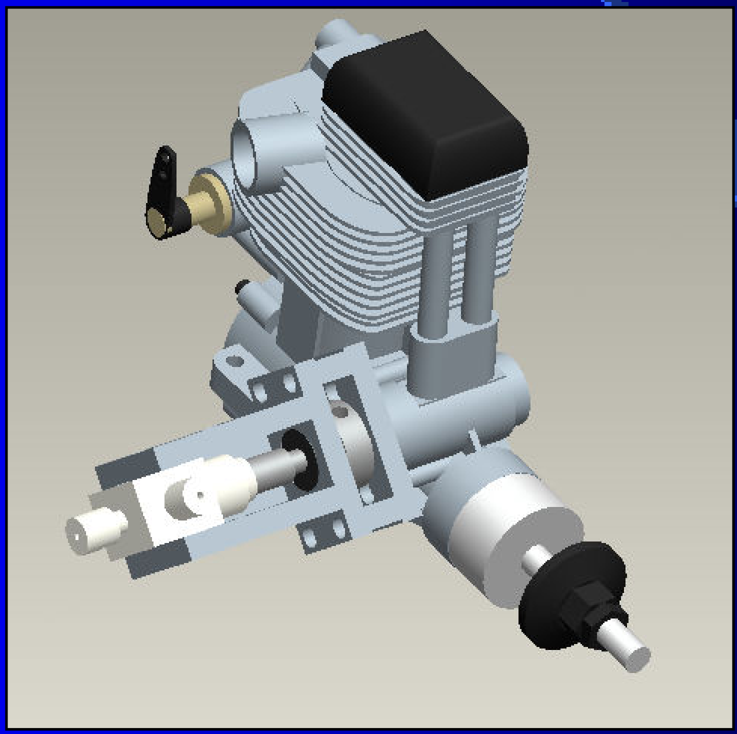
Eglin Air Force Base

INTEGRITY - SERVICE - EXCELLENCE

AMERICA'S AIR FORCE

Converting an R/C Aircraft Engine for use with Hydrogen



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SUMMARY

The goal of this project was to convert a small Radio Controlled Aircraft engine to be used with Hydrogen fuel. This report outlines the research and concepts that went into developing a feasible design. A 4-stroke engine was chosen as the base engine for the project. The modification chosen utilizes direct injection through the use of a rotating ball valve and a hypodermic needle imbedded into the cylinder head. Combustion will be aided by a spark system, timed using a Hall Effect sensor and magnet. A housing was designed to hold both the required valve, and the flywheel for the magnet. Although the engine could not be tested, a prototype showing the modifications made was produced. The modifications presented herein represent a viable design that could provide an efficient means of running the R/C engine off of Hydrogen.

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1.0 PROJECT SCOPE

With the world facing the growing problem of Global Warming, due to the millions of barrels of oil being consumed each day, alternative fuels are becoming more and more desirable. One alternative fuel that is becoming widely popular is Hydrogen. Hydrogen has the highest energy content per unit weight of any known fuel-52,000 Btu/lb (120.7 kJ/g). It burns cleanly with oxygen and the only byproducts are heat and water. In conjunction with the United States Air Force and the Air Force Research Laboratories (AFRL), and to broaden the FAMU/FSU College of Engineering's knowledge of the hydrogen economy, this project will show that a Remote Controlled aircraft engine, initially designed for use with a Nitromethane fuel, can be modified to run using Hydrogen. The rewards of using hydrogen fuel are that it gives off less pollution and requires a lower ignition spark.

The goal of this project is modify a remote control airplane engine to operate on hydrogen fuel. This engine should not just be able to run, but be able to run well, and for an extended period of time without wear, or seizing. Some problems that might arise are that the lower ignition energy of Hydrogen can lead to pre-ignition and backfire. Hydrogen also has a stronger potential to leak, due to its high diffusivity, which could pose serious problems if it were ignited.

The purpose of building this engine is to help educate others that Hydrogen powered vehicles are feasible and that does not mean a loss of power. In doing this project this group will become more knowledgeable and gain useful experience working with Hydrogen systems and corresponding with Sponsors and contacts.

2.0 PROJECT SPECIFICATIONS

The goal of this Project is to convert a small Radio Controlled Aircraft Engine to be able to use Hydrogen as a fuel. Current R/C Aircraft Engines have very poor emissions, making them bad for the environment. If they could be converted to run on Hydrogen, the only emission would be water vapor.

Requirements

- The Engine should be safe to operate.
- The Engine should be able to run on Hydrogen alone.
- It should be efficient, wasting as little Hydrogen as possible.
- It should be able to run for extensive periods of time without seizing up.
- It should be lightweight because it is to be used on an Aircraft.
- The engine should have as close to the same power output as an unmodified engine as possible.

Modifications Needed

- Most R/C engines require a certain amount of Lubrication content in the Fuel. Hydrogen does not have any lubricating properties; therefore a way to supply lubrication to the working parts of the engine needs to be developed.
- R/C Engines use a Glowplug as a means to aid in combustion. These devices are always on, which could lead to Pre-Ignition problems when running the engine on Hydrogen. To fix this, the Glowplug needs to be replaced with a Sparkplug.
- In order to have the Sparkplug operate correctly a timing mechanism needs to be developed, preferably one that can be adjusted allowing for precise timing.
- A battery system will have to be installed to run the Sparkplug as well as any Fuel Pump that might be required.
- A Fuel delivery system needs to be developed that can deliver the right amount of hydrogen to the engine at the right time.
- If possible there needs to be a way to adjust the Air/Fuel ratio.
- An efficient means of Hydrogen storage needs to be used, allowing for ease of use, and with little weight or cost.

3.0 BACKGROUND INFORMATION/ CONCEPT OVERVIEWS

3.1 Internal Combustion Conversion for Hydrogen Fuel

Hydrogen burning internal combustion engines, also known as H2ICE's, are the near future and bridge hydrogen fuel cells and internal combustion engines. Hydrogen burns clean with practically zero emissions and has efficiencies exceeding port fuel injection engines (PFI), and can potentially be integrated into the existing petroleum based infrastructure. With a small number of vehicles actually in use and the case-based modifications, it is difficult to explain how to repair them. Getting a hydrogen internal combustion engine to work is a relatively simple process, but getting it to run well is not.

Early attempts include a vacuum engine which atmospheric pressure drives the piston back against a vacuum to produce power. Burning a hydrogen and air mixture and allowing it to cool creates the vacuum. This was done in 1820 by Reverend W. Cecil. A second attempt was around 1865, with N. A. Otto (discoverer of the Otto cycle) who used a synthetic producer gas fuel, which had a Hydrogen content over fifty percent. Because of safety issues, gasoline pushed him towards a gaseous fuel until the invention of the carburetor which allowed for gasoline to be used safely and practically, leaving very little interest in other fuels. Hydrogen is used often in the space program because of its high energy to weight ratio (higher than any other fuels). Liquid hydrogen is used in the upper stages of launches for space vessels.

Hydrogen can be combusted with a wide range of air to fuel ratios in internal combustion engines with possibilities of lean mixtures. A lean mixture allows for a smaller amount of fuel (less than theoretical or stoichiometric) needed to combust in an engine. This will increase the fuel economy of the vehicle and reduce the amount of harmful emissions because the combustion reaction is more complete. Lean mixtures do reduce the power output due to the reduction in the volumetric heating value of the mixture.

There is a very small amount of energy needed to ignite hydrogen and the energy is significantly lower than that of gasoline, allowing for prompt ignition and use of lean mixtures. However, there are drawbacks to low ignition energy, both premature ignition and flashback can hurt performance allowing hot spots to form in the cylinder and hot gasses from other parts of the engine close to the air-fuel mixture. Flashback is pressure forced back through the supply tubing. Premature ignition is when the mixture is ignited before the spark plug causes the ignition leading to large inefficiencies and backfire. Backfire is when the ignited flame travels back into the induction system usually when both the exhaust and intake valves are open at the same time. Premature ignition is the most common problem encountered when designing and running a hydrogen engine. The smaller quenching distance, the wide flammability range and lower ignition temperature properties of hydrogen are large factors affecting the pre-ignition problem. One of the causes of premature ignition is hot spots in the cylinder including the spark plug, exhaust valve, and carbon deposits. Hot spots are locations of higher heat on the inside of the cylinder walls due to the combustion process and friction from poor lubrication, and almost any mixture ratio can be ignited. Pyrolysis of oil, a heat induced chemical decomposition, in the combustion chamber can also lead to pre-ignition. The oil can leak past the top of the piston rings, past guide seals of the valves and through the intake manifold, into the combustion chamber.

Quenching distance is another factor to consider. Hydrogen flames burn closer to the cylinder walls than gasoline, and can increase backfire. Due to its molecular size, it is easier for a hydrogen-air mixture to bypass valves than a hydrocarbon-air mixture. This also applies to the flame speed, which is high in comparison to gasoline, and allows for the system to more closely reach a thermodynamically ideal engine cycle.

Autoignition temperature has implications as well, when burning hydrogen. With a high autoignition temperature, there are issues with the compression of the hydrogen-air mixture. However, it does allow for large compression ratios compared to gasoline. These factors are important and relate to the overall thermal efficiency of the system. The temperature rise during compression is related to the compression ratio and if the temperature rises beyond the autoignition temperature, then premature ignition occurs. Hydrogen is hard to ignite with compression because of the high autoignition temperature therefore making it hart to implement into a compression-ignition or diesel system.

Chemically, hydrogen has a high diffusivity and low density. High diffusivity helps to disperse the fuel in air quicker, avoiding or minimizing safety hazards. Also, it allows for the fuel mixture to become homogeneous more quickly giving a cleaner and faster combustion reaction. The density creates challenges including large storage tanks to contain hydrogen as a gas, and also has less power density because of the hydrogen-air mixture.

Determining the air to fuel ratio requires the inclusion of nitrogen because air is used instead of pure oxygen. (For calculations, see Appendix A.)
For complete stoichiometric combustion of hydrogen in air, a ratio of 34:1 hydrogen to air is required. Hydrogen engines can actually run on mixture ratios between 34:1 and 180:1 because of its wide range of flammability. This is much higher than the 14:1 fuel to air ratio for gasoline. With hydrogen as a gas at room temperature it disperses throughout the combustion chamber more completely than that of a liquid fuel displacing about thirty percent of the volume compared to approximately two percent of the volume displaced by a liquid fuel. This can increase the power output by a range of eighty-five percent to one hundred twenty percent relative to gasoline depending on the fuel delivery system.

Pre-ignition can be reduced or eliminated by using advanced fuel delivery systems. There are three methods for fuel delivery. First is the central injection, or the use of a carburetor, which is the simplest method. A carburetor uses a throttling valve to control fuel intake. Through a vacuum created by a venturi, or a narrowing in the flow, the air intake is throttled to a higher velocity. A vacuum is created, drawing in a proportional amount of gasoline, resulting in the desired air to fuel mixture. This is injected at the inlet of the air intake manifold. Being able to function at low pressures and its ease of conversion from gasoline are advantages to this method. Disadvantages are also present with this simple solution involving irregular combustion from pre-ignition and backfire (due to less control of the air-fuel mixtures), with higher concentrations of hydrogen in the mixture compounding the problem.

Next is port injection, which injects fuel just upstream of the intake valve at the intake port of each cylinder (compared to the central point of mixing, like the carburetor). Conditions at this location are more conducive to reducing pre-ignition especially because there is less gas in the manifold at any given time. Having the air injected into the combustion chamber before the fuel, allows for cooling of the hot spots and left over gasses. However, there is a higher required inlet supply pressure than the central injection system. Using a cam-operated device to time the fuel injection is part of the constant volume injection system. Solenoid valves at each cylinder are controlled electronically for an electronic fuel injection system. The constant volume injection system uses constant injection timing and the pressure varies, while the electronic fuel injection system uses variable injection timing and the pressure remains constant.

Last the direct injection system is the most complicated, but also the most power efficient and stoichiometrically efficient. Direct injection of the fuel into the combustion chamber after the air intake valve has closed, and mixes the air and fuel within the combustion chamber. One advantage of this method is the complete elimination of pre-ignition during the intake stroke and elimination of backfire, but there is still possibility of premature ignition within the combustion chamber. A high-pressure delivery system for the fuel is required with the direct injection system though. With the decreased time for mixture of the hydrogen and air, there is possibility of a non-homogeneous mixture ignition leading to increased emissions. Power outputs are increased by twenty percent over gasoline and over forty percent compared to carbureted hydrogen engines.

Decreasing the temperature of hot spots and reducing the peak combustion temperature are methods known to help reduce pre-ignition. A method called exhaust gas recirculation takes approximately twenty-five percent of the exhaust gasses and reintroduces them into the intake manifold, helping to reduce emissions. One downfall of this method is a decrease in power output. The pressure that is created by these gasses in the combustion chamber reduces the amount of fuel mixture that can be brought in, thus reducing the power output. Introducing water into the hydrogen stream before being mixed with air has a better power output rather than introducing it into the intake manifold. Also having its downfalls, extra care must be taken to keep the seals from leaking water into the oil in the lubrication system.

Instead of modifying an existing engine, it runs much smoother to design an entire engine for hydrogen use and is more thermodynamically efficient (with emphasis on the combustion chamber). Turbulence within the combustion chamber causes problems, and making a flat piston head and a flat chamber ceiling can reduce this turbulence. Using two small exhaust valves as opposed to one large valve will increase the excavation of the exhaust gasses with less air resistance from the combustion chamber reducing pre-ignition. Implementation of a cooling system that can deliver a consistent flow to the areas of interest can increase efficiency and reduce pre-ignition.

Diesel engines, or a compression ignition system, are not able to use hydrogen without modifications because of the low ignition temperature of hydrogen. They can however be fitted with a spark plug, (this method is called a pilot ignition system) and is being utilized for natural gas in diesel engines but not for hydrogen.

At lean fuel-to-air ratios, flame velocity is greatly decreased and a dual spark plug configuration is preferred. Converting from a waste spark system should be avoided because it charges the spark each time the piston is at top dead center without regard to the compression stroke or exhaust stroke. Platinum spark plug tips cause hydrogen to oxidize with air because of its catalyst nature and should be avoided. Cold running spark plugs are beneficial in reducing pre-ignition because they transfer heat more quickly from the plug head to the cylinder head than a hot rated spark plug, increasing the precision of the timing. A hot-rated spark plugs' benefit is that it retains heat, keeping carbon from accumulating on the spark plug tip.

With the low ignition energy of hydrogen, ventilation of the crankcase is very important. It can avoid the ignition of hydrogen that has escaped past the piston rings. A minor complication is ignition in the crankcase, resulting in an engine fire causing abnormal noise and little damage. Pressure in the crankcase will increase with ignition requiring a relief valve to be installed. Hydrogen exhaust is water, and exhaust can escape past the piston rings also, this water needs to be ventilated before it mixes with the oil of the lubrication system to maintain minimal engine wear.

The Otto cycle engine has a theoretical thermodynamic efficiency based on the compression ratio and specific heat ratio of the fuel. (For calculations, see Appendix A.) Thermodynamic efficiency can be increased with increases in the compression ratio and specific heat ratio. Compression ratios are based on a fuels resistance to knock. Knock is when regular ignition occurs but a pocket of air-fuel mixture is ignited separately. These two combustion reactions collide causing a shockwave reverberating throughout the engine causing the "knock." Timing is then compromised and the ignition no longer occurs at the optimum point of the down stroke. Leaner mixtures have less chance of knock therefore tolerating higher compression ratios. Specific heat ratios are related to the molecular structure of the fuel and the more complex the molecule, the lower the specific heat ratio. Hydrogen has a specific heat of 1.4 compared to gasoline, which has a specific heat of 1.1.

Hydrogen combusted with air does produce nitrogen oxides from the high temperatures, but the ideal combustion with hydrogen and oxygen produces pure water. Carbon oxides can form should some of the oil leak into the combustion chamber. Other factors that affect emissions are the air-fuel ratio, ignition timing, compression ratio of the engine, and the speed of the engine. A leaner mixture of hydrocarbons allows for a more complete combustion and leaves a lower amount of unburned hydrocarbons. Excess oxygen also combines with carbon monoxide creating carbon dioxide, a less harmful emission.

Taking volumetric ratios into account for the power output, carbureted fuel injection systems that mix the hydrogen and air before entering the combustion chamber allow less air for combustion to enter. This method will only give a theoretical power output fifteen percent lower than gasoline. With gasoline, a liquid fuel, it occupies less volume, allowing for larger amounts of fuel to burn each stroke of the engine. Direct injection gives one hundred percent of the combustion chamber volume to air and pressurizes the chamber with the excess hydrogen, putting a theoretical power output fifteen percent higher than gasoline. There are high operating temperatures for stoichiometric combustion exhausting high levels of nitrogen oxides, which is the cause of conversion from gasoline engines to hydrogen engines. Therefore, the actual power output of most hydrogen engines is approximately half of its gasoline counterpart, but this can be increased with the use of turbochargers and superchargers. A turbocharger, powered by exhaust gasses turning the compressor, increases the pressure in the combustion chamber allowing more air and fuel into the space per combustion cycle. A supercharger works the same as a turbocharger, but gets its power directly from the crankshaft.

Hydrogen cannot be stored in the same tanks as most fuels with the exception of natural gas. Storage is usually large and cumbersome when fuels are combined from separate tanks. Hydrogen is a gas at room temperature and atmospheric pressure and will not mix with a liquid fuel in the same tank. Another property, its low boiling point, will actually cause freezing of liquid fuel if stored in the same tank. Usually these systems are impractical with the exception of the natural gas. Advantages of dual but separate systems allows for the use of hydrocarbon fuels when hydrogen is not available.

Research and development are focused on advanced spark ignition with direct injection. If implemented correctly, the efficiencies can reach that of a high efficiency diesel engine, with port fuel injected power densities. Direct injection of a mixture of hydrogen and air into the cylinder can potentially avoid problems associated with hydrogen engines including backlash and pre-ignition, also avoiding the power density losses because the fuel is injected after the intake valve has closed. Stoichiometrically, the direct injection hydrogen internal combustion engine can put out 115% of the power a gasoline internal combustion engine.

In an experiment, an automotive sized single cylinder engine with optical access for advanced laser-based optical diagnosis was used to study in-cylinder reactions. The Hydrogen needed to be injected at a high pressure of 200 bar. Using advanced forms of measurement, they were able to deduce quantitative measurements of in-cylinder mixing. In one experiment, the hydrogen is seeded with acetone, providing fuel to air ratios. This data allows for better injection strategies and chamber design.

A conglomerate of research facilities and companies are working together to convert a gasoline and natural gas engine to run on hydrogen. Their choices of motors include a 425cc single cylinder and 5.4 liter Ford V8 both using Direct injection of the hydrogen. The Ford V8 required custom fuel injectors but reduced modifications of the rest of the engine to being just the bolting in of the spark plug. Both engines were tested in a Polaris Ranger two-seater (Fig. 1).

Figure 1. Picture of Test Vehicle for the Hydrogen Conversion.
Picture courtesy of
http://www.cer.unlv.edu/research.php?sn=gas2h2

3.2 Overview of 2-Stroke and 4-Stroke Engines

2-Stroke Engine

Most applications of a 2-stroke engine are small and therefore work well in machines such as chain saws, lawn mowers and remote control engines. A 2-stroke engine will also work without complications when upside down making it appealing to hand-held applications.

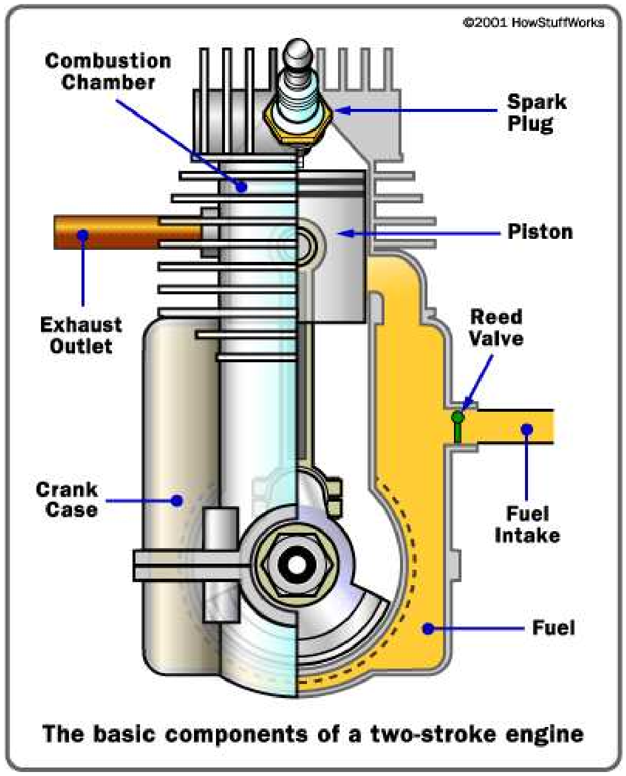


Figure 2: 2-Stroke Engine at the Top of the Compression Stroke

A 2-stroke engine has less moving parts and combines processes of a 4-stroke engine into half a revolution. Therefore, a 4-stroke engine takes two complete revolutions to complete the cycle and produce the power stroke, while a 2-stroke engine can produce a power stroke every revolution. There are multiple processes happening during one revolution. Starting with the power stroke, the piston is driven down and the air-fuel in the crankcase is compressed as seen in figure 3. The position of the piston at the bottom of the power stroke allows a release of pressurized air-fuel mixture into the combustion chamber and forces out the exhaust gasses. The piston acts as the valve for the exhaust and the crankcase as seen figure 4. The compression of the air-fuel mixture as seen in figure 5, the piston drives the volume of the air-fuel mixture down increasing the pressure and temperature. This also creates a vacuum that opens a one-way valve allowing more air-fuel mixture from the carburetor to enter the crankcase, still sealed off from the combustion chamber. At the top of the compression stroke (called top dead center, TDC), the spark plug ignites the mixture, and the piston extracts energy from the combustion and is also driven back down as seen in figure 6.

