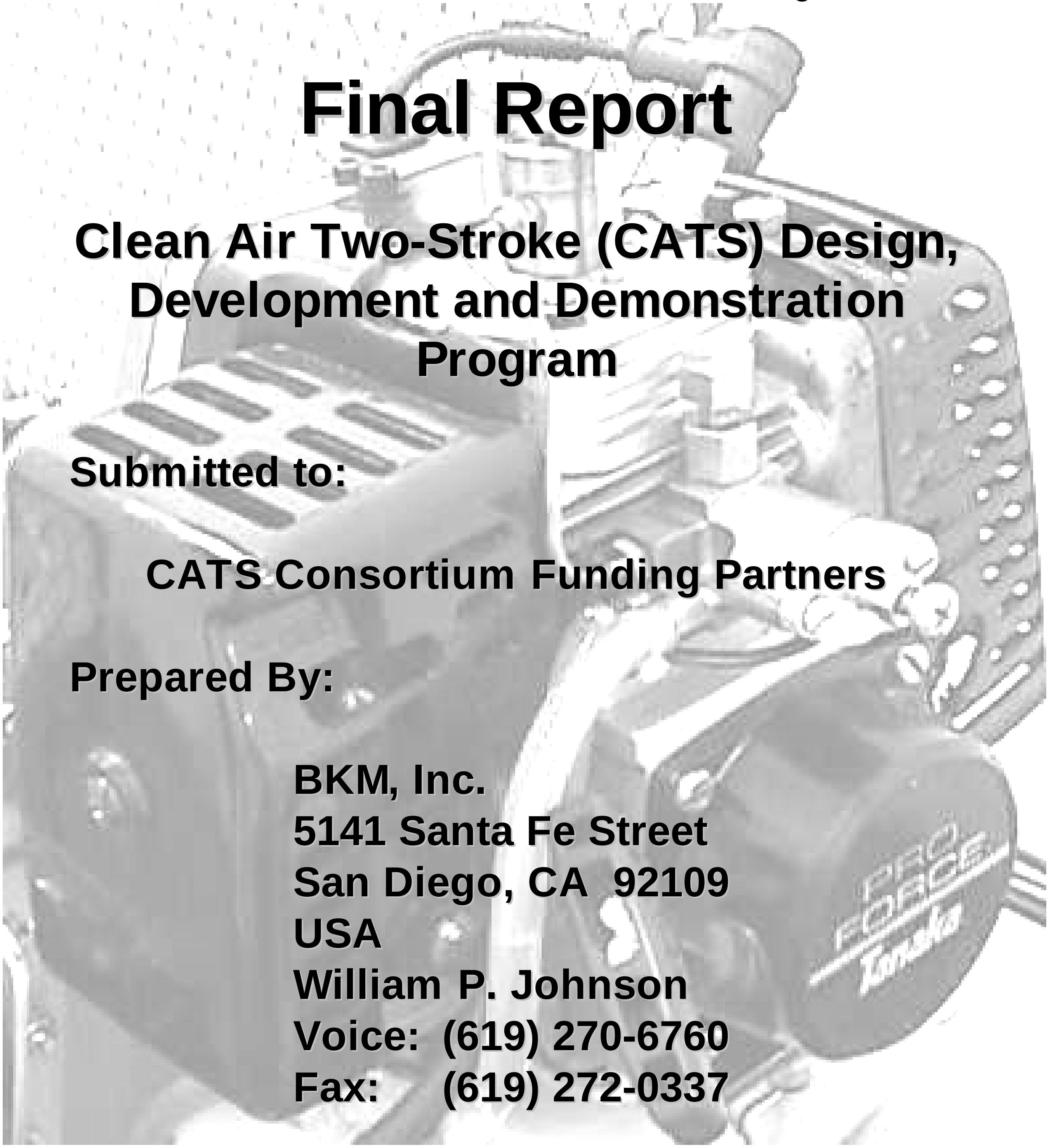
BKM, Inc.

BKM Report No. 990002
Date: 28 August, 1998



Final Report

Clean Air Two-Stroke (CATS) Design, Development and Demonstration Program

Submitted to:

CATS Consortium Funding Partners

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1. Introduction

1.1. Scope and Purpose

BKM has developed and demonstrated a prototype single cylinder engine based on a novel Electronic Direct Fuel Injection (EDFI) system tailored to small, low cost and high production volume two-stroke engines. By offering non-exclusive license options to several engine builders as well as attracting some public funding through the California Air Resources Board (CARB), BKM formed a funding consortium to develop and demonstrate this system. The recipients of this report are the consortium members who assisted with the funding and who have secured non-exclusive technology license options. We have demonstrated exhaust emissions compliance with CARB tier II regulations for the year 2000 and beyond for handheld utility engines. We have also completed preliminary testing on a 50cc moped installation. Suzuki Corporation in Japan is currently conduction additional testing on this 50cc engine. In another program, our license option holder in China, Honglin, is currently operating the system on a 125cc Nanfang motorcycle for demonstration to engine manufacturers within their country. Five samples of this 125cc motorcycle have been manufactured. Photographs of this accomplishment are included in Appendix A.

This report will provide license and license option holders who participated in the consortium program with detailed results of the design and development activity. While the contents of this report may be considered as technology transfer material, BKM acknowledges that true technology transfer must involve ongoing communication and cooperation for the benefit of all stakeholders in the technology.

1.2. Background

Due to the high power density and simple construction of the two-stroke cycle gasoline engine, it has been instrumental in the development of the two-wheeler transportation market, the outboard marine engine market and the handheld power equipment industry. However, the exhaust emissions from conventional two-stroke engines are very high due to the basic design and operating principles of the engine. These engines produce from 10 to 15 times the levels of unburned hydrocarbons compared to four-cycle engines.

In a conventional, carbureted two-stroke engine, the fuel air mixture is pumped into the cylinder during a portion of the cycle in which both the intake and exhaust ports are open. The primary activity during this portion of the engine cycle is the scavenging, or removal of combustion byproducts from the previous engine cycle. This process results in the loss of approximately 30% of the fuel, which escapes out the exhaust port prior to ignition. This loss of both fuel and fresh air is referred to as "scavenge loss". Figure 1 illustrates the scavenge loss of a contemporary two-stroke utility engine.

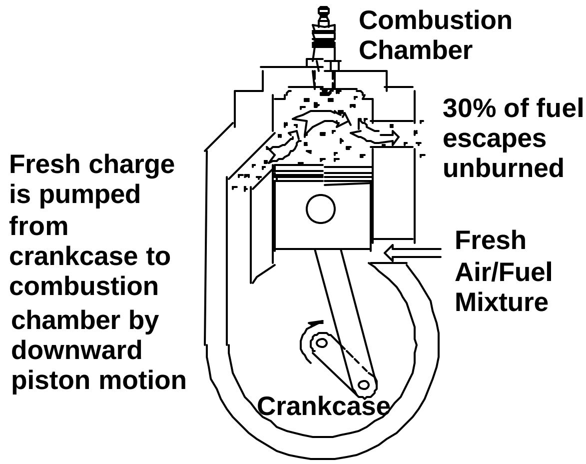

Figure 1 - Two-stroke Engine Scavenging Loss

The high level of exhaust emissions and poor fuel economy typical of small piston ported two-stroke spark ignited engines mandates the need for improved combustion over the operating range of the engine. Direct, in-cylinder injection has been demonstrated to significantly reduce unburned hydrocarbon emissions by timing the injection of fuel in such a way as to prevent the escape of unburned fuel from the exhaust port during the scavenging process.

Figure 2 illustrates the typical relationship between exhaust emissions and the air/fuel ratio, defined by the excess air factor lambda (λ). Lambda is the ratio between actual air/fuel ratio and stoichiometric air/fuel ratio. Stoichiometric air/fuel ratio is the theoretically perfect ratio for most efficient and complete burning. Lambda less than 1.0 is a rich mixture and lambda greater than 1.0 is a lean mixture.

$$l = \frac{(Air / Fuel)_{actual}}{(Air / Fuel)_{stoichiometric}}$$

In a naturally aspirated engine such as the low cost two-stroke, air supply is dependent on the piston motion and engine power is proportional to the amount of fuel burned. Therefore, a rich mixture increases power and a lean mixture reduces power.

As shown in Figure 2, many contemporary two-stroke engines operate in the range of 0.70 to 0.75 lambda in order to optimize power and reduce combustion temperature. Unfortunately, this condition results in very high CO emissions as well as adding to the already high unburned HC emissions. The Oxides of Nitrogen (NOx) emissions however, are very low due to the low temperature of this rich combustion mixture.

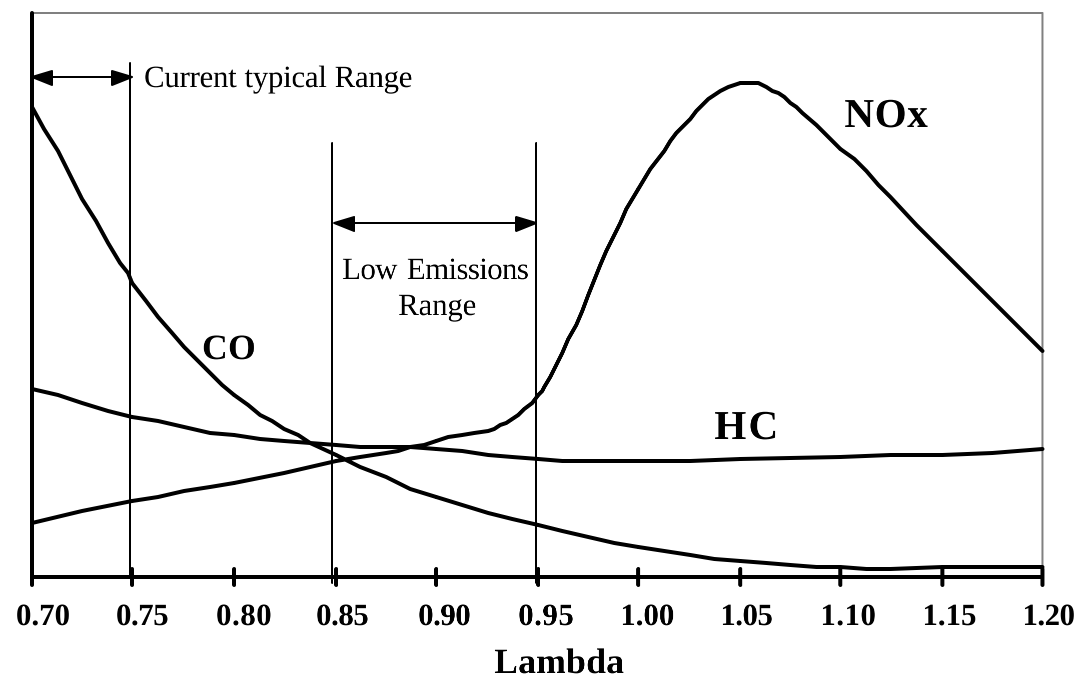

Figure 2 - Influence of Excess Air Factor, Lambda, on Emissions

Exhaust emissions can be minimized if lambda is very lean (greater than approximately 1.5). Such lean air/fuel ratios may be achievable using direct injection of fuel as proposed. However, without additional air charge boosting, maximum engine power is reduced to an unacceptable level. In the range of lambda 0.85 to 0.95, emissions can be minimized without significant power loss. It has been demonstrated that the combination of in-cylinder fuel injection (reduced scavenge loss) and operation in this air/fuel ratio range (λ=0.85-0.95) results in significantly reduced emissions levels.

