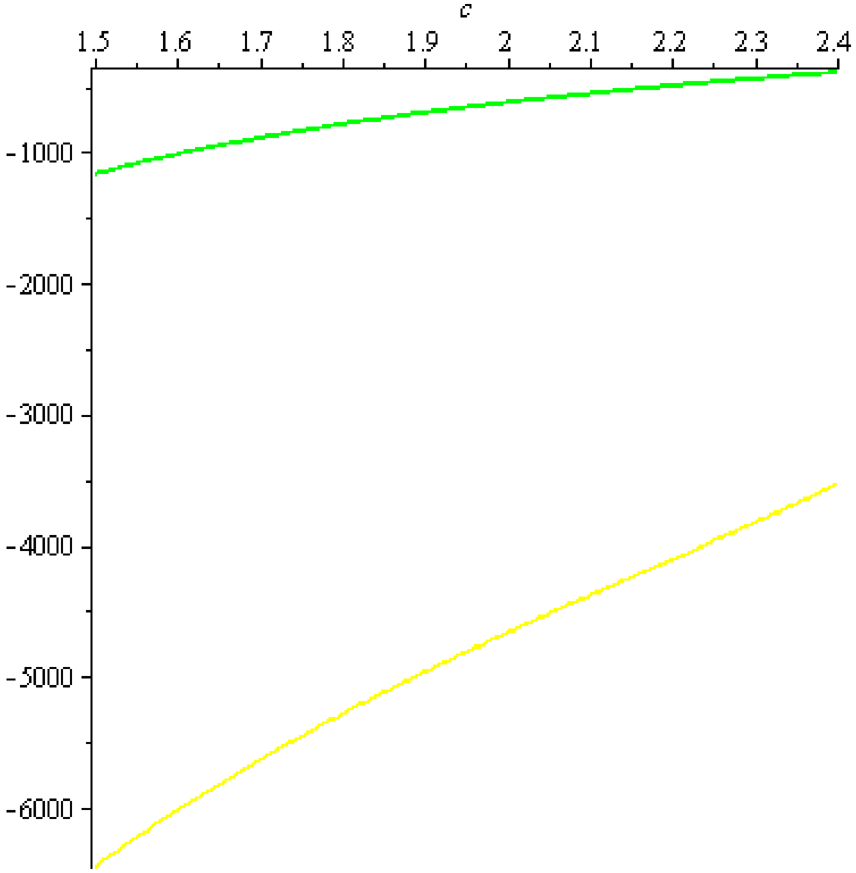
$$s1 := PLOT(\ldots)$$

> $s2 := plot(\sigma_{hoop,\ inner}, c = 1.5\ ..2.4, color = yellow)$

$$s2 := PLOT(\ldots)$$

> *#Show the stress as a function of outer diamter for a interference of 0.001*

> $display(s1, s2)$



> *#Repeate the above calculations for an interference of 0.002"*

> delta := 0.002

$$\delta := 0.002$$

> $s3 := plot(\sigma_{radial,\ inner}, c = 1.5\ ..2.4, color = blue)$

$$s3 := PLOT(\ldots)$$

> $s4 := plot(\sigma_{hoop,\ inner}, c = 1.5\ ..2.4, color = violet)$

$$s4 := PLOT(\ldots)$$

> $p2 := plot(FTorque, c = 1.5\ ..2.4, color = blue)$

$$p2 := PLOT(\ldots)$$

> *#Again, repeat for an interference of 0.003"*

> delta := 0.003

$$\delta := 0.003$$

> $s5 := plot\left(\sigma_{radial,\, inner}, c = 1.5\,..2.4, color = black\right)$

$$s5 := PLOT(\ldots)$$

> $s6 := plot\left(\sigma_{hoop,\, inner}, c = 1.5\,..2.4, color = brown\right)$

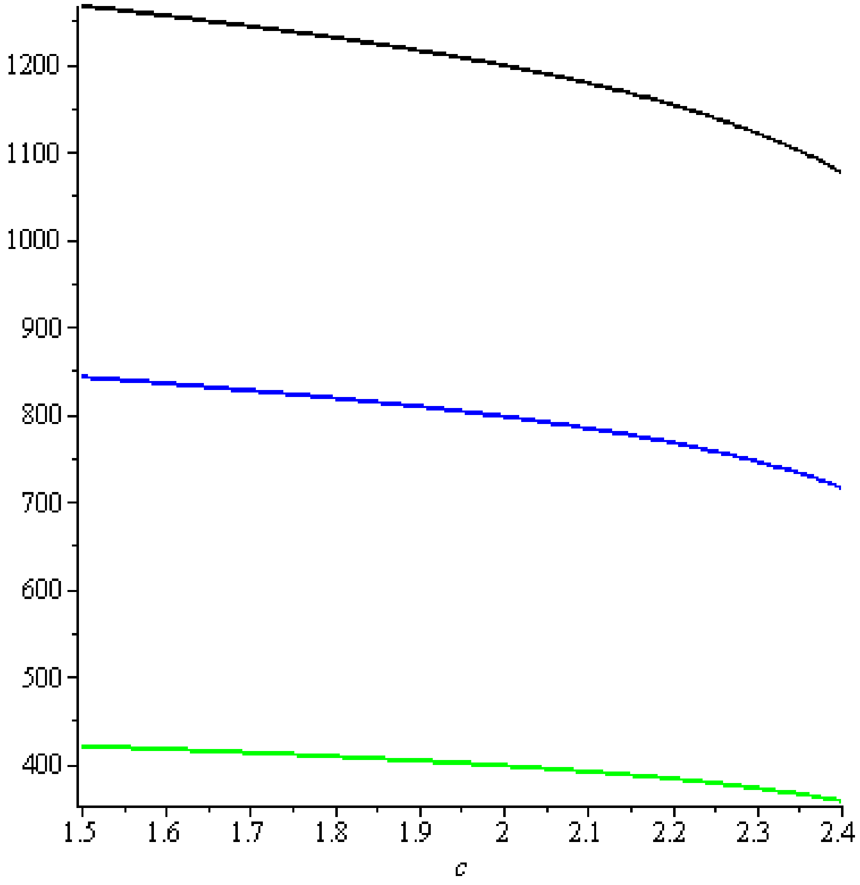
$$s6 := PLOT(\ldots)$$

> $p3 :=$

$$p3 := PLOT(\ldots)$$

> *#This plot compares the torque which can be transmitted at vaious interface radii to the difference interference values which were mentioned above*

> $display(p1, p2, p3)$



>

> *#Calculations for the final design*

> *#First Reduction*

> $l := 0.5$

$$l := 0.5$$

> $c := 2.4$

$$c := 2.4$$

> $a := c - .25$

$$a := 2.15$$

> $b := \frac{5.6}{2}$

$b := 2.800000000$

>

> delta := 0.0025

$\delta := 0.0025$

> *evalf*(*FTorque*)

896.7279718

> $\sigma_{hoop,\ inner}$

-8796.866277

> $\sigma_{radial,\ inner}$

-972.8266567

> *Pressure*

974.8544346

> *# For the frist reduction, a diamterical press fit of 0.005 inches at a diameter of 4.8" will be run. This will allow 869 ftlbs of torque to be transmitted, a safety factor of over 5. The max stress comes from the hoop stress and is 4,558 PSI inward.*

> *#What temperature change would be required to get that fit?*

> *#deltaT = (radius change)(radius·alpha)*$^{-1}$*, radius is the initial radius,* $\frac{\textit{alph a is units of microinch}}{\textit{inch}\cdot\textit{degree F}}$

> alpha := 13.1

$\alpha := 13.1$

> $detlaT := \frac{-\mathrm{delta}}{(c + \mathrm{delta})\cdot(\mathrm{alpha}\cdot 10^{-6})}$

$detlaT := -79.43379588$

>

>

> *#Second Reduction*

> $l := 1$

$l := 1$

> $c := 2.3$

$c := 2.3$

> $a := c - .25$

$a := 2.05$

> $b := \frac{5.333}{2}$

$b := 2.666500000$

>

> delta := 0.003

$\delta := 0.003$

> $evalf(FTorque)$

$$2122.259359$$

> $\sigma_{hoop,\ inner}$

$$-10813.96258$$

> $\sigma_{radial,\ inner}$

$$-1252.801094$$

> *#For the second reduction, a diametrical press fit of 0.006 inches at a diamter of 4.6" will be run. This will allow 2,122 lbf of Torque to be transmitted, a safety factor of just over 5. The hoop stress is the maxiumum, at -9649 psi.*

> alpha := 7

$$\alpha := 7$$

> $detlaT := \frac{\text{delta}}{(c)\cdot\left(\text{alpha}\cdot 10^{-6}\right)}$

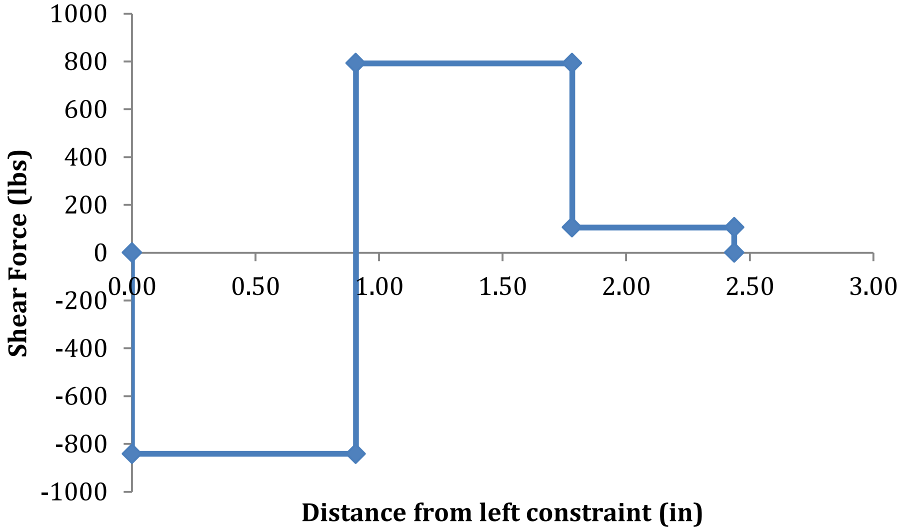
$$detlaT := 186.3354037$$

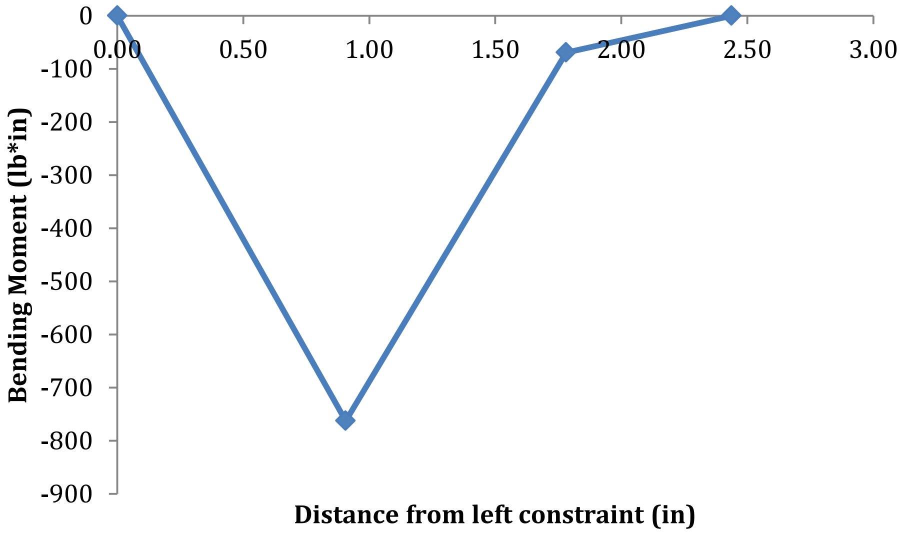
> $Pressure$

$$1256.071402$$

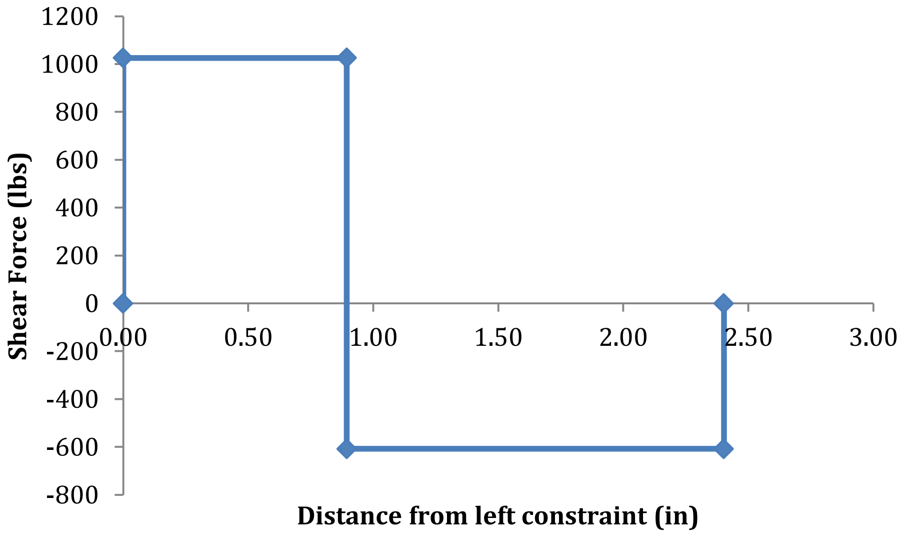
APPENDIX D- Shaft Diagrams

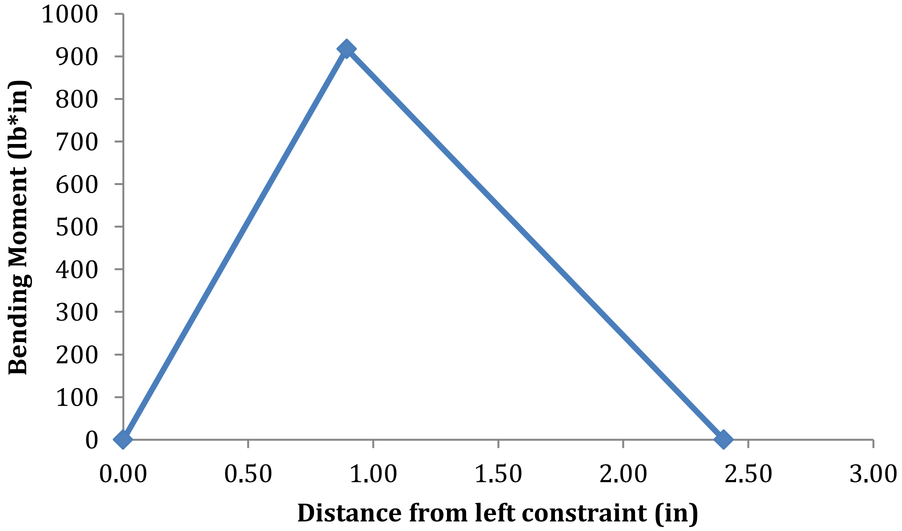
Intermediate Shaft Diagrams





Output Shaft Diagrams





APPENDIX E-Safety Reports

ME450 Task W-5 Safety Form

Semester: Fall
Year: 2012 **Project Number:**
6 **Project Title:** Baja Gearbox
Reduction

Task Category:
Manufacturing/Prototyping

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Process done by: Jenna Kudla Present: Calvin O'Brien, Bridget Quick, Erin Ebsch

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

Starting October 20, 2012

Where:

Describe the exact location where you intend to conduct this task.
On-campus locations: List the building and room.
Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".
Off-campus locations: List the address.

On Campus: Wilson Student Project Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

1)Vacuum pump 2)

2) Inputs & Outputs

Inputs: Tooling board and G-Code Outputs: machined tooling board

3) Procedure Summary

1) Apply tooling board to CNC Router table 2) Create G-Code for part 3) Start machine and run G-Code 4)Clean up router debris

4) Setup Figure

5) Mitigation Steps

1) Safety Glasses will be worn 2) Vacuum system to prevent dust in the air

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

We hope to create a prototype housing for our DR2 out of tooling board. This allows us to consider spacing

ME450 Task W-5 Safety Form

Semester: Fall
Year: 2012 **Project Number:** 6
Project Title: Baja Gear Reduction

Task Category:
Manufacturing/Prototyping

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Jenna Kudla, Calvin O' Brien, Erin Ebsch, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

11/15/2012 for 2 weeks depending on material delivery

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

Wilson Student Team Project Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

Haas VF-2SS CNC Mill, Bridgeport Mill Series I, multiple sized end mills

2) Inputs & Outputs

7075 Aluminum, 4043 Steel

3) Procedure Summary

On the Bridgeport Mill machine the jig for the gear case out of the steel and create the stock material for the Haas out of the aluminum. Create the G-Code for the gearbox via GibbsCam. Attach the stock material to the jig and run the gcode on the Haas

4) Setup Figure

5) Mitigation Steps

To avoid overheating and chip mitigation coolant will be run. At all time safetly glasses will be worn for flying objects

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

For the fabrication of the gearbox.

ME450 Task W-5 Safety Form

Semester: Fall
Year: 2012 **Project Number:**
6 **Project Title:** Baja Gear Reduction

Task Category:
Manufacturing/Prototyping

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Jenna Kudla, Calvin O' Brien, Erin Ebsch, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

11/15/2012 for 2 weeks depending on material delivery

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

Wilson Student Team Project Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.** Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

Tormax Romi Lathe, multiple drill bits, cutting and turning tools

2) Inputs & Outputs

6061 Aluminum

3) Procedure Summary

1. Place material in chuck 2. Turn down material to needed size 3. Use cutoff tool to remove part from material

4) Setup Figure

5) Mitigation Steps

To avoid overheating and chip mitigation coolant will be run. At all time safetly glasses will be worn for flying objects

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

For the fabrication of the spacers for the gearbox.

ME450 Task W-5 Safety Form

Semester: Fall
Year: 2012 **Project Number:**
6 **Project Title:** Baja Gear Reduction

Task Category:
Experiment/Validation

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Jenna Kudla, Calvin O' Brien, Erin Ebsch, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

11/28/2012 for 2 weeks depending on material delivery

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

Wilson Student Team Project Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

Global 236999 Scale

2) Inputs & Outputs

Assembled gearbox

3) Procedure Summary

Place gearbox on scale and record the final weight

4) Setup Figure

5) Mitigation Steps

Safety glasses will be woren

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

The weight of the gearbox is needed to validate our design

ME450 Task W-5 Safety Form

Semester: Fall
Year: 12 **Project Number:**
6 **Project Title:** Baja Gear Reduction

Task Category:
Experiment/Validation ▾

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Calvin O' Brien, Jenna Kudla, Erin Ebsch, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

11/15/12

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

Wilson Student Team Project Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

2 torque wrenches, vise

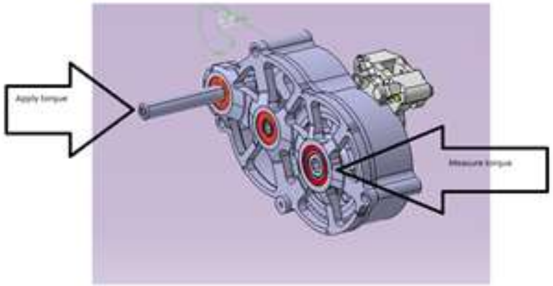
2) Inputs & Outputs

Applying a torque to the completed reduction

3) Procedure Summary

The team will clamp the gearbox in the vise to prevent it from moving. The team will apply a measured torque to the system with the torque wrench and measue the torque coming out of the system with the second torque wrench

4) Setup Figure



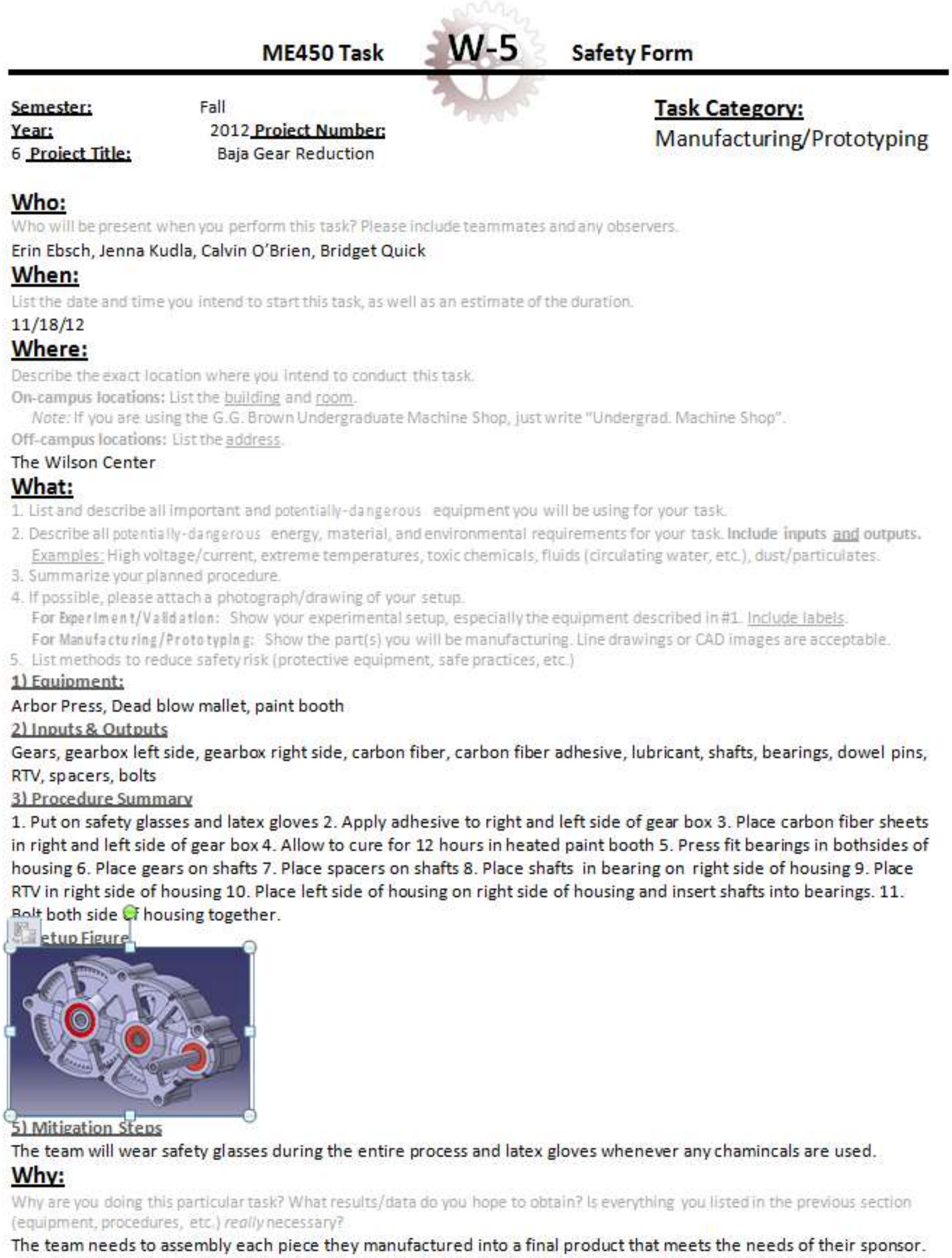
5) Mitigation Steps

The team will be wearing safety glasses

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

This will prove one of the goals of the system which is efficiency. Measuring the torque to rotate is a critical step.