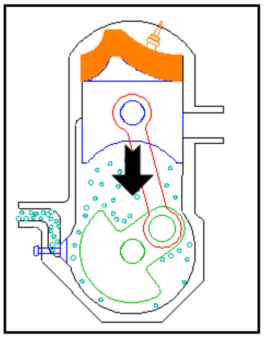


Figure 3: Power Stroke

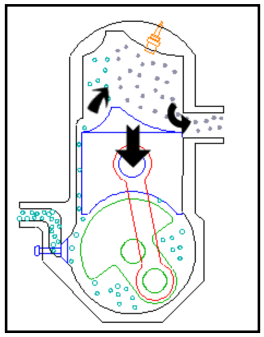


Figure 4: Fuel intake and Exhaust

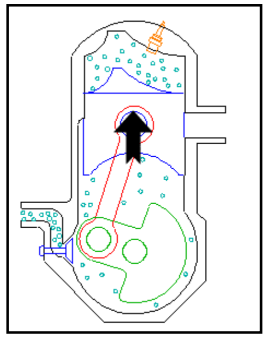


Figure 5: Compression Stroke

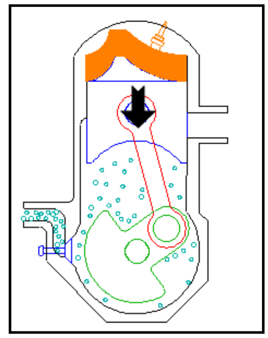


Figure 6: Ignition and Power Stroke

Pictures courtesy of Keveney.com

Disadvantages of a 2-stroke outweigh the extra power output. Because there are not valves for the intake and exhaust, some of the air-fuel mixture rushes through the combustion chamber and out with the exhaust leaking gas and oil into the environment. With emissions being the big issue with hydrocarbon fuels and engines today, 2-stroke engines emit much more harmful emissions than its 4-stroke counterpart. Energy efficiency is a big issue with the 2-stroke also for reasons including the wasted fuel that is not kept in the combustion chamber, and most do not utilize direct fuel injection.

Another disadvantage is the lubrication system. There is not one, the oil is injected with the fuel into the engine giving less lubrication than a separate system like the 4-stroke has, creating worse emissions and shorter lifespan due to ware. The implication of this in an automobile would require approximately four ounces of oil per gallon of gas, and this is not practical.

4-Stroke Engine

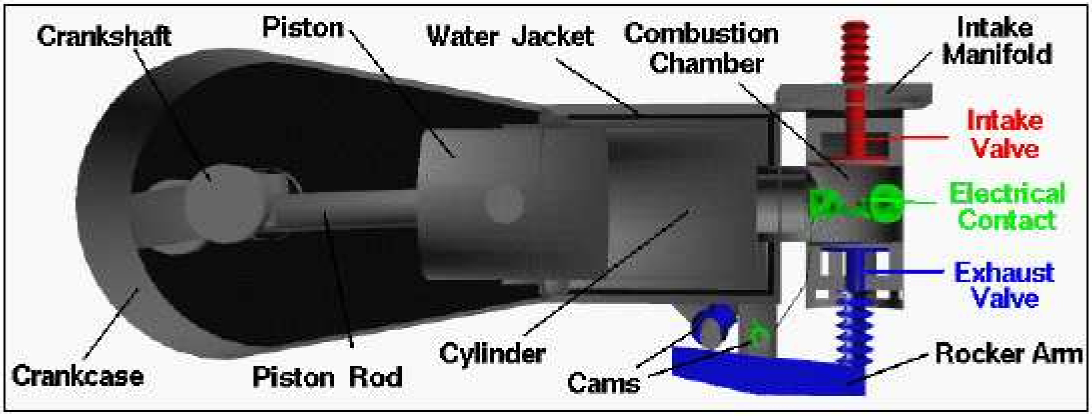


Figure 7: Otto Cycle Engine Parts

(Courtesy of http://wright.nasa.gov/airplane/engopt.html)

The Otto cycle as shown in figure 7, also known as a 4-stroke engine, uses valves and ignition timing to create power from combustion. First, there is an intake stroke, where the piston is driven down and a vacuum is created and a valve is released to allow the air-fuel mixture to enter as shown in figure 8. Next, there is the compression stroke, where the gas in the combustion chamber is compressed, decreasing the volume and increasing the pressure and temperature as seen in figure 9. As the piston reaches the top, the timed spark plug ignites the fuel and the combustion drives the piston down outputting power as shown in figure 10. Finally, there is another compression stroke, but instead a valve is opened allowing the exhaust gasses to be forced out from the combustion chamber as seen in figure 11. Then the process repeats.

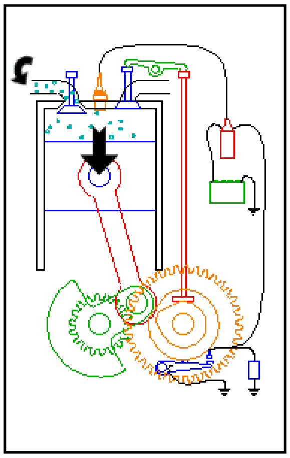


Figure 8: Intake Stroke

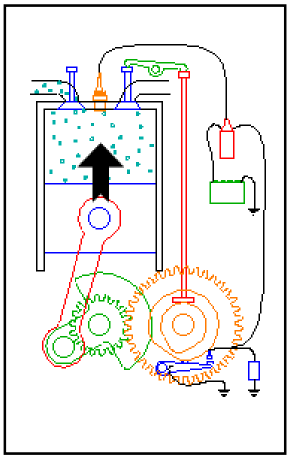


Figure 9: Compression Stroke

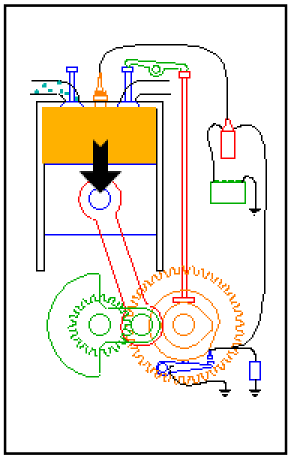


Figure 10: Power Stroke

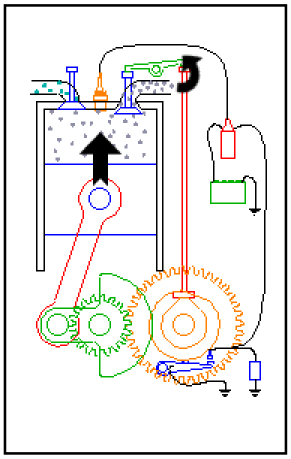


Figure 11: Exhaust

Stroke

A 4-stroke engine utilizes two revolutions per power stroke, giving it half the power output of a 2-stroke. There are advantages though. First, there is a separate process for intake and exhaust so fuel is not excavated from the combustion chamber without being part of the combustion process. Second, there is a separate crankcase that allows for more durable oil, in a reservoir, to stay separate from the rest of the system, father reducing engine ware.

Timing can be an issue, but the use of a camshaft (a lobed rod pressing buttons at the correct times to release valves) can help to solve these problems. Camshafts are geared to rotate at one revolution per power stroke, or one revolution per two revolutions of the crankshaft. Spark plug timing is usually run from a computer chip, and is timed with only one cylinder igniting at a time, allowing for maximum smoothness. This also incorporates the camshaft timing.

Three major reasons for issues include a bad spark plug, a bad air-fuel mixture, or bad compression. First, the spark plug might have a snipped wire or worn out wire, causing a bad or no connection. Also, the spark timing might be off and power is being distributed at anything but the optimal timing. Second, the air intake could be clogged flooding the engine with fuel and there is no air for combustion, there might not be any gas and the engine is just getting air, or the mid ground where the air-fuel mixture is improperly proportioned. There can also be impurities in the fuel like water causing problems in the combustion process. Last, there could be bad or no compression occurring. If there were a leak at either of the valves, intake or exhaust, there would be less compression than required. At the top of the cylinder, where the spark plug is inserted, there could be a break down of the gasket that seals the cylinder, again causing a leak.

Power output can be increased with many options. Displacement can be increased, with the principle: the more volume displaced the more power per revolution. To accomplish this, more cylinders and or larger cylinders can be used. Compression ratios can be increased, with the problem of early ignition. High-octane fuels accommodate for early ignition from high compression ratios. Higher pressures in the combustion chambers will increase the amount of air and fuel in the cylinder per combustion cycle, increasing the power. If the incoming air is cooled, it occupies less space and will expand more increasing the power stroke. Also, airflow resistance into the cylinder will take away power from the power stroke to pull in the air lessening the power output. Lower pressure losses in the filter and valves can help offset the losses.

4.0 CONCEPT GENERATION

This project involves the modification of an existing R/C Aircraft Engine so that it can be run using Hydrogen Fuel. These engines operate using a Nitromethane Fuel with an oil content of approximately 18%, and can be either 2-stroke or 4-stroke. Most R/C engines are relatively small, with an output of around 1~2 hp. These engines use a Fuel/Oil mixture that acts as both the fuel and the lubrication for the engine. The fuel is allowed to fill the Crankcase before it enters the Combustion Chamber so that all of the internal parts are lubricated. Both of these engines would easily run by simply pumping Hydrogen into them; however neither would be very efficient and would seize very quickly due to heat from friction. Both types of engines would require modifications to be able to operate efficiently without seizing.

Contents:

4.1 Engine

For the purpose of this project only one type of engine will be selected for modification. The modifications that would be required for both engines are discussed below. These engines are going to be studied further as well as the modifications they require at which point a choice will be made as to which engine will be selected for the Hydrogen Conversion.

2-Stroke Engine

The standard Two Stroke engine operates on the Two Stroke cycle. They fire once every revolution instead of once every other revolution as a Four Stroke does. Two Stroke engines do not have any valves, making them easier to construct. They have a much higher Power-to-Weight Ratio than most Four Stroke engines and can operate in almost any orientation.

Below is an example of an R/C Aircraft Two Stroke Engine

Figure 12. O.S. 91FX Two Stroke
Aircraft Engine

4-Stroke Engine

The Four Stroke engine is widely used in automotive applications as well as in some Airplane applications. It operates on the Otto cycle, where combustion occurs once every other revolution. Four Stroke engines operate using Valves that open and close as the Crankshaft rotates. These allow the piston to expel the exhaust gasses on one stroke, and then pull in fuel on the next stroke. These engines produce less power than Two Stroke engines, however they are much more efficient.

Below is an example of an R/C Aircraft Four Stroke Engine

Figure 13. O.S. FS 70-II Surpass Four Stroke Engine

4.2 Fuel Delivery System

Required By: Both the 2-Stroke and the 4-Stroke

There are Three ways that Hydrogen can be introduced into the engine:

1) Through the Carburetor
2) A Port Injection System
3) A Direct Injection System

Carburetor

This is the simplest method for delivering Hydrogen to the engine. It does not require that the Hydrogen have as high a supply pressure as in the other methods. Also, the R/C engines that are to be used in this Project are already equipped with Carburetors, making the modifications easier. The disadvantage of using this type of system is that it increases the risk of backfire and pre-ignition because of the larger amount of Air/Fuel in the intake manifold.

Port Injection System

This type of system injects the Hydrogen fuel into the intake manifold at each intake port. Air is first injected at the beginning of the Intake stroke which allows any residual gases to be diluted as well as cooling off any hot spots. The Hydrogen is then injected during the Intake stroke. This process allows a smaller amount of gas to be in the manifold at any one time, reducing the risk of pre-ignition and backfire. The inlet supply pressure for this type of system needs to be higher than for a carbureted system, but less than needed for a Direct Injection system.

Direct Injection

Figure 14. Quantum Technologies Gaseous Injector

Direct Injection is the most sophisticated type of Fuel delivery that can be used. In this process the Hydrogen is injected during the Compression Stroke, after the Intake valve has closed. This completely eliminates the risk of Pre-ignition and backfire during the intake stroke. One downside of using this type of system is that there is reduced mixing time of the Air and Hydrogen, which leads to a non-homogenous mixture. The result of this is that it can lead to higher NOx emissions than that of other methods. This type of system requires a higher fuel pressure than that of any of the other methods.

For both the Port Injection System and the Direct Injection System some type of metering device will need to be used. This will allow the proper amount of fuel to be added at the precise time that is required.

4.3 Spark Plug and Timing

Required By: Both the 2-Stroke and the 4-Stroke

Most R/C engines run using a Nitromethane Fuel. This fuel has a higher Oxygen content than Gasoline, allowing it to combust with a smaller amount of available air. In the engines it is combusted through the use of a Glowplug. This is a constant temperature heat source. This works fine when running on a Nitromethane Fuel, however it poses a serious risk when using Hydrogen. The low Ignition Energy of Hydrogen means that it can be combusted by any hotspots in the engine. If a Glowplug were used with Hydrogen it would lead to severe Pre-ignition and Backfire problems.

Figure 15. Glow Plug

To fix this, the Glowplug needs to be replaced with a Spark plug. This will only fire when it receives a charge from the ignition source and can be controlled so that the Hydrogen is only ignited when it is the right time.

This then leads to the issue of timing. With a Glowplug there is no need for a timing mechanism because it is always hot, however a Spark plug needs to be told when to fire. There are Two ways that Timing can be added onto the engine:

1) Use a Mechanical Timing Device
2) Use an Electrical Timing Device

<u>Mechanical Timing</u>

A Mechanical Timing mechanism would work by using a cam connected to the camshaft to mechanically activate a switch, sending a signal to the Spark plug telling it to spark. This solution would be a relatively cheap option, however it could prove difficult to implement, given the small size of the engine. It could also lead to pre-ignition and Backfire problems if the cam is not positioned correctly.

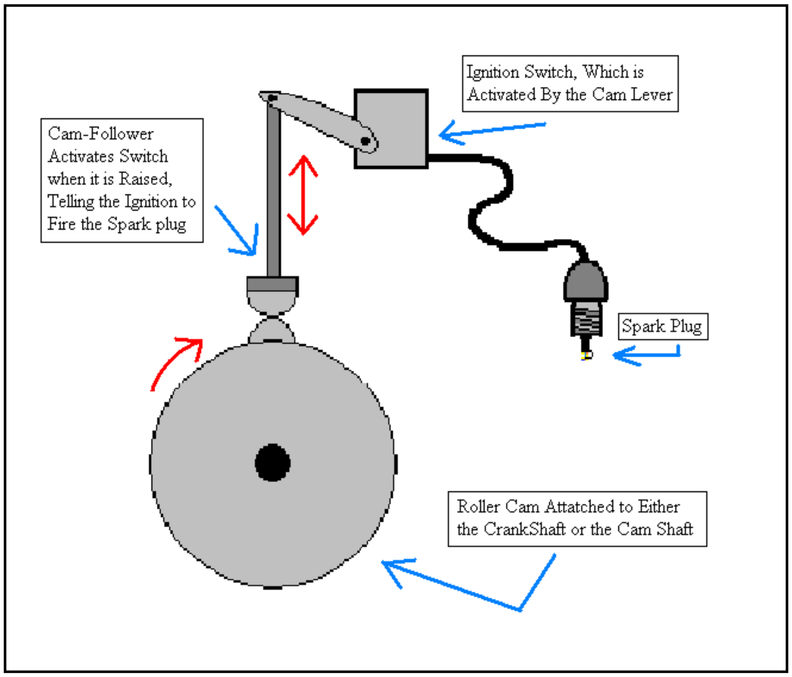


Figure 16.

An Example of a

Mechanical Timing Device

Electrical Timing

This Timing mechanism can built using a Hall-Effect Sensor and a magnet placed on the Prop Hub. When the shaft is spinning, the Prop Hub with the magnet on it will rotate as well. When the magnet passes under the Hall-Effect Sensor it will send a signal to the Ignition telling it that it needs to fire.

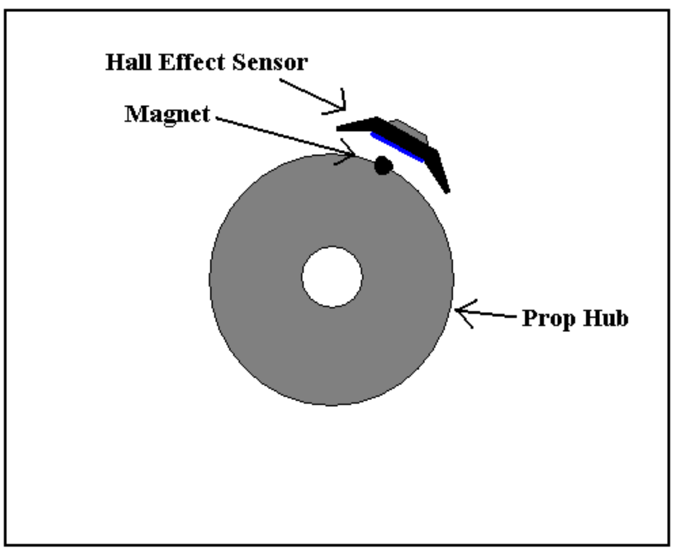


Figure 17. Diagram of an Electrical Timing Mechanism

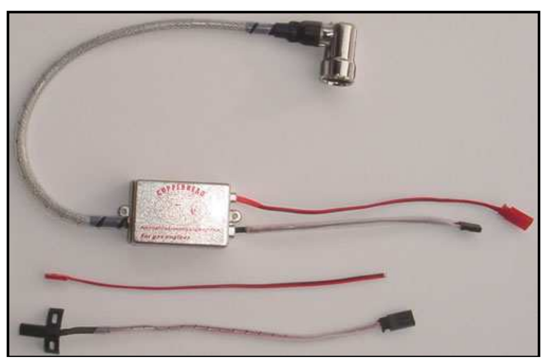


Figure 18. Copperhead Aviation RCEXL Electronic Ignition

An Electronic Ignition will also need to be added. These can be purchased from Hobby shops and require a small 4V battery to operate. One example is shown above, on the right.

4.4 Lubrication System

Required By: Both the 2-Stroke and the 4-Stroke

Both the 2-stroke and the 4-stroke engines will require some sort of lubrication system. R/C engines operate using a Nitromethane fuel containing a certain amount of oil content. This acts as both the Fuel and the lubrication for the engine. Because Hydrogen has no lubricating properties a way to supply oil to the moving parts of the engine needs to be developed.

In the 2-stroke engine the fuel passes through the engine body before it enters the carburetor, much like a reservoir. All of the moving parts are then lubricated as this fuel passes through the engine.

The 4 stroke engine is lubricated from air-fuel-oil and exhaust mixture that travels from the rocker cover, down the rocker arm retainer and into the crankcase. The mixture lubricates all moving parts (crankshaft, connecting rod and camshaft bearings, piston, and valve rocker) before it is routed back into the intake pipe.

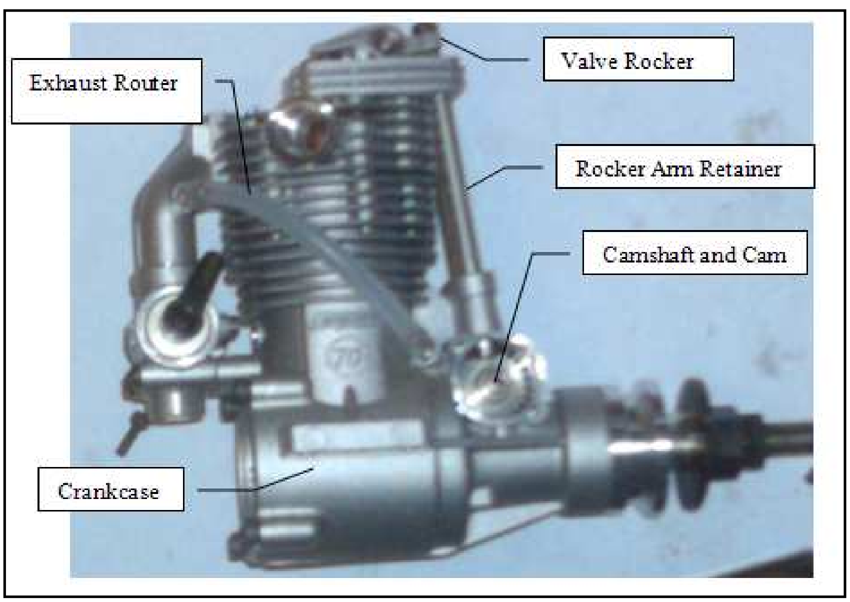


Figure 19. Picture of 4-Stroke Engine.

