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An Examination of ME449 Redesign and Prototype Fabrication: A New Senior/Grad Design and Fabrication Course at the University of Wisconsin –Madison

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An Examination of ME449:

A New Design and Fabrication Course in the Department of Mechanical Engineering at the University of Wisconsin - Madison

Introduction

This paper details the development of a new design and fabrication course in the Department of Mechanical Engineering. The intended goals, the problems encountered in implementation, the adjustments made to the course curriculum, and the final outcomes will be discussed.

Justification of Need

It was determined through feedback from students of the undergraduate Mechanical Engineering program, their potential employers, and the department's Industrial Advisory Board that a more extensive design and fabrication experience was desired. Initial feedback pointed to the need for a design experience at the sophomore/junior level to fill the large time void between the College of Engineering's Freshman Design Experience and the student's senior capstone design course. A proposal was developed for the creation of a sophomore level design course that would include an extensive fabrication component. The funding for the development of this course was provided through a generous private benefactor with strong ties to the University and the Mechanical Engineering Department along with a history of support for undergraduate education. This provided summer funding for course development and the hiring of a teaching assistant for the first semester. The instructional staff associated with the course during its initial four semesters is given in Table 1. The course was initially offered using the department's course development number, ME 601. This developmental course number would prove problematic to the stated course goals due to our intended target audience. The course is being offered under its formal course number, ME 449, for the first time in Spring 2015.

Table 1: ME 449 (formerly ME 601) Instructional Staff by Semester

Semester	Instructional Staff	Teaching Assistant
Fall, 2012	Prof. Jay Martin Prof. Frank Pfefferkorn	Scott Jahanek
Spring, 2013	Prof. Jay Martin Kim Manner, Senior Lecturer	Scott Jahanek
Fall, 2013	Prof. Frank Pfefferkorn Kim Manner, Senior Lecturer	Christopher Westphal
Spring, 2014	Prof. Frank Pfefferkorn Kim Manner, Senior Lecturer	Christopher Westphal

The Stirling Engine

During the semester, each student will fabricate and test their own Stirling engine: a thermo-mechanical device. A Stirling engine is a heat engine that operates by cyclic compression and expansion of a working fluid (e.g., air) at different temperatures[1]. Based upon the Stirling cycle, it is a closed-cycle regenerative heat engine. This means that the system uses two constant volume regenerative cycles. The regenerator can be a wire or ceramic mesh, or any kind of porous plug with a high thermal mass[2]. It is this use of a regeneration system that distinguishes the Stirling engine from other types of heat engines. In our case the regenerator was constructed from non-woven ultra-fine grade silicon carbide material (Scotch Brite™ UltraFine Pad). Silicon carbide does possess a high thermal conductivity and relatively high specific heat for a solid[3], however, the effectiveness of our regenerators were never evaluated. Despite this, we will continue to refer to this device as a Stirling Engine in this paper.

The Stirling Engine used for the course is based upon a design by Dr. James R. Senft, Professor Emeritus of Mathematics, University of Wisconsin – River Falls, and referred to as a Gamma-Type[5]. The engine is capable of sustained operation with a 20°C temperature differential between the hot and cold reservoirs of the engine, which in this case are the upper and lower plates of the containment volume (Figure 1 and Appendix Figures A2-A3).

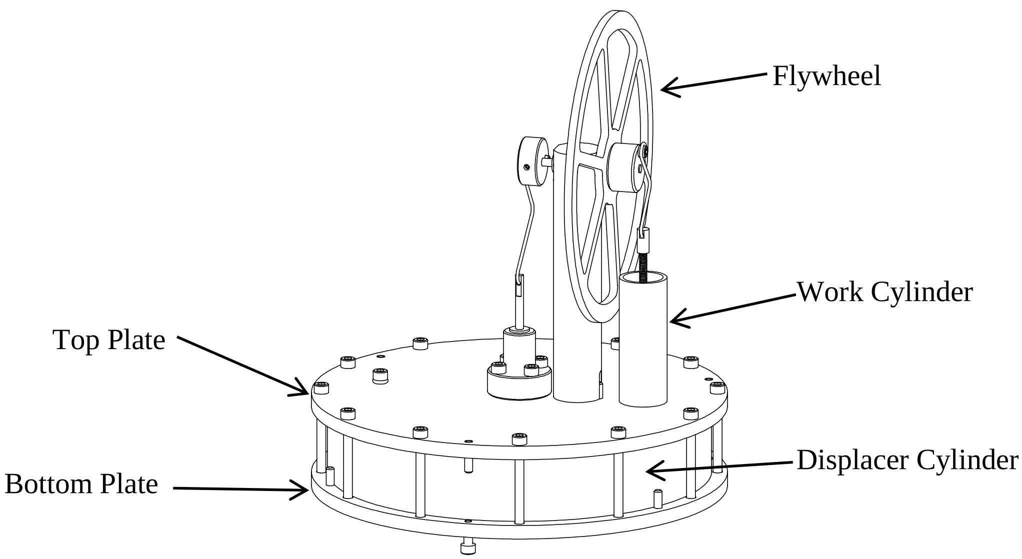


Figure 1: Schematic of gamma-type Stirling engine used in the course

The Stirling engine was chosen as the semester-long build and redesign focus of the course because of its mechanical and operational simplicity. Despite this simplicity, it still provides ample areas for design improvement and requires a keen attention to detail during its fabrication. The theoretical calculated efficiency for the Stirling cycle at a 20°C temperature differential is less than 7%. This calculation is based upon calculation of efficiency of a Carnot cycle using the same temperature differential. By calculating this efficiency we can set an upper limit to the Stirling efficiency since no engine operating between heat reservoirs can have a higher efficiency than the Carnot cycle.