Compounding the basic two-stroke inefficiencies described above, it is normal for crankcase scavenged two-stroke engines to misfire at part load. Part load operation of spark ignited engines involves reducing both the fuel flow and throttling the airflow through the engine in an attempt to maintain an ignitable, stoichiometric air/fuel mixture. Misfire at part load in a two-stroke engine is caused by the presence of residual exhaust gas, degraded scavenge efficiency and the resulting degraded air/fuel ratio control. This part load misfire contributes greatly to added unburned fuel emissions and increased fuel consumption. Direct in-cylinder injection alone does not solve this part load misfire problem.

The dynamic fueling range is another challenge for fuel injection equipment. The fuel injector must accommodate both the full load fueling rate, as well as the minimum fueling rate required to idle the engine. A major difficulty with conventional fuel injection concepts for small two-stroke engines is the inability to provide precise well-atomized fuel sprays at these very small fuel deliveries, particularly as fuel consumption and emissions are reduced.

1.3. Technical Approach

A cost effective hardware design and control method has been developed to operate low cost two-stroke spark ignited engines, which are fueled by electronically actuated accumulator type fuel injectors. This system is referred to as a Single Plunger System (SPS) to differentiate it from the BKM's previous Common Rail System (CRS) development for multi-cylinder engines. It is also now apparent that the SPS system may be desirable for multi-cylinder engines in order to achieve cylinder-to-cylinder fuel delivery trimming. During the project, the injection system hardware has been simplified compared to existing EDFI concepts, for compatibility with small engine market requirements. Prior to the CATS consortium program, BKM was granted U.S. Patent Number 5,438,968, which completely describes this low cost fuel system solution. In addition, BKM has been granted U.S. Patent Number 5,685,273 describing the preferred fuel delivery control method. Copies of these two primary patents are included in Appendix B.

1.3.1. Injector Operation

The BKM SPS electronic gasoline injector consists of three elements:

1. Solenoid valve
2. Accumulator
3. Nozzle tip

These elements are shown schematically in Figure 3.

Fuel pressure is provided to the injector by means of a single plunger pump, integrated into the engine design and timed to the engine cycle. Due to the compressibility of the fuel, the mass of fuel in the accumulator increases as the accumulator pressure increases. When the accumulator pressure and inlet fuel pressure equalize at the maximum inlet pressure value, a check valve at the accumulator entrance closes, thereby trapping high pressure fuel within the accumulator. The solenoid valve is the interface between the injector and the electronic controller. When the solenoid is energized, pressure on top of the needle valve is vented, and a pressure imbalance is produced across the needle valve, which lifts the needle and opens the nozzle tip to the fuel stored in the accumulator.

Injection takes place until the pressure in the accumulator drops to the needle valve closing pressure, preset by spring force. Injection duration depends only on total nozzle flow area and the pressure drop from peak pressure to needle

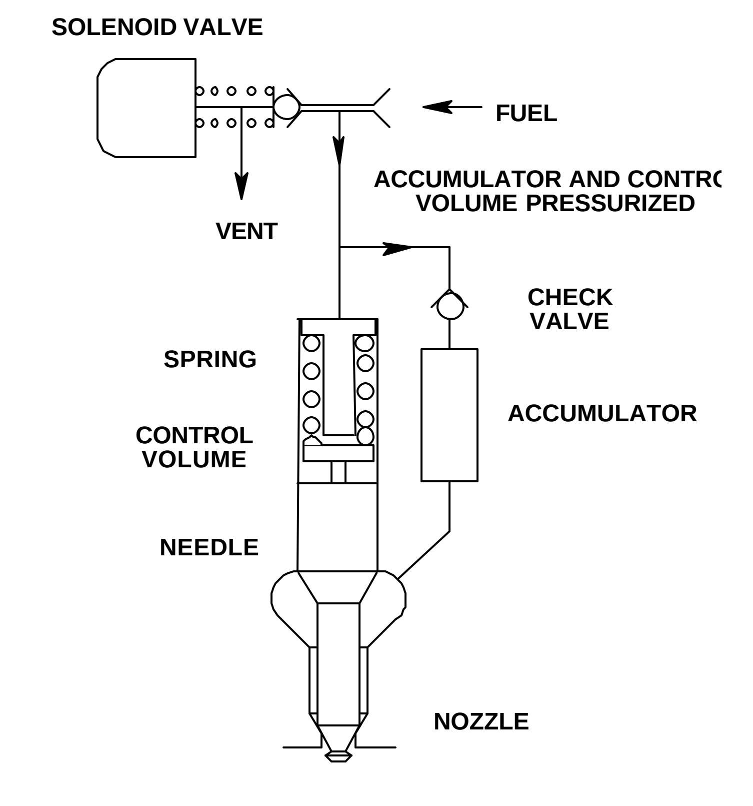

Figure 3 - Injector Schematic

closing pressure. The hydraulic system includes a single plunger pump providing pressurized fuel to the injector, and a return line from the injector to the low-pressure side of the system. Engine power or injection delivery is either controlled by the regulation of the rail pressure or by the "skip-fire" sequencing of injection events. For pressure regulation, holding the solenoid valve open longer than necessary from the previous injection event wastes a portion of the pump plunger motion, thereby limiting the pressure buildup to a calibrated value based on solenoid valve timing. This patented control method provides for both injection timing as well as injection quantity on a cycle-by-cycle basis. The injector charging event and control by pressure regulation are illustrated in Figure 4.

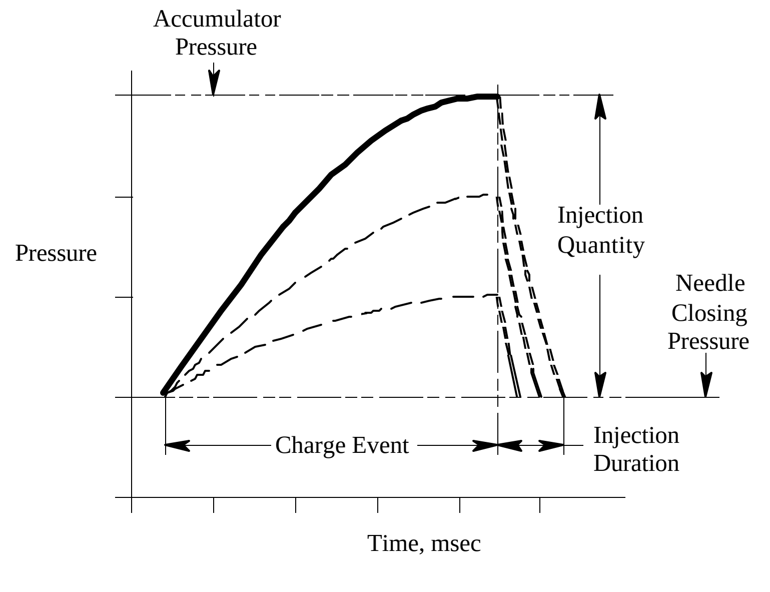

Figure 4 - Injector Charging and Pressure Metering

As mentioned above, the "skip-fire" sequencing of injection events can be used for control purposes. In its basic form, skip-fire is also used to provide improved combustion efficiency at part load operation. In this demonstration program, skip-fire has been limited to provide improved efficiency at idle only, with good results.

The SPS injector spray characteristic produces very small droplets of gasoline, which promotes good fuel and air mixing and consistent combustion. These small droplets are maintained by means of non-uniform velocity with respect to time, as illustrated in Figure 5. The first droplets leaving the nozzle have the fastest injection rate, followed by progressively slower rate droplets. BKM refers to this non-coalescing spray characteristic as "expanding cloud" fuel injection. The result is a finely atomized spray and optimized mixture preparation.

Advantages of this operating principle include the following:

- Simple, low cost hardware and design integration into the engine
- High operating speeds, since injector charging occurs over a large portion of the engine cycle
- Cycle-by-Cycle control of fuel delivery and injection timing
- Intermittent cycle injection (skip-fire) provides part load combustion improvement if desired (not used in tests results presented in this report)
- Spray quality at starting and low engine speeds is maximized because injection pressure and duration are independent of engine speed
- A non-coalescing “expanding cloud” injection spray results from the decreasing injection rate during the injection event
- Injection can occur mechanically, for starting without electric power.

An overall scheme of the fuel system is illustrated in Figure 6.

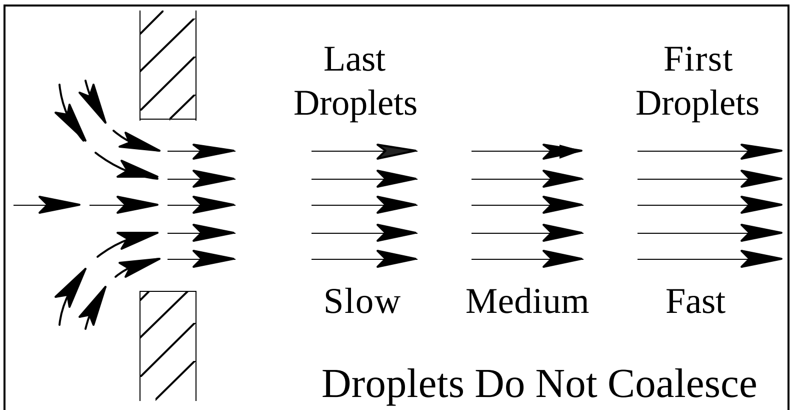

Figure 5 - Droplet Velocity

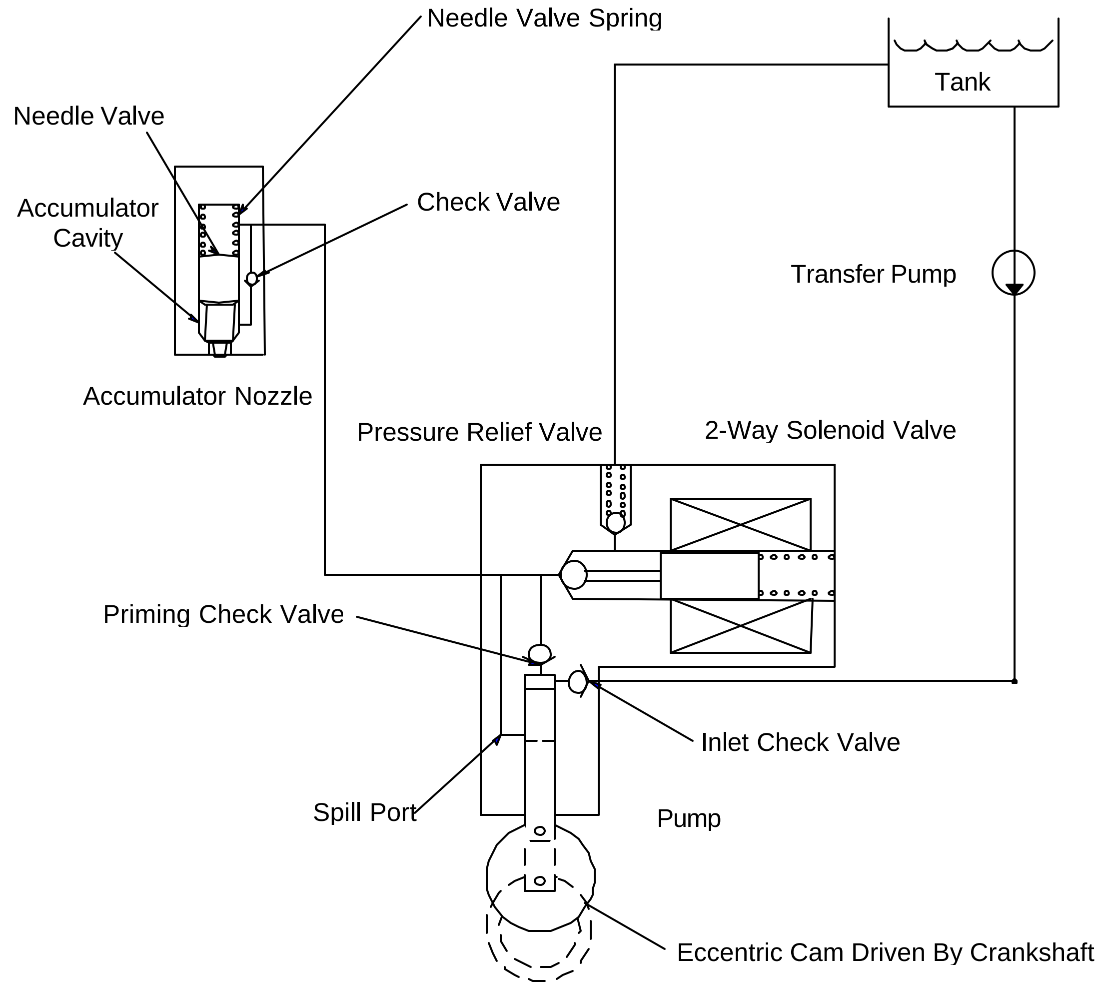

Figure 6 - Single Plunger System (SPS) Configuration

2. Prototype Development

The program was divided into the following tasks:

1. Bench Test and Development of Major Components
2. Design the Prototype Development Engine (46cc Tanaka utility engine)
3. Development of controls and software calibration
4. Prototype Manufacturing
5. Test Planning and Setup
6. Performance and Emissions Development
7. Additional 50cc Suzuki 2-wheeler project

2.1. Bench Test and Development of Major Components

2.1.1. Fuel Injection System

System concept design included the definition of basic fuel injector and pump components as well as variations to be evaluated, such as methods to control injection quantity. An option to initiate injection hydromechanically for starting was also examined. In each case, these design alternatives offer advantages and disadvantages which were evaluated.