After looking at the two engines and studying how typical engines are lubricated, three methods were chosen as possible ways to lubricate the chosen engine. These are: a Wet Sump, a Dry Sump, and a Direct Oil Application method.

Wet Sump

The standard method of lubrication for 4 stroke cycle engines is the wet sump system. An oil reservoir is located beneath the crankcase, which supplies oil to the oil pump. The pump delivers oil to the main bearings, connecting rod bearings and piston pin through internal passages in the crankshaft and connecting rod (illustrated below). The oil pump also feeds into the camshaft and the valve rocker assembly.

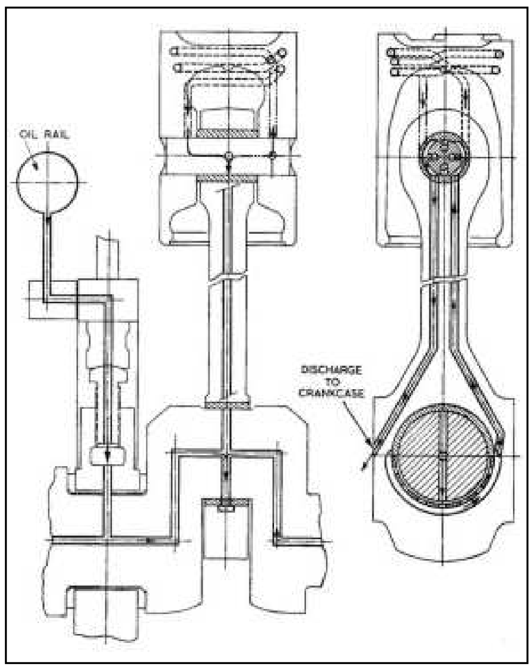


Figure 20. Traditional Lubrication System
(Courtesy of marinediesels.co.uk at
http://www.marinediesels.info/Basics/lubrication_system.htm)

This method would be the most complicated of the three methods because the internal passages that the oil flows through would have to be machined without doing damage to the engine.

Dry Sump

Another method is the Dry Sump, in which the oil that trickles back down into the oil pan is then pumped into an external reservoir. This system needs an additional displacement pump to move the oil into the reservoir, which can reduce engine power, but allows for a smaller oil pan underneath the engine. From the external tank, the lubricant is pumped out and supplied to the engine in the same manner as the wet sump.

For both of the above options a Sump will have to be added below the engine. An example of this is seen in the picture below.

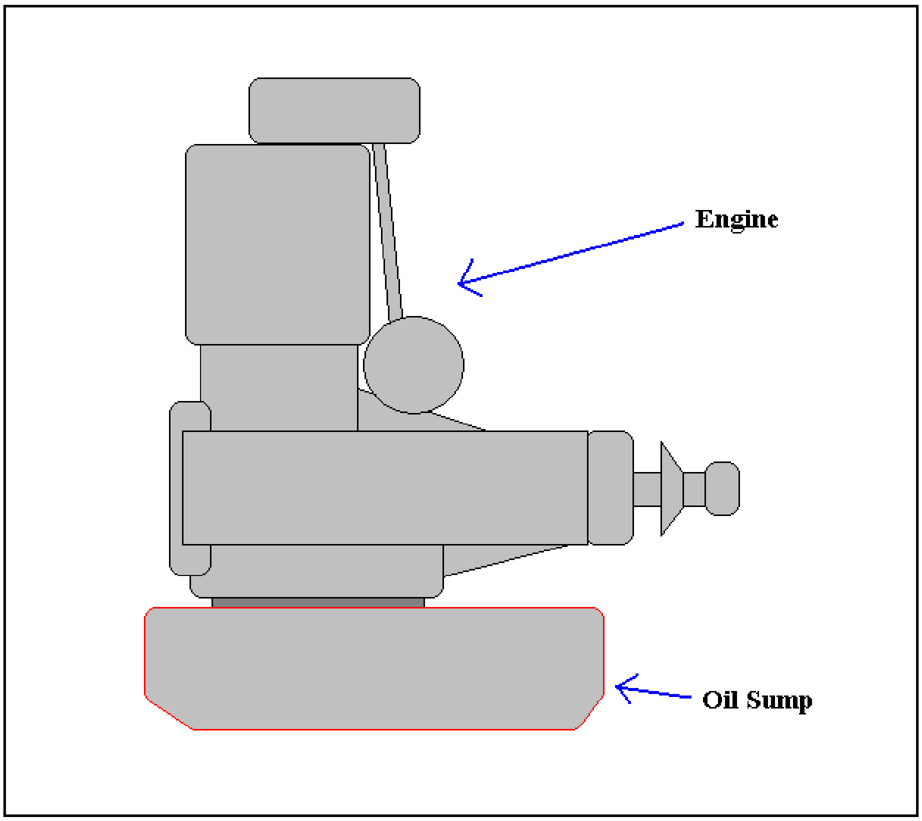


Figure 21. Example of Sump Placement

The sump can be made of thin aluminum and connected back to the top of the engine through a small oil pump so that the oil will continue to circulate and supply adequate lubrication.

Direct Oil Application

Due to the small size of the engines that are being used for this project, the two sump methods mentioned above might be too difficult to implement. One way to lubricate the engine without using an oil pump and sump would be to directly apply oil to the engine. This method would involve creating a small inlet into the crankshaft or camshaft and then filling the engine with enough oil to last one or two runs. The engine would then have to be checked after every couple of runs to determine the oil level and to refill if necessary. This method would not be the most efficient method but it would allow lubrication without the risk of permanently damaging the engine. Once the engine has been filled with the proper amount of oil the inlet will be plugged using a durable rubber stopper, or a metal plug with a rubber o-ring. This will prevent the oil from leaking during engine operation.

Graphite Powder

For some parts of the engine, a very fine grain graphite powder could be used as lubricant. Graphite powder is not water soluble, and can withstand high temperatures and pressures. It would not be suitable for use in the entire engine but would best be used in small spaces. Lubricating the rocker arms and the pushrods would be ideal areas for this type of lubricant to be used.

4.5 Piston Cylinder Lining

Required By: 2-Stroke

On the Two Stroke R/C engines, the Piston Cylinder is designed so that as the Piston moves up and down it pulls in Fuel from the Crankcase and expels exhaust out the Muffler. It does this through openings in the Piston Cylinder Lining. Since Hydrogen has no lubricating properties, there is no need for it to be allowed into the Crankcase. To stop the piston from pulling fluid in from the Crankcase the Piston Cylinder Lining will need to be sealed up or replaced.

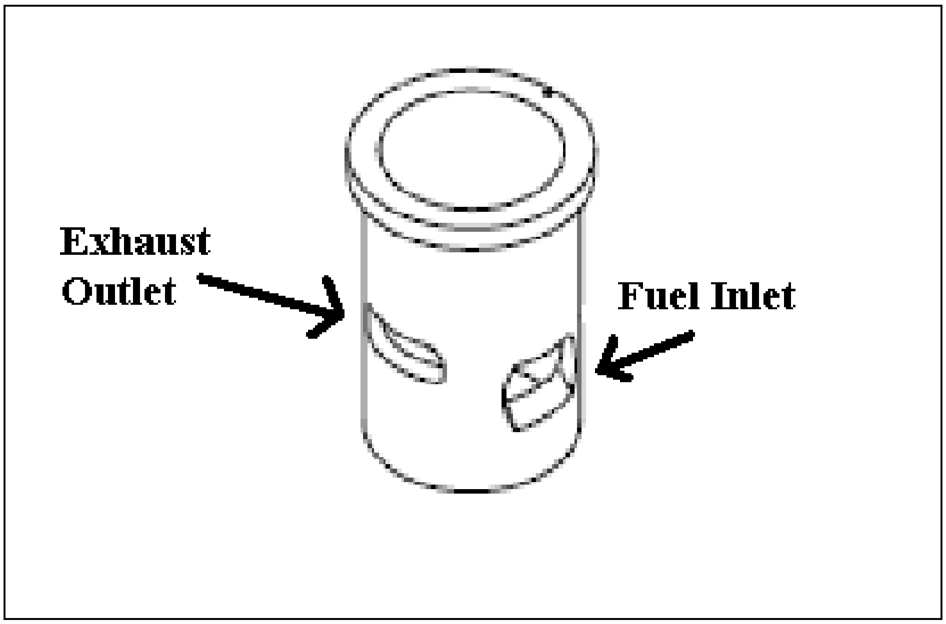


Figure 22. Piston Cylinder Lining

4.6 Type of Hydrogen Storage to be Used

Hydrogen is to be the fuel for these engines and needs to be safely supplied to them. There are Three main ways that this can be done.

1) Liquid Hydrogen Storage
2) Gaseous Hydrogen Storage
3) Metal Hydride Storage

<u>Liquid Hydrogen</u>

Liquid Hydrogen would not be very feasible because it would have to be super-cooled. This would require a cooling mechanism as well as insulation, which would add lots of weight as well as cost to the project.

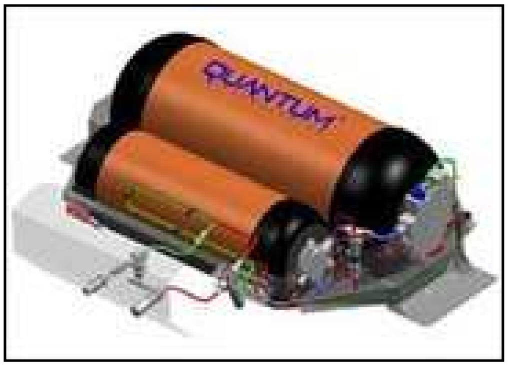


Figure 23. Quantum Technologies Automotive Liquid Hydrogen Tank

<u>Gaseous Hydrogen</u>

This method involves compressing the Hydrogen in storage tanks. This would be relatively cheap and weigh less than the Liquid Hydrogen storage. It would not require any external devices other than a pressure regulator.

Figure 24. Two Types of High Pressure Hydrogen Tanks

Metal Hydride Storage

This type of storage uses cylinders that contain a metal hydride powder. This powder absorbs the Gaseous hydrogen and then releases it when the tank is heated. This method is the safest method for Hydrogen storage because if there is a leak the hydrogen does not rapidly shoot out, but instead very slowly disperses as it evaporates out of the metal hydride. These are more expensive though, as well as being slightly heavier than using compressed Hydrogen.

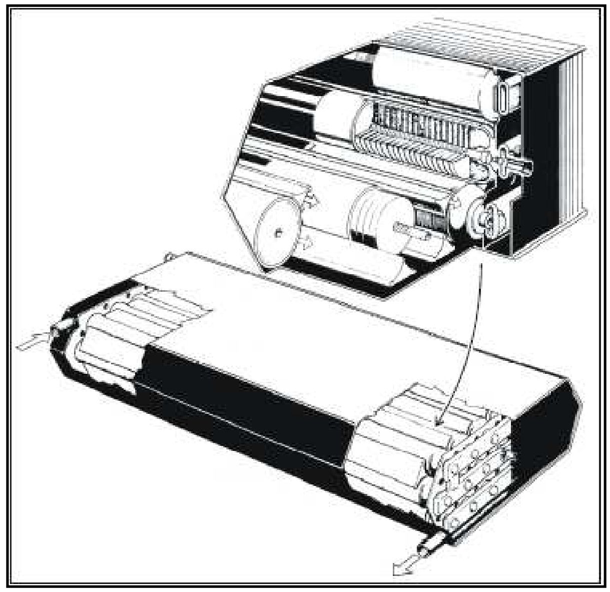


Figure 25. Metal Hydride Vehicle Storage Tank, Sectioned

5.0 DESIGN SELECTION

This section describes the selection process that was used when determining which designs to use for the modification of the R/C engine. It also presents the choices made in a Design Matrix format, so that the selection process can be easily understood. In order to make a good choice certain criteria need to be taken into account. In each section the criteria that have been chosen will be explained followed by the Decision Matrix quantifying them. These matrices use a scale from 1 to 5, where 1: Worst and 5: Best. The selected choice will be the item with the highest total score.

Contents:

5.1 Type of Engine to Modify

This decision is an important one, given that the type of engine chosen will ultimately determine what type of modifications are required. Both engines were looked at thoroughly and ran using Nitromethane, so that there operation could be better understood. The criteria that were chosen as a basis for the choice of engine are as follows:

Ease of Modification

This criterion deals with how easy it will be to make the actual modifications on the selected engine. A high score means that the modifications will be relatively easy to perform and a low score means that the modifications will require extensive work.

Power Output

This criterion was included because even though this project is essentially a Proof-of-Concept, the engine should still be able to provide adequate power for an aircraft. When switching to a Hydrogen fuel the power output can change from 25% below to 15% above what the original output is. It is better to start with a higher output engine so that if the power output is reduced it will still have enough power to perform adequately.

Safety

Safety is a major concern. Given Hydrogen's nature if there are any leaks or hot spots it could lead to a serious problem. For the purpose of this decision, the safety aspect deals with how safe the selected engine will be when used with hydrogen. Since the 4-stroke has valves as opposed to the 2-stroke, which merely has openings, it would be a safer choice.

Fuel Efficiency

This criterion was selected because the underlying purpose of this project is to help the environment. An engine that has a better fuel efficiency will have a higher power output while at the same time using up less fuel.

Engine Cost & Proposed Modification Cost

Since this project is on a budget it is necessary for the Cost of the parts to be taken into account when determining which one to modify.

Engine Selection Decision Matrix

(1-5; 1: Worst, 5: Best)

Engine	Ease of Modifiation	Power Output	Safety	Fuel Efficiency	Engine Cost	Proposed Modification Cost	Total
2-Stroke	2	5	3	3	4	2	19
4-Stroke	4	3	4	4	4	3	22

Figure 26

Decision: The 4-Stroke Engine has been Selected for Modification

5.2 Type of Fuel Delivery System to Use

The Type of Fuel Delivery to use will determine what the power output of the Engine will be. It will also help determine the type of Hydrogen storage that is to be used and the pressure that it needs to be at.

Ease of Addition

This criterion is based on how easy it will be to install the selected Fuel Delivery device as well as how easy it will be to set it up properly. The injectors would have to put the correct amount of fuel in the engine at precisely the right time. To do this some type of metering device would have to be added. This would increase the difficulty of using those systems on the selected engine.

Proposed Cost

As stated before the Cost of the components is a determining factor due to the limited budget of this project.

Safety

When using different types of Fuel Delivery devices, its safety is its ability to successfully limit Backfire and Pre-ignition. These are two of the major problems encountered when using Hydrogen fueled I.C.E.'s, therefore any method that reduces that risk is a good method to use.

Efficiency

The Efficiency of the Fuel Delivery device is its ability to put Fuel into the combustion chamber at precisely the right time, and in the precise amount required. If this is not done properly the timing of the engine will be thrown off and it will be more susceptible to Pre-ignition and backfire problems.

Fuel Delivery System Decision Matrix

(1-5; 1: Worst, 5: Best)

Type of Fuel Delivery	Ease of Addition	Proposed Cost	Safety	Efficiency	Total
Direct Injection	2	1	5	5	13
Port Injection	2	2	4	3	11
Carburetor	4	5	1	1	11

Figure 27

Decision: The Use of a Direct Injection System has been Chosen as the Means of Fuel Delivery for the Selected Engine.

5.3 Type of Ignition/ Timing Mechanism to Use

The Ignition/ Timing mechanism will regulate the firing of the Spark plug. It is necessary to have an accurate timing and ignition device so that the engine fires exactly when it is supposed to.

Ease of Addition

This criterion deals with how easy it will be to add the timing mechanism to the selected engine. Ultimately the best option will be the one that requires a minimal amount of machining, and can be installed easily.

Proposed Cost

Again cost is an important aspect of every part of this project.

Adjustability

This criterion refers to the ability of the timing mechanism to be adjusted. This is necessary so that it can be fine tuned to match the need of the engine. Depending on what type of fuel delivery system is used as well as the type of the spark plugs, the timing will change. The timing mechanism needs to be easily adjustable so that if any changes are made to the engine it will not require extensive work to set it properly.

Ignition/ Timing Decision Matrix

(1-5; 1: Worst, 5: Best)

Type of Ignition/Timing	Ease of Addition	Proposed Cost	Adjustablity	Total
Mechanical	1	4	1	6
Electrical	4	2	5	11

Figure 28

Decision: The Use of an Electrical Timing Device was Chosen as the Best Option for this Project.

5.4 Method of Engine Lubrication

Lubrication is a major aspect of this design project. Without properly lubricating all of the parts of the engine it could seize from extreme temperatures. The engines chosen for this project though, are very small and could prove very difficult to lubricate with a sump and oil pump. A good medium between performance and ease of installation needs to be the basis for the chosen method of lubrication.

Efficiency

The efficiency of the lubrication method is very important. If the engine is not properly lubricated it will get very hot due to friction. This will cause very parts of the engine to seize up, making the engine unusable.

Ease of Modification

As stated above, the small size of these engines would make any extensive modification quite difficult. When the modification is made it needs to be done on a way that will not damage the engine.

Cost

Again, cost is a very important criterion and should be taken into account for every decision that needs to be made.

Lubrication Method Decision Matrix

(1-5; 1: Worst, 5: Best)

Lubrication Method	Efficiency	Ease of Modification	Cost	Total
Wet Sump	5	2	2	**9**
Dry Sump	4	2	2	**8**
Direct Oil Application	3	5	5	**13**

Figure 29

Decision: The chosen method of lubrication is to use the Direct Application Method.

5.5 Type of Hydrogen Storage

The method of Hydrogen storage is very important. Given that the engine being modified is for use on board an R/C aircraft the fuel tank should be lightweight, and be able to carry enough fuel for an adequate period of time. It should also be safe, because it will be containing Hydrogen, which is dangerous.

Safety

Safety is one of the biggest concerns when dealing with Hydrogen fuel. If any leaks develop or if too high of a temperature is present, it could be disastrous. The best method of Hydrogen storage will be one that is safe to operate, allowing for a minimal chance of failure.

Cost

Again, cost is always a deciding factor.

Weight

Weight is also a major concern, because it needs to be light enough to fit on an R/C airplane without reducing its airworthiness.

Hydrogen Storage Decision Matrix

(1-5; 1: Worst, 5: Best)

Type of Storage	Safety	Cost	Weight	Total
Liquid Hydrogen	3	3	2	8
Gaseous Hydrogen	2	4	3	9
Metal Hydride	4	1	2	7

Figure 30

Decision: Gaseous Hydrogen Tanks were Chosen as the Best Option for Storing Hydrogen Fuel.

6.0 DETAILED DESIGN

In this section all of the choices that have been made concerning the selected engine's modification will be explained further. This will also serve as a guide as to how the device should be assembled and run. These decisions were made after extensive research and are believed to be the best possible setup for this project. Once the engine has been set up it will be run to determine the effectiveness of this setup, whereupon modifications and/or additions will made.

<u>Contents:</u>

6.1 Fuel Inlet

For the purpose of this design it was decided that the use of a Direct Injection System would be the best way to feed Hydrogen into the selected engine. Although this is the most difficult option to implement, it is the best option given its efficiency and safety.

The Hydrogen will be supplied to the engine by a small compressed gas cylinder, such as the one at right, which is available at www.FuelCellStore.com. The hydrogen flows out of the cylinder and through a regulator so that the pressure is decreased to a level that is suitable for this application.

Figure 31. Compressed Gas Cylinder

Most modern engines that use Fuel injection require the use of an electronic control device to meter the fuel to the engine in the correct amounts and at the right time. For the purposes of this project a similar metering device will need to be implemented. This device should be able to accurately meter the hydrogen into the combustion chamber at the precise time, so that the engine runs efficiently and safely. For this design a non-computerized device should be used given the overall complexity of any available electronic control unit.