ME450 Task **W-5** **Safety Form**

Semester: Fall
Year: 2012 **Project Number:** 6
Project Title: Baja Gear Reduction

Task Category:
Manufacturing/Prototyping

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Erin Ebsch, Jenna Kudla, Calvin O'Brien, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

11/18/12

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

The Wilson Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

Arbor Press, Dead blow mallet, paint booth

2) Inputs & Outputs

Gears, gearbox left side, gearbox right side, carbon fiber, carbon fiber adhesive, lubricant, shafts, bearings, dowel pins, RTV, spacers, bolts

3) Procedure Summary

1. Put on safety glasses and latex gloves 2. Apply adhesive to right and left side of gear box 3. Place carbon fiber sheets in right and left side of gear box 4. Allow to cure for 12 hours in heated paint booth 5. Press fit bearings in bothsides of housing 6. Place gears on shafts 7. Place spacers on shafts 8. Place shafts in bearing on right side of housing 9. Place RTV in right side of housing 10. Place left side of housing on right side of housing and insert shafts into bearings. 11. Bolt both side of housing together.

etup Figure

5) Mitigation Steps

The team will wear safety glasses during the entire process and latex gloves whenever any chamincals are used.

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

The team needs to assembly each piece they manufactured into a final product that meets the needs of their sponsor.

ME450 Task W-5 Safety Form

Semester: Fall
Year: 2012 **Project Number:**
6 **Project Title:** Baja Gear Reduction

Task Category:
Experiment/Validation

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Erin Ebsch, Jenna Kudla, Calvin O'Brien, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

1/6/12

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

The Wilson Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

Fume hood, glass beaker, safety glasses, latex gloves, paper towel

2) Inputs & Outputs

Chemicals

3) Procedure Summary

1. Put on latex gloves and safety glasses 2. Pour lubricant into a glass beaker in a fume hood 3. A piece of cured composite will be placed in the beaker using forcepts 4. Allow the composite to sit in the lubricate for 12 hours 5. The composite will be removed from the lubricate and wiped clean using paper towel 7. The composite will be visually inspected

4) Setup Figure

5) Mitigation Steps

The team will all wear latex gloves and safety glasses. The chemicals being used are not toxic but the team will still conduct this experiment under a fume hood

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

This test is being completed to ensure that the lubricant is compatable with the composite

ME450 Task W-5 Safety Form

Semester: Fall
Year: 2012 **Project Number:**
6 **Project Title:** Baja Gear Reduction

Task Category:
Manufacturing/Prototyping

Who:

Who will be present when you perform this task? Please include teammates and any observers.

Jenna Kudla, Calvin O' Brien, Erin Ebsch, Bridget Quick

When:

List the date and time you intend to start this task, as well as an estimate of the duration.

10/29/2012 for 2 weeks depending on surface finish

Where:

Describe the exact location where you intend to conduct this task.

On-campus locations: List the building and room.

Note: If you are using the G.G. Brown Undergraduate Machine Shop, just write "Undergrad. Machine Shop".

Off-campus locations: List the address.

Wilson Student Team Project Center

What:

1. List and describe all important and potentially-dangerous equipment you will be using for your task.
2. Describe all potentially-dangerous energy, material, and environmental requirements for your task. **Include inputs and outputs.**
   Examples: High voltage/current, extreme temperatures, toxic chemicals, fluids (circulating water, etc.), dust/particulates.
3. Summarize your planned procedure.
4. If possible, please attach a photograph/drawing of your setup.
   For Experiment/Validation: Show your experimental setup, especially the equipment described in #1. Include labels.
   For Manufacturing/Prototyping: Show the part(s) you will be manufacturing. Line drawings or CAD images are acceptable.
5. List methods to reduce safety risk (protective equipment, safe practices, etc.)

1) Equipment:

Vacuum pump, hose + attachments, carbon fiber mold, resipirator, safety glasses, latex gloves

2) Inputs & Outputs

Release Wax, Expoy resin, Hardener, Carbon Fiber, Peely ply, breather, vacuum bag, sealer tape

3) Procedure Summary

1. Apply release wax on and off 4 times 2. Cut carbon fiber to shape 2b) put on safety glasses, gloves, long sleeve shirt 3. Mix epoxy to hardener in a 5:1 volume ratio 4 . Apply mixture to carbon fiber and spread around with paddles 5. Apply carbon fiber to mold in as may layers as needed 6. Place peel ply on top of carbon fiber 7. Place breather ontop of peel plyl 8. Apply sealer tape around mold 9. Apply vacuum bag to sealer tap to prevent air from escaping. 9 connect hose to vacuum bag. 10. Turn on vacuum 11. Wait 6 hours for epoxy to cure. 12. Remove composite from mold. 12 trim carbon with dremel, safety glasses, long sleeve shirt and respirator

4) Setup Figure

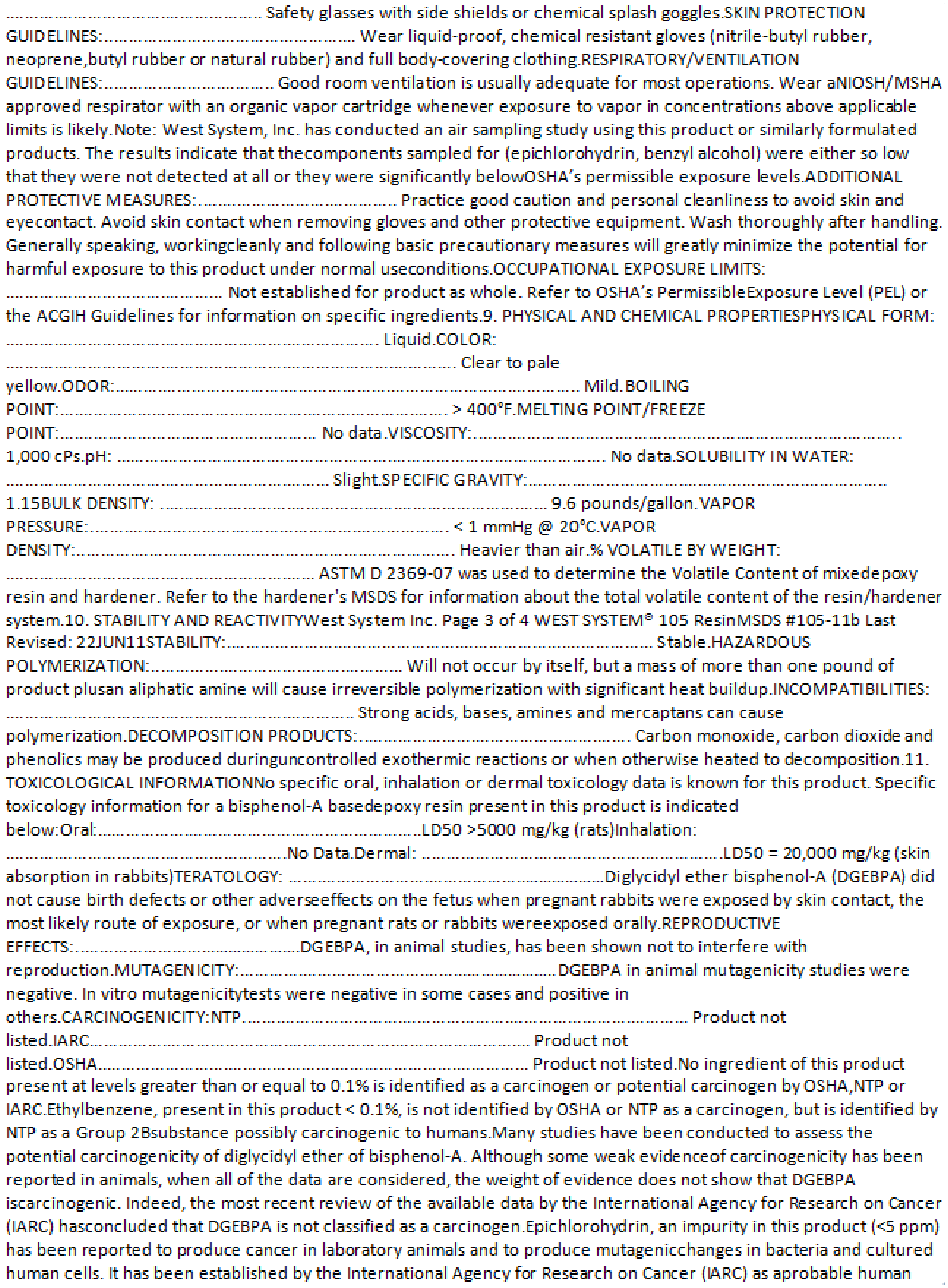
5) Mitigation Steps

To prevent chemical burns: latex gloves, long sleeve shirts and safety glasses are worn. To prevent the harm from debris: a respirator and safety glasses are worn

Why:

Why are you doing this particular task? What results/data do you hope to obtain? Is everything you listed in the previous section (equipment, procedures, etc.) *really* necessary?

This is being done to create the side shield of the gear reduction box MATERIAL SAFETY DATA SHEETWest System Inc.MSDS #105-11b Last Revised: 22JUN111. CHEMICAL PRODUCT AND COMPANY IDENTIFICATIONPRODUCT NAME:……………………………………WEST SYSTEM® 105 Epoxy Resin®.PRODUCT CODE:……………………………………105CHEMICAL FAMILY:…………………………………Epoxy Resin.CHEMICAL NAME:……………………………………Bisphenol A based epoxy resin.FORMULA:……………………………………………Not applicable.MANUFACTURER: EMERGENCY TELEPHONE NUMBERS:West System Inc. Transportation102 Patterson Ave. CHEMTREC:………………. 800-424-9300 (U.S.)Bay City, MI 48706, U.S.A. 703-527-3887 (International)Phone: 866-937-8797 or 989-684-7286 Non-transportationwww.westsystem.com Poison Hotline: ……………. 800-222-12222. HAZARDS IDENTIFICATIONEMERGENCY OVERVIEWHMIS Hazard Rating: Health - 2 Flammability - 1 Physical Hazards - 0WARNING! May cause allergic skin response in certain individuals. May cause moderate irritation to the skin. Clear to light yellow liquid withmild odor.PRIMARY ROUTE(S) OF ENTRY:…………………………………………. Skin contact.POTENTIAL HEALTH EFFECTS:ACUTE INHALATION:…………………………………………………………… Not likely to cause acute effects unless heated to high temperatures. Ifproduct is heated, vapors generated can cause headache, nausea, dizziness and possible respiratory irritation if inhaled in high concentrations.CHRONIC INHALATION: ………………………………………………………. Not likely to cause chronic effects. Repeated exposure to high vaporconcentrations may cause irritation of pre-existing lung allergies and increase the chance of developing allergy symptoms to this product.ACUTE SKIN CONTACT:…………………………………………………… May cause allergic skin response in certain individuals. May causemoderate irritation to the skin such as redness and itching.CHRONIC SKIN CONTACT:……………………………………………………… May cause sensitization in susceptible individuals. May cause moderateirritation to the skin.EYE CONTACT: ………………………………………………………………… May cause irritation.INGESTION:……………………………………………………………………… Low acute oral toxicity.SYMPTOMS OF OVEREXPOSURE: …………………………………………… Possible sensitization and subsequent allergic reactions usually seen asredness and rashes. Repeated exposure is not likely to cause other adverse health effects.MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE:……………. Pre-existing skin and respiratory disorders may be aggravated by exposureto this product. Pre-existing lung and skin allergies may increase the chance of developing allergic symptoms to this product.3. COMPOSITION/INFORMATION ON HAZARDOUS INGREDIENTSINGREDIENT NAME CAS # CONCENTRATIONBisphenol-A type epoxy resin 25085-99-8 > 50%Benzyl alcohol 100-51-6 < 20%Bisphenol-F type epoxy resin 28064-14-4 < 20%4. FIRST AID MEASURESFIRST AID FOR EYES.………………………………………………………… Flush immediately with water for at least 15 minutes. Consult a physician.FIRST AID FOR SKIN.…………………………………………………………… Remove contaminated clothing. Wipe excess from skin. Remove withwaterless skin cleaner and then wash with soap and water. Consult a physician if effects occur.FIRST AID FOR INHALATION.…………………………………………………. Remove to fresh air if effects occur.West System Inc. Page 2 of 4 WEST SYSTEM® 105 ResinMSDS #105-11b Last Revised: 22JUN11FIRST AID FOR INGESTION…………………………………………………… No adverse health effects expected from amounts ingested under normalconditions of use. Seek medical attention if a significant amount is ingested.5. FIRE FIGHTING MEASURESFLASH POINT:…………………………………………………………………. >200°F (Tag Closed Cup)EXTINGUISHING MEDIA: …………………………………………………… Foam, carbon dioxide (CO2), dry chemical.SPECIAL FIRE FIGHTING PROCEDURES: ………………………………. Wear a self-contained breathing apparatus and complete full-body personalprotective equipment. Closed containers may rupture (due to buildup of pressure) when exposed to extreme heat.FIRE AND EXPLOSION HAZARDS: ………………………………………. During a fire, smoke may contain the original materials in addition tocombustion products of varying composition which may be toxic and/or irritating. Combustion products may include, but are not limited to:phenolics, carbon monoxide, carbon dioxide.6. ACCIDENTAL RELEASE MEASURESSPILL OR LEAK PROCEDURES: ………………………………………… Stop leak without additional risk. Dike and absorb with inert material (e.g.,sand) and collect in a suitable, closed container. Warm, soapy water or non-flammable, safe solvent may be used to clean residual.7. HANDLING AND STORAGESTORAGE TEMPERATURE (min./max.): ………………………………… 40°F (4°C) / 120°F (49°C)STORAGE:………………………………………………………………………. Store in cool, dry place. Store in tightly sealed containers to preventmoisture absorption and loss of volatiles. Excessive heat over long periods of time will degrade the resin.HANDLING PRECAUTIONS: ………………………………………………. Avoid prolonged or repeated skin contact. Wash thoroughly after handling.Launder contaminated clothing before reuse. Avoid inhalation of vapors from heated product. Precautionary steps should be taken when curingproduct in large quantities. When mixed with epoxy curing agents this product causes an exothermic, which in large masses, can produce enoughheat to damage or ignite surrounding materials and emit fumes and vapors that vary widely in composition and toxicity.8. EXPOSURE CONTROLS/PERSONAL PROTECTIONEYE PROTECTION GUIDELINES:



