May 12, 2010
Calvin College
ENGR 340

Andrew DeJong
Marc Eberlein
John Mantel
Tim Opperwall
Jim VanLeeuwen
Executive Summary

Fossil fuels are being used at an alarming rate and unconventional methods need to be considered to help reduce the dependency on these fuels. The primary goal of this project is to increase the efficiency of a standard internal combustion engine. The six stroke engine is a unique opportunity for improving the efficiency and sustainability of engines. A four stroke engine has been modified to a six stroke engine by adding a steam cycle; such that the engine (1) intakes, (2) compresses, (3) combusts, (4) exhausts, (5) injects water, (6) re-exhausts. The rapid vaporization of the water during the fifth stroke is similar to the combustion of the gasoline. The combustion converts chemical energy into usable power, and likewise, the vaporization of water converts waste heat energy into usable power. By harnessing waste heat, the added strokes effectively reduce fuel consumption, and therefore emissions, without significantly compromising on power.

The largest conversion has been replacing the traditional camshaft with electronically controlled components. This means that the camshaft driven valves have been replaced by linear-solenoid-driven valves controlled by a micro-processing engine control unit (ECU). The ECU calculates the exact position of the cylinder based on an optical driveshaft sensor which outputs a signal when the piston passes top dead center.

The second conversion has been to expand the electrically controlled four stroke engine to include two additional strokes: water injection and a second exhaust. A gasoline direct injection (GDI) injector has been converted to inject water instead of gasoline. This too is controlled by the ECU.

While both of these conversions have been fully designed, there is not a complete, working prototype. The design calls for the solenoids to push the core away from the solenoid coil, so that the force is highest when the core begins moving. This allows for the peak force to be at the beginning of the exhaust stroke. However, the push/pull solenoids provided by the manufacturer do not operate in a push manner. They are only capable of pulling the core towards the coil. That is, the solenoid is always weakest at the beginning of the stroke, and therefore unable to open the exhaust valve. A solenoid-assisting spring setup has been designed and installed which is able open the exhaust. However, this solenoid-spring setup is still not fast enough to open and close the valves at operating speed.
The total budget for this project was projected to be approximately $825. Since many of the ECU components had already been purchased through ENGR 315, the effective projected budget for ENGR 339 was $675. Of that budget, $673 was used, finishing the project $2 under budget.

In summary, the project finished under budget with a complete design and time constraints stalling the working prototype.
Table of Contents

I. Introduction .................................................................................................................. 1
   I.A. Team Introduction ................................................................................................. 1
       I.A.i. Tim Opperwall ............................................................................................... 1
       I.A.ii. John Mantel .................................................................................................. 1
       I.A.iii. Andrew DeJong ......................................................................................... 2
       I.A.iv. Marc Eberlein ............................................................................................. 2
       I.A.v. Jim VanLeeuwen ......................................................................................... 2
   I.B. Project Introduction .............................................................................................. 2
       I.B.i. The Energy Challenge .................................................................................... 2
       I.B.ii. The 6 Stroke Answer ................................................................................... 2

II. Problem Definition .................................................................................................... 3
   II.A. Design Requirements ......................................................................................... 3
       II.A.i. Design a 6 Stroke Engine ............................................................................. 3
       II.A.ii. Manufacture a 6 Stroke Engine ................................................................... 3
   II.B. Design Norms ..................................................................................................... 3
       II.B.i. Stewardship .................................................................................................. 4
       II.B.ii. Transparency ............................................................................................... 4
       II.B.iii. Safety ......................................................................................................... 4
   II.C. Prior Work .......................................................................................................... 4
       II.C.i. Existing Patents ............................................................................................ 5
       II.C.ii. Bruce Crower’s Engine .............................................................................. 5

III. Proposed Solution .................................................................................................... 6
   III.A. Project Management ......................................................................................... 6
       III.A.i. Task Deligations ......................................................................................... 6
       III.A.ii. Budget ....................................................................................................... 7

IV. Table 1. Final budget for the six stroke engine ..................................................... 8
   IV.A. Design ............................................................................................................... 8
       IV.A.i. Valve Control Designs ................................................................................. 8
       IV.A.ii. Solenoid Assisting Spring Design ............................................................. 19
List of Figures

Figure 1. Current gearing for camshaft. .......................................................... 9
Figure 2. The original four stroke camshaft. .................................................. 10
Figure 3. The original valve lift profile. .......................................................... 11
Figure 4. (a) The original gear reduction, and (b) the new gear reduction. .......... 12
Figure 5. The designed six stroke camshaft. ................................................ 13
Figure 6. A cutaway view of the crankcase modification design. ...................... 14
Figure 7. The MathCAD calculation for the exhaust force. .............................. 15
Figure 8. The MathCAD calculation for the required solenoid timing. ............... 16
Figure 9. An Autodesk Inventor model of the Ledex 5SF solenoid. ................... 16
Figure 10. Solenoid bracket design. ............................................................... 17
Figure 11. The solenoid setup. Solenoids act as valve actuators and replace the cam. 18
Figure 12. Core and solenoid detail, with the core in closed position. ................. 19
Figure 13. Force curves for springs and solenoids. ........................................ 21
Figure 14. Spring attachment mounts. ............................................................ 21
Figure 15. Spring mounts attached to solenoid bracket. ................................... 22
Figure 16. The original head for the engine. .................................................... 23
Figure 17. The new head with the intake valve open. ...................................... 24
Figure 18. The new valve seats. The inside chamfer matches the edge .............. 25
Figure 19. The new head. .............................................................................. 26
Figure 20. A non-production model inductive sensor. ...................................... 27
Figure 21. The Banner optical sensor. A light beam passes. ............................. 28
Figure 22. Wiring diagram for the Banner optical sensor. ............................... 28
Figure 23. The 1000 tooth encoder used to communicate engine speed to the ECU. .......... 29
Figure 24. The optical sensor and encoder bracket design. .................................................. 30
Figure 25. The dimensioned AutoCAD design for the optical sensor and encoder bracket. .... 30
Figure 26. The GDI injector chosen to inject water during the fifth stroke. ......................... 32
Figure 27. Water injection system using 100 psi air line in the Engineering Building. ............ 33
Figure 28. The water injector coupling to the pressurized water line. ............................. 33
Figure 29. Current requirement for GDI injector .............................................................. 35
Figure 30. Initial water injector circuit design ................................................................. 35
Figure 31. The Arduino microcontroller ............................................................................ 36
Figure 32. Crydom relays used between microcontroller and high power components. ....... 38
Figure 33. Crydom relay wiring diagram .......................................................................... 38
Figure 34. The full circuit diagram for the proposed six stroke engine. ............................. 39
Figure 35. The encoder wiring diagram for the ECU. ....................................................... 40
Figure 36. The optical sensor wiring diagram for the ECU. ............................................. 40
Figure 37. The solenoid relay wiring diagram for the ECU .................................................. 41
Figure 38. The injector relay wiring diagram for the ECU. .................................................. 41
Figure 39. The microprocessor wiring diagram for the ECU ............................................. 42
Figure 40. The home-made circuit board that houses the microprocessor and the solenoid relays. Similar boards have been made for the injector relay, the encoder circuit, and the optical sensor circuit. ............................................................................................................. 43
Figure 41. Output data from the ECU for 4-Stroke cycle .................................................. 44
Figure 42. Output data from the ECU for 6-Stroke cycle .................................................. 45
Figure 43. An example PV diagram generated by the EES program for a similar six stroke engine. ....................................................................................................................................................................................... 47
Figure 44. The Lotus setup for the one cylinder, four stroke engine .................................. 48
Figure 45. The Lotus building environment and engine building interface. ....................... 48
Figure 46. Valve lift as a function of shaft angle ............................................................... 49
Figure 47. Lotus valve and piston simulation graphic ....................................................... 49
Figure 48. Lotus results window .................................................................................... 50
Figure 49. Lotus graphical results plot  ............................................................................. 51
List of Tables

Table 1. Final budget for the six stroke engine................................................................. 8
Table 2. Wire signals for encoder ..................................................................................... 29
Table 3. Board and pin specifications for the Arduino microcontroller.......................... 37

List of Acronyms

BDC      Bottom Dead Center (piston location)
DC       Direct Current
ECU      Engine Control Unit
EES      Engineering Equation Solver
GDI      Gasoline Direct Injection
IC       Internal Combustion
MIG      Metal Inert Gas
TDC      Top Dead Center (piston location)
VDC      Voltage of a Direct Current
I. Introduction

I.A. Team Introduction

From left: Tim Opperwall, John Mantel, Andrew DeJong, Marc Eberlein, and Jim VanLeeuwen.

I.A.i. Tim Opperwall

Timothy Opperwall is from Grandville, Michigan and will be graduating with a Bachelor’s Degree in Engineering with a mechanical concentration. He is attending graduate school at Purdue University to study mechanical engineering.

I.A.ii. John Mantel

John Mantel is from Chelsea, Michigan and will be graduating with a Bachelor’s Degree in Engineering with a mechanical concentration. He is employed part time at ControlNET and will continue on to full employment after graduation.
I.A.iii. Andrew DeJong

Andrew DeJong is from Grand Rapids, Michigan and will be graduating with a Bachelor’s Degree in Engineering with a mechanical concentration. He will be attending George Washington University for graduate work in mechanical systems.

I.A.iv. Marc Eberlein

Marc Eberlein is from Jamestown Township, Michigan and will be graduating with a Bachelor’s Degree in Engineering with a mechanical concentration. He is currently employed at Highlight Industries and will continue working there full time after graduation.

I.A.v. Jim VanLeeuwen

Jim VanLeeuwen is from Jenison, Michigan and will be graduating with a Bachelor’s Degree in Engineering with a mechanical concentration. He is currently participating in an internship program at Perrigo Company and will be seeking full time employment after graduation.

I.B. Project Introduction

I.B.i. The Energy Challenge

The modern world is driven by fossil fuels. Consequently, society has been consuming exhaustible resources at an ever increasing rate. There are many possible long term solutions including nuclear, hydroelectric, solar and geothermal energy sources. However, these solutions cannot be realistically implemented quickly and effectively. In the short term, unconventional and hybrid solutions must be implemented to reduce the consumption of fossil fuels and provide more valuable time for the long term solutions to be implemented.

I.B.ii. The 6 Stroke Answer

To further the research in short-term, unconventional solutions, a one cylinder, four-cycle, 16-horsepower, internal combustion engine has been modified with the goal of higher efficiency. A four stroke engine has been modified to a six stroke engine by adding a steam cycle, such that the engine (1) intakes, (2) compresses, (3) combusts, (4) exhausts, (5) injects water, (6) re-exhausts. The rapid vaporization of the water during the fifth stroke is similar to the combustion of the gasoline. The combustion converts chemical energy into usable power, and likewise, the vaporization of water converts waste heat energy into usable power. By
harnessing waste heat, the added strokes effectively reduce fuel consumption, and therefore emissions, without significantly compromising on power.

II. Problem Definition

II.A. Design Requirements

The goal of this project is to increase the efficiency and sustainability of a standard internal combustion engine. Since the path to this goal is long, it has been broken down into two intermediate goals.

II.A.i. Design a 6 Stroke Engine

In accordance with the transparency design norm discussed below, the design for the six stroke engine must be usable by future design and research groups. Consequently the design must include detailed specifications, diagrams, and drawings such that any knowledgeable engineer could pick up the design and begin to manufacture the engine. The designed engine must follow the six strokes listed above and use the third and fourth strokes to produce usable power in the driveshaft.

II.A.ii. Manufacture a 6 Stroke Engine

To verify that a design for a six stroke engine works, the engine must be built. This may happen through modifications of a current engine, or by manufacturing new parts. The operating engine must follow the six strokes listed above and use the third and fourth strokes to produce usable power in the driveshaft.

II.B. Design Norms

Just as design requirements specify physical guidelines and requirements for the project, design norms specify moral and ethical guidelines and requirements. As Professors Gayle E. Ermer and Steven H. VanderLeest explain, “Normative design attempts to balance design trade-offs not only among technical constraints but also among ethical constraints. Designing to such norms forces the engineer to consider the broader impact of the design on the society in which it
will be embedded.”

This team is dedicated to considering both physical and moral requirements for the finished product and its design.

II.B.i. Stewardship

The design must use the Earth’s resources in a careful, conservative manner. Proper stewardship of these resources means minimizing economic, material, and energy waste. The way fuels are currently used can be improved to better protect resources. Increasing fuel and thermal efficiency is one way the team can minimize economic and energy waste.

II.B.ii. Transparency

This project is part of larger research with the goal of greater efficiency. Withholding data and calculations, or reporting falsified or incomplete data, is not conducive to advancing research. Researchers and users of this technology need to know exactly what has been done and what the results are. Consequently, the design must be thoroughly documenting all the calculations and modifications. This documentation is presented in this report.

II.B.iii. Safety

The design must maintain the current level of physical safety expected with small engines. Understanding that there is some inherent risk involved with combustion, the six stroke engine must in no way decrease the safety of the manufacturers, assemblers, end users, or anyone other person. No part of the engine can create significant risk due to failure during normal operation.

II.C. Prior Work

The concept of using water to increase the efficiency and power of an internal combustion (IC) engine is not new. Patents have been awarded to inventors for their ideas and work on six stroke engines since the early twentieth century. However, there has been no documented attempt to build a working six stroke engine until recently by Bruce Crower.