A Carnot cycle engine using an ideal gas as an operating fluid has an efficiency given by;

$$\eta = 1 - \frac{T_C}{T_H}$$

where T_C *and* T_H are the temperatures (in Rankin) of the hot and cold reservoirs[4]. Using the values of $T_C = 0\ ^\circ\mathrm{C}$ *and* $T_H = 20\ ^\circ\mathrm{C}$, as proposed for our testing procedure, we obtain a 7% maximum efficiency.

Of course, the actual efficiency of our Stirling engine design is significantly lower. All losses through mechanical sources (friction), thermal sources (heat transfer) and fluid flow (aerodynamic and pressure loss), reduce this efficiency below the 7% ceiling. Due to its low efficiency, simply obtaining a running engine requires students to pay close attention to topics such as their machining tolerances and assembly techniques.

Our engine testing procedure involves placing the engine (Figure 1) upon an ice bath, waiting 30 seconds to allow heat transfer transients to diminish (i.e., stabilization of the bottom and top plate temperatures), starting the engine by a small push of the flywheel and then after another 30 seconds of run time, recording the speed of the engine based upon the RPM of the flywheel. This procedure provides for an approximately 20°C temperature differential between the top plate at approximately 20°C (room temperature) and the bottom plate at approximately 0° C (ice bath). Thermocouples are used to measure the actual temperatures during testing.

Formal Course Description

This course has a lecture/lab format. There are (2) one hour lectures and (1) three hour lab per week. The lectures cover topics such as the principals of both product design and product re-design along with the manufacturing processes the students will be using during the course of Stirling engine fabrication. The lecture period also provides discussions of the thermal and mechanical processes occurring within the engine and areas of potential energy loss. Additional topics of relevance to the students are lectures on Design for Manufacturability and Design for Assembly (DFM/DFA), aesthetics in design, and the use of prototyping in the design process. A copy of the course syllabus is given in the Appendix, Document 1.

Students in the class receive a basic design for a Gamma-Type, Stirling Engine. A Gamma-Type engines is one in which the engine displacer and power piston exist in different cylinders[5]. The design materials provided to the students consist of a complete set of model files for the fabricated components along with an assembly drawing with a bill of materials (BOM). In addition, students are given machining protocols for the components that they will fabricate. Students generate formal detail drawings of the fabricated components during the course of the semester. Examples of the machining protocol and the technical drawing for one of the Stirling engine components are given in the Appendix in Document 2 and Figure A1, respectively. The Stirling engine assembly and BOM are also provided (Appendix, Figures A2-A4).

Each student does all the manufacturing (e.g., machining, wire bending, laser cutting) required for the majority of the fabricated components themselves, under the supervision of the course TA and the College of Engineering Student Shop staff. The exception is the flywheel component which is laser cut by a local vendor and the displacer is laser machined in the Student Shop. The students do however, design the flywheel (Figure 2) within vendor and assembly constraints and handle all interactions with the vendor, providing another valuable design experience. Components that are purchased include the glass work cylinder (part 18), graphite piston (part

19), o-rings, bearings, and fasteners. Starting in the Spring 2015 semester the displacer bushing (part 9) is being printed in the Student Shop on an FDM machine. In prior semesters, the displacer bushing was machined out of nylon.

Figure 2: Flywheels designed by students

Also, the student must fully assemble the basic design of the Stirling Engine. Once completed, the engine is then tested to establish benchmark values of speed at a measured temperature differential as well as build quality and aesthetics. The build quality and aesthetic evaluations are performed as peer evaluations by the class as a whole. As an ancillary project during the course, students are also required to fabricate a sheet metal box which will be used as their containment vessel for the ice bath. The students are given a square piece of sheet metal to use in fabrication and the final overall dimensions of the box. These sheet metal boxes are also evaluated for build quality, aesthetics, dimensional accuracy, safety (i.e., sharp edges), and water tightness.

Students are asked to perform a critical examination of the functions of each of the components for the basic Stirling Engine design with the intent of identifying design changes that would provide improvements in performance. Performance could include operational increases in speed for a given temperature differential. When considering these design improvements, identifying areas where energy losses can be reduced is critical. Evaluation could also include a critical examination of the machining protocols provided using Design for Manufacturing (DFM) principals presented during the course lectures or aesthetic improvements to the engine. Proposed design changes must be justified by defining metrics for evaluation and analytically or empirically demonstrating an improvement. In conducting these evaluations, students are asked to consider;

What characteristic needs to be measured?
How is the characteristic measured?
What target values are you hoping to meet?
Under what conditions will the characteristics be measured?

and from this information design and write a test protocol.

Students are then required to fabricate any redesigned components, and demonstrate a performance improvement against their benchmark values. This effort must be fully documented in deliverables: a written report and oral presentation, at the end of the course. The students get to keep their engines (Figure 3).

