DOE/CS/51237-T2

DOE/CS/51237--T2

DE82 005389

MASTER

FINAL REPORT/E-4
FOR

A FUEL-VAPOR-INJECTION/
IGNITER SYSTEM

CONTRACT NO. E(04-3)-1237
15 April 1976 to 15 January 1977

AC03 76 CS 51237

FUEL INJECTION DEVELOPMENT CORPORATION

110 Harding Avenue

Bellmawr, New Jersey 08029

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

1. Summary.....	1
2. Background Information.....	2
3. Start-up of Contract.....	5
4. Hardware Development.....	7
5. Laboratory Testing.....	20
6. Field Testing.....	46
7. High Speed Photography.....	49
8. Other Developments.....	55
9. Hardware Delivery.....	66
10. Fiscal Data.....	68
11. Conclusions, Recommendations, and Proposals.....	70
12. Appendix.....	75

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

JS

1. SUMMARY

E.R.D.A. Contract No. E(04-3)-1237 was started on April 15, 1976 and is scheduled to be completed on February 15, 1977. The objectives of the contract were to develop and furnish for testing, a system which could be retrofitted to existing vehicles, for the purpose of conserving fuel in a cost effective manner. Detailed objectives are given in the Program Plan which is included in the Appendix.

The funding for this contract was supplied in semi-monthly progress payments scheduled to total \$156,220.00. Direct contract costs are listed in the Fiscal Data section of this report.

Contract work consisted of Hardware Development, Laboratory Testing, Field Testing, High Speed Photography, and Hardware Delivery. Each of these tasks is described in detail in the body of this report.

All contract objectives have been achieved. In addition, several original and far-reaching developments have been demonstrated concurrently with this contract. These devices function synergistically with the F.V.I., and are described in detail in the section of this report entitled Other Developments.

2. BACKGROUND INFORMATION

The Fuel Vapor Injector Igniter was invented in the fall of 1973 by Ervin Leshner and Michael Leshner, for the purpose of providing an improved ignition means for internal combustion engines. A U. S. patent was applied for on June 21, 1974, and was issued on December 16, 1975, assigned the number 3,926,169. The F.V.I. is a combined Fuel Injector and Spark-plug, which receives liquid fuel, vaporizes the fuel in a heat exchange region, delivers the vaporized fuel to the ignition region, and produces a spark.

Early development indicated that a given fuel-air charge could be ignited by an F.V.I. with higher statistical reliability than by a standard sparkplug, resulting in improved emissions and fuel economy characteristics. A proposal for development of the F.V.I. was submitted to E.R.D.A. on April 21, 1975, and Contract No. E(04-3)-1237 was started on April 15, 1976.

Prior to the start of this contract, a fuel-air metering and preparation system was developed for use in conjunction with the F.V.I.'s. Motivation for the development of this metering system came as a result of the first attempts to measure the performance of F.V.I.'s in an eight cylinder

engine. It was found that the cylinder to cylinder mixture variations were so great, that exhaust gas temperatures varied by as much as 250°C during steady state operation. When attempts were made to lean the overall mixture at the carburetor, one of the cylinders became so lean that it would not fire at light loading. It became apparent that if any advantage was to be found from lean combustion, some means of improving the intake manifold distribution would have to be employed.

Another problem that arose was the task of finding the optimum fuel-air ratio for use with the F.V.I. The solution to these problems took the form of a unique type of fuel injection system, employing gas phase induction and servo-feedback control of the fuel-air ratio. The induction system is a simple liquid fuel metering regulator coupled to a heat exchanger in the exhaust system. Liquid fuel is vaporized in the heat exchanger and is then mixed with metered air prior to induction. The fuel and air are metered to a crude rich mixture (approximately 12:1) and the servo-feedback control adds air to the mixture to produce an optimum fuel-air ratio.

The feedback control makes use of a power sensing means, and servos the mixture so as to maintain engine operation at the lean limit; regardless of what that lean limit is at any

instant. This control is referred to as the Optimizer, and it has developed to a point where it is a key element in the evolution of the F.V.I. system.

The Optimizer has been valuable as a research tool for evaluating the performance of F.V.I.'s, and as a retrofit control for leaning the mixture produced by a carburetor, in order to realize the advantages of F.V.I. operation. The gas-phase induction system was successful in improving intake manifold distribution, and was used for F.V.I. development and field testing.

A more complete description of the Optimizer and Gas Phase Induction System are given in the Appendix.

3. START-UP OF CONTRACT

Starting on April 15, 1976, the staff of F.I.D.C. was expanded to six full-time employees, including a machinist, instrumentation and test engineer, and four mechanical engineers. The facilities were expanded to include instrumentation for exhaust gas analysis and other combustion-related investigations. A Ford Pinto, Chevrolet Malibu, and International Harvester School Bus were instrumented for use as test vehicles, and baseline data was taken.

The initial investigations were carried out using a single cylinder Engine/Generator set which was instrumented to measure airflow, fuel flow, R.P.M., load, exhaust gas temperature, and exhaust gas composition. Eight F.V.I. configurations were manufactured with identical valves, stems, ceramics, and shells; the only variable being the geometry of the ignition region. The purpose of this testing was to compare the direct injection and prechamber methods of charge stratification, and to determine which was more effective with the F.V.I. The test results clearly indicated that a compromise between the two methods produced the greatest combination of advantages. It was found that a cup, surrounding the ignition region, with a large exit area, was the most advantageous design.

Subsequent investigations have shown that some physical shrouding is necessary to prevent mixing of the rich and lean mixture regions inside the combustion chamber, but that a prechamber which restricts the flame propagating from the rich ignition region produces thermal quenching and slow burning of the main fuel-air charge. A large portion of the contract work was spent developing a suitable firing-end geometry, which includes the spark gap and shroud.

The initial test configuration which yielded the most promising results was manufactured, and installed in a four cylinder Ford Pinto 122 C.I.D. and an eight cylinder Chevrolet 350 C.I.D., which were then subjected to Laboratory and Field Testing.

A project was begun in cooperation with Drexel University, to take high speed photographs of the F.V.I. in operation, in order to obtain information which would aid in the design optimization.

4. HARDWARE DEVELOPMENT

Requirements for the design of the F.V.I. system were as follows:

A. The proper fuel flow per stroke had to be determined for all speeds and loads. Too little flow would be insufficient to perform the local enrichment function, while too much flow would create an overly rich ignition region resulting in poor ignition, high emissions, and eventually wet and cold fouling of the spark gap, stopping all ignition. In addition, the F.V.I. check valve operating temperature is influenced by fuel flow.

B. F.V.I. check-valve operation is critical. The valve had to be designed to allow fuel to flow at a pressure differential of 2 p.s.i., yet resist reverse flow at 1,000 p.s.i. In addition, the valve operates at high frequency (10 to 100 cycles per second) in a hot and dirty environment. The design required a low level of complexity for manufacturing purposes, and a very high degree of uniformity to assure uniform fuel flow.

C. Stem dimensions had to be established. The internal volume and surface area of the injector tube are primary

variables affecting the heat transfer and flow dynamics of the F.V.I. Since vaporizing and flame quenching occur alternately inside the stem, each one affecting the other, the stem design became too complex for theoretical analysis, and had to be worked out empirically.

D. The shroud at the combustion end of the F.V.I. had to be designed so that mixing of the rich and lean regions would be controlled; too much mixing would negate the effect of the charge stratification, yet too little mixing would result in an overly rich condition in the ignition region. The spark location and gap also had to be determined.

E. All materials and manufacturing processes needed to be checked for durability. In addition, heat range specifications had to be determined for the F.V.I.

Vehicle Distribution System

At the start of the contract period, fuel delivery was performed as follows: A constant regulated pressure was delivered by means of 1/8" teflon flexible tubing to a metal chamber containing a needle valve-controlled feedline for each F.V.I. An 1/8" exit line from the chamber to a fuel-vapor

separator was provided; this was controlled by an .030" orifice. Flow rate to each F.V.I. was determined visually and was controlled by hand adjustment of each needle valve.

The objections to this system of delivery were as follows:

A. The metal chamber mounted on the engine valve cover vaporized too much of the fuel; the return was overloaded under hot running conditions, and the F.V.I.'s, which require some liquid fuel at the check valve, did not receive it.

B. The nature of the common chamber was such that if one F.V.I. check valve did not operate correctly, the resulting cylinder gas backflow would block any fuel flow to the other F.V.I.'s sharing the chamber.

The fuel delivery system was redesigned as follows: A constant regulated fuel pressure was delivered to the bottom of a plexiglass chamber with four vertical tubes and a 1/8" return line at the top of the chamber. A needle valve controlled the flow to each of the four F.V.I. feed lines. The plexiglass chamber was mounted on each inner fender of the engine compartment, to reduce premature vaporization. Individual vertical fuel tubes for each F.V.I. meant that in the event one F.V.I. check valve malfunctioned, its cylinder gas

blow-back would be taken out the vapor return and would not impede fuel flow to the other F.V.I.'s.

As F.V.I. development continued, visual adjustment of individual needle valves was found to be too imprecise. Attempts were made to outfit each feed tube with an orifice to control the fuel flow. One half inch long stainless orifice tubing of .010", .008", and .006" were tried in place of the needle valves. In addition to this testing, .010" orifice tubing was tried in the F.V.I. itself, just above the check valve. Initial results showed wide variations of flow to each F.V.I. which was attributed to dimensional variations between F.V.I. check valves. Trouble was noted in that the small feed orifices were very prone to clogging, especially when check valves malfunctioned. A final problem was that high temperatures in the V8 led to the melting of one plexiglass chamber.

The fuel delivery system was redesigned as follows: A phenolic metering block was built incorporating four small wells for liquid build-up in order to feed the F.V.I.'s, and a common vapor return line controlled by an .030" orifice. At the bottom of each well was a needle valve and a .010" stainless steel orifice. F.V.I. Flow Adjustment was made by turning each needle valve a fixed number of turns and then checking flow visually. An experiment was performed which eliminated the individual needle valve controls, and substi-

tuted a single needle valve control on the inlet of the metering block. The metering block material was changed to teflon in order to solve the problem of fuel leakage at the joints. The only objections to this system of delivery was that the high volume of fuel contained in the system was subject to vaporization, especially when a fully heated engine was turned off and restarted. In the time the engine was off, boiling of the fuel in the lines and block had flooded each F.V.I., and drained the delivery system. In addition, a problem with too much fuel delivery to the F.V.I. at idle caused fouling and High Hydrocarbon Emissions.