---

http://soa.asee.org/paper/conference/paper-view.cfm?id=16995
II.C.i. Existing Patents

II.C.i.a. US Patent 1339176 – May 4, 1920

Leonard H Dyer patented the basic idea of using a water injecting fifth stroke to increase efficiency and simplify the cooling of an internal combustion engine.\(^2\)


Robert C Tibbs expanded on Dyer’s patent to include a piston with a higher heat capacity and an exhaust system that condenses and filters the water after it is exhausted from the cylinder.\(^3\)

II.C.i.c. US Patent 4736715 – April 12, 1988

Gregory J. Larsen patented a six stroke engine that supercharges and reheats the intake air. The two intake ports for the cylinder are cam actuated.\(^4\)


David M Prater patented a six stroke engine that contains the combustion products in a separate heat regenerator, injects water into the regenerator, and then opens the regenerator to the cylinder, providing another power stroke.\(^5\)

II.C.i.e. US Patent 6311651 – November 6, 2001

Satnarine Singh patented a six stroke engine with a computer controlled water injection system. The patent calls for a turbine that removes additional energy from the exhaust steam and a condenser that recycles the used water.\(^6\)

II.C.ii. Bruce Crower’s Engine

Bruce Crower, owner of Crower Cams and Equipment Company, modified a four stroke diesel engine to run a six stroke cycle similar to the one proposed in this project. His ran for over


\(^3\) Ibid.

\(^4\) Ibid.

\(^5\) Ibid.

\(^6\) Ibid.
an hour and was only warm to the touch. Crower was not available for comment due to medical complications.

III. Proposed Solution

III.A. Project Management

III.A.i. Task Deligations

Tim Opperwall and Andrew DeJong collaborated on much of their work, which consisted heavily of project managing and designing and assembling the engine control unit (ECU). From a project management standpoint, they acted as team leaders and organized much of the scheduling and budgeting of the project. They worked to keep team members accountable to their respective tasks and tried to keep the project running smoothly by quickly moving team members to new assignments at task completion. Along with project management, Tim and Andrew completed all of the work on the ECU. They worked together to design and assemble all of the hardware, including the circuit layout, wire placement and soldering, power supply, and signal monitoring from the sensor and encoder to the solenoids and water injector. In addition to the ECU hardware, Tim designed and wrote the signal processing software for the Arduino microcontroller, using C programming language. He also designed and implemented the spring option to increase solenoid speed. Andrew completed thermodynamic calculations to assist in the design for the engine.

Marc Eberlein was responsible for the design of the new cylinder head. He designed the head in AutoCAD and selected and purchased a block of aluminum for the head material. Highlight Industries, Marc’s employer, collaborated with him to machine the new cylinder head. Furthermore, Marc designed valve seat and stem placements in the new cylinder head. Marc also designed and built the solenoid bracket that mounts onto the cylinder head and ordered the optical sensor and encoder.

______________________________


http://www.autoweek.com/article/20060227/FREE/302270007
Jim VanLeeuwen was responsible for the design of the water injection system. He selected a water injector and a hydraulic pump to supply back pressure for the injector. He assembled the water injection system and injector pressure control. Jim also selected the solenoids and collaborated with Marc Eberlein to mount them on the brackets that Marc assembled. Jim also collaborated with Marc concerning dynamometer testing of the engine.

John Mantel was responsible for the first revision of the sensor bracket design and assembly. John was also responsible for the original starter motor assembly. He also worked on engine simulation, using LOTUS, an engine simulation program, to verify team design calculations.

**III.A.ii. Budget**

Table 1 shows the final budget for the project. The total budget for this project was projected to be approximately $825. Since many of the ECU components had already been purchased through ENGR 315, the effective projected budget for ENGR 339 was $675. Of the budget $673 was used, finishing the project $2 under budget.
Table 1. Final budget for the six stroke engine.

<table>
<thead>
<tr>
<th>Item</th>
<th>Purchased by ENGR 315</th>
<th>Purchased by ENGR 340</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>$0</td>
<td></td>
</tr>
<tr>
<td>Electric Valves</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ledex Solenoids (x4)</td>
<td>$271</td>
<td></td>
</tr>
<tr>
<td>Crydom Relays (x4)</td>
<td>$79</td>
<td></td>
</tr>
<tr>
<td>30&quot; Threaded Rod</td>
<td>$5</td>
<td></td>
</tr>
<tr>
<td>Compression Springs(X2)</td>
<td>$39</td>
<td></td>
</tr>
<tr>
<td>Universal Connectors (x2)</td>
<td>$30</td>
<td></td>
</tr>
<tr>
<td>Camshaft Position Sensor</td>
<td>$42</td>
<td></td>
</tr>
<tr>
<td>Banner Optical Sensor</td>
<td>$23</td>
<td></td>
</tr>
<tr>
<td>Encoder (**borrowed)</td>
<td>$0</td>
<td></td>
</tr>
<tr>
<td>Water injection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GDI Injector</td>
<td>$0</td>
<td></td>
</tr>
<tr>
<td>Hydraulic System</td>
<td>$0</td>
<td></td>
</tr>
<tr>
<td>Crydom Relay</td>
<td>$34</td>
<td></td>
</tr>
<tr>
<td>Cylinder Head</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Block</td>
<td>$54</td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>$60</td>
<td></td>
</tr>
<tr>
<td>Control System</td>
<td>$100</td>
<td></td>
</tr>
<tr>
<td>Instrumentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouples</td>
<td>$50</td>
<td></td>
</tr>
<tr>
<td>Tooling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spark plug tap</td>
<td>$13</td>
<td></td>
</tr>
<tr>
<td>Reamer</td>
<td>$23</td>
<td></td>
</tr>
<tr>
<td>Approved Budget</td>
<td>--</td>
<td>$675</td>
</tr>
<tr>
<td>Final Budget</td>
<td>$150</td>
<td>$673</td>
</tr>
</tbody>
</table>

III.B. Design

The proposed design can be separated into five main sections: the valve control designs, head design, engine speed monitoring, water injection system design, and the ECU design. The first four sections have been analyzed individually with the fifth section, the ECU, connecting all the parts.

III.B.i. Valve Control Designs

To better design a new valve control system for the six stroke engine, the original four stroke valve control system must be known. Since the six stroke engine first operates the original
four strokes, the new system has been based off of the original camshaft. Two new valve control systems have been considered: an alternative six stroke camshaft, and solenoid driven valves.

### III.B.i.a. Original Camshaft

The unmodified engine utilizes a mechanical control of the engine cycles. The original angular speed of the camshaft is one-half that of the crankshaft, such that the camshaft rotates once for every two revolutions (or four strokes) of the crankshaft. This original gearing system is shown in Figure 1.

![Crankshaft and Camshaft](image)

*Figure 1. Current gearing for camshaft.*

The crankshaft of the unmodified engine has a 29 tooth beveled gear on the crankshaft mating to a 58 tooth beveled gear on the camshaft. The camshaft has two lobes, one for the intake valve and one for the exhaust valve. The camshaft is shown in Figure 2. Each lobe is in contact with a flat follower pushrod which moves a rocker arm inside of the head. The other side of the rocker arms pushes the valve inside of the cylinder. A valve spring returns the valve back to the original position.
Figure 2. The original four stroke camshaft.

To properly replicate the original four strokes in the new six stroke engine, the original camshaft has been reverse engineered to determine the proper valve lift profile, shown in Figure 3. This profile shows the valves’ lift at any angular position of the crankshaft. This has been found by attaching a wheel to the crankshaft with laser cut notches at every angle. At every five degree rotation of the crankshaft, the intake and exhaust valves’ lift has been recorded. These findings have been used to determine the necessary valve lift in the six stroke valve control system design.
III.B.i.b. Alternative 6 Stroke Camshaft

A new camshaft and gearing system has been designed for the six stroke engine. As discussed previously, the original camshaft is geared to turn one revelation every two revolutions (or four strokes) of the crankshaft. The six stroke camshaft has been designed to turn one revolution every three revolutions (or six strokes) of the crankshaft. Being a pushrod engine, the camshaft is geared directly to the crankshaft. This makes it impossible to change the number of teeth on each shaft to achieve the correct speed due to size constraints. Because of this, the design calls for a third shaft to be installed and a double reduction gearing system to be used. This new reduction system is compared to the original system in Figure 4.
The six stroke design does not use the existing spur gears, but has straight tooth gears on all three shafts. The reduction ratio has been determined to be a 29-58 tooth pair of gears for a 1:2 reduction between the crankshaft and the reduction shaft and 20-30 tooth pair of gears for a 2:3 reduction between the reduction shaft and the camshaft. This gives an overall gear reduction of 1:3 between the crankshaft and the camshaft.

The idler gear design causes the camshaft to rotate in the opposite direction of the original camshaft. This issue has been addressed by the six stroke camshaft design. The six stroke design has the lobes on the cams 2/3 the size of, and at opposite angles of the four stroke cams. The exhaust cam has been designed to have two lobes, one for each exhaust stroke. The first exhaust lobe opens the exhaust valve to release the combustion products; the second love opens the exhaust valve to release the water expansion products. The shaft has been extended to allow room for a cam for the injector. The injector cam has been designed to have a sharp lobe that passes across an inductive sensor which sends a signal to the gasoline direct injection (GDI) injector in the head of the engine. The cam design has been drawn in AutoCAD and Autodesk Inventor. The inventor model of the six stroke cam is shown in Figure 5.
Two design options have been considered for camshaft fabrication. The first design is to send the camshaft design to a professional cam manufacturer to be built. However, professional cams are very expensive, and well outside this project’s budget. The second design calls for a home-made camshaft. This saves money and allows for several attempts at achieving the correct timing. In this design, a steel shaft is used as the base and machined down to fit the existing bearings in the crankcase. The lobes have been designed in Autodesk Inventor to be laser cut from steel slightly oversized and ground down for more accuracy. The lobes are then welded onto the shaft at the proper angle. The gear is placed on the shaft and uses a key to lock it into position with a pair of setscrews to secure it. This allows for easy removal and modification.

For either of these designs, the lower end of the engine needs to be heavily modified for the new camshaft to be installed. This includes building a new cover for the lower end that extends out and allows room for the idler shaft. This is shown in Figure 6.
A new bearing for the crankshaft is required for this design because the diameter of the crankshaft is reduced inside the new cover. To have enough of the crankshaft left to attach to driven mechanisms, a coupling is used to extend the crankshaft. Also, the idler shaft is supported by two bearings mounted in the new cover. These bearing are slotted and room is left in the design to shim them for greater accuracy. For ease of fabrication, the cover is designed from a steel plate, welded together and then machined for accuracy. The machining starts on the bottom of the cover and all bearing holes and mounting holes would be machined from that reference point. The stock gasket can be used to prevent oil leakage or a new gasket can be cut from gasket material.

However, both of these camshaft designs (professional and home-made) have not been implemented. The first design has been rejected because a professionally manufactured cam is highly cost prohibitive. Consequently, manufacturing a cam in house was considered. Although Mr. Tubergen has generously offered laser cutting services for this project, the home-made camshaft design has also been rejected. This design has been rejected because of the inability to machine cams accurately. Cams are typically made out of tool steel for durability purposes. Tool steel is also highly cost prohibitive, so the prototype design must be manufactured from rolled steel, decreasing the strength and life of the cams. Additionally, once manufactured, cams are not adjustable. Although the home-made camshaft design allows for exchanging cams on the camshaft, each cam cannot be optimized for the correct timing. Finally, these camshaft designs have been rejected because of their inability to switch from a four stroke cycle to a six stroke cycle. Cams driven valves are mechanically driven; to change from four strokes to six strokes requires a mechanical change. This creates a difficulty for starting a cold engine, since cold
engines do not have enough internal energy to convert water to steam. This renders the water cycle useless, creating an extra burden on the engine. Consequently, an alternative to camshaft driven valves has been designed: solenoid driven valves.

**III.B.i.c. Solenoid Driven Valves**

As discussed above, solenoids have been selected to move the intake and exhaust valves. According to the results of a Lotus simulation (discussed below), the pressure inside the cylinder right before the exhaust valve needs to open is approximately 1.9 bar. The required force to open the exhaust valve has been calculated to be 32 lbf. This calculation is shown in Figure 7.

![Figure 7. The MathCAD calculation for the exhaust force.](image)

Although the Lotus simulation calculated the pressure to be 1.9 bar, this pressure was very sensitive to the engine specifications in Lotus. Given the uncertainty in the engine specifications, it is not unreasonable to design for pressures up to 5.4 bar. The required force to open the exhaust valve at this pressure has been calculated to be 84 lbf. The response time required of the solenoids has been calculated by knowing the angular velocity of the crankshaft. The exhaust solenoid is required to actuate in 1/6 of a crankshaft revolution. The required response time was calculated to be 8.5 ms. This calculation is shown in Figure 8. Consequently, an appropriate solenoid for this design can produce at least 84 lbf and actuate in less than 8.5 ms.
Ledex low-profile solenoids have been selected to operate the valves. Low-profile solenoids have a faster response time, higher force output, and a shorter stroke than other types of solenoids. This is ideal for this application because of the high forces and short traveling distances required. The 5SF solenoid has been selected because at a 100% duty cycle the force is 85 lb at a response time of 8ms. The full specifications for the Ledex 5SF solenoids can be found in Appendix A. An inventor model of the solenoid is shown in Figure 9.

The solenoids have been attached to the head using a set of brackets made from 10 gauge steel. The brackets have been computer designed and laser cut to a tolerance of seven
thousandths, and then welded together using a metal inert gas (MIG) welder. Figure 10 shows the brackets as designed.

