

DEVELOPMENT OF SMALL-SCALE PLASTIC RECYCLING ASSEMBLY

Paul Calderon

Taryn Langtry

Morgan Ransom

Cecelia Vassallo

ABSTRACT

This project utilizes a motorized shredding machine and injection molding equipment to recycle and repurpose high-density polyethylene. Design concepts were chosen based on ease of design and fabrication, and were executed with considerations such as material properties, torque requirements, tolerancing, and structural finite element analysis. Utilizing this shredder and mold assembly, the project represents a small-scale initiative that can increase awareness of material use on college campuses. Due to delays in manufacturing, it is difficult to analyze the fulfillment of the specifications, but all requirements are in the process of being met or have already been met.

PROBLEM DEFINITION

Plastic waste generated on campus at the University of Rochester is substantial, with a significant portion coming from single-use plastic containers used at Starbucks. The creation and application of small-scale recycling equipment re-purposes these single-use plastics, diverting them from waste disposal systems like landfills or incinerators.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

Deliverables	Description
1	Prototype device.
2	Technical report with test data.
3	1000 plastic items.
4	Theory of operation manual.

Requirements	Description
1	Plastic must come from campus waste.
2	Standard injection molding protocols will be followed.
3	All collected plastic must be recyclable in a similar manner, i.e. similar melting points.
4	Safety protocols will be recognized and evaluated by appropriate safety staff.
5	The molded pieces will be formed in one shot based on the injection molder's shot capacity.
6	Mold material should support the quantities required.
7	Mold needs vents to prevent plastic from burning.

Specification Number	Value	Units	Description	Method of Evaluation
1	1000	units	Produce by May 4 th	Counting
2	24	hours	Maximum time spent injection molding items	Clock
3	5/16	in	Maximum shredded particle size	Ruler
4	440-490	°F	Applicable injection molder operating temperatures	Temperature

CONCEPTS

One of the most critical design considerations was the power source for the shredder machine. Both a manual crank and an electric motor were considered. Although a motor-powered machine required a more complicated design, prescribed a more difficult manufacturing timeline, and introduced more safety concerns, the advantages of motor-power outweighed the disadvantages. As seen in the Pugh matrix below, the ease and speed at which plastic containers could be shredded led to motor-power being chosen over manpower.

	Hand-crank	Motorized
Ease of Design	0	-2
Ease of Fabrication	0	-1
Safety	0	-1
Ease of Operation	0	+2
Speed of Shredding	0	+2
Compactness	0	+1
Aesthetic Appeal	0	+1
Total	0	+2

With motor power having been selected, the best method of motor speed reduction became another critical design consideration. A belt-pulley system, a chain-sprocket system, and a worm-reducer were considered. Concerns about belt

slippage and tensioning eliminated the first option. With the chain having to transmit a high amount of torque, safety and tensioning concerns also eliminated this method. Thus, the worm-reducer was selected as it was the easiest and most efficient means of reducing the motor's speed. The only significant disadvantage of the worm reducer was cost.

	Belt and Pulley	Chain and Sprocket	Worm Reducer
Ease of Design	0	0	+2
Ease of Fabrication	0	0	-1
Safety	0	-2	+1
Compactness	0	0	+1
Cost	0	-1	-2
Total	0	-3	+1

As for the injection-molded item, the involute gear poker chip topped a standard poker chip, a chip clip, and a ruler in the selection process. The involute gear poker chip satisfied the requirements of the injection molder, meaning the volume did not exceed that of the shot capacity, while remaining relatively simple to manufacture at a reasonable cost. It also served as a symbol of the university's mechanical engineering department, of which the team is a part.

	Baseline (Dice)	Standard Poker Chip	Involute Gear Chip	Chip Clip	Ruler
Meets Requirements of Machine	0	-1	+1	0	-1
Ease of Manufacture	0	+1	0	-1	0
Cost	0	0	0	-1	0
Total	0	0	+1	-2	-1

MECHANICAL ANALYSIS

The key component of the shredding machine is the mechanism that actually shreds the collected plastic containers. Fortunately, this component was inherited from this project's previous iteration, meaning that most design time was spent analyzing the power transmission method opposed to the shredding component itself.

One of the first analyses completed was a computation of how much torque is required to shred the plastic containers. The first approach to this analysis considered the shredding plane geometry and the material properties of the plastic to be shredded. This method proved untenable for two reasons: the plastic undergoes substantial non-linear deformation during the shredding process, thus resulting in a constantly changing shredding plane, and consistent values for the ultimate shear strength of the considered plastics were not readily available.

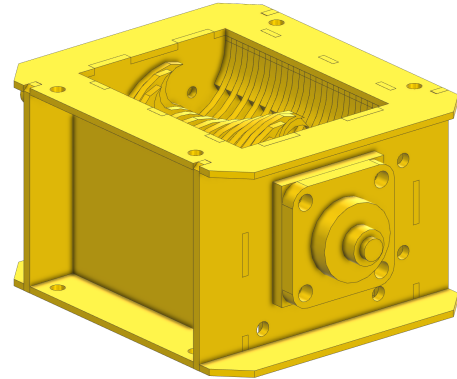


Figure 1: CAD render of inherited shredding component, also referred to as the "shredder box."