Figure 3: Final redesigned Stirling engine of a student

Difficulties Encountered in Implementation

During the first semester that the course was offered, Professors Martin and Pfefferkorn taught this course with Scott Johanek as the TA. Despite the period of summer development, it soon became apparent that the instructional staff were not fully prepared for the complex task of guiding students in the process of manufacturing and assembling the Stirling Engines. A critical mistake was the failure to actually build one of the engines before the semester started and therefore learn from the process. Additionally, the course TA had not machined all the components himself before the start of the class.

A different test method from that currently used for engine evaluation was employed during the first semester. Engines were placed on a hot plate and the temperature was increased until the engine would run. The estimated temperature difference (between the hot plate and room temperature) was recorded along with the speed (RPM) of the engine. The instructors recall that only 50% of the student's engines actually ran by the end of the semester. In one memorable incident, a student during their attempt to make their engine run tested it on a kitchen stove and melted the polycarbonate displacer cylinder (part 3). So much time was devoted to building the engines and making them operate that very little time was devoted to redesigning the engine. By the third semester that this course was offered (Table 1) every student had their engine running on an ice bath by the end of the semester.

As mentioned earlier, the use of the developmental course number ME 601 caused its own problems. In the Department of Mechanical Engineering, formal engineering courses with a number of 400 or greater may be taken for technical elective credit by undergraduate students and for program credit by graduate students. This, along with the subject matter, made the course attractive to these students. Since course enrollment occurs for students in order of their classification (graduate students, then seniors, juniors, etc.), the course would tend to fill before the original target audience of sophomores were able to register. Also, because the developmental number is “601” there was a perception by many sophomores that this was a 600-level course and not something that would be suitable for them. This perception persisted despite our efforts to advertise the new course offering and clearly state that sophomores were encouraged to enroll. This is reflected in the enrollment numbers listed in Table 2.

Table 2: Semester Enrollment in ME 449 (formerly ME 601)

Semester	Sophomore	Junior	Senior	Graduate
Fall, 2012	3	6	2	3
Spring, 2013	0	2	14	8
Fall, 2013	0	2	13	3
Spring, 2014	0	2	17	5

Additionally, it was noted during that first semester that students with lower technical backgrounds, e.g., those who had not completed courses in both thermodynamics and heat transfer, were at a disadvantage, even when the material was presented qualitatively rather than quantitatively. Another issue involving the sophomores is that many at that level had not yet been accepted into a degree program. Program acceptance required maintaining a prescribed minimum grade point average GPA). The sophomores involved in that initial semester commented that the time commitment involved with the course, especially the time spent in the Student Shop, hampered their efforts to maintain the GPA necessary to enter a department.

Adjustments to Course

During subsequent semesters, the composition of the course changed as fewer lower level undergraduate students enrolled (Table 2). Due to this change, the material within the course was adjusted such that expectations were raised in terms of the analytical efforts of the students. By the third time the class was offered, a mid-term exam was added. Formal calculations of energy losses were required of the students.

One critical development that occurred for the third offering of the course (Fall, 2013) was the hiring of a new TA for the course, Christopher Westphal, who possessed a strong skill set in machining and design. He improved and documented the machining protocols (see Appendix, Document 2), developed more detailed lab materials for the students, created training videos for certain manufacturing procedures, and built manufacturing fixtures for some of the parts.

Recommendations

After four semesters of development it was determined that the course was best suited for senior undergraduates and graduate students. Material had evolved along with the changes in enrollment (see Table 2) to contain higher expectations of academic rigor. With these considerations, the final formal course description was developed. This was submitted and approved by the departmental curriculum committee and eventually the University's Physical Sciences Divisional Committee. The course was assigned a formal course number of ME 449 and was offered for the first time as an official course during the Spring 2015 semester.

While committed to retaining the new ME449 course as a senior/grad technical elective, we did not wish to abandon the original objective of a sophomore/junior design experience with a fabrication component. Toward this end, the course faculty has indicated to the departmental curriculum committee the need for a low-level developmental course number so as to avoid the registration problems previously experienced. The course faculty, based upon input from the rest of the department faculty, came to the conclusion that a sophomore/junior design course should be a required course for the department and course development should take that into account. This does present several problems which would need to be addressed. First and foremost is identifying if the additional credits required for such a course would increase the program degree requirements or come from removing or modifying an existing required course. In addition, a sophomore/junior design course would have to serve 120-140 students a semester based upon current enrollments. It rapidly became apparent that any serious fabrication component within such a class would overburden our already crowded Student Shop facility, and hence would not be feasible at this time. In conclusion, the concept of a sophomore/junior design experience is still being considered and at this writing, proposals are being developed which address the issues identified.

Outcomes

Despite the heavy workload of the course, particularly in terms of the time spent working in the student machine shop, the course has been well received by students. This is evidenced by the results of semester student course evaluations for the course (Table 3). Scores for ME449 (previously ME601) were consistently higher than those for all ME required classes and scored very well when compared to all senior/graduate level courses (technical electives), even those with very low enrollments (6 – 8 students) which has a tendency to skew higher in approval.

It was noticed that the scores for the course varied significantly over the four semesters. It is the author's opinion that the rise in student approval during the first three semesters was due to ongoing adjustments made to improve the course, in particular, making the connections between the lecture material more obviously relevant to the redesign and prototyping process. The drop for the Spring 2014 semester is likely due to the move to electronic surveying methods, which decreased the student response rate and in the minds of many faculty at our institution, skewed responses to the negative, based upon the opinion that those students who had a bad experience were more likely to take the time to respond.

