Reduction in Exhaust Port Heat Losses for a Landfill Gas Generator

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Abstract

The research and study conducted in this project focuses on determination of ways to reduce the heat loss in the exhaust port in the cylinder head of a 6G7 engine. This reduction in heat losses may improve the efficiency of an engine by reducing the load on the cooling system powered by the engine, resulting in an increased net output. Our modification will be the introduction of a heat shield. This modification will reduce the overall heat transfer of the exhaust gas into the exhaust port by introducing an air gap liner into the exhaust port. This project serves to increase the revenue generated by 100 kWh LMOP landfill gas projects which stimulates landfills to adopt generators driven by this engine, which uses landfill gas as fuel.

Objectives

The fundamental objective of this project is to increase the efficiency of a generator driven by a converted automobile engine. We are modifying a cylinder head for a converted 6G7 engine, on account of professor Michael Swain and professor Matthew Swain, which uses the methane obtained in landfill gas as fuel; more specifically, the engine operates in low--methane concentration levels (~30% CH4). We aim to reduce the heat loss from the exhaust gas to the exhaust port walls in the cylinder head of the engine in order to increase the overall efficiency of the generator. With curtailment of heat loss in the exhaust port, less energy will be required or exerted to remove heat by the water jacket from the radiator. Because the engines referred to in this study are functioning as generators, they are stationary and do not have the airstream as a working fluid, as regular automobiles do. Therefore, the generator must also power a fan to artificially induce the airstream and this process can consume approximately 10% of the energy produced in the generator. If there is less heat load on the radiator, the fan will require less energy resulting in more net power output, thereby increasing the efficiency of the generator. With a more efficient generator, the energy out per input of landfill gas would increase, resulting in more money per input of landfill gas.

Background

In the United States alone, municipal solid waste landfills are the third largest source of human produced methane emissions in the form of landfill gas.[1,2,5] Landfill gases are naturally occuring emissions due to the decomposition of waste as a byproduct of microorganism activity. After the first year of aerobic decomposition of waste deposition, anaerobic conditions are established and methane begins emitting from the landfill. Methane is a greenhouse gas which ranges anywhere from 20 to 30 times more active than carbon dioxide[2] and by transforming methane into carbon dioxide we can reduce the greenhouse effect.[1,2,3,5]

LMOP, the Landfill Methane Outreach Program organized by the Environmental Protection Agency (EPA), aims to reduce and nullify methane emissions while also endorsing the retrieval and practical application of biofuels in environmentally friendly methods. Landfills account for 15.4% of the methane produced in the United States[8], which can be found on the 'Basic Information About Landfill Gas' section of the LMOP website. Currently, any landfill which consists of 2.5 million metric tons or more are obligated by law to flare the landfill gas to stop the methane from entering the atmosphere[5]; however, this flaring procedure neither uses the methane for any useful purpose, nor to its full energy producing potential. These emissions represent a massive loss in opportunity of a significant energy source. Energy from landfill can be used to power homes and factories and can be refined for automobile fuel.[2,3]

Our associated project takes part as one of the many LFG projects that LMOP is currently sponsoring. In 2014 the EPA reported 258 million tons of waste produced. Of the 258 million produced 134.16 million was deposited into landfills[3]. This accumulates to 40248 cubic feet per minute or 2.115 billion cubic feet of waste was produced for the year.[3] As of February 2019, there are 619 operational energy projects, comprised of 2,044 MegaWatt generators, in 48 states; LMOP estimates that approximately 480 additional landfills are considerable candidates for such methane sourced energy projects.[9] Cooperatively, operational landfills annually produce approximately 15 billion kilowatt-hours of electricity and 100 billion cubic feet of LFG for direct use.

Currently, diesel engines are being converted into 3000 kW (kilowatt) energy producing generators for the sole purpose of converting the methane fuel mixture into energy. The initial expense of such an engine along with the annual maintenance cost makes this a costly investment for landfills and why many opt out of adopting this method of reducing methane production. A 3 Megawatt engine that burns Methane costs around 5,250,000 dollars and the annual maintenance and repairs has been estimated to be upwards of 600000 dollars[3].

Dr. Michael Swain has performed research on how to properly convert and optimize the operation and conversion of a combustion engine to run leaner to use propane as a fuel[7]. This extensive research revolves around finding a proper method to convert the automotive engine into an electric generator at a low cost and minimal design changes. The research paper authored by Dr. Swain highlighted how the engine will have to meet EPA standards and operate at different conditions than what an internal combustion is designed for. The EPA standards for emissions dictate the emission requirements which are different for automobiles and generators. Since this fuel delivery is a conversion of an automobile into a stationary generator it will have to be adjusted to match this conversion. The paper explains how it is meant to reduce the cost of having and operating a generator and compete with industrial level equipment. The engine was optimized to function at 19 kW max to remain consistent with the class II EPA emission requirements[7]. The engine was designed to drive a 4 pole generator so a speed of 1800 RPM was chosen to produce 60 cycle AC current[7]. Other variables that had to be accounted for are motion and turbulence that are decayed considerably by the end of the compression stroke which varies the lean limit of the fuel. Several factors had to be considered such as reduction in friction and higher compression ratios.

The repurposed engine application method is being implemented for utilizing landfill gas containing an lean methane concentration - 30% - for energy generation as an LMOP site generator. The available concentration of methane at any landfill site ranges from 30 to 60 percent and engines currently used at qualifying landfill sites are able to produce energy from the methane gas at a concentration of 50%[2,5], but the converted automobile engine design by Dr. Swain will burn at a leaner concentration of approximately 30 percent.

As landfill gas is composed of compounds other than methane, the properties of the gas can vary. Thus, variations in gas temperature simultaneously cause variations in the ratio of specific heats of the gas, since specific heat is a function of temperature. In order to model the behavior of the gases, calculations were taken over a range of ratio of specific heat values from 1.3 to 1.4 and pressures from 50 psi to 100 psi, found in Appendix A.2. Appendix A.2E shows that the ratio of specific heats of the the gases, however, do not vary the percentage of gases left in the cylinder greatly. As the ratio of specific heat values change, we find that as we increase in pressure, we get less variation of the volume of gases left in the cylinder. This implies that despite the leanness and temperature of the landfill gas, we can expect the gases to behave very similarly over a range of pressures. Appendix A.2E shows the standard deviation of the percentage of gasses left in the cylinder for each ratio of specific heat of which no value exceeds .91. Blow down percentages are also shown in appendix A.2E.

Once the procedure for converting an automobile engine into an electric generator was established we designed an apparatus to improve the efficiency of the converted engines. We decided to decrease the heat exchange in the cylinder head exerted through the exhaust port. By containing the heat in the exhaust gas as it passes through the exhaust port and by reducing heat exchange we increase the efficiency of the engine. Most importantly, the efficiency of the generator would increase because less energy is required to cool the engine, due to the lower heat exchange, and subsequently, more energy is delivered as output. A higher efficiency results in a quicker payback that benefits the local communities of this project.

In designing a solution to given this background, we operated within the set of Design Constraints listed below:

<u>Economic</u>

A portion of the appeal of the 100 kwh energy generator for landfills is that the time it takes the landfill site to obtain profit is very small compared to the 10 to 15 year payback of 3 MW units[8]

(Appendix A.6). We are constrained to retain relatively low maintenance and installation costs. The heat shield should be of minimal addition to obtain the highest possible efficiency increase. Therefore, our heat shield should consist of a minimal number of independent pieces for attachment, thus conserving cost in machining and installation.

Environmental

The EPA does not consider carbon dioxide created from combusting landfill gas in emission totals, the carbon dioxide created from the engine will not affect the total emissions for a landfill that adopts the modified engine as the methane is considered about 20-30 times more potent than carbon dioxide[2]. Therefore we are not environmentally constrained by carbon dioxide emissions. We are required, however, to be sure not to incite the production of NOx, unburned hydrocarbons, and Carbon Monoxide from the exhaust gas through our design[10].

Social Impact

While a landfill gas engine project will provide revenue for landfills and jobs for installation and maintenance, our adjustment of the exhaust port heat transfer reduction is not constrained by the amount of jobs created or the revenue produce, despite increasing the overall revenue by increasing generator efficiency.

Political

With the EPA introducing LMOP in 1994[3], political forces encouraged the use of landfill methane gas as fuel for energy production. LMOP was established to create partnerships among states, energy users/provided, the landfill gas industry and communities. As the design will only promote this application of landfill methane gas, the design is not constrained politically.

Ethical

The result of this project would increase the efficiency of generating electricity from landfill methane gas. As this process produces carbon dioxide that is less dangerous as a greenhouse gas than methane and our design will increase energy output, the project is not ethically constrained.

Health and Safety

Our design must not pierce the water jacket of the cylinder head as this would cause the engine to overheat due to the engine having no cooling potential. This will cause the engine to overheat and be unsafe. Furthermore, our design cannot allow for exhaust gas to leave the exhaust manifold as carbon monoxide is dangerous to anyone close to the engine, such as a mechanic.

Manufacturability

As welding the cylinder head can warp the shape of the cylinder which would allow for coolant leakage and subsequent overheating of the engine, welding the cylinder head is not considered for this project. Furthermore, the geometric changes in the cylinder head made through machining are limited to only existing geometry and areas that would not pierce the water jacket.

Sustainability

In 2014, 258 million tons of municipal solid waste was collected in the US and approximately 134.16 million was deposited into landfills[5]. As waste will continue to be produced in the US, landfill methane will be consistently available; therefore, this project is not constrained by sustainability.

Codes and Standards

This project is limited by CFR 40 Chapter 1 Subchapter C Part 90 which mandates rules regarding the “Control of Emissions From Nonroad Spark-Ignition Engines at or below 19 Kilowatts”[10]. These rules limit the emission of Non-methane hydrocarbons and NOx to 12.1 g/kWh and CO to 610 g/kWh for a 19 KW engine which our test engine falls under[10].

Significance

Certain automobile engines can be modified to utilize alternative fuels in consumption and energy production. Our project impacts sustainability and waste management - considering the global production of waste, this project bases consumption on a renewable resource, methane. Energy production through such an outlet has potential for typical electrical, residential and commercial consumption, as well as direct pipeline uses.

This research serves to make a generator driven by a methane engine more efficient. Less cooling load is put on the radiator system because the exhaust gas transfers less heat to the cylinder head to be removed by the radiator. Because less cooling load is put on the generator, more energy is used for electricity production, resulting in a more efficient engine. A higher efficiency results in quicker payback and benefits the local communities of this project.

Furthermore, the higher exhaust gas temperature will be acceptable in meeting exhaust emission standards for an engine with a three way catalyst, despite our application not containing a three way catalyst. Because the exhaust will be at a higher temperature due to the reduced heat loss, it will reach its activation energy with the catalyst earlier, meaning that the catalyst will be more efficient in catching NOx, CO, and unburned hydrocarbons and will last longer without replacement. This is an important benefit because the catalyst is made of expensive precious metals such as platinum, palladium, or rhodium. The longer these materials will last, the more effective the catalyst will be economically.

An engine which has a turbo can also benefit from this increase in exhaust gas temperature. As the turbo recycles the exhaust gas to use during combustion, the combusted gases will have an overall higher temperature, resulting in a higher pressure during combustion, resulting in a higher energy output during the power stroke. This serves to raise the efficiency of the engine with a turbocharger even more.

The November 2018 electric rate found on *Electricity Rates by State,* the Choose Energy webpage, displays the cost of energy state by state; for reference, the charge ranges from 9.01 cents in Louisiana to 34.43 cents in Hawaii. Florida was listed at 11.86 cents per kilowatt hour. Using the price per kilowatt hour, the number of hours in a year, and understanding the output of the engine, we can compute the revenue generated by Landfill gas in a year(Appendix A.6) and we can estimate the an engine's cost return time.

Our research will display the benefits of using smaller LFG engines compared to larger generators, such as caterpillars. A smaller 100 kilowatt industrial generator, automobile engine powered, costs around $25000[4]. Maintenance and upkeep costs are to be determined but are small compared to the maintenance of the 3MW unit. Investing in smaller generators results in quick and secure payback including much less maintenance cost. In the table below one can determine the payback from an engine with larger output is much greater, however 3 MW engine expenses are tremendous. Our design will seek to improve the performance of a 100 kilowatt engine in order to see the benefits of LMOP LFG research. Table A.6 shows how much money is made each year from LFG.

Design and Study Approach

Design:

To reduce the heat transfer of the exhaust gas to the exhaust port, we are implementing a 2 inlet, 1 outlet heat shield for the exhaust port. With an inner diameter of 1.054 inches which is approximately a 30% decrease in the flow diameter of the original port. The heat shield has an outer diameter of 1.13 inches which leaves an air gap insulator in the heat shield of approximately .185 inch depth in circumference around the shield. The overall reduction in heat transfer surface area results in 30.5%. The shield will be made of aluminum to ensure that the material will not melt with the higher temperature exhaust gas and can be bonded with epoxy. Each piece of the shield will be coupled and cemented together using the epoxy bond JB Weld Extreme Heat inside of the head in order to have each piece fit inside the cylinder head. The cylinder head will be machined to allow for the cap to be flush with the side of the cylinder head.