![Figure 10. Solenoid bracket design.](image)

The solenoids have then been attached to the bracket system using 1/4-28 threaded rod. This allowed for fairly fine adjustment of the valve throw. The original cores of the solenoids have been removed and custom cores have been made from one inch diameter cold rolled steel. Each core has been designed to replace both cores from a pair of solenoids and to act as the stop when the valve is completely open. The valve seat acts as the stop for the valve when it is closed, to assure complete sealing. The valves have been attached to the pushrods using universal joints. This eliminates binding if the bracket and head are not exactly in line with each other. The pushrods pass through a pair of solenoids and the cores have been pinned to them to complete the system. Figure 11 shows the completed solenoid setup mounted on the head and Figure 12 shows the core and solenoid in detail.
Figure 11. The solenoid setup. Solenoids act as valve actuators and replace the cam.
III.B.ii. **Solenoid Assisting Spring Design**

The solenoid’s largest load occurs at the beginning of the exhaust stroke, when the valve must open against the pressurized combustion products. All solenoids are strongest when the core is nearest to the coil, and weaken exponentially with respect to the distance between the core and the coil. The solenoids specified in this design are able to exert 80 lb$_f$ when the core is near the coil, as shown in Appendix A. The solenoids are labeled as push/pull solenoids by the manufacturer. The design calls for the solenoids to push the core away, so that the force is highest when the core begins moving. This allows for the peak force to be at the beginning of the exhaust stroke. However, the push/pull solenoids provided by the manufacturer do not operate in a push manner. They are only capable of pulling the core towards the coil. That is, the solenoid is
always weakest at the beginning of the stroke, and therefore unable to open the exhaust valve. When the manufacturer was contacted about this issue, the manufacturer explained that the solenoid is able to apply a force in either direction by turning the solenoid around and pulling in the other direction. More accurately, the solenoids are pull/pull solenoids and the direction of the force is determined by the solenoid orientation.

A true push solenoid is made with a magnetic core such that the magnetic field generated by the coil repels, or pushes, the core away from the coil. This type of solenoid delivers the strongest force at the beginning of the stroke. However, no commercially available solenoids have been found that meet the project requirements.

The team has identified three possible solutions to this problem. The first is to have a high powered push solenoid custom made by a professional manufacturer. However, this solution is extremely cost prohibitive, and the lead time for receiving the solenoids extends beyond the term of this project. The second solution is to design and build home-made solenoids that meet the project specifications. However, this solution is extremely time prohibitive, and the theory behind designing high powered solenoids is still very experimental in nature. After consulting with the team’s faculty advisor, it has been determined that both of these solutions are beyond the scope of this project. The third solution is to design and install springs to assist the solenoids at their weakest point. The springs provide a force at the point in the stroke where the solenoids cannot provide it, and then work against the solenoids when the solenoids are strongest. Figure 13 shows the force curves for the spring and solenoids, as well as the overall net force acting on the valves. The horizontal axis represents the space between the solenoids which also corresponds to the length of the valve stroke. For example, when the Solenoid 1 Force is high at 0 in displacement, it is holding the spring back. When the solenoid turns off, the spring applies a force of approximately 30 lb where Solenoid 2 could provide only 3 lb. When the valve is halfway open the spring force is neutral and Solenoid 2 can finish moving the valve to the other end of its stroke. Figure 14 shows the method for fixing both ends of the springs to allow for use in both extension and compression. Figure 15 shows the mount attached to the solenoid bracket, where the plate end of the mount is bolted to the bracket, and the round end is pinned to the valve push-rod.
Figure 13. Force curves for springs and solenoids.

Figure 14. Spring attachment mounts.
Figure 15. Spring mounts attached to solenoid bracket.

III.B.iii. Head Design

The fifth stroke of the six stroke engine requires water injection, which requires additional hardware to be added to the head. However, the original head does not have room for such modifications. The original head was part of an air-cooled, pushrod valve train, four stroke engine. It was designed with space for the pushrods to pass through it and for rocker-arms to connect the pushrods to the valves. With these parts in the original head, there is not room for additional hardware. It also had cooling fins, which removed heat from the engine necessary for a six stroke cycle. Consequently, a new head has been designed and manufactured for the six stroke engine.
III.B.iii.a. Original Head

Although the original head does not have room for the required hardware, many of the parts have been salvaged for the new head. The new six stroke head has been designed to include the original valves, the original sparkplug, and the original intake and exhaust port designs. Many dimensions have been taken from the original head, shown in Figure 16, to be used in the new head.

![Original Head](image)

*Figure 16. The original head for the engine.*

III.B.iii.b. New Head

A new head has been designed based on the original head, including space to accommodate a water injector. This new head has also been designed to be used with solenoid-actuated valves, therefore removing the bulky pushrods and allowing for more room in the head itself. Measurements have been taken from the original head, and the new head has been designed with similar size intake and exhaust passages. The original valves have also been used, and to make the new top end of the engine oil-free, they have been coated with Molykote 3400,
an anti-friction coating. Because this engine was a prototype, the valve guides have been
designed as part of the aluminum head since longevity was not an issue. However, the valve
seats have been machined from steel and pressed into the head. Figure 17 shows a computer
model of the head with an approximate location of the water injector, and Figure 18 shows the
machined valve seats.

Figure 17. The new head with the intake valve open.
Figure 18. The new valve seats. The inside chamfer matches the edge of the valves to provide an adequate seal.

The new cylinder head is made of 6061 Aluminum to a tolerance of approximately one thousandth. The valve guides have been precision reamed three thousandths larger than the valve stem diameters. To assure a good seal between the valves and seats, a lapping compound has been used. The spark plug hole has been tapped to size M14-1.25 to accept the original spark plug. Figure 19 shows the head as machined before it was installed.
III.B.iv. Engine Speed Monitoring

Since the six stroke engine has been designed with solenoid driven valves, the crankshaft speed and position must be known at all times of operation. This is used to determine the appropriate valve timing and water injection timing. Inductive sensors, optical sensors, and encoders have been considered as means of determining the current crankshaft position and speed.

III.B.iv.a. Inductive Sensors

Non-production model inductive cam sensors have been provided for the team by Nick Hendriksma, one of these is shown in Figure 20. Sensors similar to these have been used in motor vehicles for a long time. In modern cars, these sensors read the position of the crankshaft based on a cam lobe passing through the magnetic field around the sensor. These sensors are widely used in industry and are a good option for this project. However, they are built to communicate with the controller for a specific car model, and the circuits that have been built by
the team did not establish a reliable signal. Given the time constraints and the lack of progress in achieving a signal, the inductive sensor option has been replaced by the optical sensor as described below.

![Image of optical sensor](image)

*Figure 20. A non-production model inductive sensor.*

**III.B.iv.b. Optical Sensor**

Another type of sensor widely used in industry is optical sensors. These sensors operate by establishing a light beam across a gap. This beam is broken when a physical object passes through the U-shaped section of the Banner sensor shown in Figure 21. A single tooth gear attached to the driveshaft is used to trigger the sensor exactly as the piston reaches top dead center (TDC). This signal ensures that the ECU knows when the piston reaches TDC and to switch the ECU to the next cycle. The specifications for this sensor are shown in Appendix B. The wiring diagram from the specifications shows how the sensor has been connected to the rest of the system is shown in Figure 22.
Figure 21. The Banner optical sensor. A light beam passes across the gap at the ends of the prongs.

Figure 22. Wiring diagram for the Banner optical sensor.

III.B.iv.c. Encoder

To produce a highly accurate measurement of the speed of the shaft and subsequently the placement of the piston relative to TDC, an encoder is used to output a square wave to the ECU at a frequency proportional to the speed of the engine. The selected encoder, shown in Figure 23, houses a gear with 1000 equally spaced teeth. As the shaft spins, the teeth cause a square wave output at 1000 times the frequency of the shaft. Table 2 lists the output wire assignments. The full specifications can be seen in Appendix C.
Figure 23. The 1000 tooth encoder used to communicate engine speed to the ECU.

Table 2. Wire signals for encoder.

<table>
<thead>
<tr>
<th>7 conductor cable assembly #CA14D431</th>
<th>Series 525 and 625</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLOR CODE</td>
<td>FUNCTION</td>
</tr>
<tr>
<td>Red</td>
<td>SIG A</td>
</tr>
<tr>
<td>Yellow</td>
<td>SIG Z (if used)</td>
</tr>
<tr>
<td>Black</td>
<td>Common</td>
</tr>
<tr>
<td>Blue</td>
<td>SIG B</td>
</tr>
<tr>
<td>White</td>
<td>+Volts</td>
</tr>
<tr>
<td>Green</td>
<td>No Connection</td>
</tr>
<tr>
<td>Shield</td>
<td>Case</td>
</tr>
</tbody>
</table>

III.B.iv.d. Sensor Bracket

In order for the optical sensor and encoder to be used, a bracket has been designed to which the optical sensor and encoder have been mounted. The bracket has been made out of three pieces of aluminum that have been welded together as shown in Figure 24. The AutoCAD design of this bracket, along with all relevant dimensions, is shown in Figure 25. The bracket has been designed such that the optical sensor attaches to the bracket at Part 3, with the open end of the U-shape facing up, while the encoder has been attached to the outside face of Part 2 with the shaft facing inward, toward the driveshaft, through the hole in Part 2. The shaft of the encoder has then been coupled to the driveshaft. The bracket has been designed to attach to the engine via the tabs on Parts 1 and 3.
Figure 24. The optical sensor and encoder bracket design.

Figure 25. The dimensioned AutoCAD design for the optical sensor and encoder bracket.
III.B.v. Water Injection System Design

Integral to the design of the six stroke engine is the injection of water into the cylinder. Since the six stroke design does not include a camshaft, the water injection must be electronically controlled. The water injection system consists of three main components, the injector, the water pressurizing system, and the electronic control system.

III.B.v.a. Water Injector

The water injector that has been chosen is a high pressure GDI fuel injector from a 2008 Pontiac Solstice GXP. This particular injector has been chosen because it was generously supplied by Nick Hendriksma as an injector likely to work well with water. The manufacturer drawing provided with the injector is shown in Figure 26.
Figure 26. The GDI injector chosen to inject water during the fifth stroke.

III.B.v.b. Water Pressure Design

The water pressure system that has been designed is shown in Figure 27. A water line connects a pressurized tank of water to the injector. For this prototype, the water tank is pressurized using the compressed air lines in the Engineering Building.
Figure 27. Water injection system using 100 psi air line in the Engineering Building.

The coupling system between the injector and water lines has been designed and prototyped. As shown in Figure 28, a brass coupling has been machined to connect the injector to the water line. The O-ring and backup-ring shown in Figure 26 provide a water tight seal around the injector. This coupling is shown in Figure 28.

Figure 28. The water injector coupling to the pressurized water line.
III.B.v.c. Water Injection Circuit Design

The injector was provided with some specifications on the power requirements to operate as intended by the manufacturer. Figure 29 shows the current specifications to operate the injector at 2000 psi. The signal peaks at approximately 10 A then holds for 1 ms at 3 A. The specifications also called for a 70 V spike at the signal peak. A proposed circuit to meet the specifications is shown in Figure 30. The value for the unmarked resistor may be chosen based on desired current flow from the power supply.

Given the potential safety hazard of operating at 70 V and 10 A, an alternate design has been considered. As mentioned above, the proposed water pressure design involves using a 100 psi pressurized water tank, rather than the 2000 psi specified with the injector. Consequently, the team hypothesized that reducing the back pressure on the injector would reduce the power requirements. To test this hypothesis, the injector has been connected to the 100 psi pressurized water line and a +5 volts direct current (VDC) signal has been applied to the injector, resulting in a 3.5 A current spike from the power supply. The resulting mist spraying from the injector confirms the team’s hypothesis, and allows for a simplification of the circuit in Figure 30. This simplified design removes the capacitor and lowers the power supply to +5 VDC.
Figure 29. Current requirement for GDI injector

Figure 30. Initial water injector circuit design
III.B.vi. Engine Control Unit Design

The ECU has been designed to replace the original camshaft. The main components of the ECU are the microprocessor, the power supplies, the relays, and the wiring to connect all the parts.

III.B.vi.a. Microprocessor

The brain of the ECU is a flexible, open-source prototyping board made by Arduino, shown in Figure 31. It is programmed in C to receive an input signal from the optical sensor and encoder described above. The program then determines the position of the piston and the appropriate valve and injector response. The board specifications can be found in Table 3.8

Figure 31. The Arduino microcontroller.

8 “Arduino Duemilanove Information,” Arduino.
<http://www.arduino.cc/en/Main/ArduinoBoardDuemilanove>
Table 3. Board and pin specifications for the Arduino microcontroller.

<table>
<thead>
<tr>
<th>Specification</th>
<th>ATmega168</th>
<th>ATmega328</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>ATmega168</td>
<td></td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>5V</td>
<td>16 MHz</td>
</tr>
<tr>
<td>Input Voltage (recommended)</td>
<td>7-12V</td>
<td>512 bytes (ATmega168) or 1 KB (ATmega328)</td>
</tr>
<tr>
<td>Input Voltage (limits)</td>
<td>6-20V</td>
<td></td>
</tr>
<tr>
<td>Digital I/O Pins</td>
<td>14 (of which 6 provide PWM output)</td>
<td></td>
</tr>
<tr>
<td>Analog Input Pins</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>DC Current per I/O Pin</td>
<td>40 mA DC</td>
<td></td>
</tr>
<tr>
<td>Current for 3.3V Pin</td>
<td>50 mA</td>
<td></td>
</tr>
<tr>
<td>Flash Memory</td>
<td>16 KB (ATmega168) or 32 KB (ATmega328) of which 2 KB used by bootloader</td>
<td></td>
</tr>
<tr>
<td>SRAM</td>
<td>1 KB (ATmega168) or 2 KB (ATmega328)</td>
<td></td>
</tr>
<tr>
<td>EEPROM</td>
<td>512 bytes (ATmega168) or 1 KB (ATmega328)</td>
<td></td>
</tr>
</tbody>
</table>

III.B.vi.b. Power Supplies

Custom power supplies made at Calvin College have been used to power all circuitry. These power supplies have +5, ±12, and ±15 VDC output pins. Each voltage pin also has a corresponding ground pin, but only the ground pin associated with the +5 Volts is grounded to the wall outlet; all other ground pins are floating unless wired to the absolute ground. While these power supplies are limited in their precision, they are able to deliver the high electric current required for some of the components (measured as high as 3.5 A at 5 VDC).

