Development of a Small Scale Impact Erosion Test Apparatus

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Abstract

This paper presents the development of a fully operational experimentally testing apparatus for testing erosion rates on metal samples to assist in developing more accurate erosion modeling. A group of three undergraduates developed the project from a concept provided by a faculty advisor and constructed a working prototype during a two semester senior design capstone design project integrating both mechanical and electrical fundamentals learned in their studies. The system consists of a pneumatically operated double diaphragm pump for flow, a custom designed abrasive loading and delivering system, custom tank and filtration system, and electronic controls and monitoring capabilities that allow the device to be almost fully autonomous when initiated. The apparatus is able to erode various metal samples at various angles and with varying flowrate controlled by the input fluid pressure and rotation of a custom sand loading auger. The prototype was fully evaluated during a successful summer research project with a completely new set of students. The ability to design a working, usable prototype illustrates the students' effectiveness at using basic engineering practices. This paper presents the design and the processes followed to accomplish this goal.

Keywords

Senior Design Project, Mechanical, fluid flow, erosion

Introduction

Erosion of metal components when exposed to sand laden slurries continue to be a problem in many industries[1]. The cost associated with replacement of eroded parts and the downtime needed when replacing these components often result in large losses to corporations. The ability to model erosional effects on metal components accurately can aid in the reduction of the cost associated with the losses by allowing these metal components to be placed in optimal locations and to allow for replacement to occur before catastrophic failure occurs. A senior design team was tasked with building a custom liquid/solid impact erosion test fixture that would allow testing on various shape and sizes of metal components to satisfy their requirement for a capstone design project. This experimental apparatus should have enough flexibility to allow for changes in multiple parameters in order to execute at minimum a lab study or small scale research project.

Background

Erosion has been studied by many researchers over the years. Ambrosini et al[2] study the erosion behavior of AISI 4140 steel under various heat treatment conditions. Harsha et al[3] carried out research to study the erosion behavior of ferrous and non-ferrous materials and compared the data to various published data and models. Hutchings[4] developed erosion models for normal and oblique angle for various materials and determined the process that causes erosions during the impact events. These include micro ploughing, small craters of indentation, and micro-cracking[5]. Many others took these models and improved upon them via testing [5-11]. The common thread between these models and predictions are the ability to run experiments to test the impact of erosion.

Two main types of solid particle erosion testing equipment exist: the centrifugal tester or the injector tester. The centrifugal tester is based on the projection of particles through centrifugal forces. The particles are fed through the center of a rotating disk accelerated through radial ceramic tubes and ejected onto samples placed around the disk[12]. The second type is the most frequently used system. It is based on specifications found in the ASTM standard G76[13]. The standard test consists of exposing the sample surface for a fixed total mass of powder and evaluating the amount of volume or mass loss. The erosion rate of the tested sample is calculated by dividing the worn volume by the total mass of particles that have impacted the surface[13]. However, the particle velocity and the particle feed rates need to be accurately measured and controlled before and during testing.

This investigator is interested in the differences between the gas injector studies and erosion rates observed in liquid/solid environments. These tests will differ from the standard by using liquids as the flowing fluid and injecting solids in the fluid stream before impact on the test specimen surface. Hence, the students were tasked with building a liquid/solid impact jet tester. The students in this study had vast experience differences which actually complimented the design process for this particular project. Student A was a nontraditional student formerly in the military and had worked in various machine and fabrication shops. Students B and C were traditional engineering students; however, one was an electrical engineering student and the other was a mechanical engineering student.