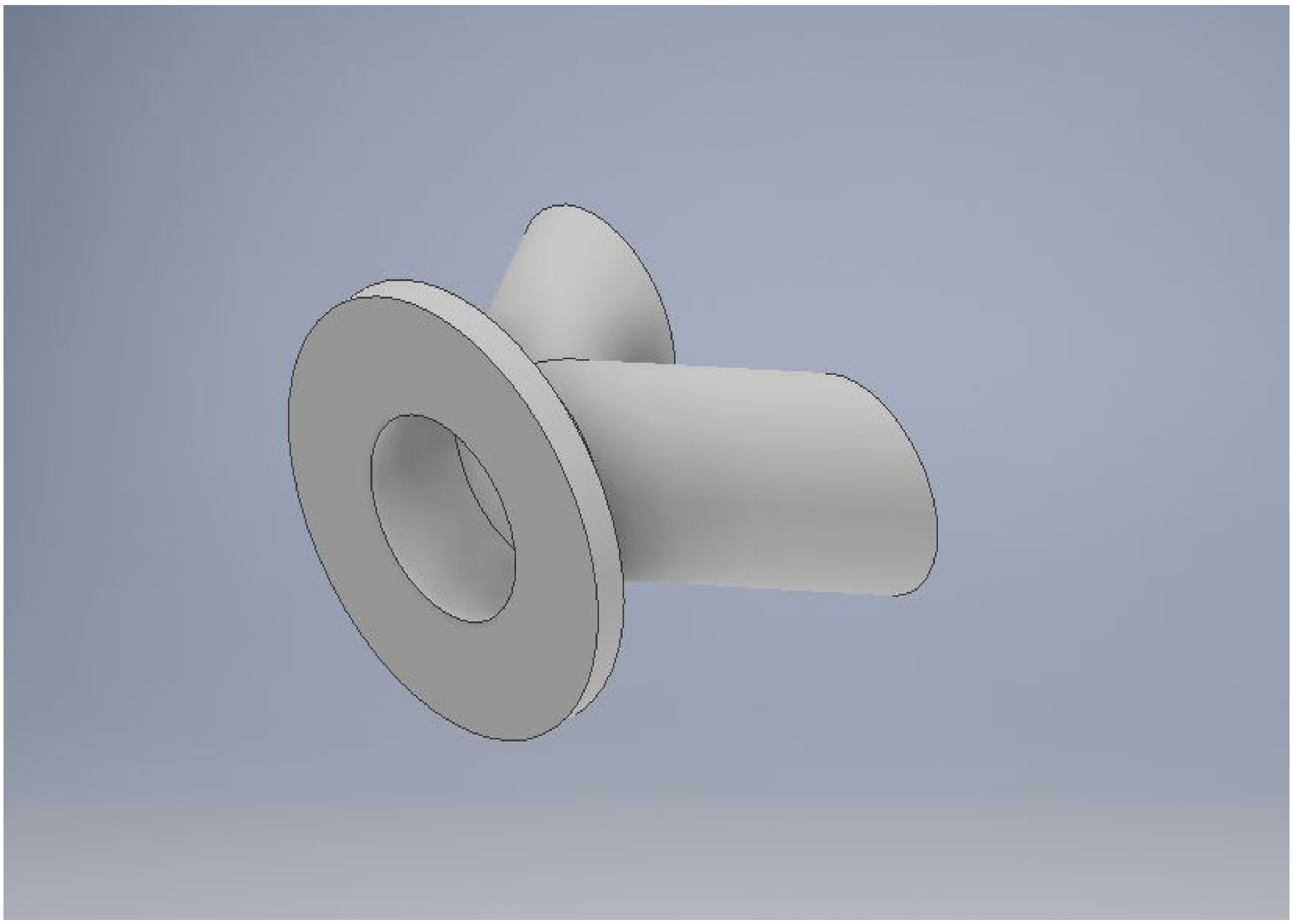


Fig 1. Assembled Heat Shield

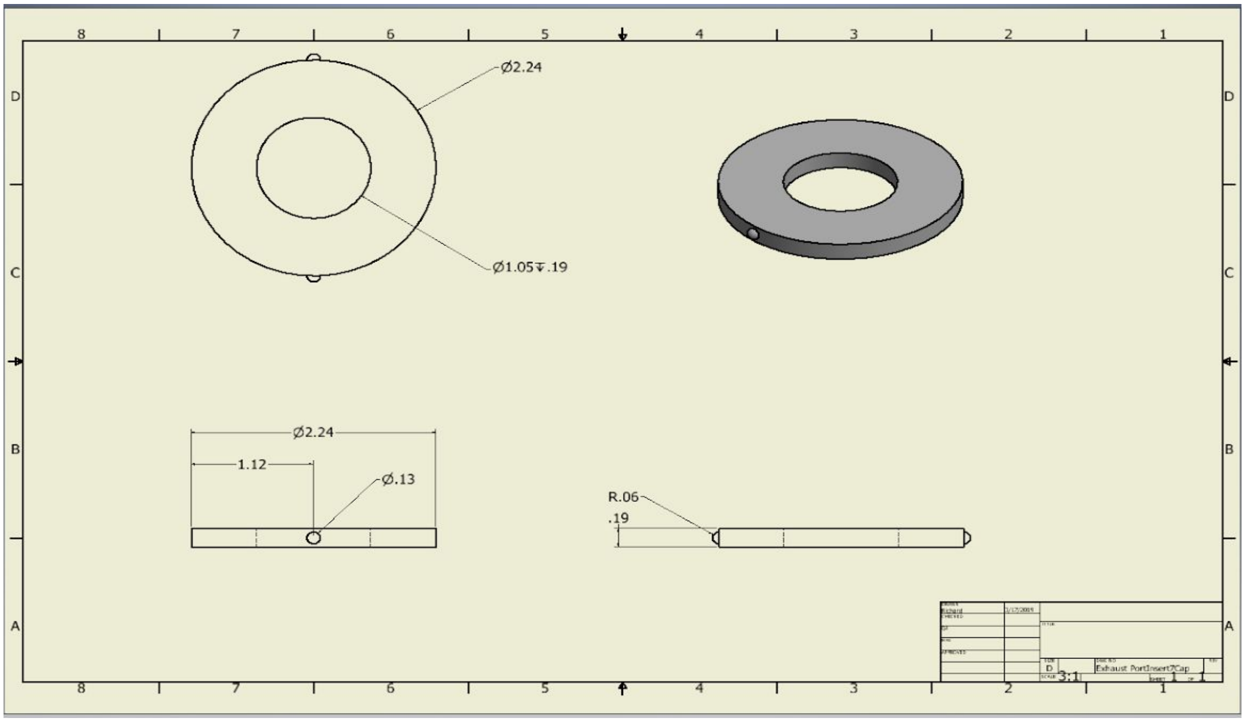


Fig 2. Heat Shield Cap

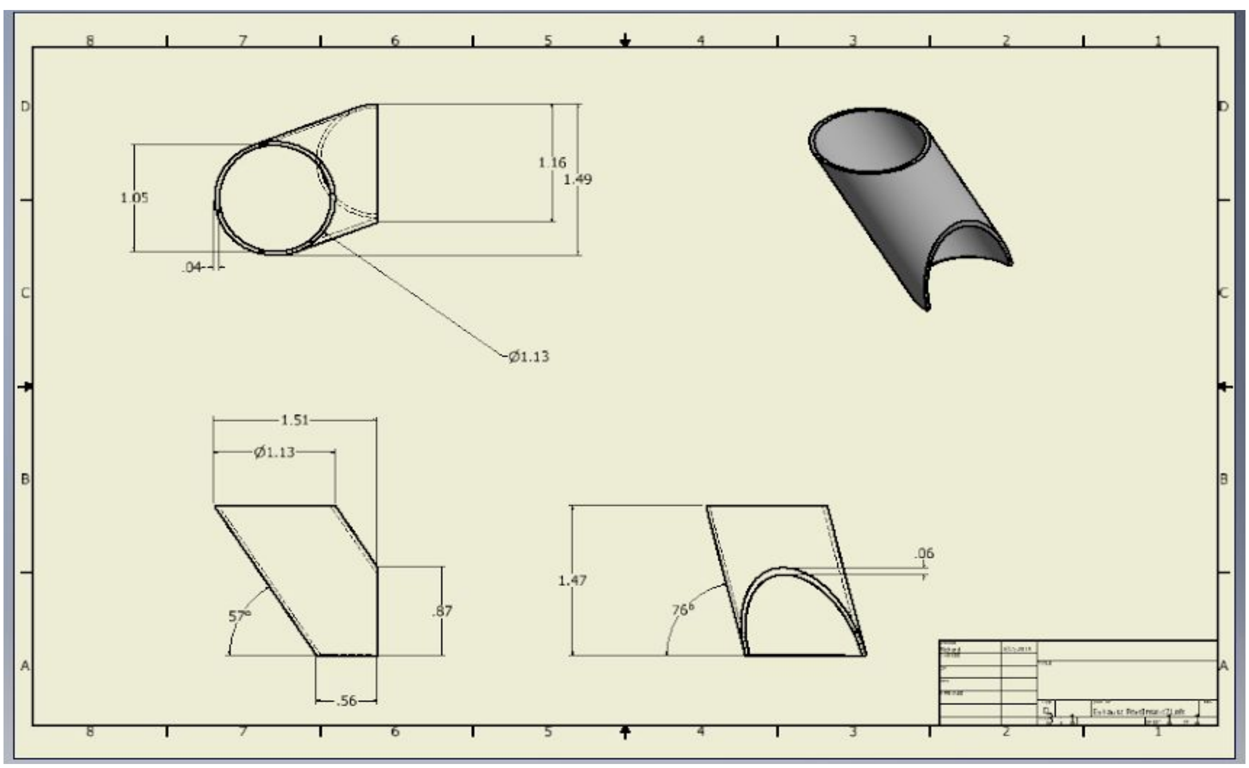


Fig 3. Heat Shield Left Inlet Tube

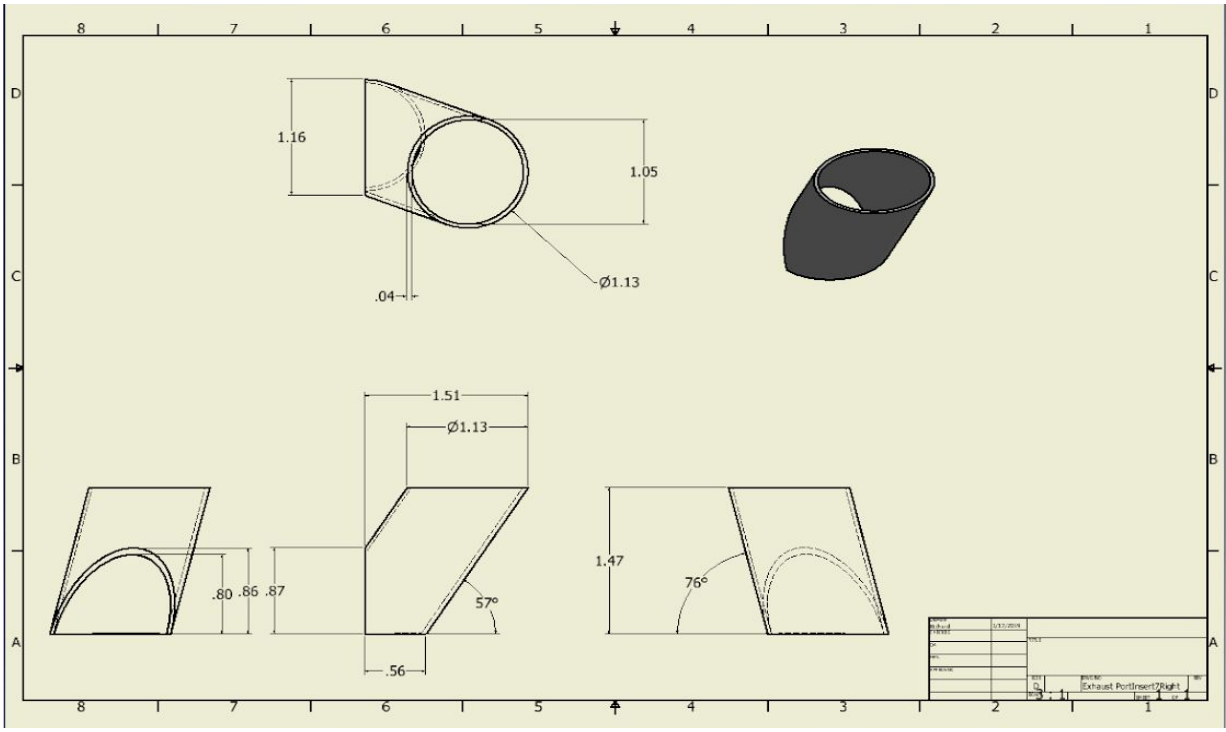


Fig 4. Heat Shield Right Inlet Tube

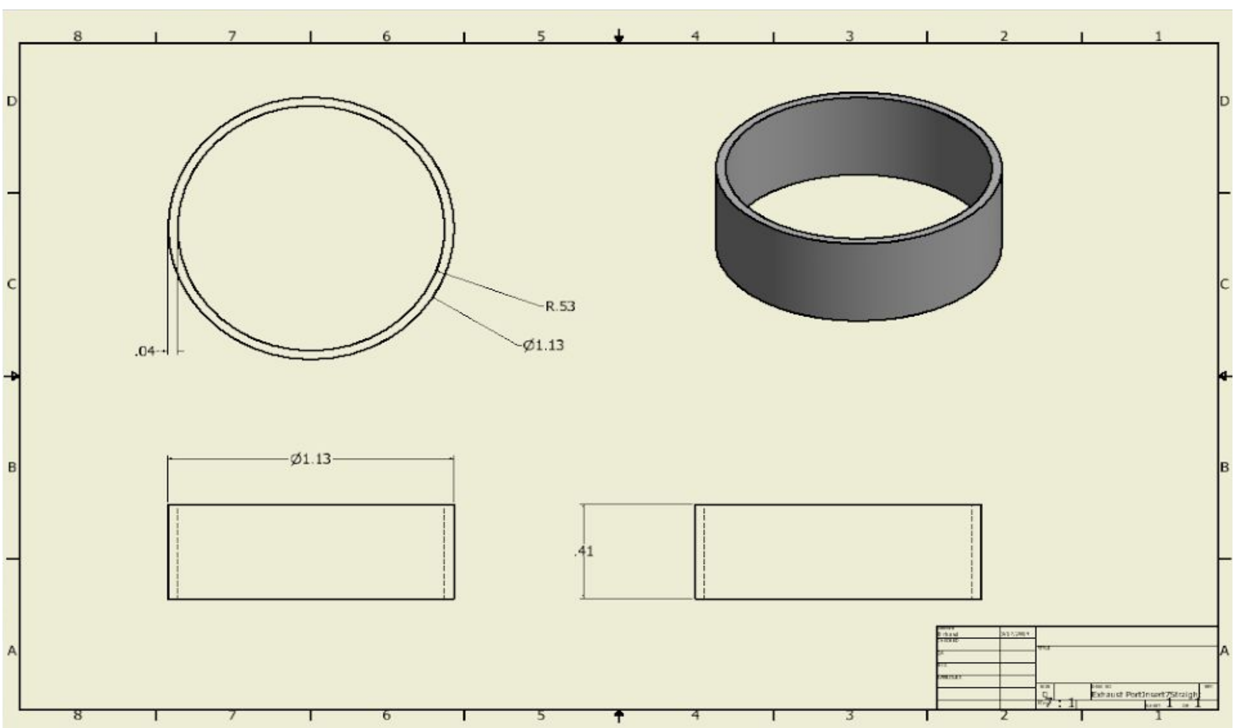


Fig 5. Heat Shield Flow Conduit

Study Approach:

To determine the effectiveness of the design, testing must be conducted in two stages. The first stage is to determine the flow efficiency using a flow bench to test the flow coefficient of our design compared to the baseline flow coefficient of the unaltered exhaust ports to obtain the pressure drop across the part. The second stage of testing is to determine the heat rejection of the design as compared to the baseline unaltered exhaust ports.

The first stage of testing will be conducted on the flow bench. As shown in Appendix A.5. using the amount of gases in the cylinder, the pressure, and the specific heat ratio we find that we will operate at flow rate of 14.62 Cubic Feet per Minute (CFM), the average amount of gases left in the cylinder after blowdown. The minimum gases left in cylinder, 10.90 Cubic Feet per Minute, will be tested also as well as the maximum gases left in the cylinder: 19.87 CFM . This flow rate occurs during the exhaust stroke of the engine. The purpose of this testing is to calculate the pressure drop across the designed heat shield by attaining the flow coefficient with the flow bench. If the pressure drop is too great along the heat shield, the design must be adjusted to operate closely to the baseline pressure drop. That being said there is leeway in that the engine is operating at approximately ⅓ the rated RPM (operating at 1800 RPM vs 5500 RPM) for the cylinder head so there is space for alterations to be made. This stage of testing must be passed in order to proceed to the second stage of testing.

The second stage of testing will be conducted with a ATI designed heating apparatus with thermocouples used to obtain temperatures. The heating apparatus will pass hot air of temperature 800 °F, a standard exhaust gas temperature for similar engines under similar load according to Dr. Michael Swain, into the cylinder head into a port that will have the designed heat shield. The temperature of the hot air will be measured at the outlet of the heating apparatus, to obtain the initial temperature of the gas, and at the outlet of the exhaust port, to obtain the final temperature of the exhaust gas. Through comparison between these two temperatures, the overall effectiveness of the designed heat shield can be determined as the percentage decrease in these temperature related to the baseline temperature.

In this type of testing apparatus, thermocouples have been shown to report a wide range of temperatures in the exhaust port depending on the position of the thermocouple[6]. With this in mind, temperature will be taken at the center of the heating apparatus and at the center of the exhaust port. If this approach provides too much variance in the data, effectiveness can be determined by examining the temperature of the water jacket from inlet to outlet and applying the heat equation, $Q = m*cp*dT$. The effective change in Q from the baseline assessment to the altered exhaust port assessment will determine how effective the designed heat shield was at reducing the heat transfer in the exhaust port. However, measuring the mass flow rate of the water will be difficult and is outside the scope of the project if the thermocouples provide stable readings.

Results

Flow Results:

- Baseline
  - Inclined Manometer Reading: 1.525 inH2O
  - Corresponding CFM: 201.7 CFM
  - Rated RPM: 5500

- Heat Shield
  - Inclined Manometer Reading: .225 inH2O
  - Corresponding CFM: 77.5 CFM
  - Rated RPM: 1800

- Flow Ratios
  - (RPM for our corresponding flow)/(Rated RPM) = 1800 / 5500 = .327
  - 77.5 CFM / 201.7 CFM = .384

Heat Transfer Results:

Average Percentage of Exhaust Gas Heat Retained Over Flow Range

Exhaust Gas Temperature	4.85 CFM	10.82 CFM	19.4 CFM
250 °F	93.63221583	102.553870	103.4621578
350 °F	90.52783803	98.2295831	99.94337486
450 °F	82.29453944	94.81905181	98.21130985
550 °F	86.32185979	89.81064022	------------------------
650 °F	81.0707457	89.11965282	------------------------

- We omitted data points for the higher temperatures at the higher flow because the readings were inconsistent between the two ports.