On the positive side, the course has also been very well received by members of the department's Industrial Advisory Board and company interviewers. Students have discovered that discussing the course with potential employers and even bringing their Stirling Engine to interviews to be particularly impactful. One instance involved a student who claimed he received an internship at the Harley Davidson Corporation due to his involvement in the course. One anecdotal outcome of note involves a department alumnus, who upon seeing a course demonstration at an open house and meeting and talking with several students, made a six figure donation to the department targeting instructional efforts in design.

Table 3: Student Response to "Overall, how would you rate this course?"

Semester Taught	*Response to Question for ME601/449*	*Average Response for all required ME undergraduate courses*	*Average response for all ME senior/grad technical electives*
Fall 2012	*3.83*	*3.62*	*4.45*
Spring 2013	*4.19*	*3.66*	*4.41*
Fall 2013	*4.82*	*3.34*	*4.07*
Spring 2014	*3.79**	*3.56**	*4.11**
Average Response	***4.19***	***3.55***	***4.26***

** The results for the Spring, 2014 semester represent the first time that all Student Evaluations in the Department of Mechanical Engineering were conducted electronically. The response rate for this semester was less than 60%. Paper evaluation response had been greater than 80%.*

Conclusions

This is a lab-intensive course with a semester project that students spend between 50 to 80 hours on, by their own estimates. Instructional cost to the department is somewhat high due to the fact that each lab section is capped at eight students, the extensive use of machine shop resources, and the use of a TA. In the Department of Mechanical Engineering this is the only 400-level course (for which graduate credit is given) with a TA. Material costs for creation of the Stirling Engine and sheet metal box are approximately $100 per student. There is currently little expense to students as the material expense in borne by the department and there is no text for the course.

Despite the cost, this course will be offered as a technical elective once per academic year. Both undergraduate and graduate students learn a great deal from hands-on experience using the manufacturing tools/processes available in the college of engineering while participating in a complete engineering experience that combines: design, dimensioning and tolerancing, manufacturing, and quantitative analysis. The course is important to undergraduates interested in careers in design and manufacturing and an important addition to the department's design offerings. The course is invaluable to any graduate student working in an experimental lab environment. One of the authors requires that all of his new graduate students take this course in order to prepare them for conducting research experiments.

References

[1] "Stirling Engines", G. Walker (1980), Clarenden Press, Oxford, page 1
[2] “Thermodynamics: An Engineering Approach”, Yunus A. Cengal, Michael A. Boles (1998), WBC McGraw-Hill, ,pp. 504-505
[3] Silicon Carbide, SiC Ceramic Properties, Accuratus Corporation, <http://accuratus.com/silicar.html>
[4] “Engineering Thermodynamics”, J.B.Jones, R.E.Dugan (1996), Prentice Hall, New Jersey pp. 300-305
[5] “An Introduction to Low Temperature Differential Stirling Engines”**,** James R, Senft (1996), Moriya Press

Appendix

Document 1: Syllabus for ME 449 for Spring 2015

#	Date			Topic	Assignment(s) Due
	Jan.	19	M	MARTIN LUTHER KING JR. DAY (NO LECTURE)	
1		21	W	Introduction to the class	
Lab		22	Th	***Metrology & Red Permit Seminar***	
2		26	M	Introduction to the Stirling engine	
3		28	W	Dimensioning and tolerancing	
Lab		29	Th	***Green Part Seminar (every student must attend)***	Red Part; Green Permit Quizzes
4	Feb.	2	M	Introduction to design process (customer base)	
5		4	W	Design for Manufacturability	
Lab		5	Th	***Computer Aided Design Software (SolidWorks) – Rm. 1263 ME***	
6		9	M	Determining customer requirements & engineering requirements	
7		11	W	The lathe and turning operations	
Lab		12	Th	***Lathe 1 - Displacer Bearing Sleeve***	Green Part; Engr. Drawings for Parts 5-10, Model of Part 16
8		16	M	Concept generation techniques - Concept evaluation (Manner)	
9		18	W	Fasteners (Manner)	
Lab		19	Th	***Lathe 2 - Pressure Turn Top and Bottom Plate***	Parts 5-10 (per lab instr.); Complete Parts 9 & 10; Engr. Drawings for Parts 1 & 2
10		23	M	The milling machine and live tooling	
11		25	W	Stirling engine analysis 1	
Lab		26	Th	***Mill 1 - Machine Parts 1, 2 & 5 per Lab Instructions***	Parts 1, 2, & 5 (per lab instr.); Obtain CNC Mill 1 Upgrade
12	Mar.	2	M	Stirling engine analysis 2	
13		4	W	Stirling engine analysis 3	
Lab		5	Th	***Sheet Metal – Make Watertight Tray***	
14		9	M	Stirling engine analysis 4	
15		11	W	**Sheet metal box competition**	Sheet metal box
Lab		12	Th	***Mill 2 – Complete Parts 5 and 8 (started in Lathe 2)***	Complete Parts 1, 2, & 5
16		16	M	Guest speaker from Milwaukee Tool (Design Process)	
17		18	W	Rapid prototyping	**Midterm (take home)**
Lab		19	Th	***Rapid Prototyping – Laser Cutting Displacer***	Engr. Drawings for Part 4; Complete Parts 6-8
18		23	M	Stirling engine performance measurement 1	
19		25	W	Stirling engine performance measurement 2	
Lab		26	Th	***Odds and Ends (finish small parts that do not require machine tools, and Consultation with Shop Staff)***	Complete Parts 13 & 14
	Mar. 28 – Apr. 5			SPRING BREAK (NO LECTURES OR LAB)	
20	Apr.	6	M	Benchmark stirling engine performance	Operating Stirling engine
21		8	W	Benchmark stirling engine performance	Operating Stirling engine
Lab		9	Th	***Prototyping with Common Materials – Start Transport Vehicle***	
22		13	M	Discussion of Stirling engine design refinements	
23		15	W	Discussion of Stirling engine design refinements	
	Apr. 16-18			Engineering EXPO 2015 (NO LECTURES OR LAB)	
24		20	M	Transport Vehicle Competition (1st Floor ECB)	Transport vehicle
25		22	W	Transport Vehicle Competition (1st Floor ECB)	Transport vehicle