Design Specifications

The students were provided with a problem statement and minimum specifications that the device needed. The problem statement was to develop a safe, controlled method for experimentally testing particle impact erosion rates on metal samples to assist in more accurate erosion modeling. Minimum specifications were provided as:

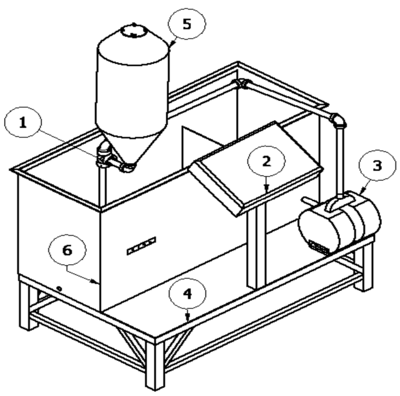
- Maximum test stand dimensions of 8 feet x 8 feet
- Pressure to be no less than 80psi and maximum pressure of standard schedule 80 PVC
- Ability to flow sand/water mixture at low solid to liquid concentrations (<10%)
- Use standard power and air from lab space
- Ability to attach pressure gauges at various locations especially at pump and nozzle
- Testing parameters must be measurable and controllable

Various test configurations were proposed and analyzed and the design chosen after a merit analysis was a system using an auger to load the sand into the flow stream. This system used an auger located near the nozzle to force the sand from the hopper into the fluid flow. The rate of sand input into the flow will be controlled by the rpm of the auger. The fluid/medium mixture would be directed to the sample material by the nozzle. After contacting the sample, the mixture would disperse into the tank.

The table and figure below illustrate the major components of the erosion test fixture that met the required specifications.

Table 1: Final design specifications

Sand Input Method	Auger System
Pump Selection	Double Diaphragm
Controller Type	Arduino Mega 2560
Motor Type	Brushless DC NTM Prop Drive Series 35-36A
Display Screen	LCD Screen



Item Number	Part Description
1	Auger
2	Control Box
3	Diaphragm Pump
4	Frame
5	Sand Hopper
6	Settling Tank

Figure 1: Proposed erosion test fixture Design

This system will be placed on a steel framed stand that is relatively close to the ground to allow for ease of access to components. The top of the stand will be covered with a sheet of treated plywood and a waterproof mat which supports all of the system components. The auger system will be located below the sand hopper and near the nozzle to reduce to length of pipe that will be subject to the abrasive flow. The control box will be located on the stand that will be used to regulate the RPM of the auger system and to display pressures readings at the pump and nozzle. A sample holder will be located inside of the tank to hold the test sample under the nozzle.

Mechanical Design and Manufacturing Process for Sand Delivery

All parts and calculations were made and done by students involved in the study. The first components that were manufactured were the auger system components. It was one of the more complex mechanical system of the assembly. The auger assembly consists of a housing, auger, and various end collars and attachments to seal the chamber and to connect it to other piping in the system.

Since student A has had experience in the machine shop, this task was his primary task. The first component of the auger assembly that was manufactured was the auger housing. Standard threads, as opposed to pipe threads, were chosen for the motor end of the housing because it would allow for different styles and thickness of seals. Custom knurled threaded collars that corresponded with the threaded housings were the next process. A drawing of the two collars can be seen in **Figure 2.**

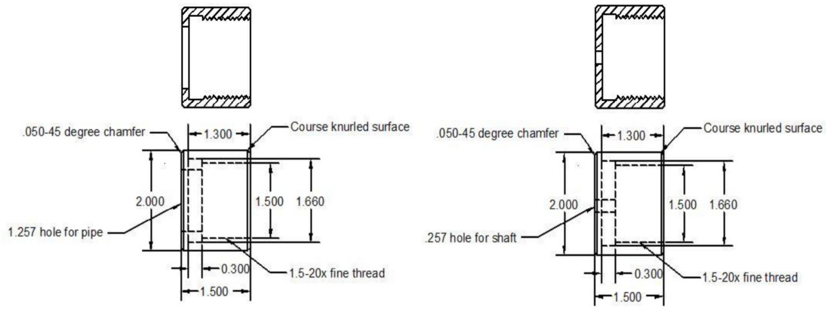


Figure 2: Working Drawings for Custom Knurled Threaded Caps

Figure 3: Internal Threaded on Lathe **Figure 4: Knurling on Lathe**

The rest of the assembly was then manufactured by cutting tube stock to the correct length and welding in place. Before the welding operation, the nut that will connect the sand hopper to the Auger Housing was installed. This nut will be threaded directly to the hopper to fully seal the two components together.