III.B.vi.c. Relays

The microprocessor outputs are limited to 40 mA direct current (DC) as shown in Table 3. Since the solenoids require around 1.5 A, there must be relays in between the microprocessor and the solenoids. Crydom DC60S3 relays, as shown in Figure 32, have been chosen because the operating voltages and currents fall within the relay limits, and they have response times around 1ms. Additionally, a similar Crydom relay has been chosen to be wired between the microcontroller and the injector. As the injector requires even higher power, a Crydom DC60S7 has been chosen because it allows current flow up to 7A on the high power side. The full specifications for these relays can be found in Appendix D.
III.B.vi. Circuitry

To connect all of the components to the ECU, an overall circuit diagram is laid out in Figure 34. The dashed blue circles highlight specific regions of the diagram that are laid out in the following figures. Figure 35 through Figure 39 show the diagram around the encoder, optical sensor, solenoid relays, injector relay, and microprocessor respectively.
Figure 34. The full circuit diagram for the proposed six stroke engine.
Figure 35. The encoder wiring diagram for the ECU.

Figure 36. The optical sensor wiring diagram for the ECU.
Figure 37. The solenoid relay wiring diagram for the ECU.

Figure 38. The injector relay wiring diagram for the ECU.
Figure 39. The microprocessor wiring diagram for the ECU.

The physical implementation of several of these circuits has been simplified using homemade circuit boards using 3/4” MDF panels, brass screws, and solder. Figure 40 shows a circuit board that houses the microprocessor and solenoid relays. Brass screws are used as terminals to wire the board to other components, such that all internal wiring on the board is secure.
III.B.vi.e. ECU Outputs

A program for the ECU has been written and loaded onto the microcontroller. This code takes the input from both the optical sensor and the encoder, and uses them to generate a timing cycle for the physical components. This has been first accomplished for the four stroke cycle. This code is operated by switching between cycles 1/2 and 3/4 based on the reset signal from the optical sensor, and then calculating the current piston position based on the speed signal from the encoder. The piston position then determines the on/off signals to the solenoids.

The ECU outputs for the four stroke engine, shown in Figure 41, have been designed to mirror the measured valve displacements as shown previously in Figure 3. The dark blue points are actual data recorded from the microcontroller. The red lines are extensions of the data to explain the signals the solenoids are actually receiving. The dots differ from the lines because the blue dots only show when the microcontroller is trying to write an output pin high or low. When a pin is not being written to, it simply remains at the value that it was most recently at.
The second iteration of this code is similar to the four stroke code, but includes the fifth and sixth strokes. The outputs from this code are shown in Figure 42. The outputs here use an additional pin to control the injector, and there is also an additional iteration of the exhaust included in stroke six. The timing of the valve movement is completely customizable by simply changing the angle variable in the code. The full code for the six stroke ECU can be found in Appendix E. In accordance with the transparency design norm, the full code is also available on the project website.⁹

The ECU design also includes the ability to switch between running in four stroke mode to six stroke mode. This is necessary because the water injected into the cylinder cannot vaporize without sufficient heat inside the engine. This switch is based on the temperature reading from a thermocouple. The thermocouple is wired through an amp, which sends an analog signal proportional to the temperature to the microprocessor. This feature allows the engine to properly heat up before water is injected into the cylinder.

---

⁹ Team 6 Stroke.

If the code outputs from Figure 42 are interpreted from left to right:

1) The intake-open solenoid turns on simultaneously with the intake-close solenoid turning off for a short while. This constitutes the air/fuel intake.

2) There is a gap with no change in outputs; this is the compression, combustion, and expansion of the air/fuel.

3) The exhaust-open solenoid turns on simultaneously with the exhaust-close solenoid turning off for a while just after the piston reaches bottom dead center (BDC). This constitutes the exhaust of the combustion products.

4) The water injector turns on for a short while. This is followed by a short time where the water vapor flashes into steam and expands.

5) The second exhaust happens just after the piston reaches BDC, after which the cycle begins again about halfway across the image.

One of the most important factors in the decision to go with an ECU over a conventional camshaft is the adaptability the code allows. For example, it is extremely easy to change the
timing of the engine to increase the length of the intake. This would allow more air and fuel into the engine with the click of a button. With the code working with the entire assembly it is easy to switch between running four strokes and six strokes. This allows for the engine to run in four stroke mode until there is enough internal energy to sustain the vaporization during the fifth stroke. Then the engine would switch flawlessly to six stroke mode and run at a higher efficiency. The ECU also allows troubleshooting through code modification instead of expensive and time prohibitive physical modifications.

III.C. Thermodynamics

As part of the design of the six stroke engine, the thermodynamic state of each stroke has been determined using a control volume approach. Using the cylinder walls as the control volume, the thermodynamic state of the fluids inside the control volume at the end of each stroke has been determined using Engineering Equation Solver (EES). The code uses the engine specifications set by the user to determine the energy flow rates and efficiencies of a six stroke engine. Since the results depend on engine specifications and experimentally found values, the results do not have any meaning for this project yet. However, as an example of how the program works, Figure 43 shows the PV diagram for a similar six stroke engine. The area inside the curves represents the work delivered to the driveshaft from both the combustion of gasoline and the evaporation of water, as labeled in the figure. It is important to note that the shape of this curve is completely dependent on the variables chosen by the user. Many of these variables, such as temperatures, must be found experimentally. Since these experiments have not yet been run, the variables, and hence, the figure, are entirely hypothetical based on arbitrarily chosen values.

The full code for the calculations can be found in Appendix F. In accordance with the transparency design norm, the full code is also available for download on the project website.¹⁰

¹⁰ Team 6 Stroke.

III.D. Engine Simulation in Lotus

In order to better verify design results and calculations, a trial version of the computer program called Lotus Engine Simulation v5.05 has been used. The advantage of Lotus Engine Simulation is in its fully customizable engine setup. The user interface of this program allows for selection and placement of various engine components such as valves, ports, cylinders, etc., along with the input of all of the specifications of these components. Due to the relative simplicity of the engine in this project relative to other more complex engines (more cylinders, etc.) the setup in Lotus has been very straightforward, as shown in Figure 44.
Figure 44. The Lotus setup for the one cylinder, four stroke engine.

As shown in Figure 45, the components have been selected from the component menu on the left-hand side of the screen. Once the components have been selected and placed in the building environment and nodes have been correctly connected, the program allows the user to input important specifications, such as bore and stroke, into the input menu.

Figure 45. The Lotus building environment and engine building interface.
One of the very useful applications of this customizability is Lotus’ capacity for regulation of valve timing. Figure 46 shows the window provided to display valve timing and Figure 47 is the subsequent graphic that Lotus outputs to model the piston’s movement in conjunction with the valves.

![Diagram of valve lift as a function of shaft angle.](image)

*Figure 46. Valve lift as a function of shaft angle.*

![Diagram of Lotus valve and piston simulation graphic.](image)

*Figure 47. Lotus valve and piston simulation graphic.*
Once all of the components and inputs have been entered into Lotus, the simulation of the engine operation has been completed and some important results are shown in Figure 48 and Figure 49. Along with these results, an extremely detailed results window is produced by Lotus that is useful for comparison to calculations. For a desired speed of 1000 RPM, the results show that the exhaust pressure is 1.9 bar and the power output is 5 horsepower. This speed has been chosen for testing and running the prototype because it is a reasonably low speed and was predicted to be the limiting factor on running the engine. At this speed the engine will run at an idle, with decreased requirements on the valve displacement and solenoid speeds. Figure 49 shows a linear fit to the power curve as the engine speed increases, with the range of power exactly where it should be for the 16-horsepower engine that has been modified.

Figure 48. Lotus results window.
III.E. Running the Engine

III.E.i. Starter Motor

A common four stroke engine is able to sustain its cycles after a few full revolutions of the driveshaft. This is frequently initiated by the user pulling on a starter cord. It is anticipated that the six stroke engine designed here will require a larger number of revolutions to begin sustaining itself. For this purpose, a starter motor assembly has been designed. The starter motor will turn the driveshaft at idling speed until the engine is able to accelerate under its own power. At this point, the motor is turned off and the engine runs independently, still turning the motor. The starter motor is a large DC motor with a built in speed control box. The assembly includes sprockets that provide a 2:1 speed reduction. For extended testing the starter motor can be attached using a freewheel clutch. The starter motor and chain attachment can be seen in Figure 50.

Figure 49. Lotus graphical results plot.
III.E.ii. Prototype Testing

Attempts have been made to assemble and operate the six stroke design as described in the above sections. The failure of any of the five main sections of the proposed design can prohibit the six stroke engine from sustaining a combustion cycle. During these attempts multiple combustions have been sustained, but the engine was not able to run independent of the starter motor. This is because the valves could not actuate fast enough. When the engine gained speed the intake valve could not close before compression started, or the exhaust valve could not close before intake started. This interrupts the cycles and the engine stops running. Video footage of these attempts can be found on the project website.\footnote{Team 6 Stroke.}

\url{https://knightvision.calvin.edu/bbcswebdav/orgs/ENGR/senior-projects/2009_10/team14/web/progress.html}
IV. Conclusion

IV.A. Lessons Learned

While the list of lessons learned during the course of this project is too long to fully explain, several key lessons stand out.

IV.A.i. Begin Testing Early

A major lesson that was learned was to get critical parts in on time and fully tested. This team relied on solenoids to be able to push or pull as the manufacturer labeled them as push/pull solenoids. It was not realized that this was not accurate until too late in the project to recover. In the future, teams should investigate fully into critical parts of the design to ensure that off the shelf components behave in the fashion for which they were selected.

IV.A.ii. See the Big Picture

Another of the most important lessons learned is to always look at the big picture. For example, several weeks were lost to dynamometer testing the original engine, with no
results. Looking back, those weeks would have been much better spent working on the new engine and making sure it would run. Getting side-tracked by individual tasks cannot be allowed to interfere with overall project progress.

**IV.A.iii. Plan the Path to Success**

Setting preliminary goals is also important. For instance, if the engine will not run as a four stroke, it will not run as a six stroke either. These preliminary goals break a complex project into attainable sub-projects. Breaking the complex project down creates a simpler, more attainable path to success.

**IV.B. Recommendations and Future Work**

As there is a divide between the current six stroke design and a working six stroke model, there are several key recommendations to those who might continue in a project of this sort.

**IV.B.i. Redesign the Solenoids**

As the solenoids are the major obstacle standing between the team and a running six stroke engine, an obvious starting point for future work is to design solenoids with the force and speed required. There are two paths this could follow. First, a true push solenoid could be designed with a permanent magnetic core. With a permanent magnet instead of a steel core, the magnetic fields could be aligned such that the magnetic fields repelled each other. This would allow the solenoids to be strongest right as they turned on, facilitating a much faster and stronger response. Second, stronger pull solenoids similar to the ones discussed in the design could be built or purchased to specifications. As no commercial model with the required strength could be found, new solenoids with more turns of wire and a new case could be built. This solution has a theoretical limit, as more turns of wire results in a longer response time, and wire wrapped a greater radius from the core creates less and less magnetic force.

**IV.B.ii. 6 Stroke Camshaft**

Another recommendation could be to consider the camshaft design more thoroughly. Implementing the camshaft design would eliminate the response time and force requirement issues of the current solenoid design. Although this design is not without its own issues, further development needs to be considered in order to fully rule out its role in the six stroke engine solution.
In conclusion, individuals with an expertise or an interest in solenoids or camshafts could advance from the proposed designs and perhaps attain a running engine. Once a running engine is attained, the design could be optimized for efficiency.

V. Acknowledgements

Throughout the course of this project Team 6 Stroke has received help on many levels from a variety of people. While the team is thankful for everyone who has helped, the team would especially like to acknowledge the following individuals for their gracious assistance.

V.A. Ned Nielsen

Professor Nielsen is the faculty advisor to Team 6 Stroke. With experience in automotive engineering, he is a valuable resource for advice on project issues and has helped us find contacts for specific help.

V.B. Ren Tubergen

Dr. Tubergen is owner of Gumbo Product Development and has agreed to work with the team as an industrial consultant. He has been especially valuable in pointing out risks and opportunities in our project as well as in providing team and project management advice.

V.C. Nick Hendriksma

Mr. Hendriksma is an engineer working for the General Motors in the company formerly known as Delphi. He is extremely knowledgeable on fuel injectors and has agreed to act as a mentor for the team. Mr. Hendriksma has also generously provided parts and specifications for this project.

V.D. Phil Jasperse

Phil Jasperse, of the Calvin College machine shop, has provided invaluable advice and assistance in prototyping the engine.

V.E. Highlight Industries

Highlight Industries has helped the team in several ways including supplying parts, machining, and mentoring. Carl Reiser has been a huge help in the design and machining of the
new cylinder head. The company also helped the team by supplying important parts, including the encoder.