Lab		23	Th	***Free Time to Work on Stirling Engine (TA available)***	
26		27	M	Discussion of Stirling engine design refinements	
27		29	W	Discussion of Stirling engine design refinements	
Lab		30	Th	***Free Time to Work on Stirling Engine (TA available)***	
28	May	4	M	Semester Project Presentations (8-10 AM, room 1025 ECB)	PowerPoint presentation
29		6	W	Semester Project Presentations (8-10 AM, room 1025 ECB)	
Lab		7	Th	***Semester Project (Stirling Engine) Evaluation***	Improved Stirling engine; Final report on Stirling engine

Document 2: Example of Manufacturing Protocol (part 6)

Example Manufacturing Protocol
Cylinder Base

1. Original Material Ordered
    a. Supplier: Liebovich Aluminum & Steel
    b. Material: Aluminum 6061-T6
    c. Dimensions: 0.75"OD x 12'L
    d. Cost: $29.12
2. Stock Material
    a. 0.75"OD x 2.75"L
3. Tools
    a. To be checked out at the shop window
        i. Mill Bastard File
        ii. 6" Caliper
        iii. 6" Ruler
        iv. #4 Center Drill
        v. 5/16" Twist Drill
        vi. Countersink
        vii. 0.093" Groove Tool with Shim – *remind staff that this is in the ME601 box*
        viii. Hole-Deburring Tool
    b. To be found in the shop
        i. OD turning tool – *ask staff*
        ii. Parting tool – *at your lathe's workbench*
        iii. Empty tool holder – *at your lathe's workbench*
        iv. Drill chuck – *at your lathe's workbench*
        v. 5mm Allen wrench – *at the shop's workbench, by the staff podium*
        vi. Bubble Level and Adapter – *ask staff*
4. Tool Setup
    a. Set the height of the OD Turning Tool, Groove Tool, and Parting Tool
        i. Before seating the OD turning tool onto the tool post, clean the dovetail groove and bottom side of the knurled height adjustment nut. Also, clean the dovetail groove and top surface of the tool post.
        ii. Secure the tool into the tool post.
        iii. Adjust the height of the OD turning tool by screwing the adjustment nuts up and down until the bubble level is in the center.
        iv. Thread the hex nut against the knurled adjusting nut and finger tighten.
        v. Remove the OD turning tool and repeat the above steps for the Groove Tool and Parting Tool
    b. Square the tool post
        i. Prior to securing the drill chuck into the tailstock, make sure you do the following:
            1. Wipe off the shank of the drill chuck with your hands
            2. Clean the inside of the tailstock quill
        ii. To insert the drill chuck into the quill, extend the quill out past the tailstock by more than one (1) inch. Rotate the drill chuck until the tang seats into its slot. Retract the jaws of the drill chuck and use your palm to lock it into the quill.
        iii. Bring the face of the quill in contact with the tool post that has been previously loosened. Lock the tool post in place by tightening the tool post nut.