The current delivery system incorporates an Engine R.P.M. controlled on-off solenoid which allows no F.V.I. flow below 1,000 R.P.M. The manifold feed tube is .030" I.D. thickwall stainless steel tubing. This fuel feed tube feeds a very small common chamber incorporating a pourous-metal filter. A .010" I.D. thickwall stainless steel tube 16 inches long feeds each F.V.I. and no vapor separation system is employed. This distribution scheme gives satisfactory uniformity of flow, and minimizes fuel volume in the system.

The final delivered F.V.I. Fuel Delivery system performs as follows:

- A. Boil off of fuel and F.V.I. flooding has been minimized.
- B. Idle enrichment has been eliminated.
- C. The fuel flow rate has been fixed, and is non-adjustable.
- D. Fuel line clogging has not been experienced.
- E. Excess fuel vaporization in the feed lines is still a problem. However, the present design F.V.I. check valves are able to accomodate a liquid-vapor mixture, and aluminum radiation shields are used to reduce fuel line vaporization.

~~Due to the trouble-free nature of this delivery system, this basic layout is probably final. Further feed tube vaporization control could be realized by relocating the common chamber to a cooler location.~~

Check Valve Development

~~At the start of the contract period the check valve consisted of a 3/32" diameter brass ball sealing a 60° stainless steel seat. A neoprene "O" ring located in the ball just below the seat to aid quick movement of the ball to the sealed position. F.V.I.'s using this type of valve showed marginal durability and were very difficult to assemble~~

initially because the seat for the ball valve had to be lapped in by hand. Furthermore, the "O" ring thickness and differing depths of the stainless seat made standardization of fuel flow from one unit to another impossible to achieve.

The check valve was redesigned, eliminating the neoprene "O" rings. In order to aid assembly, the valve was made of brass, and featured a recessed seat, still cut at 60°. Finishing of the ball valve seat was accomplished either by lapping as before (an easier process since brass is softer than stainless steel), or by using a spherical tool and mallet to establish a round seat.

Acceptable performance was obtained with this configuration only after very careful assembly. In order to establish uniformity of flow, a ball locating copper washer had to have a varying amount of thickness and the amount needed could only be determined by trial and error selective assembly on each F.V.I.

In order to improve check valve action and ease of assembly, various size and type check balls were tried. Stainless balls, while able to accept moisture without damage, could not be obtained with the precision of concentricity required to provide an absolute seal at 1,000 p.s.i. Teflon balls were tried in hopes of solving sealing problems but they

could not withstand the cylinder pressures and temperatures acting upon them for more than a minute of running.

High Precision Chrome Steel Balls were tried in sizes of $1/16''$, $3/32''$ and $1/8''$ to see which afforded the best flow rate and sealing action. It was decided that Chrome Steel Balls, $3/32''$ diameter, $\pm .000025''$ gave the best results.

A test was made to determine the feasibility of feeding fuel vapor to the F.V.I., but it was decided that this aggravated the already marginal check valve operation.

Tests were made using a valve with good sealing action to determine the optimum check valve travel. A distance of $.0025''$ was decided to be the best, but from $.0015''$ to $.006''$ was found to function properly.

A redesign of the check valve was made to provide for easier assembly and more uniform flow. The unfinished check valve seat was now squared off instead of being 60° , and a swedging tool was used to force the seat to an included angle of 90° , with uniform depth and concentricity. The valve swedging operation is done with a tapered tool that centers itself on the valve and is actuated by an arbor press. A dial indicator readout produces uniform check valve travel by assuring a constant amount of valve seat distortion.

In order to minimize check valve malfunction due to dirt on the valve seat, ultrasonic cleaning in a trichloroethane solution is employed during assembly^{Assembly} and cleaning is done in a separate room with a low dust and dirt content.

The performance of the delivered check valves can be summarized as follows:

A. Tooling improvements and reduced tolerances have made manufacture of valves possible with an acceptable rejection rate (approximately 5%).

B. On-vehicle performance is still marginal with regard to flow rate uniformity. Care in manufacture makes it possible to hold F.V.I. flow to 10% variation per set when installed. This uniformity is critical to assure proper operation. Extended tests have shown some F.V.I. flows in an installed system to vary in flow rate by as much as 100%. More work is needed in adapting the check valve to its harsh operating environment, and to the high number of cycles in its service life. Complete check valve failure in service is rare, but the current flow variations; whether caused by valve dimension change or injector stem deposits are not acceptable.

C. The present valve design is acceptable with regard to cost and complexity of manufacture and assembly.

High volume production would necessitate coining of the valve pieces, rather than machining. Production Tooling, when used, will provide valve part uniformity and high percentage yield of finished parts.

Stem and Sealing Development

At the start of the contract period, F.V.I. center electrodes were made of a single length of 304 stainless steel tubing, .093" O.D. x .025" wall x 4" long. This tube was bonded to the ceramic insulator of an otherwise standard spark plug using a silica porcelain cement (Sauerisen Electrotemp #8). The internal volume of the tube was reduced by the insertion of a .030" diameter stainless steel wire, 4" long. This wire serves to increase the surface-to-volume ratio inside the tube, which aids in fuel vaporization on the intake stroke, and flame quenching on the power stroke. The wire will be referred to as a quench rod.

Pressure sealing and Flame Control using this stem-quench rod configuration was acceptable, however several failures of these F.V.I.'s were traced to the stem. It was determined that Gaps in the cement between the stem and the ceramic insulator impeded heat transfer from the stem, enough to cause overheating of the stem at its bottom end with resulting material failure from pre-ignition damage.

Consultation with Prestolite Corporation, an established manufacturer of spark plugs, resulted in an attempt to improve the insulator to stem seal by substitution of glass as the cementing agent. The process entailed forcing crushed lab glass between the two pieces, and firing the pieces in an inert atmosphere to 2000°F, allowing the glass to melt, and a seal to form. The F.V.I. assembly is then cooled over a period of time in order to reduce the number of trapped air bubbles.

Tests of F.V.I.'s assembled in this manner showed a high failure rate due to combustion chamber pressure leakage. The problem was traced to insufficient flow of the melted glass, leaving large areas unsealed. No method of resolving this problem was found.

~~Porcelain Cement was again used to seal the stem to the~~
ceramic insulator. The overheating problem at the bottom of the stem was attacked in two ways: First, the bottom 1" of the stem was constructed of inconel, which can withstand a much higher temperature before failure. Secondly, this inconel tip was fastened to a .125" O.D. copper tube, 2 inches long, and stainless steel was retained for the upper one inch of the tube, resulting in a three-piece stem construction. It was felt that this inconel-copper-stainless assembly would transfer excess heat up the tube and prevent the local overheating

problem of the past design. A further advantage of this heat transfer would be more rapid vaporization of the fuel injected down the tube.

Tests of this design showed adequate material strength, and sealing performance. In order to achieve even more rapid fuel vaporization, the copper tube O.D. was increased to .160", and the shell-insulator assembly was changed to the next higher heat range.

Current design on delivered F.V.I.'s incorporates the three-piece design using either the .125" or .160" O.D. copper center tube, bonded to the ceramic shell by means of Sauereisen No8 cement.

~~This design has shown good performance and excellent reliability. With respect to cost and assembly complexity,~~ it is adequate for low volume experimental work, however a simpler method would be needed for mass production. The establishment of this method does not appear to be a large or difficult problem.

Stem Covering

In order to avoid unwanted electrical arcing from the F.V.I. stem to the engine, all F.V.I.'s are coated with an 1/8" thickness of silicone rubber. Early F.V.I.'s used G.E.

R.T.V. no. 630 which gave acceptable results. Delivered injectors used R.T.V. no. 631 which features a higher tear resistance for increased durability.

Shroud

A large part of the F.V.I. laboratory research was aimed at finding the best compromise in shroud configuration. All F.V.I. Shrouds are constructed of 304 Stainless Steel, and fastened to the shell by means of silver solder. Ground electrodes are also 304 stainless steel unless otherwise specified. Inconel would be a better choice of material for production units.

Designs using a wire across the shroud to determine spark location have given needed reliability when these wires have been located in the shroud and anchored by welding. Butting the cross wire against the shroud without a thru-hole has resulted in failures under high speed and load and is not acceptable.

In general shroud reliability has not been a problem; all laboratory configurations have shown the required durability. High volume production of a finalized shroud would be accomplished by incorporating the shroud into the cold extrusion process used to make the shell. A detailed explanation of shroud development will be found in the section on Laboratory Testing.

5. LABORATORY TESTING

The purpose of all laboratory testing was to obtain performance data on F.V.I. components undergoing design changes and to evaluate the ability of the F.V.I. to ignite leaner mixtures than a standard spark plug with resultant better economy and lower emissions.

Initial tests were performed on a 13 C.I.D. L-Head Tecumseh engine instrumented to measure main fuel flow, F.V.I. fuel flow, airflow, ignition timing, spark voltage, R.P.M., exhaust gas temperature, and exhaust emissions. This engine drove an alternator which was connected to a bank of light bulbs, which provided an adjustable load. A Voltmeter and ammeter measured this load.

The first procedure established was a run-in and test of the check valve function. All new assemblies are subjected to 3 minutes of 2,500 R.P.M.-50% load operation. Any check valve sealing deficiencies are shown by fluctuations in the F.V.I. fuel flow meter; these fluctuations occurring at engine frequency. Complete check valve failure is characterized by a reversal of flow in the F.V.I. fuel feed line. The run-in and valve function test is still used to check all new assemblies.

Early F.V.I. testing on the Single Cylinder Test Engine provided information regarding the optimum amount of fuel to

be metered to the F.V.I. It also provided information on the type of shroud configuration best able to achieve stratified charge operation. Seven shroud variations were tested extensively against a standard spark plug. It was necessary during this time to redesign the check valve (see hardware development, check valve), due to their high rate of initial failure and general short life. Results of the configuration tests showed that all F.V.I.'s tested were able to run leaner than stoichiometric and that both designs with a closed shroud and a design with open shroud incorporating side spark location would do the same work as a standard spark plug while using less fuel.