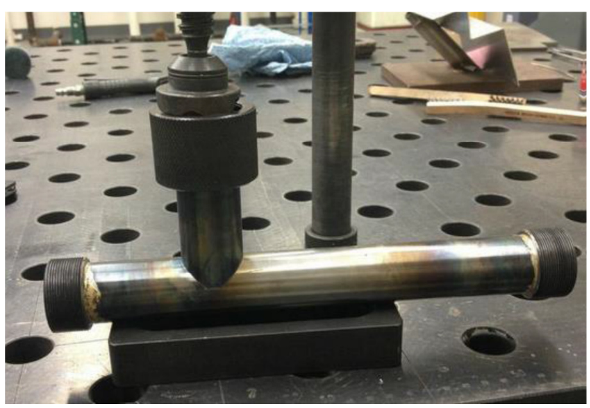


Figure 5: Auger Housing

To machine the augers an elaborate setup had to be made for the manual milling machine. The mill required a fourth axis that was not on that machine. To accomplish this geometry an indexing head was mounted on the bed of the knee mill. A transmission was made to link the bed feed handle to the gearing of the indexing head. A tailstock was also going to be necessary to reduce end movement during the milling process. There would be two passes 180 degrees out of phase from each other to produce a double lead auger. Once the setup was complete, three test runs were made on nylon pieces to ensure that the process would yield a workable piece.

After the nylon augers were built, small modifications were made to the manufacturing procedure to ensure better quality and repeatability. Two augers were machined out of bronze using this process one with double the pitch as the other. Removal of the second lead would increase the input of the sand through the housing if needed.

Figure 6: Bronze Auger Bits

The shaft end of the auger assembly required a seal assembly to work properly. The team designed an assembly that would support the auger and seal while in motion. A 6-32 set screw was installed approximately one inch from the end to lock the auger to the 0.250in shaft. A nylon bearing housing was manufactured to hold the bearing and further increase the seal in the rear of the housing.

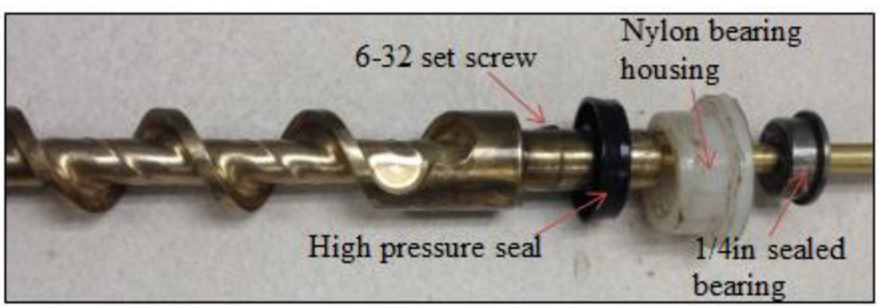


Figure 7: Auger Rear Bearing Support

The final part needed for this assembly was the sand hopper. It was made of stainless steel and consisted of a funnel shape connected to a cylinder with a hinged lid that was held down with six toggle clamps. To fabricate the cylinder, a rectangle with the dimensions of the height and the circumference of the cylinder was cut. The stainless rectangle was pulled through a roller to form a cylinder. The seam that was located on the newly formed cylinder was tack welded in place.

The cone profile was laid-out on another piece of stainless steel. The intersection point of the lines from the side profile was used to define the two arcs necessary to form the conical shape after it was bent. After shaping the cut piece of metal, the funnel was tack welded into the correct form. The funnel was then tack welded to the cylinder and hinges and a lid was made to fit the top of the hopper.