A more robust method of determining the needed torque was found in directly measuring it. A nut was welded onto the input shaft of the shredding component (also called the "shredder box") thereby allowing the use of a torque wrench to determine this value. After shredding both polypropylene (PP) and high-density polyethylene (HDPE) with this method, the needed torque was observed as <600 inch-pounds for precut material, and >600 inch-pounds for non-precut material. Following this, computations for what output torque could be had with readily available worm-reducers were done using MATLAB and Kornucopia. Assuming a power input of 1 horsepower at 1725 RPM, a gear reduction of 60:1, and a manufacturer-reported efficiency of 66%, the theoretical available torque was computed as 1447 inch-pounds, more than double the observed requirement for precut material. This test and analysis therefore validated the choice of using a worm-reducer for speed reduction. Further details can be found in Appendix A.

In order to connect the output shaft of the motor to the worm-reducer, and the output shaft of the worm-reducer to the shredder box, couplers needed to be considered. Universal joints were first investigated due to their allowance of significant shaft misalignment but were eventually ruled out due to their high cost and large space requirements. Different types of flexible and rigid shaft couplers available from McMaster-Carr were considered next, but this route also proved untenable for two primary reasons: nearly all the couplers within the scope of the project's budget were rated for speeds and torques below the motor and worm-reducer's outputs, and those that had sufficient ratings were not available in shaft and key sizes compatible with the selected power transmission components. Four different shaft and key configurations drove the design and analysis towards custom rigid couplers.

Straight rigid couplers were first considered on account of their simplicity, but because each coupling interface has two different shaft diameters, which would have required excessively sized keyways to be broached in each coupler, this approach was abandoned.

Flange couplers proved to be the best remaining choice, as they can be easily designed and allow for shafts of wildly differing diameters to be coupled so long as the bolt pattern on both couplers' respective flanges is the same. The disadvantages

of this choice included needing two different components for each coupling interface, (yielding four in total) resulting in an increased time requirement for manufacturing. Both disadvantages, however, could have had their impacts reduced by retaining the same basic geometry for all couplers.

Solid Mechanics Analysis

Using the “Standard Handbook of Machine Design” by Shigley and Mischke as a guide [1], a solid mechanics analysis on each designed coupler was completed using MATLAB and Kornucopia. The geometry of each coupler was dictated by the shaft it needed to accommodate, in addition to ¼"-20 fasteners being used for joining interfacing flanges. The results from this analysis are shown in the table below. The relevant MATLAB scripts can be found in Appendix B.

Coupler Name	Max. Outer Stress (psi)	Keyway Stress (psi)
Motor	145.9	306.8
Gearbox In	132.2	246.9
Gearbox Out	2229.6	5283.9
Shredder	5776.9	8607.4

Material Selection

For material selection, it is assumed that the yield stress in shear is 57.7% that of the yield stress in tension, based on the distortion energy theory of failure. For 6061 aluminum, this means that a tensile yield stress of 35,000 psi signifies a yield stress in shear of 20,000 psi. Since none of the couplers in this analysis were predicted to exceed 20,000 psi, 6061 aluminum was taken as a viable design material.

FEA

The solid mechanics analysis did not consider the stress at the flange where the smaller outer diameter increases to the larger outer diameter. The stress here would technically be infinite as it is a 90-degree angle with no relief radius. A fully-fledged finite element analysis (FEA) was also not conducted for this reason, as preliminary investigations made it clear that decreasing the element size resulted in divergence towards infinite stress.

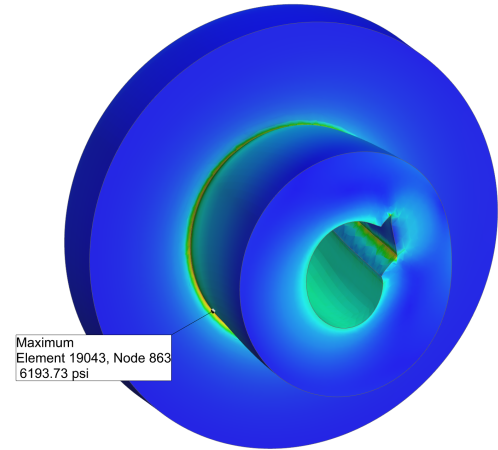


Figure 2: FEA results of shredder coupler with location of maximum stress denoted. Computer simulations often corroborate concepts known from first principles.

Mold Flow Analysis

A mold flow analysis of the poker chip was conducted to simulate the pressure drop and maximum cooling time during the injection molding process. The gate was placed on the surface of a gear tooth, while the air trap was positioned on the opposite side of the gear to prevent plastic burning. The analysis can be found in Figure C1 in Appendix C.

Fatigue Analysis

A fatigue analysis of the couplers was done on account of their design material being aluminum. Because aluminum does not exhibit an endurance limit, it is expected that the couplers have a finite service life.

Since a comprehensive mechanism of failure via fatigue has yet to be formulated [2], experimental data must often be referenced for fatigue analyses. Thus, fatigue design curves were referenced for the coupler fatigue analysis [3]. These design curves correlate both non-zero mean stress and zero mean stress data to number of cycles to failure for 6061-T6 aluminum.