An injection system bench test rig was designed and constructed for the functional development and parametric studies of injector and pump system. The objective of this unit was to provide a flexible test rig capable of determining the optimum placement of components, the advantages and disadvantages of design configuration variables, as well as establishing design criteria for the sizing, timing and tolerances to be used for subsequent engine design. Some of the design configuration variables were discussed above. Additional alternatives which merit study, such as the location of the injector solenoid valve related to the nozzle were included in the design of this flexible test rig.

A schematic for this injection system test rig is illustrated in Figure 7. The detail design, including cam drive and solenoid valve location alternatives, is shown in Figures 8 and 9.

A series of pump operational tests were conducted on the fuel system test rig. Results were encouraging, as the cycle-to-cycle peak pressure appeared to be controllable by a pressure relief valve as planned. These tests were conducted with the fuel lines to the injector blocked, to isolate the pump evaluation from the rest of the system. Problems with the inlet check valve, air entrainment (priming problems) and miscellaneous leaks were incurred and either corrected or compensated for, with solutions proposed for future design activity.

The system successfully demonstrated injection of fuel under engine starting conditions as well as high-speed operation. Initial design changes were incorporated and retested relating to cam and plunger durability improvement and cost reduction. Four areas of required development were identified and have been addressed in subsequent engine design activity.

1. The sensitivity of the adjustable peak pressure control regulator indicates that peak injection pressure control and therefore injector calibration will be difficult to achieve consistently with the current design. Revising the relief valve spring rate, seat area and the adjustment thread pitch, could develop a less sensitive pressure relief valve design. However, the need for rapid, cycle to cycle fuel delivery adjustment emphasized by commercial project partners has led to a revised fuel quantity control strategy using the existing solenoid valve. In this

strategy, holding the solenoid valve open longer than necessary from the previous injection event wastes a portion of the pump plunger motion, thereby limiting the pressure buildup to a calibrated value based on solenoid valve timing. This revised strategy was subsequently patented (U.S. No. 5,685,273) and incorporated in the control design.

2. The prototype solenoid valve appeared to stick open and fail to close under some operating conditions. This problem has been resolved by a revised electronic driver circuit design and was determined not to be a solenoid valve hardware issue. However, detail setup dimensions for the valve, such as spring pre-load, were determined to be critical for consistency of operation.

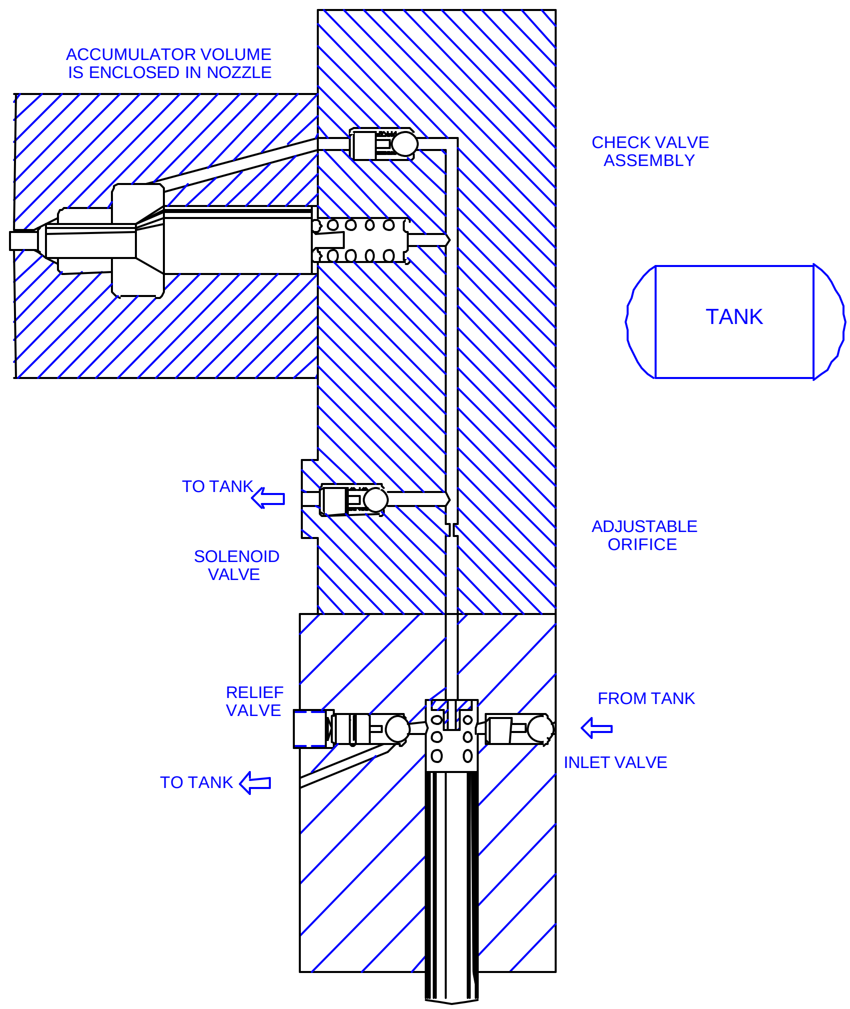

Figure 7 - Fuel Injection Bench Test Schematic

3. Priming the system with the original design of fluid passages proved to be unacceptably difficult. The addition of a check valve at the pump outlet provided

self-priming capability and has also been incorporated in the subsequent engine application design.

4. The addition of the self-priming check valve eliminated an important feature required for starting engines without the need for battery power. To compensate for this defect, an alternative hydromechanical starting feature, referred to as a spill port, requiring drilled holes in the pump housing was incorporated in the engine application design.

In order to prevent undue delay in the engine application design as well as risk to the project budget, the improvements proposed to the bench test injection system rig were incorporated directly into the test engine design for validation during subsequent engine testing.