Figure 8: Sand Hopper

Using lessons learned in engineering classes at Mercer University, the students knew they should test before moving forward with this concept. The students decided to test the sand delivery process by measuring the volumetric flowrate of dry 20/40 sand and determine the necessary auger RPM that would be needed to deliver at the defined rate. The 20/40 refers to the mesh sizes that the sand is sieved between and corresponds to particle diameter sizes of 0.017-in and 0.033-in, such that most sand grains are between those two diameters. These augers were attached to the assembly and a power drill was used to turn the auger while feeding sand into the top of the sand hopper and a Digital Photo Tachometer was used to monitor the RPM of the drill chuck as it rotated. To ensure the accuracy of the Digital Photo Tachometer's RPM reading, a Digital Stroboscope was used to measure the RPM of the drill chuck and these readings were compared to the readings produced by the Digital Photo Tachometer which were identical.

Figure 9: Sand Flow through Auger System Test

The drill was operated at a set RPM and a collection bin was placed underneath the output of the auger assembly. After both the drill RPM and sand flow was observed to be steady state, the outflow was observed for 30sec for each test. The mass of the collected sample was then measured using a Mettler SB12001 scale in units of grams. This mass was then converted into a volume, in units of cubic meters, by dividing the mass of sand collected from the test by the density of the fracturing sand. An auger volumetric flowrate was then obtained by dividing the volume of the collected sample by the time of the test, 30sec.

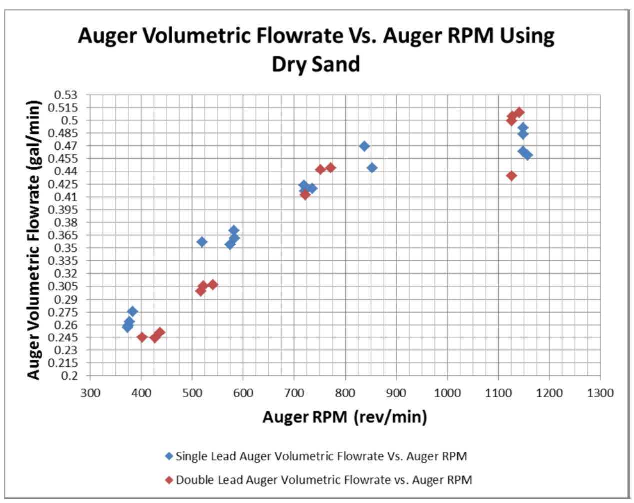


Figure 10: Sand Flow Test through Auger

It was first observed that the volumetric flowrate difference between the single and double lead auger was minor and therefore either auger would be suitable to use for the fully assembled erosion test fixture. A maximum RPM range that produced a linear increase in volumetric flowrate was then observed.

Mechanical Design and Manufacturing Process for Fluid Holding and Fluid Delivery

The settling tank that is used to hold the water and the sample piece used in the experiment was made next. Student A, Student B, and Student C, all contributed to this portion of the design and manufacturing. To determine the size of the tank, the students used the space requirements from the design specifications; however, for the settling tank some design constraints must be considered. For the design to be effective at settling out the sand particles before entering the suction side of the pump, the particles must settle at a rate greater than the flow of water through the tank. From Stokes' Law it was calculated that the smallest particle size of 20/40 sand, 0.017 in, settled at a rate of 0.55ft/sec. What about more than one particle? The students were tasked with determining if they would see a difference in settling of one particle versus a collection of particles. To test this, a settling rate experiment was setup. Through slow motion video, clear tube, and a yard stick this test revealed that a collection of sand particles settled at a rate of approximately 0.5ft/sec. Now that the settling rate has been verified, a width of the tank can be determined to ensure that the water velocity across the bottom of the tank is much slower than the settling velocity of a particle of sand.

The settling tank was made of stainless steel with the dimensions of 48in long, 18in wide, 24in tall, and a wall thickness of 0.035in. Stiffening members were made from the leftover metal from the tank. These were riveted around the rim of the tank and the middle of the tank to stiffen it from excessive bulging when filled with water. The base for the assembly was then constructed. Student C constructed this portion of the assembly. The dimensions for the stand were 48in x 32in x13in. The legs were made of 2in square tubing, the frame was made with 1.5in square tubing and the gussets were made of 1in square tubing. The assembly was clamped together and quality checked, then welded together. The welds on the top of the base were ground flat to allow for a plywood deck to be installed on the surface and a grey rubber mat was place on the top of the wood surface to further protect it from water. Tank holding brackets were manufactured out of 1/8in stainless steel sheet metal to fasten the tank to the base without having to drill holes through the tank. The brackets were designed to grip onto the opposite ends of the tank and apply pressure to it putting it into compression. A foam rubber barrier was place between the mating surfaces to avoid any damage on the tank due to vibrations.