………………………………………………. Safety glasses with side shields or chemical splash goggles.SKIN PROTECTION GUIDELINES:…………………………………………… Wear liquid-proof, chemical resistant gloves (nitrile-butyl rubber, neoprene,butyl rubber or natural rubber) and full body-covering clothing.RESPIRATORY/VENTILATION GUIDELINES:……………………………. Good room ventilation is usually adequate for most operations. Wear aNIOSH/MSHA approved respirator with an organic vapor cartridge whenever exposure to vapor in concentrations above applicable limits is likely.Note: West System, Inc. has conducted an air sampling study using this product or similarly formulated products. The results indicate that thecomponents sampled for (epichlorohydrin, benzyl alcohol) were either so low that they were not detected at all or they were significantly belowOSHA's permissible exposure levels.ADDITIONAL PROTECTIVE MEASURES:…………………………………… Practice good caution and personal cleanliness to avoid skin and eyecontact. Avoid skin contact when removing gloves and other protective equipment. Wash thoroughly after handling. Generally speaking, workingcleanly and following basic precautionary measures will greatly minimize the potential for harmful exposure to this product under normal useconditions.OCCUPATIONAL EXPOSURE LIMITS: …………………………………… Not established for product as whole. Refer to OSHA's PermissibleExposure Level (PEL) or the ACGIH Guidelines for information on specific ingredients.9. PHYSICAL AND CHEMICAL PROPERTIESPHYSICAL FORM: ……………………………………………………………… Liquid.COLOR: ………………………………………………………………………………. Clear to pale yellow.ODOR:……………………………………………………………………………………… Mild.BOILING POINT:……………………………………………………………… > 400°F.MELTING POINT/FREEZE POINT:…………………………………………… No data.VISCOSITY:…………………………………………………………………………….. 1,000 cPs.pH: ……………………………………………………………………………… No data.SOLUBILITY IN WATER: ……………………………………………………… Slight.SPECIFIC GRAVITY:……………………………………………………………… 1.15BULK DENSITY: ……………………………………………………………… 9.6 pounds/gallon.VAPOR PRESSURE:……………………………………………………………… < 1 mmHg @ 20°C.VAPOR DENSITY:……………………………………………………………………… Heavier than air.% VOLATILE BY WEIGHT: ……………………………………………………… ASTM D 2369-07 was used to determine the Volatile Content of mixedepoxy resin and hardener. Refer to the hardener's MSDS for information about the total volatile content of the resin/hardener system.10. STABILITY AND REACTIVITYWest System Inc. Page 3 of 4 WEST SYSTEM® 105 ResinMSDS #105-11b Last Revised: 22JUN11STABILITY:……………………………………………………………………… Stable.HAZARDOUS POLYMERIZATION:…………………………………………… Will not occur by itself, but a mass of more than one pound of product plusan aliphatic amine will cause irreversible polymerization with significant heat buildup.INCOMPATIBILITIES: ……………………………………………………………… Strong acids, bases, amines and mercaptans can cause polymerization.DECOMPOSITION PRODUCTS:…………………………………………… Carbon monoxide, carbon dioxide and phenolics may be produced duringuncontrolled exothermic reactions or when otherwise heated to decomposition.11. TOXICOLOGICAL INFORMATIONNo specific oral, inhalation or dermal toxicology data is known for this product. Specific toxicology information for a bisphenol-A basedepoxy resin present in this product is indicated below:Oral:…………………………………………………………LD50 >5000 mg/kg (rats)Inhalation: ……………………………………………………No Data.Dermal: ……………………………………………………LD50 = 20,000 mg/kg (skin absorption in rabbits)TERATOLOGY: ……………………………………………………Diglycidyl ether bisphenol-A (DGEBPA) did not cause birth defects or other adverseeffects on the fetus when pregnant rabbits were exposed by skin contact, the most likely route of exposure, or when pregnant rats or rabbits wereexposed orally.REPRODUCTIVE EFFECTS:…………………………………………DGEBPA, in animal studies, has been shown not to interfere with reproduction.MUTAGENICITY:…………………………………………………………DGEBPA in animal mutagenicity studies were negative. In vitro mutagenicitytests were negative in some cases and positive in others.CARCINOGENICITY:NTP……………………………………………………………………… Product not listed.IARC……………………………………………………………………………… Product not listed.OSHA……………………………………………………………………………… Product not listed.No ingredient of this product present at levels greater than or equal to 0.1% is identified as a carcinogen or potential carcinogen by OSHA,NTP or IARC.Ethylbenzene, present in this product < 0.1%, is not identified by OSHA or NTP as a carcinogen, but is identified by NTP as a Group 2Bsubstance possibly carcinogenic to humans.Many studies have been conducted to assess the potential carcinogenicity of diglycidyl ether of bisphenol-A. Although some weak evidenceof carcinogenicity has been reported in animals, when all of the data are considered, the weight of evidence does not show that DGEBPA iscarcinogenic. Indeed, the most recent review of the available data by the International Agency for Research on Cancer (IARC) hasconcluded that DGEBPA is not classified as a carcinogen.Epichlorohydrin, an impurity in this product (<5 ppm) has been reported to produce cancer in laboratory animals and to produce mutagenicchanges in bacteria and cultured human cells. It has been established by the International Agency for Research on Cancer (IARC) as aprobable human carcinogen (Group 2A) based on the following conclusions: human evidence – inadequate; animal evidence – sufficient. Ithas been classified as an anticipated human carcinogen by the National Toxicology Program (NTP). Note: It is unlikely that normal use ofthis product would result in measurable exposure concentrations to this substance.12. ECOLOGICAL INFORMATIONPrevent entry into sewers and natural waters. May cause localized fish kill.Movement and Partitioning:Bioconcentration potential is moderate (BCF between 100 and 3000 or Log Kow between 3 and 5).Degradation and Transformation:Theoretical oxygen demand is calculated to be 2.35 p/p. 20-day biochemical oxygen demand is <2.5%.Ecotoxicology:Material is moderately toxic to aquatic organisms on an acute basis. LC50/EC50 between 1 and 10 mg/L in most sensitivespecies.13. DISPOSAL CONSIDERATIONSWASTE DISPOSAL METHOD:…………………………………………………… Evaluation of this product using RCRA criteria shows that it is not ahazardous waste, either by listing or characteristics, in its purchased form. It is the responsibility of the user to determine proper disposalmethods.Incinerate, recycle (fuel blending) or reclaim may be preferred methods when conducted in accordance with federal, state and local regulations.West System Inc. Page 4 of 4 WEST SYSTEM® 105 ResinMSDS #105-11b Last Revised: 22JUN1114. TRANSPORTATION INFORMATIONDOTSHIPPING NAME:……………………………………………………………………… Not regulated.TECHNICAL SHIPPING NAME:………………………………………………… Not applicable.D.O.T. HAZARD CLASS: ………………………………………………………… Not applicable.U.N./N.A. NUMBER:……………………………………………………………………… Not applicable.PACKING GROUP:……………………………………………………………………… Not applicable.IATASHIPPING NAME:……………………………………………………………………… Not regulated.TECHNICAL SHIPPING NAME:………………………………………………… Not applicable.HAZARD CLASS:……………………………………………………………………… Not applicable.U.N. NUMBER: …………………………………………………………………… Not applicable.PACKING GROUP:……………………………………………………………………… Not applicable.15. REGULATORY INFORMATIONOSHA STATUS: …………………………………………………………………… Slight irritant; possible sensitizer.TSCA STATUS:………………………………………………………………………… All components are listed on TSCA inventory or otherwise comply withTSCA requirements.Canada WHIMIS Classification:……………………………………………… D2BSARA TITLE III:SECTION 313 TOXIC CHEMICALS …………………………………… None (deminimus).STATE REGULATORY INFORMATION:The following chemicals are specifically listed or otherwise regulated by individual states. For details on your regulatory requirements you shouldcontact the appropriate agency in your state.COMPONENT NAME/CAS NUMBER CONCENTRATION STATE CODEEpichlorohydrin106-89-8 < 5ppm1CAPhenyl glycidyl ether122-60-1 <5ppm1CAEthylbenzene100-41-4 < 0.1%1CA, NJ, PABenzyl alcohol100-51-6 < 20% MA, PA, NJ1.These substances are known to the state of California to cause cancer or reproductive harm, or both.16. OTHER INFORMATIONREASON FOR ISSUE:…………………………………………………………………. Changes made in Sections 10, 11, 14 & 15.PREPARED BY:…………………………………………………………………………. G. M. HouseAPPROVED BY:…………………………………………………………………………. G. M. HouseTITLE: ……………………………………………………………………………………. Health, Safety & Environmental ManagerAPPROVAL DATE: ………………………………………………………………… June 22, 2011SUPERSEDES DATE:………………………………………………………………….. February 6, 2011MSDS NUMBER:…………………………………………………………………………. 105-11bNote: The Hazardous Material Indexing System (HMIS), cited in the Emergency Overview of Section 3, uses the following index to assess hazardrating: 0 = Minimal; 1 = Slight: 2 = Moderate; 3 = Serious; and 4 = Severe.This information is furnished without warranty, expressed or implied, except that it is accurate to the best knowledge of West System Inc. The data onthis sheet is related only to the specific material designated herein. West System Inc. assumes no legal responsibility for use or reliance upon thesedata. MATERIAL SAFETY DATA SHEET West System Inc. MSDS #205-11a Last Revised: 10FEB11 1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION PRODUCT NAME: ……………………………………….WEST SYSTEM® 205 Fast Hardener®PRODUCT CODE: ……………………………………….205 CHEMICAL FAMILY: …………………………………….Amine. CHEMICAL NAME:……………………………………….Modified aliphatic polyamine. FORMULA: ………………………………………………….Not applicable. MANUFACTURER: EMERGENCY TELEPHONE NUMBERS:West System Inc. Transportation 102 Patterson Ave. CHEMTREC: …………………800-424-9300 (U.S.) Bay City, MI 48706, U.S.A. 703-527-3887 (International) Phone: 866-937-8797 or 989-684-7286 Non-transportation www.westsystem.com Poison Hotline: ………………800-222-1222 2. HAZARDS IDENTIFICATION EMERGENCY OVERVIEW HMIS Hazard Rating: Health - 3 Flammability - 1 Physical Hazards - 0DANGER! Corrosive. Skin sensitizer. Moderate to severe skin, eye and respiratory tract irritant. May cause allergic reactions. Amber colored liquid with ammonia odor. PRIMARY ROUTE(S) OF ENTRY:………………………………………………… Skin contact, eye contact, inhalation. POTENTIAL HEALTH EFFECTS:ACUTE INHALATION: ……………………………………………………………… May cause respiratory tract irritation. Coughing and chest pain may result. CHRONIC INHALATION:……………………………………………………………… May cause respiratory tract irritation, coughing, sore throat, shortness of breath or chest pain. ACUTE SKIN CONTACT: ………………………………………………………………… May cause strong irritation, redness. Possible mild corrosion. CHRONIC SKIN CONTACT:……………………………………………………………… Prolonged or repeated contact may cause an allergic reaction and possible sensitization in susceptible individuals. Large dose skin contact may result in material being absorbed in harmful amounts. EYE CONTACT:………………………………………………………………………… Moderate to severe irritation with possible tissue damage. Concentrated vapors can be absorbed in eye tissue and cause eye injury. Contact causes discomfort and possible corneal injury or conjunctivitis.

INGESTION:……………………………………………………………………………………… Single dose oral toxicity is moderate. May cause gastrointestinal tract irritation and pain. Aspiration hazard. SYMPTOMS OF OVEREXPOSURE:…………………………………………………… Respiratory tract irritation. Skin irritation and redness. Possible allergic reaction seen as hives and rash. Eye irritation. Possible liver and kidney disorders upon long term skin absorption overexposures. MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE:……………… Chronic respiratory disease, asthma. Eye disease. Skin disorders and allergies. 3. COMPOSITION/INFORMATION ON HAZARDOUS INGREDIENTS INGREDIENT NAME CAS # CONCENTRATIONReaction products of TETA with Phenol/Formaldehyde 32610-77-8 > 25% Polyethylenepolyamine 68131-73-7 < 25% Triethylenetetramine (TETA) 112-24-3 < 10% Hydroxybenzene 108-95-2 < 10% Reaction Products of TETA and propylene oxide 26950-63-0 < 10% Tetraethylenepentamine (TEPA) 112-57-2 < 10% 4. FIRST AID MEASURESFIRST AID FOR EYES:………………………………………………………………… Immediately flush with water for at least 15 minutes. Get prompt medical attention. FIRST AID FOR SKIN:…………………………………………………………………… Remove contaminated clothing. Immediately wash skin with soap and water. Do not apply greases or ointments. Get medical attention if severe exposure. West System Inc. Page 2 of 4 WEST SYSTEM® 205 Hardener MSDS #205-11a Last Revised: 10FEB11 FIRST AID FOR INHALATION:…………………………………………………… Move to fresh air and consult physician if effects occur. FIRST AID FOR INGESTION:……………………………………………………… Give conscious person at least 2 glasses of water. Do not induce vomiting. Aspiration hazard. If vomiting should occur spontaneously, keep airway clear. Get medical attention. 5. FIRE FIGHTING MEASURESFLASH POINT:……………………………………………………………………… >270°F (PMCC) EXTINGUISHING MEDIA:…………………………………………………………… Dry chemical, alcohol foam. carbon dioxide (CO2), dry sand, limestone powder. FIRE AND EXPLOSION HAZARDS: …………………………………………… During a fire, smoke may contain the original materials in addition to combustion products of varying composition which may be toxic and/or irritating. Combustion products may include, but are not limited to: oxides of nitrogen, carbon monoxide, carbon dioxide, volatile amines, ammonia, nitric acid, nitrosamines. When mixed with sawdust, wood chips, or other cellulosic material, spontaneous combustion can occur under certain conditions. If hardener is spilled into or mixed with sawdust, heat is generated as the air oxidizes the amine. If the heat is not dissipated quickly enough, it can ignite the sawdust. SPECIAL FIRE FIGHTING PROCEDURES:……………………………… Use full-body protective gear and a self-contained breathing apparatus. Use of water may generate toxic aqueous solutions. Do not allow water run-off from fighting fire to enter drains or other water courses. 6. ACCIDENTAL RELEASE MEASURES SPILL OR LEAK PROCEDURES:…………………………………………………… Stop leak without additional risk. Wear proper personal protective equipment. Dike and contain spill. Ventilate area. Large spill - dike and pump into appropriate container for recovery. Small spill - recover or use inert, non-combustible absorbent material (e.g., sand, clay) and shovel into suitable container. Do not use sawdust, wood chips or other cellulosic materials to absorb the spill, as the possibility for spontaneous combustion exists. Wash spill residue with warm, soapy water if necessary. 7. HANDLING AND STORAGESTORAGE TEMPERATURE (min./max.):………………………………… 40°F (4°C) / 90°F (32°C). STORAGE:……………………………………………………………………………… Store in cool, dry place away from high temperatures and moisture. Keep container tightly closed. HANDLING PRECAUTIONS:…………………………………………………………… Use with adequate ventilation. Do not breath vapors or mists from heated material. Avoid exposure to concentrated vapors. Avoid skin contact. Wash thoroughly after handling. When mixed with epoxy resin this product causes an exothermic reaction, which in large masses, can produce enough heat to damage or ignite surrounding materials and emit fumes and vapors that vary widely in composition and toxicity 8. EXPOSURE CONTROLS/PERSONAL PROTECTION EYE PROTECTION GUIDELINES:…………………………………………… Chemical splash-proof goggles or face shield. SKIN PROTECTION GUIDELINES:…………………………………………… Wear liquid-proof, chemical resistant gloves (nitrile-butyl rubber, neoprene, butyl rubber or natural rubber) and full body-covering clothing. RESPIRATORY/VENTILATION GUIDELINES: ……………………………… Use with adequate general and loca exhaust ventilation to meet exposure limits. In poorly ventilated areas, use a NIOSH/MSHA approved respirator with ar organic vapor cartridge. Note: West System, Inc. has conducted an air sampling study using this product or similarly formulated products. The results indicate that the components sampled for (phenol, formaldehyde and amines) were either so low that they were not detected at all or they were well below OSHA's permissible exposure levels. ADDITIONAL PROTECTIVE MEASURES:…………………………………… Use where there is immediate access to safety shower and emergency eye wash. Wash thoroughly after use. Contact lens should not be worn when working with this material. Generally speaking, working cleanly and following basic precautionary measures will greatly minimize the potential for harmful exposure to this product under normal use conditions. OCCUPATIONAL EXPOSURE LIMITS: ……………………………………… Not established for product as whole. Refer to OSHA's Permissible Exposure Level (PEL) or the ACGIH Guidelines for information on specific ingredients. 9. PHYSICAL AND CHEMICAL PROPERTIES PHYSICAL FORM……………………………………………………………………… Liquid. COLOR ……………………………………………………………………………………… Amber. ODOR……………………………………………………………………………………… Ammonia-like. BOILING POINT………………………………………………………………………… > 440°F. MELTING POINT/FREEZE POINT……………………………………………… Approximately 23°F. pH ……………………………………………………………………………………… Alkaline. SOLUBILITY IN WATER………………………………………………………………… Appreciable. SPECIFIC GRAVITY ………………………………………………………………… 1.05 West System Inc. Page 3 of 4 WEST SYSTEM® 205 Hardener MSDS #205-11a Last Revised: 10FEB11 BULK DENSITY……………………………………………………………………… 8.85 pounds/gallon. VAPOR PRESSURE ………………………………………………………………… < 1 mmHg @ 20°C. VAPOR DENSITY …………………………………………………………………… Heavier than air. VISCOSITY ……………………………………………………………………………… 1,000 cPs% VOLATILE BY WEIGHT………………………………………………………… ASTM 2369-07 was used to determine the Volatile Matter Content of mixed epoxy resin and hardener. 105 Resin and 205 Hardener, mixed together at 5:1 by weight, has a density of 1137 g/L (9.49 lbs/gal). The combined VOC content for 105/205 is 7.91 g/L (0.07 lbs/gal). 10. STABILITY AND REACTIVITYSTABILITY:…………………………………………………………………………… Stable. HAZARDOUS POLYMERIZATION:……………………………………………… Will not occur. INCOMPATIBILITIES:.………………………………………………………………… Avoid excessive heat. Avoid acids, oxidizing materials, halogenated organic compounds (e.g., methylene chloride). External heating or self-heating could result in rapid temperature increase and serious hazard. If such a reaction were to take place in a waste drum, the drum could expand and rupture violently. DECOMPOSITION PRODUCTS:……………………………………………… Very toxic fumes and gases when burned or otherwise heated to decomposition. Decomposition products may include, but not liminted to: oxides of nitrogen, volatile amines, ammonia, nitric acid, nitrosamines. 11. TOXICOLOGICAL INFORMATIONNo specific oral, inhalation or dermal toxicology data is known for this product. Oral: ……………………………………………………………Expected to be moderately toxic. Inhalation:………………………………………………………Expected to be moderately toxic. Dermal:…………………………………………………………Expected to be moderately toxic. Adsorption of phenolic solutions through the skin may be very rapid and can cause death. Lesser exposures can cause damage to the kidney, liver, pancreas and spleen; and cause edema of the lungs. Chronic exposures can cause death from liver and kidney damage. CARCINOGENICITY:NTP……………………………………………………………………………… No. IARC ……………………………………………………………………………………… No. OSHA……………………………………………………………………………………… No. No ingredient of this product present at levels greater than or equal to 0.1% is identified as a carcinogen or potential carcinogen by OSHA, NTP or IARC. 12. ECOLOGICAL INFORMATION Wastes from this product may present long term environmental hazards. Do not allow into sewers, on the ground or in any body of water. Hydroxybenzene (phenol) (CAS # 108-95-2) biodegradability = 99.5% at 7 days. 13. DISPOSAL CONSIDERATIONS WASTE DISPOSAL METHOD:…………………………………………………… Evaluation of this product using RCRA criteria shows that it is not a hazardous waste, either by listing or characteristics, in its purchased form. It is the responsibility of the user to determine proper disposal methods. Incinerate, recycle (fuel blending) or reclaim may be preferred methods when conducted in accordance with federal, state and local regulations. 14. TRANSPORTATION INFORMATION DOT SHIPPING NAME:…………………………………………………………………… Polyamines, liquid, corrosive, n.o.s. TECHNICAL SHIPPING NAME:……………………………………………………… (Triethylenetetramine) D.O.T. HAZARD CLASS: ……………………………………………………………… Class 8 U.N./N.A. NUMBER:……………………………………………………………………… UN 2735 PACKING GROUP: ………………………………………………………………… PG III IATA SHIPPING NAME:…………………………………………………………………… Polyamines, liquid, corrosive, n.o.s. TECHNICAL SHIPPING NAME:……………………………………………………… (Triethylenetetramine) HAZARD CLASS:…………………………………………………………………… Class 8 U.N. NUMBER:……………………………………………………………………………… UN 2735 PACKING GROUP:

…………………………………………………………………… PG III 15. REGULATORY INFORMATIONOSHA STATUS:…………………………………………………………………………… Corrosive; possible sensitizer. West System Inc. Page 4 of 4 WEST SYSTEM® 205 Hardener MSDS #205-11a Last Revised: 10FEB11 TSCA STATUS:……………………………………………………………………………. All components listed on TSCA inventory or otherwise comply with TSCA requirements. Canada WHIMIS Classification: D2A, D2B, E SARA TITLE III:SECTION 313 TOXIC CHEMICALS:……………………………………… This product contains hydroxybenzene (phenol) and is subject to the reporting requirements of Section 313 of Title III of the Superfund Amendments and Reauthorization Act of 1986 and 40 CFR Part 372. STATE REGULATORY INFORMATION:The following chemicals are specifically listed or otherwise regulated by individual states. For details on your regulatory requirements you should contact the appropriate agency in your state. COMPONENT NAME /CAS NUMBER CONCENTRATION STATE CODETetraethylenepentamine 112-57-2 <10% MA, NJ, PA Tetraethylenetriamine 112-24-3 <10% MA, NJ, PA Phenol 108-95-2 <10% NJ, RI, PA, MA, IL 16. OTHER INFORMATIONREASON FOR ISSUE:………………………………………………………………… Changes made in Sections 5, 10, 14 & 15. PREPARED BY: ……………………………………………………………………………. G. M. House APPROVED BY: ……………………………………………………………………… G. M. House TITLE: ……………………………………………………………………………………… Health, Safety & Environmental Manager APPROVAL DATE:……………………………………………………………………… February 10, 2011 SUPERSEDES DATE: ……………………………………………………………………. January 3, 2008 MSDS NUMBER: ……………………………………………………………………… 205-11a Note: The Hazardous Material Indexing System (HMIS), cited in the Emergency Overview of Section 3, uses the following index to assess hazard rating: 0 = Minimal; 1 = Slight; 2 = Moderate; 3 = Serious; and 4 = Severe. This information is furnished without warranty, expressed or implied, except that it is accurate to the best knowledge of West System Inc. The data on this sheet is related only to the specific material designated herein. West System Inc. assumes no legal responsibility for use or reliance upon these data.

APPENDIX F-Material Assignment

Team 6 analyzed the shafts, gearbox and finger guards in both CES and SimaPro. From this analysis they were able to determine the ideal material, manufacturing process and environmental effects of each component, described below.

Functional Performance

Shafts

The shafts must be strong and stiff to effectively transfer rotational momentum from the input shaft to the output shaft. Strength is usually measured by yield strength, σ, and stiffness is measured via Young's Modulus, E. The stiffness of the shafts is affected by the applied force, F, and the area the force is applied to, A_0, shown in Equation F.1. The Young's Modulus is dependent on the yield strength, σ, the amount of elongation, dl, and the original length, l, shown in Equation F.2. One of the objectives of the project is to minimize the weight of the total gear reduction, therefore, the density, ρ, of the shafts should be considered to minimize weight. The density depends on the mass, m, and the volume, V, shown in Equation F.3.

$$\sigma = \frac{F}{A_0} \qquad \text{Equation F.1}$$

$$E = \frac{\sigma}{dl/l} \qquad \text{Equation F.2}$$

$$\rho = m/V \qquad \text{Equation F.3}$$

A summary of the function, objectives, and constraints is shown below in Table F.1.

Table F1: Shaft Summary

Function:	Support the gears and transfer rotation momentum
Constraints:	Hard Constraints → Strong and Stiff Strength Properties: σ >45 ksi Stiffness Properties: E>10 $*10^6$ psi Density: ρ <650 lb/ft^3 Soft Constraints → Cost Cost: C<$2 USD/lb
Objectives:	Maximize Yield Strength Maximize Young's Modulus Minimize Density Minimize Price

Using the CES software, two graphs were plotted. The first is a graph of Young's Modulus versus the density of the material, which is shown in Figure F.1 on Page 76. The second graph shows the yield strength versus the density of the material, which is shown in Figure F.2 on below.