The graph on the following page plots fuel flow vs. measured horsepower output for a standard J-12Y spark plug and 2 configurations of F.V.I.'s; one open shroud configuration and one closed shroud configuration.

The F.V.I.'s are shown to do the same work with approximately 15% less fuel flow. In all cases, main fuel flow was the least that the engine would use and still produce the required output.

Exhaust emissions on F.V.I. tests were comparable to those on spark plug tests, provided the F.V.I. fuel flow was kept less than 20% of the total flow. F.V.I.'s showed no

change from standard spark plug performance when less than 5% of the fuel was delivered through the F.V.I. A decision was made to supply a nominal 10% of the fuel through the F.V.I. at cruise speeds and loads on vehicle systems.

F.V.I. fuel flow was found to vary inversely with load, this variation being approximately 30% from idle to wide open throttle.

A test was made at this time to determine a workable quench rod specification. With stem I.D. at .042", flame travel up the F.V.I. stem at high R.P.M. and load consistently damaged check valves. Tests of F.V.I.'s not fitted with quench rods in which the flame did not reach the valve showed neither improvement nor worsening of performance with a quench rod. Later quench rod tests using improved stems showed similar results. Since a negative result using quench rods was never seen in any testing, and because there appeared to be a benefit to F.V.I. operation in check valve reliability and fuel vaporization rate, a quench rod specification of 304 Stainless .030" diameter, 4 inches long was incorporated into all F.V.I. designs.

With the data gathered from this early series of tests, F.V.I. sets were constructed for the 350 C.I.D. Chevrolet engine and the 122 C.I.D. Pinto engine in the closed shroud configuration.

Test results showed higher emissions and reduced fuel economy. At this time a flow testing and adjusting procedure was incorporated into F.V.I. manufacture to reduce initial flow variations to 10% per set. Continued poor test results led to improvement of check valve design and vehicle distribution systems in an attempt to standardize F.V.I. flow between cylinders (see Hardware Development). When adequate check valve operation, more uniformity of F.V.I. fuel flow and a better distribution system were achieved tests were run on both Chevrolet and Pinto to measure exhaust emissions and fuel economy. HC and CO emissions were no better than with standard spark plugs, and fuel economy tended to be worse, in part because check valve performance still often resulted in less than acceptable equalization of F.V.I. fuel flows.

The failure to achieve improvement over standard plugs in vehicle testing led to the conclusion that F.V.I. shroud configurations that successfully stratified the charge on an L-Head engine would not necessarily stratify the charge on an overhead valve engine, due to the inherently higher turbulence on the better breathing O.H.V. engine.

In order to examine F.V.I. performance on an O.H.V. engine more closely, the no. 1 cylinder on a 232 C.I.D. AMC Gremlin was isolated by cutting the intake manifold port off

from the others and attaching a separate small carburetor (see Photo, following page).

A pressure transducer was placed in the head of No. 1 cylinder to monitor pressure-time patterns, and other instrumentation monitored No. 1 cylinder main fuel flow, F.V.I. fuel flow, airflow, exhaust gas temperature, cylinder spark timing, HC, CO, and NOx emissions, and R.P.M.

Early testing revealed that the type of shroud configuration established as best on the S.C.T.E. showed little difference over standard in lean limit; nor did it show any pattern of lower emissions at A/F ratios in the 15:1 to 20:1 range.

~~An effort was made at this time to test many widely varying shroud configurations and to establish performance patterns of each. All configurations were tested with F.V.I. fuel flow relative to totals at rates of 0 to 20% and lean running emissions and absolute lean limit were measured. Later, promising prototypes were given reliability tests at higher F.V.I. flow rates to determine resistance to wet and cold fouling.~~

A chart of 12 basic shroud configuration types is shown on the following pages.

AMC Gremlin 232 C.I.D. Intake Manifold, Modified
for Detailed F.V.I. Investigations on Number 1
Cylinder.

A pattern began to emerge during this test period. When F.V.I. flows and rich region exit geometry (shroud) were varied to a point where better than standard performance occurred, the region inside the shroud showed a brownish color and the outside of the shroud was very white. When the region inside the shroud was white, performance was equal to standard and when this inner region was black, performance was equal to or worse than standard.

Test Procedure--AMC Gremlin

A uniform test cycle encompassing 6 data points was used to measure the ability of each F.V.I. to run at lean mixtures with hydrocarbon concentration under 1,000 p.p.m.

~~First, the vehicle was run up to operating temperature, and the calibrated HC-CO infrared analyzer connected to No. 1 test cylinder. Air flow rate was adjusted to the indicated test specification (see below). Fuel was metered initially at a 14:1 A/F ratio. Air was then held constant and fuel reduced so that the A/F ratio became leaner in increments of 1 A/F ratio. The engine performed at each set mode for 30 seconds, and at that time, the HC reading was taken. The recorded A/F ratio in the data table is the leanest that the test F.V.I. would fire, at under 1,000 p.p.m. HC emission.~~

232 C.I.D. A.M.C. Injectors

The following chart indicates the basic geometric variations used in the A.M.C. Gremlin testing. Minor variations of each of these basic types were also tested.

Type 1

Closed-type shroud
extended electrode
.043" gap

Type 2

Closed type shroud
cut-back electrode
.073" gap

Type 3

Open type shroud
extended electrode
tab cutout of shroud to
provide gap (.060")

Type 4

Open type shroud
recessed electrode
tab cutout to provide gap
(.060")

Type 5

Open type shroud
split electrode determines gap
.060"
side spark location

Type 6

Open type shroud extended to
.600" deep
recessed electrode
side spark location .060" gap

Type 7

Open type shroud
2 tabs cutout of shroud and
twisted to provide gap (.060")
and turbulence

Type 8

Open type shroud undercut in
base
2 tabs cutout of shroud and
twisted to provide gap (.060")
and turbulence

Type 9

Open type shroud
4 tabs cut out of shroud and
twisted to provide gap (.060")
and turbulence

Type 10

Open type shroud .600" deep
2 tabs cut out of shroud and
twisted to provide gap (.060")
and turbulence

Type 11

Reduced volume shroud provides
gap (.060")

Type 12

Standard type
N-12Y Champion Spark Plug
(.060" gap)

The test cycle measures performance at six common vehicle speed/load conditions:

Test 1:	1850 RPM	road load	580 CFH Air	Timing 41°BTDC
Test 2:	1850 RPM	light load	500 CFH Air	Timing 41°BTDC
Test 3:	1450 RPM	road load	500 CFH Air	Timing 30°BTDC
Test 4:	1450 RPM	light load	350 CFH Air	Timing 30°BTDC
Test 5:	2500 RPM	heavy load	700 CFH Air	Timing 42°BTDC
Test 6:	800 RPM	no load	200 CFH Air	Timing 16°BTDC

The eleven F.V.I. shroud configurations were tested with optimum F.V.I. fuel flow; against a standard spark plug at all 6 test points on the cycle.

In addition to the above test cycle, the standard plug and two of the best performing F.V.I.'s were tested for absolute lean limit in the following manner: Engine R.P.M. was set at 1450 with light load (Air 350 CFH). Mixture was set at the previous recorded lean limit and then fuel flow was diminished until the exhaust gas temperature diminished to 200°C (not firing). The mixture was then richened until the E.G.T. stabilized at a value over 300°C. The A/F ratio was noted and an HC reading taken.

Plug No.	F.V.I. Fuel Flow/Total	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Absolute Lean Limit A/F
1	10%	15.5	15.5	15	15.5	16	15	
2	10%	14.5	16	15	16	15.5	15	
3	10%	16.5	16	15	15.5	15	15	
4	8%	15	16	15	15.5	15	15.5	
5	12%	17	17	18	19	17	17	22 (HC=3000)
6	9%	17.5	17.5	19.5	17.5	16.5	16	
7	11%	18	17.5	19.5	16.5	17	18	25 (HC=2500)
8	10%	18	17.5	19	16.5	*	17.5	
9	11%	16	15	16	16	16	15	
10	10%	16.5	16	16.5	16	16.5	15	
11	8%	16.5	17.5	19	18	17.5	17	
12	N.A.	16	15.5	16	15.5	15.5	14.5	20 (HC=2100)

* Preignition prevented test reading

F.V.I. configuration #7 ran leaner than a standard spark plug by two A/F ratios with the same HC concentration.

F.V.I. configurations #5, 6, 8 and 11 ran leaner than a standard spark plug by 1 A/F ratio with the same HC concentration.

F.V.I. configurations #1, 3, 4, 9 and 10 showed no improvement over standard spark plug operation.

F.V.I. configuration #2 showed a 1 A/F ratio decrease in ability to run at lean mixtures with low HC emissions.

At this time, an effort was made to determine workable flow rates and shroud geometries by using a comparison of HC emission during lean running conditions on a set mode of operation that varied speed and load. Results showed that an

open shrouded configuration with side spark and tabs that swirled the injected vapor mixture would run with lower HC than standard at mixtures of 17:1 to 20:1, when given a fuel flow between 10 and 20% of total. This configuration would also ignite overall cylinder mixtures of 25:1 although HC emission was 2500 p.p.m., and cylinder loading at this mixture was low.

The turbulating fin design was tested thoroughly. Initial good results were confirmed and F.V.I. sets in this configuration were made for the 350 Chevrolet, 122 Pinto, and 232 Gremlin.

Further tests on the isolated cylinder were made with #7 F.V.I. to determine resistance to wet/cold fouling at 25% flow, cold start, and hour long operation. Tests showed that this F.V.I. was the best so far at resisting fouling. It was found that operation was enhanced when the most heat possible was passed up the stem. The 2 inch stem copper O.D. was increased from .125" to .160" and tests were rerun, with no difference between the two. A test was made with a design that forced the fuel to pass down a tube, up another tube and then back down, using concentric tubes.

This design could not equal the ability of standard spark plugs to ignite lean mixtures when fuel was fed through the

F.V.I. It was decided that the large internal volume and long passages impeded vapor injection prior to ignition, and probably led to vapor injection during the late power cycle and early exhaust stroke. Additional testing brought out the fact that restricting the exit also hurts F.V.I. performance because of late vapor injection. This led to a decision to shorten quench rod length 1 inch, to prevent any closing of the stem delivery end during the service life of the F.V.I. Tests with shortened quench rods showed that flame travel up the tube remained acceptable, though approximately 1 inch higher than with the longer rod. There was little closing off of the stem end by combustion residue.