Figure 11: Tank and Frame Assembly

The last component that required manufacturing was the sample holder again made by Student C. The chosen dimensions for the sample holder were 17in x17in at the base and 12in high. It was made out of basic steel flat bar and a 12in piece of tubing. Then base had an H-shape with the tube protruding out of the middle. A small plate was welded to the top of the tube to hold the sample. Later, two pieces of angle iron that were 16in long were added to the end to hold the diffuser screen.

Figure 12: Sample Holder

Electrical Design and Manufacturing Process

Student B was the electrical engineering student on this team and was responsible for all of the electronic components. An Arduino Mega 2560 Microcontroller operated the motor and communicated with the attached pressure transducers. The Arduino was powered from standard AC current that supplies a regulated 9V/1000mA. Two LCD screens with LED backlights were connected to the Arduino to display motor controls and pressure readings. The LCD screen was powered from the output of the Arduino while the LED backlight was powered from an AC/DC converter that converts 120VAC to 12VDC. The LED backlight operates on 3.7VDC – 4.4 VDC max, therefore a converter is used to step down the 12VDC to 4VDC. The LCD screen was able to have adjustable contrast; however the darkest contrast was best because it could be seen in all light levels.

A keypad was salvaged from an old telephone to be able to accept input from the user to control the speed of the auger. The keypad used continuity checks to determine which key was being pressed. The keys were wired in a matrix form, so by determining which row and column had continuity, the key being pressed can be determined

The motor was controlled from the Arduino by using Pulse Position Modulation (PPM). This essentially sends pulses to turn the windings of the Brushless DC NTM Prop Drive Series 35-36A motor 120 degrees out of phase with the previous pulse. The motor was powered via an Electronic Speed Controller (ESC) rated at 30A constant and can handle a surge of 40A with a maximum voltage of 16VDC. The ESC was also powered from the AC/DC converter. The ESC provides a Battery Eliminator Circuit (BEC) which provides 5VDC and up to 3A. This motor was rated at 350W, which provides sufficient power output required to turn the auger under a load. At 12VDC, the motor shaft was estimated to spin at 10,920 RPM which required the shaft to be geared down using an 8.3:1 gear ratio.

The motor was attached to a transmission that turns the auger shaft. Timing pulleys were chosen for the drive train and calculations showed that the required drive trains needed for the gear reduction were: two 1.019in pitch, a 2.80in1pitch, and a 3.056in pitch pulley. Three axels were necessary for this assembly. Bearing supports are used to hold the shafts and slotted holes milled in the bases to allow for adjustment.

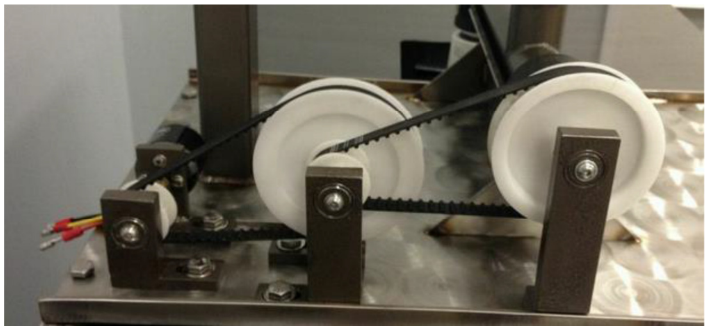


Figure 13: Transmission Assembly

After the transmission setup was installed on the erosion test fixture assembly, reference RPM measurements for the motor and auger based on the power input of the motor were taken. The readings were taken using a Digital Photo Tachometer under the condition that the motor and auger were not placed under a load to verify calculations. Once verified, all components were placed in the control box which was installed on the platform.