Mean stress can be readily computed using the following formula:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (1)$$

Using the shredder coupler as an example, if it is assumed that a given fiber in its keyway is subjected to a tensile load of ~8600 psi and a compressive load of ~8600 psi approximately 28 times per minute, then the mean stress is computed as zero. With this, the stress amplitude data is used instead, with stress amplitude given as:

$$\sigma_a = \left| \frac{\sigma_{max} - \sigma_{min}}{2} \right| \quad (2)$$

Using the tabulated stress amplitude versus cycles to failure data, the service lifetime of the shredder coupler was computed using MATLAB and Kornucopia. Service lifetimes for the other three couplers were not computed as data was not available for their respective subjected stress amplitudes. This may be inconsequential, as the shredder coupler is subjected to the

highest stress as predicted by the solid mechanics analysis, meaning it drives the effective service life of the machine.

With a maximum mean stress of 8607.4 psi and a loading rate of 28.75 cycles per minute, the service lifetime of the shredder coupler was estimated to be approximately 260 hours. Given that the requirements allot no more than 24 hours to be spent injection molding the poker chips, and that shredding the plastic containers is generally taken as less time intensive than the injection molding process, failure due to fatigue is not expected to occur during the timeline of this project. If the shredding machine were to be used extensively outside of the time restrictions of the project, the service lifetime would have to be observed dutifully. Full details of the fatigue analysis can be found in Appendix D.

Fastener Torque Calculation

A fastener torque calculation was done for the bolts which fasten both the motor plate and the gearbox riser to the plywood base which all the shredding equipment is mounted to. These connections are especially critical as part separation during the shredding process is highly undesirable.

Both sets of bolts are zinc-plated, of size ½"-13 and made of grade 8 steel. Using a proof strength of 120,000 psi and a tensile stress area of 0.1419 in², the proof load is computed via the following equation:

$$F_p = A_t S_p \quad (3)$$

With a computed proof load of 17,028 lbf, the preload is taken as 75% of this, yielding 12,771 lbf. This was done as disassembly of the shredder machine is desirable.

Using a bolt condition factor of 0.20 and the nominal diameter of 0.500 in, the needed fastener torque is given by the following equation:

$$T = K F_i d \quad (4)$$

Thus, the fastener torque for this set of bolts is computed as approximately 1277 in lbf, or 106 ft lbf.

Bearing Analysis

A bearing analysis of the ball bearing blocks used in the shredder was completed. These bearing blocks are mounted to the side of the shredder and endure a large portion of the load induced by the motor. An estimation of the service life of these bearings was calculated. The desired load and life requirements were related to the rated load and life requirements using equation 5.

$$C_{10} = F_R (L_R n_R 60)^{\frac{1}{a}} = F_D (L_D n_D 60)^{\frac{1}{a}} \quad (5)$$

For a factor of safety of 2, the bearings are expected to last for over 3 million hours, which is more than sufficient for the scope of this project. See Appendix E for a detailed calculation of this process.

Tolerance Analysis

A tolerance analysis was performed for the holes at the base of the hopper, to ensure that they will be able to fit around the rod. It was determined that the largest hole diameter for the hopper would be 0.3785 in, seen in Figure F1, in Appendix F. However, due to variations in the sheet metal and alignment, it was necessary to make the holes larger than anticipated.

MANUFACTURING

Prior to manufacturing the power transmission system, several modifications were made to the inherited shredder box. The welded legs from the previous iteration were first cut off with an angle grinder and then surface finished on a ProtoTRAK CNC machine. Since the key slot on the shredder box shaft was damaged, in addition to a testing-nut having been welded to it, a new ¼" key slot was machined using a manual mill.

Another modification made to the shredder box was refabricated bearing block spacers. These spacers were needed as the bearing blocks would interfere with the rotating blades otherwise. Aluminum was initially bought to manufacture these spacers, but Delrin was used instead, as it is easier to machine and gives a cleaner edge finish when machined. The ProtoTRAK CNC machine was used to reduce the time spent machining the central clearance hole.

Tolerance stack ups proved a significant challenge during the shredder box inspection and reassembly. Ideally, the rotating blades and shaft would move as a rigid body with little to no slop. At the same time, the rotating blades must not interfere with the stationary blades. Upon the first reassembly, it was discovered that whether interference occurs is highly dependent on the tightness of certain fasteners. When the rotating blades were tightly stacked and compressed along the main shaft via the end-nuts, they tended to interfere with the stationary blades. Thus, a balance was found when tightening the end-nuts in order to prevent blade interference while minimizing slop or "wobbliness" in the rotating blades. A similar process was applied to those fasteners used to secure the stationary blades, as well.

Several other steps were also taken to facilitate reassembly of the shredder box, particularly its problematic main shaft. The center holes of the rotating blades and their spaces were all deburred with a file, surface finished using Scotch-Brite, and generously greased during the reassembly process.

For the shredder machine, a variety of materials and manufacturing methods were used.

All of the alignment plates and risers are made of ultra-high molecular weight polyethylene. (UHMW PE) This material was selected as large stock pieces (exceeding 6" in height/width and 12" in length) were available for purchase at reasonable prices. (less than \$50 per piece) This material was also listed as relatively machinable on McMaster-Carr's webstore, having a machinability rating of ~70% when compared to Delrin. For these reasons, it was an ideal candidate for fabricating the alignment plates.