Two viable methods that were decided upon are:

1) The use of a check valve
2) The use of a rotating valve

<u>Check Valve</u>

The check valve would work by only allowing the hydrogen to flow through when the pressure in the hydrogen tank is greater than that of the combustion chamber. After combustion takes place the pressure inside the combustion chamber increases dramatically, which would cause the check valve to close, eliminating the possibility of backflow into the hydrogen tank. A description can be seen below:

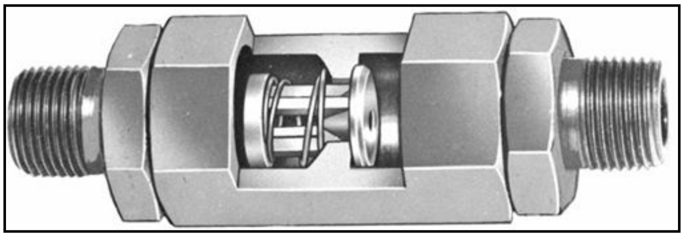


Figure 32. Traditional Check-Valve
Courtesy www.CheckAll.com

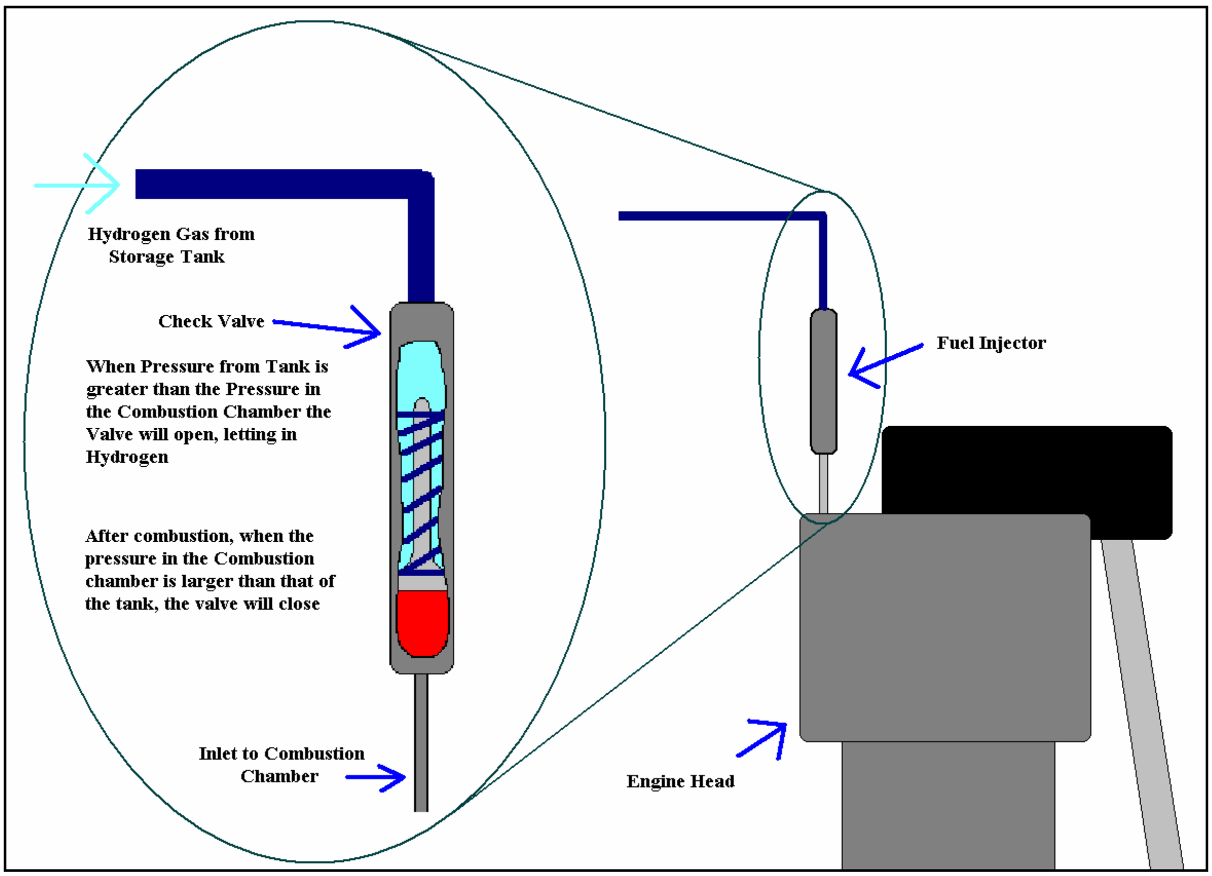
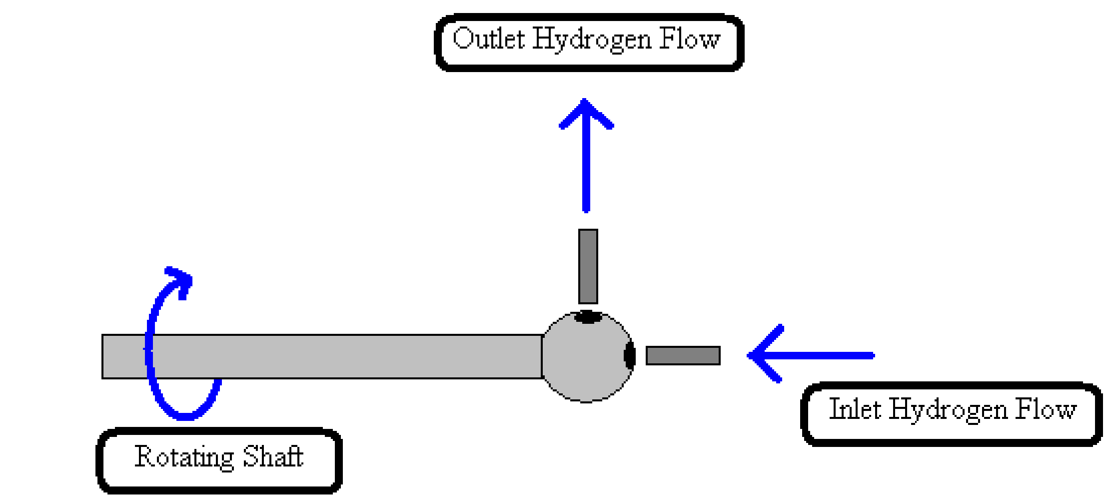


Figure 33. Description of Check-Valve Implementation

This type of metering device would be easy to implement and would successfully eliminate backflow from the combustion chamber. It would, however, be very inefficient, as its only form of timing would be from pressure differences in the hydrogen tank and the combustion chamber.

<u>Rotating Valve</u>

A rotating valve consists of a ball valve connected to a shaft. As the shaft rotates, the ball valve rotates as well, and when holes on the ball line up with holes on the valve cover, flow is allowed. This type of valve needs some form of driving motor to rotate it at the correct speed. For the use of this project the best way to do this would be to drive the valve off of the engine's camshaft. This would allow it to be perfectly timed with the engine regardless of the engine speed.



Flow will occur only when the holes on the ball line up with the inlet and oulet. In the case of this particular ball valve, the inlet hole is always lined up, while the outlet hole lines up only once per revolution.

Figure 34. Description of Rotating Ball Valve

This type of fuel injector would be better than one that used a check valve. It would be perfectly timed to the engine, and it would only allow fuel to flow at the correct time for the most efficient ignition and combustion.

It was decided that, given the ball valve's greater efficiency and ease of timing, it would be the best option for a fuel-metering device.

In order to have it run off of the camshaft it is necessary to extend the camshaft outside of the engine, so that it can be mated onto the valve shaft. The best way to do this would be to drill and tap into the shaft of the camshaft and then machine a shaft that can be threaded into the camshaft.

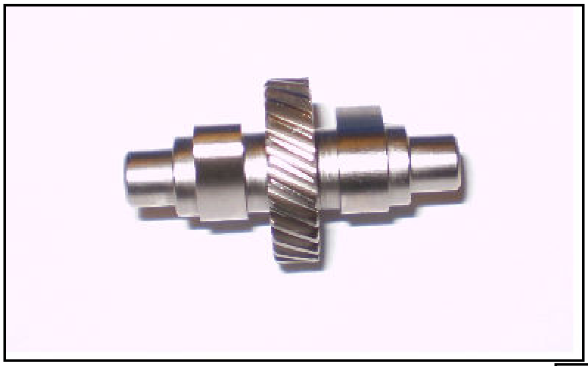


Figure 35. Unmodified Camshaft

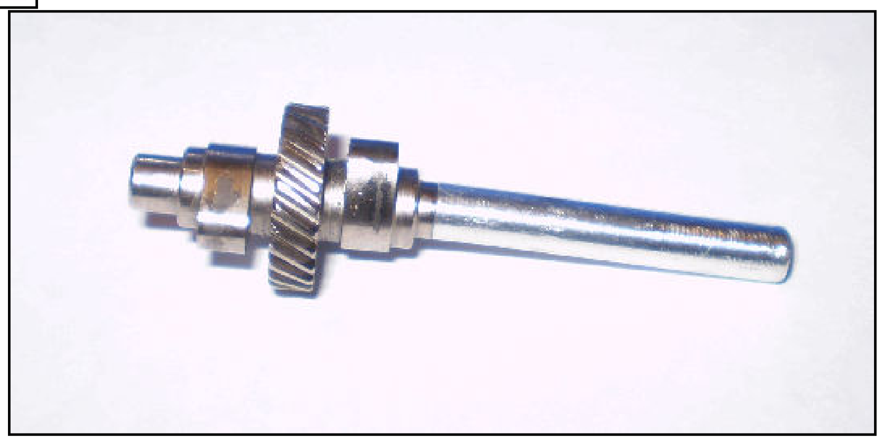


Figure 36. Modified Camshaft

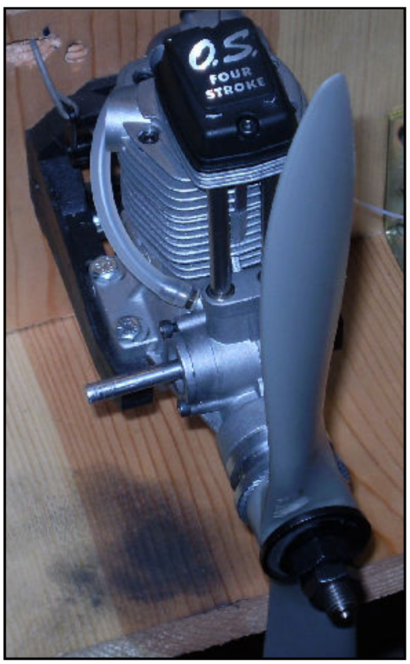


Figure 37. View of Engine with Camshaft Extension

Since the camshaft spins in the right-hand direction while the engine is operating, it should be tapped with a left-hand threaded tap. This will ensure that the extension does not unscrew during engine operation.

Once the camshaft has been extended out, a sleeve can be used to join it with the shaft of the ball valve. The sleeve will be secured to both shafts through the use of two set-screws.

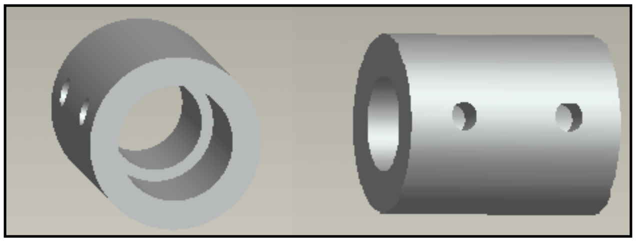


Figure 38. Sleeve (shaft connector)

Figure 39. Selected Ball Valve
Swagelok 45° valve

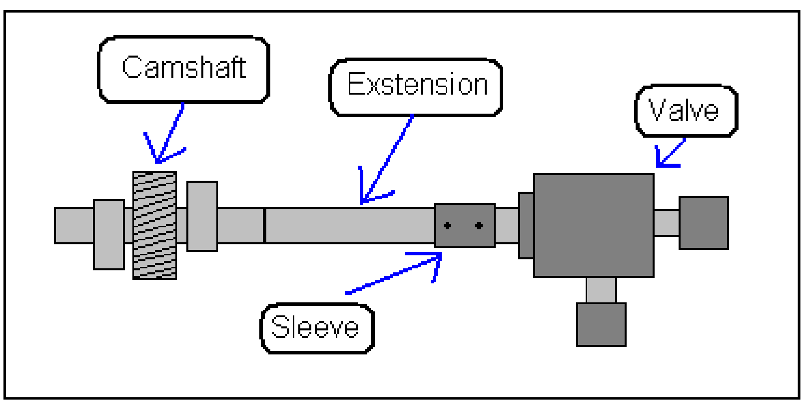


Figure 40. Camshaft to Valve
Explanation

Now that a way to meter the fuel has been chosen, it is necessary to come up with a way to inject the fuel into the combustion chamber. Since direct injection was chosen as the best option, the fuel will need to be injected directly into the combustion chamber. This needs to be done in an effective and safe way. One solution to this is to use a hypodermic needle. As long as the inner diameter of this needle is less than 0.025in (the Quenching diameter of Hydrogen) then the flame from combustion will not be able to propagate back up the tubing. The inner diameter will also help to determine the mass flow rate of the fuel.

The hypodermic needle chosen has an inner diameter of 0.008in.

The hypodermic needle was added by drilling into the cylinder head and then pressing it in until it was in the desired position. It is secured in place by using a high-temperature epoxy.

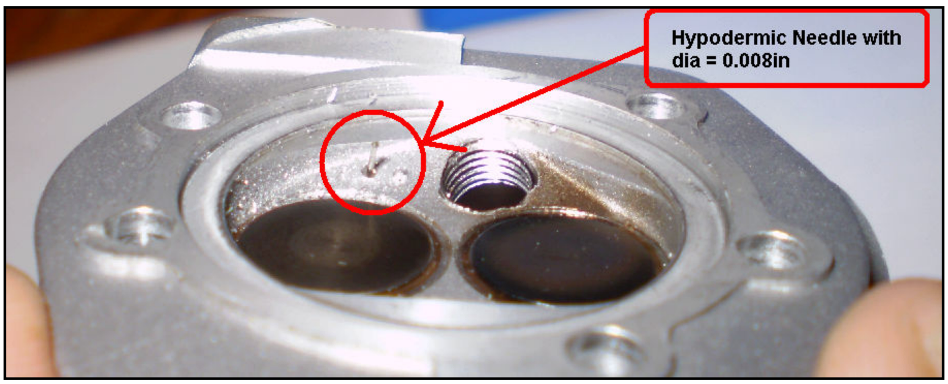
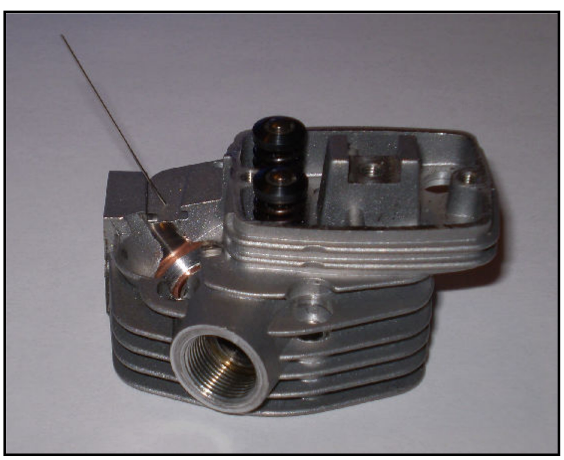


Figure 41. Hypodermic Needle Pushed
Through Cylinder Head



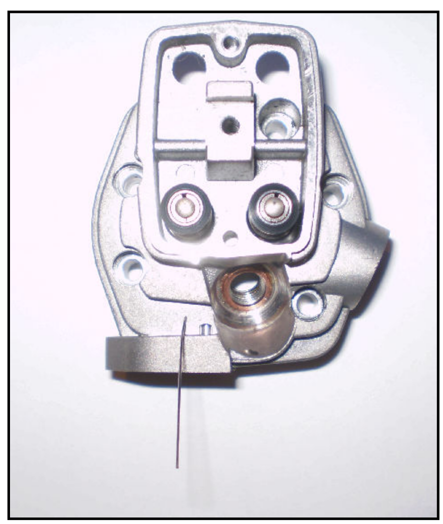


Figure 42 & 43. Pictures of Cylinder
Head with Hypodermic Needle

To allow the hydrogen to flow from the valve to the hypodermic needle, tubing will need to be used. Because of the change in diameters between the two, the tubing will need to be stepped down, using adapters. A picture of this tubing with the valve is shown below.

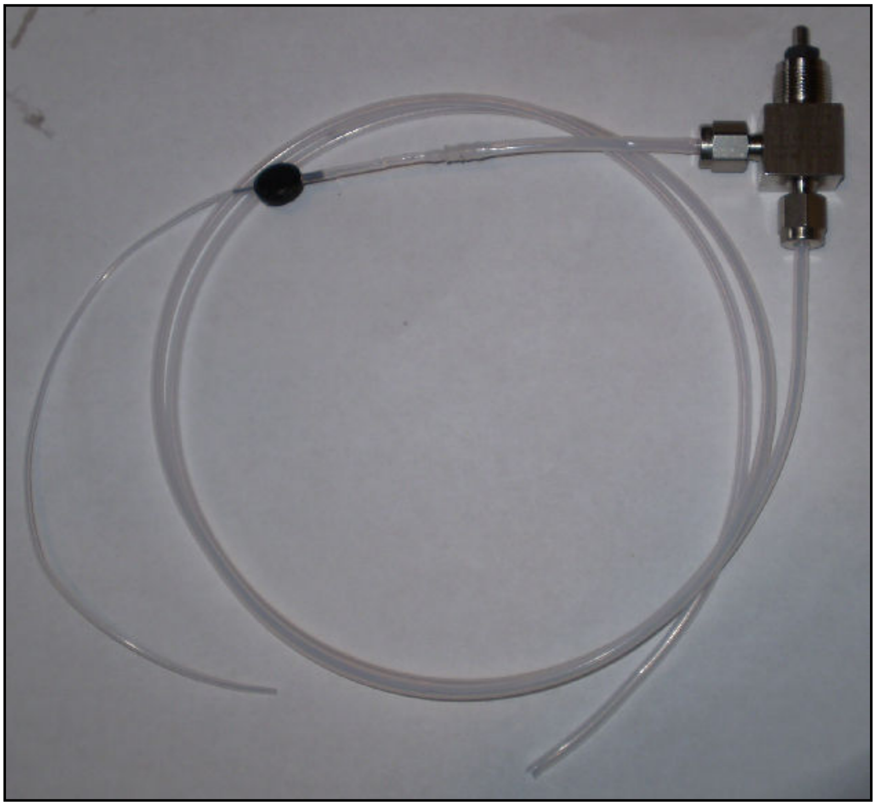


Figure 44. Tubing and Valve

6.2 Ignition Setup

The ignition source for the Spark plug will be supplied via an Electronic Ignition Unit. This ignition runs on a 4.8V battery. The ignition will supply the spark plug with a charge every time it is triggered by the Hall Effect sensor. A Hall Effect sensor is a type of sensor that can detect when a magnetic source passes by it.

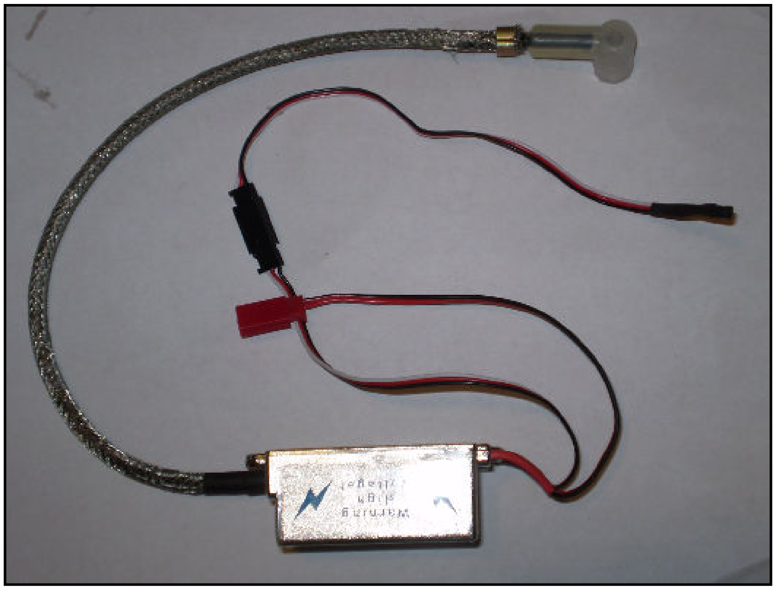


Figure 45. Electronic Ignition Unit

Figure 46. Rimfire V3 ¼-32 Spark Plug

The Hall Effect sensor will be triggered by a small magnet imbedded into a flywheel.

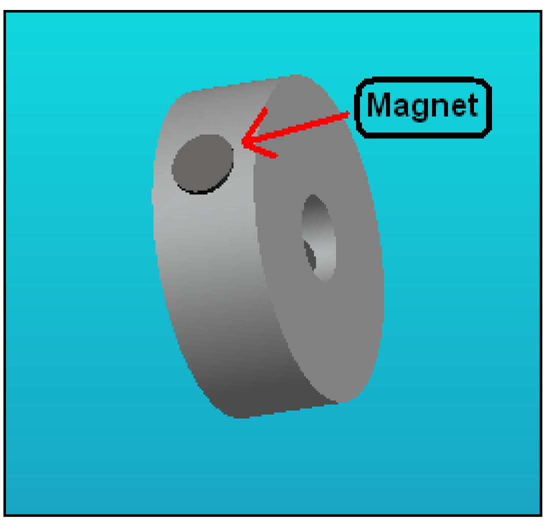


Figure 47. Flywheel with Magnet

As the flywheel spins the magnet will pass underneath the Hall Effect sensor, triggering the ignition, and causing the spark plug to spark. It will be driven by the same shaft as the ball valve. This will allow both to be timed using the camshaft.