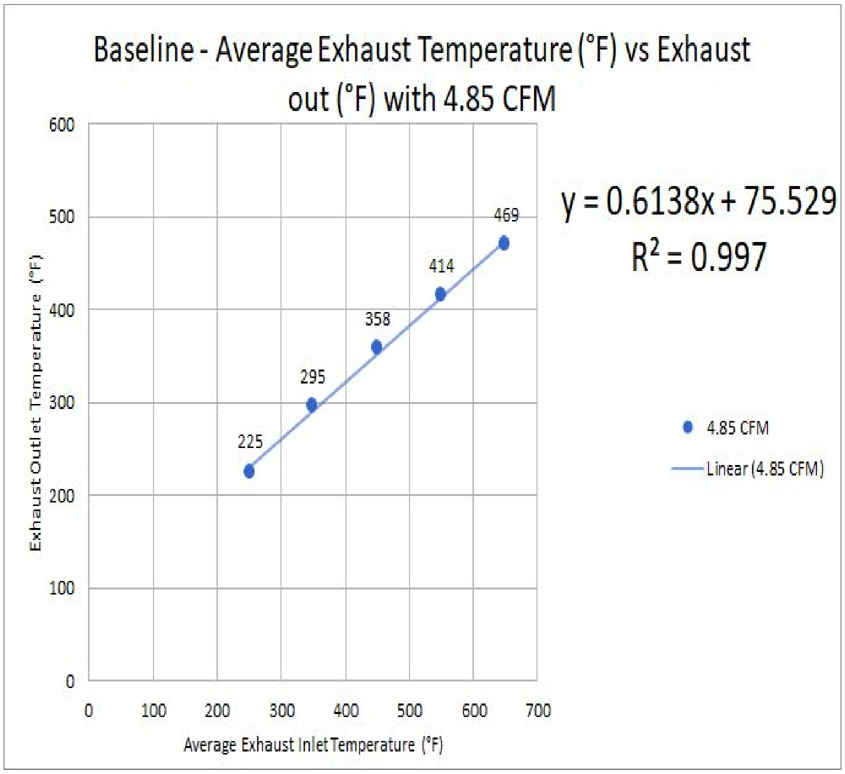


Fig 6. shows the performance for a flow of 4.85 cubic feet per minute for the baseline exhaust port.

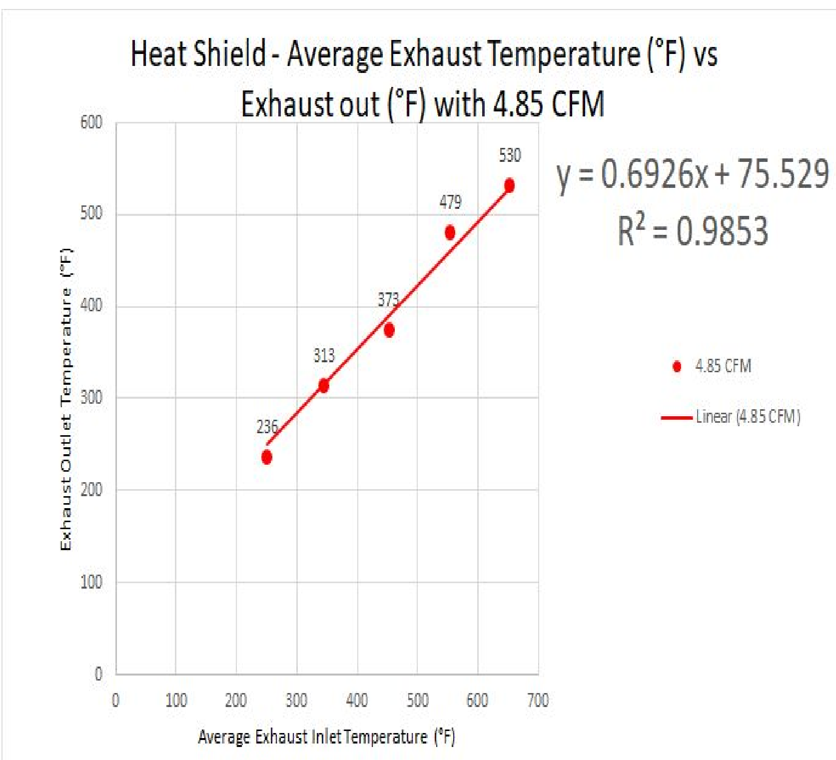


Fig 7. shows the performance for a flow of 4.85 cubic feet per minute for the modified exhaust port.

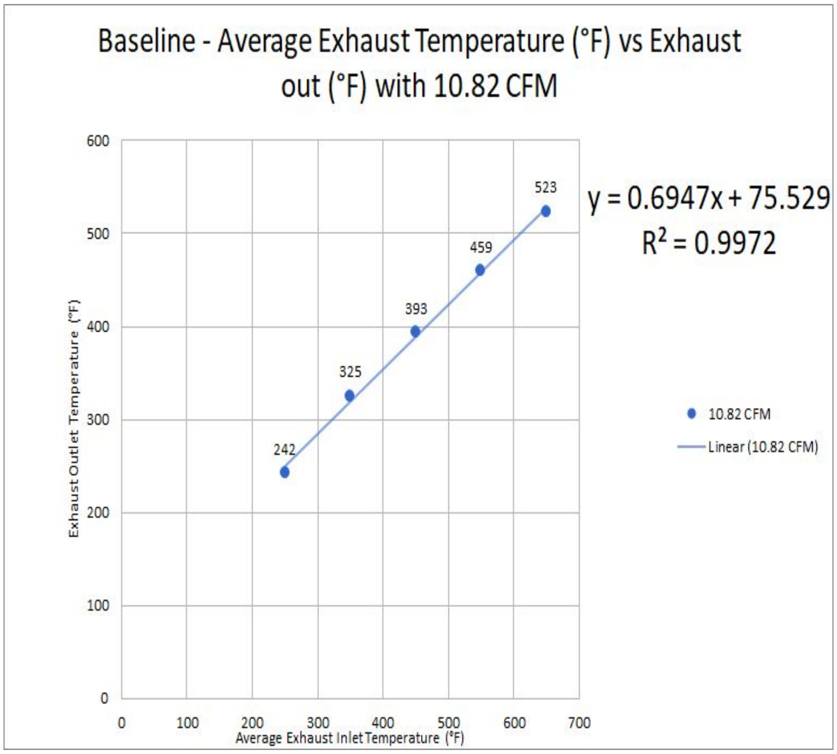


Fig 8. shows the performance for a flow of 10.82 cubic feet per minute for the baseline exhaust port.

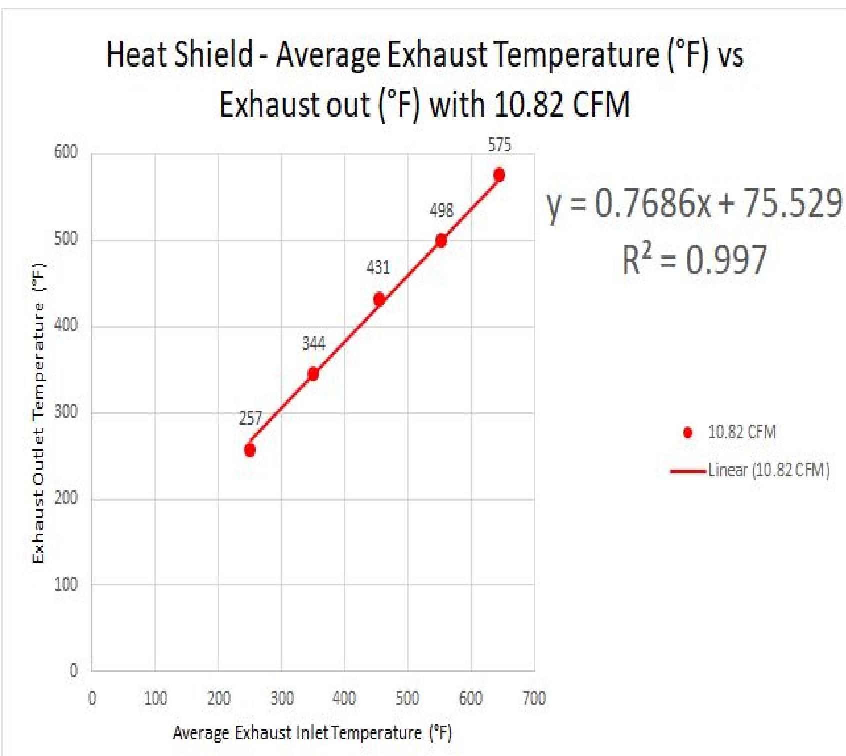


Fig 9. shows the performance for a flow of 10.82 cubic feet per minute for the modified exhaust port.

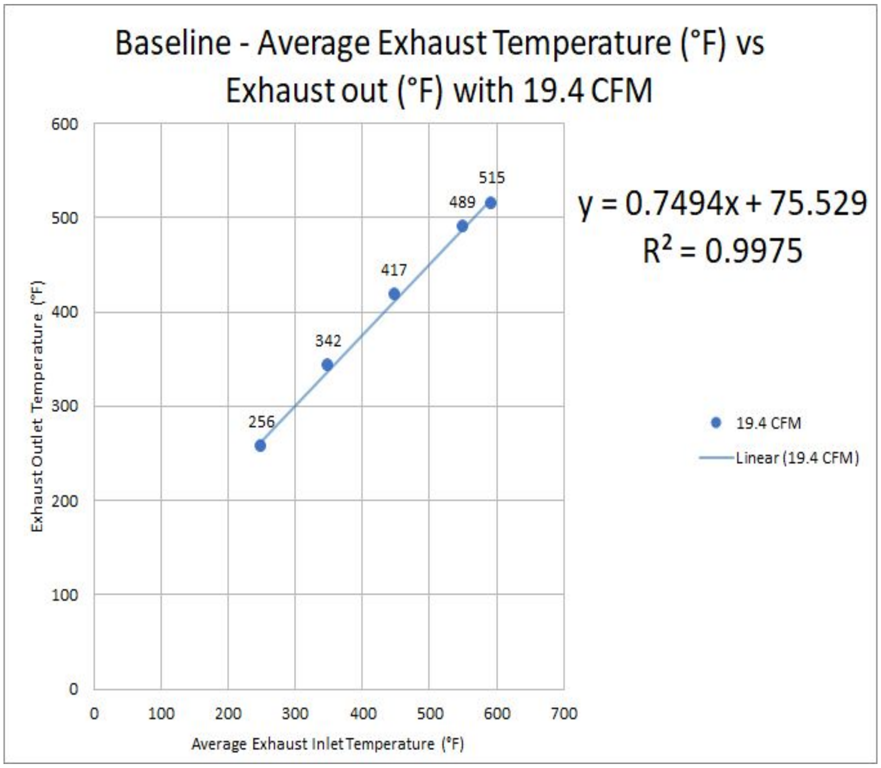


Fig 10. shows the performance for a flow of 19.4 cubic feet per minute for the baseline exhaust port.

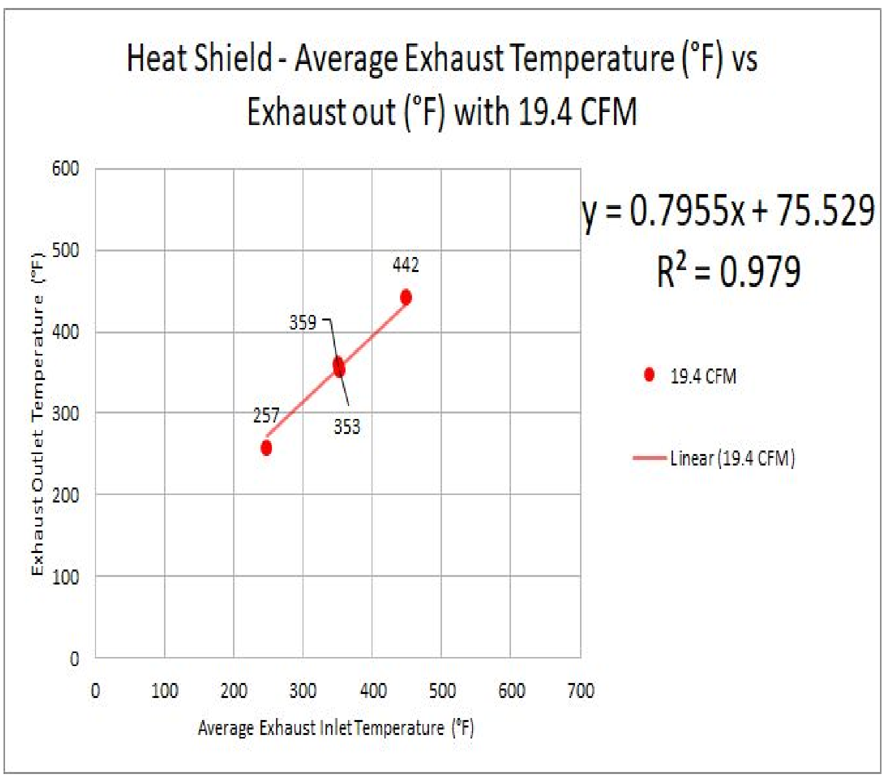


Fig 11. shows the performance for a flow of 19.4 cubic feet per minute for the modified exhaust port.

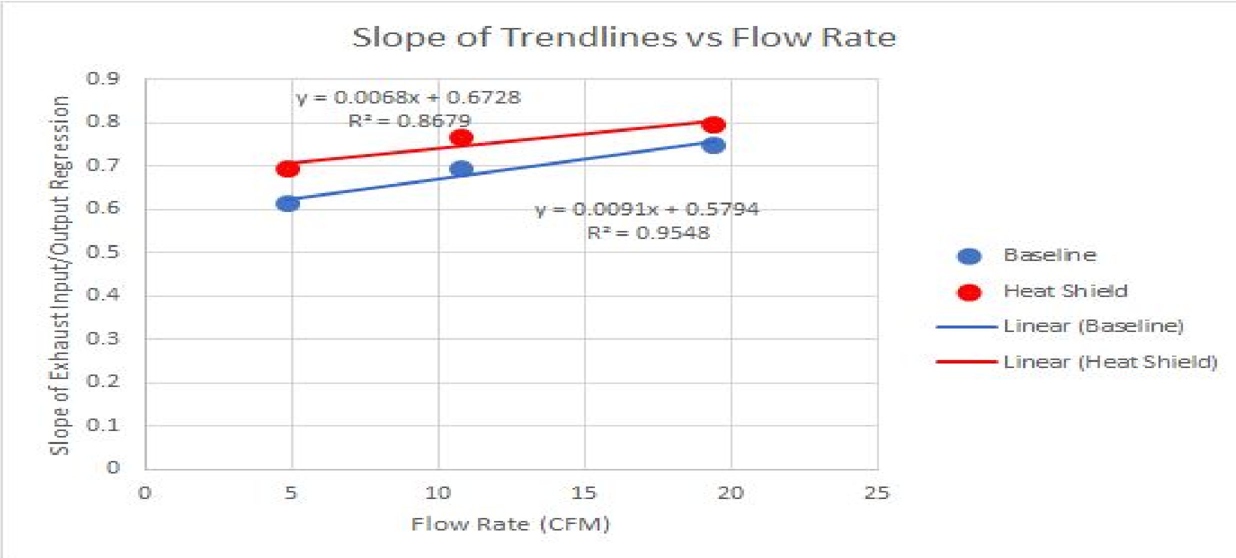


Fig 12. shows a plot of the linear regression lines for each Flow Rate.

Analysis

Our Results show that our design can positively impact LMOP LandFill Gas Projects. Our baseline testing shows the percentage of the heat that is retained in the exhaust ports of small engines used in current LMOP projects. Our heat shield design performs better than the baseline cylinder head. This is evident by slope values of the two test shown in figure 12.