All the couplers were made of 6061 aluminum rod stock. Aluminum was chosen as it has a significantly higher yield and ultimate stress when compared to nearly all plastics and has higher machinability when compared to steel. Making the couplers out of 1144 steel was discussed in preliminary design reviews due to its superior yield stress and claimed "easy-to-machine" quality but was eventually ruled out as concerns about not meeting the project's deadline and potentially damaging tooling became too great.

Both the motor alignment plate and the gearbox riser had their respective holes and slots made using the ProtoTRAK CNC machine equipped with a 1/4" endmill. This method was selected as it permitted using the original designs with no modifications made to the slot geometry.

The shredder box risers were first cut to roughly their specified height using a table saw and then finished to the specified height using a manual milling machine equipped with a 1/2" endmill. The same machine was equipped with a spot drill, and 1/8" and 13/32" drills for drilling the holes.

To manufacture the couplers, both rod stock pieces were first cut in half using a horizontal band saw, producing four rough pieces. A flange profile for each piece was then cut using a HAAS CNC lathe in order to reduce manhours spent machining. For three of the four couplers, the main bore was made using a manual lathe equipped with a 4-jaw chuck, first by drilling the hole undersize and then finishing it to the specified diameter with a boring bar. A 4-jaw chuck and boring bar were opted for in order to avoid accidentally cutting the holes oversize, as shaft-coupler interfacing was critical. The remaining (motor) coupler had its bore made using the ProtoTRAK CNC machine. This machine was also used for cutting the alignment features on the couplers which had them, in addition to boring the flange holes.

The mounting base was made of two sections of 4' x 4' x 3/4" untreated plywood, first glued together with polyurethane adhesive and then further strengthened with a 4 x 4 pattern of wood screws.

The hopper was designed to be made from sheet metal that was plasma cut, bent, welded together, and eventually bolted to the top of the shredder mechanism. The decision to use sheet metal was influenced by the previous teams' design, which used plexiglass and an adhesive that joined each edge together. The adhesive did not work properly, and there were issues with the hopper breaking along the adhered edges. Utilizing the Langmuir plasma cutter, two pieces of sheet metal were cut out to form half of the hopper. The plasma cutter left significant burrs on the metal, which were necessary to grind off to ensure proper cleaning for welding. After being cut and deburred, each metal piece was bent in three places: the flange, base, and center to form a corner of the hopper. Many issues arose alongside the bending of these pieces of metal, but once they were able to fit together, they were welded together. After welding, the complete hopper was further bent to ensure each corner had a 90° angle.

Lastly, a piece of perforated stainless steel was welded to the inside of the hopper to act as a window to the interior processes.

Utilizing a tolerance analysis, the size of the holes needed to bolt the hopper to the pre-existing holes on the top of the shredder was determined. However, due to variations in the sheet metal during bending, the holes in the hopper needed to be significantly larger than those in the shredder. This allows the rods to sit vertically in both the hopper and shredder holes, with large washers ensuring stability.

The mold was designed with two halves, an additional cut-out bar to hold the ejector pins in alignment, two ejector pins, and two dowel pins.

The mold contains two cavities for the poker chips, along with a runner and two gates. One half of the mold (the cavity side) includes the recycling arrows and two holes in the center of each gear feature for the ejector pins. The opposing half of the mold is flat and has the Rochester "R" engraved into it.

The original manufacturing plan was to machine the mold halves from steel and use the EDM with a copper electrode to burn the Rochester "R" and recycling arrow features. However, because the EDM process is highly detail-oriented and time-consuming, the design was revised, and the initial mold was instead manufactured from aluminum.

The two mold halves, as well as the ejector pin support plate, were machined on the HAAS CNC using a 0.5" flat end mill, a 60° engraving tool, and a spot drill. The ejector pin holes were produced using drill bits and a reamer. The dowel pin holes were intentionally oversized to ensure proper alignment, and the original runner geometry was modified to a full-depth design.

TEST PLAN AND RESULTS

To confirm that 1000 units are produced by May 4th, the items will be hand-counted. Production of these items is expected to begin by April 28th. Due to delays in manufacturing, this specification may not be met, but it is difficult to confirm this with full confidence.

As production has yet to begin, the time spent injection molding these items in the shop is zero. The second specification requires this time to be under twenty-four hours and will be tracked using a clock. If this specification is not upheld, it is not detrimental to the project's completion.

To minimize plastic jams inside the injection molder, the third specification calls for the maximum shredded plastic size to be no larger than 5/16 in. A sieve with 1/5 in holes has been manufactured and will sit directly underneath the shredder's rotating blades. The sieve will filter out any larger pieces and allow smaller than 1/5 in pieces to fall through; therefore, this specification will be met.

Lastly, to ensure the safety of the injection mold user, the typical melting range for HDPE was specified. As the project shifted from shredding and injection molding single-use Starbucks cups to milk jugs used by Starbucks, so did this specification. This change in plastic, from polypropylene to HDPE, meant there was a change in melting ranges as well.