Below is a description of how the ball valve and the flywheel will be implemented on the engine:

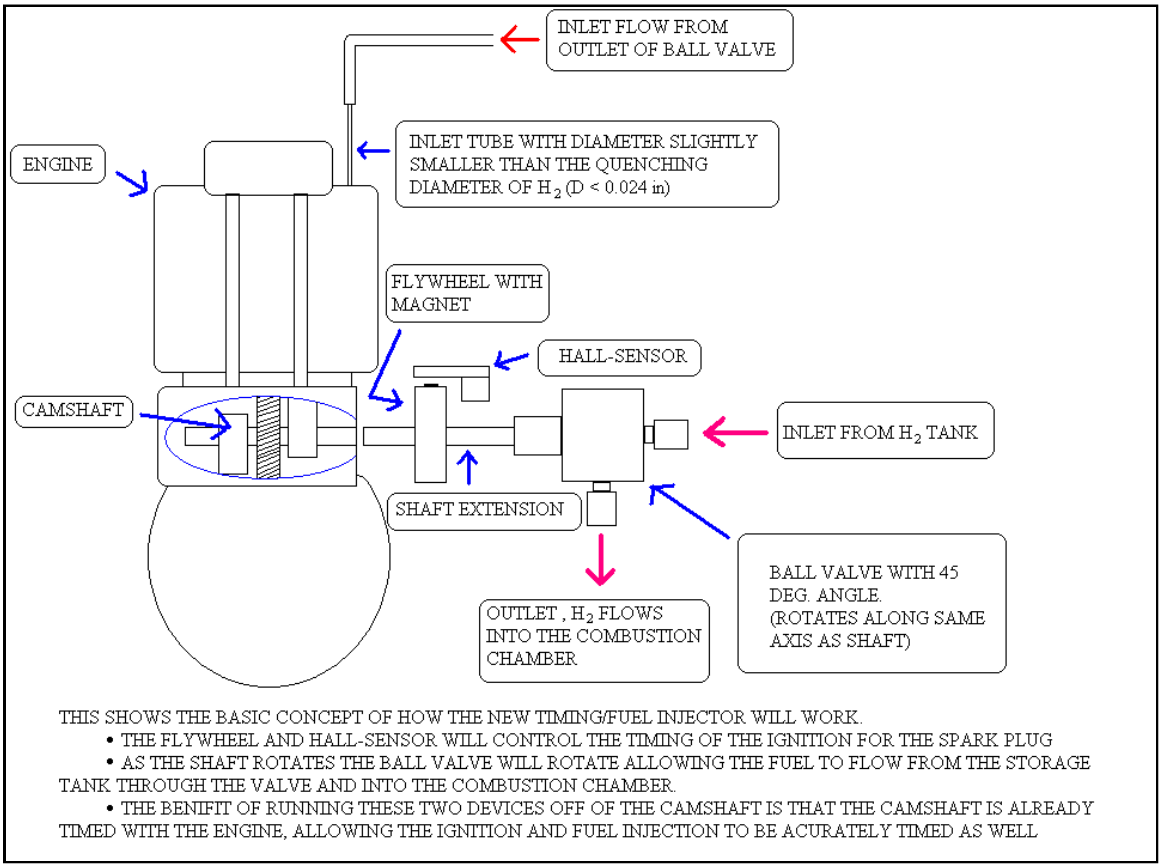


Figure 48. Ball Valve/Flywheel Implementation

Housing Mechanism

A housing will need to be built to house both the flywheel and camshaft and allow them to be held in place so that they can be driven off of the camshaft. It should be designed so that it connects to the existing screw slots on the camshaft faceplate.

Below are pictures of the housing that was designed for this purpose:

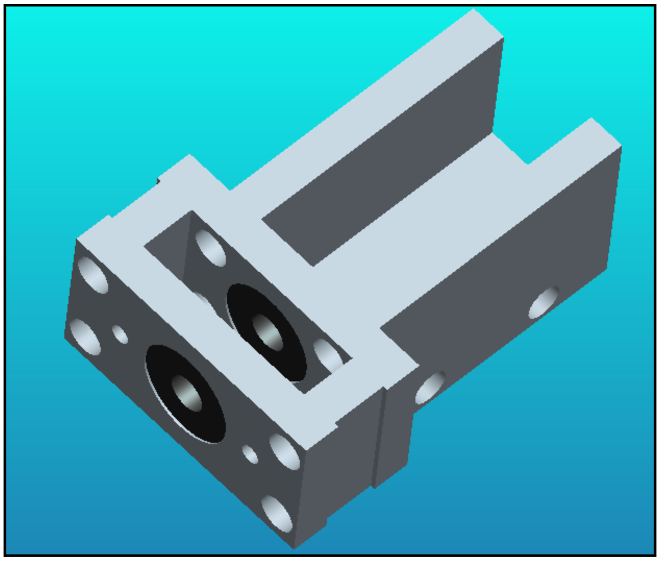


Figure 49. Picture of Housing

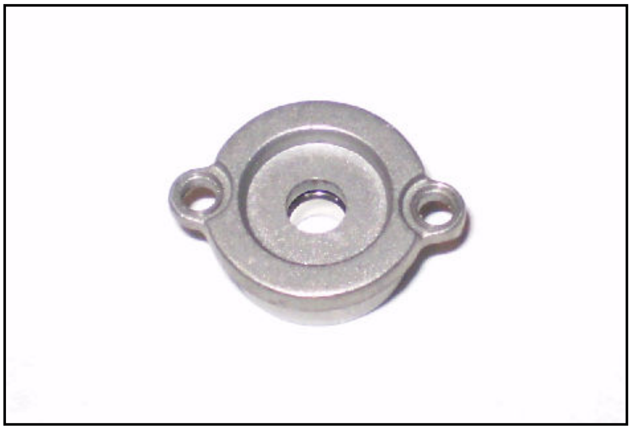


Figure 50. Camshaft Faceplate, Modified for the Shaft Extension

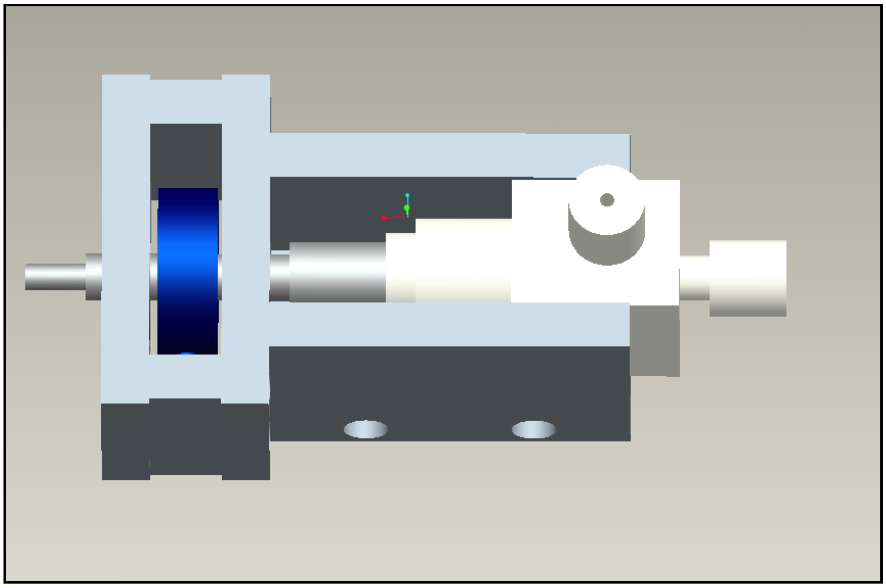


Figure 51. Housing with Valve and Flywheel

6.3 Lubrication System

Ideally the engine would be able to have a sump system with an oil pump as the lubrication system, however since the engine is so small this was deemed unfeasible. Instead the engine will be lubricated by directly applying oil into the engine through an access port. Every time the engine is done being run it will need to be checked to determine if more oil needs to be added. The temperature of various parts of the engine will also be monitored constantly to ensure that the lubrication system is working. If at any time the engine gets too hot it will be cut off and allowed to cool. It will then be cleaned out and refilled with oil.

The engine will be tested with various amounts of oil to determine the optimal amount needed. Ideally there should be a minimal amount of oil, while still being able to fully lubricate all parts of the engine.

The access port chosen is part of the existing design. There is a blow-by line, which allows fuel that is in the camshaft/crankshaft area to feed back into the inlet so that the pressure does not get to high. The inlet side of the line will be plugged, and the camshaft/crankshaft side will be used as the access port. This was decided as the best option because it did not require drilling into the engine body.

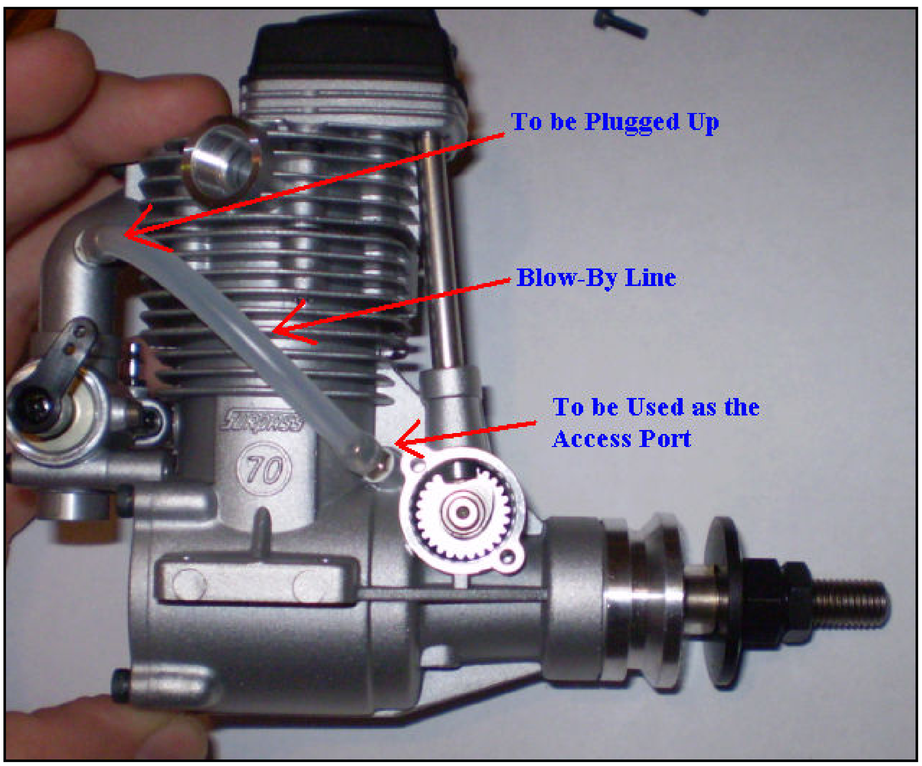


Figure 52. Blow-By Line Detail

It was also decided to use Graphite to lubricate the rocker arms and the push rods, incase the oil did not reach these parts of the engine. The type of graphite that will be used is a very fine mesh graphite powder. It will be brushed onto those parts of the engine and re-applied as necessary after each engine run.

Figure 53. Graphite


Figure 54. Graphite

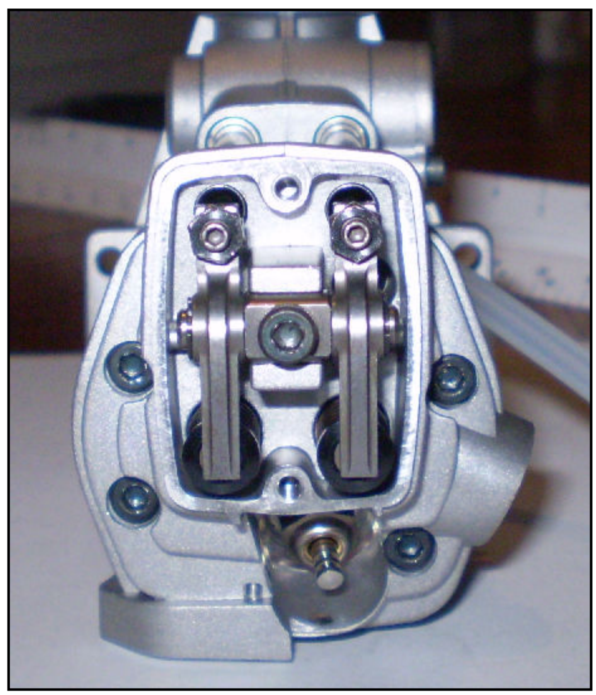


Figure 55. View of Rocker Arms

6.4 Mounting Setup

Once all of the modifications have been made they will need to be setup so that the engine can be run. Many different configurations were thought up, and probably more than one will be used. The first setup is a design that is based around the fact that the system is being designed for use on an R/C airplane, so everything should fit into the space that one of these planes would allow.

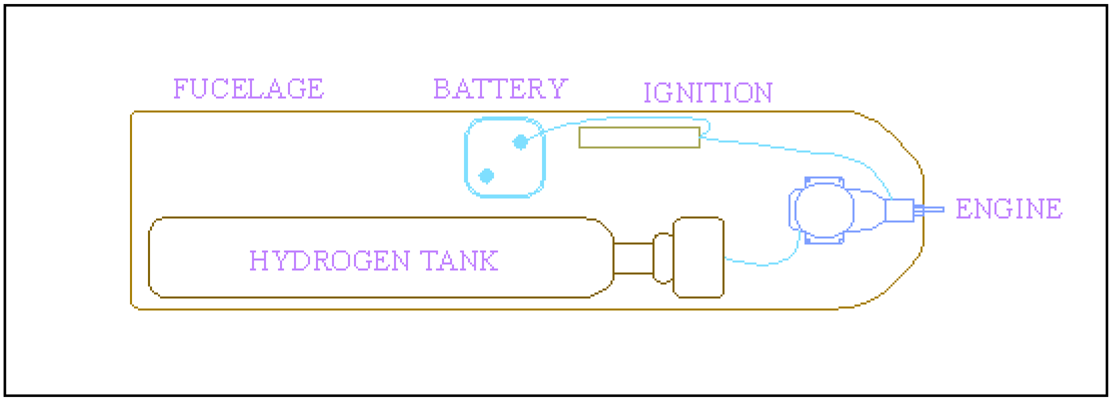


Figure 56. Initial Mounting Setup

The next picture is of the actual mounting system that was utilized. This design was chosen based on its ease of assembly and the convenience of the parts. When the engine is run it vibrates a lot. This mounting design allowed the engine to be thoroughly secured and eliminated most of the unwanted vibration.

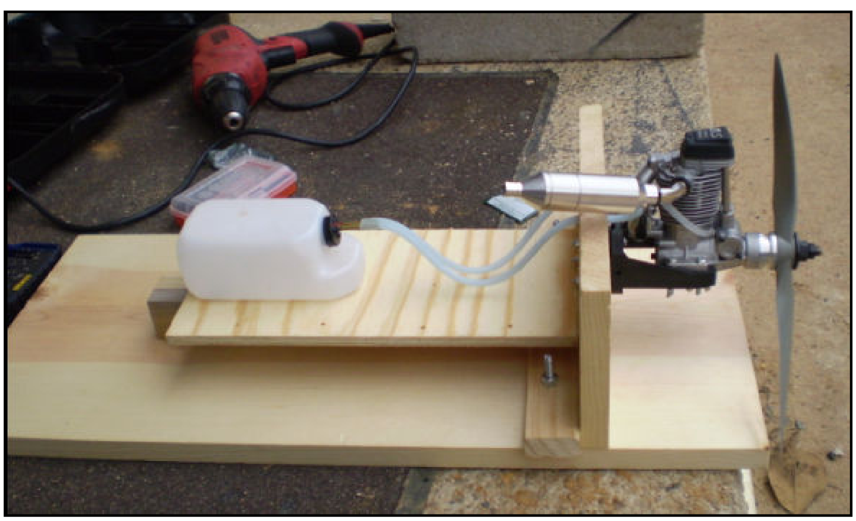


Figure 57. Actual Mounting Setup

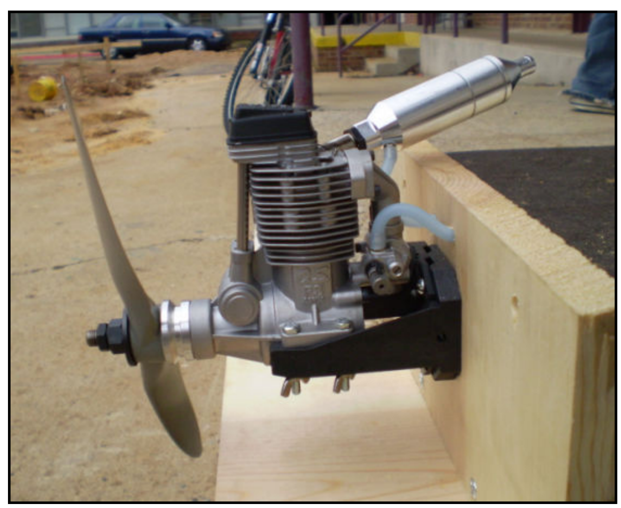


Figure 58. Actual Mounting Setup

6.5 The Complete System

Now that all of the individual components have been discussed, they need to be put together into the overall system. This section will consist of pictures with descriptions of what the engine will look like when completely modified.

Adding the Housing assembly onto the Engine

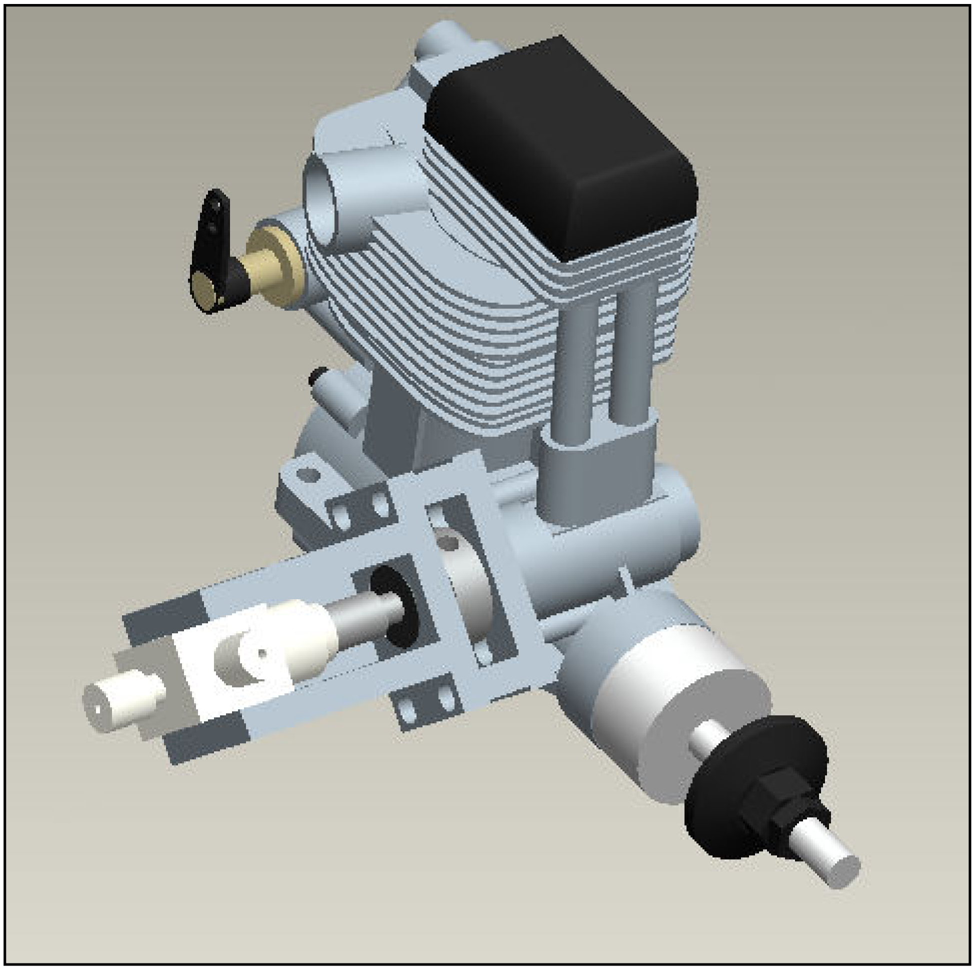


Figure 59. Engine with Housing Assembly

The housing assembly will mount onto the camshaft faceplate using the existing screw slots. It will be configured as above. The shaft will be aligned so that the valve and flywheel perform their function at the desired time with respect to the engine's operation.