According to the flow results, the heat shield flows sufficiently to be incorporated into a LMOP engine. The ratio of rated RPMs between the baseline port to the modified port can be approximated as the ratio of flow through the port assuming a constant diameter for the flow. The pressure drop along the test piece was brought to 28 in H20 (1 psi) and the corresponding flow rate was determined from the inclined manometer, shown in the data as “Corresponding CFM.” The ratio of the flow rates between the baseline port and the modified port was calculated to be .384. This is greater than the ratio of the rated RPMs, .327, meaning that the port flows well enough to ensure no gases are left in the cylinder and engine misfiring is not a concern. It is notable that this testing procedure is different than the proposed study approach for flow. This information is satisfactory to show the same conclusion using this method..0

Figures 6 through 11 show lines that plot inlet vs. outlet Temperature. The plots for the inlet vs. the outlet temperature represent how effectively heat is retained in the exhaust port. The greater the data point for the heat shield is above the baseline design at a given temperature, the better the performance. Figure 12 is a plot of the trendline for the slope at each flow rate. In Figure 12 we clearly see that the data points for the heat shield are above the data points for the baseline cylinder head. This means at each Flow Rate our design's performance was higher than the baseline performance. At all three Flow Rates we can see that the Heat Shield performs more effectively than the cylinder head without the insert because the data point at each temperature is higher for the heat shield than the unaltered cylinder head.

The difference between the two points at each temperature represents the increase in performance for our design. The average of the difference of points of baseline and our design was about 5.81%. This means that on average at flow rates of 4.82, 10.82, 19.4 CFM the modified exhaust port can retain 5.81% more heat than the baseline cylinder head.

A portion of the power produced goes to the fan. The fan uses up approximately 10 percent of the power. Because we know that our design retains 5.81% more heat than the baseline cylinder head, this means that we reduced 5.81% of the load on the fan. By having a greater heat retention in the cylinder head we can have the engine perform with a greater efficiency and help us meet the emission requirements set by LMOP.

Our results show that our design does in fact generate more revenue than the baseline cylinder head. In Figure 13 we see that the cost outputs of the heat shield are greater than the cost output for the baseline data. On average we will save $578.65 per year if we implement our heat shield design on LandFill gas projects.

Years	100 KWH payback in US dollars (Baseline)	100 KWH payback in US dollars (Heat Shield)	Revenue saved from our design
1	99601.2	100179.883	578.682972
2	199202.4	200359.7659	1157.365944
3	298803.6	300539.6489	1736.048916
4	398404.8	400719.5319	2314.731888
5	498006	500899.4149	2893.41486
6	597607.2	601079.2978	3472.097832
7	697208.4	701259.1808	4050.780804
8	796809.6	801439.0638	4629.463776
9	896410.8	901618.9467	5208.146748
10	996012	1001798.83	5786.82972
11	1095613.2	1101978.713	6365.512692
12	1195214.4	1202158.596	6944.195664
13	1294815.6	1302338.479	7522.878636
14	1394416.8	1402518.362	8101.561608
15	1494018	1502698.245	8680.24458
16	1593619.2	1602878.128	9258.927552
17	1693220.4	1703058.011	9837.610524
18	1792821.6	1803237.893	10416.2935
19	1892422.8	1903417.776	10994.97647
20	1992024	2003597.659	11573.65944

Figure 13. Payback Table

The heat shield is subject to different sources of error. Exhaust inlet thermocouples display diverging temperature values which shows that there is disproportional flow at the 2 exhaust inlets. Producing the heat shield subjects us to human error because the heat shield is assembled and bonded by hand. During testing we had to omit several data points due to exhaust inlets not being able to reach the desired temperature.

Future Work

Work can be done to improve the design and ensure efficient performance. One aspect which would improve the design is to make both exhaust ports more symmetrical. The flow test through the exhaust port clearly shows that one exhaust ports flows better than the other. This disproportional flow was proven by the difference in exhaust inlet temperatures. As we reached higher temperatures, the difference became drastic, one exhaust port required longer time to obtain high temperatures.

Testing the expansion properties of the Extreme Heat JB weld two-part epoxy would prove helpful in further design. During standard operation, the cylinder head will be heated and cooled so it is important to understand the epoxy's ability to withstand being rapidly heated over time. Due to the composition, the epoxy will contract and expand at a different rate in comparison to the aluminum, galvanized steel, and cylinder head. With differing expansion rates, fluxuations may supply negative impacts on airflow and thus increased heat transfer.

During the assembly of our design we applied the JB weld epoxy by hand however this may introduce potential error. Difficulties were faced when applying the epoxy during the assembly process, however, after allowing time for the epoxy to dry - 24 hours for completion - we were able to grind down excess remnants. Developing an efficient epoxy application process would prove beneficial in reducing potential restrictions on flow.

Appendix

A.1. Purchased Items

Thanks for your purchase Richard! Your order is confirmed.

We'll let you know when it's on the way. In the meantime, we have more things you'll love at unbeatable prices!

View order details | Browse deals

Driver Left Cylinder Head Fits 95-00 AVENGER 41837

Total: $135.00
Item ID: 142760392513

ebay MONEY BACK GUARANTEE

Seller: kramers_auto (6156)
99.6% positive feedback

More from this seller →

Order total:

Price	$85.00
Shipping	$50.00
Total charged to PayPal	$135.00

Cost of the cylinder head used

A.2. Blowdown Spreadsheet (All values range from pressures of 50 psi to 100 psi and a ratio of specific heats from 1.3 to 1.4

This Appendix Section shows the theoretical values used for the blowdown calculations

A

Cylinder Volume	30.5											
		K										
Atmospheric Pressure	14.7	1.3	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.4
Cylinder Pressure	50	78.2102	77.6500	77.1022	76.5665	76.0424	75.5295	75.0276	74.5362	74.0552	73.5841	73.1226
	51	79.4107	78.8327	78.2677	77.7150	77.1745	76.6456	76.1280	75.6214	75.1255	74.6399	74.1643
	52	80.6057	80.0100	79.4275	78.8580	78.3009	77.7560	77.2228	76.7009	76.1901	75.6899	75.2001
	53	81.7955	81.1819	80.5820	79.9955	79.4219	78.8609	78.3120	77.7748	77.2490	76.7343	76.2303
	54	82.9801	82.3485	81.7312	81.1277	80.5376	79.9604	79.3957	78.8432	78.3025	77.7731	77.2549
	55	84.1597	83.5101	82.8753	82.2548	81.6480	81.0546	80.4742	79.9063	79.3506	78.8066	78.2741
	56	85.3343	84.6667	84.0143	83.3767	82.7533	82.1437	81.5475	80.9642	80.3934	79.8348	79.2880
	57	86.5040	85.8184	85.1485	84.4937	83.8536	83.2278	82.6157	82.0170	81.4312	80.8579	80.2968
	58	87.6691	86.9653	86.2778	85.6058	84.9491	84.3069	83.6790	83.0648	82.4639	81.8760	81.3005
	59	88.8295	88.1076	87.4023	86.7132	86.0397	85.3813	84.7374	84.1078	83.4918	82.8891	82.2993
	60	89.9854	89.2453	88.5223	87.8160	87.1257	86.4509	85.7911	85.1460	84.5149	83.8974	83.2932
	61	91.1369	90.3785	89.6378	88.9142	88.2070	87.5159	86.8402	86.1795	85.5333	84.9011	84.2825
	62	92.2840	91.5073	90.7488	90.0079	89.2839	88.5764	87.8847	87.2084	86.5471	85.9001	85.2671
	63	93.4268	92.6318	91.8555	91.0972	90.3564	89.6324	88.9248	88.2329	87.5564	86.8946	86.2472
	64	94.5655	93.7522	92.9580	92.1823	91.4246	90.6842	89.9605	89.2530	88.5613	87.8847	87.2229
	65	95.7000	94.8683	94.0563	93.2632	92.4885	91.7316	90.9919	90.2688	89.5618	88.8705	88.1942
	66	96.8306	95.9804	95.1505	94.3400	93.5483	92.7749	92.0192	91.2804	90.5582	89.8520	89.1612
	67	97.9572	97.0886	96.2406	95.4127	94.6041	93.8141	93.0423	92.2879	91.5504	90.8293	90.1241
	68	99.0799	98.1928	97.3269	96.4815	95.6558	94.8493	94.0614	93.2913	92.5386	91.8026	91.0829
	69	100.1988	99.2932	98.4093	97.5463	96.7037	95.8806	95.0765	94.2907	93.5227	92.7718	92.0376
	70	101.3140	100.3898	99.4879	98.6074	97.7477	96.9080	96.0877	95.2863	94.5029	93.7372	92.9884
	71	102.4256	101.4827	100.5627	99.6647	98.7879	97.9316	97.0952	96.2780	95.4793	94.6986	93.9354
	72	103.5335	102.5720	101.6339	100.7183	99.8244	98.9515	98.0989	97.2659	96.4519	95.6563	94.8785
	73	104.6378	103.6577	102.7015	101.7682	100.8572	99.9677	99.0988	98.2501	97.4208	96.6103	95.8179
	74	105.7387	104.7399	103.7655	102.8147	101.8865	100.9802	100.0952	99.2307	98.3860	97.5605	96.7536
	75	106.8362	105.8187	104.8261	103.8576	102.9122	101.9893	101.0880	100.2077	99.3477	98.5072	97.6858
	76	107.9302	106.8940	105.8833	104.8970	103.9345	102.9949	102.0774	101.1812	100.3058	99.4504	98.6143
	77	109.0210	107.9660	106.9370	105.9331	104.9534	103.9970	103.0632	102.1513	101.2605	100.3901	99.5394
	78	110.1085	109.0347	107.9875	106.9659	105.9689	104.9958	104.0457	103.1180	102.2117	101.3263	100.4611
	79	111.1928	110.1002	109.0347	107.9953	106.9811	105.9913	105.0249	104.0813	103.1596	102.2592	101.3794
	80	112.2739	111.1625	110.0787	109.0216	107.9901	106.9835	106.0008	105.0413	104.1042	103.1888	102.2944
	81	113.3519	112.2217	111.1196	110.0446	108.9959	107.9724	106.9735	105.9981	105.0456	104.1152	103.2061
	82	114.4268	113.2777	112.1573	111.0645	109.9985	108.9583	107.9430	106.9517	105.9838	105.0383	104.1146
	83	115.4988	114.3307	113.1920	112.0814	110.9980	109.9410	108.9093	107.9022	106.9188	105.9583	105.0200
	84	116.5677	115.3808	114.2236	113.0952	111.9945	110.9206	109.8726	108.8496	107.8507	106.8752	105.9222
	85	117.6337	116.4278	115.2523	114.1060	112.9880	111.8973	110.8329	109.7939	108.7796	107.7890	106.8214
	86	118.6968	117.4720	116.2780	115.1139	113.9785	112.8709	111.7902	110.7353	109.7054	108.6998	107.7175
	87	119.7571	118.5133	117.3009	116.1189	114.9661	113.8417	112.7445	111.6737	110.6284	109.6076	108.6107
	88	120.8146	119.5517	118.3209	117.1210	115.9509	114.8095	113.6959	112.6092	111.5483	110.5125	109.5010
	89	121.8693	120.5874	119.3381	118.1203	116.9327	115.7745	114.6445	113.5418	112.4655	111.4146	110.3883
	90	122.9212	121.6203	120.3525	119.1168	117.9118	116.7367	115.5903	114.4716	113.3797	112.3138	111.2729
	91	123.9705	122.6505	121.3643	120.1105	118.8882	117.6961	116.5333	115.3986	114.2912	113.2102	112.1546
	92	125.0171	123.6780	122.3733	121.1016	119.8618	118.6528	117.4735	116.3229	115.2000	114.1038	113.0335
	93	126.0611	124.7029	123.3796	122.0900	120.8327	119.6068	118.4110	117.2444	116.1060	114.9947	113.9098
	94	127.1025	125.7252	124.3834	123.0757	121.8010	120.5581	119.3459	118.1633	117.0093	115.8830	114.7833
	95	128.1413	126.7449	125.3845	124.0589	122.7667	121.5069	120.2782	119.0796	117.9100	116.7686	115.6542
	96	129.1777	127.7621	126.3831	125.0395	123.7298	122.4530	121.2078	119.9932	118.8081	117.6515	116.5225
	97	130.2115	128.7768	127.3792	126.0175	124.6904	123.3966	122.1349	120.9043	119.7036	118.5319	117.3882
	98	131.2429	129.7890	128.3728	126.9931	125.6484	124.3376	123.0595	121.8128	120.5966	119.4098	118.2513
	99	132.2718	130.7987	129.3640	127.9662	126.6040	125.2762	123.9816	122.7189	121.4871	120.2851	119.1120
	100	133.2984	131.8061	130.3527	128.9368	127.5572	126.2123	124.9012	123.6225	122.3751	121.1580	119.9701