**V.F. Professor Brouwer, Professor VanderLeest, and Paul Bloem**

These electrical engineers assisted in Team 6 Stroke’s electrical troubleshooting process. Their expertise in the field proved extremely useful and their insight very helpful.

**V.G. Chuck Holwerda**

Chuck Holwerda, of the Calvin College electrical shop, has helped the team by offering advice on purchasing electrical components and verifying designs before risking implementation.

**V.H. Paulo Ribeiro**

Professor Ribeiro has helped the team through his knowledge of control systems. He has worked with several team members on the ECU as part of a project for his Engineering 315 Control Systems class.

**V.I. David Benson**

Professor Benson has provided some guidance for the team for future exhaust gas composition testing. He is also a valuable contact in the Calvin College Chemistry Department who has volunteered some of his time and knowledge to help the team.
VI. Appendix A

VI.A. Solenoid Specifications

**Ledex® Low Profile Size 5SF — Push or Pull**

Short Stroke, Flat Face  
Part Number: 129450-XX

---

### Performance

<table>
<thead>
<tr>
<th>Maximum Duty Cycle</th>
<th>100%</th>
<th>50%</th>
<th>25%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum ON Time (sec)</td>
<td>100</td>
<td>36</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

when pulsed continuously

<table>
<thead>
<tr>
<th>Maximum ON Time (sec)</th>
<th>160</th>
<th>44</th>
<th>13</th>
</tr>
</thead>
</table>

for single pulse

<table>
<thead>
<tr>
<th>Watts (at 20°C)</th>
<th>42</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Ampere Turns (at 20°C)</th>
<th>866</th>
<th>1220</th>
<th>1720</th>
<th>2570</th>
</tr>
</thead>
</table>

### Coil Data

<table>
<thead>
<tr>
<th>Avg Resistance (20°C)</th>
<th>Nominal Resistance (Nom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.03 298</td>
<td>6.1 8.6 12.1 19.2</td>
</tr>
<tr>
<td>3.20 360</td>
<td>7.6 10.0 15.3 24.0</td>
</tr>
<tr>
<td>4.91 660</td>
<td>9.6 13.6 19.2 31.0</td>
</tr>
<tr>
<td>7.72 590</td>
<td>12.1 17.1 24.0 38.0</td>
</tr>
<tr>
<td>11.12 636</td>
<td>15.0 21.0 30.0 48.0</td>
</tr>
<tr>
<td>18.79 860</td>
<td>19.2 27.0 39.0 61.0</td>
</tr>
<tr>
<td>29.48 1089</td>
<td>24.0 34.0 48.0 77.0</td>
</tr>
<tr>
<td>44.86 1275</td>
<td>30.0 43.0 61.0 96.0</td>
</tr>
<tr>
<td>70.90 1596</td>
<td>38.0 54.0 76.0 121.0</td>
</tr>
<tr>
<td>109.00 1976</td>
<td>47.0 67.0 95.0 150.0</td>
</tr>
<tr>
<td>175.00 2496</td>
<td>60.0 84.0 121.0 192.0</td>
</tr>
</tbody>
</table>

### Specifications

**Dielectric Strength**

| 23 awg, 1000 VRMS | 24-33 awg, 1200 VRMS |

**Recommended Minimum Heat Sink**

Maximum watts dissipated by solenoid are based on an unrestricted flow of air at 20°C, with solenoid mounted on the equivalent of an aluminum plate measuring 7/8" square by 1/16" thick.

**Coil Resistance**

<table>
<thead>
<tr>
<th>Avg Resistance (20°C)</th>
<th>Nominal Resistance (Nom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 awg, 1000 VRMS</td>
<td>24-33 awg, 1200 VRMS</td>
</tr>
</tbody>
</table>

**Weight**

9.2 oz (259 gms)

**Holding Force**

81.875" x 0.680" L (See page G17)

---

### How to Order

Add the coil avg number (XX) to the part number (for example: to order a 25% duty cycle unit rated at 30 VDC, specify 129450-027).

Please see www.ledex.com (click on Stock Products tab) for our list of stock products available through our North American distributors.

---

**Linear Low Profile**

---

Size 5SF — Typical Force @ 20°C

Force - lb (newtons) vs Stroke - in (mm)

---

Size 5SF — Typical Speed @ No Load, 20°C

Time - ms vs Stroke - in (mm)

---

Force values for reference only.  
All specifications subject to change without notice.

Ledex® Solenoids

G10  www.ledex.com  1.937.454.2345  Fax: 1.937.890.0624
Ledex® Low Profile Dimensions

Inches (mm)

All solenoids are illustrated in energized state

Size 4EF/4EC

Size 5SF

Size 5EC

All specifications subject to change without notice.
VII. Appendix B

VII.A. Optical Sensor Specifications

<table>
<thead>
<tr>
<th>Models</th>
<th>Slot Width</th>
<th>Cable*</th>
<th>Supply Voltage</th>
<th>Output Type</th>
<th>Response</th>
<th>Repeatability</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLO30VB6</td>
<td>30 mm (1.2&quot;)</td>
<td>2 m (6.5&quot;) 5-wire cable</td>
<td>10-30V dc</td>
<td>Bipolar NPN (sinking) and PNP (sourcing)</td>
<td>1 millisecond</td>
<td>250 microseconds</td>
</tr>
<tr>
<td>SLO30VB6Q</td>
<td>30 mm (1.2&quot;)</td>
<td>5-Pin Euro-style QD</td>
<td>10-30V dc</td>
<td>Bipolar NPN (sinking) and PNP (sourcing)</td>
<td>300 microseconds</td>
<td>75 microseconds</td>
</tr>
<tr>
<td>SLO30VB6Y</td>
<td>30 mm (1.2&quot;)</td>
<td>2 m (6.5&quot;) 5-wire cable</td>
<td>10-30V dc</td>
<td>Bipolar NPN (sinking) and PNP (sourcing)</td>
<td>1 millisecond</td>
<td>250 microseconds</td>
</tr>
<tr>
<td>SLO30VB6YQ</td>
<td>30 mm (1.2&quot;)</td>
<td>5-Pin Euro-style QD</td>
<td>10-30V dc</td>
<td>Bipolar NPN (sinking) and PNP (sourcing)</td>
<td>300 microseconds</td>
<td>75 microseconds</td>
</tr>
</tbody>
</table>

*NOTES: 1) 9 m (30 ft) cables are available by adding suffix "W/30" to the model number of the cabled version (e.g., SLO30VB6 W/30). 2) A model with a QD connector requires an accessory mating cable. See page 4.

**WARNING... Not To Be Used for Personnel Protection**

Never use these products as sensing devices for personnel protection. Doing so could lead to serious injury or death.

These sensors do NOT include the self-checking redundant circuitry necessary to allow their use in personnel safety applications. A sensor failure or malfunction can cause either an energized or de-energized sensor output condition. Consult your current Banner Safety Products catalog for safety products which meet OSHA, ANSI and IEC standards for personnel protection.
SLO Series Slot Sensor

SLO Series Slot Sensor Overview
The SLO Series Slot Sensor (sometimes called a “Fork Sensor”) comprises an opposed-mode emitter and its receiver inside a single convenient housing. Opposed-mode sensing is very reliable, and the single self-contained housing provides easy installation, with no sensor alignment required. In addition, the molded-in arrow on the emitter portion of the housing and the slotted design on the receiver portion of the housing show at a glance the position of the beam, simplifying installation placement.

Using the SLO Series Slot Sensor

Light/Dark Operate Select
Selecting Light or Dark Operate is a simple procedure: connect the gray wire (see hookups, page 3), to +V (10-30V dc) for Dark Operate, and to dc common (or open) for Light Operate.

LED Indicators
The Slot Sensor features two LED Indicators: Power (green) and Signal (yellow). They indicate the following:

- **Green ON steady**: Power ON
- **Yellow ON steady**: Sensor sees light
- **Yellow flashing**: Excess gain is marginal (1 to 1.5x) in light condition

![Figure 1. SLO Series features](Image)

![Figure 2. SLO Series typical applications](Image)
SLO Series Slot Sensor

Figure 3. SLO Series Slot Sensor dimensions

**SLO Series Slot Sensor Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot Opening</td>
<td>30 mm (1.2&quot;) wide x 45 mm (1.8&quot;) deep overall; beam set in 10 mm (0.4&quot;) from outer edge</td>
</tr>
<tr>
<td>Supply Voltage and Current</td>
<td>10 to 30V dc, 30 mA</td>
</tr>
<tr>
<td>Supply Protection Circuitry</td>
<td>Protected against reverse polarity and transient voltages</td>
</tr>
<tr>
<td>Output Configuration</td>
<td>Bipolar: NPN (current sinking) and PNP (current sourcing)</td>
</tr>
<tr>
<td>Output Rating</td>
<td>150mA, each output</td>
</tr>
<tr>
<td>Output Protection Circuitry</td>
<td>Protected against false pulse on power-up and short-circuit of outputs</td>
</tr>
<tr>
<td>Output Response Time</td>
<td>1 millisecond or 300 microseconds, depending on model</td>
</tr>
<tr>
<td>Repeatability</td>
<td>250 microseconds or 75 microseconds, depending on model</td>
</tr>
<tr>
<td>Adjustments</td>
<td>None</td>
</tr>
<tr>
<td>Indicators</td>
<td>Green: Power ON/OFF indicator, Yellow: Signal Condition indicator</td>
</tr>
<tr>
<td>Construction</td>
<td>Housing: ABS/poly carbonate, Lenses: Acrylic</td>
</tr>
<tr>
<td>Environmental Rating</td>
<td>IP67, NEMA 6</td>
</tr>
<tr>
<td>Connections</td>
<td>2 m (6.5&quot;) or 9 m (30&quot;) 5-conductor PVC-jacketed attached cable or 5-pin Euro-style quick-disconnect (QD) connector. QD cables are ordered separately; see page 4.</td>
</tr>
<tr>
<td>Operating Conditions</td>
<td>Operating Temperature: -40° to +70°C (-40° to +158°F)</td>
</tr>
<tr>
<td></td>
<td>Maximum relative humidity: 90% @ 50°C (non-condensing)</td>
</tr>
</tbody>
</table>

**SLO Series Slot Sensor Hookups**

**Cabled models**

- For Dark Operate, connect gray wire to (brown).
- For Light Operate, connect gray wire to (blue) or leave circuit open.

**Quick-Disconnect models**

- 10 - 30V dc

---

Banner Engineering Corp. • Minneapolis, U.S.A
Website: http://www.banner.com • Tel: 888.373.6767

Page 3
VIII. Appendix C

VIII.A. Encoder Specifications

Series HR25

- Ultra-reliable, heavy-duty Size 25 (2.5") encoder
- Unbreakable code disk
- Complete electrical protection and noise immunity
- Environmentally sealed to NEMA4/IP66
- Up to 1024 PPR with optional marker pulse

**APPLICATION/INDUSTRY**
The Dynapar brand Series HR25 is a rugged, reliable and economical encoder for industrial motion applications.

**DESCRIPTION**
The unbreakable code disk meets the demands of the most severe shock and vibration generating processes, and keeps the bearings that keep tough loads from disrupting internal alignment, avoiding failure due to the disk "cracking" or typically in competitive encoders. Protection against installation problems such as wiring errors prevents the encoder from damage, while immunity to electrical noise keeps the encoder signal intact. A NEMA4 / IP66 sealing option protects against damage from contamination.

Packaged in an industry standard 2.5" enclosure, the Series HR25 offers a variety of mechanical options: servo or linear mounting, and 1/4" or 3/8" shafts. Electrical options include resolutions from 1 to 1024 pulses/revolution, bi-directional operation with optional index, single ended open collector or push-pull outputs, or differential line drivers, and connector or cable exit terminations.

The Series HR25 utilizes the latest technology optical emitters and sensors, surface mount assembly, and precision manufactured metal components to deliver high reliability and performance in a compact and economical package.