Figure 14: Control Box Assembly

Two AST4100 pressure transducers were connected to the device. These pressure transducer used a ratio-metric output of .5VDC - 4.5VDC to translate pressure readings of 0 – 100PSI and were excited by an input of 5VDC, which was supplied by the BEC of the ESC. The pressure transducers were secured into the fixture by a 1/8 NPT nipple affixed to the end of the transducer. The pressure transducers were installed at the pump and right before the nozzle on the erosion test fixture, which allows the user to be able to estimate the flow rate of the system. The complete flow charts of the electronics are shown in the figure below.

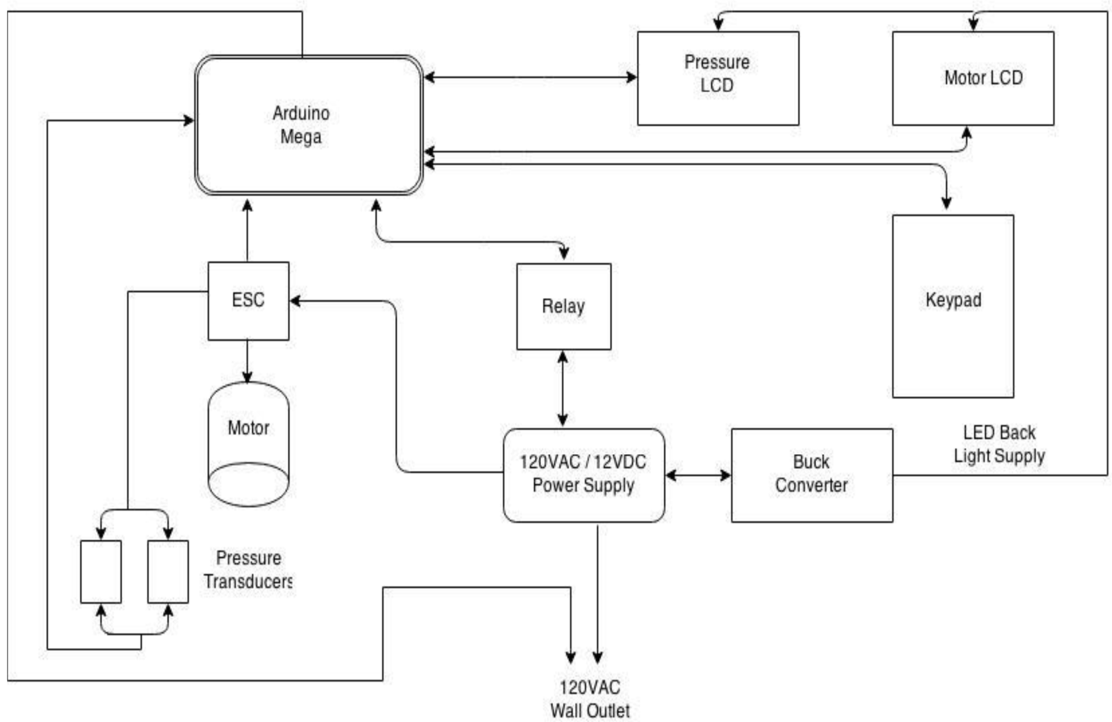


Figure 15 Control System Flow Chart

Final Assembly and Prototype Testing

The next step was to install the pump to the base. The pump is a double diaphragm pneumatic pump that uses air pressure to provide a one to one pressure to the fluid it is displacing. The pump is connected to the air supply in the lab space and controlled with an air regulator.

PVC piping is used to connect the pump to the rest of the assembly. The nozzles used are small ceramic sand blasting nozzles that can vary in size from 0.15-in to 0.27-in. These are attached in a metal holding sleeve where the fluid and sand are introduced together. A small threaded connection is used to remove and check the diameter of the nozzle before and after each test.