5. Setup 1
    a. Remove all chips and debris from your work piece with your hands as well as the mating surfaces of the jaws. Use the chuck key to secure your part in the chuck, ensuring that it extends past the face of the jaws by 1.25”.
    b. Finish by securing your work piece into the chuck by tightening all three pinions.
6. Operations
    a. Set the DRO
        i. Turn the lathe on, to about 800RPM, and bring the OD turning tool into contact with the face of the work piece, just enough to take a chip. Retract the tool along the X-axis and zero the Z-axis on the DRO.
        ii. Move the OD turning tool towards the chuck by about 0.015” and zero the Z axis on the DRO once more. Take a facing cut towards the center of the work piece. When completed, move the tool away from the chuck and work piece.
        iii. Bring the OD turning tool into contact with the outer diameter of the work piece until a chip flies or a shiny ring forms. Without moving the X axis handwheel, move the cutter off the work piece along the Z axis.
        iv. Zero the x-axis on the DRO.
        v. Take a skim cut of about 0.015” off the outer diameter of the work piece. Slowly move the tool along the Z axis for a distance of about 0.875”. Stop the lathe and move the tool away from the chuck/work piece, but only along the Z axis.
        vi. Measure the outside diameter of the work piece and enter that value into the DRO for the X axis.
        vii. Move the OD turning tool inward by steps of about 0.030” at a time until the desired diameter has been achieved.
        viii. Remember to leave about 0.005” on the diameter for a finishing pass!
    b. Turn down the shoulder to the correct diameter and length.
        i. With the DRO calibrated, start to rough out the shoulder. Remove no more than 0.030” from the diameter per pass and remember to stop about 0.010” short of the desired shoulder length. The last cut on both the OD and shoulder face should be no more than 0.010” in order to achieve a smooth finish.
    c. Cut the O-ring groove
        i. Set the OD groove tool into the tool post and carefully bring the edge into contact with the face of the work piece.
        ii. Zero the Z axis on the DRO.
        iii. Move the grooving tool to where the groove will be cut and turn the lathe on to approximately 300RPM. Carefully bring the cutting edge of the tool into contact with work piece until a small chip forms.
        iv. Enter the known diameter of the work piece.
        v. Cut the groove carefully and with plenty of oil. Break long chips by pausing when feeding the OD groove tool into the part.
    d. Machine the center hole
        i. Prior to inserting the drill chuck into the quill of the tailstock, clean the shank of the chuck and the inside of the quill. Move the quill out past one inch and rotate the chuck in the quill until it is seated.
        ii. Chuck a #4 center drill into the drill chuck and turn the lathe on to about 800RPM. Use a pecking motion to create the starting hole
        iii. Chuck a 5/16” drill bit into the chuck and turn the lathe on to about 800RPM. Drill a 5/16” hole into the work piece using a pecking motion
        iv. Chamfer the hole with the countersink.

e. Part-off the Cylinder Base
    i. Carefully bring the side of the parting tool in contact with the face of the work piece while the lathe is OFF and zero the Z-axis on the DRO.
    ii. Retract the cutting tool along the X-axis so it is clear of the part.
    iii. Measure the thickness of the parting tool and move the carriage towards the head stock by that amount. Re-zero the Z-axis on the DRO.
    iv. Move the carriage closer to the head stock until you have reached the location where you would like to part-off the Cylinder Base.
    v. Turn the lathe on to about 300RPM and begin to part off the piece. Feed the parting tool into the work piece carefully, being sure to pause often to break the chip.
    vi. Before finishing the parting operation, use a file to deburr the sharp edges, especially those of the groove.
    vii. Resume parting until the Cylinder Base separates from the work piece.

f. Clean up the end face of the work piece
    i. Use the OD turning tool to face the end of the work piece.

g. Clean up Cylinder Base
    i. The face in contact with the parting tool can be cleaned up by using a file and the hole can be deburred with a hand-held hole deburring tool.

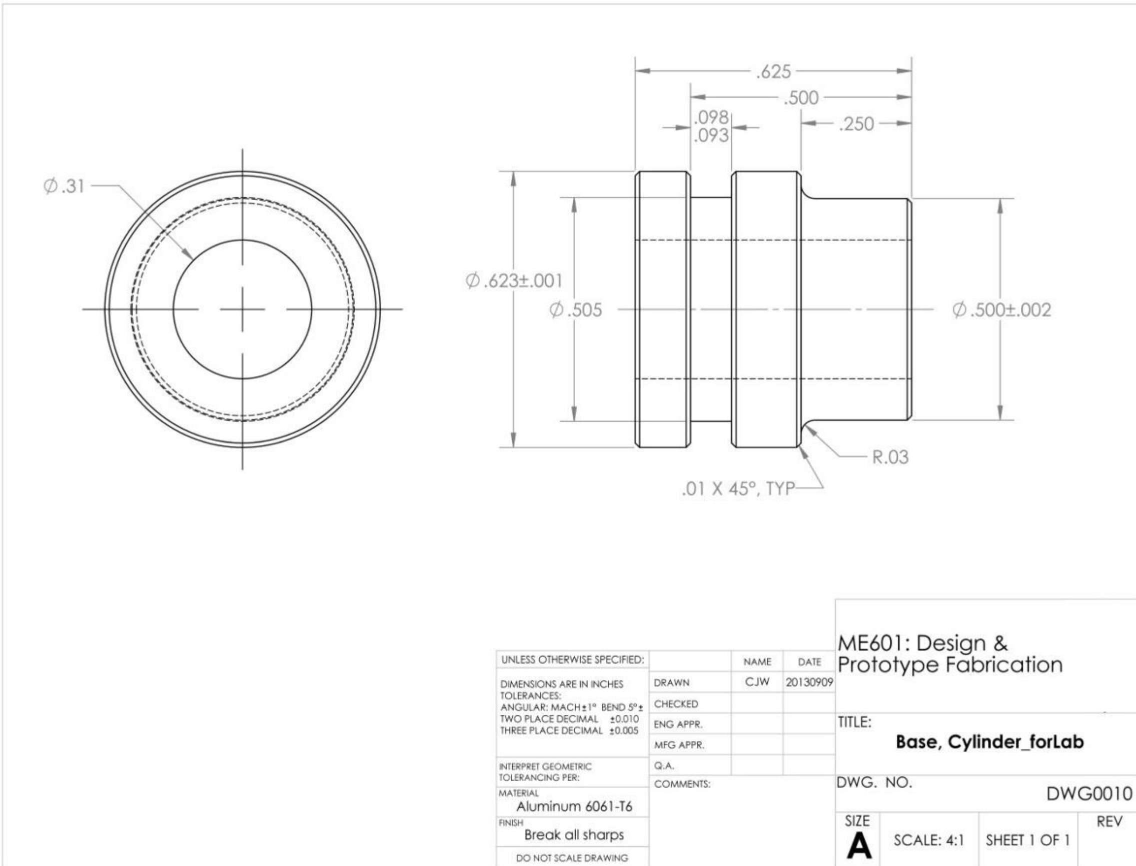
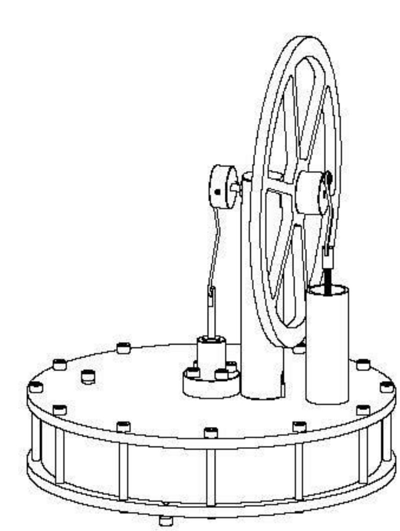