HDPE has a melting range of 356-536°F, whereas polypropylene melts from 392-536°F [4]. In order to avoid burning the plastic and inhaling plastic fumes, the specification was adjusted to better suit HDPE. This specification has been tested for its suitability in melting HDPE and was approved by the sponsor. Once production begins, the temperature of the injection molder will be confirmed using the digital readout on the equipment.

Regarding the project requirements, they have either been met or are in the process of being met. The first requirement stated that the plastic must come from campus waste. The plastic used for this project is being collected from the University of Rochester's Starbucks facilities, so this requirement has been met. Since the same type of plastic (HDPE) is being used, the melting point remains consistent; therefore, this requirement has also been met.

It was also stated that standard injection molding protocols must be followed, which has been done and will continue to be done. Once the shredder is fully assembled, safety protocols will be reviewed and evaluated by the appropriate safety staff, thus that requirement will be met.

The final three requirements pertain to the design and manufacturing of the mold, and all three have been met. The total volume of the molded product is less than the total shot volume, the mold material (aluminum and steel) will support the quantity required (1000), and proper venting is incorporated in the mold to prevent the plastic from burning.

The mold was tested with both HDPE and polypropylene. Since the shredder is not yet operational, the HDPE used consisted of pieces that were hand-cut into sizes small enough to fit into the injection molder. The polypropylene used was provided by the university in the form of small pellets.

The first test was conducted using HDPE. Initially, a temperature of 450°F was used; however, the melted plastic was too viscous for successful mold filling. The temperature was then increased to 465°F, which resulted in easier injection without burning. Although the mold was fully filled and two poker chips were produced in a single shot, it was found that one side of the mold was not completely flat. This resulted in flash formation. The mold was then flattened and tested a second time, this time using polypropylene. At a temperature of 420°F, the mold was filled successfully, and two poker chips were produced.

Since this testing was preliminary, several improvements have been identified for producing 1000 parts. More consistent force should be applied during injection to ensure uniform filling and to prevent underfilling or overfilling of the mold. Additionally, the packing and holding phase should be extended to minimize shrinkage or surface concavity, ensuring that the poker chip maintains its shape and that the design details remain clearly defined.

INTELLECTUAL PROPERTY

The shredder used in this project was originally designed by the previous group and was based on a design developed by Precious Plastics [5]. Precious Plastic's designs are not patented; rather, they are developed as open-source resources and distributed under a Creative Commons Attribution license. This

allows individuals to use, modify, and build the machines, provided the proper credit is given and any improvements are shared. The shredder used in this project was designed, manufactured, and refined by the previous group based on this open-source framework. The current team also implemented additional modifications to improve functionality; however, these changes do not constitute a novel invention. As a result, neither the original design nor the subsequent modifications meet the criteria for patent protection, and there are insufficient grounds for pursuing a patent.

There are existing patents with designs similar to those developed by Precious Plastics. One example is patent US20180015477A1, which describes a plastic shredder [6]. Another example is patent US6520435B1, which is a plastic bottle shredding assembly [7].

In Rochester, New York, there are several local companies whose goals are to collect used plastic, recycle it in an environmentally responsible manner, and reuse it productively. These companies include Tycom Recycling, Inc. [8], and Empire Resource Recycling, Inc. [9].

SOCIETAL AND ENVIRONMENTAL IMPLICATIONS

This project ultimately aims to recirculate plastic by transforming used plastic into new objects through shredding and injection molding. Recycling plastic is a lower energy process than the creation of virgin plastic, requiring three times less expended energy to recycle HDPE than to create it from synthesizing plastic resin [10]. Expended energy in this case refers to the energy required to operate processes as well as transportation [10]. However, recycling plastic is not a permanent solution. Repeated thermal and mechanical processing degrades plastics, reducing material quality [11]. As a result, plastic is typically only recycled one to two times, meaning recycling is merely postponing landfilling or other waste disposal methods [11].

From an ethical standpoint, small-scale recycling initiatives may inadvertently shift responsibility from large-scale corporations and manufacturers to individual consumers. Additionally, while the system encourages sustainable behavior, it may contribute to the misconception that recycling alone is sufficient to address plastic waste, when in reality, upstream reduction is more impactful.

In terms of energy usage, the shredder and injection molder systems consume electricity. To reduce environmental impact, renewable energy sources could be utilized. Furthermore, continual shredder energy use could be reduced to zero through use of a hand crank; however, this trades production efficiency for energy use optimization.

The project also has implications for user health and safety. The shredder contains rotating blades and pinch points that pose injury risks, which are mitigated through the inclusion of a hopper. Additionally, the injection molding process involves elevated temperatures (440-470°F), creating burn hazards and potential exposure to plastic fumes. Proper ventilation and adherence to safety protocols are necessary to minimize these risks.

In conclusion, the benefits of this project include reusing plastic waste destined for waste sites, lowering energy consumption compared to virgin plastic production, and serving as an educational tool to increase awareness of material reuse. However, there are drawbacks. Material degradation limits the long-term effectiveness of recycling, and the scale of this system restricts its overall impact. Moreover, the process still requires energy input, particularly for the motorized shredder and injection molding equipment, which may offset some environmental benefits depending on the energy source.