Figure F.1: Graph developed using Ashby method to determine a material for the shafts by evaluating Young's Modulus (10^6 psi) and the density of the material (lb/ft^3).

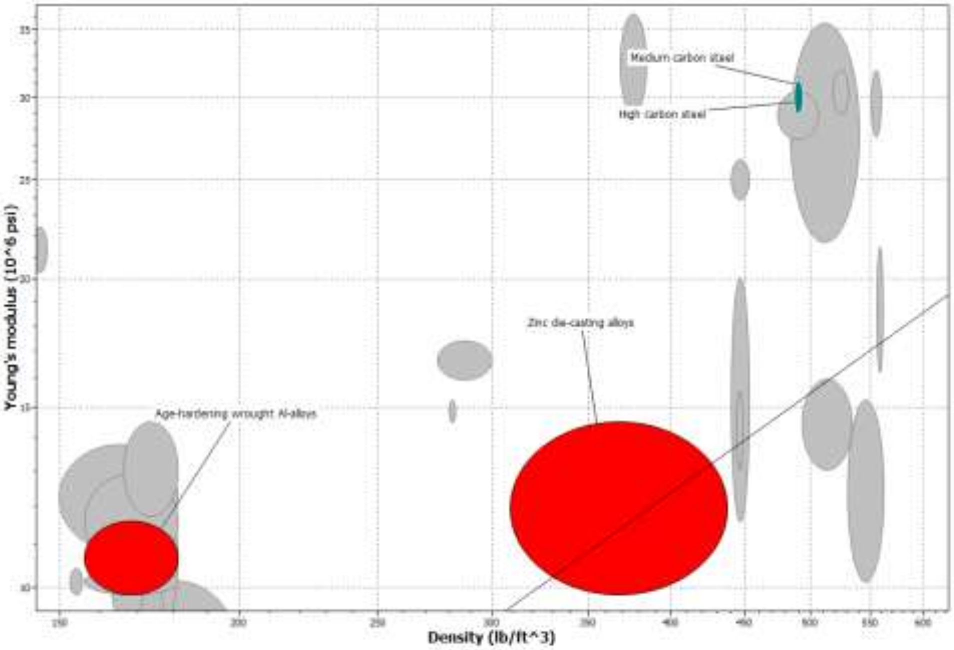
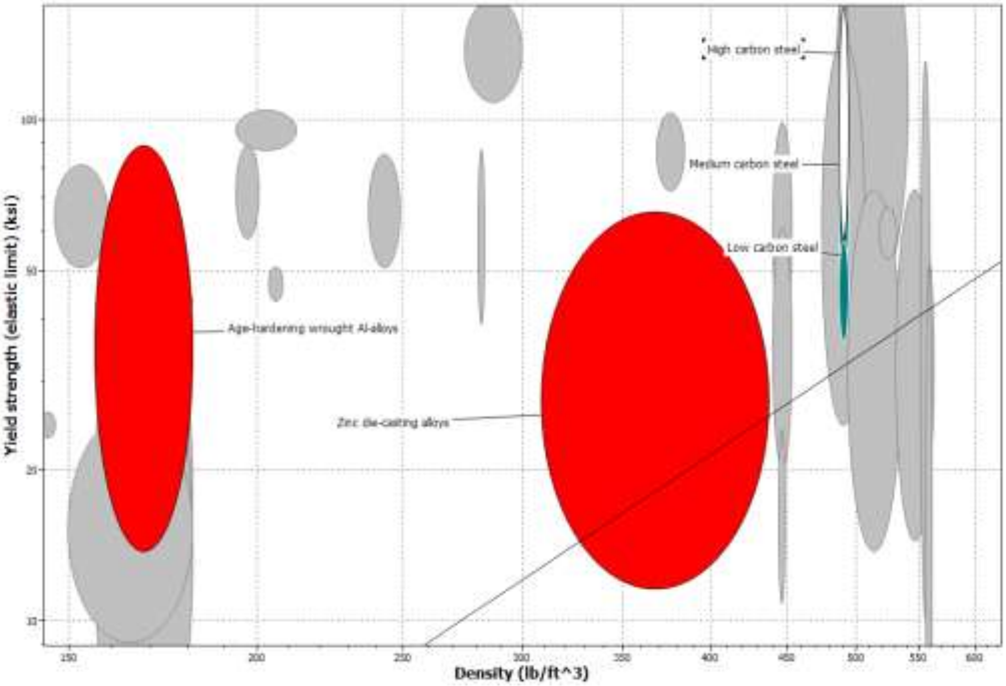


Figure F.2: Graph developed using Ashby method to determine a material for the shafts by evaluating yield strength (10^6 psi) and the density of the material (lb/ft^3).



From these two graphs five materials were identified:

Material	σ (ksi)	E (10^6 psi)	ρ (lb/ft^3)	C (USD/lb)
Age-hardening wrought Al-alloys	13.8-88.5	9.86-11.6	156-181	1.07-1.17
High carbon steel	**58-168**	**29-31.2**	**487-493**	**.345-.79**
Low carbon steel	36.3-57.3	29-31.2	487-493	.303-.334
Medium carbon steel	44.2-131	29-31.3	487-493	0.321-0.353
Zinc die-casting alloys	11.6-65.3	9.86-14.5	309-437	1.1-1.21

High carbon steel has the highest young’s modulus and yield strength so it was chosen for the shafts.

Gearbox

Since the gearbox supports the shafts, many of the properties that affect the shafts also affect the gearbox. There are lower forces on the gearbox therefore, Young’s Modulus and yield strength are lower. The gearbox is larger than the shafts so the density affects the weight of the gearbox more, therefore the maximum density was lowered. Table F.2 provides a summary of the function, objectives, and constraints.

Table F.2: Gearbox summary

Function:	Support the shafts and serve as an attachment point for the car to the gearbox
Constraints:	Hard Constraints → Strong and Stiff Strength Properties: σ > 40 ksi Stiffness Properties: E> 15*10^6 psi Density: ρ < 450 lb/ft^3 Soft Constraints → Cost Cost: C<$5 USD/lb
Objectives:	Maximize Yield Strength Maximize Young’s Modulus Minimize Density Minimize Price

Using the CES software, the same graphs as the shafts the assessments were plotted, in Figures F.3 and F.4 on Page 78.

Figure F.3: Graph developed using Ashby method to determine a material for the gearbox by evaluating Young's Modulus (10^6 psi) and the density of the material (lb/ft^3).

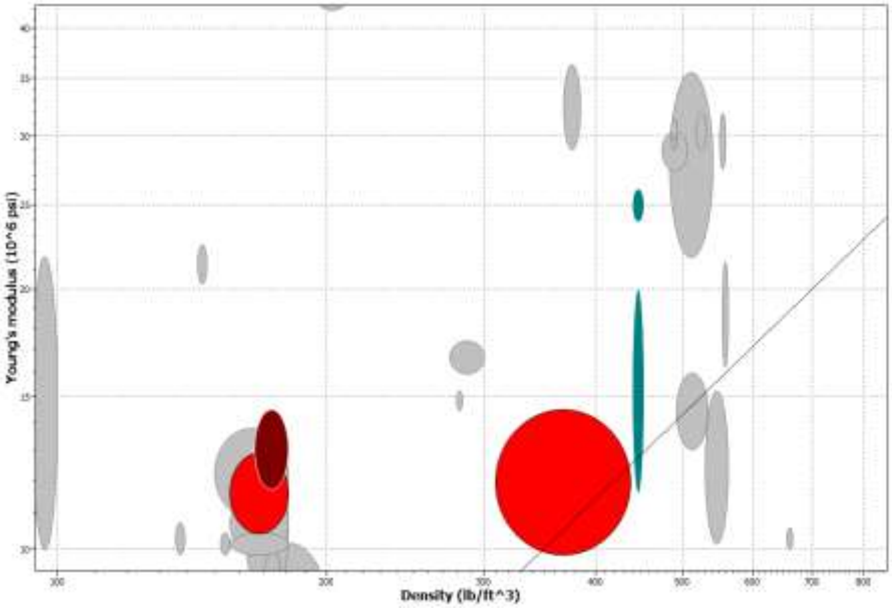
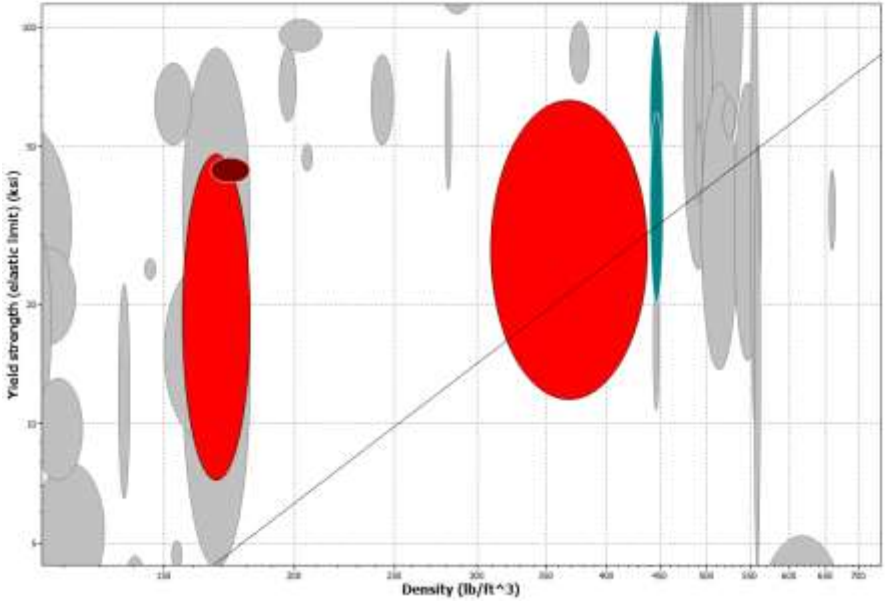


Figure F.4: Graph developed using Ashby method to determine a material for the gearbox by evaluating yield strength (10^6 psi) and the density of the material (lb/ft^3).



From these two graphs and material constraints five materials were identified:

Material	σ (ksi)	E (10^6 psi)	ρ (lb/ft^3)	C (USD/lb)
Aluminum/Silicon Carbide Composite	40.6-47	11.7-14.5	166-181	2.82-3.76
Cast Al-alloys	**7.25-47.9**	**10.4-12.9**	**156-181**	**1.11-1.22**
Cast iron, ductile (nodular)	36.3-98.6	23.9-26.1	440-453	.295-.324
Cast iron, gray	20.3-60.9	11.6-20	440-453	.258-.284
Zinc die-casting alloys	11.6-65.3	9.86-14.5	309-437	1.1-1.21

Team 6 decided to use cast Al-Alloys due to the very low density and relatively low cost.

Finger Guards

The finger guards contain a lubricant in the gearbox and prevent any objects from getting into the gearbox. Therefore, the finger guards needed to be molded to integrate well into the complex geometry of the gearbox. Moldability is measured on a scale from one to five in CES. These figure guards should not see any forces, so the yield strength is not a constraint; however, the finger guards need to be stiff so that they do not deform, to the point where they interfere with the gears.

Table F.3: Finger Guards Summary

Function:	Maintain separation between the environment inside and outside the gearbox
Constraints:	Hard Constraints → Stiffness and Mold Stiffness Properties: E> $0.5*10^6$ psi Moldability: M > 4 Soft Constraints → \$ Cost ρ < 120 lb/ft^3 Cost: C<10 \$USD/lb
Objectives:	Maximize Young's Modulus Maximize Moldability Minimize Density Minimize Price

Figure F.5: Graph developed using Ashby method to determine a material for the finger guards by evaluating Young's Modulus (10^6 psi) and the density of the material (lb/ft^3).

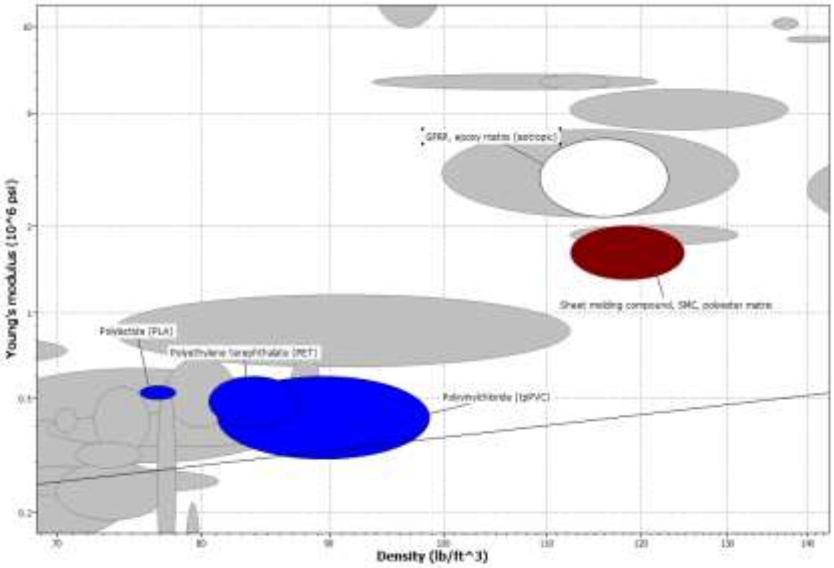
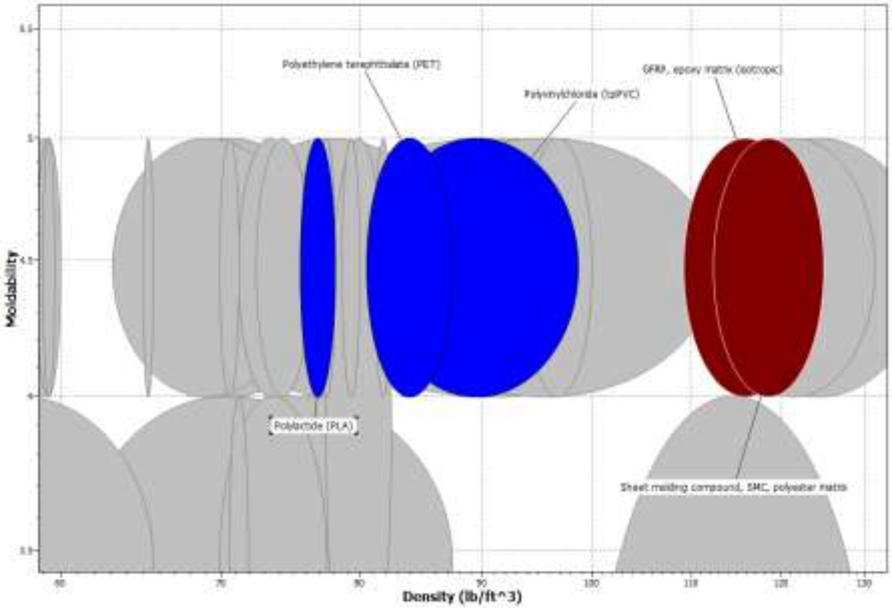


Figure F.6: Graph developed using Ashby method to determine a material for the finger guards by evaluating moldability and the density of the material (lb/ft^3).



From these graphs five materials were identified:

Material	E (10^6 psi)	M	ρ (lb/ft^3)	C (USD/lb)
GFRP, epoxy matrix (isotropic)	**2.18-1.06**	**4-5**	**109-123**	**8.8-9.71**
Polyethylene terephthalate (PET)	0.4-0.6	4-5	80.5-87.4	0.748-0.826
Polylactide (PLA)	0.5-0.555	4-5	75.5-78	1.1-1.21
Polyvinylchloride (tpPVC)	0.31-0.6	4-5	81.2-98.6	0.608-0.667
Sheet molding compound, SMC, polyester matrix	1.31-2.03	4-5	112-125	2.43-2.67

Team 6 chose an epoxy matrix due to the high stiffness. The epoxy matrix is denser and more expensive compared to the other options. However, epoxy finger guards are easier to manufacture, as the team is only creating one gearbox. If it was mass produced then PLA would be the best option.

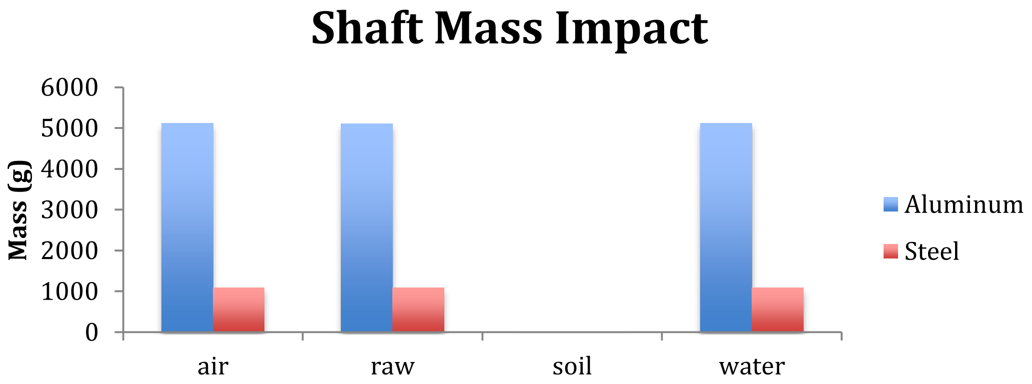
Environmental Performance

When placing a product into mass manufacturing a major concept to consider when choosing materials is the effect that production will have on the environment. Many states have environmental requirements, and if the company chooses a more toxic material, it could lead to more costs in the long run. Therefore, when discussing a certain part’s material in mass production it is important to consider multiple options, in order to choose the most environmental and cost efficient material.

Shafts

The first component that was analyzed was the shaft material. The materials compared in Simapro were aluminum alloy and steel. Figure F.7 demonstrates that the aluminum has a larger mass impact for the environment than steel in all of the mass categories except for soil, but this is a minor amount compared to the other environmental categories.

Figure F.7: The mass impact of shafts when using aluminum or steel for the environment shows that aluminum was much worse compared to steel



When looking at the normalization in Figure F.9 and the inventory values in Figure F.8, one can see that the that the aluminum alloy is worse in every environmental category. This is due to the process in which the alloy is manufactured and the need to get the aluminum from the raw form of bauxite. This is why the fossil fuels and inorganic environmental damage are the largest problems when the values are normalized against each other.

Figure F.8: The inventory figure shows that aluminum is much worse percentage wise than steel.