**FEATURES AND BENEFITS**
- Unbreakable code disk and long life 80 to 100,000 miles available
- Extended temperature range available
- Industry Standard, Size 25 Form B Factor
- NEMA4 / IP66 washdown rating option

**ELECTRICAL FEATURES**
- Noise Immune to ESD, RFI, and electrical transients
- High current outputs
- Over-Voltage protection
- Reverse Voltage protection
- Output Short-Circuit Protection

**SPECIFICATIONS**

- **Code**: Incremental
- **Resolution**: 1 to 1024 PPR (pulses/revolution)
- **Accuracy**: 0.01% case any edge to any other edge ± 0.1 arc-min.
- **Format**: Two channel quadrature (A/B) with optional index (Z) and complementary outputs
- **Phase Sense**: A leads B for CW or CCW shaft rotation as viewed from the shaft end of the encoder; see Ordering Information
- **Quadrature Phasing**: 90° ± 3.5° electrical
- **Symmetry**: 5.0° ± 1.0° electrical
- **Index**: 180° ± 18° electrical (gated with B low)
- **Waveform**: Squarewave with rise and fall times less than 1 microsecond into a load capacitance of 1000 pf

**ELECTRICAL**

- **Input Power**: 4.5 VDC to 28 VDC max. at 50 mA max., not exceeding output limits
- **Outputs**:
  - 7220 Open Collector: 30 VDC max., 40 mA sink max
  - 7221 Push-Pull and Differential Line Driver: 40 mA sink or source
  - 4460 Differential Line Driver: 100 mA sink or source
- **Frequency Response**: 100 kHZ min
- **Electrical Protection**: Overvoltage, reverse voltage and output short circuit protected
- **Noise Immunity**: Tested to EN60068-2 (Heavy Industrial) for Electro Static Discharge, Radio Frequency Interference, Electrical Fast Transients, Conducted and Magnetic Interference

**CONNECTIONS**

- Mating Connector:
  - 7 pin, style MS3150A-15S-15 (MCN-N5)
  - 10 pin, style MS3150A-15S-15 (MCN-N8)
- 5 pin, style MT12: Cable with connector available
- 5 pin, style MT12: Cable with connector available

**MECHANICAL**

- **Shaft Loading**: (at 0.25" from encoder face) 80 lbf., radial, 80 lbf., axial
- **Shaft Speed**: 10,000 RPM max
- **Shaft Runout**: 0.0001" max. TIR
- **Moment of Inertia**: 3.0 x 10^4 oz-in. sec²

**ENVIRONMENTAL**

- **Operating Temperature**: Standard: 0 to 70°C
  - Expanded: -40 to +85°C
- **Storage Temperature**: -40 to +80°C
- **Shock**: 55 G for 11 milliseconds duration
- **Vibration**: 5 to 2000 Hz at 20 g
- **Humidity**: 95% without condensation
- **Enclosure Rating**: HR25: NEMA4/IP66 (dust tight, splash proof); HR42: NEMA4/IP66 (dust tight, washdown)
**ELECTRICAL CONNECTIONS**

Prewired Cable or Accessory Cables with 7 or 10 Pin MS Connector - when Code 4-0 to 6, or A, B, C, D or G

<table>
<thead>
<tr>
<th>Pin</th>
<th>Function (if Used)</th>
<th>Wire Color Code</th>
<th>Cable Accessory Color Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Signal A</td>
<td>BRN</td>
<td>BRN</td>
</tr>
<tr>
<td>B</td>
<td>Signal B</td>
<td>ORN</td>
<td>ORN</td>
</tr>
<tr>
<td>D</td>
<td>Signal Z</td>
<td>YEL</td>
<td>YEL</td>
</tr>
<tr>
<td>D</td>
<td>Power Source</td>
<td>RED</td>
<td>RED</td>
</tr>
<tr>
<td>E</td>
<td>No Connection</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>F</td>
<td>Common</td>
<td>BLK</td>
<td>BLK</td>
</tr>
<tr>
<td>G</td>
<td>Case</td>
<td>GRN</td>
<td>GRN</td>
</tr>
<tr>
<td>H</td>
<td>Signal R</td>
<td>BRNWHT</td>
<td>BRNWHT</td>
</tr>
<tr>
<td>I</td>
<td>Signal B</td>
<td>ORNWHT</td>
<td>ORNWHT</td>
</tr>
<tr>
<td>J</td>
<td>Signal Z</td>
<td>YELWH</td>
<td>YELWH</td>
</tr>
</tbody>
</table>

*Cable Accessory: PN 14034310010*

Cable Configuration: PVC jacket, 105 °C rated, overall foil shield, 3 twisted pairs 26 AWG (output signals), plus 2 twisted pairs 24 AWG (input power).

5 & 8 Pin M12 Accessory Cables - when Code 4- H to Z

<table>
<thead>
<tr>
<th>Encoder Function</th>
<th>Cable # 112959-</th>
<th>Cable # 112800-</th>
<th>Cable # 112900-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sig. A</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sig. B</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Sig. Z</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Power +V</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Comm</td>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Sig. A</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Sig. B</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Sig. Z</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
</tbody>
</table>

*Index not provided on all models. See ordering information*

Cable Configuration: PVC jacket, 105 °C rated, overall foil shield, 54 AWG conductors, minimum

See "Accessories" Section for Connectors and Cable Assemblies Ordering Information
Series HR25

Code 3: Mechanical

Code 4: Output

Code 6: Termination
## Ordering Information

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HR 25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6 Pin Connector or Cable

- 0: Single ended, no index, Format A, Table 2
- 1: Single ended, with index, Format A, Table 2
- 4: Single ended, with index, Format B, Table 2
- 6: Differential, no index, Format C, Table 3
- A: Single ended, with index, Format C, Table 2
- C: Single ended, no index, Format C, Table 2
- G: Single ended, with index, Format D, Table 2

### 7 Pin Connector or Cable

- 2: Differential, no index, Format A, Table 1
- 3: Differential, with index, Format A, Table 1
- 5: Differential, with index, Format C, Table 1
- D: Differential, no index, Format C, Table 1

### 10 Pin Connector or Cable

- 1: Single ended, no index, Format A, Table 4
- 3: Single ended, with index, Format A, Table 4
- K: Single ended, with index, Format B, Table 4
- L: Single ended, with index, Format C, Table 4
- M: Single ended, no index, Format C, Table 4

### 5 Pin M12 Connector

- H: Single ended, no index, Format A, Table 5
- J: Single ended, with index, Format A, Table 5
- K: Single ended, with index, Format B, Table 5
- L: Single ended, with index, Format C, Table 5
- M: Single ended, no index, Format C, Table 5

### 8 Pin M12 Connector

- P: Single ended, no index, Format A, Table 6
- Q: Single ended, with index, Format A, Table 6
- R: Single ended, with index, Format B, Table 6
- S: Single ended, with index, Format C, Table 6
- T: Single ended, no index, Format C, Table 6
- U: Single ended, with index, Format D, Table 6
- W: Differential, no index, Format A, Table 6
- X: Differential, with index, Format A, Table 6
- Y: Differential, with index, Format B, Table 6
- Z: Differential, no index, Format C, Table 6

### Available when Code 1 is HR25

- 0: End Mount Connector
- 1: Side Mount Connector
- 2: 18" Cable, Side
- 3: 6" Cable, Side
- 4: 6" Cable, Side
- 5: 10" Cable, Side
- 6: 15" Cable, Side
- J: 18" Cable, End
- K: 3" Cable, End
- L: 5" Cable, End
- M: 10" Cable, End
- N: 15" Cable, End

### PS LED Output Indicator

- Available when Code 4 is 0 thru 2, and Code 6 is 0 or 1.
IX. Appendix D

IX.A. Relay Specifications

Series DC60
3-7Amp - 60 Vdc - DC Output

- Cost Effective
- Industry Standard Package
- AC or DC Control
- Panel Mount

Bipolar transistor outputs are available in 3.6 and 7 amp ratings. Cost-effective relays offer 4000 Volt isolation and come in Crydom's standard panel-mount package. Manufactured in Crydom's ISO 9001 Certified facility for optimum product performance and reliability.

<table>
<thead>
<tr>
<th>MODEL NUMBERS</th>
<th>DC CONTROL</th>
<th>AC CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DC60S3</td>
<td>DC60S5</td>
</tr>
<tr>
<td>OUTPUT SPECIFICATIONS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Voltage Range [Vdc]</td>
<td>3-60</td>
<td>3-60</td>
</tr>
<tr>
<td>Load Current Range [A]</td>
<td>0.2-3</td>
<td>0.2-5</td>
</tr>
<tr>
<td>Max. Surge Current [A]</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Max. On-State Voltage Drop @ Rated Current [Vdc]</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Thermal Resistance Junction to Case (@25°C) [°C/W]</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Max. Off-State Leakage Current @ Rated Voltage [mA]</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Max. Turn-On Time [ms]</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Max. Turn-Off Time [ms]</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

INPUT SPECIFICATIONS | DC CONTROL | AC CONTROL |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Voltage Range</td>
<td>3.5-32 Vdc</td>
<td>90-200 Vrms</td>
</tr>
<tr>
<td>Max. Turn-On Voltage</td>
<td>3.5 Vdc</td>
<td>90 Vrms</td>
</tr>
<tr>
<td>Min. Turn-Off Voltage</td>
<td>1.0 Vdc</td>
<td>10 Vrms</td>
</tr>
<tr>
<td>Nominal Input Impedance</td>
<td>1500 Ohms</td>
<td>60k Ohms</td>
</tr>
<tr>
<td>Typical Input Current</td>
<td>2.2mA @ 5 Vdc</td>
<td>2mA @ 120 Vrms, 4mA @ 240 Vrms</td>
</tr>
</tbody>
</table>

GENERAL NOTES

1. All parameters at 25°C unless otherwise specified.
2. Heat sinking required, for ratings, see page 2.
Series DC60
3-7Amp • 60Vdc • DC Output

GENERAL SPECIFICATIONS
Dielectric Strength 5060Hz (Input/Output, base) 4000Vrms
Insulation Resistance (Min.) @ 500Vdc 1000MΩ
Max. Capacitance Input/Output 8pF
Ambient Operating Temperature Range -30 to 80°C
Ambient Storage Temperature Range -30 to 125°C

MECHANICAL SPECIFICATIONS
Weight (typical) 3.0 oz. (85 g)
Encapsulation: Thermally Conductive Epoxy
Terminals: Screws and Saddle Clamps Furnished, Unmounted

Transient Protection
All loads are inductive; overcurrent that are not so labeled. An inductive load will produce harmful transient voltages when it is turned off. Initially, they have a low resistance type with IH rated greater than supply voltage.

Crydom Heat Sinks offer excellent thermal management and are perfectly matched to the load current ratings of Crydom panel mount relays. Request. Crydom’s Heat Sink specification sheet for all the details.

© 2006 CRYDOM CORP. Specifications subject to change without notice.
X. Appendix E

X.A. Six Stroke ECU Code

/*------------------
This program was written by Andrew DeJong and Tim Opperwall of
Calvin College, 20 Nov 2009
*/

// allocate input and output pins
int toothcountpin = 2;  // tooth counting pin - digital
//int resetpin = 0;      // reset pin - digital
int intakepin = 11;     // intake valve output - digital
int intakepinclose = 10;
int exhaustpin = 13;    // exhaust valve output - digital
int exhaustpinclose = 12;  // exhaust valve output - digital
int injectorpin = 7;    // injector pin output - digital
int temppin = 0;        // read in the thermocouple temp to analog 0

// allocate all variables
int window = 40;        // time window (in deg) to ensure that pin in written at least once
boolean previouscount = false;  // previous input from the tooth counter
boolean currentcount = false;   // current input from the tooth counter - digital
double crankspeed;        // rotational speed of crank shaft
double clk1, clk2, clk3, clk4 = 0;   // time between tooth counts
double currentangle;      // current rotation angle of crank shaft
double resettime;         // time at last reset
double currenttime;       // current time since last reset
int strokeid=1;           // 1=strokes 1 and 2; 2=strokes 3 and 4; 3=strokes 5 and 6;
int strokeidea=1;
int toothid=1;            // which tooth is currently on
double interrupttime;     // most recent time in loop for use in interrupt
double temperature = 20;       //base temp

//set the temperature in degrees C for which the engine would begin to switch to 6-stroke cycle
double steamtemp = 21;       //in degrees C

// setup() runs once to ID the pins and interrupts
void setup() {
    pinMode(toothcountpin, INPUT);
    //pinMode(resetpin, INPUT);
    pinMode(intakepin, OUTPUT);
    pinMode(intakepinclose, OUTPUT);
    pinMode(exhaustpin, OUTPUT);
    pinMode(exhaustpinclose, OUTPUT);
    pinMode(injectorpin, OUTPUT);
    Serial.begin(57600);
    pinMode(temppin, INPUT);

    //attachInterrupt(0,reset,RISING); // call function reset() whenever reset pin rises
    attachInterrupt(0,timing,RISING); // call function timing() whenever toothcountpin rises
}

// loop() runs continuously when the chip is active
void loop(){
    currenttime=millis()-resett ime; //Calculates how long since the last cycle reset
    currentangle = crankspeed*currenttime; //Converts time into a piston position
    Serial.println(currentangle);      //Outputs the current piston position

    // Serial.println(crankspeed);       //Ouputs the calculated speed
    interrupttime = millis();           //Finds the current time

    switch(strokeid){                  //Switches between strokes 1/2,2/3, and 5/6

    }
case 1: //Used for Strokes 1 and 2
    // Serial.println("case 1");
    if(currentangle<(0+window)){ //The intake starts closing at 125deg, but cannot cannot fully close before 180
        digitalWrite(intakepin,HIGH);
        // Serial.println("1001");
        digitalWrite(intakepinclose,LOW); //Writes value to output pin
        // Serial.println("1004"); //Writes value to text output
        digitalWrite(exhaustpin,LOW);
        // Serial.println("1006");
        digitalWrite(exhaustpinclose,HIGH);
        // Serial.println("1007");
    }
    else if(currentangle<(175));
    else if(currentangle<(175+window)){
        digitalWrite(intakepin,LOW);
        digitalWrite(intakepinclose,HIGH);
        // Writes value to output pin
        // Serial.println("1002"); // Writes value to text output
        // Serial.println("1003");
    }
    break;

case 2:
    // Serial.println("case 2");
    if(currentangle<140);
    else if(currentangle<(140+window)){ // The exhaust startss closing at 255deg, but cannot fully close before 360
        digitalWrite(exhaustpin, HIGH);
        // Serial.println("1005");
        digitalWrite(exhaustpinclose, LOW); // Writes value to output pin
        // Serial.println("1006");
        digitalWrite(exhaustpinclose, HIGH);
        // Serial.println("1007");
    }
    else if(currentangle<(175+window)){ // The intake starts closing at 125deg, but cannot cannot fully close before 180
        digitalWrite(intakepin,HIGH);
        // Serial.println("1001");
        digitalWrite(intakepinclose,LOW); //Writes value to output pin
        // Serial.println("1004"); //Writes value to text output
        digitalWrite(exhaustpin,LOW);
        // Serial.println("1006");
        digitalWrite(exhaustpinclose,HIGH);
        // Serial.println("1007");
    }
    else if(currentangle<(175+window)){ // The exhaust startss closing at 255deg, but cannot fully close before 360
        digitalWrite(intakepin,LOW);
        digitalWrite(intakepinclose,HIGH);
        // Writes value to output pin
        // Serial.println("1002"); // Writes value to text output
        // Serial.println("1003");
    }
    break;
Serial.println("1008");  // Writes value to text output
}
else if(currentangle<(355));
else if(currentangle<(355+window)){
digitalWrite(exhaustpin, LOW);
Serial.println("1006");
digitalWrite(exhaustpinclose, HIGH);
Serial.println("1008");
}
break;
case 3:
Serial.println("case 3");
if(currentangle<(20)){
digitalWrite(exhaustpin,LOW);
Serial.println("1006");
digitalWrite(exhaustpinclose,HIGH);  // Writes value to output pin
Serial.println("1007");  // Writes value to text output
digitalWrite(injectorpin, HIGH);
Serial.println("1009");
}
else if(currentangle<140){
digitalWrite(injectorpin, LOW);
Serial.println("1010");
}
else if(currentangle<(140+window)){  // The exhaust starts closing at 255deg, but cannot fully close before 360
digitalWrite(exhaustpin, HIGH);
Serial.println("1005");
digitalWrite(exhaustpinclose, LOW);
Serial.println("1008");
}
else if(currentangle<(355));
else if(currentangle<(355+window)){
    digitalWrite(exhaustpin, LOW);  // Writes value to output pin
    // Serial.println("1006");  // Writes value to text output
    digitalWrite(exhaustpinclose, LOW);
    // Serial.println("1008");
    }
    break;
}