RECOMMENDATIONS FOR FUTURE WORK

Future work on this project should prioritize the optimization of this assembly. Issues faced this semester have been regarding the blades inside the shredder, as a proper tolerance analysis has not been completed. Performing this calculation will allow the team to increase rigidity and understand which components are negatively impacting the performance of the machine.

Additionally, an improved process for plastic cleaning and pre-processing can be developed to optimize the system. Currently, the shredding mechanism is too small to shred an entire HDPE milk jug, so the team has used scissors to cut the jugs into roughly eight pieces. This is effective but takes up a significant amount of time for the team, as a significant amount of milk jugs are needed to meet our specifications.

ACKNOWLEDGMENTS

The team would like to acknowledge Dr. Christopher Muir, Matthew Hook, Chris Pratt, Jim Alkins, Bill Mildenerger, Paul Osborne, and Samantha Kriegsman. We greatly thank them as their assistance to this project was both immense and invaluable.

REFERENCES

- [1] Shigley, J. E., and Mischke, C. R., 1996, *Standard Handbook of Machine Design*, McGraw-Hill, NY.
- [2] Budynas, R. G., and Nisbett, J. K., 2015, *Shigley's Mechanical Engineering Design*, McGraw-Hill, NY.
- [3] Yahr, G. T., 1993, "Fatigue Design Curves for 6061-T6 Aluminum," Oak Ridge National Laboratory.
- [4] Precious Plastic. (n.d.). The Basics of Plastics. Precious Plastic Community. <https://community.preciousplastic.com/academy/plastic/basics>.
- [5] Precious Plastic. (n.d.-a). Build A Shredder Machine. Precious Plastic Community. <https://community.preciousplastic.com/academy/build/shredder>.
- [6] Moore, C. (n.d.). US20180015477A1 - Plastic Shredder. Google Patents. <https://patents.google.com/patent/US20180015477A1/en?q=US20180015477A1%2B>.
- [7] Robinson, H. F. (n.d.). US6520435B1 - Plastic Bottle Shredding Assembly. Google Patents. <https://patents.google.com/patent/US6520435B1/en?q=US6520435B1>.
- [8] Plastic Recycling and Shredder. Tycom Recycling. (n.d.). <https://www.tycomrecycling.com/>.
- [9] ITI Solutions. (n.d.). Empire Resource Recycling . Empire Resource Recycling, Inc. <https://www.empireresource.com/>.
- [10] *The Association of Plastic Recyclers White Paper: Virgin vs. Recycled Plastic Life Cycle Assessment Energy Profile and Life Cycle Assessment Environmental Burdens*. The Association of Plastic Recyclers. (2020, May 12). <https://plasticsrecycling.org/wp-content/uploads/2024/08/APR-Recycled-vs-Virgin-LCA-May2020.pdf>
- [11] United Nations Development Programme. (2023, November 28). *Why aren't we recycling more plastic?* . <https://stories.undp.org/why-arent-we-recycling-more-plastic>.

TABLES

Name	Paul	Taryn	Morgan	Cece	Total
Hours	88.67	85.25	68.73	101.65	344.3

Table 1. Total Hours Worked by Each Team Member

	Hours	Cost/Hour	Cost
Cost of Materials	N/A	N/A	\$976.76
Shop Time/Labor Cost	2	\$100/hr	\$200
Team Labor Cost	344.3	\$100/hr	\$34,430
Total Cost			\$35,606.76

Table 2. Total Cost Breakdown

Appendix A

```

%% SCRIPT FOR COMPUTING NEEDED TORQUE TO SHRED PLASTIC
% Torque script, Calderon 03/05/2026, v1.0
%% CLEARING:
clear ;
clc ;
%% SETTING UP KORNUCOPIA:
k_unitsPreferenceActivate('ft_lbf_s') ;
k_unitsVariables('kg, mm, m, cm, in, gm, N, s, RPM, rpm, hp') ;
%% WHAT IS TORQUE WE HAVE ACCESS TO VIA THE MOTOR?:
motor_hp = 1*hp ;
motor_rpm = 1725*RPM ;
motor_torque = motor_hp/motor_rpm ; % KORNUCOPIA HANDLES ALL THE UNITS
motor_torque = motor_torque.convert('in*lbf') ;
%% WHAT CAN WE STEP THE TORQUE UP TO VIA THE GEARBOX?
gearbox_ratio = 60 ; % NO UNITS
gearbox_efficiency = 0.66 ; % PERCENT
output_torque = gearbox_efficiency*gearbox_ratio*motor_torque ;
output_torque = output_torque.convert('in*lbf') ;
%% DISPLAYING RESULTS:
disp('MOTOR TORQUE = ') ;
disp(motor_torque) ;
disp('OUTPUT TORQUE FROM GEARBOX = ') ;
disp(output_torque) ;
*****
MOTOR TORQUE =
    36.54*in*lbf

OUTPUT TORQUE FROM GEARBOX =
    1447*in*lbf
*****

```

	Torque (in. lbf.)
HDPE and PP Non-Precut	>600
HDPE and PP Precut	<600
Motor Output	36.54
Gearbox Output	1447