Sample of Average Temperature from Required Volume

B

		K										
Atmospheric Pressure	14.7	1.3	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.4
Cylinder Pressure	50	1671.320	1683.377	1695.337	1707.200	1718.967	1730.639	1742.217	1753.701	1765.093	1776.394	1787.604
	51	1678.975	1691.284	1703.495	1715.609	1727.626	1739.547	1751.373	1763.105	1774.744	1786.291	1797.747
	52	1686.516	1699.074	1711.533	1723.894	1736.159	1748.326	1760.398	1772.376	1784.259	1796.050	1807.748
	53	1693.946	1706.750	1719.455	1732.061	1744.570	1756.982	1769.297	1781.517	1793.643	1805.675	1817.614
	54	1701.268	1714.316	1727.264	1740.113	1752.864	1765.517	1778.073	1790.533	1802.899	1815.169	1827.347
	55	1708.487	1721.776	1734.965	1748.054	1761.044	1773.936	1786.730	1799.429	1812.031	1824.539	1836.952
	56	1715.606	1729.133	1742.560	1755.886	1769.113	1782.242	1795.273	1808.207	1821.044	1833.786	1846.433
	57	1722.628	1736.391	1750.053	1763.614	1777.076	1790.439	1803.704	1816.871	1829.941	1842.915	1855.794
	58	1729.556	1743.552	1757.447	1771.241	1784.935	1798.530	1812.026	1825.425	1838.726	1851.930	1865.039
	59	1736.392	1750.619	1764.745	1778.770	1792.694	1806.519	1820.244	1833.872	1847.401	1860.834	1874.170
	60	1743.140	1757.596	1771.950	1786.203	1800.355	1814.408	1828.361	1842.215	1855.971	1869.630	1883.192
	61	1749.802	1764.484	1779.065	1793.544	1807.922	1822.200	1836.378	1850.457	1864.438	1878.321	1892.106
	62	1756.380	1771.287	1786.092	1800.795	1815.397	1829.898	1844.299	1858.601	1872.805	1886.910	1900.917
	63	1762.877	1778.006	1793.033	1807.958	1822.782	1837.505	1852.127	1866.650	1881.074	1895.400	1909.627
	64	1769.296	1784.645	1799.892	1815.036	1830.080	1845.022	1859.864	1874.606	1889.249	1903.793	1918.239
	65	1775.637	1791.205	1806.669	1822.032	1837.293	1852.453	1867.513	1882.472	1897.332	1912.093	1926.755
	66	1781.904	1797.688	1813.369	1828.947	1844.424	1859.800	1875.076	1890.250	1905.325	1920.301	1935.178
	67	1788.099	1804.096	1819.991	1835.784	1851.475	1867.065	1882.554	1897.943	1913.232	1928.421	1943.511
	68	1794.222	1810.432	1826.540	1842.545	1858.448	1874.250	1889.952	1905.552	1921.053	1936.453	1951.755
	69	1800.277	1816.698	1833.015	1849.231	1865.345	1881.358	1897.269	1913.080	1928.791	1944.401	1959.913
	70	1806.265	1822.894	1839.420	1855.845	1872.168	1888.389	1904.509	1920.529	1936.448	1952.267	1967.987
	71	1812.187	1829.023	1845.757	1862.388	1878.918	1895.346	1911.674	1927.900	1944.026	1960.052	1975.979
	72	1818.046	1835.087	1852.025	1868.862	1885.598	1902.231	1918.764	1935.196	1951.528	1967.759	1983.891
	73	1823.842	1841.086	1858.229	1875.269	1892.208	1909.046	1925.783	1942.419	1958.954	1975.389	1991.725
	74	1829.577	1847.024	1864.368	1881.611	1898.752	1915.792	1932.731	1949.569	1966.307	1982.944	1999.482
	75	1835.254	1852.900	1870.445	1887.888	1905.230	1922.471	1939.610	1956.650	1973.588	1990.427	2007.165
	76	1840.872	1858.717	1876.460	1894.102	1911.644	1929.084	1946.423	1963.661	1980.800	1997.837	2014.775
	77	1846.433	1864.475	1882.416	1900.256	1917.995	1935.633	1953.170	1970.606	1987.942	2005.178	2022.314
	78	1851.940	1870.177	1888.314	1906.349	1924.284	1942.119	1959.852	1977.486	1995.018	2012.451	2029.784
	79	1857.392	1875.823	1894.154	1912.385	1930.514	1948.544	1966.472	1984.301	2002.029	2019.657	2037.185
	80	1862.791	1881.415	1899.939	1918.363	1936.686	1954.908	1973.031	1991.053	2008.975	2026.797	2044.520
	81	1868.139	1886.954	1905.669	1924.285	1942.800	1961.215	1979.530	1997.744	2015.859	2033.874	2051.789
	82	1873.436	1892.441	1911.346	1930.152	1948.858	1967.463	1985.969	2004.376	2022.682	2040.888	2058.995
	83	1878.684	1897.877	1916.971	1935.966	1954.861	1973.656	1992.352	2010.948	2029.444	2047.841	2066.138
	84	1883.884	1903.264	1922.545	1941.727	1960.810	1979.794	1998.678	2017.463	2036.148	2054.734	2073.220
	85	1889.036	1908.601	1928.068	1947.437	1966.707	1985.877	2004.949	2023.921	2042.794	2061.568	2080.242
	86	1894.141	1913.891	1933.543	1953.097	1972.552	1991.908	2011.166	2030.324	2049.384	2068.344	2087.205
	87	1899.201	1919.134	1938.970	1958.707	1978.347	1997.888	2017.330	2036.674	2055.918	2075.064	2094.111
	88	1904.217	1924.332	1944.349	1964.269	1984.092	2003.816	2023.442	2042.970	2062.399	2081.729	2100.960
	89	1909.189	1929.484	1949.683	1969.784	1989.788	2009.695	2029.503	2049.214	2068.826	2088.339	2107.754
	90	1914.118	1934.592	1954.971	1975.253	1995.437	2015.525	2035.515	2055.407	2075.201	2094.896	2114.493
	91	1919.005	1939.658	1960.215	1980.676	2001.040	2021.307	2041.477	2061.550	2081.524	2101.401	2121.179
	92	1923.851	1944.681	1965.415	1986.054	2006.597	2027.043	2047.392	2067.644	2087.798	2107.855	2127.813
	93	1928.657	1949.662	1970.573	1991.389	2012.108	2032.732	2053.259	2073.690	2094.023	2114.258	2134.396
	94	1933.423	1954.603	1975.689	1996.680	2017.576	2038.376	2059.081	2079.688	2100.199	2120.612	2140.928
	95	1938.150	1959.504	1980.764	2001.930	2023.001	2043.976	2064.856	2085.640	2106.327	2126.918	2147.411
	96	1942.839	1964.365	1985.798	2007.138	2028.383	2049.533	2070.588	2091.547	2112.410	2133.176	2153.845
	97	1947.491	1969.188	1990.793	2012.305	2033.723	2055.047	2076.275	2097.409	2118.446	2139.387	2160.232
	98	1952.106	1973.973	1995.749	2017.433	2039.022	2060.518	2081.920	2103.226	2124.438	2145.553	2166.572
	99	1956.685	1978.722	2000.667	2022.521	2044.282	2065.949	2087.522	2109.001	2130.385	2151.673	2172.865
	100	1961.228	1983.433	2005.548	2027.571	2049.501	2071.339	2093.083	2114.733	2136.289	2157.749	2179.114

Pound Moles of gases in State 1 at given specific heat ratio

C

K

		1.3	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.4
Cylinder Pressure	50	4.92E-05	4.89E-05	4.85E-05	4.82E-05	4.79E-05	4.75E-05	4.72E-05	4.69E-05	4.66E-05	4.63E-05	4.60E-05
	51	5.00E-05	4.96E-05	4.93E-05	4.89E-05	4.86E-05	4.82E-05	4.79E-05	4.76E-05	4.73E-05	4.70E-05	4.67E-05
	52	5.07E-05	5.03E-05	5.00E-05	4.96E-05	4.93E-05	4.89E-05	4.86E-05	4.83E-05	4.79E-05	4.76E-05	4.73E-05
	53	5.15E-05	5.11E-05	5.07E-05	5.03E-05	5.00E-05	4.96E-05	4.93E-05	4.89E-05	4.86E-05	4.83E-05	4.80E-05
	54	5.22E-05	5.18E-05	5.14E-05	5.11E-05	5.07E-05	5.03E-05	5.00E-05	4.96E-05	4.93E-05	4.89E-05	4.86E-05
	55	5.30E-05	5.26E-05	5.22E-05	5.18E-05	5.14E-05	5.10E-05	5.06E-05	5.03E-05	4.99E-05	4.96E-05	4.93E-05
	56	5.37E-05	5.33E-05	5.29E-05	5.25E-05	5.21E-05	5.17E-05	5.13E-05	5.09E-05	5.06E-05	5.02E-05	4.99E-05
	57	5.44E-05	5.40E-05	5.36E-05	5.32E-05	5.28E-05	5.24E-05	5.20E-05	5.16E-05	5.12E-05	5.09E-05	5.05E-05
	58	5.52E-05	5.47E-05	5.43E-05	5.39E-05	5.35E-05	5.31E-05	5.27E-05	5.23E-05	5.19E-05	5.15E-05	5.12E-05
	59	5.59E-05	5.54E-05	5.50E-05	5.46E-05	5.41E-05	5.37E-05	5.33E-05	5.29E-05	5.25E-05	5.22E-05	5.18E-05
	60	5.66E-05	5.62E-05	5.57E-05	5.53E-05	5.48E-05	5.44E-05	5.40E-05	5.36E-05	5.32E-05	5.28E-05	5.24E-05
	61	5.73E-05	5.69E-05	5.64E-05	5.60E-05	5.55E-05	5.51E-05	5.46E-05	5.42E-05	5.38E-05	5.34E-05	5.30E-05
	62	5.81E-05	5.76E-05	5.71E-05	5.66E-05	5.62E-05	5.57E-05	5.53E-05	5.49E-05	5.45E-05	5.41E-05	5.37E-05
	63	5.88E-05	5.83E-05	5.78E-05	5.73E-05	5.69E-05	5.64E-05	5.60E-05	5.55E-05	5.51E-05	5.47E-05	5.43E-05
	64	5.95E-05	5.90E-05	5.85E-05	5.80E-05	5.75E-05	5.71E-05	5.66E-05	5.62E-05	5.57E-05	5.53E-05	5.49E-05
	65	6.02E-05	5.97E-05	5.92E-05	5.87E-05	5.82E-05	5.77E-05	5.73E-05	5.68E-05	5.64E-05	5.59E-05	5.55E-05
	66	6.09E-05	6.04E-05	5.99E-05	5.94E-05	5.89E-05	5.84E-05	5.79E-05	5.74E-05	5.70E-05	5.65E-05	5.61E-05
	67	6.16E-05	6.11E-05	6.06E-05	6.00E-05	5.95E-05	5.90E-05	5.85E-05	5.81E-05	5.76E-05	5.72E-05	5.67E-05
	68	6.23E-05	6.18E-05	6.12E-05	6.07E-05	6.02E-05	5.97E-05	5.92E-05	5.87E-05	5.82E-05	5.78E-05	5.73E-05
	69	6.31E-05	6.25E-05	6.19E-05	6.14E-05	6.09E-05	6.03E-05	5.98E-05	5.93E-05	5.89E-05	5.84E-05	5.79E-05
	70	6.38E-05	6.32E-05	6.26E-05	6.21E-05	6.15E-05	6.10E-05	6.05E-05	6.00E-05	5.95E-05	5.90E-05	5.85E-05
	71	6.45E-05	6.39E-05	6.33E-05	6.27E-05	6.22E-05	6.16E-05	6.11E-05	6.06E-05	6.01E-05	5.96E-05	5.91E-05
	72	6.52E-05	6.45E-05	6.40E-05	6.34E-05	6.28E-05	6.23E-05	6.17E-05	6.12E-05	6.07E-05	6.02E-05	5.97E-05
	73	6.58E-05	6.52E-05	6.46E-05	6.40E-05	6.35E-05	6.29E-05	6.24E-05	6.18E-05	6.13E-05	6.08E-05	6.03E-05
	74	6.65E-05	6.59E-05	6.53E-05	6.47E-05	6.41E-05	6.35E-05	6.30E-05	6.24E-05	6.19E-05	6.14E-05	6.09E-05
	75	6.72E-05	6.66E-05	6.60E-05	6.54E-05	6.48E-05	6.42E-05	6.36E-05	6.31E-05	6.25E-05	6.20E-05	6.15E-05
	76	6.79E-05	6.73E-05	6.66E-05	6.60E-05	6.54E-05	6.48E-05	6.42E-05	6.37E-05	6.31E-05	6.26E-05	6.21E-05
	77	6.86E-05	6.79E-05	6.73E-05	6.67E-05	6.60E-05	6.54E-05	6.49E-05	6.43E-05	6.37E-05	6.32E-05	6.26E-05
	78	6.93E-05	6.86E-05	6.80E-05	6.73E-05	6.67E-05	6.61E-05	6.55E-05	6.49E-05	6.43E-05	6.38E-05	6.32E-05
	79	7.00E-05	6.93E-05	6.86E-05	6.80E-05	6.73E-05	6.67E-05	6.61E-05	6.55E-05	6.49E-05	6.43E-05	6.38E-05
	80	7.07E-05	7.00E-05	6.93E-05	6.86E-05	6.80E-05	6.73E-05	6.67E-05	6.61E-05	6.55E-05	6.49E-05	6.44E-05
	81	7.13E-05	7.06E-05	6.99E-05	6.92E-05	6.86E-05	6.79E-05	6.73E-05	6.67E-05	6.61E-05	6.55E-05	6.49E-05
	82	7.20E-05	7.13E-05	7.06E-05	6.99E-05	6.92E-05	6.86E-05	6.79E-05	6.73E-05	6.67E-05	6.61E-05	6.55E-05
	83	7.27E-05	7.19E-05	7.12E-05	7.05E-05	6.98E-05	6.92E-05	6.85E-05	6.79E-05	6.73E-05	6.67E-05	6.61E-05
	84	7.34E-05	7.26E-05	7.19E-05	7.12E-05	7.05E-05	6.98E-05	6.91E-05	6.85E-05	6.79E-05	6.73E-05	6.67E-05
	85	7.40E-05	7.33E-05	7.25E-05	7.18E-05	7.11E-05	7.04E-05	6.97E-05	6.91E-05	6.85E-05	6.78E-05	6.72E-05
	86	7.47E-05	7.39E-05	7.32E-05	7.24E-05	7.17E-05	7.10E-05	7.03E-05	6.97E-05	6.90E-05	6.84E-05	6.78E-05
	87	7.54E-05	7.46E-05	7.38E-05	7.31E-05	7.23E-05	7.16E-05	7.09E-05	7.03E-05	6.96E-05	6.90E-05	6.83E-05
	88	7.60E-05	7.52E-05	7.45E-05	7.37E-05	7.30E-05	7.22E-05	7.15E-05	7.09E-05	7.02E-05	6.95E-05	6.89E-05
	89	7.67E-05	7.59E-05	7.51E-05	7.43E-05	7.36E-05	7.29E-05	7.21E-05	7.14E-05	7.08E-05	7.01E-05	6.95E-05
	90	7.74E-05	7.65E-05	7.57E-05	7.50E-05	7.42E-05	7.35E-05	7.27E-05	7.20E-05	7.13E-05	7.07E-05	7.00E-05
	91	7.80E-05	7.72E-05	7.64E-05	7.56E-05	7.48E-05	7.41E-05	7.33E-05	7.26E-05	7.19E-05	7.12E-05	7.06E-05
	92	7.87E-05	7.78E-05	7.70E-05	7.62E-05	7.54E-05	7.47E-05	7.39E-05	7.32E-05	7.25E-05	7.18E-05	7.11E-05
	93	7.93E-05	7.85E-05	7.76E-05	7.68E-05	7.60E-05	7.53E-05	7.45E-05	7.38E-05	7.31E-05	7.24E-05	7.17E-05
	94	8.00E-05	7.91E-05	7.83E-05	7.74E-05	7.66E-05	7.59E-05	7.51E-05	7.44E-05	7.36E-05	7.29E-05	7.22E-05
	95	8.06E-05	7.98E-05	7.89E-05	7.81E-05	7.73E-05	7.65E-05	7.57E-05	7.49E-05	7.42E-05	7.35E-05	7.28E-05
	96	8.13E-05	8.04E-05	7.95E-05	7.87E-05	7.79E-05	7.71E-05	7.63E-05	7.55E-05	7.48E-05	7.40E-05	7.33E-05
	97	8.19E-05	8.10E-05	8.02E-05	7.93E-05	7.85E-05	7.76E-05	7.69E-05	7.61E-05	7.53E-05	7.46E-05	7.39E-05
	98	8.26E-05	8.17E-05	8.08E-05	7.99E-05	7.91E-05	7.82E-05	7.74E-05	7.67E-05	7.59E-05	7.51E-05	7.44E-05
	99	8.32E-05	8.23E-05	8.14E-05	8.05E-05	7.97E-05	7.88E-05	7.80E-05	7.72E-05	7.64E-05	7.57E-05	7.50E-05
	100	8.39E-05	8.29E-05	8.20E-05	8.11E-05	8.03E-05	7.94E-05	7.86E-05	7.78E-05	7.70E-05	7.62E-05	7.55E-05

Pound Moles of Gases in state 2 at given specific heat ratio

D

		K										
		1.3	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.4
Cylinder Pressure	50	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	51	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	52	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	53	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	54	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	55	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	56	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	57	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	58	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	59	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	60	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	61	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	62	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	63	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	64	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	65	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	66	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	67	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	68	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	69	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	70	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	71	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	72	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	73	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	74	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	75	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	76	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	77	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	78	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	79	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	80	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	81	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	82	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	83	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	84	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	85	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	86	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	87	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	88	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	89	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	90	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	91	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	92	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	93	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	94	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	95	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	96	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	97	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	98	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	99	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05
	100	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05	1.92E-05