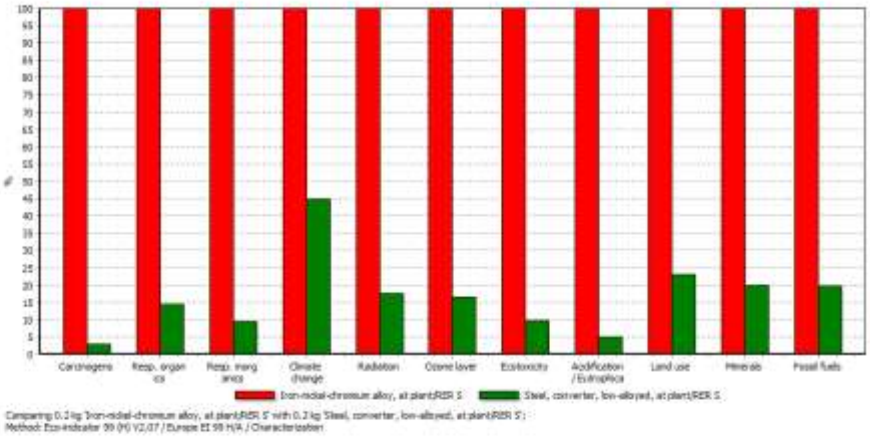


Figure F.9: The normalized values shows that the inorganic and carcinogins are the worse categories for aluminum

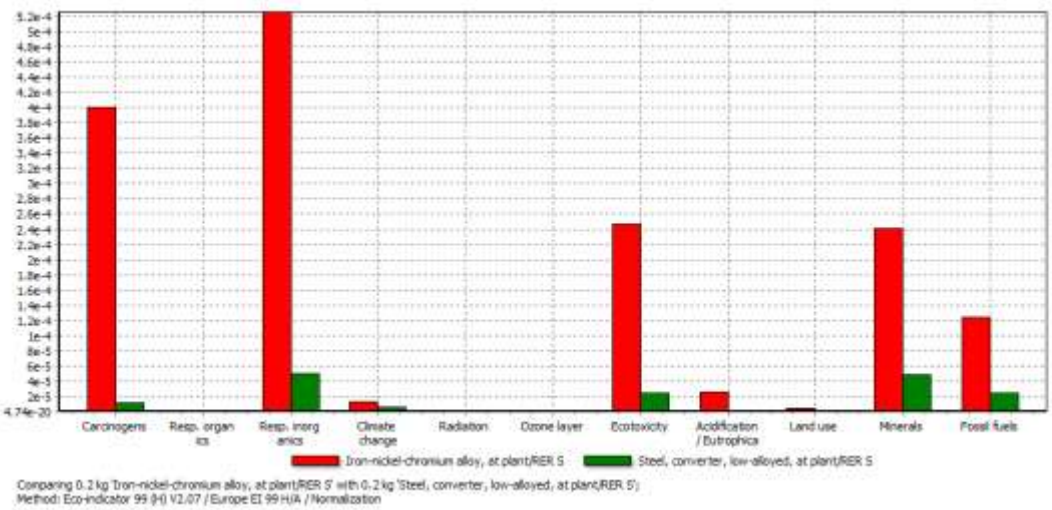
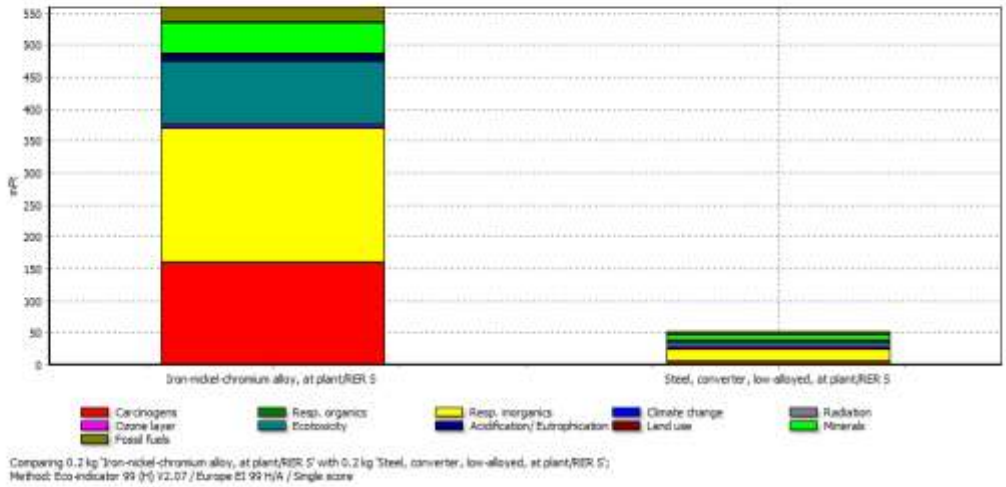


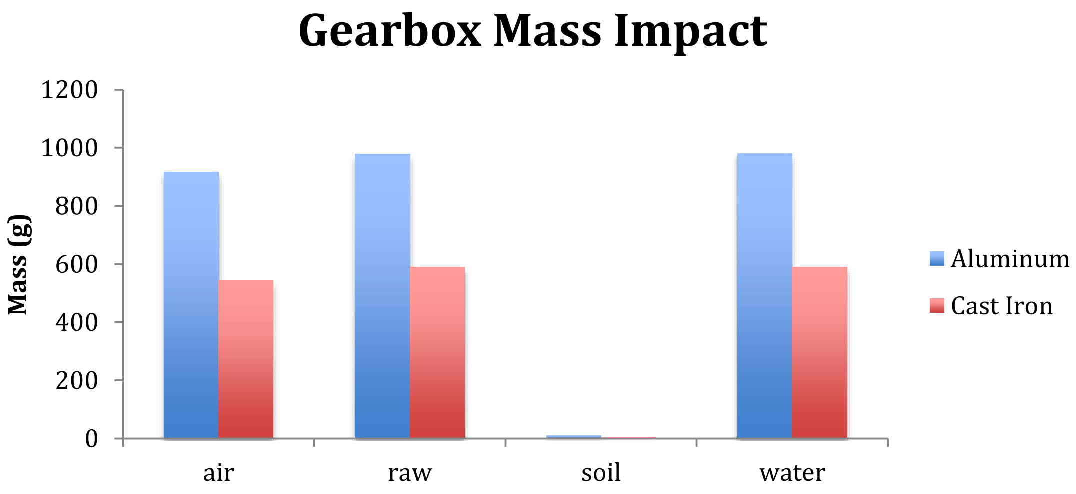
Figure F.10: The sum or single point values show that aluminum is 10 times worse for the environment than steel



Gearbox

The second component that was analyzed was the gearbox material. The closest materials chosen in Simapro were an aluminum alloy and cast iron. Figure F.11 demonstrates that the aluminum has a larger mass impact for the environment than cast iron in all of the mass categories affecting product manufacturing.

Figure F.11: The mass impact of gearbox when using aluminum or cast iron for the environment shows that aluminum was much worse compared to cast iron.



When looking at the inventory values in Figure F.12 and the normalization in Figure F.13, one can see that the that the aluminum alloy is worse in every environmental category, affecting eco-toxicity and human health. This is due to the process in which the alloy is manufactured and the need to get the aluminum from the raw form of bauxite. Therefore, the fossil fuels and inorganic environmental damage are the largest problems when the values are normalized against each other.

Figure F.12: The inventory figure shows that aluminum is worse for the environment in every category.

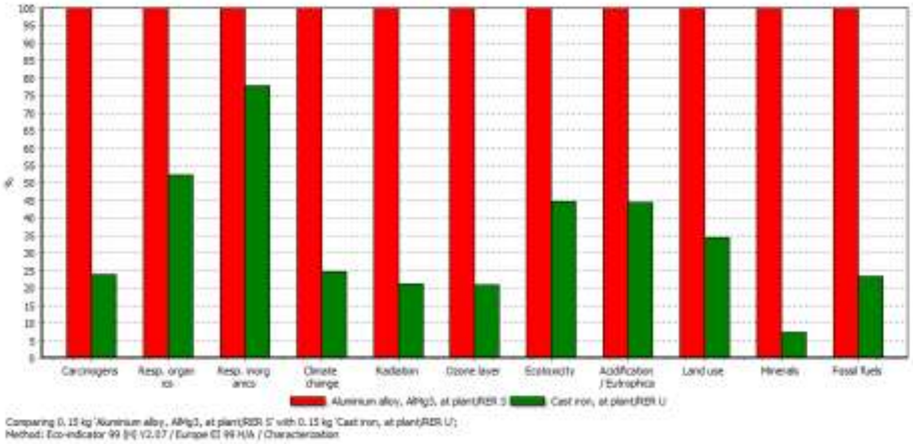
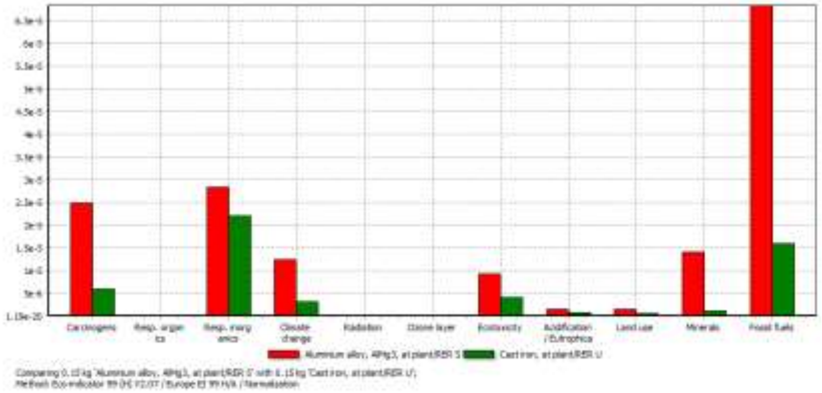
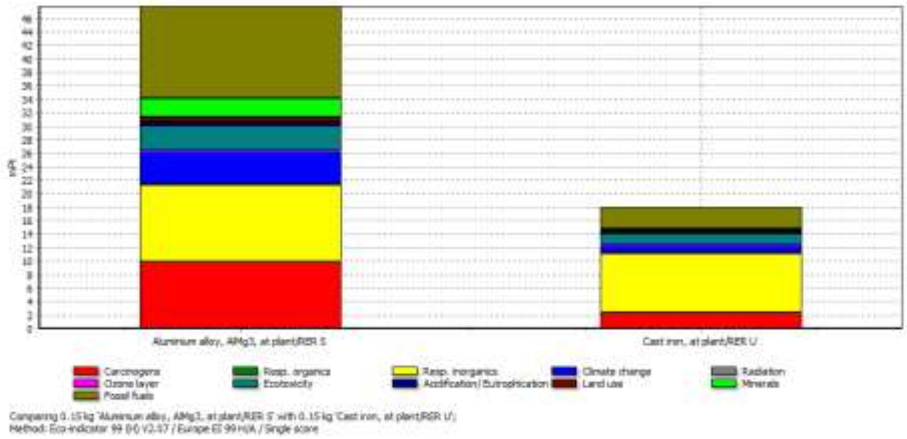


Figure F.13: The normalized values shows that the inorganic and carcinogins are the worse categories for aluminum



The team then looked at the single point values, shown in Figure F.14, to determine which material creates a higher sum of its environmental impact. From Figure F.14, one can see that the aluminum alloy has a much larger sum and is therefore much worse for the environment.

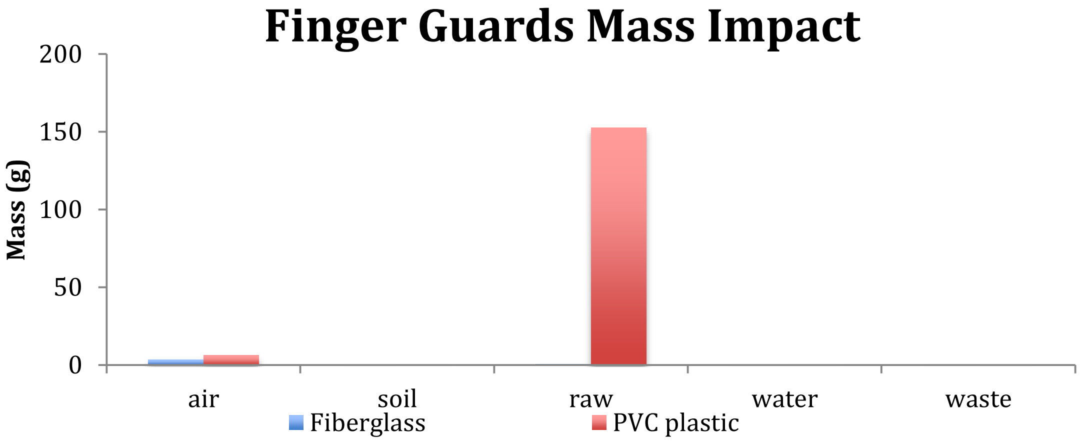
Figure F.14: The sum or single point values show that aluminum is 10 times worse for the environment than cast iron



Finger Guards

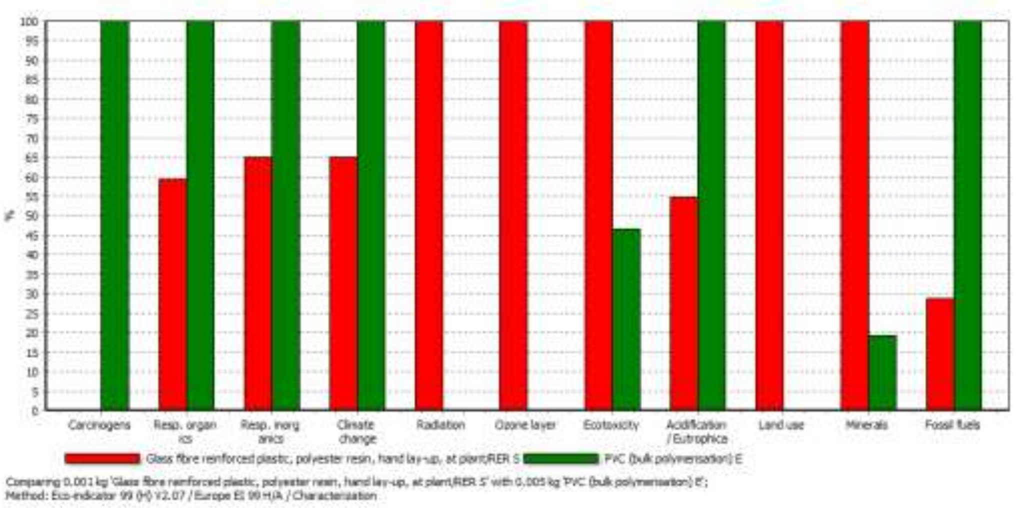
The final component that was analyzed was the finger guards. The closest materials that were found in Simapro were a hand lay-up fiberglass and PVC plastic. Figure F.15 shows that PVC plastic has a large ecological impact in terms of raw mass. When looking at the calculated mass values the only term that PVC had less of an environmental impact was soil.

Figure F.15: The mass impact of the finger guards when using fiberglass and PVC for the environmental impact, shows that PVC is much worse than fiberglass



The team then analyzed the sum, also known as single point, of each of the materials in order to compare the overall environmental impact. By examining Figure F.16, one can see that PVC is much worse for the environment than fiberglass. The carcinogens created while producing the material make it very destructive to the environment along with the large amount of fossil fuels that need to be used for raw materials in order to create a minimal amount of product, as seen in Figure F.17. The overall impact of PVC is over 20 times worse than fiberglass as seen from the single point graph, Figure F.18. Therefore, when looking at the materials the most important factor to focus on is human health factor in relation to the carcinogens.

Figure F.16: The normalized values shows that each material has its weaknesses and strengths in from the release of toxins by the manufacturing process.



Comparing 0.001 kg 'Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER S' with 0.005 kg 'PVC (bulk polymerisation) E';
Method: Eco-indicator 99 (H) V2.07 / Europe EI 99 H/A / Characterisation

Figure F.17: The sum or single point values show that PVC is 20 times worse for the environment than cast iron

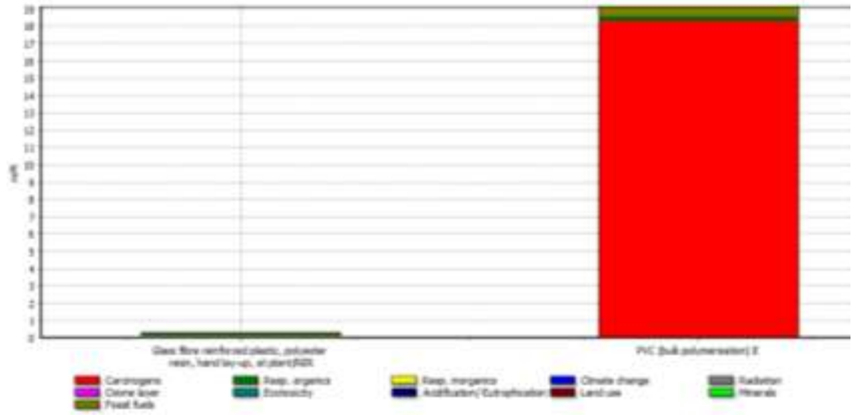
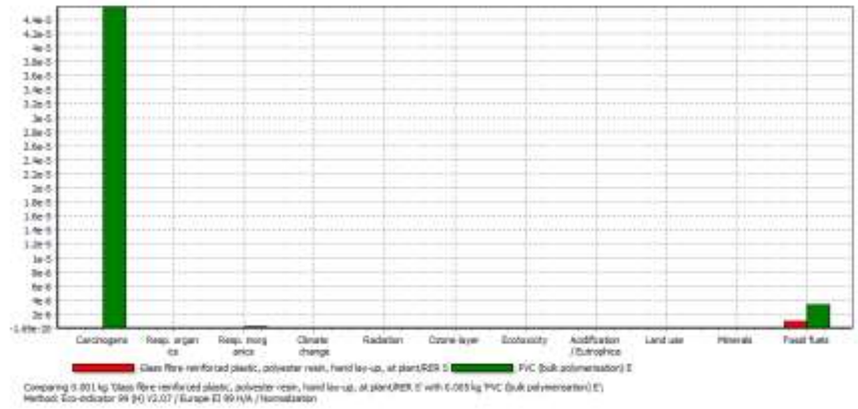


Figure F.18: The figure shows that carcinogens produced by manufacturing PVC outweigh any toxin made in the manufacturing process



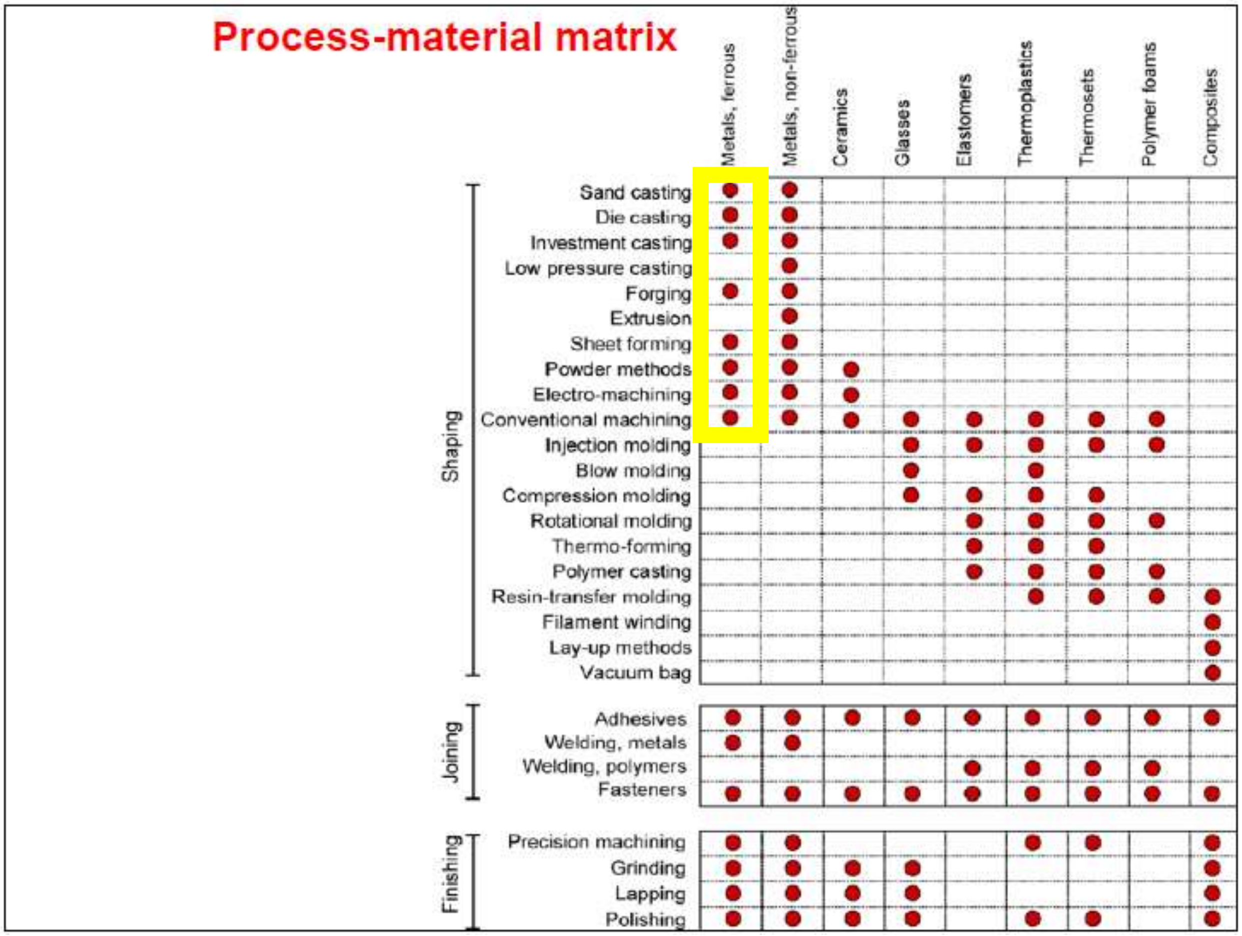
Manufacturing Process

Unlike other projects that could be created for users other than the sponsor, Team 6's product is neither a prototype nor intended for a production volume of more than one. As mentioned, the Baja SAE Team is a student team that redesigns a single vehicle each year. At competition, however, they are assessed on the assumption that their design will be produced at a production volume of 5,000. Based on this competition aspect, Team 6 will complete their manufacturing process selection based on a production volume of 5,000.

Shafts

CES Manufacturing process selector narrows possible machining processes using a series of charts that account for characteristics of the part being manufactured. The first component Team 6 analyzed using the CES Materials Selector was the shafts. Made from high carbon steel, a ferrous metal, this material selection limits the practical manufacturing possibilities in the Figure F.19 seen below.