Figure 16: Ceramic Sand Blasting Nozzle

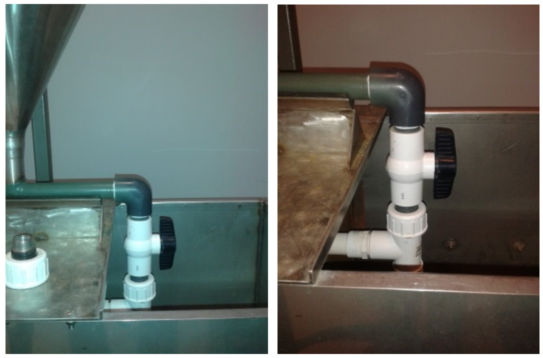


Figure 17: Manifold from Hopper to Nozzle

Pressure is measured within the sand hopper as well since water does fill the tank during operation. To reduce the area and strengthen the top connection, the large opening at the top was modified to have the large lid welded in place to seal the hopper and a 3in access hole was cut into the center of the lid and six studs were installed to bolt and seal the new lid on. The new lid was drilled to match the bolt pattern and a pressure gauge and pressure relief valve was installed. Fluid/Sand mixture leaves the hopper and is introduced into the main flow that then flows into and out of the nozzle and impacts the sample attached to the sample holder.

Figure 18: Final Assembly

After the erosion test fixture was fully assembled, the team then conducted various tests to prove the project met the initial specifications. In all cases the design did. The fixture was able to run for over 15 minutes per test and erode various samples at various orientations.

A summer project was held with visiting students from the Brazil Mobility Program where they ran tests to illustrate the differences in erosion between steel and aluminum samples at various impact angles. They were able to generate some basic erosion data that can be compared to previous work in this area.

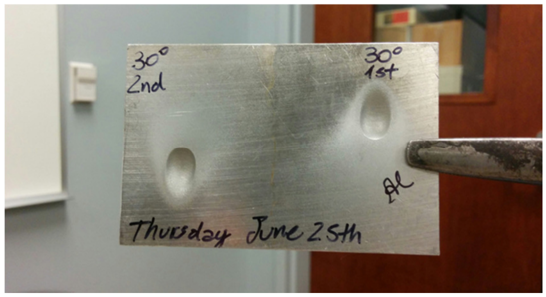


Figure 19: Erosion Sample Coupon

Student Evaluation

Students were evaluated on the design process and the actual design. Students A, B, and C all provided equal effort on the design phases while leveraging much on Student A's manufacturing ability learned in previous experiences. All students were involved in the build and testing of the apparatus as well as the troubleshooting that occurred during the process. The students also provided detail reports, presentations, and weekly updates to the client involved and technical advisors assigned to the project. All evaluators ranked the members of the team high using the rubric in the appendix. All received high rankings due to completeness and level of work.

Conclusions

The goal of this project is to develop a safe, controlled method for experimentally testing erosion rates on metal samples to assist in more accurate erosion modeling. The team started the design process of the erosion test fixture by selecting a feasible design through engineering analysis. These analyses gave the team the ability to select proper design components to ensure a successful build. As this design was built, component level testing was performed to ensure that the finally design had the best chance of being a workable full scale apparatus. And finally, the full scale apparatus was verified to erode both steel and aluminum metal samples. Furthermore, the device was used in a 10-week summer research project with another set of students not familiar with the design or the process itself. The device ran perfectly throughout that project as well. The erosion test apparatus project was a success and will become a part of undergraduate research projects at Mercer University in fluid flow and materials processing.

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Stephen Hill Ph.D.

Stephen Hill received his doctorate from Georgia Institute of Technology in 1999. He is currently an associate professor in the School of Engineering at Mercer University. He worked for the oilfield services giant Schlumberger for 14 years before returning to academia in 2013 to pursue his goal of educating the next wave of engineers entering the work force. His experience in the work force was in product development of downhole tools related to the extraction of oil and natural gas from various reservoirs. His current research interests include impact erosion, two phase flow phenomena, solid/liquid phase change, and highly ionized plasma.