Laboratory test results of the open shroud turbulent F.V.I. installed in the Pinto 122 and Chevrolet 350 showed no advantage over standard spark plugs. Gremlin economy was slightly improved in field tests.

Since distribution and manufacturing processes were identical between vehicles, conclusion from the test was that different engines faced different operating conditions in the rich flame area. Conditions of turbulence intensity and distribution are affected in large magnitude by engine breathing characteristics, combustion chamber shape, valve size, valve location, valve timing, and by spark plug location.

It was decided that since many design parameters of the F.V.I. were unknown, and since turbulence in the F.V.I. rich region could not be measured, the best F.V.I. shroud design would have to be worked out by experimentation on each basic engine type.

Since F.V.I. evaluation was to be done by Jet Propulsion Laboratories on a Chevrolet 350 engine, another test program similar to the A.M.C. Gremlin work was undertaken.

No. 2 cylinder of the 350 C.I.D. Chevrolet engine was isolated from the other seven cylinders by cutting and welding the intake manifold (see photo, following page). Fuel was metered to the No. 2 cylinder through a flow meter and was controlled by a needle valve. A similar needle valve and flow meter apparatus controlled F.V.I. fuel flow. Number 2 cylinder E.G.T., Air Flow, HC, CO, NOx, Timing, and R.P.M. were also measured.

A test pattern was established. The engine was run up to normal operating temperature at 1500 R.P.M. with 35° BTDC spark timing. No. 2 cylinder was metered 1.0 lb./hr. fuel, and air flow was then adjusted to vary the A/F ratio from 15:1 to 25:1, in A/F increments of 1. At each A/F ratio HC was noted, and later tests on promising configurations compared HC and NOx with that of a standard spark plug.

Chevrolet 350 C.I.D. Intake Manifold, Modified for
Detailed F.V.I. Investigations on No. 2 Cylinder.

F.V.I. shroud geometries of many types and sizes were tested in this manner. An attempt was made to test all reasonable shroud designs at several F.V.I. flow rates.

F.V.I. Shroud Chart--Chevrolet Tests

Type 1

Half Shell Shroud .063" gap
Crush Washer Indexes Plug
Position
(Plug Shroud toward Intake Valve)

Type 2

Large Half Shell Shroud .063" gap
Ground Electrode cut from shroud
Crush Washer Indexes Plug
Position
(Plug Shroud toward Intake Valve)

Type 3

Open shroud configuration
.032" stainless steel crossbar
determines spark gap (.063")

Type 4

Open shroud configuration
.032" stainless steel wire
determines gap (.063")

Type 5

Open shroud configuration
4 tabs (.045" square) determine
gap (.063")

Type 6

Long (.500") open shroud con-
figuration
.032" stainless steel crossbar
determines gap (.063")

Type 7

Open shroud configuration
2 tabs cut and twisted to provide
gap (.063") and turbulence

Type 8

Open shroud configuration---
Recessed Electrode
.032" stainless crossbar-- .032"
stainless gap wire from electrode
(.060") gap

Type 9

Open shroud configuration
.062" stainless crossbar determines
gap (.063")

Type 10

Open shroud configuration
 2 .032" stainless steel crossbars
 determine gap (.063")

Type 11

Open shroud configuration
 .032" crossbar determines gap
 (.040")

Type 12

Half Shell Shroud determines gap
 (.063")
 Crush Washer Indexed Plug
 (Shroud points toward intake valve)
 Shroud with reduced volume--ragged
 edges to produce turbulence

Type 13

Standard Type Spark Plug
 AC R44TX .063" gap

Test Results--Chevrolet No. 2 Cylinder

HC Emission vs. A/F Ratio

Plug No.	15	16	17	18	19	20	21	22	23	24
1	1000	1000	900	1100	1300	1600	2000+	--	--	--
2	500	500	600	1500	1500	2000	--	--	--	--
3	500	450	500	500	500	400	500	1500	2000	--
4	150	200	500	500	500	550	1000	1300	2500	--
5	200	350	200	200	250	600	1000	1500	2000	--
6	250	250	275	325	375	500	800	1500	2000	--
7	250	250	250	350	500	900	1500	2000	--	--
8	250	225	250	300	450	600	900	1200	1900	--
9	250	225	250	375	425	750	950	1450	1900	--
10	400	375	400	400	700	900	1100	1500	2000	--
11	600	600	700	600	1000	1000	1600	2500	--	--
12	300	300	300	350	500	600	900	1400	--	--
13	175	175	300	525	850	1100	1600	2000	--	--

F.V.I.'s #1, 2 and 11 showed higher HC emission at all A/F ratios than standard spark plugs.

F.V.I.'s #3, 4, 5, 6, 7, 8, 9, 10 and 12 showed higher HC emissions than standard spark plugs at A/F ratios from 15:1 to 17:1. HC emissions from 18:1 to 23:1 were less than were standard plugs.

The graphs on the following two pages plot HC emission vs. A/F ratio and NOx emission vs. A/F ratio for F.V.I. No. 9 and for the average of 5 runs with standard spark plugs.

No improvement in HC emission is noted until 18:1 mixture; at leaner mixtures than 18:1, F.V.I.'s show an improvement which widens as the mixture becomes leaner up to 23:1.

NOx emission is reduced by 40% by F.V.I.'s at a mixture of 15:1. As the mixture is made leaner the difference lessens, and at mixtures leaner than 20:1 there is no significant difference over standard spark plugs.

When performance data for all shroud configurations was compared, certain patterns emerged: First, very small changes in shroud geometry produced large variations in lean running performance. Secondly, no geometry emerged with a clear-cut advantage, i.e., designs that had similar spark location and turbulence control performed almost the same despite having very different appearances. It was decided that three important criteria for F.V.I. shrouds were:

A. Turbulence control--The vapor injected for local

enrichment must be partially contained to avoid being swept away from the ignition area prior to ignition.

B. Vapor mixing--More consistent results were obtained when a provision was made to mix the injected vapor with the main charge to prevent an over rich condition in the ignition region.

C. The flame kernel must have room to expand into the main charge, without interference from the F.V.I. shroud.

It became evident that the major problem affecting shroud configuration design was meeting these three criteria at all engine speeds and loads.

The most consistent gains were shown by an open shroud-crossbar configuration, provided the bar was located between .050" and .100" from the vapor exit. Single and double bar configurations gave similar results, provided the bar cross-sectional area was not greater than 20% of the inner shroud area; a condition that impeded flame travel from the shroud. It is believed that having a crossbar in the path of the injected vapor mixes the vapor with the main charge while retaining enough of this mixture near the spark gap to achieve stratified charge operation. Crossbar designs produced less HC and NOx emissions than standard spark-plugs at mixtures from 19:1 to 24:1. Total fuel flow through the F.V.I. was kept in the range of 5 to 10% of the total fuel flow, for optimum results.

The clear difference of coloration between the inside and outside of the shroud as noted in the 232 A.M.C. tests earlier in this section, did not materialize, and this can be explained in one of two ways:

A. The high turbulence and hot location of the spark plug in this engine prevents or minimizes deposit build-up. Or:

B. F.V.I. operating efficiency equal to that of the Gremlin has not occurred on the 350 C.I.D. Chevrolet.

The delivered set of F.V.I.'s for the 350 C.I.D. Chevrolet had a single crossbar; and the C.F.R. F.V.I. set had turbulence creating fins.

While these shroud configurations and flow rates showed good capability of stratified charge performance, it is likely that further experimentation will produce improved results, both in consistency and absolute lean limit extension.

Most recent laboratory test time has been spent testing complete F.V.I. engine installations in the 232 A.M.C. and the Chevrolet 350 C.I.D. To date, HC and CO emissions have remained close to standard; fuel economy has improved marginally, and NOx concentration has been reduced approximately 40%.

6. FIELD TESTING

The purpose of field testing the F.V.I.'s and their associated hardware was to measure the durability of each of the system components, and to evaluate the performance of the system. With each change in the F.V.I. system as it developed, test vehicles were modified and used for daily transportation and weekend trips by company employees. Driveability, fuel economy, and failures were noted. A total of approximately 20,000 miles were accumulated on four test vehicles, with the F.V.I. system in operation.

Early testing indicated a problem common to all test vehicles. Nonuniform fuel flow to the F.V.I.'s resulted in three types of problems. Fuel flow that was too high tended to cause wet fouling, low fuel flow allowed the check valve to accumulate dirt, and the nonuniformity itself produced mixture variations between cylinders. All of these problems produced a reduction in fuel economy, and probably caused an increase in emissions.

These nonuniformity problems were traced to nonuniformities in the manufacture of check valve components, and solutions to these problems were worked out in the laboratory. With each major variation in design, modifications were made to test vehicle systems, and field testing continued.

Another failure mode which was discovered under field testing was caused by a poor bond between the center electrode and ceramic insulator. The bond affects both heat transfer phenomena and mechanical pressure sealing. Preignition at the center electrode tip was traced to poor bonding, which prevented normal heat flow from the center electrode to the engine cooling system. Failure of the mechanical pressure seal did not affect engine operation measurably, however one catastrophic failure was noted when the center electrode "blew out" completely. Considerable attention was given to the bonding process, and is described in the section on Hardware Development.

The work done on the International Harvester 340 C.I.D. School Bus involved two types of field testing, which yielded two types of results. The first phase of testing was done unloaded, with only the driver in the bus. The F.V.I.'s used in this testing were of an early design, incorporating a one-piece stainless steel center electrode. Although quantitative measurements were not made, the F.V.I.'s seemed to perform satisfactorily, and peak power output seemed to improve. Unfortunately, field testing of the unloaded bus was not indicative of normal operation.

The second phase of testing was done in actual service with a full load of 50 people. After one day of service,

seven of the eight F.V.I.'s had suffered preignition damage.

The bus testing indicated a severe underestimation of the heat transfer requirements for heavy-duty service, and resulted in a redesign of the stem portion for all F.V.I. applications.

After the uniformity and bonding problems were worked out, no failures occurred during 4,000 cumulative miles on three vehicles.

Fuel economy was measured at each refueling. Early testing with nonuniform F.V.I.'s resulted in fuel economy reductions of approximately 12% on the Chevrolet, and an improvement of 23% on the Ford Pinto. The School Bus was not operated long enough to measure fuel economy. After the uniformity and bonding problems were worked out, and after implementation of the Optimizer for mixture control, fuel economy improvements were measured on all field tests.