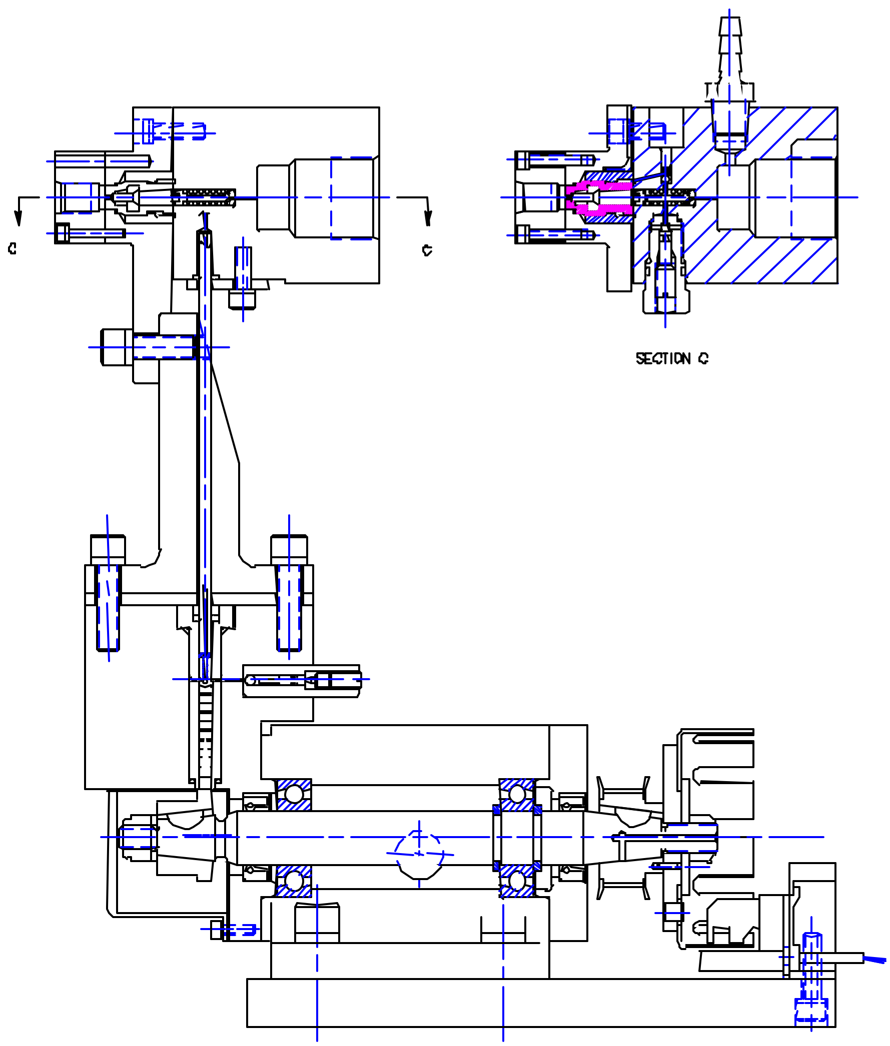

Figure 8 - Fuel Injection Bench Test Rig Design

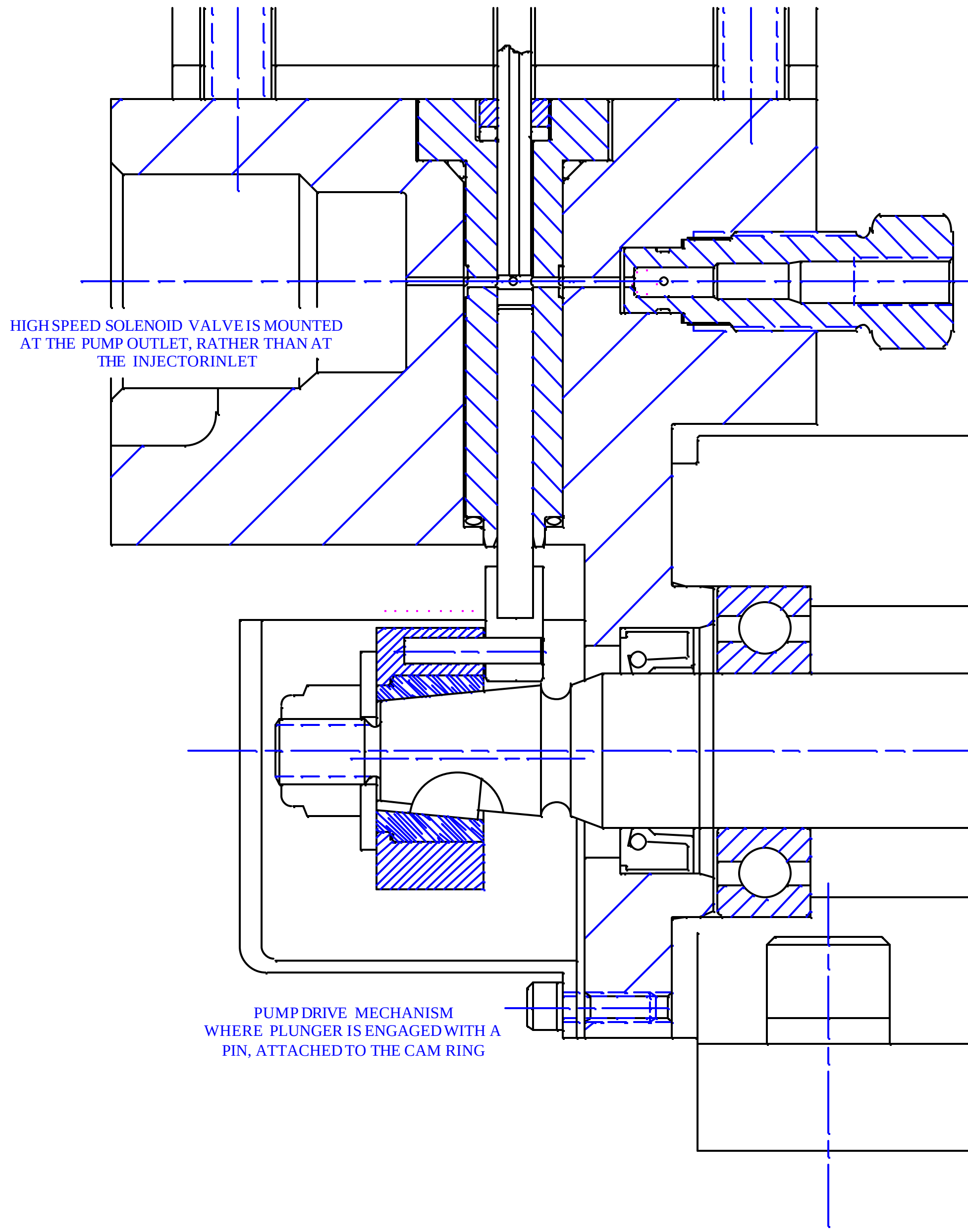

Figure 9 - Alternative Cam Drive Design and Solenoid Valve Location

2.1.2. High Speed Solenoid Valve

The high speed solenoid valve and a breadboard driver circuit for injector activation was designed in prototype form for development testing. Sample prototype valves were manufactured for testing. For this design, the following specification was developed:

Type	-	2-way normally closed
Rated pressure	-	14 MPa (2,000 psi)
Minimum Flow Area	-	0.5 mm^2
Function	-	Accumulator injector vent
Liquid compatibility	-	Gasoline
Life expectancy	-	4.0 x 10^8 cycles
Timing precision	-	± 25 microseconds
Response time	-	Less than 2.0 milliseconds
Operating frequency	-	10 to 250 Hz
Voltage	-	12 VDC
Power requirement	-	Less than 8 watts at 5 % duty cycle
	-	Less than 50 watts at 30% duty cycle
Storage temperature	-	-50 to + 105 ºC
Operating temperature	-	-40 to + 200 ºC
Mechanical shock	-	100 g
Mechanical vibration	-	50 g at 5 to 200 Hz
Humidity	-	100 %
Cost, including royalties (production rate greater than 500,000 units/year)	-	Less than $4.50

An instrumented test block was manufactured to allow testing with hydraulic pressure applied. Results of this initial test were encouraging as the frequency capability of the valve exceeded 300 Hz, which was faster than required for injector operation.

As previously discussed, the solenoid valve appeared to stick in the open position as well as fail to completely close under some injector operating conditions. The problem was symptomatic of an electronic driver circuit problem, which resulted in revised component specifications in the circuit design. Subsequent testing did not indicate continuation of the problem.

After initial functional testing, additional tests were conducted to study total energy consumption requirements for coordination with alternator power generation specifications and development testing targets. In addition, the revised fuel delivery control strategy previously mentioned warranted further study of valve opening and closing accuracy and delay periods. These tests were subsequently conducted with satisfactory results.

2.1.3. Lubrication System

Two different lubrication concepts were evaluated.

1. For the lowest cost engines, a venturi effect system was considered. This calibration involved determining a proper size inlet orifice between the oil supply sump and the engine intake air passage. A simple, low opening pressure check valve was placed in the oil supply line between sump and venturi. This system was similar in concept to the basic fuel control concept of a carburetor. The fuel injected project engine, based on an existing 46cc Tanaka brush cutter engine, was equipped with this lube oil system and calibrated for the required oil flow during subsequent engine testing.

2. In the case of motorbike or marine engines, several candidate engines for fuel injection already utilize a separate oil injection pump and oil reservoir. For these engines, no further design integration activity is anticipated other than calibrating the pumps for minimum oil flow rate requirement. This will be an engine specific calibration and will be delegated to individual engine builders.

A small, potentially low cost model of the oil injection pumps found on the more sophisticated engines was eventually identified. This pump is currently used on a 25cc Kioritz utility engine produced for applications in Japan. Coordination with the vendors Mikuni and Walbro have resulted in identifying the models applicable for low cost engines and samples were obtained. A design to integrate this pump into the Tanaka prototype fuel injected engine was completed.

2.1.4. Electronic Control Unit (ECU)

During the preliminary work on this project, prior to the CATS consortium program, a developmental circuit board had been designed. In the course of the CATS program, revisions to controller specifications related to control strategy resulted in reconsideration of the controller design. In addition, a more conservative approach to providing a controller in the early stages of fuel system development resulted. In order to accelerate availability of a development controller and to concentrate on software calibration and validation, a decision was made to conduct initial testing with an existing, commercial multi-cylinder engine controller designed specifically for control flexibility and laboratory calibration. In parallel with the calibration development using this large ECU, a new prototype small engine ECU was designed. This design activity was initiated by reviewing the cost and performance trade-off of several candidate microprocessors.

Another aspect of the overall ECU design was the driver circuit for the two-way latching solenoid valve developed for the fuel injector actuation. A breadboard version of this driver circuit was developed and used successfully for operation of the solenoid valve. It was also used:

a) for optimization of component sizing, such as the capacitors used to magnetize and de-magnetize the latching solenoid
b) to develop turn-on and turn-off dwell times for minimum energy consumption
c) to establish compatibility with "alternator only" variable voltage electrical supply.

2.1.5. Electrical Power Generator

Attempts were made to take advantage existing flywheel mounted ignition system magnets as a potential energy source for providing power to the ECU and solenoid valve. Several iterations of simple coil and core assemblies were constructed and tested using the 46cc engine flywheel magnets. In all cases, electrical power generation fell short of the estimated requirement.

A small alternator assembly using a full circle magnet group and tailored to fit on small engines was obtained for evaluation. This alternator was adapted to a variable speed test rig for initial fuel system and solenoid driver circuit development and also adapted to the prototype engine design. The alternator provided up to 90 watts of power at 10,000 rpm. In conjunction with solenoid and solenoid driver circuit design, it was determined that the minimum alternator speed to activate the solenoid was approximately 2,500 rpm. This performance was compatible with the 3,000 rpm idle speed for the prototype engine. Note that the fuel system design allows for engine starting without activation of the solenoid valve. Although this alternator provides a comfortable margin compared to the predicted high-speed power consumption, the minimum speed to provide solenoid actuation power is considered the critical factor.

The test alternator is self-contained, including a steel cup used to house the circular magnet group. It is anticipated that this magnet group may also be integrated into the flywheel design on production design applications. Value engineering to minimize coil windings, core mass or magnet group strength was postponed.

Note that all applications other than handheld utility engines, for which this fuel system is being considered, already include battery and alternator systems, so that calibration for constant 12 volt to 14 volt supply is possible.

2.2. Design the Prototype Development Engine

A decision was made early in the project to consider basing the prototype engine design on an existing production engine in order to maximize the use of available parts not related to the fuel system integration. Evaluation of possible engine types revealed that the handheld utility engines presented the largest number of challenges. A decision was made to answer these challenges by selecting this engine type. These challenges include the lubrication system, as most other engine types already use oil delivery pumps, and the electrical power generation system, as several other applicable engines already use battery systems with recharging alternators. Although these recharging alternators may require size increase to add power capacity, the constant voltage output of the battery is not as severe a challenge for the fuel system control design as the variable voltage output of a simple alternator. A Tanaka 46cc engine was selected for the prototype design basis.

The prototype fuel injection and ancillary systems design was completed for this 46cc utility engine. Key views extracted from the design layout are shown in Figures 10 thru 12**.** The lower, crankcase section of the engine includes installation of the alternator, cam driven fuel injection pump and a crankcase pressure pulse driven fuel transfer pump. Several iterations of the fuel injector design were evaluated for cost and size comparison. The features evaluated in these designs include number of parts, number of machined surfaces (including lapped surfaces for high-pressure sealing), spring design and ease of assembly.

All of the drawings created for the design and manufacturing of the 46cc utility engine are included in Appendix C for reference regarding design dimensions, tolerances, materials and so on.

Subsequent to the 46cc engine design, an additional adaptation was created for a 50cc moped engine in cooperation with Suzuki. The rational for this additional task was the need to validate the applicability of the CATS technology to applications requiring more complex transient operation and other issues relative to drivability. The major cost for engine hardware and testing for this additional task was offered by Suzuki. All of the drawings for this application are included in Appendix D. Views from the design layout are shown in Figure 13.

Two separate analytical tools were developed to provide engine builders with a design tool as well as to assist with evaluation of development testing results. These programs will be transferred to system licensees as a design aid to various engine configurations. The following is a description of both calculations.

1. A static, preliminary calculation was created in the form of a spreadsheet (Microsoft Excel) which includes all major dimensions, volumes, spring settings and so on which determine injector calibration and performance. This is a very handy tool for establishing and verifying initial design details for the injector. The variable values which can effect the injector output, duration and pressures can be selected within practical ranges. A sample calculation using this spreadsheet is included in Appendix F. This Excel spreadsheet will be transmitted to consortium participants upon request.

2. A dynamic simulation program was created to aid in the determination of design arrangement and dimensions for the specific engine to be tested. This FORTRAN based program provides time based graphical results of pressures, motions and flow rates for critical areas within the system. This tool may be used for predicting injector performance and for identifying potential imperfections in system design or operation prior to fabrication and testing. Sample outputs from this program are shown in Figures 14, 15 and 16 for a fuel delivery and injection timing sensitivity study. A complete manual describing the simulation program and providing instructions for its use is included as Appendix G. The graphical software use by BKM for the presentation of data called GRAPHER and will be made available to consortium participants upon request.