Percentage of gases left in the cylinder after blowdown

E

							K						Cylinder Volume	Standard Deviation
		1.3	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.4	30.5	
	50	39.00%	39.28%	39.56%	39.83%	40.11%	40.38%	40.65%	40.92%	41.19%	41.45%	41.71%		0.0090
	51	38.41%	38.69%	38.97%	39.25%	39.52%	39.79%	40.06%	40.33%	40.60%	40.86%	41.12%		0.0090
	52	37.84%	38.12%	38.40%	38.68%	38.95%	39.23%	39.50%	39.76%	40.03%	40.30%	40.56%		0.0090
	53	37.29%	37.57%	37.85%	38.13%	38.40%	38.68%	38.95%	39.22%	39.48%	39.75%	40.01%		0.0090
	54	36.76%	37.04%	37.32%	37.60%	37.87%	38.14%	38.42%	38.68%	38.95%	39.22%	39.48%		0.0090
	55	36.24%	36.52%	36.80%	37.08%	37.36%	37.63%	37.90%	38.17%	38.44%	38.70%	38.97%		0.0090
	56	35.74%	36.02%	36.30%	36.58%	36.86%	37.13%	37.40%	37.67%	37.94%	38.20%	38.47%		0.0090
	57	35.26%	35.54%	35.82%	36.10%	36.37%	36.65%	36.92%	37.19%	37.45%	37.72%	37.98%		0.0090
	58	34.79%	35.07%	35.35%	35.63%	35.90%	36.18%	36.45%	36.72%	36.99%	37.25%	37.52%		0.0090
Cylinder Pressure	59	34.34%	34.62%	34.90%	35.17%	35.45%	35.72%	35.99%	36.26%	36.53%	36.80%	37.06%		0.0090
	60	33.89%	34.18%	34.45%	34.73%	35.01%	35.28%	35.55%	35.82%	36.09%	36.35%	36.62%		0.0090
	61	33.47%	33.75%	34.03%	34.30%	34.58%	34.85%	35.12%	35.39%	35.66%	35.92%	36.19%		0.0090
	62	33.05%	33.33%	33.61%	33.89%	34.16%	34.43%	34.70%	34.97%	35.24%	35.51%	35.77%		0.0090
	63	32.65%	32.93%	33.20%	33.48%	33.76%	34.03%	34.30%	34.57%	34.83%	35.10%	35.36%		0.0090
	64	32.25%	32.53%	32.81%	33.09%	33.36%	33.63%	33.90%	34.17%	34.44%	34.70%	34.97%		0.0090
	65	31.87%	32.15%	32.43%	32.70%	32.98%	33.25%	33.52%	33.79%	34.05%	34.32%	34.58%		0.0090
	66	31.50%	31.78%	32.05%	32.33%	32.60%	32.88%	33.15%	33.41%	33.68%	33.94%	34.21%		0.0090
	67	31.14%	31.41%	31.69%	31.97%	32.24%	32.51%	32.78%	33.05%	33.31%	33.58%	33.84%		0.0090
	68	30.78%	31.06%	31.34%	31.61%	31.89%	32.16%	32.43%	32.69%	32.96%	33.22%	33.49%		0.0090
	69	30.44%	30.72%	30.99%	31.27%	31.54%	31.81%	32.08%	32.35%	32.61%	32.88%	33.14%		0.0090
	70	30.10%	30.38%	30.66%	30.93%	31.20%	31.47%	31.74%	32.01%	32.27%	32.54%	32.80%		0.0089
	71	29.78%	30.05%	30.33%	30.60%	30.87%	31.14%	31.41%	31.68%	31.94%	32.21%	32.47%		0.0089
	72	29.46%	29.74%	30.01%	30.28%	30.55%	30.82%	31.09%	31.36%	31.62%	31.88%	32.15%		0.0089
	73	29.15%	29.42%	29.70%	29.97%	30.24%	30.51%	30.78%	31.04%	31.31%	31.57%	31.83%		0.0089
	74	28.84%	29.12%	29.39%	29.67%	29.94%	30.20%	30.47%	30.74%	31.00%	31.26%	31.52%		0.0089
	75	28.55%	28.82%	29.10%	29.37%	29.64%	29.91%	30.17%	30.44%	30.70%	30.96%	31.22%		0.0089
	76	28.26%	28.53%	28.81%	29.08%	29.35%	29.61%	29.88%	30.14%	30.41%	30.67%	30.93%		0.0089
	77	27.98%	28.25%	28.52%	28.79%	29.06%	29.33%	29.59%	29.86%	30.12%	30.38%	30.64%		0.0088
	78	27.70%	27.97%	28.24%	28.51%	28.78%	29.05%	29.31%	29.58%	29.84%	30.10%	30.36%		0.0088
	79	27.43%	27.70%	27.97%	28.24%	28.51%	28.78%	29.04%	29.30%	29.57%	29.83%	30.09%		0.0088
	80	27.17%	27.44%	27.71%	27.98%	28.24%	28.51%	28.77%	29.04%	29.30%	29.56%	29.82%		0.0088
	81	26.91%	27.18%	27.45%	27.72%	27.98%	28.25%	28.51%	28.77%	29.04%	29.29%	29.55%		0.0088
	82	26.65%	26.92%	27.19%	27.46%	27.73%	27.99%	28.26%	28.52%	28.78%	29.04%	29.29%		0.0088
	83	26.41%	26.68%	26.95%	27.21%	27.48%	27.74%	28.00%	28.27%	28.53%	28.78%	29.04%		0.0087
	84	26.17%	26.43%	26.70%	26.97%	27.23%	27.50%	27.76%	28.02%	28.28%	28.54%	28.79%		0.0087
	85	25.93%	26.20%	26.46%	26.73%	26.99%	27.26%	27.52%	27.78%	28.04%	28.30%	28.55%		0.0087
	86	25.70%	25.96%	26.23%	26.50%	26.76%	27.02%	27.28%	27.54%	27.80%	28.06%	28.31%		0.0087
	87	25.47%	25.74%	26.00%	26.27%	26.53%	26.79%	27.05%	27.31%	27.57%	27.83%	28.08%		0.0087
	88	25.25%	25.51%	25.78%	26.04%	26.30%	26.57%	26.83%	27.08%	27.34%	27.60%	27.85%		0.0087
	89	25.03%	25.29%	25.56%	25.82%	26.08%	26.34%	26.60%	26.86%	27.12%	27.38%	27.63%		0.0086
	90	24.81%	25.08%	25.34%	25.61%	25.87%	26.13%	26.39%	26.64%	26.90%	27.16%	27.41%		0.0086
	91	24.60%	24.87%	25.13%	25.39%	25.65%	25.91%	26.17%	26.43%	26.69%	26.94%	27.19%		0.0086
	92	24.40%	24.66%	24.92%	25.19%	25.45%	25.71%	25.96%	26.22%	26.48%	26.73%	26.98%		0.0086
	93	24.19%	24.46%	24.72%	24.98%	25.24%	25.50%	25.76%	26.01%	26.27%	26.52%	26.78%		0.0086
	94	24.00%	24.26%	24.52%	24.78%	25.04%	25.30%	25.56%	25.81%	26.07%	26.32%	26.57%		0.0085
	95	23.80%	24.06%	24.33%	24.59%	24.84%	25.10%	25.36%	25.61%	25.87%	26.12%	26.37%		0.0085
	96	23.61%	23.87%	24.13%	24.39%	24.65%	24.91%	25.16%	25.42%	25.67%	25.92%	26.18%		0.0085
	97	23.42%	23.68%	23.94%	24.20%	24.46%	24.72%	24.97%	25.23%	25.48%	25.73%	25.98%		0.0085
	98	23.24%	23.50%	23.76%	24.02%	24.27%	24.53%	24.78%	25.04%	25.29%	25.54%	25.79%		0.0085
	99	23.06%	23.32%	23.58%	23.83%	24.09%	24.35%	24.60%	24.85%	25.11%	25.36%	25.61%		0.0084
	100	22.88%	23.14%	23.40%	23.65%	23.91%	24.17%	24.42%	24.67%	24.92%	25.17%	25.42%		0.0084

Min	22.88%
Max	41.71%
Average	30.69%
Average Blowdown %	69.31%

A.3. Calculations for amount of households that can be provided for with electricity from landfill gasses in 2008.

$$780\ KWH \left(\frac{24\ hrs}{day}\right)\left(\frac{365\ days}{year}\right) = 6832800\ \frac{KWH}{Year}$$

EESI number of how much gas can be made from landfill gas per day

6832800

(EESI, LMOP)

Avg Household $\rightarrow \frac{897\ KWH}{month} \rightarrow \frac{10767\ Kwh}{Year}$ (LFG Landfill Gas Facts)

$$\frac{6832800\ \frac{KWH}{Year}}{10{,}767\ KWH/year} = 634.6054\ \text{Households}$$

price of KWH (Average) = .12 dollars (Average of Cost of KWH in US from LFG landill Gas basics

$$634\ \text{households} * \frac{10{,}767\ KWH}{\text{household}}\ \frac{.12\ \text{dollars}}{KWH} = 819{,}153$$

$$\frac{\$819153}{634\ \text{homes}} = 1{,}290\ \text{dollars}$$

This currently shows how with our project we could power homes and make 1,290 dollars per home per year

These calculations show approximately how much money can be made selling Electricity from Landfill Gas Projects.

A.4 Sample Blowdown Calculations

Blowdown Calculations

Richard Dale

April 2019

1 Assumptions

- When the exhaust valve is open, pressure in the cylinder becomes atmospheric pressure (14.7 psia).
- Exhaust gas temperature for this engine configuration ranges from 698°F to 914°F(397°C to 490°C). Average Temperature across this range is 806°F which will be approximated to 800 °F.
- Exhaust Gas is an Ideal Gas

$$PV = nRT \tag{1}$$

- State 1 in Figure 1 represents the gases after the power stroke but before the exhaust valve opens. State 2 in Figure 1 represents the gases after the exhaust valve opens.

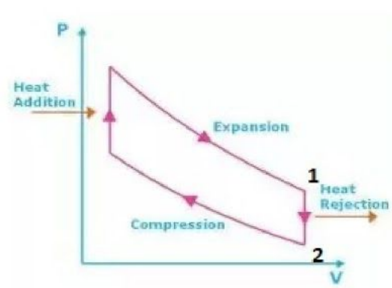


Figure 1: The Otto Cycle

2 Parameters

Cylinder Volume:

$$V_1 = 30.5in^3 \tag{2}$$

Cylinder Pressure:

$$P_1 = 100psi \tag{3}$$

Ratio of Specific Heats:

$$K = 1.4 \tag{4}$$

As per the Ideal Gas Law:

$$P_n V_n^K = C \tag{5}$$

$$P_1 V_1^K = P_2 V_2^K \tag{6}$$

In this equation $\mathrm{P}_1, V_1, and P_2 are known.$

V_2 represents the state of the gases if allowed to expand isentropically until the gases reach atmospheric pressure and can be solved for with equation 5.

3 Solve for $\mathbf{V}_2$

$$V_2 = (\frac{P_1 V_1^K}{P_2})^{1/K} \tag{7}$$

$$V_2 = (\frac{100psi \cdot (30.5in^3)^1.4}{14.7psi})^{1/1.4} \tag{8}$$

$$V_2 = 119.97in^3 \approx 120in^3 \tag{9}$$

4 Solve For $\mathbf{T}_1$

As per the Ideal Gas Law:

$$T_n V_n^{K-1} = C \tag{10}$$

$$T_1 = T_2 \cdot (\frac{V_2}{V_1})^{K-1} \tag{11}$$

$$T_1 = (800^\circ F + 460^\circ F)^\circ R \cdot (\frac{120in^3}{30.5in^3})^{1.4-1} \tag{12}$$

$$T_1 = 2179.33^\circ R \approx 2180^\circ R \tag{13}$$

5 State Values

State 1 represents the gases in the cylinder before the exhaust valve is open. State "Expanded" represents the state of the gases if the gases were allowed to expand isentropically after the exhaust valve is open. State 2 represents the state of the gases contained in the cylinder after the valve opens but before the exhaust stroke.

State 1:

$$V_1 = 30.5in^3 \tag{14}$$

$$P_1 = 100psi \tag{15}$$

$$T_1 = 2180^\circ R \tag{16}$$

State "Expanded":

$$V_e = 120in^3 \tag{17}$$

$$P_e = 14.7psi \tag{18}$$

$$T_e = 1260^\circ R \tag{19}$$

State 2:

$$V_2 = 30.5in^3 \tag{20}$$

$$P_2 = 14.7psi \tag{21}$$

$$T_2 = 1260^\circ R \tag{22}$$

6 Solve for n for State 1

n represents the lbmol of gas in the cylinder. R is the ideal gas constant of $18540 in \cdot lbf$ lbmol $\cdot ^\circ R$

$$n_1 = \frac{P_1 \cdot V_1}{R \cdot T_1} \tag{23}$$

$$n_1 = \frac{100psi \cdot 30.5in^3}{18540inlbf/lbmol^\circ R \cdot 2180^\circ R} \tag{24}$$

$$n_1 = .00007546lbmol \tag{25}$$

7 Solve for n for State 2

n represents the lbmol of gas in the cylinder. R is the ideal gas constant of $18540 in \cdot lbf$ lbmol $\cdot ^\circ R$

$$n_2 = \frac{P_2 \cdot V_2}{R \cdot T_2} \tag{26}$$

$$n_1 = \frac{14.7psi \cdot 30.5in^3}{18540inlbf/lbmol^\circ R \cdot 1260^\circ R} \tag{27}$$

$$n_1 = .000019193lbmol \tag{28}$$

8 Calculate Percentage of Gases in the Cylinder

$$\frac{n_2}{n_1} = \%RemainingGases \tag{29}$$

$$\frac{.000019193lbmol}{.00007546lbmol} \cdot 100\% = 25.4\% \tag{30}$$

A.5 Flow Rate Calculations

Flow Rate Calculations

Richard Dale

April 2019

1 Assumptions

- Engine operating at 1800 RPM
- 2 cylinders operating during one cycle

2 Parameters

Volumetric efficiency:

$$\epsilon_1 = .75 \tag{1}$$

Cylinder Volume:

$$V = 30.5in^3 \tag{2}$$

Speed:

$$RPM = 1800RPM \tag{3}$$

3 Solve for the flow rate

Flow rate is calculated using:

$$FlowRate = \epsilon \cdot \frac{V}{stroke} \cdot \frac{stroke}{min} \cdot \frac{1ft^3}{1728in^3} \tag{4}$$

$$\frac{stroke}{min} = \frac{1800rev}{min} \cdot \frac{2stroke}{rev} = \frac{3600strokes}{1min} \tag{5}$$

$$FlowRate = .75 \cdot \frac{30.5in^3}{stroke} \cdot \frac{3600stroke}{min} \cdot \frac{1ft^3}{1728in^3} = 47.65CFM \tag{6}$$

4 Solve for Flow Rates after Blowdown

Minimum gases left in the cylinder (at 100 psi and K=1.3 from Appendix A.2E) = 22.88%

$$47.65CFM \cdot .2288 = 10.90CFM \tag{7}$$

Maximum gases left in the cylinder (at 50 psi and K=1.4 from Appendix A.2E) = 41.71%

$$47.65CFM \cdot .4171 = 19.87CFM \tag{8}$$

Average gases left in the cylinder = 30.69% from Appendix A.2E

$$47.65CFM \cdot .3069 = 14.62CFM \tag{9}$$

A.6 100 KWH generator payback in Florida in 2017

Years	100 KWH payback in US dollars	
1	9960120	
2	19920240	
3	29880360	
4	39840480	
5	49800600	Price of electricity in Florida in 2017
6	59760720	11.37
7	69720840	Hours in a year
8	79680960	8760
9	89641080	Engine Output in KiloWatts
10	99601200	100
11	109561320	
12	119521440	
13	129481560	
14	139441680	
15	149401800	
16	159361920	
17	169322040	
18	179282160	
19	189242280	
20	199202400	

<u>A.7 Pressure Drop Calculation</u> Note: Moody Chart used for friction factor with operating point marked in green.