Fuel Economy Improvement (Highway Driving)

	Ford Pinto 122	Chevrolet Malibu 350	A.M.C. Gremlin 232
Standard	26.0	16.0	22.0
F.V.I.	32.0	18.8	24.5
Improvement	23%	17.5%	11.4%

7. HIGH SPEED PHOTOGRAPHY

A project was arranged with the Mechanical Engineering Department of Drexel University, in which Drexel's facilities would be used for the high speed photography of ignition and combustion in a C.F.R. engine, using a F.V.I. The work was done by a part-time F.I.D.C. employee, who is also a Drexel student.

The first requirement for the project was the design and construction of a suitable optical system. The viewing window was mounted in a fixture which was screwed into the spark plug threads of the engine. The F.V.I. was mounted in a port which normally accepts a pressure transducer. This arrangement allowed direct viewing of the ignition region inside the combustion chamber. A focusing lens and a supplementary lens completed the optical path. A schematic of the Optical System is shown on the following page.

Although the internal volume added by the window fixture, and the unusual spark location did not make for ideal engine operation, this arrangement was the only one which would yield an optical path to the ignition region. A volume of approximately one cubic inch, directly below the F.V.I., was in focus when viewed through the camera lens. A Hycam camera was used with several types of film, at several film speeds.

OPTICAL SYSTEM

Many attempts were made to photograph both spark plugs and F.V.I.'s in operation. The original objectives of the project were to confirm the existence of charge stratification, compare flame speed between F.V.I. and spark plug operation, and to use the results as a design tool for F.V.I. development.

The first significant result to emerge was the fact that the engine would not operate at mixtures leaner than stoichiometric with a spark plug, but would run out to approximately 20:1 with a F.V.I. Since comparison of flame speed was not meaningful unless the overall fuel-air ratio was equivalent, comparisons could not be made at the mixtures of interest; those leaner than stoichiometric.

Most of the photo sets were difficult or impossible to interpret, until color film was tried. The results of color photography shed new light on the interpretations, since rich and lean flames could be distinguished from one another by their color. A series of color photographs is presented with this report.

Engine and camera conditions are given in the following table:

Recorded and Computed Data:

camera speed	8,000 pictures per second
engine speed	1,000 revolutions per minute
engine output	1.40 kilowatts
emissions:	
HC	425 p.p.m.
CO	0.8%
approximate air-fuel ratio	18 to 1
crankshaft degrees per picture	0.750
photographic coverage	12° crankshaft rotation
photographs begin	0° (TDC)
photographs end	12° (ATDC)
ignition timing	0° (TDC)

Photographs are presented on the following page

(Note: Photos are enlarged to approximately actual size)

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

HIGH SPEED PHOTOGRAPHS

We interpret the photographs as follows:

Ignition occurs in frame #1. The orange-yellow areas in all frames correspond to the rich flame areas directly below the F.V.I. The lighter blue areas surrounding the rich flame corresponds to a lean flame, propagating across the combustion chamber.

The fact that an orange (rich) and blue (lean) flame can be seen in the combustion chamber simultaneously, with the rich flame occurring directly adjacent to the F.V.I. location, is clear evidence of torch ignition, or stratified charge operation.

8. OTHER DEVELOPMENTS

A. Two Cycle Application

A F.V.I. was fitted to a 100 c.c. Yamaha motorcycle engine, and fed by a regulated fuel pressure source at from 5 to 50 p.s.i.g. All of the fuel was supplied through the F.V.I., and the air was controlled by the carburetor throttle. No fuel was supplied by the carburetor. The engine could be made to idle at 5 p.s.i.g. fuel pressure and wide open throttle airflow, indicating true stratified charge operation. A fuel pressure of 50 p.s.i.g. was required to bring the engine speed up to 6000 r.p.m. Hydrocarbon Emissions were in the range of 1600 to 2000 p.p.m. The same engine was fed by a carburetor and hydrocarbons were measured in the range of 4000 to 6000 p.p.m.

~~After several weeks of development, the same engine was~~
made to run at 35 p.p.m. hydrocarbon emissions using a modified F.V.I. The F.V.I. was used to inject fuel vapor into the vicinity of a standard spark plug, which was used for ignition. These measurements were made at the tailpipe with wide open throttle at 3500 r.p.m., no load, and no attempt was made to determine the extent of thermal reaction in the exhaust system. Later measurements were taken at the exhaust port, and the results are shown in the following table.

Measured at Exhaust Port

R.P.M.	Fuel Pressure (p.s.i.g.)	Exhaust Gas Temp. (O.C.)	HC Emissions (p.p.m.)	Measured A/F Ratio
6200	45	625	200	19:1
5200	40	650	400	20:1
3100	32	600	1600	18:1
2400	26	560	2000	19:1

Yamaha 100 cc Two Cycle Motorcycle Engine Timing: 0° (TDC)

B. Optimizer

The Optimizer can be used successfully in conjunction with the F.V.I.'s with a carburetor, gas phase induction system, or any other type of fuel injection scheme. When the Optimizer was tested using standard spark plugs, it was found that the Optimizer itself contributed significantly to improvements in emissions, performance, and fuel economy.

A series of tests was run using the A.M.C. Gremlin outfitted with standard spark plugs and standard carburetor. The first set of data was taken with all adjustments set at factory specifications. The Exhaust Gas Recirculation system was operative, and ignition timing was set at 8° B.T.D.C.

Fuel economy and emissions were measured on the Dynamometer in the Federal Driving Cycle, and at 50 m.p.h. steady state, at road load horsepower. A second set of data was measured under the same test conditions using standard spark plugs, standard carburetor, Optimizer, 16° B.T.D.C. ignition timing, and without Exhaust Gas Recirculation. The Optimizer tests produced improvements in fuel economy, emissions, and performance. Data is shown on the following page.

This data is a clear indication that the Optimizer itself is a valuable retrofit item which is more effective than Exhaust Gas Recirculation for controlling Oxides of Nitrogen emissions.

Optimizer Tests--Gremlin 232 (1976)

3 Speed, Manual Transmission

	CO (gm./mi.)	HC (gm./mi.)	NOx (gm./mi.)	Fuel Economy (m.p.g.)	Acceleration 30-60 m.p.h. Third Gear (sec.)
Federal Emissions Certification Test (Urban)					
Standard	9.1	1.88	2.87	16.85	
Optimizer	7.0	2.46	2.74	17.29	

Steady State, 50 m.p.h., Road Load
(Highway)

Standard	1.67	.10	2.67	26.01	11.9
Optimizer	1.67	.067	1.37	28.01	10.8

The Federal Test Cycle data was gathered at Scott Environmental Technology, Inc., Plumsteadville, Pennsylvania, in a set of Standard Emissions Certification Tests.

C. Gas Phase Induction

The combination of a liquid fuel-air regulator and heat exchanger in the Exhaust System allows one hundred percent vaporization of the fuel. Since the air is not mixed with fuel until after the fuel is vaporized, there is very little loss of volumetric efficiency due to heating of the charge. Equally important to vaporization of fuel, is the complete mixing of the fuel and air.

Mixing is accomplished by means of a series of vanes placed at the entrance to the intake manifold, which create a strong swirling fluid motion. The Gas Phase Induction System was successful in improving fuel-air distribution in an eight cylinder engine. Exhaust gas temperature measurements are shown on the following page for a 350 C.I.D. Chevrolet engine with a 1975 production intake manifold, comparing standard carburetion with Gas Phase Induction.

The vaporization of fuel before induction also allows the energy which would have been used to vaporize fuel in the combustion chamber to be recovered as useful work. For gasoline, the latent heat of vaporization represents a very small percentage of the work output. However, when fuels with very high latent heats of vaporization such as methanol are used, the energy recovered by pre-vaporization becomes quite significant.

Exhaust gas temperature measurements for each cylinder of a 350 CID engine with production manifold. Comparison is made between operation with stock carburetion and Gas Phase Induction (vaporized fuel) at 35 mph road load horsepower

The latent heat of vaporization of gasoline is only 0.56% of its higher heating value, while methanol requires 5% of its higher heating value to vaporize.

Another significant advantage of pre-vaporization is the ability to encourage chemical dissociation of the fuel before combustion. By making use of a catalyst in the heat exchanger, and by allowing a small amount of exhaust gas (from a lean flame, containing excess oxygen) to flow into the heat exchanger with the liquid fuel, a series of chemical reactions known as Oxydative Pyrolysis breaks the fuel molecules into smaller ones, releasing fuel constituents which were not present in the original fuel. These lighter fuel molecules can improve the ignition characteristics and flame speed of the mixture and allow further extension of the lean limit.

Samples of vaporized fuel were drawn off the Chevrolet in operation, and analyzed at Princeton University using a Gas Chromatograph. Evidence of Oxydative Pyrolysis was found.

D. Multifuel Testing

One of the by-products of the Gas Phase Induction and Optimizer developments is a fuel metering and preparation system which is inherently multifuel in nature. Since the latent heat of vaporization does not have any affect on distribution or combustion, and since the Optimizer produces a fuel-air ratio which optimizes engine efficiency, fuels with varying properties may be used interchangeably without adjustment of the metering system.

Normally, the Optimizer operates within a range of approximately 12:1 to 24:1 fuel-air ratio. For purposes of multifuel testing, the range was adjusted to approximately 6:1 to 20:1 and the different fuels were introduced into a hot, running engine. The problems of cold starting were not considered in these tests. Gasoline, kerosene, diesel, and methanol were run at 35 m.p.h., road loading, and fuel economy and emissions were measured at standard timing of 12° B.T.D.C. and an advanced timing of 24° B.T.D.C. Results of these tests are shown on the following page.

The most significant result of these tests is not the fuel economy or emissions of the various fuels, but the fact that fuels of varying properties could be compared on an equal basis, by a single fuel metering and preparation system, without introducing any preprogrammed fuel-air ratio.

Multifuel Tests

Pinto 122 C.I.D. Equipped with Gas Phase Induction, Fuel Vapor
Injector Igniters and Optimizer, All Tests at 35 m.p.h. Road
Load.