60:1 Right Angle Cast Iron Worm Gear Reducer 1.16 HP Right Output
HDRS-262-60-R

Surplus Center Item #602013

\$312.45

WorldWide Electric

1750 RPM max. input speed

3/4" dia. x 2" keyed input shaft

1 1/8" dia. x 2 5/8" keyed output shaft

66% efficiency

Appendix B

```
%% SCRIPT SUMMARIZING SOLID MECHANICS ANALYSIS OF SHREDDER COUPLERS
% Final coupler script, Calderon 04/25/2026, v1.0
%
%% CLEARING:
clf ;
close all ;
clear ;
clc ;
%% SETTING UP KORNUCOPIA:
k_unitsPreferenceActivate('none') ;
k_unitsVariables('kg, mm, m, cm, in, gm, N, s, RPM, rpm, hp, lbf, kPa, psi') ;
%% DEFINING GEOMETRY AND TORQUE PARAMETERS FOR DIFFERENT COUPLER SECTIONS:
L = 2*in ; % ALL COUPLERS ARE 2 INCHES IN LENGTH
% MOTOR:
motor_T = 36.54*in*lbf ;
motor_Di = 0.625*in ;
motor_Do = [ 1.1875 , 2.8125 , 1.1218 ]*in ;
motor_w = 0.1875*in ;
motor_h = 0.1081*in ;
% GEARBOX IN:
gboxin_T = 36.54*in*lbf ;
gboxin_Di = [ 0.75 , 0.75 , 1.125 ]*in ;
gboxin_Do = [ 1.1875 , 2.8125 , 2.8125 ]*in ;
gboxin_w = 0.1875*in ;
gboxin_h = 0.161*in ;
% GEARBOX OUT:
gboxout_T = 1447*in*lbf ;
gboxout_Di = 1.125*in ;
gboxout_Do = [ 1.625 , 3.25 ]*in ;
gboxout_w = 0.25*in ;
gboxout_h = 0.1391*in ;
% SHREDDER:
shredder_T = 1447*in*lbf ;
shredder_Di = 0.625*in ;
shredder_Do = [ 1.625 , 3.25 , 1.1218 ]*in ;
shredder_w = 0.25*in ;
shredder_h = 0.151*in ;
%% COMPUTING STRESS:
% USING "max()" SINCE WE ONLY CARE ABOUT MAX. STRESS ... OR "WORST CASE"
%
% MOTOR:
motor_V_max = max(compute_outer_shear_stress(motor_T, motor_Do, motor_Di)) ;
motor_key = compute_keyway_stress(motor_T, motor_w, L, motor_Di, motor_h) ;
% GEARBOX IN:
gboxin_V_max = max(compute_outer_shear_stress(gboxin_T, gboxin_Do, gboxin_Di)) ;
gboxin_key = compute_keyway_stress(gboxin_T, gboxin_w, L, gboxin_Di(1, 1), gboxin_h) ;
% GEARBOX OUT:
gboxout_V_max = max(compute_outer_shear_stress(gboxout_T, gboxout_Do, gboxout_Di)) ;
gboxout_key = compute_keyway_stress(gboxout_T, gboxout_w, L, gboxout_Di, gboxout_h) ;
% SHREDDER:
shredder_V_max = max(compute_outer_shear_stress(shredder_T, shredder_Do, shredder_Di)) ;
shredder_key = compute_keyway_stress(shredder_T, shredder_w, L, shredder_Di, shredder_h) ;
%% DISPLAYING RESULTS:
% USING "max()" SINCE WE ONLY CARE ABOUT MAX. STRESS ... OR "WORST CASE"
clc ;
fprintf('-----\n') ;
fprintf('motor_V_max = %0.1f psi\n', max(motor_V_max.Data)) ;
fprintf('motor_key = %0.1f psi\n', motor_key.Data) ;
fprintf('-----\n') ;
fprintf('gboxin_V_max = %0.1f psi\n', max(gboxin_V_max.Data)) ;
fprintf('gboxin_key = %0.1f psi\n', gboxin_key.Data) ;
fprintf('-----\n') ;
fprintf('gboxout_V_max = %0.1f psi\n', max(gboxout_V_max.Data)) ;
fprintf('gboxout_key = %0.1f psi\n', gboxout_key.Data) ;
fprintf('-----\n') ;
fprintf('shredder_V_max = %0.1f psi\n', max(shredder_V_max.Data)) ;
fprintf('shredder_key = %0.1f psi\n', shredder_key.Data) ;
fprintf('-----\n') ;
```

```
%% FUNCTION WHICH COMPUTES OUTER SHEAR STRESS FOR CIRCULAR TUBE GEOMETRY
```

```
% Outer shear stress function, Calderon 04/25/2026, v1.0
```

```
function [V_max] = compute_outer_shear_stress(T, Do, Di)
```

```
    J = (pi./32).*(Do.^4 - Di.^4) ;
```

```
    V_max = (T.*Do)./(2.*J) ;
```

```
end
```

```
%% FUNCTION WHICH COMPUTES SHEAR STRESS FOR COUPLER KEYWAY
```

```
% Keyway stress function, Calderon 04/25/2026, v1.0
```

```
function [V_key] = compute_keyway_stress(T, w, L, Di, h)
```

```
    V_key = (0.577.*4.*T)./(w.*L.*(Di + h)) ;
```

```
end
```