Figure F.19: Shaft manufacturing process selection material matrix

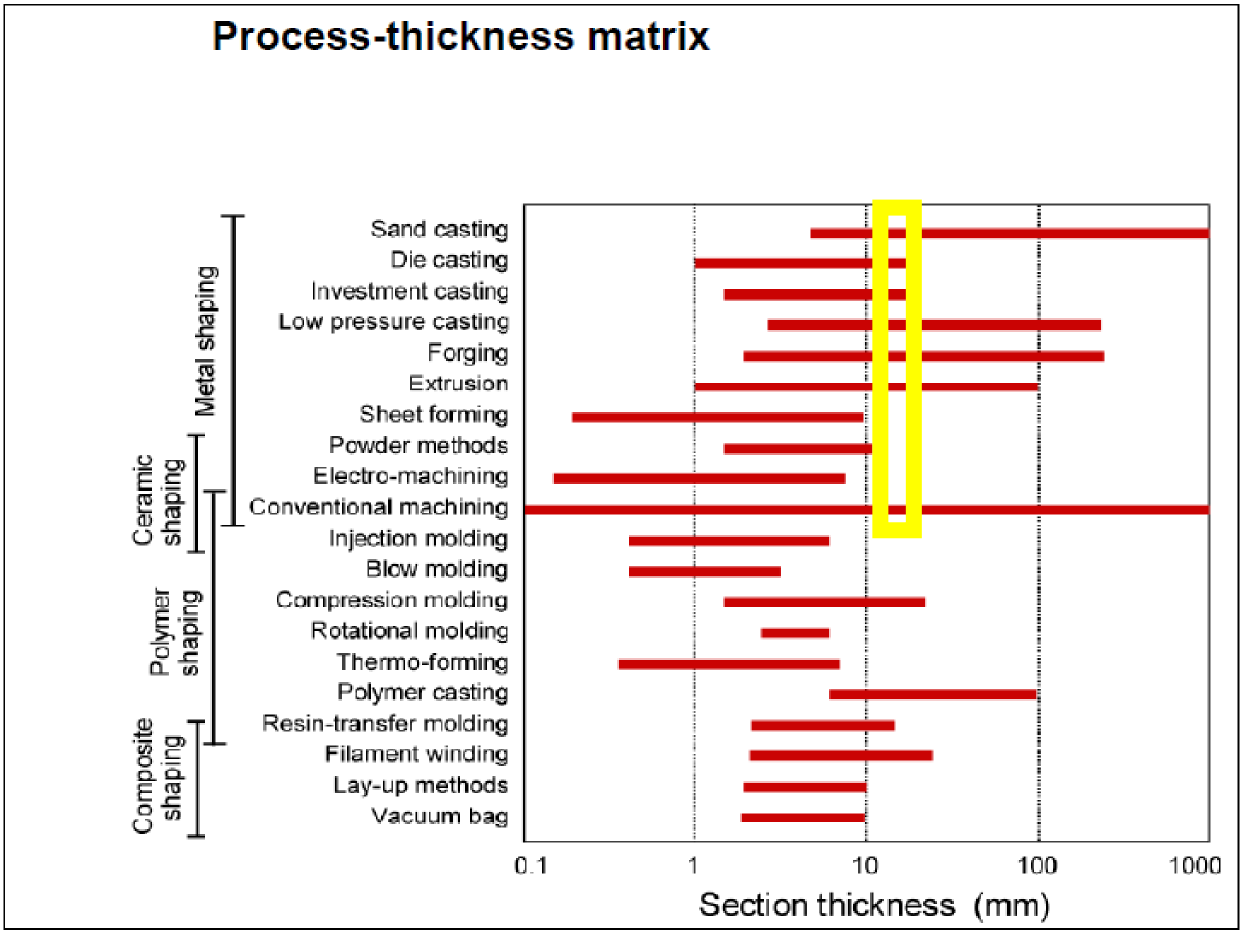


Process-material matrix

		Metals, ferrous	Metals, non-ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Sand casting	●	●							
	Die casting	●	●							
	Investment casting	●	●							
	Low pressure casting		●							
	Forging	●	●							
	Extrusion		●							
	Sheet forming	●	●							
	Powder methods	●	●	●						
	Electro-machining	●	●	●						
	Conventional machining	●	●	●	●	●	●	●	●	
	Injection molding				●	●	●	●	●	
	Blow molding				●		●			
	Compression molding				●	●	●	●		
	Rotational molding					●	●	●	●	
	Thermo-forming					●	●	●		
	Polymer casting					●	●	●	●	
	Resin-transfer molding						●	●	●	●
	Filament winding									●
	Lay-up methods									●
	Vacuum bag									●
Joining	Adhesives	●	●	●	●	●	●	●	●	●
	Welding, metals	●	●							
	Welding, polymers					●	●	●	●	
	Fasteners	●	●	●	●	●	●	●	●	●
Finishing	Precision machining	●	●				●	●		●
	Grinding	●	●	●	●					●
	Lapping	●	●	●	●					●
	Polishing	●	●	●	●		●	●		●

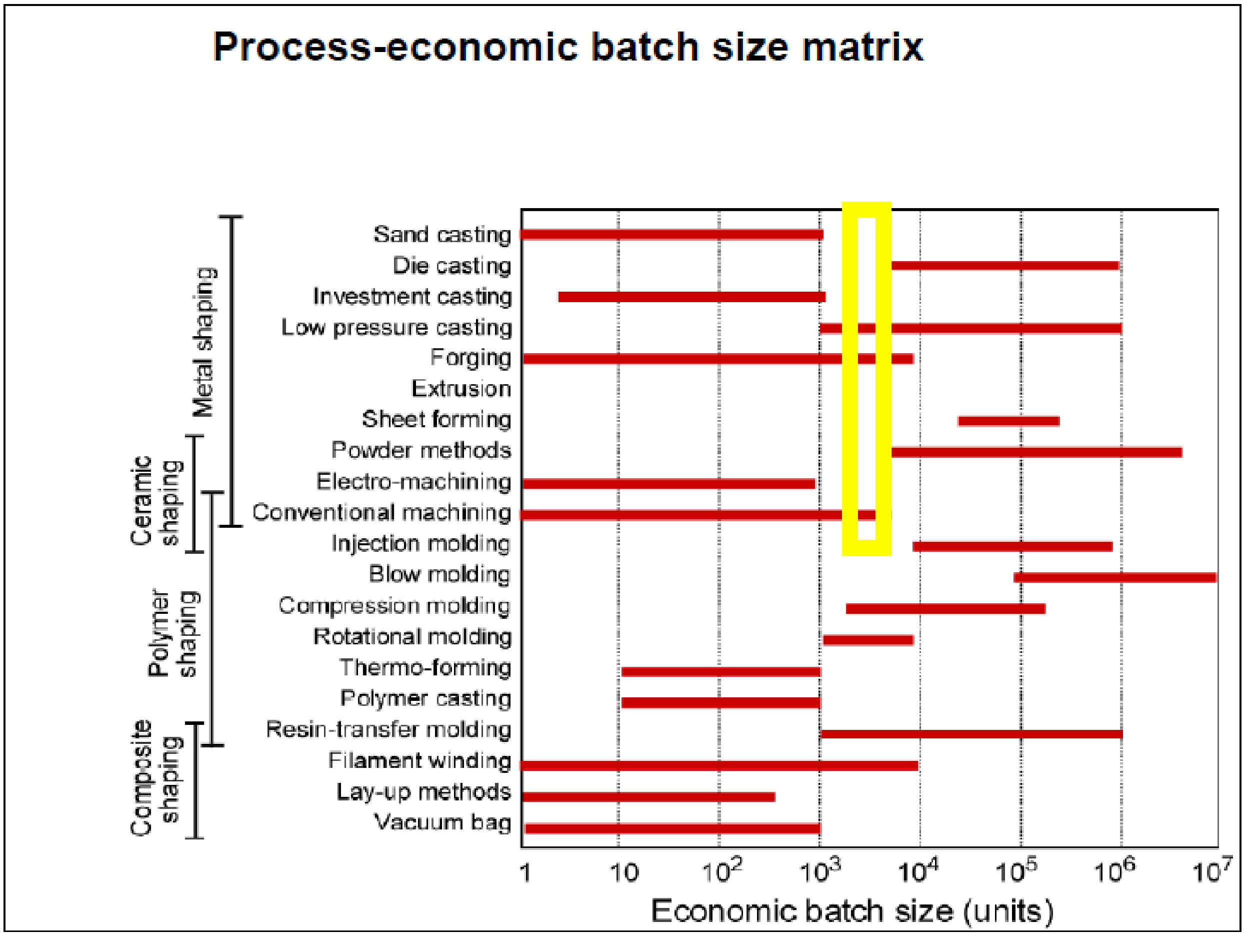
In an attempt to further narrow manufacturing choices, Team 6 used the shape of the shaft as a constraint for the corresponding shape matrix. Unfortunately, the circular prismatic shape of the shafts does not eliminate any of the feasible processes determined from the material matrix. Another factor that can be used to limit machining process options is the section thickness of the product. In this case, the section thickness of the shaft is approximately 19 mm, which limits the processes used for metal shaping seen in Figure F.20.

Figure F.20: Shaft manufacturing process selection thickness matrix



The last matrix Team 6 used to narrow their manufacturing options was the economic batch size matrix. As previously mentioned, Team 6 is identifying product materials and manufacturing assuming an economic batch size of 5,000 units. The economic batch size matrix can be seen in Figure F.21 below; batch size, in combination with the previously mentioned matrices showed that possible machining processes include conventional machining and forging. Accounting for the desire to minimize tooling and equipment cost, Team 6 identified conventional machining as the best process to produce the shafts for their design. In addition, CES showed that shafts are often fabricated using conventional machining, confirming the validity of Team 6’s decision. Specifically, the shafts would be produced by a primary process of turning, after which, they would have a secondary process of carburizing to ensure appropriate hardness. The shafts would then be finished using another turning process to account for any deformation during the hardening process. To finish the shafts, splines would be rolled onto the outer diameter

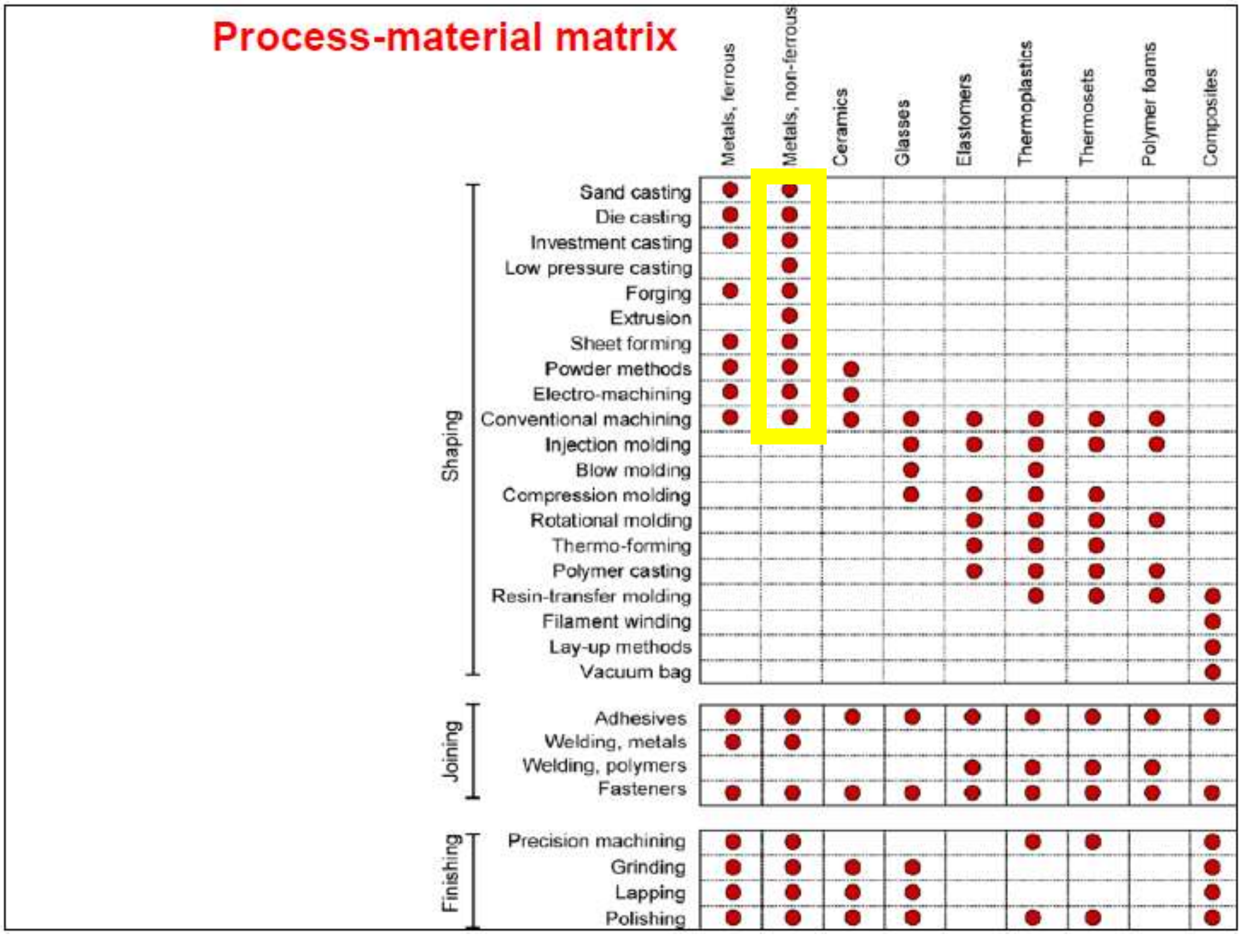
Figure F.21: Shaft manufacturing process economic batch size matrix



Gearbox

Another component Team 6 analyzed using CES Material Selector was the gearbox case, which was selected to be fabricated from cast aluminum-alloys. As a non-ferrous metal, this material selection limits the practical manufacturing possibilities, shown in the Figure F.22 below.

Figure F.22: Gearbox manufacturing process selection material matrix



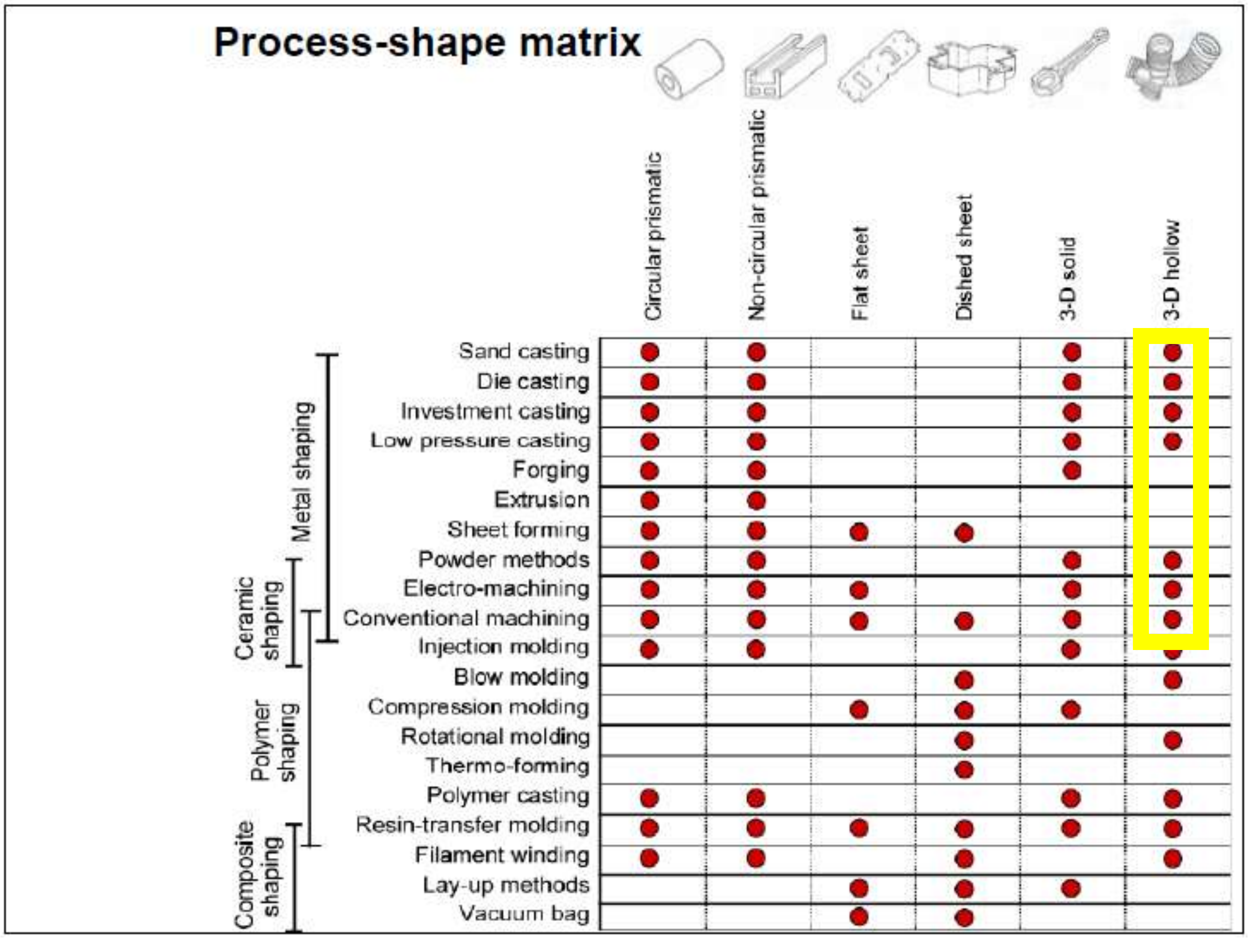
Process-material matrix

		Metals, ferrous	Metals, non-ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Sand casting	●	●							
	Die casting	●	●							
	Investment casting	●	●							
	Low pressure casting		●							
	Forging	●	●							
	Extrusion		●							
	Sheet forming	●	●							
	Powder methods	●	●	●						
	Electro-machining	●	●	●						
	Conventional machining	●	●	●	●	●	●	●	●	
	Injection molding				●	●	●	●	●	
	Blow molding				●		●			
	Compression molding				●	●	●	●		
	Rotational molding					●	●	●	●	
	Thermo-forming					●	●	●		
	Polymer casting					●	●	●	●	
	Resin-transfer molding						●	●	●	●
	Filament winding									●
	Lay-up methods									●
	Vacuum bag									●
Joining	Adhesives	●	●	●	●	●	●	●	●	●
	Welding, metals	●	●							
	Welding, polymers					●	●	●	●	
	Fasteners	●	●	●	●	●	●	●	●	●
Finishing	Precision machining	●	●				●	●		●
	Grinding	●	●	●	●					●
	Lapping	●	●	●	●					●
	Polishing	●	●	●	●		●	●		●

In an attempt to further narrow manufacturing choices, Team 6 used the constraint of the shape of the gearbox casing to correlate with the shape matrix seen in Figure F.23. Based on the knowledge that the casing design is a 3-D hollow object, Team 6 was able to eliminate three of the processes identified by the material matrix.

The last matrix Team 6 used to narrow their casing manufacturing options was the economic batch size matrix. Using the same batch size as outlined for the shafts Team 6 identified possible machining processes including conventional machining and low pressure casting. Accounting for a desire to minimize tooling and equipment costs and labor intensity, Team 6 chose low pressure casting as the primary process to mass produce the gearbox with a secondary process of conventional milling. In addition, CES pointed out that a typical use of low-pressure casting is to produce gearbox covers confirming the validity of Team 6's decision. While Team 6 identified viable materials for finger guards, they have determined that one of the major changes that would occur when producing the product at higher production volumes would be to eliminate the epoxy matrix finger guards in favor of a completely aluminum casing. This would significantly decrease the cost of product given the high cost of epoxy matrix and would also aid in lowering production time and safety concerns explained within the material selection process.