Jesse Barnes

Jesse Barnes is a graduate of Mercer University with a Bachelor of Science in Engineering with a Mechanical specialization in 2015. He is currently employed by Command and Control Communications, Engineering and Logistics LLC in Stuttgart, Germany. He is a retired U.S. Air Force Reserves Technical Sergeant and returned to school to pursue his dream of becoming an engineer. He also has over 23 years of experience as an aircraft machinist and welder

Bradley Harrison

Bradley Harrison is a graduate of Mercer University with a Bachelor of Science in Engineering with a Mechanical specialization in 2015. He is currently employed as an applications engineer at Chem-Aqua, Inc. in Macon, GA in Macon, Georgia. Chem-Aqua Inc. is a global water treatment provider that specializes in providing custom designed water filtration and water treatment programs for boiler, cooling, and process water system

Caleb Yawn

Caleb Yawn graduated from Middle Georgia College with an Associate’s Degree in Physics. He continued his pursuit of higher education at Mercer University where he simultaneously received his Master in Science and Bachelor in Science with Specialization in Electrical Engineering in 2015. Currently, Caleb works with the United States Air Force as an Electronics Engineer where he designs Automated Test Racks that help keep our warfighters flying.

Appendix

Instructor/Client/Tech Advisor Team Assessment - CDR

Name_______________________________ Date____________________________

1. Please circle the rating that best describes your perceptions of the team for each of the questions below.

a. As far as you could tell, did all members of the group share in the team's responsibilities?

Some members did no work at all	A few members did most of the work	The work was generally shared by all members	Everyone did an equal share of the work

b. Which of the following best describes the level of conflict that you observed among group members at meetings?

Open warfare: still unresolved	Disagreements were resolved with considerable difficulty	There were disagreements, but they were easily resolved	No conflict, everyone seemed to agree on what to do

c. From your perspective, how productive was the team overall?

Accomplished some but not all of the project's requirements	Met the project requirements but could have done much better	Efficiently accomplished goals	Went way beyond what was expected; exceeded goals

d. Based on your experience with other project teams, how effective over all would you say this team has been working together?

Very ineffective	Ineffective	Effective	Very effective
1	2	3	4

2. To what extent have realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability been used by the team in the design of this product? (Outcome 3(c))

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

3. Rate the team's use of modern engineering tools to complete this project. (Outcome 3(k))

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

4. Please rate the overall oral Critical Design Review on the students' ability to communicate effectively. (3(g))

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

5. Please rate the overall written Critical Design Review on the students' ability to communicate effectively. (3(g))

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

6. a. Please rate the written Critical Design Review on the student's ability to DEVELOP a Test Plan. (Outcome 3(b))

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

Did the team finish building such that some or all testing could occur (i.e., was the Test Plan Implemented?) YES NO
If YES, please answer questions 6b and 6c. (Outcome 3(b))

6b. Rate the written Critical Design Review on the students' ability to CONDUCT experiments in the Test Plan

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

6c. Rate the written Critical Design Review on the students' ability to ANALYZE and INTERPRET results obtained from execution of the Test Plan. (Outcome 3(b))

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5

CDR Instr-Client-Tech Advisor Team Assessment   Revised September 2014   7-Jan-16

7. Consider the written Critical Design Review (Outcome 3(h))

a. Rate the team's ability to assess its design from a global context. If not applicable for this project, circle N/A

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5 — N/A

b. Rate the team's ability to assess its design from an economic context. If not applicable for this project, circle N/A

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5 — N/A

c. Rate the team's ability to assess its design from an environmental context. If not applicable for this project, circle N/A

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5 — N/A

d. Rate the team's ability to assess its design from a societal context. If not applicable for this project, circle N/A

Unacceptable 1 — 2 — Acceptable 3 — 4 — Excellent 5 — N/A

Write a brief description of the problems you encountered in working with this group and how they were resolved.

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8. Please distribute 100 points among the members of the team, based on your perceptions of each member's contribution to the team's effort. Use integers only. No two people should receive the same number of points. (Outcome 3(d))

Name	# of Points
Total	100

Figure 20: Critical Design Review Audit Sheet