	<u>HC</u> (p.p.m.)	<u>CO</u> (%)	<u>NOx</u> (p.p.m.)	<u>Miles</u> Gallon	<u>Miles</u> 1000 B.T.U.
Timing 12° B.T.D.C.					
Gasoline	140	.75	500	35.3	.277
Kerosene	120	.75	200	38.6	.285
Diesel Fuel	110	.80	200	46.9	.325
Methanol	80	.70	170	25.0	.400
Timing 24° B.T.D.C.					
Gasoline	200	1.2	140	39.2	.308
Kerosene	150	.75	110	44.1	.326
Diesel Fuel	300	1.0	140	42.3	.293
Methanol	160	.13	50	24.3	.389

E. The 1972 Ford Pinto 122 C.I.D. was tested in its standard configuration, and with the Gas Phase Induction-

Optimizer-F.V.I. installation. Tests were run at 30, 40, and 50 m.p.h., road load, and both fuel economy and emissions were measured. In the second set of tests, engine calibrations were adjusted to yield emissions levels comparable to those of the standard configuration tests. Fuel economy data is presented on the following page.

○ FVI + OPTIMIZER + GAS PHASE
△ CARBURETOR

9. HARDWARE DELIVERY

On December 15, 1976, the following items were shipped to Jet Propulsion Laboratory, Pasadena, California:

4 Fuel Vapor Injector Igniters GAB1 - 1, 3, 4 and 5

1 capillary tube and filter assembly

1 spare capillary tube

1 pressure regulator with fittings

1 spare pressure regulator

1 electric fuel pump

1 electric solenoid valve

1 spark plug boot and wire for F.V.I.

2 copies of installation instructions

~~1 set of fittings and tubing~~

~~1 spare fittings and tubing~~

~~These items made up a complete F.V.I. laboratory test installation for evaluation of F.V.I.'s on a single cylinder C.F.R. engine, under laboratory conditions.~~

~~On December 30, 1976, the following additional items were shipped to J.P.L.:~~

16 F.V.I.'s ABA 1-8 BBA 1, 2, 4, 6, 21, 23, 24, 26

2 Fuel Distribution Manifold Assemblies

1 spare Fuel Distribution Manifold

1 tee fitting

1 ignition wiring harness

- 1 F.V.I. installation tool
- 1 tube piloting tool
- 1 magnetic pick-up
- 1 air addition plate
- 2 5/16 - 18 x carburetor mount bolts
- 1 Optimizer air valve
- 1 rubber air tube with clamps
- 4 fuel distribution manifold mounting clamps
- 1 Optimizer circuit
- 1 Optimizer wiring harness
- spare tubing and fittings
- 2 installation instruction reports/E-35

Both shipments were received. The second package contained all of the necessary components and instructions for a complete F.V.I. and Optimizer Retrofit installation in a Chevrolet 350 C.I.D. engine.

10. FISCAL DATA

The following pages present a complete record of contract payments and expenditures.

E.R.D.A. Contract--Cost Record E-(04-3)-1237

Date	Estimate	Total	Billed	Rec'd.	Date
Apr. 16 1976					
May 1					
May 16	12,500				
June 1					
June 16	16,000	28,500	28,500	28,500	
July 1	8,500	37,000	8,500	8,500	
July 16	8,500	45,500	8,500	8,500	
Aug. 1	8,500	54,000	8,500	8,500	
Aug. 16	8,500	62,500	8,500	8,500	
Sept. 1	8,750	71,250	8,750	8,750	
Sept. 16	8,750	80,000	8,750	8,750	
Oct. 1	8,750	88,750	8,750	8,750	11-4
Oct. 16	8,750	97,500	8,750	8,750	11-11
Nov. 1	8,500	106,000			
Nov. 16	8,500	114,500	17,000	17,000	12-12
Dec. 1	8,500	123,000	8,500	8,500	12-27
Dec. 16	8,500	131,500	8,500	8,500	1-10
Jan. 1 1977	7,250	138,750			
Jan. 16	7,250	146,000			
Feb. 1	5,120	151,120			
Feb. 16	5,100	156,220			

11. CONCLUSIONS, RECOMMENDATIONS, AND PROPOSALS

The Fuel Vapor Injector Igniter has been shown to have the ability to ignite leaner mixtures than a spark plug. When compared at equivalent overall air-fuel ratios, the F.V.I. has been shown to produce lower Hydrocarbon and Oxides of Nitrogen emissions, with equivalent Carbon Monoxide emissions. This lean ignition and low emission capability can be translated, by altering engine calibrations, into a reduction in specific fuel consumption.

When applied to a two-cycle engine, the F.V.I. reduced Hydrocarbon emissions from 4000 p.p.m. to 35 p.p.m. The two-cycle application of the F.V.I. shows far greater potential for energy conservation than anything that has ever been reported in the technical literature. Proposal No. 210761A was submitted to E.R.D.A./T.E.C. on October 12, 1976 for a feasibility demonstration of the most cost-effective, energy efficient automotive, aircraft, and marine powerplant type ever built. The two-cycle powerplant, when made to burn cleanly, shows the potential for greater efficiency and cost effectiveness than Otto, Diesel, Stirling, Rankine, or any mobile powerplant type known today.

Laboratory tests have verified the F.V.I.'s contribution to fuel economy improvements. Field testing has shown the success of a complete F.V.I. installation to be intermittent,

and when successful, the fuel economy gains which are directly attributable to the F.V.I.'s have been only marginal. Upon close examination, it was found that the Optimizer, an auxiliary mixture-leaning device, was contributing more to fuel economy improvements than the F.V.I. set. The intermittent success of the F.V.I.'s in field tests can be traced to questionable reliability.

The Optimizer was tested with standard spark plugs, and the results were impressive. While maintaining essentially equivalent emission levels on the Federal Test Cycle in a certified test, fuel economy was improved by 2.6% on the urban cycle, and 8% on the highway cycle, with an improvement of 10% in wide-open-throttle acceleration. The equipment used in these tests was far from fully developed, and the emissions data was achieved on the first try in the Federal Test Cycle. (Note: The Chief Engineer at General Motors has stated publicly that for a new emission control system to pass the certification tests on the first try would require an act of God.)

Since the Optimizer circuitry was developed and adjusted for steady state operation, large improvements may be made by further development in a simulated Federal Emissions Certification Test. The circuitry is a "natural" for adaptation to a digital microprocessor.

The Gas Phase Induction System has been shown to improve intake manifold distribution which, in turn, allows leaner engine operation and improved fuel economy, within a given set of emissions constraints.

The combination of a Gas Phase Induction System and Optimizer results in a Multifuel Metering System, the value of which is inversely proportional to the availability of gasoline to the user. In addition, the F.V.I. has been successful as a means for starting methanol-fueled vehicles, when propane is fed to the F.V.I.'s during cranking.

The synergistic results achieved by combining the F.V.I., Gas Phase Induction, and Optimizer have shown that these systems can significantly contribute to energy conservation, and ~~can be readily retrofitted to existing motor vehicles to provide alternate fuel capability in the event of an energy~~ emergency.

All data contained in this report is repeatable, and can be demonstrated for government personnel, if required.

The work carried out during the course of this contract has exposed several original approaches to energy conservation, within the constraints of environmental protection. It is recommended that E.R.D.A. funding be continued for the purpose of completing the developments which are described in this

report. A program outline for these tasks is shown on the following page.

A detailed proposal can be supplied with the final draft of this report, for the purpose of evaluating the scope and level of funding required to complete the stated tasks.

MONTH	1	2	3	4	5	6	7	8	9	10	11	12
FVI-1 MULTIFUEL &												
RELIABILITY PROGRAM	←	→	→	→	→	→						
FLEET TEST-FVI-1 OPTIMIZER							←	→	→	→	→	→
OPTIMIZER-FLEET TESTING												
PRODUCT DESIGN	←	→										
MFG			←	→								
INSTALL					←	→						
TEST (ANALOG)							←	→	→			
TEST (IMPROVED DIGITAL)										←	→	→
OPTIMIZER IMPROVEMENT PROGRAM												
DIGITAL DESIGN (MICROPROCESSOR)	←	→	→	→	→							
LAB DEVELOPMENT	←	→	→	→	→	→	→	→				
MFG & INSTALL FOR FLEET TEST							←	→	→			
GAS PHASE-MULTI FUEL PROGRAM												
COMPLETE DEVELOPMENT OF COLD START, DECELERATION & CATALYST	←	→	→	→	→	→						
MFG & INSTALL FOR FLEET TEST						←	→	→	→			
FLEET TEST										←	→	→
FINAL REPORT												X

12. APPENDIX

Program Plan

Technical Paper to be presented at the N.A.T.O./C.C.M.S.
Fourth International Symposium on Automotive Propulsion
Systems.

Oxford Pendaflex
CORPORATION

STOCK No. 752 1/3

• • •

MADE IN U.S.A.

PROGRAM PLAN
FOR
A FUEL VAPOR INJECTION/IGNITER SYSTEM

CONTRACT NO. E(04-3)-1237

FUEL INJECTION DEVELOPMENT CORPORATION
BELLMAWR, NEW JERSEY

CONTENTS

SUMMARY.....2

TASK 1 - FVI DESIGN & DEVELOPMENT.....4

Phase I - Design, Procure and Install Instrumentation.....4

Phase II - Design and Fabricate Engineering Prototypes.....4

Phase III - Parametric Testing.....5

Phase IV - Design and Fabricate Prototype System.....6

Phase V - FIDC Tests.....6

TASK 2 - FABRICATION AND DELIVERY.....7

TASK 3 - FVI TESTING AND EVALUATION.....9

PROGRAM SCHEDULES.....10

SUMMARY

This document presents the Program Plan for Contract E(04-3)-1237 between the Fuel Injection Development Corporation (FIDC) and the ERDA Division of Transportation of Energy Conservation (TEC).

This contract, to cover a period of 10 months, consists of three technical tasks (Design and Development, Fabrication and Delivery, and Test and Evaluation) with supporting documentation to develop a Fuel Vapor Injector/Igniter (FVI) System.

Fuel Vapor Injector/Igniters will be designed and manufactured with variable design configurations. These devices will be tested to determine the optimum configuration for various types of engines and methods of operation.