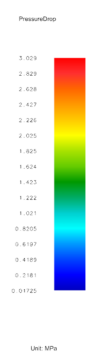
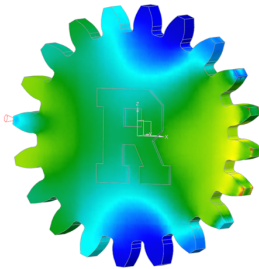
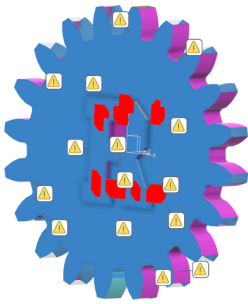
Appendix C

Morgan Ransom
 Plastics – Gate D
 Moldability Checks

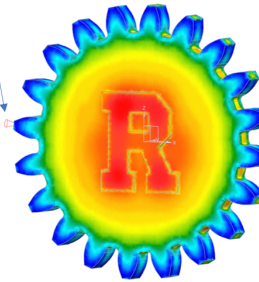
Molded Part Design Navigator

Title	Hint	Result	Information
Moldability Validation			
Thick Walls		⚠	Thickness is outside the L...
Thin Walls		✅	
Positive Draft		⚠	Draft angle found less th...
Vertical Walls		⚠	Vertical walls found in th...
Negative Draft		⚠	Draft angle found less th...
Sharp Corners		✅	
Undercut Regions		⚠	Undercut regions found l...

- Warnings from Moldability Validation:
1. Thickness is outside the limit of 3.5 mm
 2. Draft angle found < 0.5 deg in draw direction
 3. Vertical walls found in draw direction
 4. Draft angle found < 0.5 deg in reverse draw direction
 5. Undercut regions found in the draw direction



Gate



Air trap



Figure C1: Mold Fill Analysis

Appendix D

```
%% SCRIPT ESTIMATING SERVICE LIFE OF SHREDDER COUPLER
% Coupler fatigue script, Calderon 04/25/2026, v1.0
%
%% CLEARING:
clf ;
close all ;
clear ;
clc ;
%% SETTING UP KORNUCOPIA:
k_unitsPreferenceActivate('none') ;
k_unitsVariables('kg, mm, m, cm, in, gm, N, s, minute, hr, RPM, rpm, hp, lbf, kPa, psi, ksi') ;
%% DEFINING STRESS FLUCTUATION VALUES:
% NOTE: we have a mean stress of zero here, since a given coupler fiber is
% subjected to equal-in-magnitude tensile and compressive loads ~28 times
% per minute
shredder_s_max = 8607.4*psi ;
shredder_s_min = -8607.4*psi ;
%% COMPUTING STRESS AMPLITUDE:
shredder_s_a = 0.5.*abs(shredder_s_max - shredder_s_min) ;
%% DEFINING CYCLES PER MINUTE:
shredder_speed = 1725./60 ;
%% USING TABULATED DATA TO LINEARLY INTERPOLATE TO FIND CYCLES TO FAILURE:
% https://digital.library.unt.edu/ark:/67531/metadci385799/m2/1/high\_res\_d/10157028.pdf
shredder_cycle = lin_interp(8.49*ksi, 9.35*ksi, 5E5, 2E5, shredder_s_a) ;
%% COMPUTING SERVICE LIFETIME:
shredder_life = shredder_cycle./((shredder_speed./(1*minute))) ;
shredder_life = shredder_life.convert('hr') ;
%% DISPLAYING RESULTS:
clc ;
fprintf('estimated shredder coupler service life = %0.1f hrs\n', shredder_life.Data) ;
```


Appendix F

Taryn Langtry
 ME 205 – Gate D
 Tolerance Analysis

```
clear all
close all

d_shaft = 3/8;
D = 3/8;

% Tolerance Grade IT11 from Shigley
dD = 0.0035;

% Calculate plus/minus tolerances
D_max = D + dD
D_min = D
```

D_max = 0.3785
 D_min = 0.3750

Basic Sizes	Tolerance Grades					
	IT6	IT7	IT8	IT9	IT10	IT11
0-0.12	0.0022	0.004	0.006	0.010	0.016	0.024
0.12-0.24	0.003	0.005	0.007	0.012	0.019	0.030
0.24-0.40	0.004	0.006	0.009	0.014	0.023	0.035
0.40-0.72	0.004	0.007	0.011	0.017	0.028	0.043
0.72-1.20	0.005	0.008	0.013	0.020	0.033	0.051
1.20-2.00	0.006	0.010	0.015	0.024	0.039	0.063
2.00-3.20	0.007	0.012	0.018	0.029	0.047	0.075
3.20-4.80	0.009	0.014	0.021	0.034	0.055	0.087
4.80-7.20	0.010	0.016	0.025	0.039	0.063	0.098
7.20-10.00	0.011	0.018	0.028	0.045	0.073	0.114
10.00-12.60	0.013	0.020	0.032	0.051	0.083	0.126
12.60-16.00	0.014	0.022	0.035	0.055	0.091	0.142

$$D_{\max} = D + \Delta D \quad D_{\min} = D$$

Figure F1: Tolerance Analysis