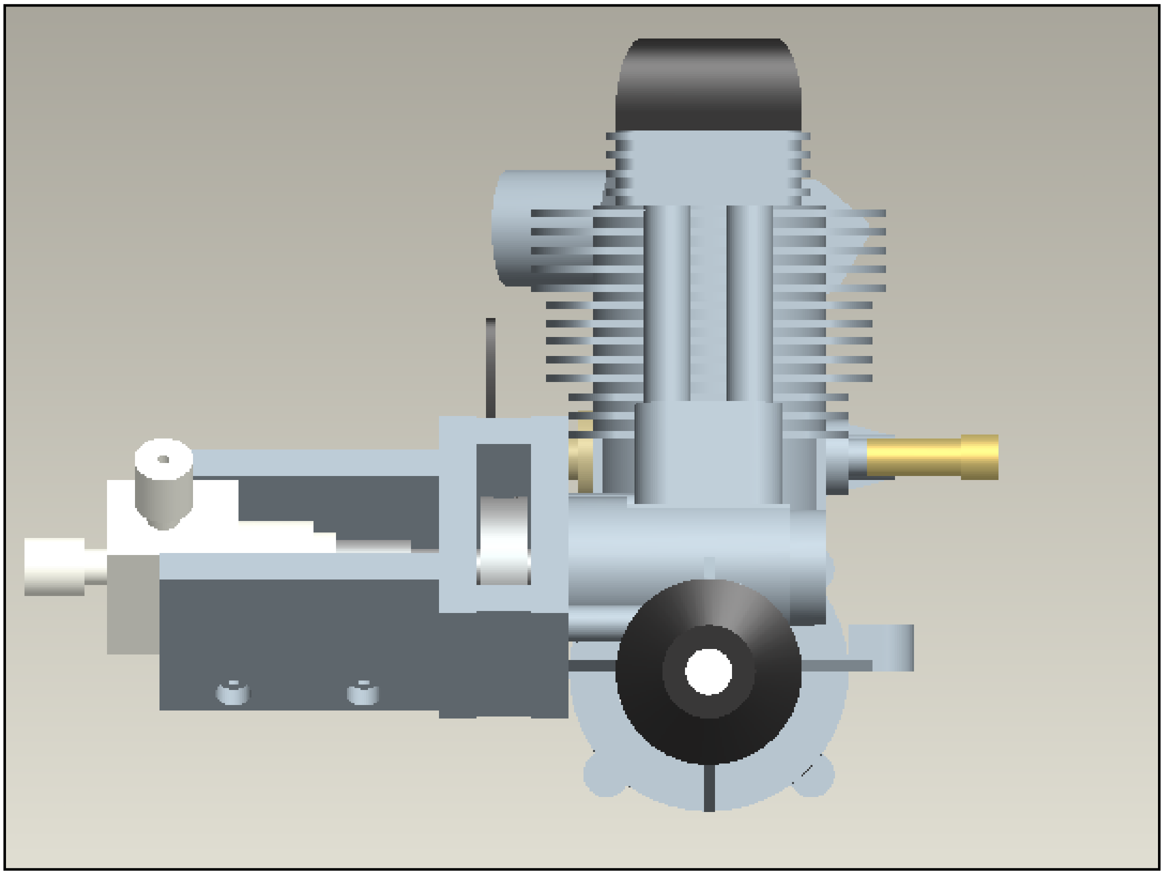


Figure 60. Another View of the Engine with the Housing Assembly

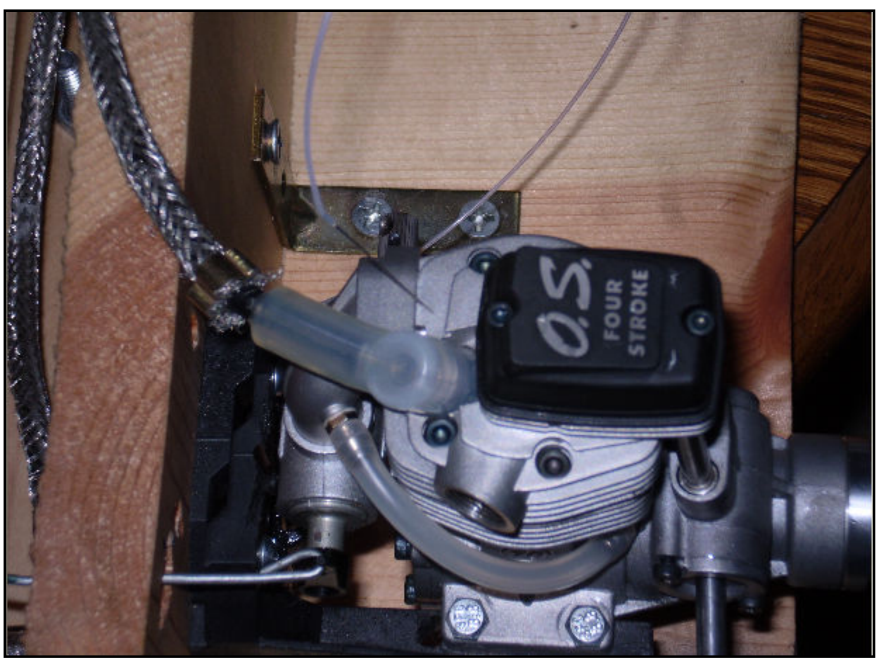


Figure 61. Engine with Spark System and Fuel Inlet

7.0 HYDROGEN SAFETY

The safety of hydrogen is known to be vital to the further development of the hydrogen economy. The development and introduction of hydrogen technologies, as well as the level of public acceptance of hydrogen applications, are presently being constrained by safety barriers. Hydrogen is perceived to be dangerous because it has properties that make its behavior during accidents different from that of most other combustible gases. It may cause material embrittlement and diffuses more easily through many conventional materials used for pipelines and vessels. Gaps that are normally small enough to seal other gases safely are found to leak hydrogen profusely. Unlike other combustible gases, it has a Joule-Thompson inversion temperature (i.e. the temperature leads to warming instead of cooling), which is well below that of many applications involving gaseous hydrogen. This makes hydrogen more inclined to ignition after sudden releases from high-pressure containment. When hydrogen's greatest safety asset, buoyancy, is not properly taken into account in the design of infrastructures and technologies for production, storage, transportation and consumption, it becomes more dangerous than conventional fuels such as gasoline, LPG and natural gas. Fortunately hydrogen has been used with great success for over 50 years in applications ranging from welding beams to launching NASA's shuttles.

Hydrogen safety is the most important function of this design. The benefits of having lower CO2 emissions do not outweigh a higher rate of accidents due to improperly handling hydrogen. When people go about routine work they can develop a relaxed attitude and a dull alertness, which can lead to horrible accidents. One of the root causes of hydrogen related accidents are that people view hydrogen like many other gases they are accustomed to using. Hydrogen simply acts different than other gases in use today. Without informing the inexperienced to the ever-present hazards of dealing with Hydrogen, lethargy and misconceptions deepen and the odds of an accident occurring can increase.

The sudden interest in using hydrogen is caused by the concern of global warming from greenhouse gas concentrations being increased due to human activity. One example is the CO2 emissions given off by gasoline burning engines. If the change was made from gasoline to hydrogen, they would only produce electricity (fuel cell application), heat, and pure water; noticeably reducing the carbon dioxide emissions

Properties of hydrogen are: it is odorless and tasteless making it very difficult to detect a leak. Its buoyancy, diffusivity, and small molecular size make it difficult to contain and its low radiant heat lowers the possibility of secondary fires. Some of the combustive properties consist of a wide range of flammability limits (4 – 74%), explosion limits (18.3 – 59.0), ignition energy (.02mJ), flame temperature (2045 deg C), and Stoichiometric air/fuel ratio (29%).

General types of hazards associated with the use of hydrogen can be characterized as physiological (frostbite, respiratory ailment, and asphyxiation), physical (phase changes, component failures, and embrittlement), and chemical (ignition and burning), or a combination of such hazards. The primary hazard is involuntarily producing a flammable or detonable mixture, leading to a fire or detonation. To avoid explosions it is best to avoid leaks inside the system and to the surroundings. Wherein, leaks can occur from deformed seals or gaskets, valve misalignment, or failures of flanges or the equipment. There is also the concern of storage vessel failures, ventilation, purging, vaporization system failure, condensation of air, and hydrogen embrittlement.

The primary safety concern for burning Hydrogen in an R/C engine is premature ignition. With hydrogen's lower ignition energy and wider flammability range premature ignition can occur when the fuel mixture in the combustion chamber becomes ignited before the spark plug ignites the mixture and results in an inefficient rough running engine. This form of premature ignition can be resolved by using a cold-rated spark plug and insuring that the fuel does not enter near the exhaust port (valve). Also if premature ignition occurs near the fuel intake valve and a flame travels back into the induction system it causes backfire conditions. If there is any non-burnt fuel that enters the crankcase through bypassing the piston rings there is a greater probability of it igniting in the crankcase and could be remedied with proper ventilation of the crankcase. When ignition within the crankcase occurs it will be a loud startling noise and the pressure within the crankcase will rise. One good way to protect against this is to use a pressure relief valve to stabilize the pressure. Lean mixtures of hydrogen are hard to ignite despite its large flammability limits and could cause a misfire in the engine, which increases unburned fuel and will cause more pollution than expected.

The first concern when dealing with Hydrogen Storage is the tank. Much development has been done over the years in tank development. One of the best tanks being developed right now is a carbon fiber reinforced 10,000psi compressed hydrogen tank that consists of a gas penetration barrier a high molecular weight polymer. The center layer of the tank is a carbon fiber-epoxy resin composite shell that is placed over the liner and acts as the gas pressure load-bearing component of the tank. The outer shell is placed on the tank for impact and damage resistance with a pressure regulator located inside the tank as well as a temperature sensor. Most of today's hydrogen tanks can withstand a drop from 90 ft in the trunk of a car with the only damage being surface marks.

Vaporization system failure occurs in the pipe ventilation system when the vapor build-up in a localized area is not released which can result in a fire or explosion. For example, many countries have building codes that require garages to have ventilation openings near the ground to remove gasoline vapors. As a result, even very slow releases of hydrogen in a poorly ventilated building will inevitably lead to the formation of an explosive mixture, initially at the ceiling-level

A present day comparison of hydrogen vehicles and gasoline vehicles results in shocking information. The storage tank on a gasoline car is nothing but annealed sheet metal and could bend under smaller forces than that of the three layered carbon-fiber reinforced hydrogen tanks. If a leak were started on both vehicles a gasoline engine car would continue to leak fuel until all the fuel has been leaked out, whereas the hydrogen tank would leak for only a short while because of 4 different leak protection devices: pressure release valves, excess flow valves, leak sensors, and fuel flow.

As long as the proper safety devices are implemented there will be no problems using Hydrogen for this project, as well as any other applications. Hydrogen has been safely produced, stored, transported, and used in large amounts in industry by following established standard practices. As long as these methods of production, storage, and use are properly followed, Hydrogen can be a safe fuel for use in many applications, with the added benefit of being completely environmentally friendly.

8.0 EXPECTED PERFORMANCE

The proposed design modifications for hydrogen fuel is expected to under perform the purchased engine which is set-up for a Nitromethane/methanol fuel mixture. For an ideal Otto cycle, the modified engine is expected to produce 26.9% more work per cycle using direct injected hydrogen fuel at wide open throttle assuming both engines run at stoichiometric air-to-fuel ratios (see calculations in Appendix A). It should be noted that direct injection is the most ideal fuel delivery system for hydrogen since it is injected after the intake valve is closed, allowing more air into the combustion chamber and eliminating backflash through and open intake valve.

The RC engine selected for modification was tested using a handheld tachometer to measure the rotational speed before the modifications were made. The results of these tests are:

Average Idle Speed:	**~3000 rpm**
Average WOT Speed	**~9000 rpm**

The expected results were obtained from calculations for an ideal Otto cycle with the respective fuel properties and delivery method, but factors such as timing loss will affect the actual results due to the difference in the fuel properties. The Otto cycle assumes that the heat release from the fuel is instantaneous, but in the actual cycle there is a loss in work output because this process is not instantaneous, known as time loss (indicated on the figure at right).

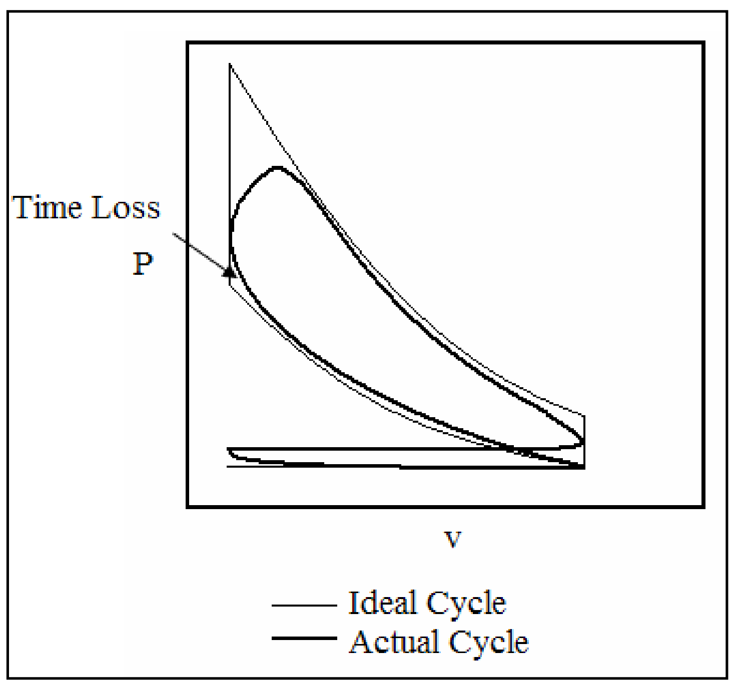


Figure 62. PV Diagram for Ideal Otto Cycle and Actual Cycle

9.0 CONCLUSIONS

Overall the designs developed in this report serve as a good solution to the problem presented. Although the modified engine was never able to be tested it serves as a well designed prototype for future development of this technology. These small R/C engines are very wasteful with fuel, and produce a lot of emissions. If these designs could ever actually be used on their respective aircraft, they would provide an efficient, clean, and reliable form of propulsion.

Contents:

9.1 Problems Encountered

The process of researching and developing a conversion that would be an effective means of running the engine on hydrogen went very well. Many problems were encountered, however, while trying to implement the conversion on the engine.

Lack of Micro-Machining Capabilities

Because of the small size of the selected engine, the parts needed were small as well. This proved to cause a problem given the lack of micro-machining capabilities at our disposal.

Camshaft

While trying to tap out the inside of the camshaft for the shaft extension, the tap became lodged inside of the camshaft and snapped off. Although backup camshafts had been ordered, the tap that broke was a specially made tap. It was a hard to find left-hand tap, and we were unable to procure one on such short notice.

To get around this it was decided to press-fit the shaft extension into the camshaft. The camshaft was drilled out and cleared off the tap piece. This worked, however it is not a sufficient enough hold to allow the engine to be run. Therefore, the engine would not be able to be tested with hydrogen, but would merely serve as a prototype of what the modified version would look like.

Housing

The housing that was designed to hold the valve and flywheel also proved to be too difficult to machine. It required precise measurements with very small tolerances, so that it would fit onto the engine correctly, and not cause the shaft to be off center. For these reasons the machine shop at our disposal declined to machine the parts.

Since the issue with the camshaft requires the engine to merely be an un-working prototype, it was decided to make the housing out of Balsa wood, with as close to the right dimensions as possible. This would allow at least a prototype for display purposes.

Hard to Find Parts

There were numerous parts that we were unable to obtain or took too long to obtain. These include the correct ignition for our chosen spark plug, for which we had to use a larger one and modify it for our purposes, and the specialty tap, which took too long to receive.

None of these problems represent deficiencies in the design, but rather hindered us from creating a working prototype of the modified engine.

9.2 Recommendations

The design developed for this project is a viable working design. Given the right resources, a working prototype would have been built. Below are a list of recommendations for further development and ease of modification.

Camshaft

Ideally the camshaft and its extension would be machined out of one piece of metal. This would eliminate all the problems encountered while trying to mate the two. It would also allow for a smoother running engine, because when extending the camshaft it is very hard to get them to line up perfectly. If this is not done, it could cause the shaft to be off center, creating unwanted torque on the shaft, potentially leading to failure.

Housing

The housing designs in this report where developed assuming solid aluminum as the working medium. This creates unwanted weight, and could potentially pull the shaft off center. It would be best if this housing could be designed with either a lighter material, or as a hollow shell, to reduce the tension on the shaft.

Lubrication

The lubrication methods suggested in this report are by no means the ways that these engines should be lubricated for repeated use. They were merely the best options given the resources available. Ideally, the engine would be developed with an attached oil sump system, as described in the lubrication section of the report. This would be the best means of lubricating the engine.

Engine Size

As is true with most applications, the larger that the engine is the easier it would be to design and implement modifications. A slightly larger engine would have provided more room for the components and would have been easier to design parts for.

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APPENDICES

Appendix A – Calculations

Appendix B – Detailed Part Drawings

Appendix C - Budget

Appendix A

Known:

Displacement Volume: $V_d := 11.5cm^3$

Density of Hydrogen: $\rho_H := 0.08376 \frac{kg}{m^3}$

Lower Heating Value of Hydrogen: $Q_{HV} := 119.93 \frac{kJ}{gm}$

Assumptions:

Constant Volume Specific Heat of Air: $c_v := 0.821 \frac{kJ}{kg \cdot K}$

Ratio of Specific Heats: $\gamma := 1.35$

Air inlet temperature: $T_i := 300K$

Air inlet pressure: $P_i := 1atm$

Assuming that there is no pressure loss in the intake flow when operating at wide open throttle (the engine selected has a short intake manifold, so the frictional losses in the flow are assumed to be low), then the pressure at the start of compression (P_1) is equal to the pressure at the inlet:

$P_1 := P_i$

$T_1 := T_i$

For the ideal otto cycle, compression and expansion are both isentropic processes, where:

$P_1 \cdot v_1^{\gamma} = P_2 \cdot v_2^{\gamma}$ and $T_1 \cdot v_1^{\gamma - 1} = T_2 \cdot v_2^{\gamma - 1}$

The pressure at P2 is:

$P_2 = P_1 \cdot \left(\frac{v_1}{v_2}\right)^{\gamma}$

– v_1 is at bottom dead center (BDC) while v_2 is at top dead center (TDC), so v_1/v_2 is equal to the compression ratio r_c.

- The manual that came with the 4 stroke engine that was chosen (O.S. Engines FS 70 II Surpass) for the conversion does not specify the compression ratio. An email reply from the distributor stated that the typical compression ratio for their engines was 9.1

$r_c := 9.1$

$P_2 := P_1 \cdot r_c^{\gamma}$

$P_2 = 1.997 MPa$

$$T_2 := T_1 \cdot r_c^{\gamma-1}$$

$$T_2 = 649.809\ K$$

For the ideal otto cycle, the fuel is ignited and burned instantaneously at TDC after the compression stroke (at a constant volume). The tempurature after combustion, T_3, can be found.

$$m_f \cdot Q_{HV} = m_m \cdot c_v \cdot (T_3 - T_2)$$

Where m_f is the mass of fuel (hydrogen) and m_m is the mass of the air-fuel mixture. The mass of the mixture can be found since it is an ideal gas.

$$P \cdot V = m \cdot R \cdot T \qquad R := \gamma \cdot c_v - c_v \qquad R = 0.287 \frac{kJ}{kg \cdot K}$$

The volume at BDC is: $V_c + V_d = V_{BDC} = V_1$ $\qquad r_c = \frac{V_c + V_d}{V_c} = 1 + \frac{V_d}{V_c}$

$$V_1 := \frac{V_d}{r_c - 1} + V_d \qquad V_c := \frac{V_d}{r_c - 1}$$

$$V_1 = 12.92\ cm^3$$

The mass of the air-fuel mixture is:

$$m_{air} := \frac{P_1 \cdot V_1}{R \cdot T_1}$$

$$m_{air} = 1.519 \times 10^{-5}\ kg$$

For direct injection fuel delivery, only air is present in the chamber at the end of the intake stroke . After the intake valve is closed, hydrogen is injected into the chamber during the compression stroke.

Directed Injection:

For a stoichiometric mix the air-to-fuel ratio is $AF := 34$

$$m_{hydrogen} := \frac{m_{air}}{AF} \qquad m_{hydrogen} = 4.466 \times 10^{-7}\ kg$$

$$T_{3DI} := \frac{m_{hydrogen} \cdot Q_{HV}}{(m_{air} + m_{hydrogen}) \cdot c_v} + T_2$$

$$T_{3DI} = 4.823 \times 10^3\ K$$

$$P_{3DI} := \frac{(m_{air} + m_{hydrogen}) \cdot R \cdot T_{3DI}}{V_c}$$

At point 3, the chamber volume is the clearance volume, V_c, since the piston is still at TDC.

$P_{3DI} = 15.261\,\text{MPa}$

The power stroke (process from 3 to 4) is isentropic for the ideal otto cycle.

$$T_{4DI} := T_{3DI}\cdot\left(\frac{1}{r_c}\right)^{\gamma-1}$$

$T_{4DI} = 2.227\times 10^{3}\,\text{K}$

$$P_{4DI} := P_{3DI}\cdot\left(\frac{1}{r_c}\right)^{\gamma}$$

$P_{4DI} = 774.246\,\text{kPa}$

For a gaseous pre-mixed solution (air-fuel mixture enters during intake stroke), the mass of air and the mass of hydrogen can be found knowing that hydrogen occupies 29.6 % of the chamber volume at stoichiometric air-to-fuel mixture (http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf).