A total of four test vehicles will be used:

1. A 6-cylinder test engine will be instrumented to measure lean limits, combustion pressures and exhaust products at various loads and speeds on a chassis dynamometer.
2. An International Harvester School Bus equipped with a 340-cubic-inch V-8 engine will be fitted with an FVI System and placed in regular service in Chetenham Township, Pennsylvania. This test will provide a hard usage evaluation, permit system debugging under field conditions and establish all product assurance factors - Reliability, Serviceability, Maintenance Requirements, Training Doctrines, etc. Fuel maintenance and fuel consumption records for the present 8000 miles of operation is available on this bus. The data compiled during the forthcoming evaluation period will be compared with the existing records to provide a valid Before-and-After summary of results. An exhaust composition analysis will be made both before and after the FVI conversion to complete the significant data.
3. A 1972 4-cylinder, 122-cubic-inch Ford Pinto and a 1975 V-8, 350-cubic inch Chevrolet equipped with FVI Systems will be operated daily to develop qualitative and quantitative data on the program.

Arrangements have been completed with Drexel University for a member of our staff to perform high speed photo studies of the FVI System on their CFR Engine.

In addition to FVI System Development, FIDC has designed and tested a Total Gas Phase Induction System* to replace conventional carburation. Total Gas Phase Induction has been shown to improve fuel distribution in the intake manifold, supplying an equal fuel/air mixture to each cylinder of a multi-cylinder engine. The advantages of Total Gas Phase Induction include:

1. Extension of the Lean Limit
2. Increased Flame Speed
3. Reduction in NOx Formation
4. Perceptible Improvement in "Smoothness"
5. Multi-fuel capability.

FIDC will supply a Total Gas Phase Induction System for test in conjunction with the delivered FVI System.

Preproduction Prototypes of the FVI System with required hardware and data will be delivered to JPL for evaluation testing in accordance with Contract Requirements.

~~Data items will be delivered in accordance with the schedule included in the Statement of Work, Exhibit I of the Contract.~~

*Liquid Fuel is vaporized in an exhaust heated Heat Exchanger and mixed with air prior to cylinder induction.

TASK 1 - FVI DESIGN AND DEVELOPMENT

Task 1 consists of five phases, which are detailed below:

PHASE I - DESIGN, PROCURE AND INSTALL INSTRUMENTATION

1. Laboratory Instrumentation:
 - a. Dynamometer (Variable Inertia) for HP and MPH*.
 - b. Exhaust Gas Temperature Probes*.
 - c. Exhaust Gas Measurement Services for CO, HC's and NOx.*.
 - d. Indicators for Engine RPM*, Manifold Pressure*, Intake Mass Air Flow, Fuel Flow and Fuel Pressure*.
 - e. Measurement of Indicated Mean Effective Pressure (an undisclosed invention to be patented by FIDC)*.
 - f. Cylinder Pressure Transducers, Oscilloscope and Scope Camera.
2. Modification to 6-cylinder Test Engine:
 - a. Cut and Weld Manifolds to isolate cylinders.
 - b. Drill Head for Pressure Probes.
 - c. Install Test Instrumentation
 - d. Install FVI System Plumbing.
3. Modify School Bus with FVI System and associated hardware.
4. Setup CFR Engine at Drexel University and perform tests.

PHASE II - DESIGN AND FABRICATE ENGINEERING PROTOTYPES

Prototype components of the FVI System will be fabricated to vary:

1. Heat ranges in the porcelain and shroud portion of the FVI System.
2. Delivery Tube Projections
3. Delivery Tube Diameters
4. Spark Gap Settings
5. Heat Transfer/Quench Rod Sizes

*Existing and Installed

PHASE III - PARAMETRIC TESTING

Perform Laboratory tests on the test engine at the speeds and conditions listed in Figure 1.

Numbers in () indicate approximate engine BHP

FIGURE 1. TEST CONDITIONS FOR 6-CYLINDER ENGINE

Fuel/Air Ratios in the main charge will be reduced until hydrocarbon levels increase - the Lean Limit. Fuel flow to the FVI System will be varied to determine the best flow for achieving the optimum lean operation.

One design parameter will be changed at each test. The data will be retained to determine the design parameter that gives the best result.

In addition to the test engine results, the V-8, 350-cubic inch Chevrolet engine with the installed FVI System will be used for qualitative and quantitative tests. Of primary concern will be the development of data for use in system debugging and reliability predictions.

All field tests during Phase III will be performed with unoptimized (present design configuration) components.

PHASE IV - DESIGN AND FABRICATE PROTOTYPE SYSTEM

Data derived from Phase III testing will be analyzed and Pre-Production Prototypes of all FVI System parts will be designed. Sufficient systems will be fabricated to re-equip all four test vehicles with prototype parts and to deliver a complete system with spares to the Jet Propulsion Laboratory for Government tests.

PHASE V - FIDC TESTS

FIDC tests will install the fabricated prototype parts on the 6-cylinder Test Engine, the 4-cylinder Pinto and the V-8 Chevrolet. Laboratory tests on the Dynamometer and road tests under actual driving conditions will be performed to determine:

1. Brake Specific Fuel Consumption per Figure 1.
2. Miles per Gallon per EPA Driving Cycles.
3. Levels of CO, HC and NOx at EPA Driving Cycles (in parts per million).
4. Acceleration Rates from 0 to 40 and 0 to 60 Miles per Hour
5. Driveability in qualitative terms.

FIDC also will install prototype parts on the School Bus and continue use of the bus in daily service. Fuel consumption and maintenance records will be maintained and reported.

TASK 2 - FABRICATION AND DELIVERY

FIDC will fabricate complete Prototype FVI Systems, spare parts, pressure regulators, specialized tools and engine modification hardware in accordance with the completed designs of Task 1.

A Total Gas Phase Induction System also will be fabricated by FIDC. This Induction System will be compatible with the 350-CID Chevrolet Engine and will be capable of use with the Prototype FVI System for test and analysis. Capability for comparing the Induction System with conventional carburation will be provided.

Instructions, calibration curves, and other necessary information will be provided to ensure complete test and evaluation of the prototype equipment.

Specific deliverables include:

DELIVERABLE TO GOVERNMENT TESTING LABORATORY*

1. For application to the Single Cylinder CFR Engine, the Contractor will provide:

a. One complete Fuel Vapor Injector/ Igniter (FVI) System designed for, and including all hardware necessary to modify a single cylinder CFR engine. Engine specifications as given in Table 1, Exhibit I (Statement of Work)	8 months after contract execution
b. Instructions for installation of FVI system on single cylinder CFR engine.	8 months after contract execution
c. Spare parts for Item 1 system to support testing. A minimum of one fuel pressure regulator and one Injector unit.	8 months after contract execution

* The hardware and other items identified shall be delivered by FIDC to a test facility as specified by the Energy Research and Development Administration (FEC).

2. For application to 350 CID Chevrolet V-8 Engine:
 - a. One complete Fuel Vapor Injector/
Igniter System designed for, and
including all hardware necessary to
modify a 350 CID Chevrolet V-8
engine. Engine specifications
as given in Table 1, Exhibit I
(Statement of Work). 8 months after
contract
execution
 - b. Instructions for installation of FVI
System on the 350 CID V-8 engine. 8 months after
contract
execution
 - c. Spare parts to support testing. 8 months after
contract
execution
A minimum of 1 fuel pressure
regulator and 4 injector units.
3. Valid, calibration curves for all FVI
units showing flow vs pressure drop
for Indoline gasoline. 8 months after
contract
execution
4. Specialized tools needed for installation
and/or servicing 8 months after
contract
execution

TASK 3 - FVI TESTING AND EVALUATION

FIDC will provide written response to Test Procedures provided by ERDA TEC for JPL Evaluation Tests. FIDC also will provide Staff Members as required to assist in installation, witness evaluation testing or help in data analysis during the final tests.

PROGRAM SCHEDULES

A Program Schedule Chart is included (Figure 2) which shows program milestones for the FVI System. Data Item deliveries also are shown on this chart. Figure 3 is a flow chart for the Program, depicting the development cycle to be followed.

FIG 3

ERDA-TEC CONTACT NO E(04-3)1237 FUEL INJECTION DEVELOPMENT CORP
 PROGRAM PLAN E/34 APR 15 1976. BELLMAWR N.J.

FIG 2.

A RETROFIT FUEL VAPOR METERING SYSTEM WITH TORCH IGNITION AND MULTIFUEL CAPABILITY

By:

Ervin Leshner, Vice President, Engineering
and

Michael D. Leshner, Chief Engineer

Fuel Injection Development Corporation

110 Harding Avenue

Bellmawr, New Jersey 08030

ABSTRACT

An air/fuel metering system has been developed to combine the advantages of premixed combustion, torch ignition and servo feedback control of the air/fuel ratio to maintain engine operation at the lean limit.

Premixed combustion is achieved by vaporizing all of the fuel in a heat exchanger using the waste heat of the exhaust gases. Torch ignition is accomplished by means of Fuel Vapor Injector/Igniters which replace conventional spark plugs and introduce a small quantity of fuel vapor into the ignition region prior to ignition. Lean limit engine operation is the result of continuous monitoring and optimization of the engine power output per unit of fuel input.

Implemented with simple, low cost hardware, the system has been retrofitted to four, six and eight cylinder vehicles. Comparison of the system with conventional metering systems has shown marked improvements in both fuel economy and exhaust emissions.

ADAPTABLE AND ADAPTIVE FUEL CONTROL SYSTEM

The fuel management system now developed provides charge stratification, conversion of fuel from liquid to gas, and control of the air/fuel (A/F) ratio so that the engine operates at its maximum power output for any given fuel flow. Making use of simple engine mounted sensors and an electronic control module, the system self adjusts to accomodate changes in types of fuels of varying stoichio-metry. For test purposes, the system has been successfully retrofit-ted to several automobiles and a two-cycle motorcycle.

The complete system consists of three subsystems: Fuel Vapor Injector/Igniters; An Optimizer; And a Fuel Regulator/Vaporizer. An electronic control system is used with the Optimizer. The sub-systems may be used individually or combined synergistically to form a complete fuel preparation and control system. Each of the subsystems is described in the sections which follow.

FUEL VAPOR INJECTOR-IGNITER

The Fuel Vapor Injector/Igniter (FVI) is a combined fuel injector and spark plug. Instead of the usual solid center bar for a center electrode, a hollow tube is used. Fuel is forced through this tube into the combustion chamber to provide local enrichment of the air/fuel mixture in the ignition region. (Figure 1)

The FVI converts an internal combustion engine to stratified charge operation. Fuel is delivered to the FVI at a constant pressure of approximately 0.5 psig. A checkvalve prevents the flow of fuel when-ever pressure in the combustion chamber is above 0.5 psig.