Pressure Drop Calculations

Richard Dale

April 2019

1 Assumptions

- Fluid is dry air at T = 800 °F and P = 75 psi (average over pressure range)

2 Parameters

Diameter:

$$D = 1.054 = .02677m \tag{1}$$

Length:

$$L = .41in = .010414m \tag{2}$$

Volumetric Flow Rate (Appendix A.2E):

$$\dot{V} = 14.62CFM \tag{3}$$

Dynamic Viscosity:

$$\nu = 13.287 \times 10^{-6}\,\mathrm{m\,s^{-1}} \tag{4}$$

Density:

$$\rho = 2.577kg/m^3 \tag{5}$$

3 Solve for Reynolds Number

$$Re = \frac{v \cdot R}{\nu} \tag{6}$$

$$v = \frac{\dot{V}}{A_c} \tag{7}$$

$$A_c = \frac{\pi * .02677^2}{4} \tag{8}$$

$$v = 14.62\frac{ft^3}{min} \cdot \frac{.0004719m^3/s}{1ft^3/min} \cdot \frac{4}{\pi * .02677^2} = 12.258\frac{m}{s} \tag{9}$$

$$Re = \frac{12.258 \cdot .013385}{.000013287} = 12348.41(Turbulent) \tag{10}$$

4 Determine Pressure Drop Along Pipe

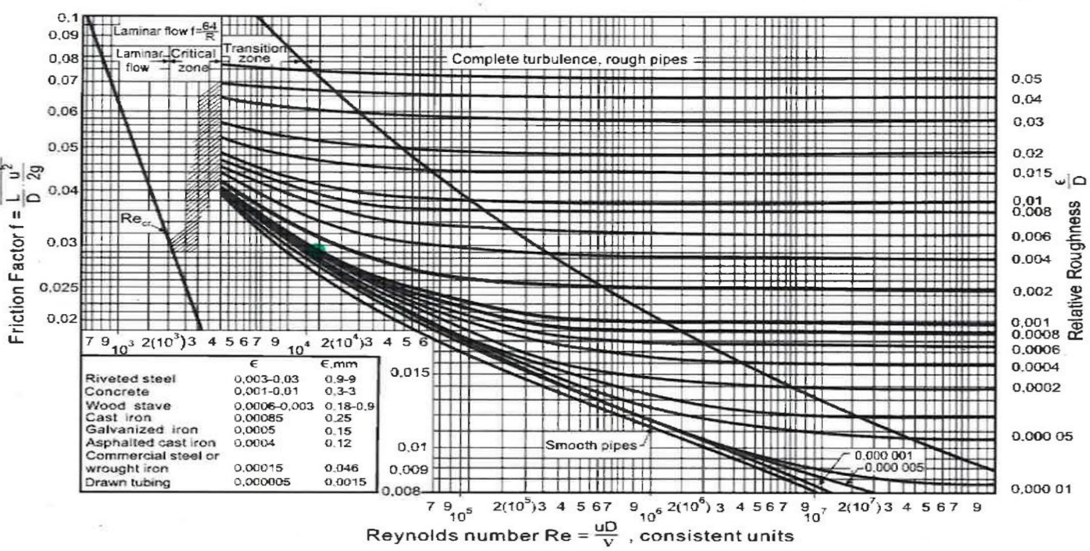
$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho}{2} \cdot v^2 \qquad (11)$$

where f is the friction factor according to a Moody Diagram.

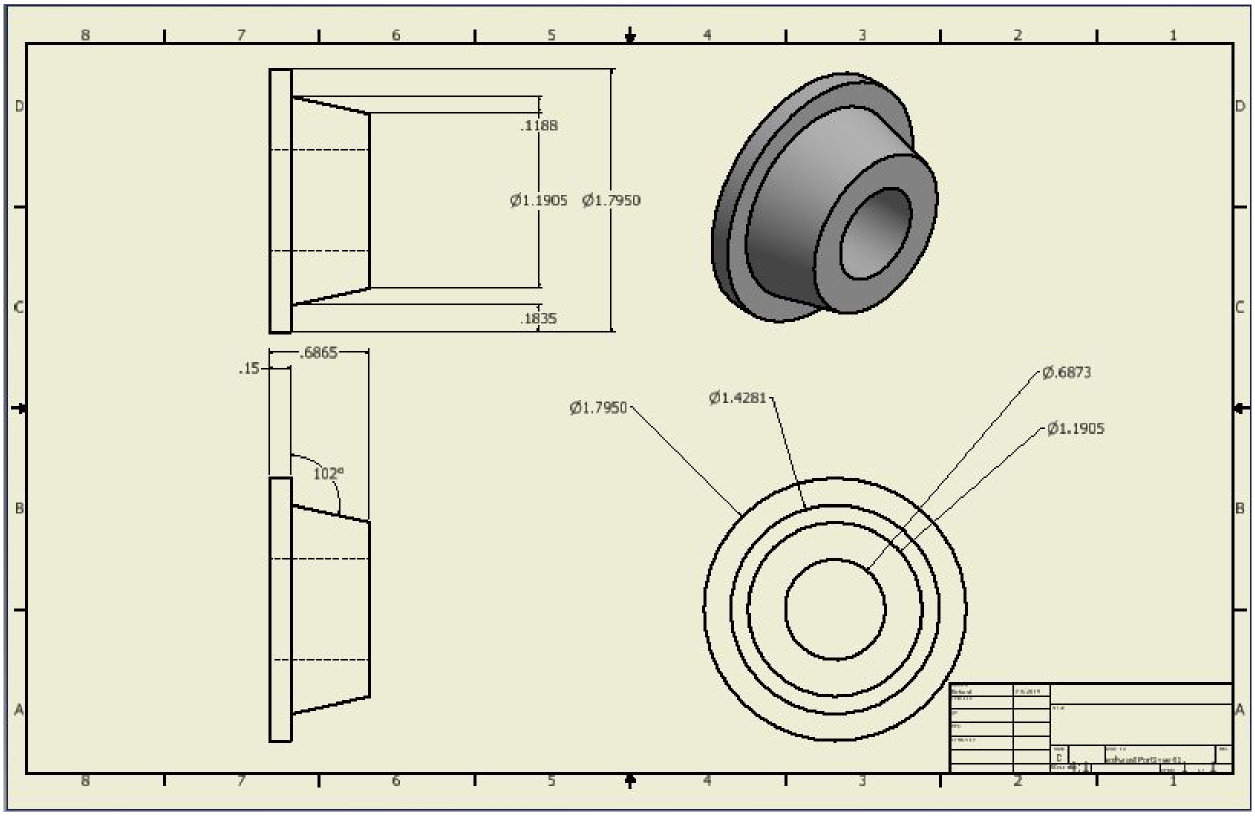
Based on the Moody Diagram where Re $=1.2348 \times 10^4$ and assuming a surface roughness $\approx .001$, $f \approx .03$

$$\Delta p = .03 \cdot \frac{.010414m}{.02677m} \cdot \frac{2.577kg/m^3}{2} \cdot 12.258(m/s)^2 = 2.26\frac{kg}{m \cdot s^2} \qquad (12)$$