// reset() runs whenever the resetpin rises
/*
void reset(){
    currentangle=0;
    switch(strokeid){
        case 1:
            strokeid=2;
            break;
        case 2:
            strokeid=1;
            break;
    }
}
*/

// timing() runs whenever the toothcountpin rises, this interrupts the other loop
// This acts as a reset whenever the piston passes TDC
void timing(){
    // switch(toothid){
// case 1:
    currentangle=0;
temperature = analogRead(temppin)/2.048;  //degrees Celsius from thermocouple
if((interrupttime - resettime)<1){
    return;
}
    resettime=interrupttime;
    strokeidea=strokeid;
    switch(strokeidea){
        case 1:
            strokeid=2;       //If the current cycle is "1", switch to "2"

            Serial.println("12");
            break;

        case 2:
            if(temperature > steamtemp){
                strokeid=3;       //If the current cycle is "1", switch to "2"

                Serial.println("13");
            }
            else{
                strokeid=1;       //If the current cycle is "1", switch to "2"

                Serial.println("11");
            }
            break;

        case 3:
            strokeid=1;       //If the current cycle is "1", switch to "2"

            Serial.println("11");
            break;
    }
// toothid=2;
//    Serial.println("case1");
//    break;
// case 2:
//  toothid=3;
//  // Serial.println("case2");
//  break;
//  case 3:
//  toothid=4;
//   // Serial.println("case3");
//  break;
//  case 4:
//  toothid=1;
//   // Serial.println("case4");
//  break;
// }

//Now it calculates the speed the driveshaft is spinning
  clk1=clk2;
  clk2=clk3;
  clk3=clk4;
  clk4 = (interrupttime);
  //Serial.println(clk1);
  //Serial.println(clk2);
  //Serial.println(clk3);
  //Serial.println(clk4);
  crankspeed = 360/(clk4-clk3);  //speed of crankshaft, in deg/sec
  // Serial.println(crankspeed);
//Now it returns to the Loop above, until the next time the sensor it tripped
}
XI. Appendix F

XI.A. Thermodynamic Calculations

"Team 14 || 6 Stroke"
"Thermodynamic Analysis of 6 Stroke engine"

"Design Variables and Constraints"
- bore = 90 [mm]
- stroke = 66 [mm]
- \( r = 8 \)
- \( \omega_{\text{engine}} = 3000 \) [1/min]
- \( k_{\text{air}} = 1.4 \)
- \( m_{\text{fuel}[1]} = 0.0047 \) [g]
- \( H_{\text{c_fuel}} = 47 \) [kJ/g]
- \( \eta_{\text{comb}} = 0.5 \)
- \( T[6] = 900 \) [K]
- \( n_{\text{water}[7]} = n_{\text{fuel}[1]}/3 \)
- \( T[10] = 350 \) [K]

"Calculated Properties and Constants"
- \( V_{\text{BDC}} - V_{\text{TDC}} = \pi \left( \frac{\text{bore}}{2} \right)^2 \times \text{stroke} \times \text{convert} (\text{mm}^3, \text{L}) \)
- \( V_{\text{TDC}} = 0.057 \times \text{convert} (\text{in}, \text{mm}) \times 1.5 \times \pi \left( \frac{\text{bore}}{2} \right)^2 \times \text{convert} (\text{mm}^3, \text{L}) + 45 \times \text{convert} (\text{mL}, \text{L}) \)
- \( \eta_{\text{th}} = 1 - \frac{T[1]}{T[2]} \)
- \( C_v_{\text{air}} = C_v(\text{air, } t = T[2]) \)

"Statepoint 0: Atmosphere"
- \( \text{Cycle}_0 = \text{Atmospheric} \)
- \( T[0] = 298 \) [K]
- \( P[0] = 101.3 \) [kPa]
- \( x_{\text{co2}[0]} = 0.003 \)
- \( x_{\text{n2}[0]} = 0.7748 \)
- \( x_{\text{o2}[0]} = 0.2059 \)
- \( x_{\text{h2o}[0]} = 0.019 \)
- \( \text{humrat} = x_{\text{h2o}[0]} \times \text{molarmass(water)} / \text{molarmass(air)} \)
- \( \rho_{\text{air}[0]} = \text{density(airH2O, } t = T[0], p = P[0], \text{w = humrat}) \)

"Statepoint 1: Intake"
- \( \text{Cycle}_1 = \text{Intake} \)
- \( T[1] = T[0] \)
- \( P[1] = P[0] \)
- \( V[1] = V_{\text{BDC}} \times \text{convert} (\text{L, m}^3) \)

- \( \text{MM_fuel} = \text{molarmass(n-octane)} \)
- \( \rho_{\text{fuel}[1]} = \text{density(n-octane, } t = T[1], p = P[1]) \)
- \( n_{\text{fuel}[1]} = m_{\text{fuel}[1]} / \text{MM_fuel} \)
- \( V_{\text{fuel}[1]} = m_{\text{fuel}[1]} \times \text{convert}(\text{g, kg}) / \rho_{\text{fuel}[1]} \)

- \( V_{\text{air}[1]} = V[1] - V_{\text{fuel}[1]} \)
- \( \rho_{\text{air}[1]} = \rho_{\text{air}[0]} \)
- \( m_{\text{air}[1]} = V_{\text{air}[1]} \times \rho_{\text{air}[1]} \times \text{convert(\text{kg, g})} \)
\[ x_{\text{co}2[1]}=x_{\text{co}2[0]} \]
\[ x_{n2[1]}=x_{n2[0]} \]
\[ x_{o2[1]}=x_{o2[0]} \]
\[ x_{h2o[1]}=x_{h2o[0]} \]

\[ n_{\text{air}[1]}=n_{\text{air}[1]}/(x_{\text{co}2[0]}*\text{molarmass(co2)}+x_{n2[0]}*\text{molarmass(n2)}+x_{o2[0]}*\text{molarmass(o2)}+x_{h2o[0]}*\text{molarmass(h2o)}) \]
\[ n_{\text{co}2[1]}=n_{\text{air}[1]}*x_{\text{co}2[1]} \]
\[ n_{n2[1]}=n_{\text{air}[1]}*x_{n2[1]} \]
\[ n_{o2[1]}=n_{\text{air}[1]}*x_{o2[1]} \]
\[ n_{h2o[1]}=n_{\text{air}[1]}*x_{h2o[1]} \]

\[ h_{\text{air}[1]}=x_{\text{co}2[1]}*\text{enthalpy(co2,t=}\text{T}[1])+x_{n2[1]}*\text{enthalpy(n2,t=}\text{T}[1])+x_{o2[1]}*\text{enthalpy(o2,t=}\text{T}[1])+x_{h2o[1]}*\text{enthalpy(h2o,t=}\text{T}[1]) \]
\[ s_{\text{air}[1]}=x_{\text{co}2[1]}*\text{entropy(co2,t=}\text{T}[1],p=x_{\text{co}2[1]}*\text{P}[1])+x_{n2[1]}*\text{entropy(n2,t=}\text{T}[1],p=x_{n2[1]}*\text{P}[1])+x_{o2[1]}*\text{entropy(o2,t=}\text{T}[1],p=x_{o2[1]}*\text{P}[1])+x_{h2o[1]}*\text{entropy(h2o,t=}\text{T}[1],p=x_{h2o[1]}*\text{P}[1]) \]

""Statepoint 2: Compressed"
Cycle$[2]='2.\text{Compressed}'
P[2]=P[1]*r
V[2]=V_{\text{TDC}}*\text{convert(L,m}^3)\]

"assumes ideal compression"
\[ V_{\text{fuel}[2]}=V_{\text{fuel}[1]} \]
\[ V_{\text{air}[2]}=V[2]-V_{\text{fuel}[2]} \]
\[ n_{\text{fuel}[2]}=n_{\text{fuel}[1]} \]
\[ m_{\text{fuel}[2]}=m_{\text{fuel}[1]}*\text{convert(g,kg)/V}_{\text{fuel}[2]} \]
\[ n_{\text{air}[2]}=n_{\text{air}[1]} \]
\[ m_{\text{air}[2]}=m_{\text{air}[1]} \]
\[ \text{rho}_{\text{fuel}[2]}=m_{\text{fuel}[2]}*\text{convert(g,kg)/V}_{\text{fuel}[2]} \]
\[ n_{\text{fuel}[2]}=n_{\text{fuel}[1]} \]
\[ m_{\text{fuel}[2]}=m_{\text{fuel}[1]}*\text{convert(g,kg)/V}_{\text{fuel}[2]} \]
\[ n_{\text{co2}[2]}=n_{\text{air}[2]}*x_{\text{co2}[2]} \]
\[ n_{n2}[2]=n_{\text{air}[2]}*x_{n2[2]} \]
\[ n_{o2}[2]=n_{\text{air}[2]}*x_{o2[2]} \]
\[ n_{h2o[2]}=n_{\text{air}[2]}*x_{h2o[2]} \]
\[ s_{\text{air}[2]}=s_{\text{air}[1]} \]

"assumes isentropic compression"
\[ h_{\text{air}[2]}=x_{\text{co2}[2]}*\text{enthalpy(co2,t=}\text{T}[2])+x_{n2[2]}*\text{enthalpy(n2,t=}\text{T}[2])+x_{o2[2]}*\text{enthalpy(o2,t=}\text{T}[2])+x_{h2o[2]}*\text{enthalpy(h2o,t=}\text{T}[2]) \]
\[ w_{\text{12}}=Cv_{\text{air}}*(T[2]-T[1])*m_{\text{air}[2]}*\text{convert(g,kg)} \]

""Statepoint 3: Combusted"
Cycle$[3]='3a.\text{Combusted}'
\[ n_{\text{fuel}[2]}*\text{C8H18} + n_{n2}[2]*\text{N2} + n_{o2}[2]*\text{O2} + n_{\text{CO2}[2]}*\text{CO2} + n_{h2o[2]}*\text{H2O} \rightarrow n_{\text{fuel}[3]}*\text{C8H18} + n_{n2}[3]*\text{N2} + n_{o2}[3]*\text{O2} + n_{\text{CO2}[3]}*\text{CO2} + n_{h2o[3]}*\text{H2O} \]
\[ V[3]=V_{\text{TDC}}*\text{convert(L,m}^3) \]
$V_{air[3]}=V[3]$
$V_{fuel[3]}=V[3]$

"Fuel Balance"
$n_{fuel[3]} = (1-\eta_{comb})\cdot n_{fuel[2]}$

"Carbon Balance"
$n_{fuel[2]}\cdot 8+n_{co2[2]}\cdot 1 = n_{fuel[3]}\cdot 8+n_{co2[3]}\cdot 1$

"Hydrogen Balance"
$n_{fuel[2]}\cdot 18+n_{h2o[2]}\cdot 2 = n_{fuel[3]}\cdot 18+n_{h2o[3]}\cdot 2$

"Oxygen Balance"
$n_{o2[2]}\cdot 2+n_{h2o[2]}\cdot 1+n_{co2[2]}\cdot 2 = n_{o2[3]}\cdot 2+n_{h2o[3]}\cdot 1+n_{co2[3]}\cdot 2$

"Nitrogen Balance"
$n_{n2[2]}\cdot 2 = n_{n2[3]}\cdot 2$

$n_{air[3]}=n_{co2[3]}+n_{n2[3]}+n_{o2[3]}+n_{h2o[3]}$
$x_{co2[3]}=n_{co2[3]}/n_{air[3]}$
$x_{n2[3]}=n_{n2[3]}/n_{air[3]}$
$x_{o2[3]}=n_{o2[3]}/n_{air[3]}$
$x_{h2o[3]}=n_{h2o[3]}/n_{air[3]}$

$m_{air[3]}=n_{air[3]}\cdot (x_{co2[3]}\cdot \text{molarmass}(co2)+x_{n2[3]}\cdot \text{molarmass}(n2)+x_{o2[3]}\cdot \text{molarmass}(o2)+x_{h2o[3]}\cdot \text{molarmass}(h2o))$