$V_{hydrogen} := 29.6\%\cdot V_1$ $\quad m_h := \rho_H\cdot V_{hydrogen}$ $\quad m_h = 3.203\times 10^{-7}\,\text{kg}$

$V_{air} := (100\% - 29.6\%)\cdot V_1$ $\quad m_a := 1.207\,\frac{\text{kg}}{\text{m}^3}\cdot V_{air}$ $\quad m_a = 1.098\times 10^{-5}\,\text{kg}$

Carborated or Port Injection:

$$T_{3PI} := \frac{m_h\cdot Q_{HV}}{(m_a + m_h)\cdot c_v} + T_2 \qquad P_{3PI} := \frac{(m_a + m_h)\cdot R\cdot T_{3PI}}{V_c}$$

$T_{3PI} = 4.791\times 10^{3}\,\text{K}$ $\quad P_{3PI} = 10.956\,\text{MPa}$

Isentropic expansion from 3 to 4:

$$T_{4PI} := T_{3PI}\cdot\left(\frac{1}{r_c}\right)^{\gamma-1} \qquad P_{4PI} := P_{3PI}\cdot\left(\frac{1}{r_c}\right)^{\gamma}$$

$T_{4PI} = 2.212\times 10^{3}\,\text{K}$ $\quad P_{4PI} = 555.851\,\text{kPa}$

Appendix A

Ideal Net Work for Direct Injection:

$$W_{netDI} = W_{3to4} - W_{1to2}$$

$$W_{netDI} := \left(m_{air} + m_{hydrogen}\right)\cdot\left[\frac{R\cdot\left(T_{4DI} - T_{3DI}\right)}{1-\gamma} + \frac{R\cdot\left(T_2 - T_1\right)}{1-\gamma}\right]$$

$$W_{netDI} = 28.836\,J$$

Ideal Net Work for Carborated or Port Injection:

$$W_{netPI} := \left(m_a + m_h\right)\cdot\left[\frac{R\cdot\left(T_{4PI} - T_{3PI}\right)}{1-\gamma} + \frac{R\cdot\left(T_2 - T_1\right)}{1-\gamma}\right]$$

$$W_{netPI} = 20.68\,J$$

$$\%difference := \frac{W_{netDI} - W_{netPI}}{W_{netPI}}$$

$\%difference = 39.437\,\%$

Direct Injection has the potential to increase the amount of net work per cycle by 39.437% over a carborated fuel delivery system.

$Q_{inDI} := m_{hydrogen}\cdot Q_{HV}$ $\qquad Q_{inDI} = 53.566\,J$

$Q_{inPI} := m_h\cdot Q_{HV}$ $\qquad Q_{inPI} = 38.416\,J$

$\frac{W_{netDI}}{Q_{inDI}} = 0.538$ $\qquad \frac{W_{netPI}}{Q_{inPI}} = 0.538$

$\frac{m_{hydrogen} - m_h}{m_h} = 39.437\,\%$

Likewise, 39.437% more hydrogen is required per cycle for stoichiometric direct injection.

Appendix A

The intended fuel for the engine selected is a nitromethane and methanol mixture. The stoichiometric air-to-fuel ratio and lower heating value for varying mixtures can be found on page 24(of "Analysis of combustion in a small homogeneous charge compression assisted ignition engine" by H. Ma, K. Kar, R. Stone, and H. Thorwarth (http://www.eng.ox.ac.uk/ice/papers/IJERSmallEnginePaper.pdf). The intended fuel is a 10% nitromethane mixture,

Lower Heating Value of Methanol: $Q_{HVmethanol} := 19.6\frac{MJ}{kg}$

LHV multiplier at 10% nitromethane: $a := 0.96$

Stoichiometric air-to-fuel ratio at 10% nitromethane: $AF_{rcfuel} := 5.77$

Lower Heating value of rc fuel mixture:

$Q_{HVrcfuel} := a \cdot Q_{HVmethanol}$ $\qquad Q_{HVrcfuel} = 18.816\frac{MJ}{kg}$

The temperatures and pressures are the same as those calculated for the hydrogen fuel at the start and end of compression (points 1 and 2) because the fuel has not been yet been ignited.

$T_1 = 300\,K$ $\qquad P_1 = 101.325\,kPa$

$T_2 = 649.809\,K$ $\qquad P_2 = 1.997\,MPa$

Knowing that $m_{fuel} \cdot Q_{HV} = m_{mixture} \cdot c_v \cdot (T_3 - T_2)$ T_3 can be calculated.

$m_{mixture} = m_{air} + m_{fuel}$ $\qquad AF = \frac{m_{fuel}}{m_{air}}$

$\frac{m_{mixture}}{m_{fuel}} = AF + 1$ $\qquad m_m := \frac{P_1 \cdot V_1}{R \cdot T_1}$

$Q_{HVrcfuel} = (AF + 1) \cdot c_v \cdot (T_3 - T_2)$

$T_{3rcfuel} := \frac{Q_{HVrcfuel}}{(AF_{rcfuel} + 1) \cdot c_v} + T_2$ $\qquad P_{3rcfuel} := \frac{m_m \cdot R \cdot T_{3rcfuel}}{V_c}$

$T_{3rcfuel} = 4.035 \times 10^3\,K$ $\qquad P_{3rcfuel} = 12.402\,MPa$

As explained before, the expansion process is ideally isentropic, so:

$$T_{4rcfuel} := T_{3rcfuel} \cdot \left(\frac{1}{r_c}\right)^{\gamma-1} \qquad P_{4rcfuel} := P_{3rcfuel} \cdot \left(\frac{1}{r_c}\right)^{\gamma}$$

$$T_{4rcfuel} = 1.863 \times 10^{3}\,\mathrm{K} \qquad P_{4rcfuel} = 0.629\,\mathrm{MPa}$$

Net Indicated Work per Cycle:

$$W_{netrcfuel} = W_{3to4} - W_{1to2}$$

$$W_{netrcfuel} := m_m \cdot \left[\frac{R\cdot\left(T_{4rcfuel} - T_{3rcfuel}\right)}{1-\gamma} + \frac{R\cdot\left(T_2 - T_1\right)}{1-\gamma}\right]$$

Ideal Net Work per Cycle:

RC Fuel Blend: $W_{netrcfuel} = 22.721\,\mathrm{J}$

Carborated Hydrogen Fuel Delivery: $W_{netPI} = 20.68\,\mathrm{J}$

Direct Injection Hydrogen Fuel Delivery: $W_{netDI} = 28.836\,\mathrm{J}$

These values are for ideal net work (before mechanical losses), which provides the maximum expected performance of the engine. The real cycle will have losses in timing (fuel does not burn instantaneously at a constant volume), heat loss to the cylinder walls and exhaust blowdown loss (exhaust valve starts opening before bottom dead center causing a pressure drop toward atmospheric pressure). Though the values are the absolute maximum possible for the assumptions made at wide open throttle and the actual indicated work (as seen at the cylinder before mechanical losses) will be lower, they provide a good estimate of how each fuel or method will perform in comparison to one another. As decided earlier, direct injection of hydrogen into the cylinder after the intake stroke will provide more work per cycle than a carbureted hydrogen engine of the same characteristics (found to produce 39.4% more work than the carbureted system for an ideal cycle at stoichiometric mixtures). The direct injection method is also expected to perform better than the than the same engine with the current RC fuel blend set-up (nitromethane and methanol blend) by up to 26.9%. The carbureted hydrogen system would be expected to have a 8.98% reduction in ideal work per cycle.

Program for Determining Pressure Regulator Setting for Correct Fuel Injection

Inputs

Intake Pressure: $P_1 := 0.5\text{atm}$

Engine Speed: $\omega := 3500\text{RPM}$

Known

Displacement Volume: $V_d := 11.5\text{cm}^3$

LHV of Hydrogen: $Q_{HV} := 119.93 \frac{\text{kJ}}{\text{gm}}$

Gas Constant for Hydrogen: $R := 4160 \frac{\text{J}}{\text{kg}\cdot\text{K}}$

Assumed Air Inlet Temperature: $T_1 := 300\text{K}$

Specific Heat of Air (Cv): $c_v := 0.821 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$

Ratio of Specific Heats: $\gamma := 1.4$

Compression Ratio: $r_c := 9.1$

Calculations

Mass of Air in Cylinder:

$$R_{air} := 0.287 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$V_1 := \frac{V_d}{r_c - 1} + V_d \qquad V_1 = 12.92\,\text{cm}^3$$

$$m_{air} := \frac{P_1 \cdot V_1}{R_{air} \cdot T_1} \qquad m_{air} = 7.602 \times 10^{-6}\,\text{kg}$$

$$m_{hydrogen} := \frac{m_{air}}{34} \qquad m_{hydrogen} = 2.236 \times 10^{-7}\,\text{kg}$$

V_1 is the volume of the chamber at bottom dead center. The mass of air inside that volume can be determined from the ideal gas equation. The mass of hydrogen can be determined knowing that the stoichiometric air-to-fuel ratio is 34.

Period for One Rotation (Camshaft):

$$T := \frac{2}{\omega}$$

$$T = 0.034\ s$$

The camshaft runs at half of the speed of the drive shaft.

The vavle is open for 60 degrees of the camshaft rotation, so the time the valve is open is:

$$T_i := \frac{60}{360} \cdot T$$

$$T_i = 5.714 \times 10^{-3}\ s$$

Average Mass Flow Rate:

$$m' := \frac{m_{hydrogen}}{T_i}$$

$$m' = 3.913 \times 10^{-5}\ \frac{kg}{s}$$

Drive Pressure:

$$\gamma_h := 1.41$$

$$A_e := \frac{(0.008in)^2}{4} \cdot \pi$$

A_e is the exit area, which is determined from the diameter of the syringe that was placed in the head of the engine.

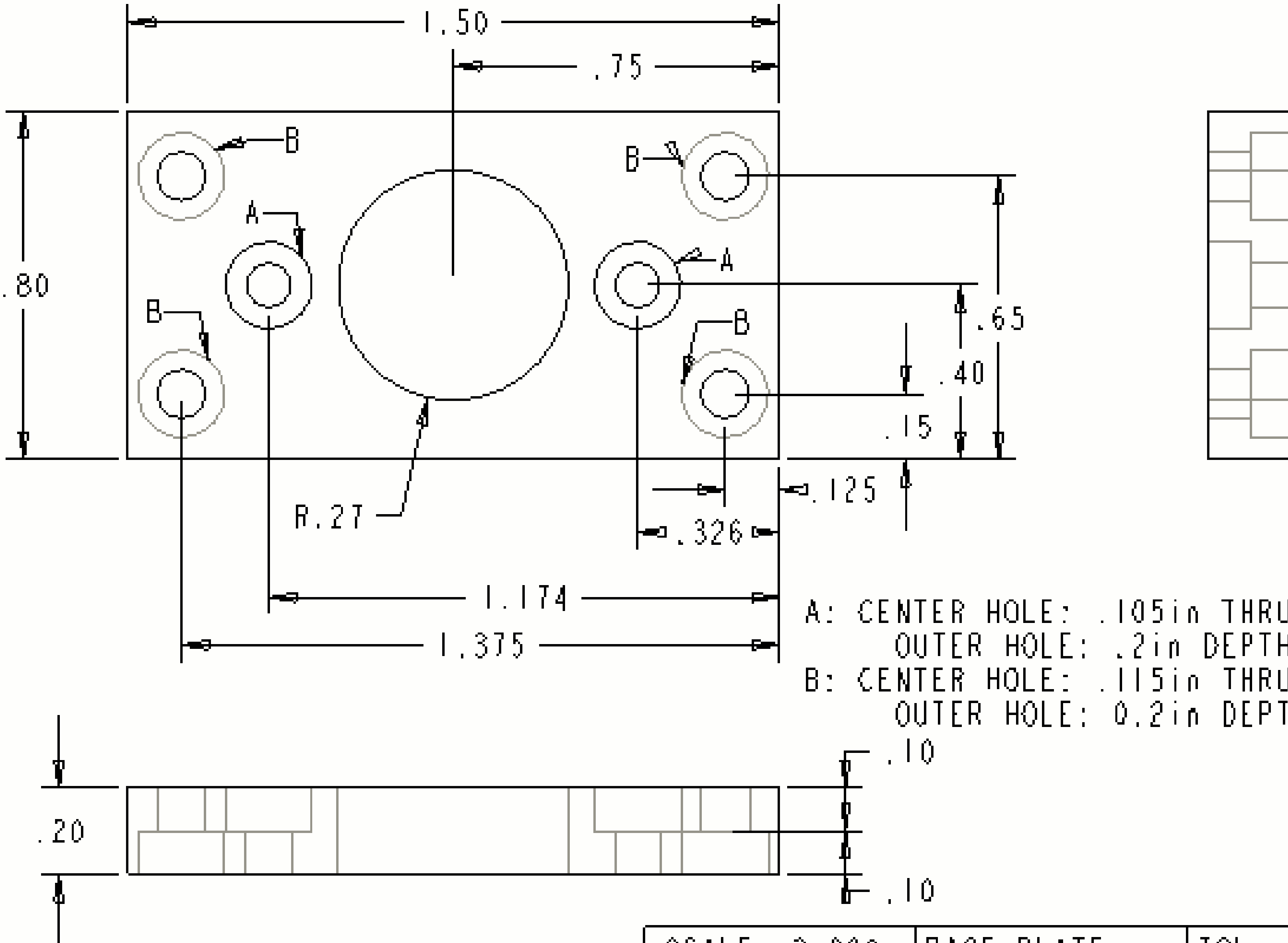
$$P_0 := \frac{m'}{A_e \cdot \sqrt{\frac{\gamma_h}{R \cdot T_1}} \cdot \left(\frac{2}{\gamma_h + 1}\right)^{\frac{\gamma_h+1}{2 \cdot (\gamma_h - 1)}}}$$

$$P_0 = 284.814\ psi$$

P_0 is the pressure regulator setting needed on the hydrogen tank for stoichiometric combustion.

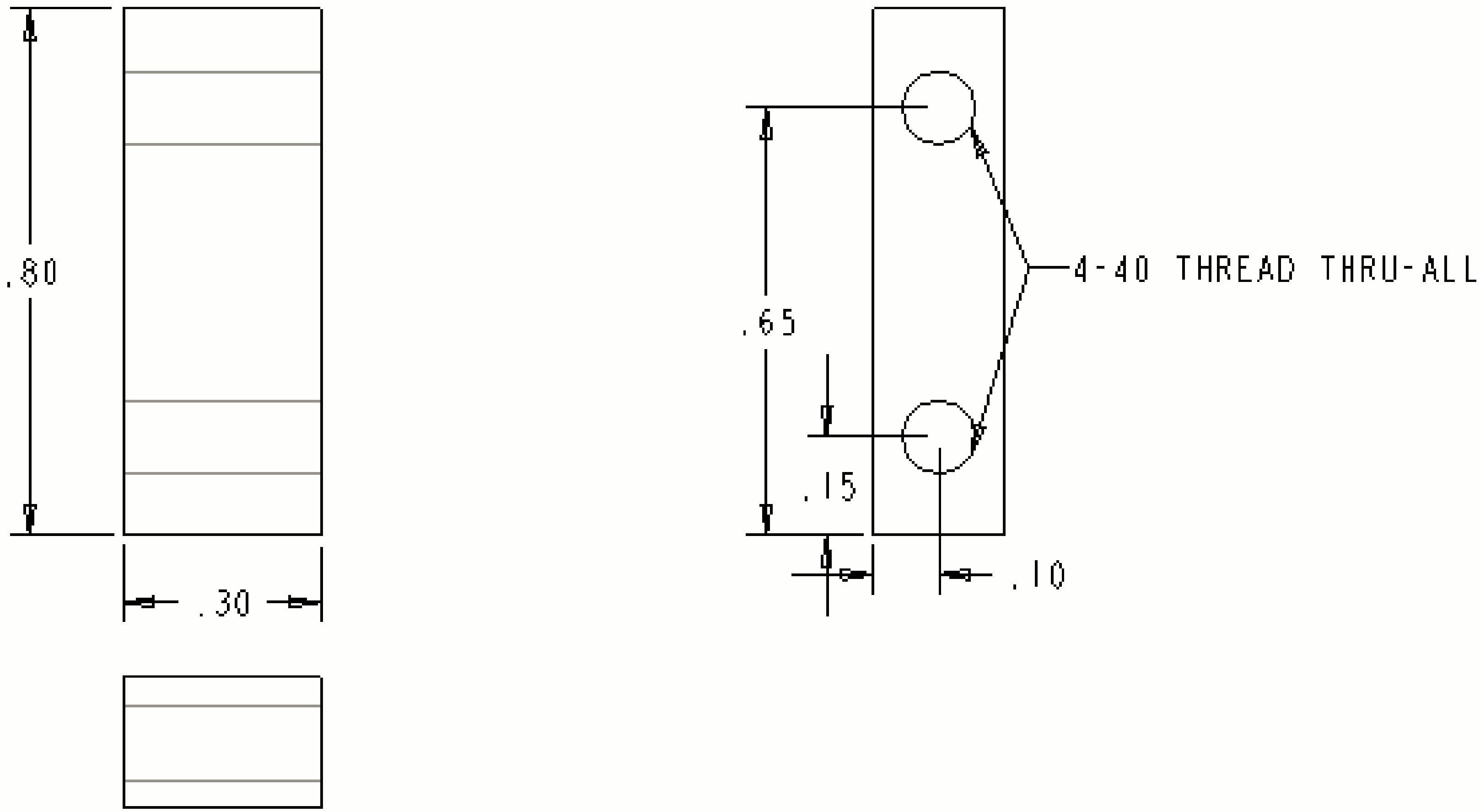
Appendix B

The following pages consist of the detailed part drawings for the various components that need to be machined.

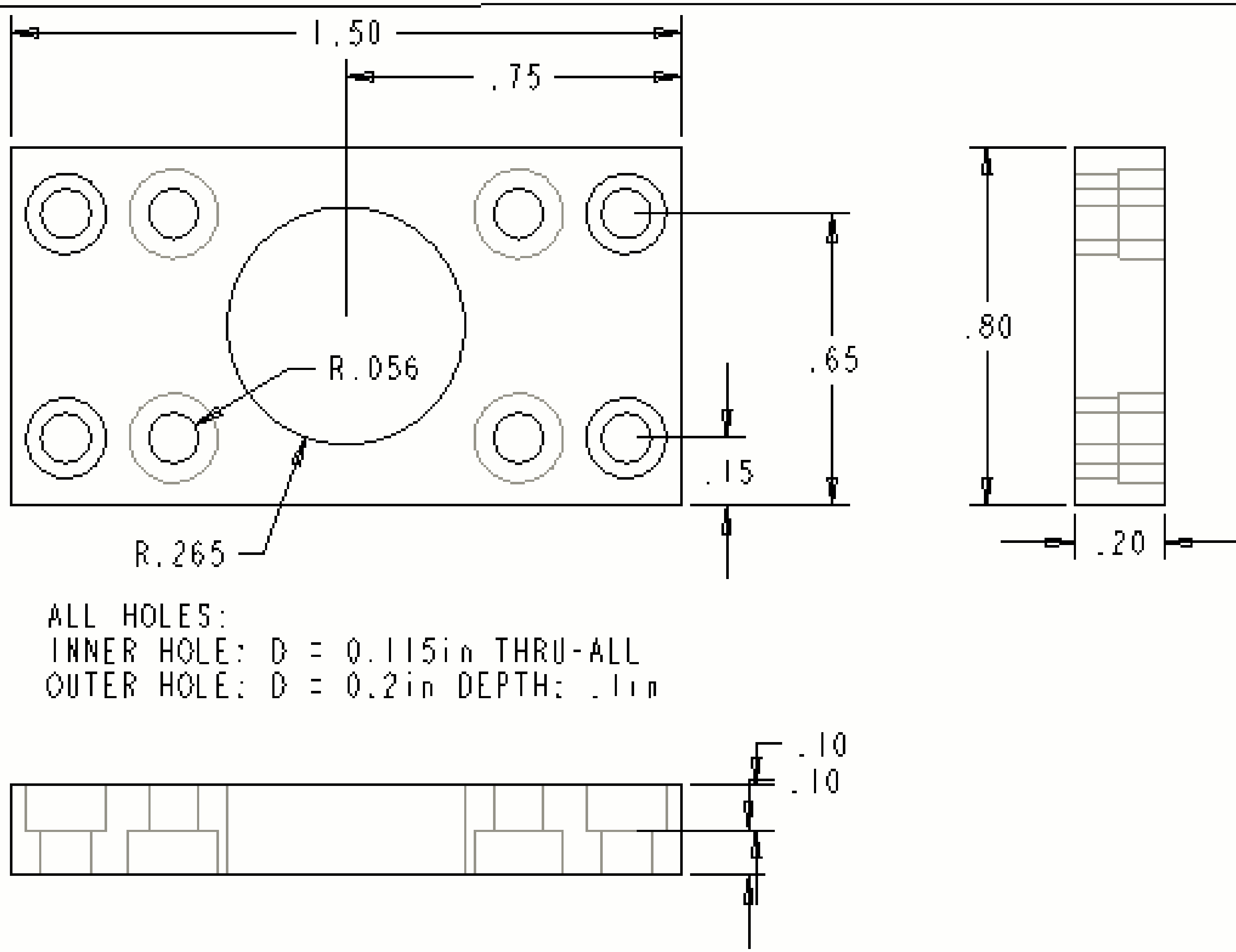


A: CENTER HOLE: .105in THRU-ALL
OUTER HOLE: .2in DEPTH: .1in
B: CENTER HOLE: .115in THRU-ALL
OUTER HOLE: 0.2in DEPTH: .1in