Figure F.23: Gearbox manufacturing process selection shape matrix

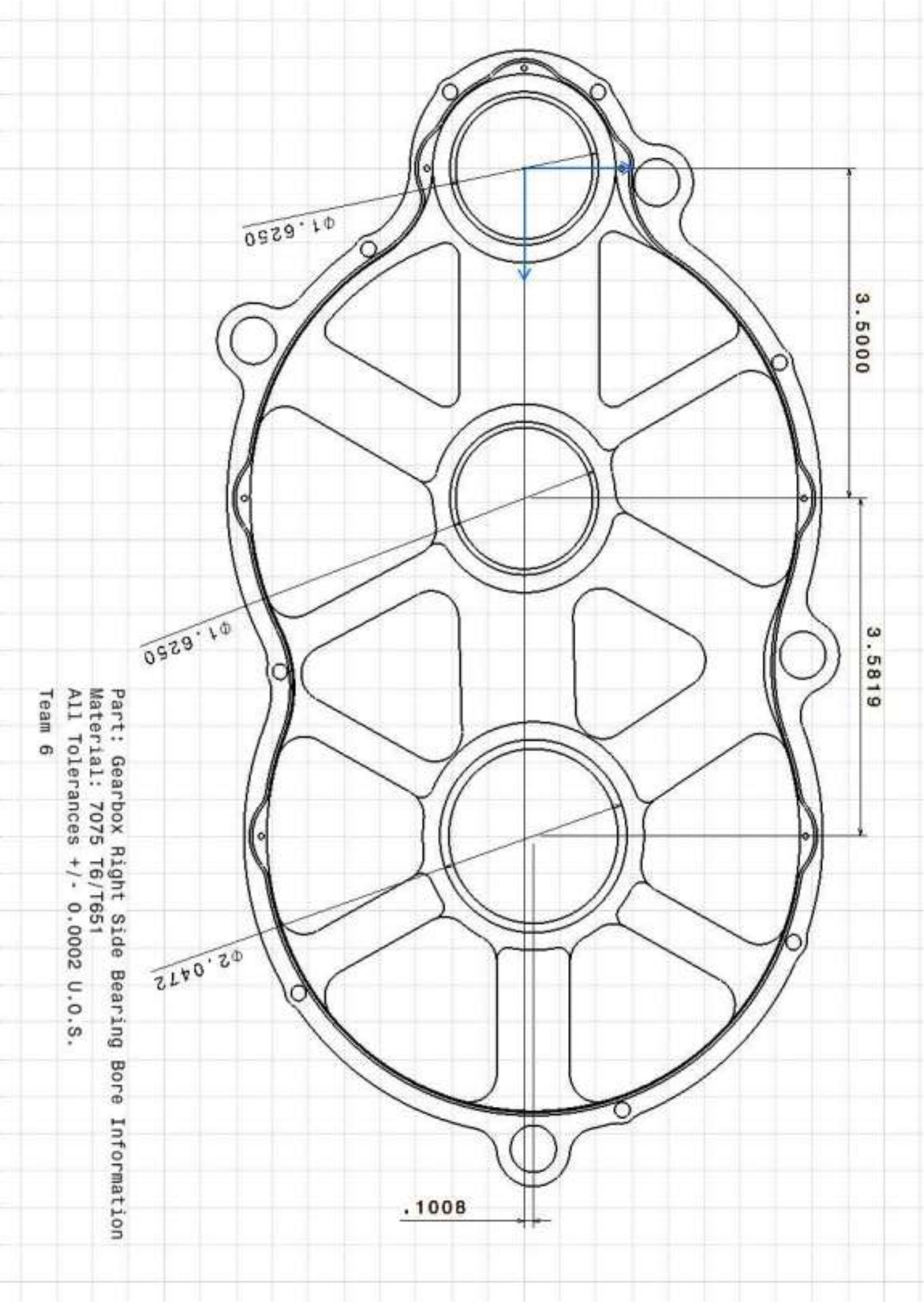


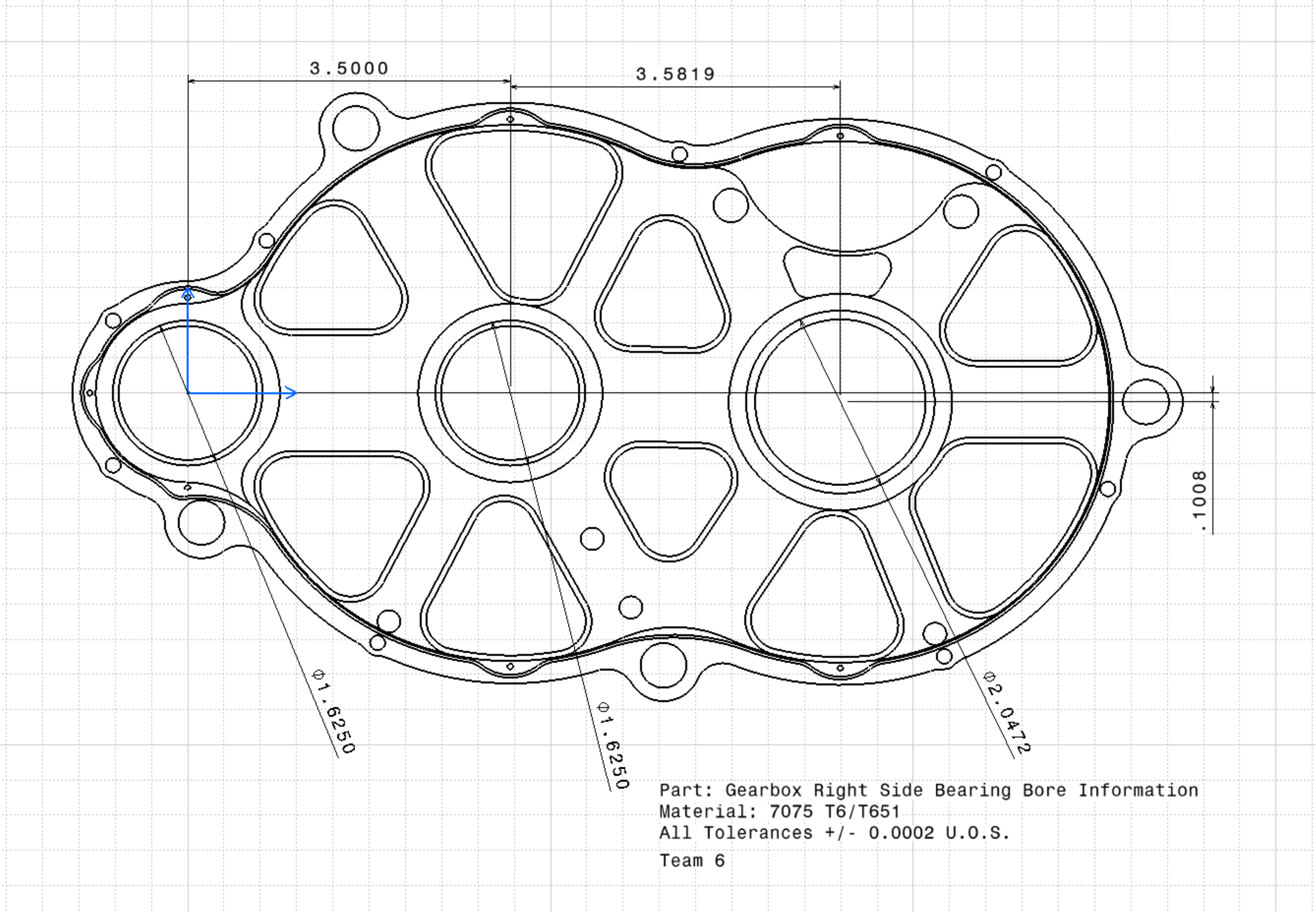
Process-shape matrix

Metal shaping
Ceramic shaping
Polymer shaping
Composite shaping

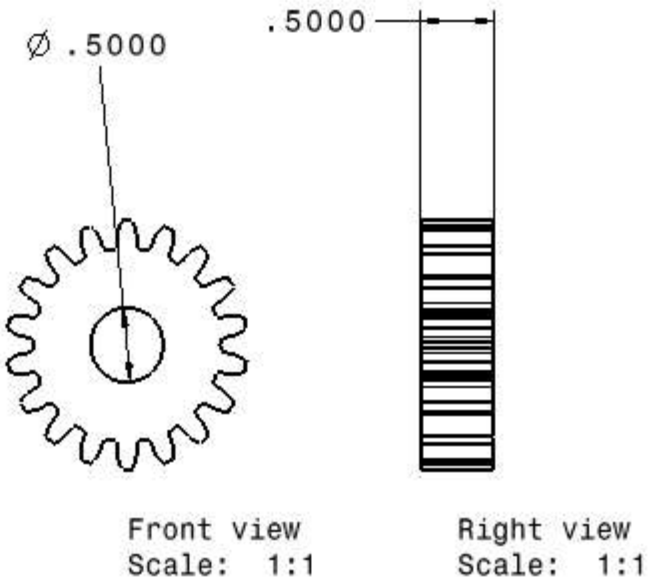
	Circular prismatic	Non-circular prismatic	Flat sheet	Dished sheet	3-D solid	3-D hollow
Sand casting	●	●			●	●
Die casting	●	●			●	●
Investment casting	●	●			●	●
Low pressure casting	●	●			●	●
Forging	●	●			●	
Extrusion	●	●				
Sheet forming	●	●	●	●		
Powder methods	●	●			●	●
Electro-machining	●	●	●		●	●
Conventional machining	●	●	●	●	●	●
Injection molding	●	●			●	●
Blow molding				●		●
Compression molding			●	●	●	
Rotational molding				●		●
Thermo-forming				●		
Polymer casting	●	●			●	●
Resin-transfer molding	●	●	●	●	●	●
Filament winding	●	●		●		●
Lay-up methods			●	●	●	
Vacuum bag			●	●		

APPENDIX G- Drawings of Individual Components



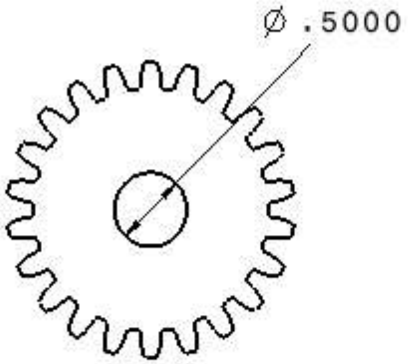


Part: Gearbox Right Side Bearing Bore Information
Material: 7075 T6/T651
All Tolerances +/- 0.0002 U.O.S.
Team 6

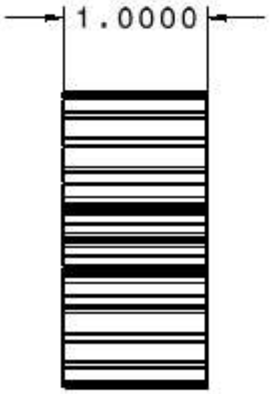


Pressure Angle: 14.5*
Pitch: 12
Number of Teeth: 18
Pitch Diameter: 1.5"

Part Name: Input Pinion Gear
Material: 9310 Steel
Qty: 4
All Dimensions Inches
All Tolerances +/-0.001
Drawing by: W. Calvin O'Brien (561) 542 3559



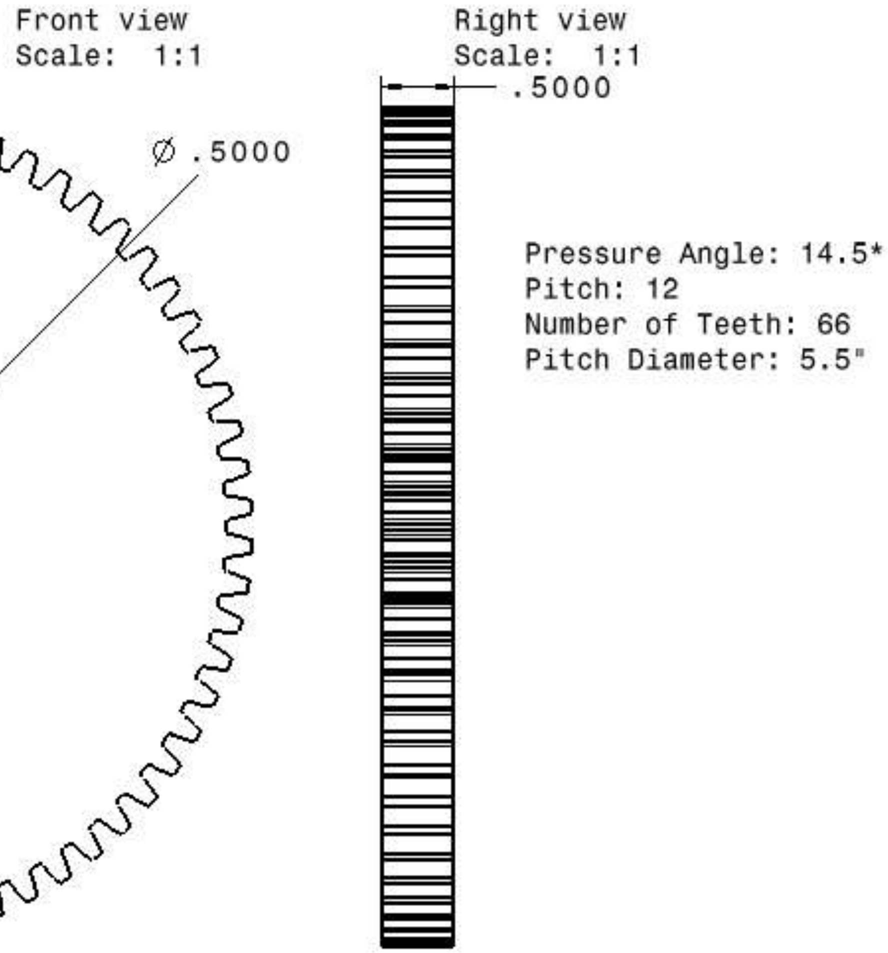
Front view
Scale: 1:1



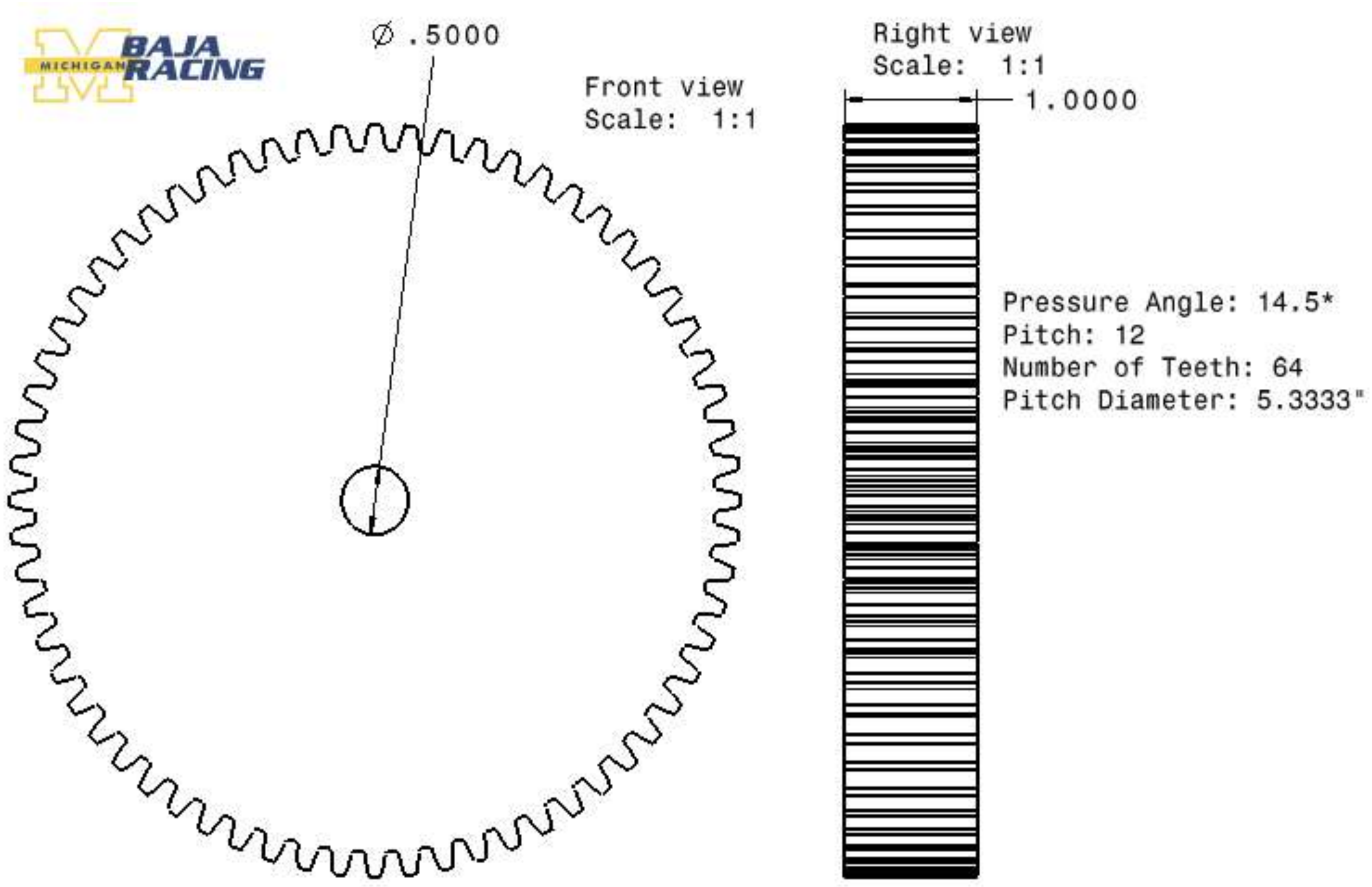
Right view
Scale: 1:1

Pressure Angle: 14.5*
Pitch: 12
Number of Teeth: 22
Pitch Diameter: 1.8333"

Part Name: Intermediate Spur Gear - Pinion 22 Teeth
Material: 9310 Steel
Qty: 4
All Dimensions Inches
All Tolerances +/-0.001
Made by: W. Calvin O'Brien (561) 542 3559



Part Name: Intermediate Gear 66 Teeth
Material:9310 Steel
Qty: 4
All Dimensions Inches
All Tolerances +/-0.001
Drawing By: W. Calvin O'Brien (561) 542 3559



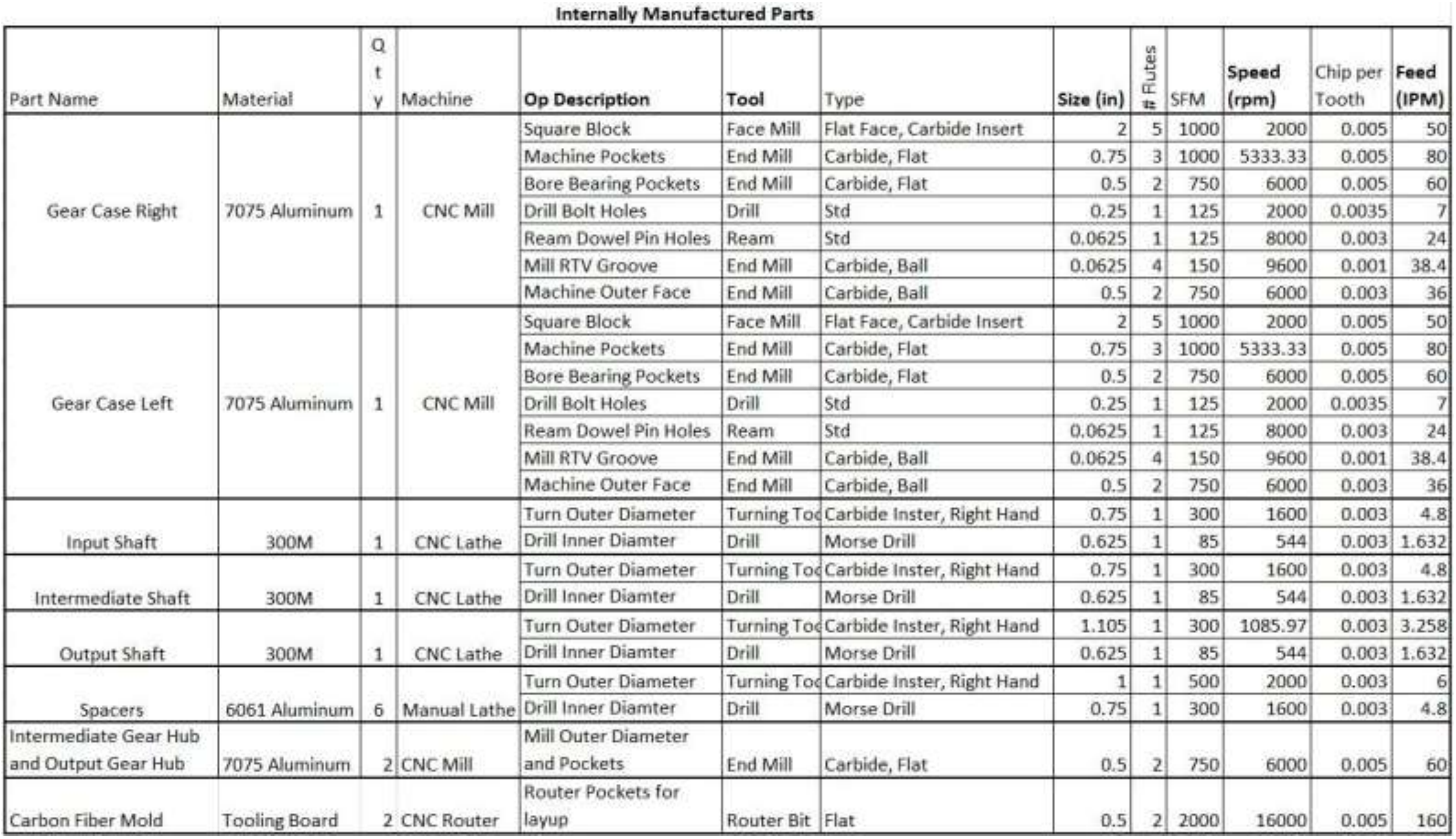
Pressure Angle: 14.5*
Pitch: 12
Number of Teeth: 64
Pitch Diameter: 5.3333"