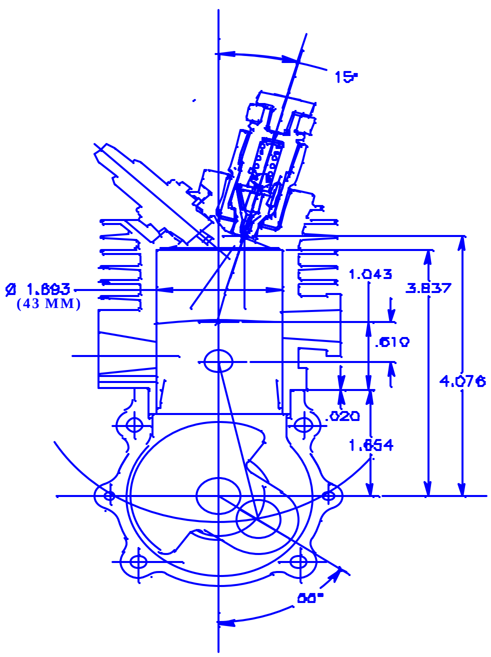

Figure 10 - Cross-Section Through Engine and Injector

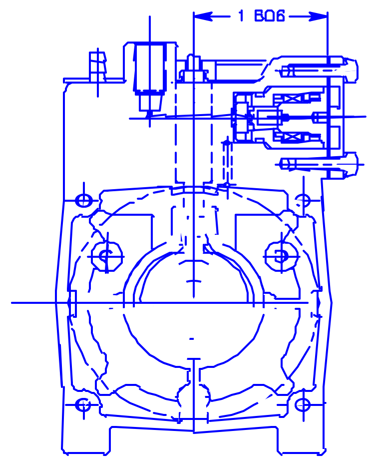

Figure 11 - Cross-section Through Cam and Solenoid Valve

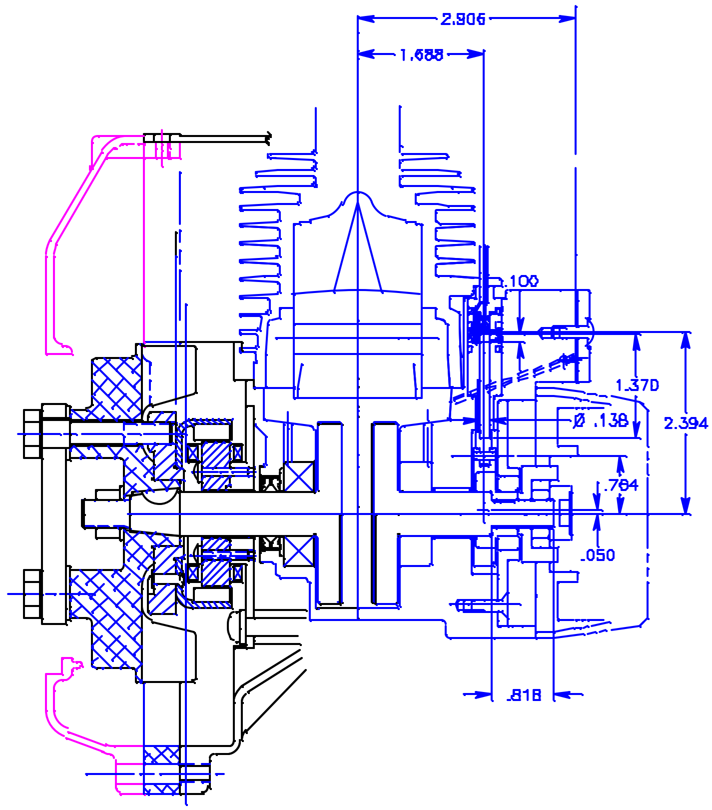

Figure 12 - Cross Section Through Crankcase, Flywheel, Alternator and Pump

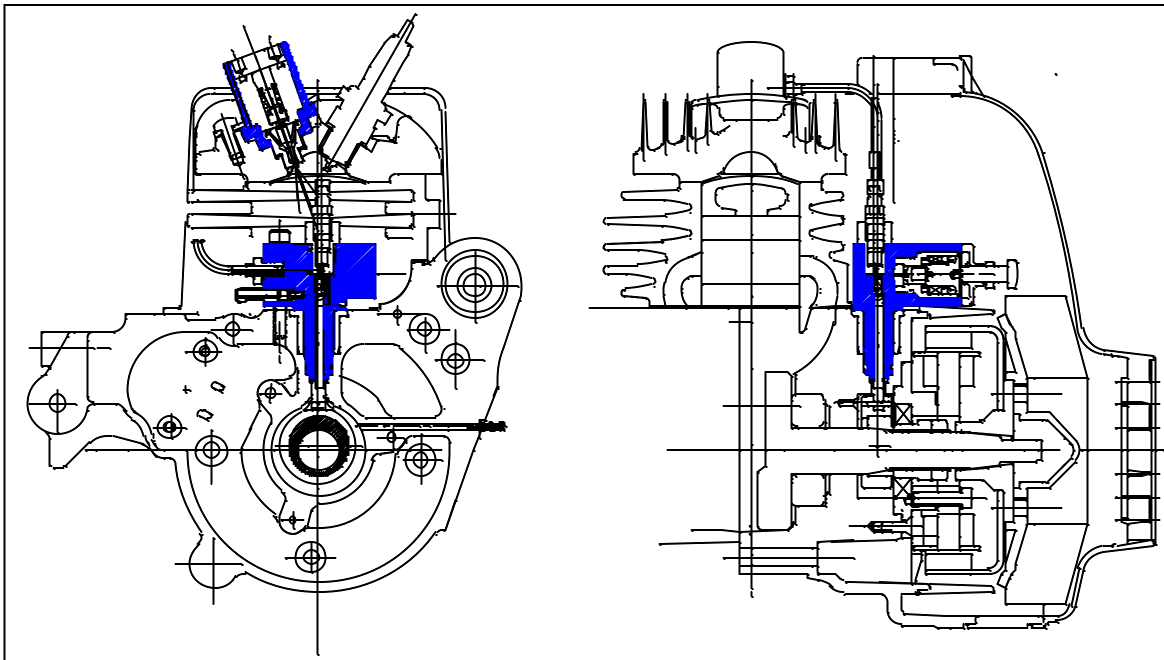

Figure 13 – 50cc Moped Design Layout

Figure 14 - Parametric Study: Injection Timing and Fuel Metering

Figure 15 - Setting and Control: Parametric and Sensitivity Study

Figure 16 - Pressure Histories: Parametric Study

2.3. Development of Controls and Software Calibration

As previously discussed, the development and demonstration testing of the fuel injection system will be controlled by a commercially available laboratory ECU with flexible calibration features. The design of a prototype, small single cylinder ECU based on low cost components was competed. A “wire wrap” or non-printed circuit board version of this controller was constructed for design validation. Adequate interface software was generated for validation of ECU function and for diagnostic purposes. The development of this ECU involved considerably more effort than presented in the CATS proposal, partly due to the change in solenoid valve type and fuel delivery control strategy introduced after initial design activity. As a result, actual engine operation software was not completed within this program. BKM will continue with the development of this software and hardware subsequent the CATS schedule. The availability of the commercial laboratory controller for calibration and demonstration removed the urgency to complete this production intent controller.

It should also be noted that our consortium partner Honglin Machinery Factory has commissioned a prototype controller based on the BKM design and has completed operational software adequate for basic engine operation. This prototype controller has successfully operated their 125cc Nanfang motorcycle engine. This activity was performed on Honglin’s own initiative and supports the feasibility of the design and a potential source for controllers.

Sensors for engine speed and position, throttle position, engine temperature and barometric pressure were identified and coordination meetings with vendors were conducted. During fuel system development, standard available components were used, as vendors were understandably reluctant to invest in engine specific sensor tooling prior to production commitments. Discussions indicate, however, that the sensors may be value engineered for size and cost pending results of the program and commercialization activity.

2.3.1. ECU Specification

Figure 17 shows the overall control logic scheme for inputs and outputs.

2.3.1.1. Inputs

Engine Speed and Crank Position Sensor - Currently using an optical sensor reading a 36 minus 2 tooth gear, which results in a 5 volt square wave. This provides both a high resolution position signal, and a once per revolution discontinuity with one gear and sensor

Throttle Position Sensor - Analog 0 to 5 volt sensor

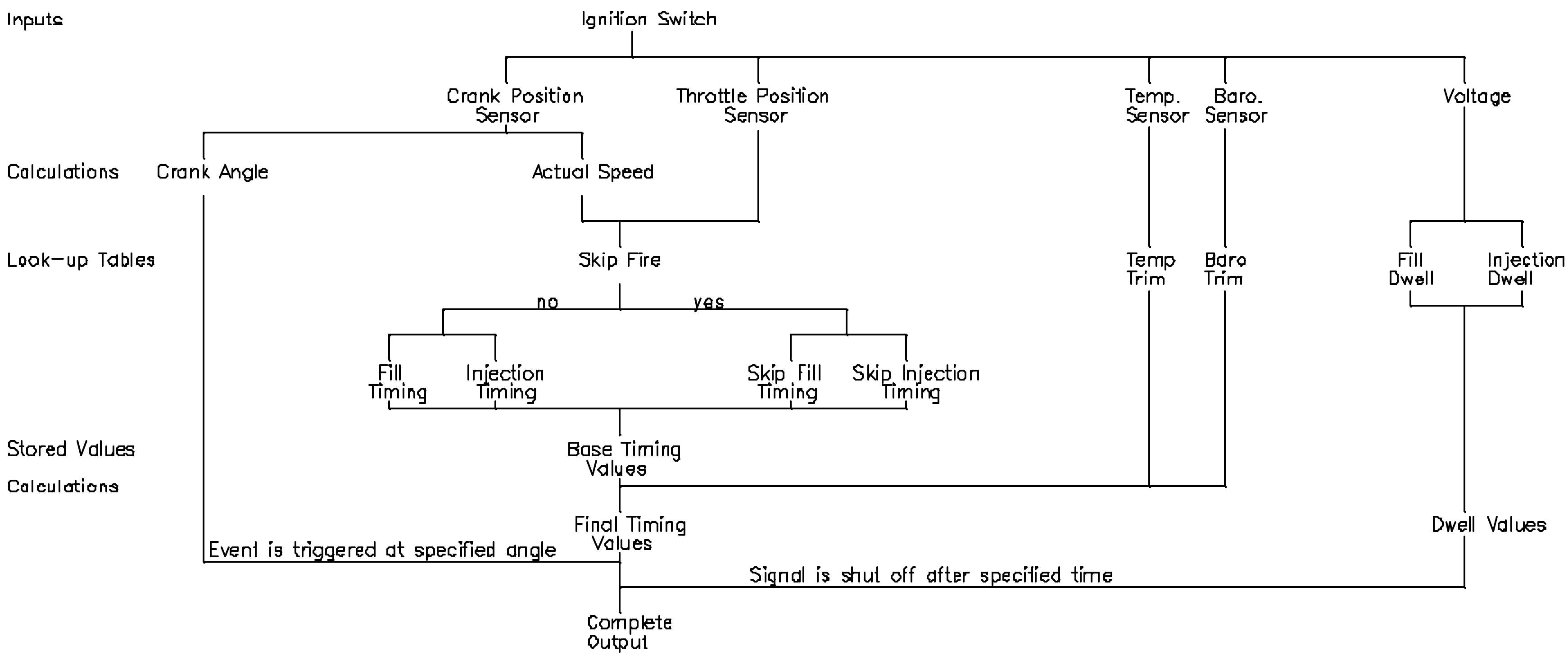

Figure 17 – CATS Control Logic

Temperature Sensor - Analog thermistor signal, best location still to be determined (may be engine specific)

Barometric Pressure Sensor - Analog signal, packaged internal to the ECU

Battery Voltage – Input directly to ECU

2.3.1.2. Outputs

Injection:

- Fill pulse duration = .7 ms at 13 volts
- Vent pulse duration = 2.0 ms at 13 volts
- Fill Timing - Leading edge of signal varies from 60 Degrees BTDC to 60 Degrees ATDC
- Vent Timing - Leading edge of signal varies from 120 Degrees BTDC to 240 Degrees BTDC

Ignition (Optional, may require a change from Motorola P6A to P8 chip for an additional timer):

- Timing -Trailing edge of signal varies from 0 Degrees BTDC to 60 Degrees BTDC
- Dwell - Depends on ignition system and voltage. Typically near 5 ms

2.3.1.3. Internal Logic

The ECU control of the fuel system is accomplished solely through the single solenoid valve. This one valve is used both as a pressure regulator and to trigger injection into the cylinder. The solenoid is a magnetically latching solenoid, so one pulse latches the valve open, then another pulse is used to de-latch, or close the valve. If the pulses to the solenoid are too short the valve will not latch or de-latch. If the pulses are too long electrical energy is wasted, or eventually components are overheated. Figure 18 illustrates an example of the system event timings, including solenoid function.