$m_{fuel[3]}=n_{fuel[3]}\cdot \text{molarmass}(n-octane)$

$\rho_{air[3]}=m_{air[3]}\cdot \text{convert(g,kg)}/V_{air[3]}$

$\rho_{fuel[3]}=m_{fuel[3]}\cdot \text{convert(g,kg)}/V_{fuel[3]}$

$h_{air[3]}=x_{co2[3]}\cdot \text{enthalpy(co2, t=T[3])}+x_{n2[3]}\cdot \text{enthalpy(n2, t=T[3])}+x_{o2[3]}\cdot \text{enthalpy(o2, t=T[3])}+x_{h2o[3]}\cdot \text{enthalpy(h2o, t=T[3])}$

$s_{air[3]}=x_{co2[3]}\cdot \text{entropy(co2, t=T[3], p=x_{co2[3]}\cdot P[3])}+x_{n2[3]}\cdot \text{entropy(n2, t=T[3], p=x_{n2[3]}\cdot P[3])}+x_{o2[3]}\cdot \text{entropy(o2, t=T[3], p=x_{o2[3]}\cdot P[3])}+x_{h2o[3]}\cdot \text{entropy(h2o, t=T[3], p=x_{h2o[3]}\cdot P[3])}$

$h_{fuel[3]}=\text{enthalpy(c8h18, t=T[3])}$

$s_{fuel[3]}=\text{entropy(c8h18, t=T[3], p=P[3])}$

"Statepoint 4: Expanded"
Cycle$[4] \equiv \text{3b. Expanded}$
$V[4]=V_{BDC \cdot convert(L,m^3)}$
$V_{air[4]}=V[4]$
$V_{fuel[4]}=V[4]$

$n_{air[4]}=n_{air[3]}$
$m_{air[4]}=m_{air[3]}$
$rho_{air[4]}=m_{air[4]}\cdot \text{convert(g,kg)}/V_{air[4]}$

$x_{co2[4]}=x_{co2[3]}$

$n_{co2[4]}=n_{co2[3]}\cdot x_{co2[4]}$

$x_{n2[4]}=x_{n2[3]}$

$n_{n2[4]}=n_{air[4]}\cdot x_{n2[4]}$

$x_{o2[4]}=x_{o2[3]}$

$n_{o2[4]}=n_{air[4]}\cdot x_{o2[4]}$

$x_{h2o[4]}=x_{h2o[3]}$

$n_{h2o[4]}=n_{air[4]}\cdot x_{h2o[4]}$

$m_{fuel[4]}=m_{fuel[3]}$
$rho_{fuel[4]}=m_{fuel[4]}\cdot \text{convert(g,kg)}/V_{fuel[4]}$

-w_{34}=Cv_{air} \cdot (T[4]-T[3]) \cdot m_{air[3]} \cdot \text{convert(g,kg)}$

$w_{\text{net}}=w_{12}+w_{34}$

$W_{\text{dot_net}}=w_{\text{net}} \cdot \omega_{\text{engine}} \cdot \text{convert(sec,min)} \cdot \text{convert(kJ/s, hp)}$
6 Stroke

h_air[4]=x_co2[4]*enthalpy(co2,t=T[4])+x_n2[4]*enthalpy(n2,t=T[4])+x_o2[4]*enthalpy(o2,t=T[4])+x_h2o[4]*enthalpy(h2o,t=T[4])

s_air[4]=x_co2[4]*entropy(co2,t=T[4],p=x_co2[4]*P[4])+x_n2[4]*entropy(n2,t=T[4],p=x_n2[4]*P[4])+x_o2[4]*entropy(o2,t=T[4],p=x_o2[4]*P[4])+x_h2o[4]*entropy(h2o,t=T[4],p=x_h2o[4]*P[4])

h_fuel[4]=enthalpy(c8h18,t=T[4])

s_fuel[4]=entropy(c8h18,t=T[4],p=P[4])

"Statepoint 5: Exhaust Opened"
P[5]=P[0]
V[5]=V_BDC*convert(L,m^3)

m_air[5]=m_air[4]
rho_air[5]=m_air[5]*convert(g,kg)/V_air[5]
rho_fuel[5]=m_fuel[5]*convert(g,kg)/V_fuel[5]

h_air[5]=x_co2[5]*enthalpy(co2,t=T[5])+x_n2[5]*enthalpy(n2,t=T[5])+x_o2[5]*enthalpy(o2,t=T[5])+x_h2o[5]*enthalpy(h2o,t=T[5])

s_air[5]=x_co2[5]*entropy(co2,t=T[5],p=x_co2[5]*P[5])+x_n2[5]*entropy(n2,t=T[5],p=x_n2[5]*P[5])+x_o2[5]*entropy(o2,t=T[5],p=x_o2[5]*P[5])+x_h2o[5]*entropy(h2o,t=T[5],p=x_h2o[5]*P[5])

h_fuel[5]=enthalpy(c8h18,t=T[5])

s_fuel[5]=entropy(c8h18,t=T[5],p=P[5])

"Statepoint 6: Exhausted"
P[6]=P[0]
V[6]=V_TDC*convert(L,m^3)

n_air[6]=P[6]*V[6]/(R*T[6])*convert(kmol,mol)
m_air[6]=m_air[5]
rho_air[6]=m_air[6]*convert(g,kg)/V_air[6]
x_co2[6]=x_co2[5];
x_n2[6]=x_n2[5];
x_o2[6]=x_o2[5];
x_h2o[6]=x_h2o[5];

h_air[6]=x_co2[6]*enthalpy(co2,t=T[6])+x_n2[6]*enthalpy(n2,t=T[6])+x_o2[6]*enthalpy(o2,t=T[6])+x_h2o[6]*enthalpy(h2o,t=T[6])

s_air[6]=x_co2[6]*entropy(co2,t=T[6],p=x_co2[6]*P[6])+x_n2[6]*entropy(n2,t=T[6],p=x_n2[6]*P[6])+x_o2[6]*entropy(o2,t=T[6],p=x_o2[6]*P[6])+x_h2o[6]*entropy(h2o,t=T[6],p=x_h2o[6]*P[6])

h_fuel[6]=enthalpy(c8h18,t=T[6])
s_fuel[6]=entropy(c8h18,t=T[6],p=P[6])

"Statepoint 7: Water Injection"
V[7]=V_TDC*convert(L,m^3)
P[7]=2*P[0]
x_co2[7]=n_co2[7]/n_air[7]
x_n2[7]=n_n2[7]/n_air[7]
x_h2o[7]=n_h2o[7]/n_air[7]
m_air[7]=n_air[7]*molarmass(co2)+x_n2[7]*molarmass(n2)+x_o2[7]*molarmass(o2)+x_h2o[7]*molarmass(h2o))
rho_air[7]=m_air[7]*convert(g,kg)/V_air[7]
m_fuel[7]=0
n_fuel[7]=0
m_water[7]=n_water[7]*molarmass(water)
h_air[7]=x_co2[7]*enthalpy(co2,t=T[7])+x_n2[7]*enthalpy(n2,t=T[7])+x_o2[7]*enthalpy(o2,t=T[7])+x_h2o[7]*enthalpy(h2o,t=T[7])
s_air[7]=x_co2[7]*entropy(co2,t=T[7],p=x_co2[7]*P[7])+x_n2[7]*entropy(n2,t=T[7],p=x_n2[7]*P[7])+x_o2[7]*entropy(o2,t=T[7],p=x_o2[7]*P[7])+x_h2o[7]*entropy(h2o,t=T[7],p=x_h2o[7]*P[7])

"Statepoint 8: Expanded"
Cycle[8]='5b.Expanded'
V[8]=V_BDC*convert(L,m^3)
V_air[8]=V[8]
P[8]=P[0]
n_air[8]=n_air[7]
m_air[8]=m_air[7]
rho_air[8]=m_air[8]*convert(g,kg)/V_air[8]
x_co2[8]=x_co2[7];
x_n2[8]=x_n2[7];
x_o2[8]=x_o2[7];
x_h2o[8]=x_h2o[7];
n_co2[8]=n_co2[8]*x_co2[8]
n_n2[8]=n_n2[8]*x_n2[8]
n_o2[8]=n_o2[8]*x_o2[8]
n_h2o[8]=n_h2o[8]*x_h2o[8]
h_air[8]=x_co2[8]*enthalpy(co2,t=T[8])+x_n2[8]*enthalpy(n2,t=T[8])+x_o2[8]*enthalpy(o2,t=T[8])+x_h2o[8]*enthalpy(h2o,t=T[8])
s_air[8]=x_co2[8]*entropy(co2,t=T[8],p=x_co2[8]*P[8])+x_n2[8]*entropy(n2,t=T[8],p=x_n2[8]*P[8])+x_o2[8]*entropy(o2,t=T[8],p=x_o2[8]*P[8])+x_h2o[8]*entropy(h2o,t=T[8],p=x_h2o[8]*P[8])

"Statepoint 9: Exhaust Opened"
P[9]=P[0]
V[9]=V_BDC*convert(L,m^3)
\[ V_{\text{air[9]}} = V[9] \]

\[ n_{\text{air[9]}} = P[9] \times V[9]/(R\# \times T[9]) \times \text{convert(kmol,mol)} \]
\[ m_{\text{air[9]}} = n_{\text{air[9]}} \times \text{convert(g,kg)}/V_{\text{air[9]}} \]
\[ \rho_{\text{air[9]}} = m_{\text{air[9]}} \times \text{convert(g,kg)}/V_{\text{air[9]}} \]
\[ x_{\text{co2[9]}} = x_{\text{co2[8]}}; \quad n_{\text{co2[9]}} = n_{\text{air[9]}} \times x_{\text{co2[9]}} \]
\[ x_{\text{n2[9]}} = x_{\text{n2[8]}}; \quad n_{\text{n2[9]}} = n_{\text{air[9]}} \times x_{\text{n2[9]}} \]
\[ x_{\text{o2[9]}} = x_{\text{o2[8]}}; \quad n_{\text{o2[9]}} = n_{\text{air[9]}} \times x_{\text{o2[9]}} \]
\[ x_{\text{h2o[9]}} = x_{\text{h2o[8]}}; \quad n_{\text{h2o[9]}} = n_{\text{air[9]}} \times x_{\text{h2o[9]}} \]

\[ h_{\text{air[9]}} = x_{\text{co2[9]}} \times \text{enthalpy(co2,t=T[9])} + x_{\text{n2[9]}} \times \text{enthalpy(n2,t=T[9])} + x_{\text{o2[9]}} \times \text{enthalpy(o2,t=T[9])} + x_{\text{h2o[9]}} \times \text{enthalpy(h2o,t=T[9])} \]
\[ s_{\text{air[9]}} = x_{\text{co2[9]}} \times \text{entropy(co2,t=T[9],p=x_{\text{co2[9]}} \times P[9])} + x_{\text{n2[9]}} \times \text{entropy(n2,t=T[9],p=x_{\text{n2[9]}} \times P[9])} + x_{\text{o2[9]}} \times \text{entropy(o2,t=T[9],p=x_{\text{o2[9]}} \times P[9])} + x_{\text{h2o[9]}} \times \text{entropy(h2o,t=T[9],p=x_{\text{h2o[9]}} \times P[9])} \]

"!Statepoint 10: Re-Exhausted"
Cycle[10] = "6b.Re-Exhausted"
P[10] = P[0]
V[10] = V_{\text{TDC}} \times \text{convert(L,m^3)}
V_{\text{air[10]}} = V[10]

\[ n_{\text{air[10]}} = P[10] \times V[10]/(R\# \times T[10]) \times \text{convert(kmol,mol)} \]
\[ m_{\text{air[10]}} = n_{\text{air[10]}} \times \text{convert(g,kg)}/V_{\text{air[10]}} \]
\[ \rho_{\text{air[10]}} = m_{\text{air[10]}} \times \text{convert(g,kg)}/V_{\text{air[10]}} \]
\[ x_{\text{co2[10]}} = x_{\text{co2[9]}}; \quad n_{\text{co2[10]}} = n_{\text{air[10]}} \times x_{\text{co2[10]}} \]
\[ x_{\text{n2[10]}} = x_{\text{n2[9]}}; \quad n_{\text{n2[10]}} = n_{\text{air[10]}} \times x_{\text{n2[10]}} \]
\[ x_{\text{o2[10]}} = x_{\text{o2[9]}}; \quad n_{\text{o2[10]}} = n_{\text{air[10]}} \times x_{\text{o2[10]}} \]
\[ x_{\text{h2o[10]}} = x_{\text{h2o[9]}}; \quad n_{\text{h2o[10]}} = n_{\text{air[10]}} \times x_{\text{h2o[10]}} \]

\[ h_{\text{air[10]}} = x_{\text{co2[10]}} \times \text{enthalpy(co2,t=T[10])} + x_{\text{n2[10]}} \times \text{enthalpy(n2,t=T[10])} + x_{\text{o2[10]}} \times \text{enthalpy(o2,t=T[10])} + x_{\text{h2o[10]}} \times \text{enthalpy(h2o,t=T[10])} \]
\[ s_{\text{air[10]}} = x_{\text{co2[10]}} \times \text{entropy(co2,t=T[10],p=x_{\text{co2[10]}} \times P[10])} + x_{\text{n2[10]}} \times \text{entropy(n2,t=T[10],p=x_{\text{n2[10]}} \times P[10])} + x_{\text{o2[10]}} \times \text{entropy(o2,t=T[10],p=x_{\text{o2[10]}} \times P[10])} + x_{\text{h2o[10]}} \times \text{entropy(h2o,t=T[10],p=x_{\text{h2o[10]}} \times P[10])} \]