Part Name: Output Gear 64 Teeth
Material: 9310 Steel
Qty: 4
All Dimensions Inches
All Tolerances +/-0.001
Made by: W. Calvin O'Brien (561) 542 3559

APPENDIX H- Bill of Materials

Item	Quantity	Source	Catalog Number	Cost	Contact
Dowel Pin	10	McMaster-Carr	97395A601	16.58	mcmaster.com
1" Cap Screws	10	McMaster-Carr	93615A456	15.24	mcmaster.com
1.25" Cap Screws	10	McMaster-Carr	92185A201	9.68	mcmaster.com
Breather Vents	2	McMaster-Carr	9833K22	2.86	mcmaster.com
Glass Sights	4	McMaster-Carr	1322K71	39.44	mcmaster.com
Carbon Fiber	1 sq. ft.	Composite Systems	FG-CFT5750	15	uscomposites.com
Mold Release	100 g.	Amazon	M0811	2	amazon.com
Epoxy Resin	2 fl. oz.	Stadium Hardware	WYS-105C	10	www.truevalue.com/stadiumhardware/Home.aspx
Epoxy Hardener	1 fl. oz.	Stadium Hardware	WYS-206B	5	ww3.truevalue.com/stadiumhardware/Home.aspx
Peelply	1 sq. ft.	Airtech	VB-P56150	5	airtechonline.com
Vacuum Tape	2 ft.	Airtech	VB-BT25	5	airtechonline.com
Breather	1 sq. ft.	Airtech	VB-BLE060	2	airtechonline.com
Vacuum Bag	1 sq. ft.	Airtech	VB-VF02110RL	2	airtechonline.com
Input and Intermediate Bearings	4	NSK	R12V	124.44	http://www.nsk.com/
Output bearings	2	NSK	60/28 VV	78.78	http://www.nsk.com/
6061 Aluminum Dia 1.75"	3 in	Alro Steel Corp.	NA	10.41	http://www.alro.com/
6061 Aluminum Dia 2"	3 in	Alro Steel Corp.	NA	17.01	http://www.alro.com/
7075, T6 Aluminum T 3"x12"	12 in	Alro Steel Corp.	NA	552	http://www.alro.com/
7075, T6 Aluminum T 1"x12"	12 in	Alro Steel Corp.	NA	217.6	http://www.alro.com/
300 M Steel 1.5" Dia	12 in	Latrobe Specalty Metals	NA	22.32	http://www.latrobesteel.com/
300 M Steel 2" Dia	6 in	Latrobe Specalty Metals	NA	17.35	http://www.latrobesteel.com/
Dry Ice	1 lb	Meijer	NA	13.95	http://www.meijer.com
Accetone	1 Gallon	McMaster-Carr	3190K16	31.34	mcmaster.com
Loctite 9430 Epoxy Structural Adhesive	.25 lb	Ellsworth Adhesive	83114	21.59	http://www.ellsworth.com/henkel-loctite-hysol-9430-epoxy-adhesive-2lb-kit-off-white/?gclid=CPiXzaPbi7QCFY9DMgod_H0A2w
Blue RVT Silicone Gasket Sealer	3 oz	Meijer	1288769	6.28	http://www.meijer.com
Wolf's Head All-Purpose Gear Lube	32 fl. Oz.	Stadium Hardware	NA	83.4	ww3.truevalue.com/stadiumhardware/Home.aspx

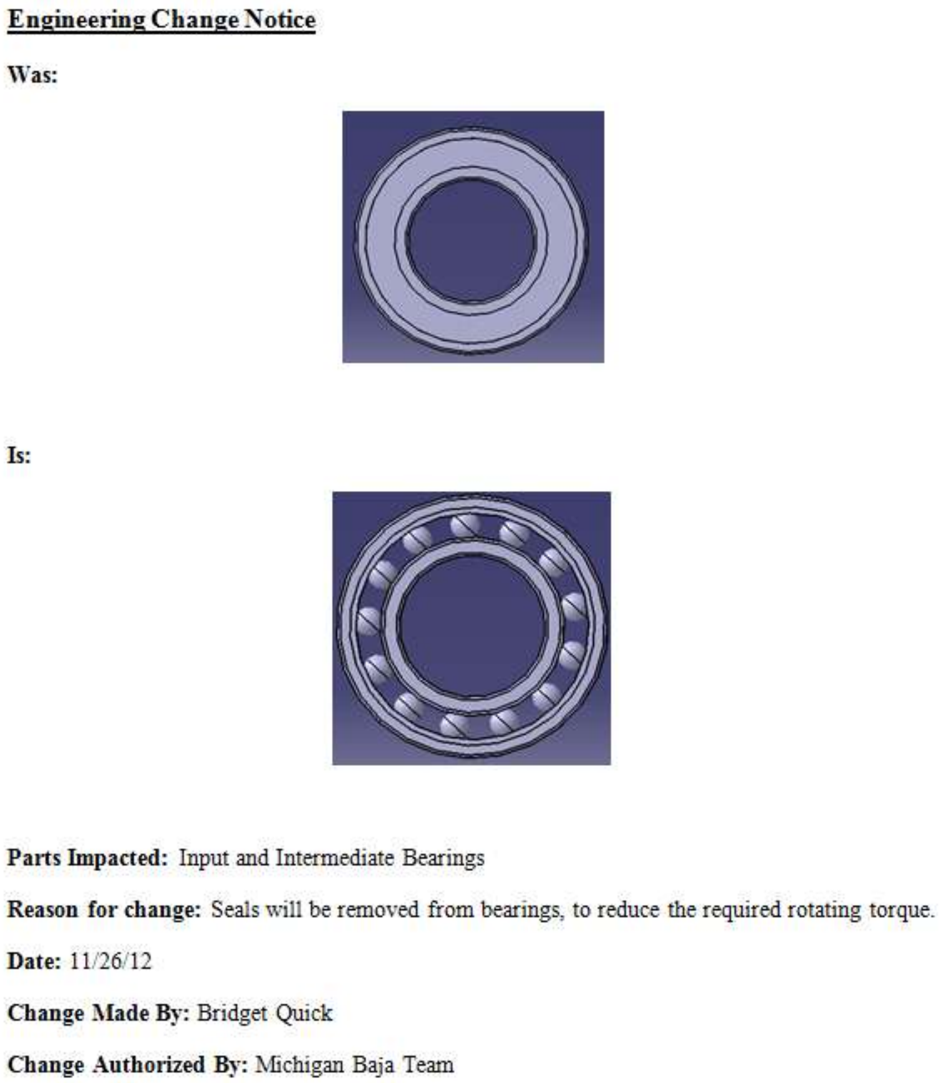
APPEDIX F- Manufacturing Details



Internally Manufactured Parts

Part Name	Material	Qty	Machine	**Op Description**	**Tool**	Type	**Size (in)**	# Flutes	SFM	**Speed (rpm)**	Chip per Tooth	**Feed (IPM)**
Gear Case Right	7075 Aluminum	1	CNC Mill	Square Block	Face Mill	Flat Face, Carbide Insert	2	5	1000	2000	0.005	50
				Machine Pockets	End Mill	Carbide, Flat	0.75	3	1000	5333.33	0.005	80
				Bore Bearing Pockets	End Mill	Carbide, Flat	0.5	2	750	6000	0.005	60
				Drill Bolt Holes	Drill	Std	0.25	1	125	2000	0.0035	7
				Ream Dowel Pin Holes	Ream	Std	0.0625	1	125	8000	0.003	24
				Mill RTV Groove	End Mill	Carbide, Ball	0.0625	4	150	9600	0.001	38.4
				Machine Outer Face	End Mill	Carbide, Ball	0.5	2	750	6000	0.003	36
Gear Case Left	7075 Aluminum	1	CNC Mill	Square Block	Face Mill	Flat Face, Carbide Insert	2	5	1000	2000	0.005	50
				Machine Pockets	End Mill	Carbide, Flat	0.75	3	1000	5333.33	0.005	80
				Bore Bearing Pockets	End Mill	Carbide, Flat	0.5	2	750	6000	0.005	60
				Drill Bolt Holes	Drill	Std	0.25	1	125	2000	0.0035	7
				Ream Dowel Pin Holes	Ream	Std	0.0625	1	125	8000	0.003	24
				Mill RTV Groove	End Mill	Carbide, Ball	0.0625	4	150	9600	0.001	38.4
				Machine Outer Face	End Mill	Carbide, Ball	0.5	2	750	6000	0.003	36
Input Shaft	300M	1	CNC Lathe	Turn Outer Diameter	Turning Toc	Carbide Inster, Right Hand	0.75	1	300	1600	0.003	4.8
				Drill Inner Diamter	Drill	Morse Drill	0.625	1	85	544	0.003	1.632
Intermediate Shaft	300M	1	CNC Lathe	Turn Outer Diameter	Turning Toc	Carbide Inster, Right Hand	0.75	1	300	1600	0.003	4.8
				Drill Inner Diamter	Drill	Morse Drill	0.625	1	85	544	0.003	1.632
Output Shaft	300M	1	CNC Lathe	Turn Outer Diameter	Turning Toc	Carbide Inster, Right Hand	1.105	1	300	1085.97	0.003	3.258
				Drill Inner Diamter	Drill	Morse Drill	0.625	1	85	544	0.003	1.632
Spacers	6061 Aluminum	6	Manual Lathe	Turn Outer Diameter	Turning Toc	Carbide Inster, Right Hand	1	1	500	2000	0.003	6
				Drill Inner Diamter	Drill	Morse Drill	0.75	1	300	1600	0.003	4.8
Intermediate Gear Hub and Output Gear Hub	7075 Aluminum	2	CNC Mill	Mill Outer Diameter and Pockets	End Mill	Carbide, Flat	0.5	2	750	6000	0.005	60
Carbon Fiber Mold	Tooling Board	2	CNC Router	Router Pockets for layup	Router Bit	Flat	0.5	2	2000	16000	0.005	160

APPEDIX J- Engineering Change Notices



Engineering Change Notice

Was:

Is:

Parts Impacted: Input and Intermediate Bearings

Reason for change: Seals will be removed from bearings, to reduce the required rotating torque.

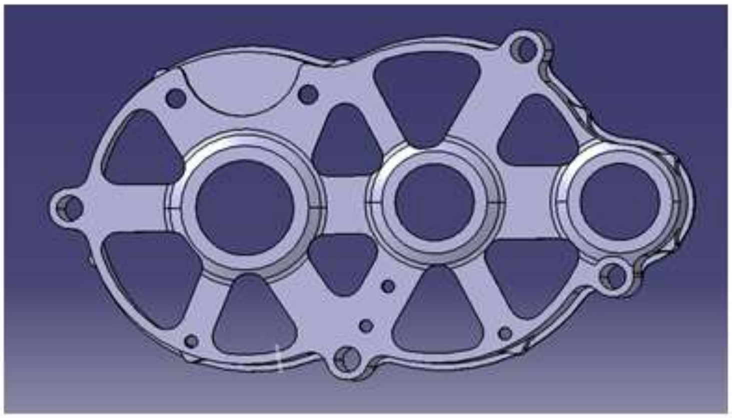
Date: 11/26/12

Change Made By: Bridget Quick

Change Authorized By: Michigan Baja Team

Engineering Change Notice

Was:



Is:

Parts Impacted: Housing

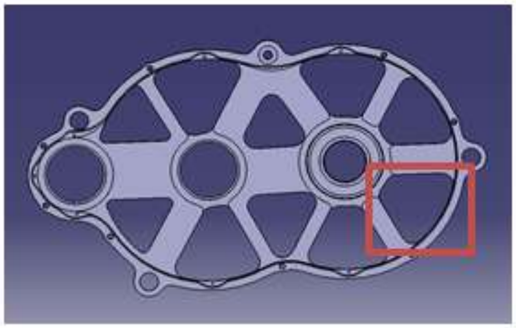
Reason for change: Material was left at both intermediate shafts and the right side of the input shaft. This was done so that unsealed bearings can be used which have a lower torque to rotate.

Date: 11/26/12

Change Made By: Calvin O'Brien

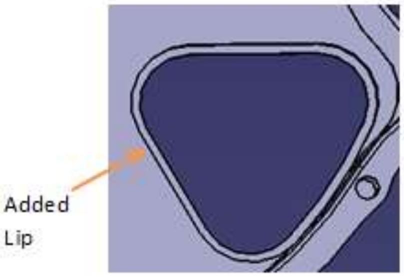
Change Authorized By: Michigan Baja Team

Engineering Change Notice



Was:

Is:



Parts Impacted: Carbon Fiber Inserts, Housing

Reason for change: Lips were created on the housing to create more surface area for the adhesive to bond to and create a better seal between the housing and the carbon fiber inserts.

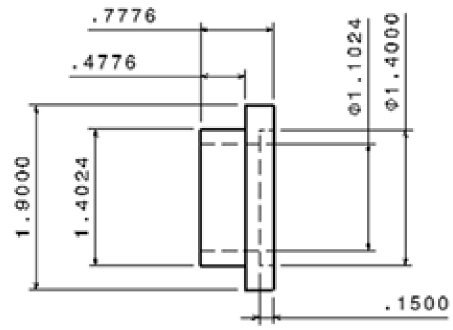
Date: 11/25/12

Change Made By: Jenna Kudla

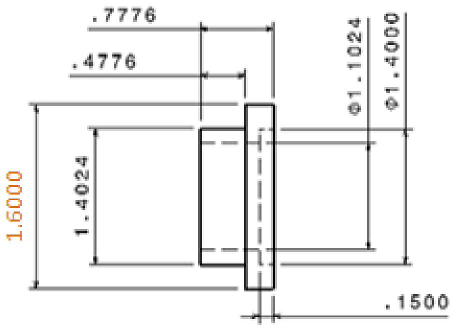
Change Authorized By: Michigan Baja Team

Engineering Change Notice

Was:



Is:



Parts Impacted: Right Output Spacer

Reason for change: The output spacer outer diameter was too large therefore it interfered with intermediate gear two.

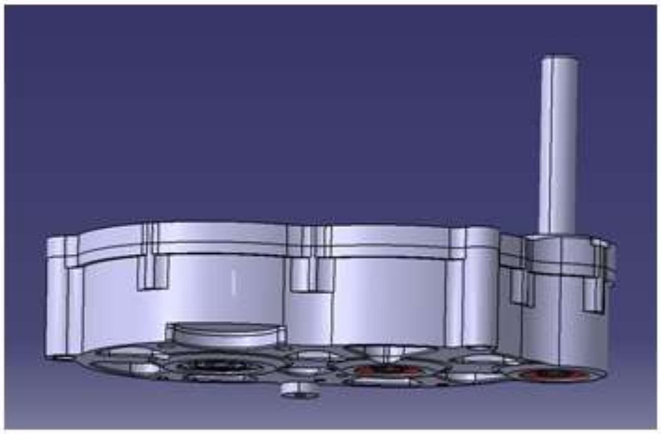
Date: 12/3/12

Change Made By: Calvin O'Brien

Change Authorized By: Michigan Baja Team

Engineering Change Notice

Was:



Is:

Parts Impacted: Housing

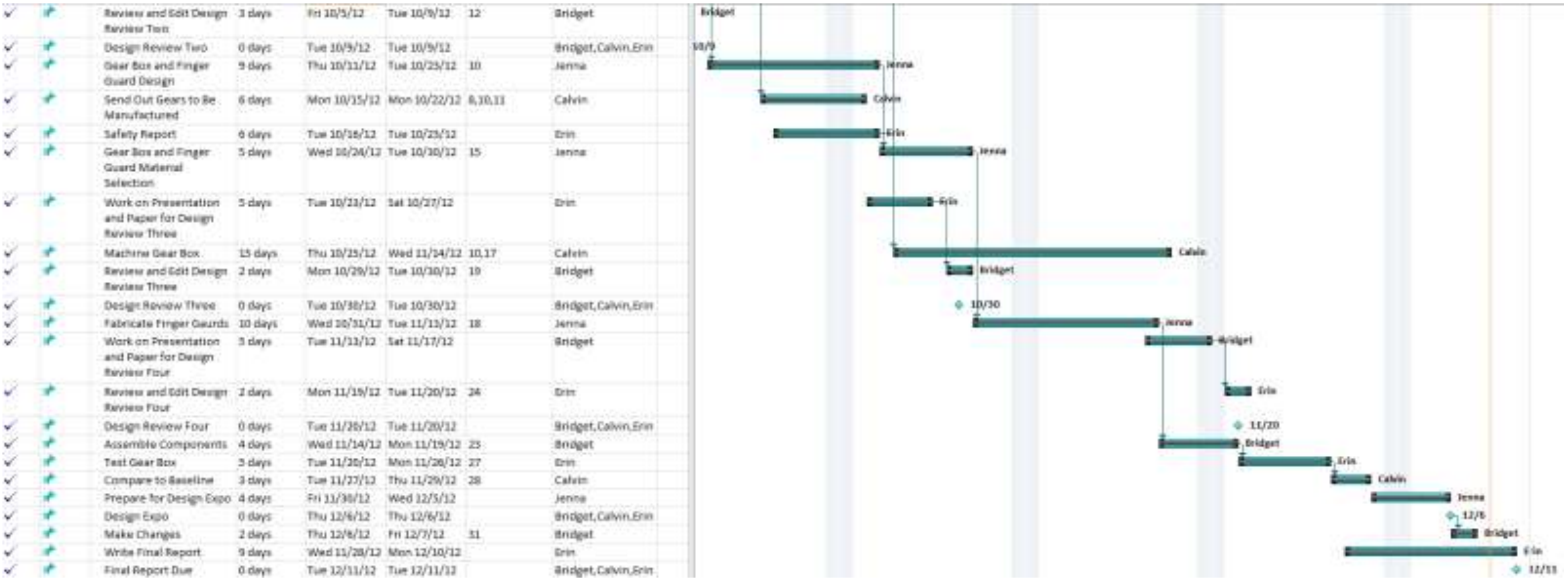
Reason for change: A slit was added by the bolt holes to make the gear box easier to disassemble.

Date: 11/28/12

Change Made By: Calvin O'Brien

Change Authorized By: Michigan Baja Team

APPENDIX K-Gantt Chart



✓	📌	Review and Edit Design Review Two	3 days	Fri 10/5/12	Tue 10/9/12	12	Bridget
✓	📌	Design Review Two	0 days	Tue 10/9/12	Tue 10/9/12		Bridget,Calvin,Erin
✓	📌	Gear Box and Finger Guard Design	9 days	Thu 10/11/12	Tue 10/23/12	10	Jenna
✓	📌	Send Out Gears to Be Manufactured	6 days	Mon 10/15/12	Mon 10/22/12	8,10,11	Calvin
✓	📌	Safety Report	6 days	Tue 10/16/12	Tue 10/23/12		Erin
✓	📌	Gear Box and Finger Guard Material Selection	5 days	Wed 10/24/12	Tue 10/30/12	15	Jenna
✓	📌	Work on Presentation and Paper for Design Review Three	5 days	Tue 10/23/12	Sat 10/27/12		Erin
✓	📌	Machine Gear Box	15 days	Thu 10/25/12	Wed 11/14/12	10,17	Calvin
✓	📌	Review and Edit Design Review Three	2 days	Mon 10/29/12	Tue 10/30/12	19	Bridget
✓	📌	Design Review Three	0 days	Tue 10/30/12	Tue 10/30/12		Bridget,Calvin,Erin
✓	📌	Fabricate Finger Gaurds	10 days	Wed 10/31/12	Tue 11/13/12	18	Jenna
✓	📌	Work on Presentation and Paper for Design Review Four	5 days	Tue 11/13/12	Sat 11/17/12		Bridget
✓	📌	Review and Edit Design Review Four	2 days	Mon 11/19/12	Tue 11/20/12	24	Erin
✓	📌	Design Review Four	0 days	Tue 11/20/12	Tue 11/20/12		Bridget,Calvin,Erin
✓	📌	Assemble Components	4 days	Wed 11/14/12	Mon 11/19/12	23	Bridget
✓	📌	Test Gear Box	5 days	Tue 11/20/12	Mon 11/26/12	27	Erin
✓	📌	Compare to Baseline	3 days	Tue 11/27/12	Thu 11/29/12	28	Calvin
✓	📌	Prepare for Design Expo	4 days	Fri 11/30/12	Wed 12/5/12		Jenna
✓	📌	Design Expo	0 days	Thu 12/6/12	Thu 12/6/12		Bridget,Calvin,Erin
✓	📌	Make Changes	2 days	Thu 12/6/12	Fri 12/7/12	31	Bridget
✓	📌	Write Final Report	9 days	Wed 11/28/12	Mon 12/10/12		Erin
✓	📌	Final Report Due	0 days	Tue 12/11/12	Tue 12/11/12		Bridget,Calvin,Erin