The fill pulse de-latches the solenoid, or closes it. The timing of the fill pulse determines the peak pressure developed by the pump, and therefore the quantity of fuel injected into the engine. By delaying the fill pulse, more of the pump stroke is vented back to the tank, so the injection pressure and quantity is less. Earlier fill times result in higher pressures and fuel flow.

The vent pulse latches the solenoid, or opens it. The timing of the vent pulse determines the actual timing of injection into the engine. When venting, the hydraulic force on top of the injector needle is greatly reduced, while a check valve in the injector holds the peak pressure below the needle. When the

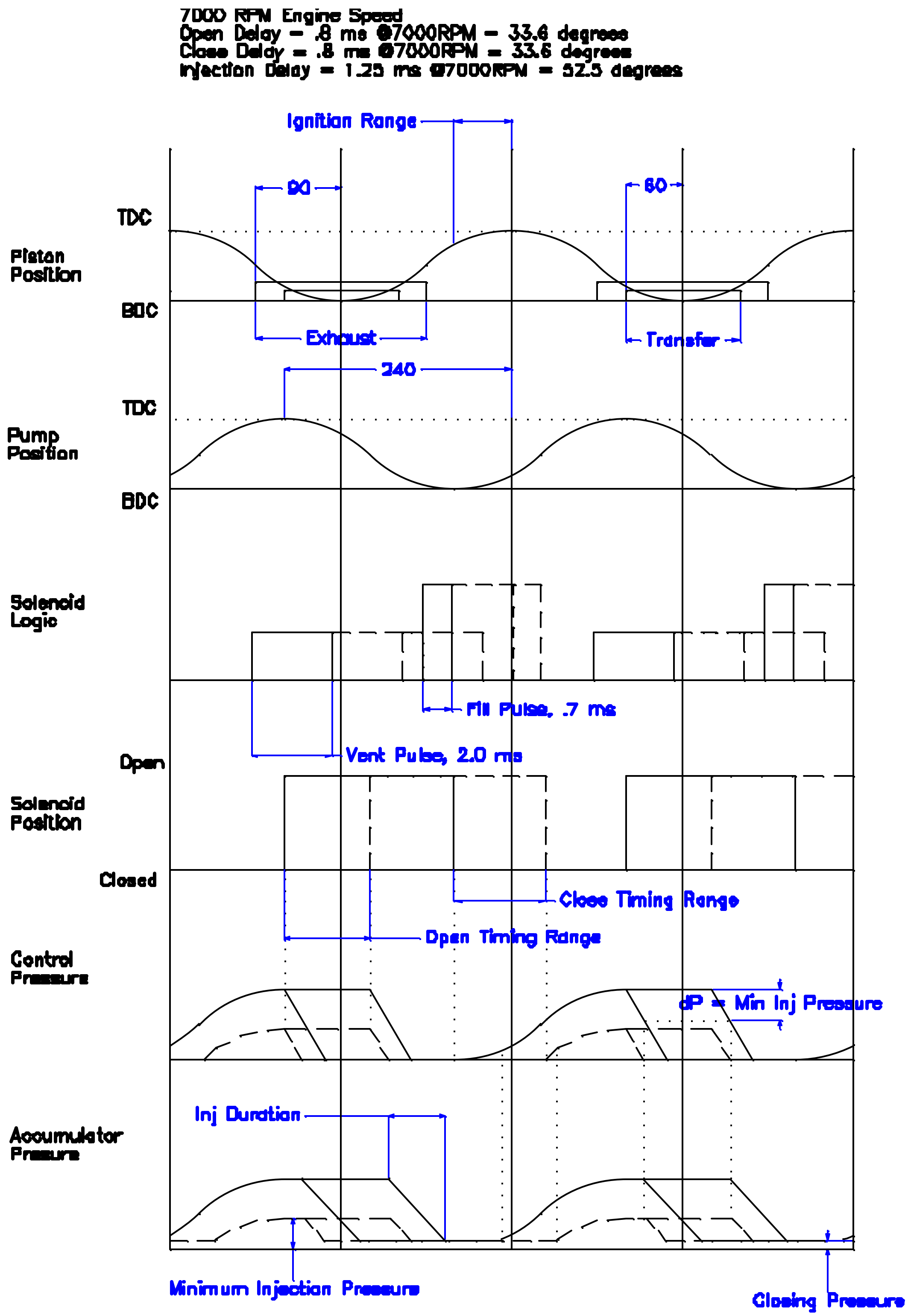

Figure 18 – CATS Timing Example

pressure on top of the needle drops low enough, the pressure on the bottom of the needle is enough to force the needle to lift, causing injection. Injection stops when the pressure on the bottom of the needle is no-longer great enough to keep the needle open against the force of the injector spring.

The ECU calculates the solenoid logic and ignition logic based on the engine rpm and throttle position. Functionally there will be the equivalent of a lookup map for fill timing, vent timing, and ignition timing versus throttle position and rpm. The outputs for throttle position and rpm between map sites will be calculated by linear regression. It may be possible in final production to reduce this map to a formula, to reduce the workload on the processor.

The logic dwells are held to a fixed value for all rpm and throttle positions, as long as the voltage to the solenoid remains constant, by means of a voltage regulator.

SAMPLE CALIBRATION MAPS:

Fill Timing, Degrees BTDC

%TP RPM

	0	1000	2000	3000	4000	5000	6000	7000	8000
100	60	0	10	15	20	25	30	30	30
80	60	0	10	15	20	25	30	30	30
60	60	0	5	10	15	20	25	15	15
40	60	0	0	5	10	15	10	0	0
20	60	-10	-5	-5	0	5	5	-20	-20
10	60	-20	-15	-20	-20	-20	-30	-40	-40
0	60	-30	-35	-40	-40	-40	-50	-60	-60

Vent Timing, Degrees BTDC

%TP RPM

	0	1000	2000	3000	4000	5000	6000	7000	8000
100	120	160	180	190	200	210	220	230	230
80	120	160	180	190	200	210	220	230	230
60	120	160	180	180	190	210	220	220	220
40	120	160	180	180	190	200	210	210	210
20	120	160	180	180	180	190	200	200	200
10	120	160	180	180	180	180	190	190	190
0	120	160	180	180	180	180	180	180	180

Ignition Timing, Degrees BTDC

%TP				RPM					
	0	1000	2000	3000	4000	5000	6000	7000	8000
100	15	20	25	30	35	30	25	20	20
80	15	20	25	30	35	30	25	20	20
60	15	20	30	35	40	35	30	25	25
40	20	20	35	40	40	40	35	25	25
20	25	25	40	40	40	40	40	30	30
10	30	30	40	40	40	40	40	35	35
0	30	30	40	40	40	40	40	35	35

Skip Fire

To improve part load conditions the system is capable of not injecting fuel every cycle. Certain cycles can have their injections "skipped". Skip fire is currently only going to used with two modes, normal two stroke operation, and then with the best overall number of cycles to be skipped between firing cycles. The number of cycles skipped in the skip fire mode will be software configurable, and chosen for each type of engine. For the skip fire operation there will be another set of maps, fill, vent, and ignition timing that the ECU will use to calculate the outputs. In addition the equivalent of an additional map with throttle position and engine rpm will be used to determine when the engine will operate as a normal two-stroke and when it will operate on skip fire.

An optional switch could be provided to either eliminate skip fire from ever occurring, or to cause the engine to operate with skip fire all of the time. This would cause the engine to run with skip fire all of the time, and would be an effective way to reduce the maximum power and speed available for some users.

Skip fire is achieved by omitting fill pulses for the cycles to be skipped. This causes the solenoid to never de-latch, or close, so all of the pump action is vented to the tank. The vent pulse can be left untouched. This ensures that the solenoid stays latched and open, but does not trigger injection because there was not enough pressure built up in the system to allow an injection to take place.

Sensor compensation

The specific application of sensor compensation depends on what the sensor is measuring. The basic logic is to have a 2 dimensional table, which provides a percentage shift in fill timing for a given reading. On the 46cc Tanaka, the full range in fill timing is from 60 degrees before piston top dead center and 60 degrees after piston top dead center, or 120 degrees. By considering -60 Degrees BTDC as zero percent fuel flow, and 60 Degrees BTDC as 100 percent fuel flow you can proportionally increase the fuel flow, from idle to WOT, by multiplying the percentage fuel flow by a single trim percentage.

The following table illustrates four examples:

Throttle position	30%	30%	100%	100%
RPM	3000	3000	7000	7000
Sensor	20	10	20	10
Sensor trim	0%	10%	0%	10%
Required fuel	50%	55%	80%	88%
Fill timing ºBTDC	0	6	36	45.6

If the sensor reading then changes to 10, and the compensation table shows a 10% trim for that reading, the new fuel flow would be 50% + (.50 x .1) = 55%. For another condition, if 80% fuel is required, this would be trimmed by the same percentage 80% + (.8 x .1) = 88%.

The compensation table will look like this:

Sensor	0	10	20	30	40	50	60	70	80
Trim %	20	10	0	-10	-20	-30	-40	-50	-60

2.4. Prototype Manufacturing

Drawings for major engine and fuel injector parts were completed and released for manufacturing. The commercial partner Tanaka provided crankshaft assemblies and completed engine cylinders with injector mounting provisions. The crankcase casting was produced by a California prototype casting firm and machined by the contractor. Most machined components for the injection system were produced by BKM. The injector nozzle assemblies, which require specialized tools for grinding, were coordinated with both domestic and overseas vendors. Spare parts were manufactured or procured on a part by part basis. Component quantities varied according to cost, complexity and risk of developmental changes.

The unique latching high-speed solenoid valve developed for this program is being supplied by Sturman Industries in Colorado. Completion of the solenoid valves included test and serialized documentation of function, including oscilloscope pressure traces and response times. As previously mentioned the development test ECU is being provided by the BKM. In parallel, the prototype small engine ECU was fabricated for functional testing.

2.5. Test Planning and Setup

BKM provided a 5-hp eddy current dynamometer for engine testing. The overall test stand layout was designed as well as detail hardware required for engine mounting and dyno coupling. The test cell electronic controller for the engine was setup and connected for engine operation as well as for the monitoring of engine control software.

Initial engine development test plans were formulated. These plans include items in the following outline:

I. Debug system and fix leaks
II. Motoring tests
  A. Verify pump function
    1. measure peak pressure, various speeds
  B. Verify mechanical injection
    1. Measure injection quantity
    2. Measure injection timing
    3. Measure injection duration
  C. Electronically control the injection event
    1. Measure fill delay
    2. Measure vent delay
    3. Measure injection quantity for various fill times
    4. Measure injection duration for various fill times
    5. Check for consistency of injections
III. Engine calibration
  A. Hardware preparation
    1. Calibrate throttle position sensor
    2. Install CO probe into engine exhaust
    3. Verify oil pump flow control, 0.2 to 0.7 cc/min
  B. Starting
    1. Adjust throttle to obtain best starting
    2. Adjust mechanical injection timing to obtain best starting
  C. Initial calibration of injection timing
    1. Good conventional idle
    2. Safe WOT sweep, near rich misfire limit
    3. Estimate timings for remainder of map
  D. Transfer pump
    1. Determine transfer pump flow requirement
  E. Idle calibration
    1. Find optimum idle throttle position, # of cycles skipped and rpm, all with optimum injection timings
    2. Investigate closed loop idle speed control with number of cycles skipped as the control parameter
  F. WOT Calibration

    1. Find peak power with baseline CO emissions
    2. Evaluate reduced air/fuel ratio, until 2% CO emissions. Consider power, temperature, fuel consumption, piston condition (seizure)
G. Part load calibration
    1. Adjust map for combustion quality and minimum fuel consumption
H. Future combustion development
    1. Spray variations
        a) Location
        b) Direction
        c) Cone angle
        d) Pressure combinations
    2. Combustion chamber
        a) Piston bowl
        b) Squish velocity

2.6. Performance and Emissions Development

2.6.1 46cc Tanaka Utility Engine

The first operation of the 46cc fuel injected engine occurred on August 23, 1997. Subsequently, the following design revisions have been implemented.