$$\Delta p = 2.26\frac{kg}{m \cdot s^2} = 2.26Pa = .000328psi \qquad (13)$$



Appendix A.8: Previous Designs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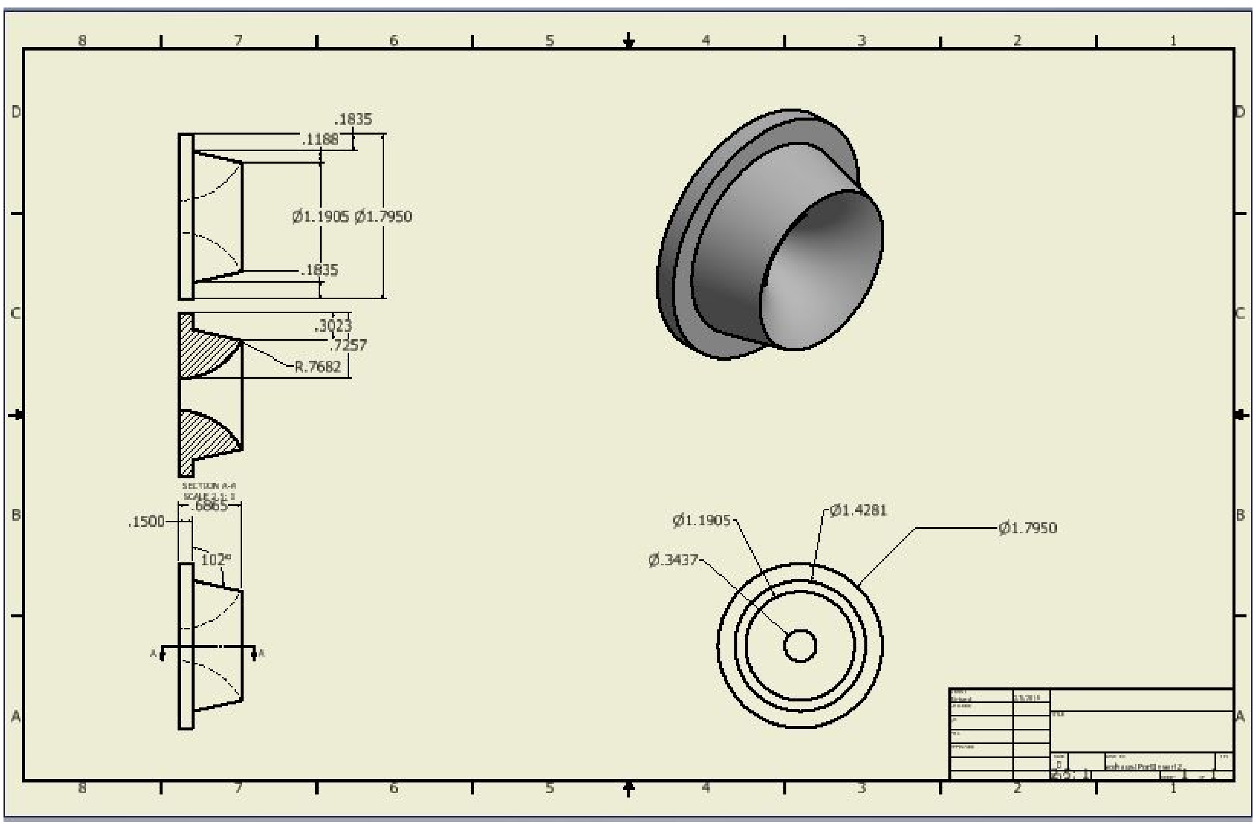
Ø1.1905 Ø1.7950
.1835
.6865
.15
102°
Ø1.7950
Ø1.4281
Ø.6873
Ø1.1905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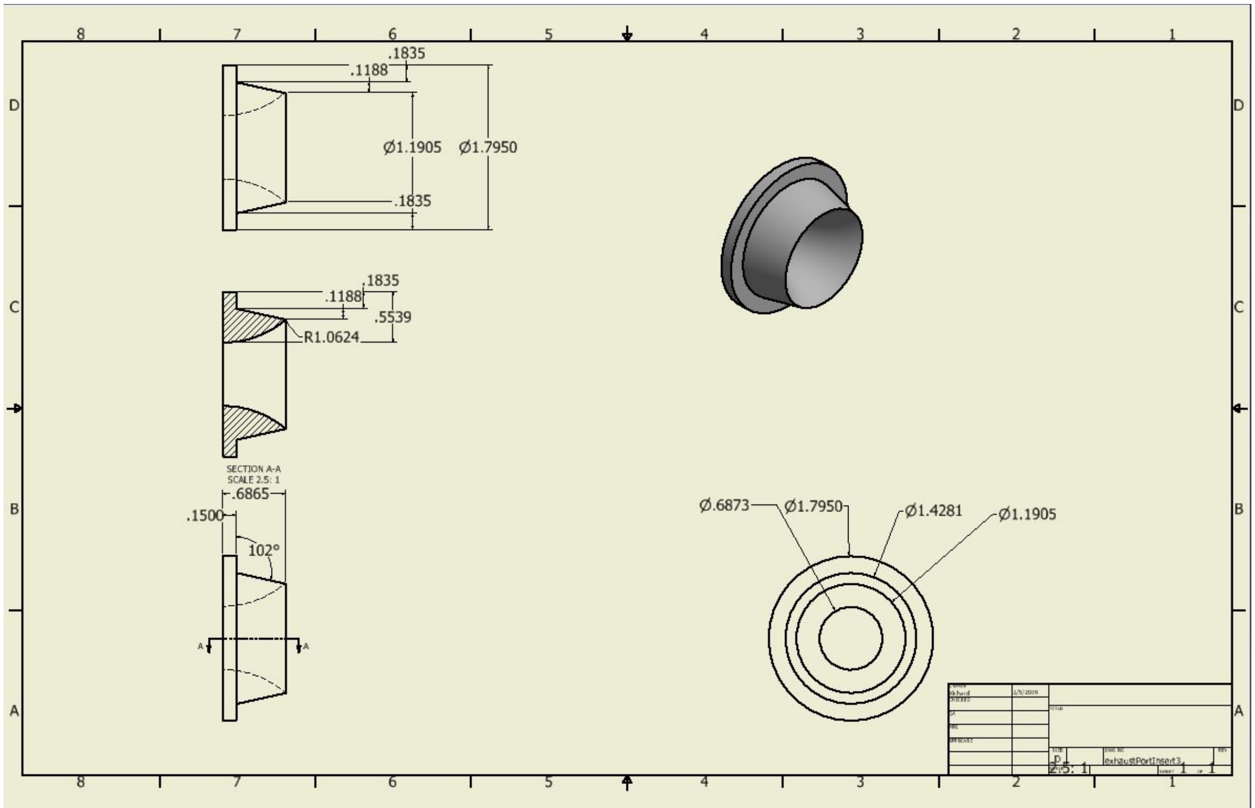
.1188
Ø1.1905 Ø1.7950
.1835
.3023
.7257
R.7682
.6865
.1500
102°
Ø1.1905
Ø1.4281
Ø1.7950
Ø.3437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Ø1.1905
Ø1.7950
.1835
.1188
.5539
R1.0624
SECTION A-A
SCALE 2.5 : 1
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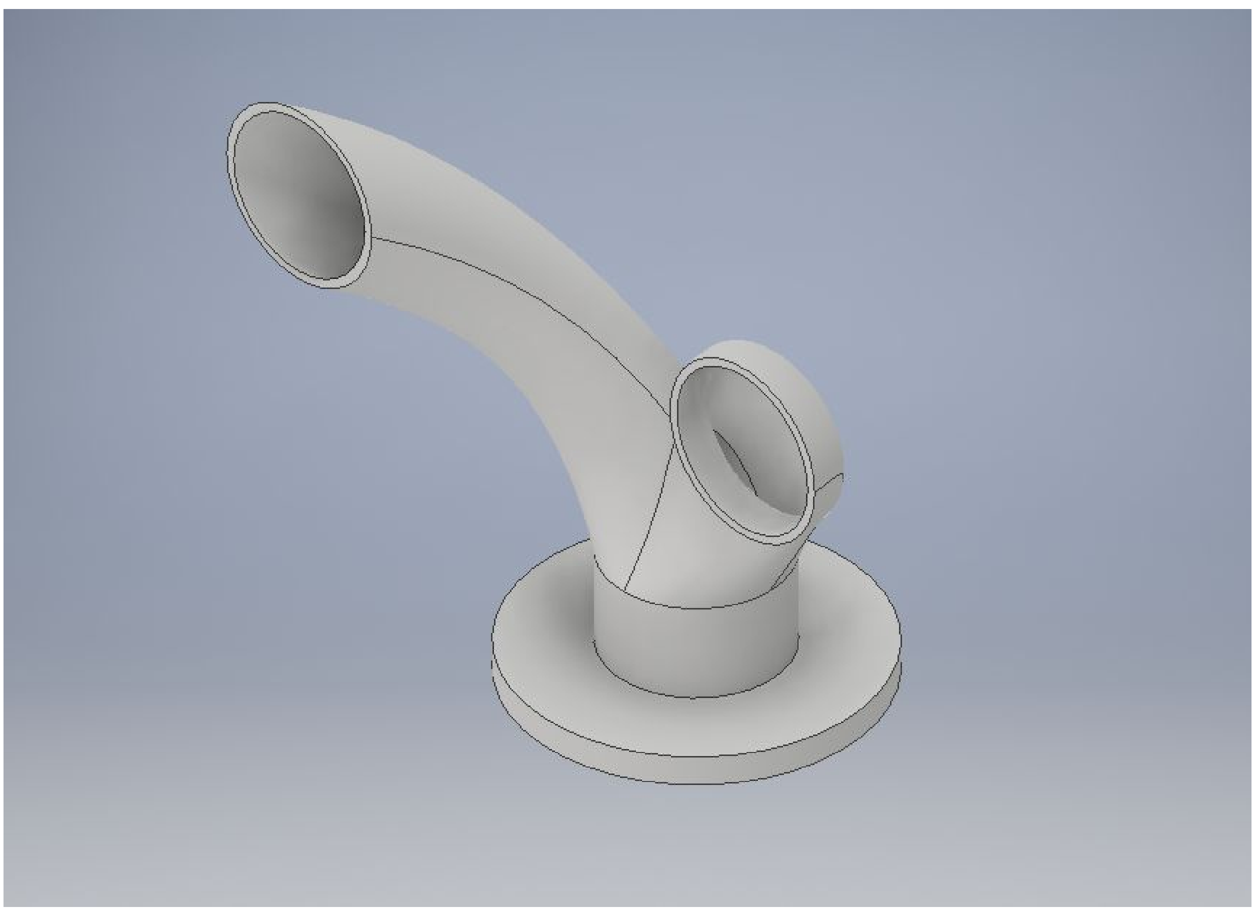
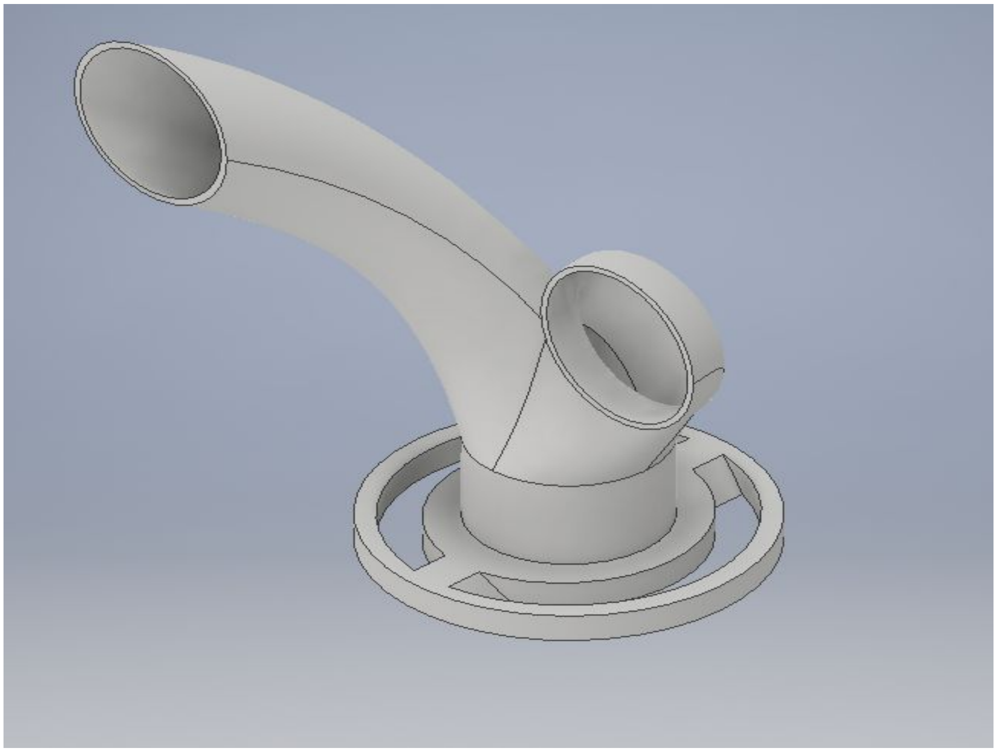
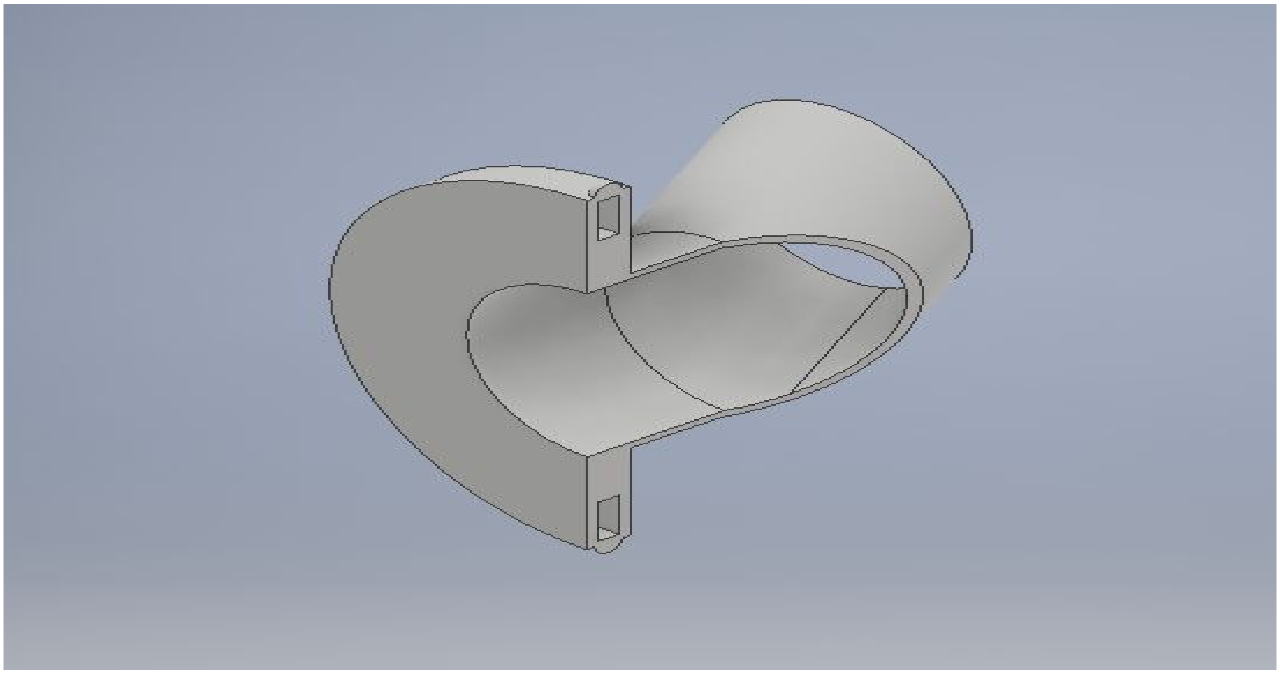
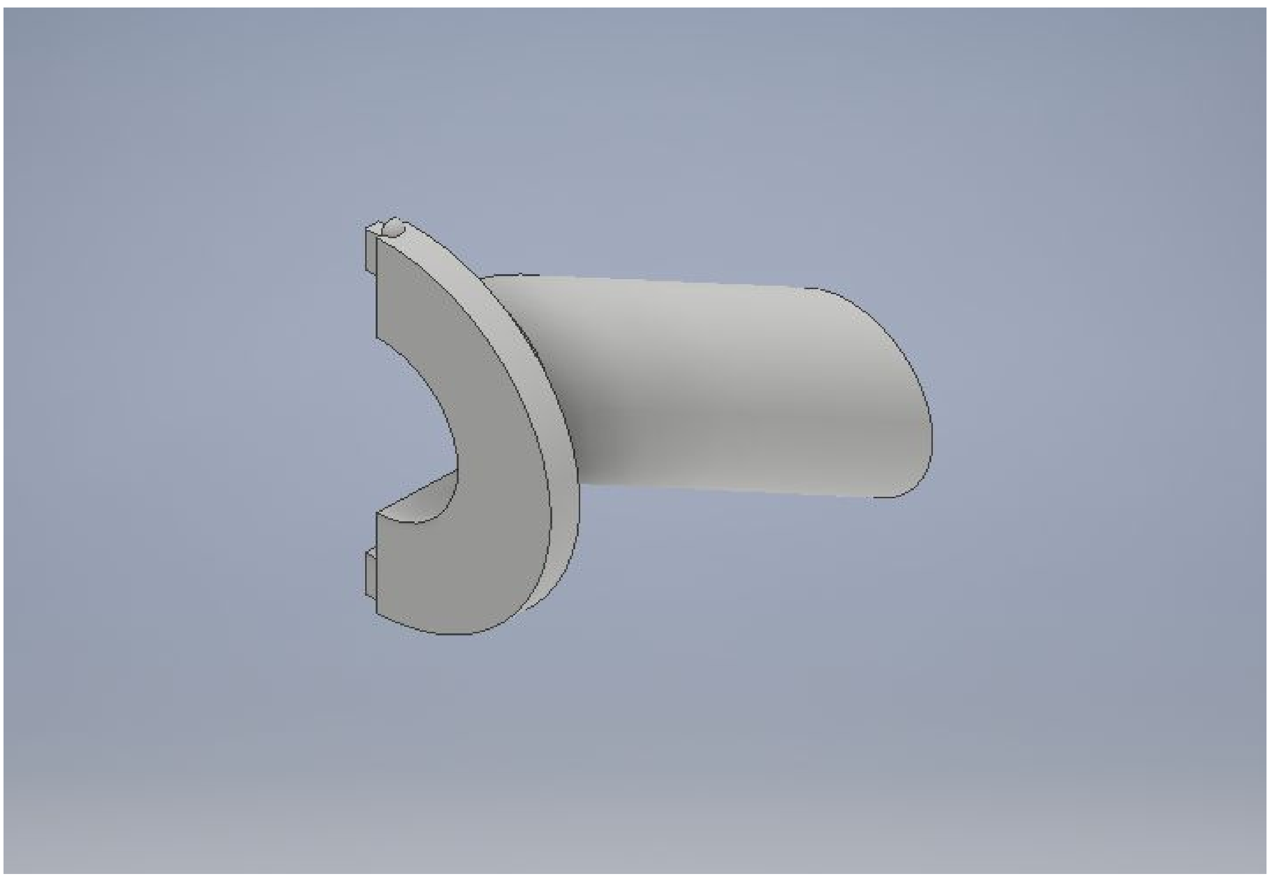
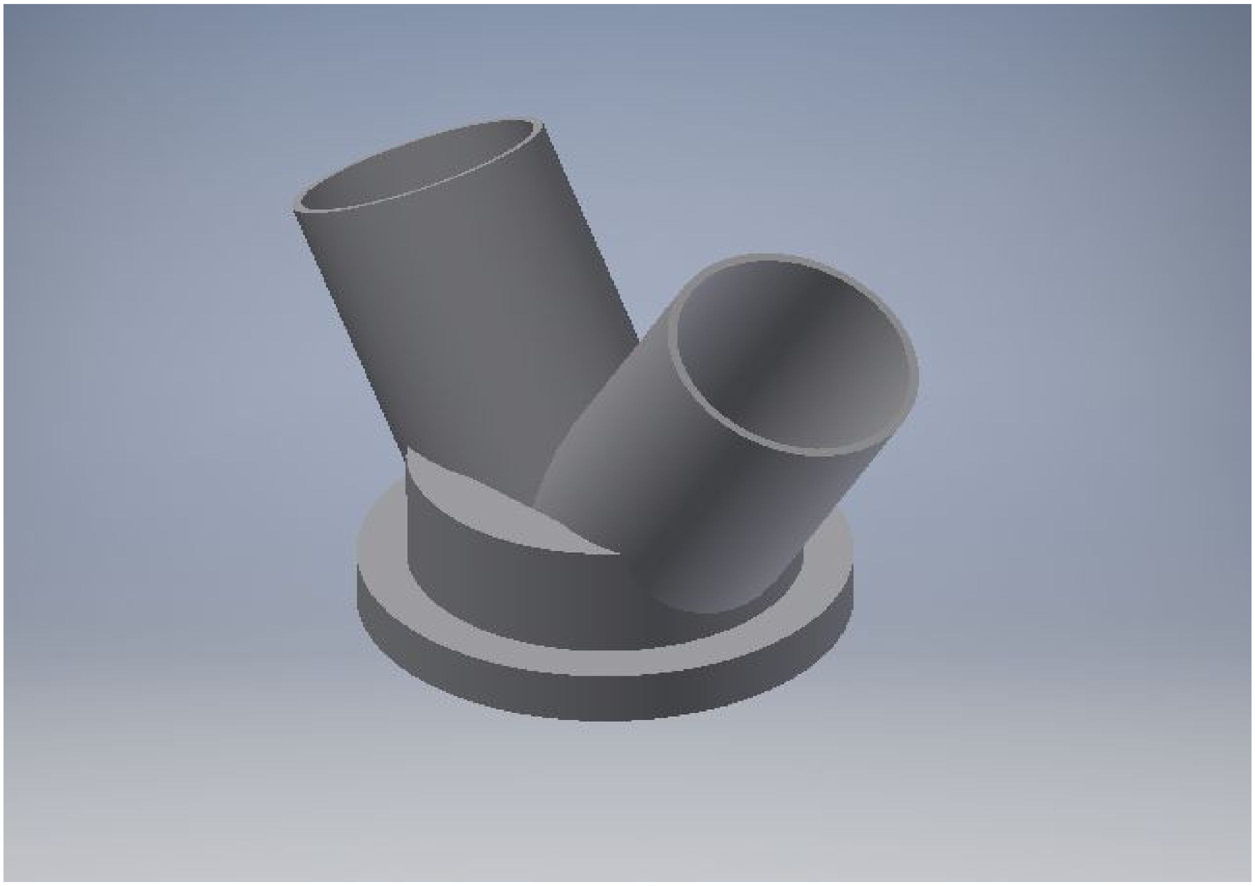
.1500
102°
Ø.6873
Ø1.7950
Ø1.4281
Ø1.1905

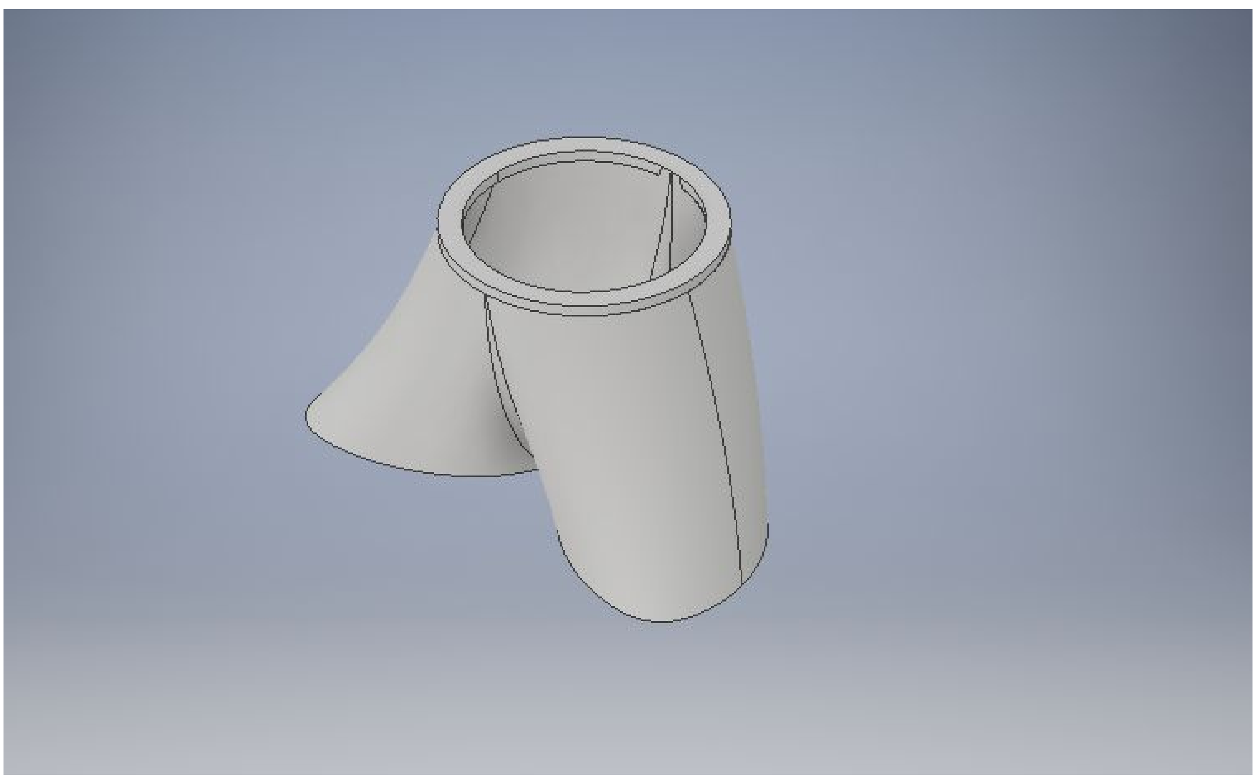












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