Figure A1: Example of a Student Detail Drawing (part 6)

ITEM NO.	PART NUMBER	QTY
1	Plate, Bottom	1
2	Plate, Top	1
3	Cylinder, Displacer	1
4	Displacer	1
5	Post, Bearing	1
6	Cylinder, Drive, Displacer	1
7	Hub, Crankshaft	1
8	Hub, Flywheel	1
9	Bushing, Displacer	1
10	Base, Cylinder	1
11	Rod, Displacer	1
12	Crankshaft	1
13	Link, Displacer	1
14	Link, Work	1
15	4-40, Nut, Eye	1
16	Flywheel	1
17	Disc, Regenerative	6
18	Cylinder, Work	1
19	Piston	1
20	Bearing, Sleeve	2
21	Bearing, Ball	2
22	Rod, Work	1
23	Dash 005 O-ring	3
24	Dash 012 O-ring	1
25	Dash 014 O-ring	1
26	5.859" O-ring	2
27	0.125, 0.5L, Dowel	1
28	6-32 x 1.5L SHCS	12
29	6-32 x .5L SHCS	4
30	6-32 x .25L SHCS	4
31	4-40 x .375L SHCS	2
32	1/4-20 x 0.75L SCHC Screw	1
33	4-40 x 0.375 SS Flat Skt	2
34	Plug, Plate, Bottom	1
35	4-40, Nut, Hex	2



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: MACH±1° BEND 5°± TWO PLACE DECIMAL ±0.010 THREE PLACE DECIMAL ±0.005	DRAWN	JBP	20150201
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