1. Due to pump leakage in the area of the spill port, the prototype pump efficiency was lower than anticipated, resulting in lower pressure than required for full power fuel delivery. In parallel with efficiency improvement changes, a cylinder/plunger assembly with increased displacement was designed and fabricated to allow for continued testing and power development. A revision to the internal volume of the injector nozzle, which results in increased fuel delivery capability, was also accomplished.

2. Due to percolation of the fuel in low pressure passages of the plumbing circuit, caused by high temperatures associated with the aluminum crankcase, it was decided to provide back pressure by installing a pressure relief valve at the venting outlet of the solenoid valve. Various values of backpressure were tested. Presently, it has been determined that a value of 5 bar is very effective in preventing fuel percolation during engine running and soak back temperature conditions.

3. Based on visible evidence on the piston crown subsequent to engine running, it was decided to prepare variations in piston crown shape for testing, to encourage retention of the fuel spray and fuel air mixture in the center portion of the combustion chamber. Carbon washing near the piston crown perimeter indicated that some fuel adheres after initial contact, then disperses across the piston crown until reaching the outer edge, near the cylinder wall. A revision was proposed by designing a combustion bowl or cup in the central area of the

piston crown. A design, which did not change the compression ratio of the engine, was developed for testing.

4. Several fuel spray and combustion bowl arrangements were evaluated in order to achieve best fuel/air mixing and fuel distribution within the combustion chamber. In addition, a unique combustion system arrangement developed by Shigeru Onishi, President, Nippon Clean Engine Laboratory Co., was tried with very good results. This system is called Impinging Fuel Jet Diffusion (OSKA) and is found in the literature regarding alternative fuel experiments as well as diesel engines. This OSKA system provides fast mixture preparation, particularly when combined with strong squish flow, and using a single hole nozzle. Application to small two-stroke gasoline engines is new. Using this technique combined with the injection rate characteristics of the BKM accumulator type injector appears desirable. BKM has subsequently acquired exclusive rights to the OSKA patent rights for gasoline two-stroke engines and intends to include this concept within the CATS license. The OSKA US Patent No. 4,770,138 is included in Appendix B.

Additional design guidelines and recommendations resulting from this 46cc test activity are included in Section 5.

Hardware iterations evaluated during this development test period include the following variables:

Injector spray configuration
  - 30° included angle hollow cone
  - Pencil stream (straight spray, no included angle)
- Injector accumulator volume
- Injector needle closing pressure (minimum spray pressure)
- Ignition
  - Standard ignition system and timing
  - Automotive IDI ignition system with variable timing
- Piston
  - Standard
  - Inserted bowl
  - Target for OSKA spray stream (various designs)
- Combustion Chamber
  - Standard
  - Central hemispherical
- Injector location
  - Central
  - Offset (various positions)
- Spark plug location
- Transfer ports
  - Original “as received” standard port design (small)

- Updated standard production port design (large)

2.6.2. 50cc Suzuki Scooter

In addition to the utility engine development testing, BKM agreed to provide support as required to a project at Suzuki to incorporate the CATS technology on a 50cc scooter engine. This project plan was desirable, since it would allow evaluation of driving performance and emissions on this large market application, using the BKM system. Since this project would occur during the period of the CATS consortium, and since some spare parts from the original program would be utilized, BKM agreed with the plan by Suzuki, provided that results would be shared with the consortium members. Durability of the cam ring design originally applied to the 50cc scooter engine has resulted in delays beyond the publication date of this report. However, this development issue is being resolved by application of a needle bearing and BKM will provide a subsequent test report, including transient operation.

Hardware setup variations were tested for comparison and final selection. Although these tests were not as comprehensive as the Tanaka engine testing, several iterations were evaluated to provide the best arrangement within a brief time period. Theses variations are outlined in Section 3. BKM then recorded basic performance and fuel consumption data for comparison with future Suzuki results. These preliminary results are also presented in Section 3. It should be noted that these preliminary results are pending validation by Suzuki and should be scrutinized accordingly.

2.7. Reports / Meetings

During this consortium program, BKM has held four program review meetings at approximately six-month intervals. These participant “summit” meetings were attended by ARB representatives, as well as engineers and executives from the consortium funding manufacturing companies. Minutes and presentation materials from each of these meetings are available on request.

Presentations by BKM engineering staff on technical aspects of the project were provided at these meetings. In addition, these meetings provided a forum for interchange and discussion between BKM, the manufacturers and ARB.

3. Test Results

3.1. 46cc Tanaka Utility Engine Results

The 46cc utility engine results include comparisons of power, fuel consumption and exhaust emissions. The 46cc engine data was recorded by University of California, Riverside, College of Engineering, Center for Environmental Research and

Technology (CE-CERT). Hydrocarbon data was recorded using a Flame Ionization Detector (FID). Emission results include data at maximum power, comparison to the California Air Resources Board (CARB) Tier II regulations for handheld utility engines and comparison to marine engine regulations set by the U.S. Environmental Protection Agency (EPA) for the year 2006.

The configuration of the 46cc engine during these tests was as follows:

- Injector spray configuration: Pencil stream
- Injector accumulator volume: 208 cu. mm.
- Injector needle closing pressure: 100 bar (est.)
- Ignition: Automotive IDI with optimized timing
- Piston: Inserted bowl
- Combustion Chamber: Central hemispherical
- Injector location: Central
- Spark plug location: Angled, intake port side
- Transfer port: Updated standard production port design (large)

The listing of test iterations performed during this program phase are outline in Table 1. Details of each individual test are included in Appendix H. The results for the engine and fuel system configuration listed above are illustrated in Figures 19 through 24.

Table 1 – 46cc Tanaka Utility Engine Test Summary

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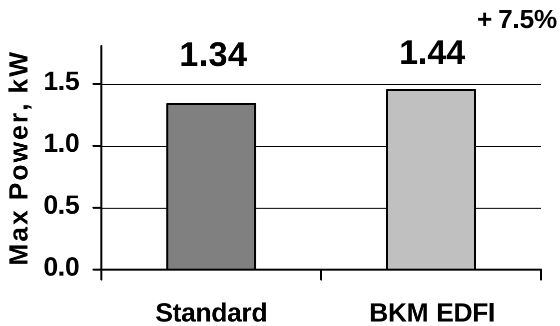


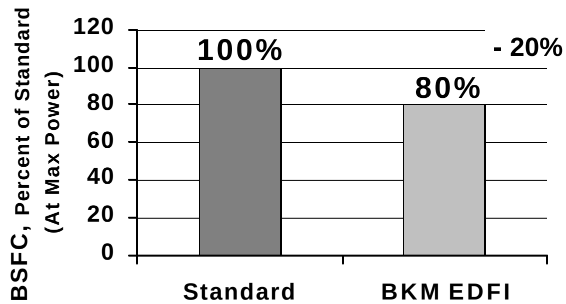
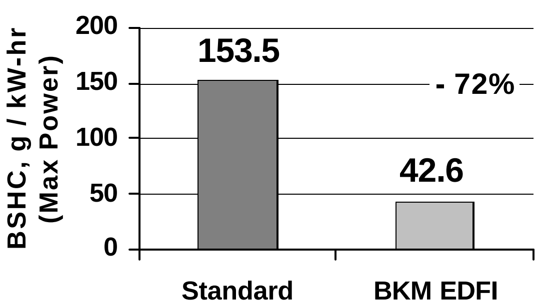


Figure 19 - 46cc Utility Engine Maximum Power Comparison at 7,000 RPM

Figure 20 - 46cc Utility Engine Brake Specific Fuel Consumption (BSFC) Comparison At Maximum Power, 7,000 RPM



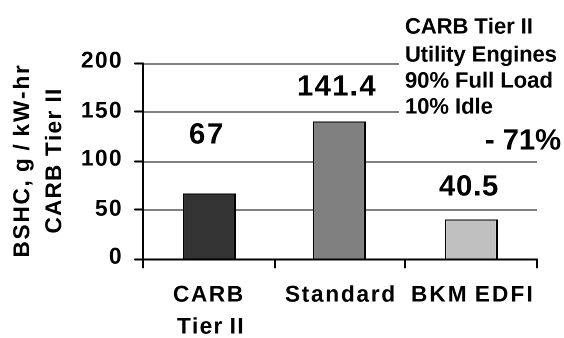
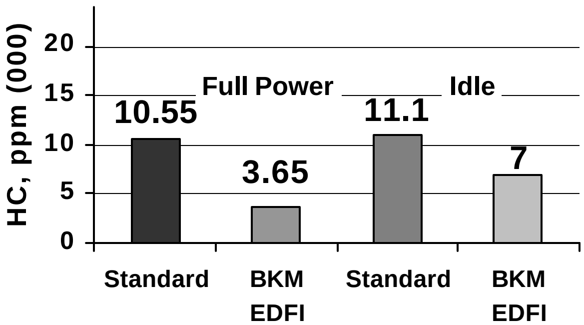


Figure 21 - 46cc Utility Engine Brake Specific Hydrocarbon Emissions (BSHC) Comparison At Maximum Power, 7,000 RPM

Figure 22 - 46cc Utility Engine Brake Specific Hydrocarbon Emissions (BSHC), CARB Tier II Comparison



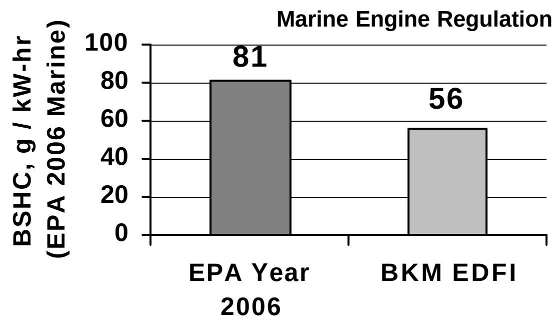


Figure 23 - 46cc Utility Engine Parts Per Million Hydrocarbon Emissions Comparison At Full Power And Idle

Figure 24 –46cc Utility Engine Brake Specific Hydrocarbon Emissions (BSHC), US EPA 2006 Marine Engine Regulation Comparison

During the test program, oscilloscope recordings were made of electronic signals to the solenoid valve driver circuit and the pressure history between the pump and injector. These dynamic events were compared to the calculated dynamic simulation with very good correlation. The recorded events and simulation for the 46cc Tanaka at three different operating points (idle, part load, full load) are provided in Appendix J.

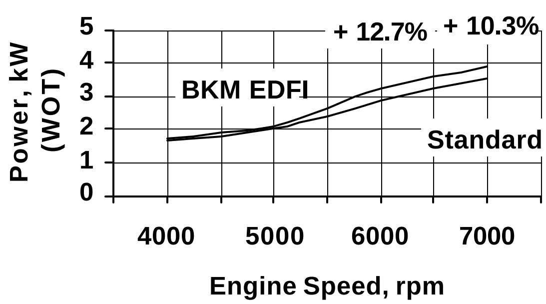
3.2. 50cc Suzuki Scooter Engine Results

The 50cc two-wheeler data includes comparisons of performance and fuel consumption with a standard (carbureted) engine. Data is compared at Wide Open Throttle (WOT) and simulated road load conditions. These are preliminary test results recorded at BKM prior to shipping the engine to Suzuki in Japan.