SCALE 3.000	BASE PLATE	TOL: ±0.002in
	PART #:	1 OF 8
GROUP 13	DRAWING #:	1 OF 9

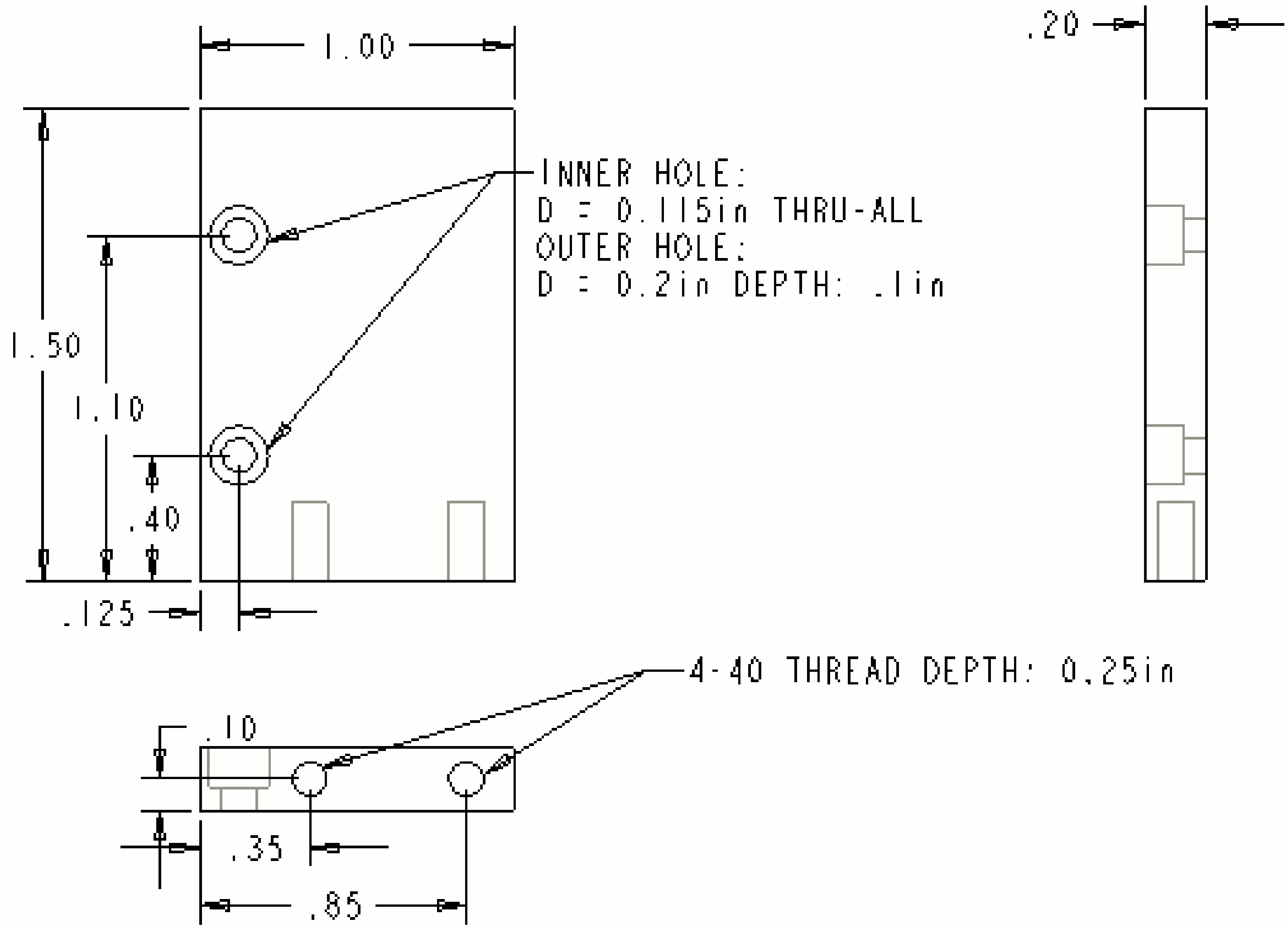


SCALE 4.000	FLYWHEEL WALL	
	PART#:	2 OF 8
GROUP 13	DRAWING#:	2 OF 9

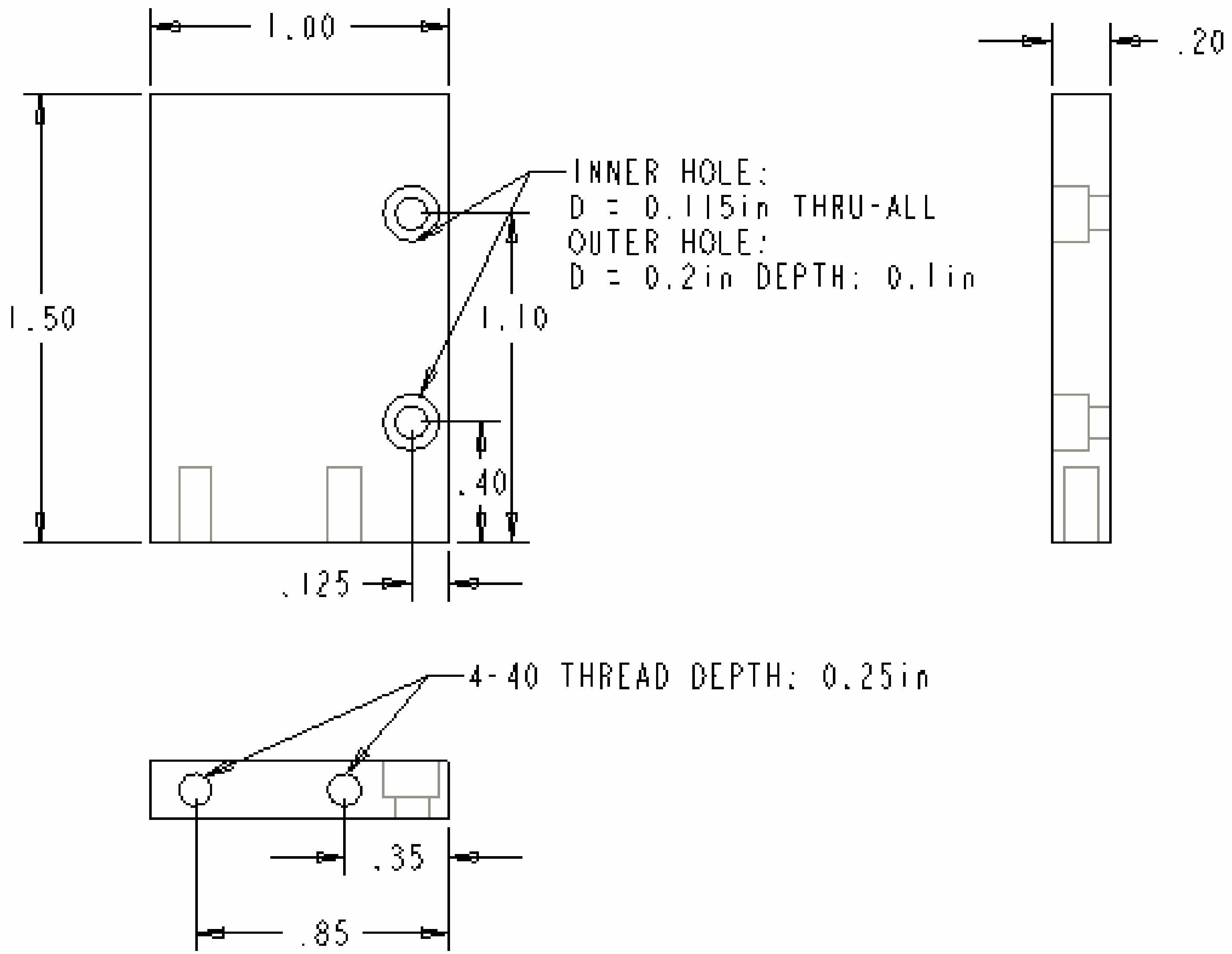


ALL HOLES:
INNER HOLE: D = 0.115in THRU-ALL
OUTER HOLE: D = 0.2in DEPTH: .1in

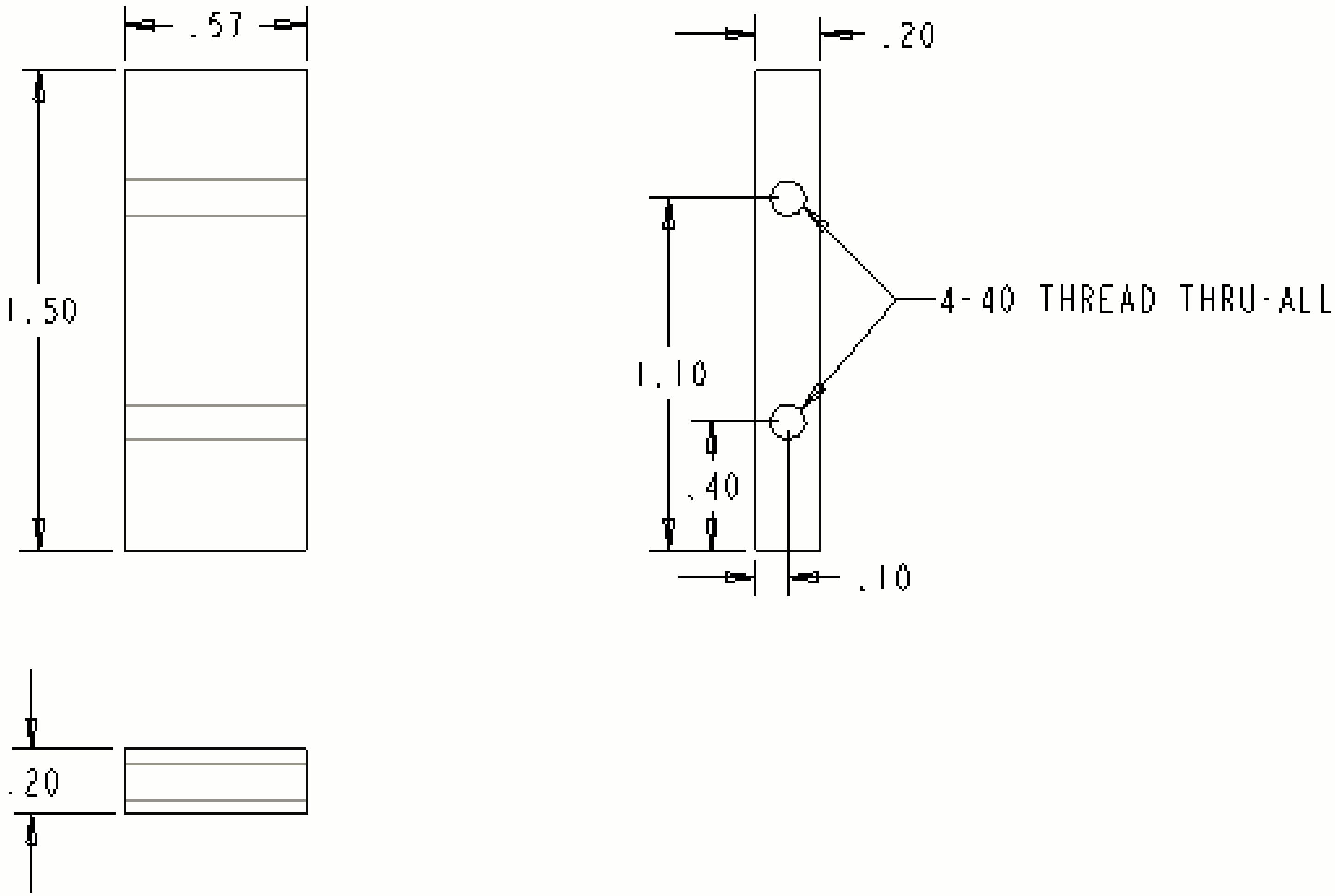
SCALE 3.000	TOP PLATE	TOL: ±0.002in
	PART #:	3 OF 8
GROUP 13	DRAWING #:	3 OF 9



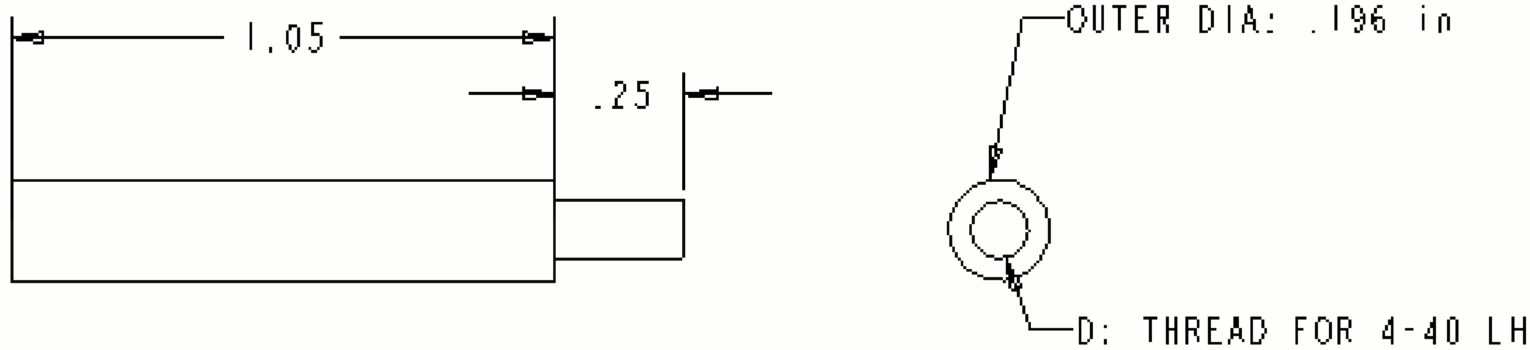
SCALE 2.000	L VALVE WALL	TOL: ±0.002in
	PART#:	4 OF 8
GROUP 13	DRAWING#:	4 OF 9



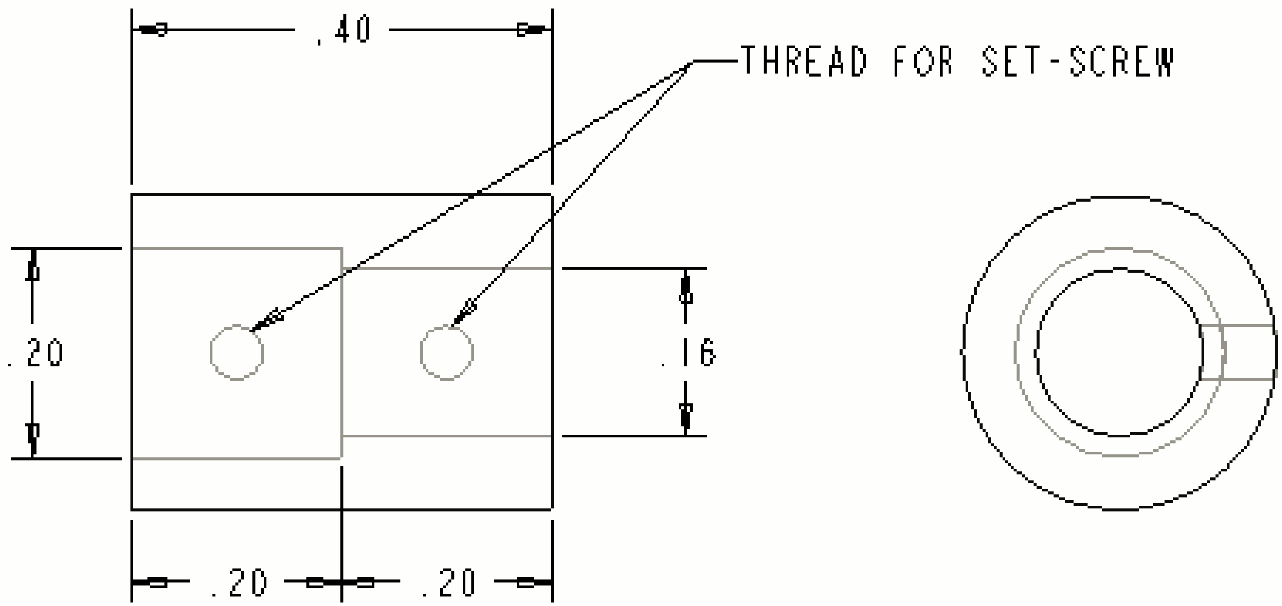
SCALE 2.000	R VALVE WALL	TOL: ±0.002in
	PART#:	5 OF 8
GROUP 13	DRAWING#:	5 OF 9



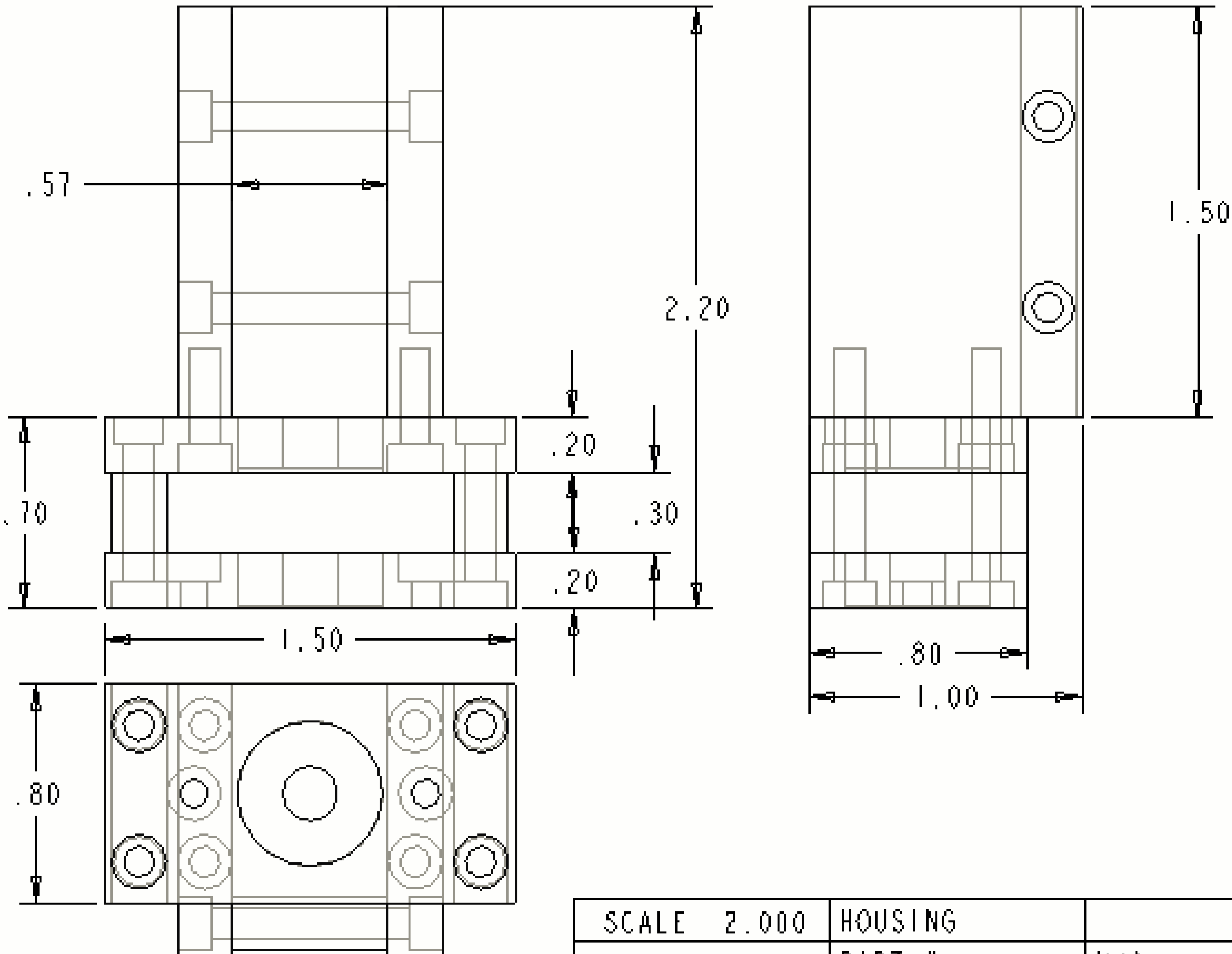
SCALE 2.000	B VALVE WALL	
	PART#:	6 OF 8
GROUP 13	DRAWING#:	6 OF 9



SCALE 3.000	SHAFT	
	PART#:	7 OF 8
GROUP 13	DRAWING#:	7 OF 9



SCALE 6.000	CONNECTOR	
	PART#:	8 OF 8
GROUP 13	DRAWING#:	8 OF 9



SCALE 2.000	HOUSING	
	PART #:	N/A
GROUP 13	DRAWING #:	9 OF 9

Appendix C

BUDGET

Items Purchased	Price ($)		Starting Budget
2 Stroke Engine	210		1500
4 Stroke Engine	210		
Engine Mount	5		
Fuel Lines	0.5		
Fuel Tank	6		
Fuel (Nitromethane)	3		
Electric Starter	70		
Electronic Ignition/with timing sensor and magnet	80		
Valve (Swagelok)	80		
Misc. Screws	10		
Stock Aluminum	10		
Extra Camshafts (50 each)	100		
Hypodermic Needle	Free		
Tubing	Free		
Spark plug	20		
Graphite Lubrication	10		
Oil	6		
Total	820.5		
Remaining Budget	679.5		