ME449: Redesign & Prototype Fabrication

TITLE: Stirling Engine

SIZE	SCALE	SHEET	REV
A	SCALE: 1:2	SHEET 1 OF 3	2

Figure A2: Stirling Engine Assembly and Bill of Materials - sheet 1

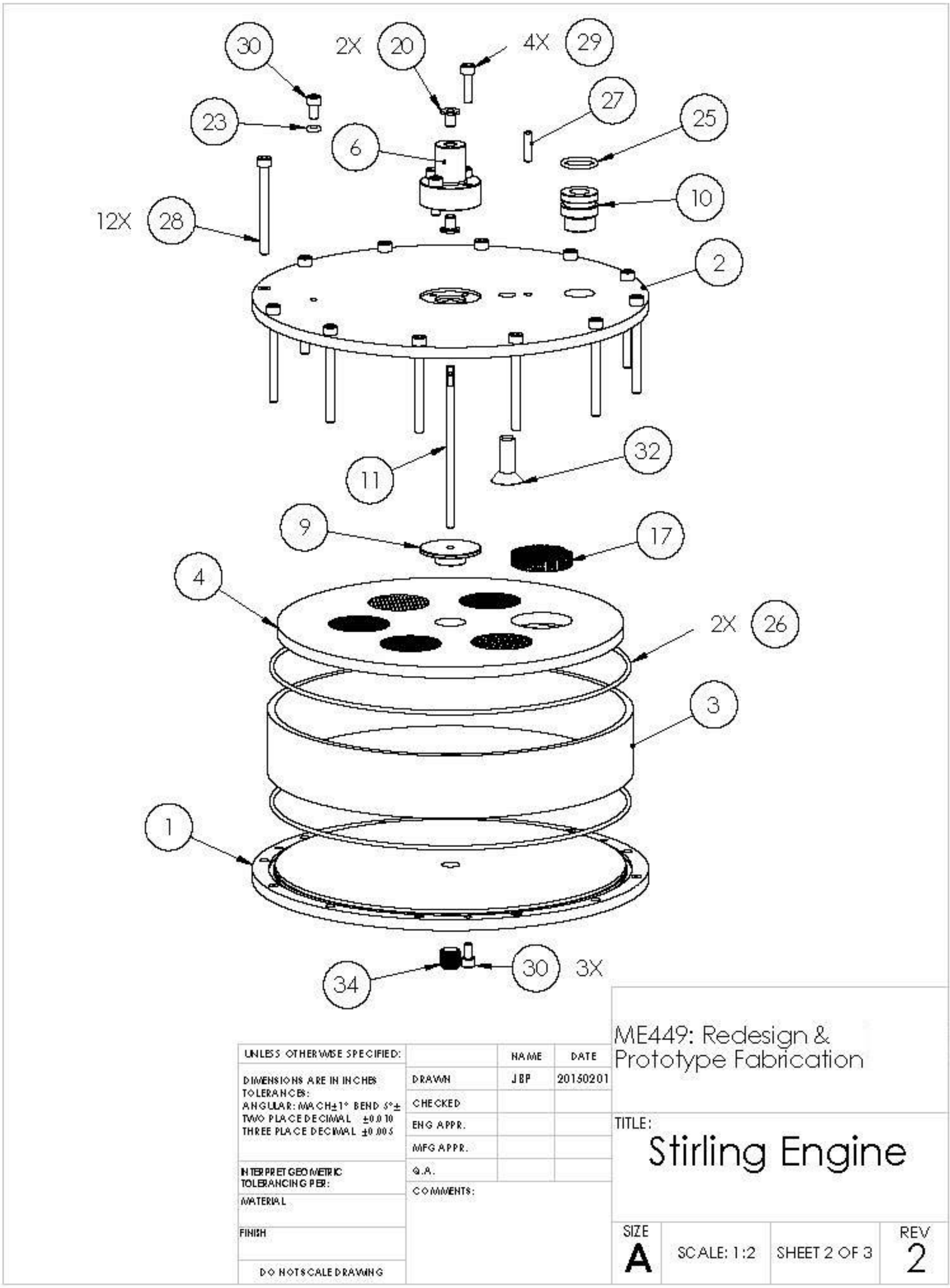


Figure A3: Stirling Engine Assembly and Bill of Materials - sheet 2

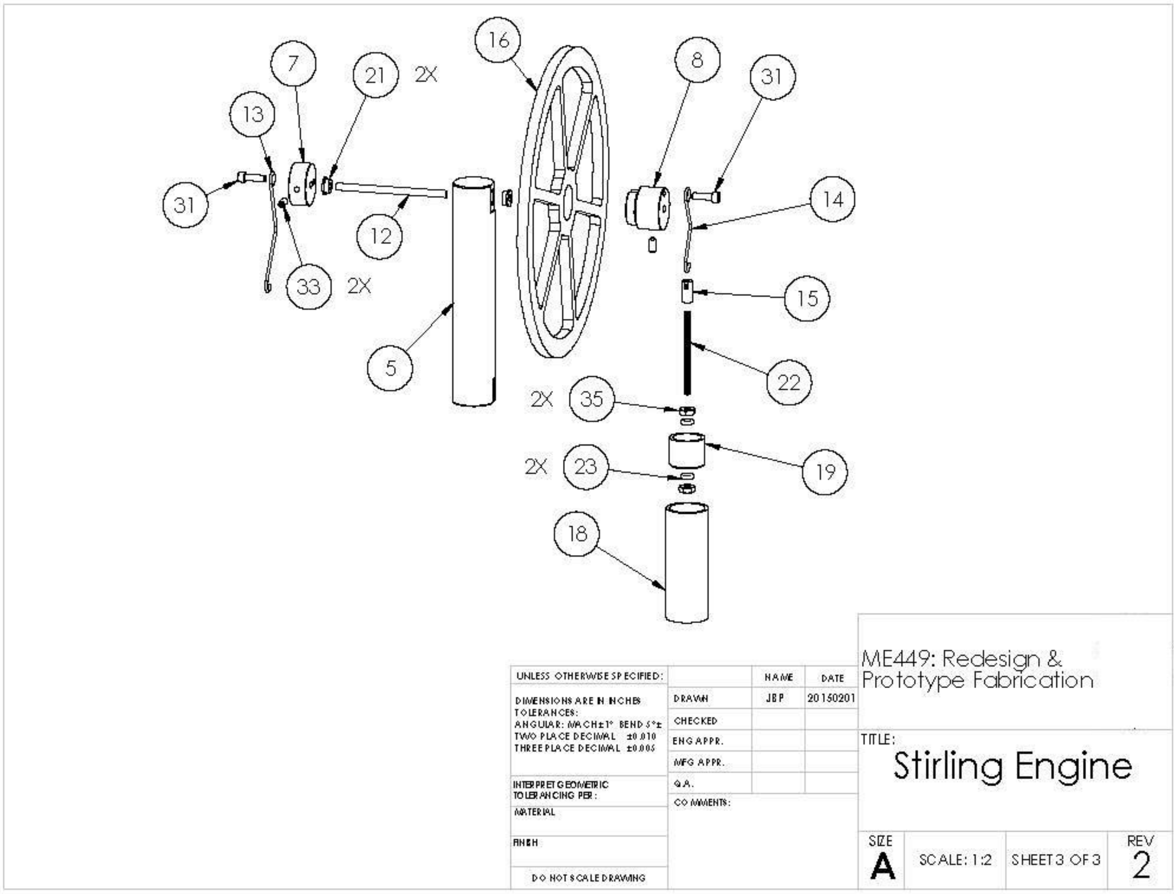


Figure A4: Stirling Engine Assembly and Bill of Materials - sheet 3