As mentioned in Section 2.6, durability problems with the cam ring bearing design for the single plunger pump in this particular engine have delayed the desired transient and vehicle test results. Therefore, rather than further delay publication of this report, these results will be provided in a separate report.

The listing of test iterations performed at BKM during this program phase are outlined in Table 2. Details of each individual test are included in Appendix I. Basic test results are illustrated in Figures 25 through 28. As mentioned in Section 2.6.2., these preliminary results are pending validation by Suzuki and should be scrutinized accordingly.

Table 2 – 50cc Suzuki Two-Wheeler Engine Test Summary



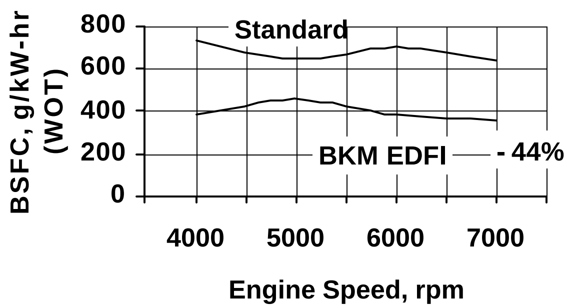
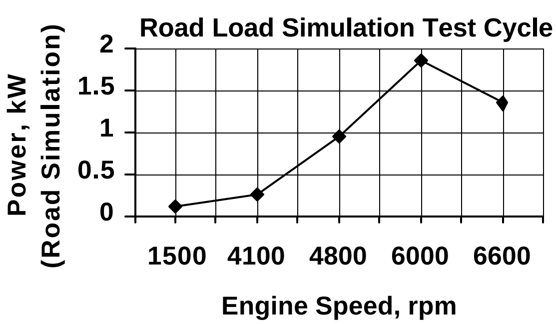


Figure 25 - 50cc Two-Wheeler Wide Open Throttle (WOT) Power Comparison

Figure 26 - 50cc Two-Wheeler Wide Open Throttle (WOT) Brake Specific Fuel Consumption Comparison



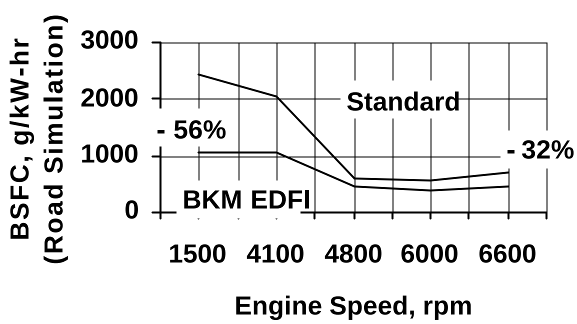


Figure 27 - 50cc Two-Wheeler Road Load Power Curve Specification

Figure 28 - 50cc Two Wheeler Road Load Fuel Consumption Comparison

4. Discussion

A detail discussion of the technology and how it works has been provided in Section 1.3. This technology provides manufacturers of 2-stroke engine powered utility engines, motorbikes, marine engines and other applications a means to significantly reduce exhaust emissions.

In addition to reducing exhaust hydrocarbon emissions and exceeding baseline engine power, the unique spray impingement combustion system, prevents engine component mechanical or thermal problems resulting from deviation from conventional evaporative cooling effects. This result occurs regardless whether the OSKA spray impingement or hollow cone spray is used, since impingement occurs with either method.

The degree to which this technology will provide environmental, economic and industrial benefits will depend on acceptance of the results of this demonstration program by the engine manufacturers. The next phase of this program will be to present these results to the CATS consortium participants and openly discuss concerns, costs, sources and so on.

Two-stroke engines dominate applications requiring a lightweight highpower powerplant. The BKM fuel injection technology is universally applicable to all current two-stroke powered products. The technology applies equally well to applications such as two-stroke utility engines, mopeds, scooters, motorcycles and outboard engines. In more sophisticated and demanding applications, the addition of catalytic converters may also be considered.

This technology focuses on pollution prevention by reducing emissions at the source. Redesigning the engine and its systems will dramatically reduce emissions from small two-stroke engines. In particular, emissions of HC, NOx and CO should comply with future exhaust emissions regulations. This program will have broadbased application since technology licensing and engine sales will apply worldwide to all low cost two-stroke engine applications.

5. Application Design Recommendations

The following comments summarize some of the lessons learned or guidelines for design application developed during the CATS program, which may not be obvious from the drawings. It is intended that new items or expanded descriptions may be distributed in the future when appropriate.

1. Durability of the bronze cam ring design, lubricated by engine oil, has been inconsistent. The 46cc Tanaka engine has operated for long periods without noticeable wear. However, the 50cc Suzuki moped engine has experienced several wear related failures. Even though the possibility of developing durable,

application specific bushing designs may be feasible, it is recommended that the overall fuel system and engine development success should not be jeopardized by this mechanical design item. Therefore, the preferred pump cam arrangement consists of :

a) A caged needle bearing assembly, similar to a crank pin bearing.
b) A case hardened steel cam ring.

In either case, the preferred oil path is first to the cam and cam ring bearing area, then migration to the crankcase. As with other system details, this design may be refined or value engineered by engine manufacturers to suit individual preferences and engine lubrication requirements.

2. For fuel quantity control by “fill time” adjustment, or wasting pump stroke by late solenoid closing, consider the solenoid valve vent flow area. Based on the flow rate from the pump, the solenoid flow area must provide adequate flow area to prevent pressure rise during the upward pump stroke, particularly at high speed. This consideration will effect the solenoid valve specification and design. It is anticipated that a small number of solenoid valve models should cover a wide range of applications.

3. In the prototype designs, BKM has used the following speed and position sensor types:

   a) A laboratory type magnetic pickup and metal gear wheel (mask)
   b) A hall effect sensor and toothed metal mask
   c) An optical sensor and “light prevention” toothed mask (metal or plastic)

   The preferred selection at this time is the optical sensor. The sensor is low cost, works well and can be used with a low cost dark colored plastic mask (input signal wheel). This mask can be integrated into any other rotating part, such as a cooling fan.

4. Due to the volatility of gasoline, it is important to prevent vapor bubbles from forming in the fuel passages with the fuel injection system. The following measures have been incorporated in the prototype engines.

   a) In the original design of the 46cc Tanaka prototype, the pump hardware was integrated into the crankcase casting. The high temperatures of the crankcase caused vapor problems with the fuel pump efficiency at high engine speeds and hot re-starts. The current design separates the pump into a housing with minimum crankcase contact area. In the design of the 50cc scooter engine, the fuel pump has been partially insulated from the main engine casings by a plastic bushing. Minimum metal-to-metal contact is included for installation tolerance control.

b) A 5 bar pressure relief valve has been added to the solenoid valve outlet, so that vented fuel must exceed the 5 bar pressure before leaving the system. As a result, 5 bar is the minimum pressure of the fuel within the heated metal passages. This pressure level has been adequate for preventing vapor bubbles forming in the pump chamber.

c) On the 50cc Suzuki moped design, BKM was able to place the fuel pump in the path of the cooling air flow before the cooling air reached the hot engine cylinder. This is a preferred location for maximum cooling of the pump. On the 46cc Tanaka design, the prototype design configuration prevented this arrangement. It is recommended that new engine design programs should consider this preference in the early stages of design to accommodate the cooler pump location.

5. The current 46cc Tanaka design uses an inlet check valve, to prevent reverse flow of fuel from the pump, back to the tank, during the pumping stroke. This check valve has a small spring closing force resulting in a holding pressure of 0.13 bar (2 psi). Therefore, the transfer pump specification must provide high enough pressure to prevent pulling vapor across the inlet check valve (greater pressure than 2 psi in this case).

   The 0.13 bar check valve used in the prototype engine is a purchased part from Lee Corporation. It may be feasible to manufacture an integrated check valve in the future, if justified by production quantity and validated by testing. If possible, a lower closing pressure may be desirable to reduce the transfer pump pressure requirement.

   A crankcase pulse diaphragm pump has been successfully used for the current test engine. Pressure drop across the 5 bar pressure relief valve at the solenoid vent outlet results in vapor bubbles. Without special vapor separation hardware, which may be available on some applications, the return flow will include too much vapor for re-circulation back to the pump inlet and therefore must be routed to the fuel tank. The transfer pump must make up injected and return fuel flow.

6. A preferred system design includes a spill port at the end of the pump plunger stroke (at maximum pump displacement). This spill port provides a late cycle vent condition which will initiate an injection event in the absence of electricity and solenoid function. This hydro-mechanical injection event occurs later in the cycle than electronically triggered injection, so that electronic injection always has priority. It is preferred that this spill port communicate only with the pump chamber, allowing the fuel to reduce pressure by expanding into the chamber, rather than to communicate with the inlet fuel passage. The reason for this preference is to prevent vapor bubbles from forming in the inlet fuel passage,

since the pump chamber is maintained at the higher 5 bar pressure, and to eliminate a leak path that would reduce the pump efficiency.

7. During prototype testing, the following arrangements were beneficial for monitoring the condition of the fuel during engine operation. These are not necessarily recommendations for final product design:

   a) External fittings provide easy viewing for potential leaks. Internal fittings, such as inside engine covers, are difficult to monitor and service.
   b) Clear or translucent low pressure fuel lines provide easy viewing for vapor bubbles or trapped air.

8. More than one seal design was tested for the fuel line connection to the injector. The preferred design is a copper washer, trapped in a counter-bore with limited side-to-side motion clearance. This design provides acceptable alignment of the fuel passages.

9. The production design cam and cam ring assembly may be placed within the main crankcase or separately mounted. In either case, any fuel leakage through the plunger clearance must pass into the main crankcase, either directly or through appropriate plumbing, and carried into the combustion process with the fresh air stream.

10. For plunger design, a square or under square bore/stroke ratio is preferred for consistent pressure rise and to minimize spill port leakage during the plunger down-stroke. Therefore, bore/stroke £ 1.0 is preferred.

11. To minimize plunger leakage and for consistent pressure calibration, the minimum plunger leak path, or length of the fitted plunger-to-bore interface, should be at least two (2) times the plunger diameter.

Glossary of Terms, Abbreviations, and Symbols

ARB	Air Resources Board
CARB	California Air Resources Board
CATS	Clean Air Two-Stroke
CO	Carbon Monoxide
CRS	Common Rail System
ECU	Engine Control Unit
EDFI	Electronic Direct Fuel Injection
EEC	Environmental Engine Corporation
EPA	Environmental Protection Agency
Expanding Cloud	Non-coalescing fuel spray
HC	Hydrocarbons
ICAT	Innovative Clean Air Technologies
MPa	Mega Pascals
NOx	Oxides of Nitrogen
OSKA	Impinging Fuel Jet Diffusion
Scavenge Loss	Fresh charge lost out the exhaust port prior to combustion
SPS	Single Plunger System
λ	Lambda, the ratio between actual air/fuel ratio and stoichiometric air/fuel ratio.
VOC	Volatile Organic Compounds

Appendix A - Honglin Photographs - 5 Nanfang 125cc Motorcycles

Appendix B – U.S. Patents 5,438,968, 5,685,273 and 4,770,138

Appendix C - 46cc Utility Engine Design Drawings

Appendix D - 50cc 2-Wheeler Engine Design Drawings

Appendix E - Electronic Control Unit Design Drawings

Appendix F - Preliminary Design Calculation – Excel Spreadsheet

Appendix G - Dynamic Injection System Simulation

Appendix H - Test Cell Data Sheets - 46cc Tanaka

Appendix I - Test Cell Data Sheets - 50cc Suzuki

Appendix J – 46cc Simulation Results and Comparison With Test