On the engine's intake stroke, when pressure in the chamber falls below 0.5 psig, a minute quantity of fuel flows past the checkvalve and into the central tube. Since the tube has been heated on the previous power stroke by hot combustion products, the fuel vaporizes and expands. The vapor exits from the tube into the ignition region. The fuel in the FVI continues to vaporize and expand during the compression stroke, further enriching the mixture in the ignition region. A shroud at the end of the FVI prevents excessive mixing of the rich injected mixture and the lean mixture which has been delivered to the cylinder through the intake valve.

The confined volume of rich mixture around the spark gap assures reliable ignition, and in some configurations creates a torching flame across the combustion chamber. Consistent ignition of mixtures leaner than 24:1 A/F ratio is a demonstrable characteristic of this device.

Results of laboratory testing indicate that the FVI is capable of reducing emissions of Hydrocarbons and Oxides of Nitrogen at any given air/fuel ratio. Further, by operating at leaner A/F ratios, specific fuel consumption may be improved. These results are shown in Figures 2 and 3.

FVI IN TWO CYCLE ENGINES

When adapted to two-cycle engines, the FVI delivers all of the fuel, which is vaporized and injected into the cylinder where it mixes with air which entered the cylinder through the intake ports. Fuel injects into the cylinder when the intake and exhaust ports are closed, thus

eliminating fuel loss during the intake and exhaust portions of the cycle. Since the charge stratifies, the rich portion remaining in the spark gap area, lean mixtures may be used with no sacrifice of reliability.

OPTIMIZER

The Optimizer is a servo operated variable orifice which admits air to the engine's induction system in proportions controlled by an electronic module which monitors engine power output. The Optimizer can be successfully used with our FVI devices, standard carburetor, Gas Phase Induction system, or any other type of fuel injection scheme.

It is well established that the most efficient A/F ratio for any engine will be the leanest mixture which will ignite and propagate a flame in the combustion chamber during the time available for combustion.⁽¹⁾ This efficiency is due to better transfer of chemical energy to pressure as the mixture becomes leaner. It's also established that the concentration of pollutants such as HC, CO, and NO_x can be minimized by supplying an I.C. engine with a mixture which is leaner than stoichiometric. Further, that as A/F ratios become leaner beyond stoichiometric, pollutants will continue to decrease in concentration until the point is reached where the A/F ratio becomes so lean that:

- a. Ignition becomes faulty.
- b. The flame quenches out due to heat transfer to the combustion chamber surfaces.
- c. The flame speed becomes so slow that efficiency is diminished.

Any of these three phenomena will result in incomplete combustion. The leanest A/F ratio that can be maintained without one of the above three phenomena occurring is defined as the lean limit.

Referring to Figure 4, it can be seen that as the A/F mixture is made leaner beyond stoichiometric, a simultaneous drop in efficiency and increase in HC emissions will occur when the lean limit is reached. Operating an engine at an A/F ratio leaner than the lean limit results in increased HC emissions and reduced efficiency due to any or all three of the factors stated above.

Operating at an A/F ratio richer than the lean limit results in increased emissions of HC, CO and NO_x. Also, there is less than optimum energy efficiency.

It is apparent that to obtain optimum efficiency (or vehicular miles per gallon) and to minimize exhaust pollutants, the A/F ratio should be maintained close to the lean limit. However, referring to Figure 4, it's easy to see that the lean limit doesn't always occur at the same A/F ratio. The lean limit mixture is dependent on many input parameters, some of which follow:

- a. Compression ratio, valve timing, wear, deposits, rpm and manifold pressure as well as coolant temperature.
- b. Ignition type, ignition timing, plug gap and system voltage.
- c. Ambient temperature, pressure and humidity.
- d. Fuel octane, lead content, air content, distillation analysis, stoichiometry and temperature.
- e. Level of fuel vaporization or atomization.

The cumulative effect of these varying parameters can cause as much as 100% variation in the lean limit A/F ratio.

Attempts have been made to continuously measure the important parameters such as manifold pressure, throttle position, spark timing and ambient temperature during engine operation. (The objective being to process the information to program a "Best Guess" A/F ratio for each possible combination of measured parameters.) In contrast to the preceding approach, the Optimizer is not programmed.

Fuel Injection Development Corporation has developed a means for detecting the lean limit, by monitoring change in instantaneous power output, and for processing this information electronically. Two different power sensing schemes have been used successfully. The first uses a magnetic transducer to monitor the engine rotational frequency, and the second monitors combustion chamber pressure and manifold vacuum. ~~Either of the two schemes can be used to detect and to maintain lean limit operation, controlling the A/F ratio supplied to an internal combustion engine. By this means, engine operation is maintained in the region of its lean limit regardless of operating conditions.~~

~~In essence, the carburetor, fuel injection system or other fuel delivery system is set to a non-critical—even crude—somewhat over-rich condition. The servo controlled orifice of the Optimizer admits air to lean the mixture to the lean limit. As stated previously, this is determined by engine mounted sensors coupled to an electronic~~

control module. The effectiveness of the Optimizer is limited primarily by the effectiveness of the engine's induction system in preparing and distributing the main air/fuel mixture.

GAS PHASE INDUCTION

Conventional fuel delivery systems (carburetors and liquid fuel injectors) meter, atomize and mix liquid fuel droplets with air to form a two-phase mixture. The disadvantages of two-phase induction are well documented. They are: Poor distribution, and poor, incomplete combustion.

To overcome the disadvantages of two-phase induction, and permit more nearly complete effectiveness of the Optimizer and the FVI system, a single-phase induction system was developed. The Gas Phase Induction system meters fuel in liquid form, vaporizes the fuel in a heat exchanger using the engine's hot exhaust gases, and mixes the gaseous fuel with air prior to induction. The system achieves remarkably uniform distribution of air and fuel to all cylinders.

Another advantage of the Gas Phase Induction system is the ability to burn fuels with high latent heats of vaporization and still maintain good distribution.

In addition to vaporizing fuel, the heat exchanger serves another function. The high temperature (500° to 700°F) and relatively long residence time (0.5 seconds) promote dissociation of the fuel. The stainless steel (10% nickel) heat exchanger and copper feed tubes

also serve as catalysts to promote dissociation.

Since a small quantity of exhaust gas (from a lean flame) containing oxygen is introduced into the heat exchanger with the liquid fuel, oxidative pyrolysis occurs, resulting in low molecular weight hydrocarbons and free hydrogen.

Low molecular weight hydrocarbons (ethane, ethene, propane) raise the octane number of the fuel and free hydrogen increases the flame speed, allowing extensions of the lean limit. To further promote oxidative pyrolysis, oxygen concentration in the heat exchanger may be increased or the catalyst surface may be expanded.

Evidence of oxidative pyrolysis was verified in samples of vaporized fuel drawn off a 350 CID Chevrolet and analyzed at Princeton University by means of a gas chromatograph.

The combination of a liquid-fuel and-air regulator plus the heat exchanger in the exhaust system allows 100% evaporation of the fuel. Since the air is not mixed with the fuel until after the fuel is vaporized, there is very little loss of efficiency due to heating of the charge. An important adjunct to vaporization of the fuel is the complete mixing of fuel and air.

Mixing is enhanced by a series of vanes placed at the entrance to the intake manifold. The vanes impart a strong swirling fluid motion to the gases. Figure 5.

The Gas Phase Induction system has proven successful in improving air/fuel distribution in an eight-cylinder engine. Figure 6 shows the exhaust gas temperature measurements for a 350 CID Chevrolet engine with a 1975 production manifold. The graph compares the

substantial temperature variations observed with standard carburetion with the strikingly even temperatures observed with Gas Phase Induction.

Vaporization of the fuel before induction also allows recovery of the energy which would have been used to vaporize the fuel in the combustion chamber. For gasoline, the latent heat of vaporization is a very small percentage of the work output. However when fuels with very high latent heats of vaporization are used, such as menthanol, the energy recovered by pre-vaporization becomes quite significant. The latent heat of vaporization of gasoline is only 0.56% of its higher heating value. Menthanol requires 5% of its higher heating value to vaporize.

The overall benefit of Gas Phase Induction was demonstrated in a test conducted on the 350 CID Chevrolet. Running at road load on a chassis dynamometer, the A/F mixture controlled by the Optimizer, and with the vaporizer in operation, fuel consumption was measured. Then without change in the A/F ratio, the metered fuel was diverted to spray unvaporized into the induction system. Fuel consumption was 8% better with the vaporizer in operation.

DESIGN CRITERIA

The system and hardware design criteria were established to provide that:

1. All system components can be retrofitted to existing vehicles.
2. Equipment and installation costs could be recovered through savings in fuel costs in one year of average use.

3. Reliability at least equivalent to existing automotive fuel management systems.
4. To minimize product design and tooling costs, all major components of the system are interchangeable through the different types of vehicles to be accomodated.
5. Multifuel capability without refit or adjustment to avoid obsolescence in the 1980s and to provide a retrofit system to meet the market needs when blended fuels become available.
6. Components are simple, low in cost and free from critical tolerances and specifications.
7. If a component fails in a mode which would increase exhaust emissions, performance would degrade and encourage the vehicle owner to seek correction--unlike present systems which often improve vehicle performance when an emission control component fails.

Within the constraints imposed by the design criteria, the three subsystems described have evolved. They can be applied in several

~~combinations to existing vehicles. The FVI subsystem can be applied~~
~~to any four-cycle engine. However, this application must be accom-~~
 panied by some means of leaning the main charge. This can be accomplished by installing leaner jets in a standard carburetor. For a retrofit system, the Optimizer is the best means of achieving the leaner mixture.

The Optimizer can be used with a conventional carburetor. An adaptor plate, Figure 5, replaces the thermal insulation gasket under the carburetor to provide a means of bleeding optimizing air into the intake manifold. The Optimizer servo-air control can be mounted at any convenient location in the engine compartment and connected by a hose to the adaptor plate. The power sensor is attached to the engine. The control computer is located in the passenger compartment to avoid the need to design the electronics to withstand the hostile under-hood environment.

TEST PROGRAM AND RESULTS

The bulk of the testing involves four four-cycle engines: A single cylinder L-head engine; a four-cylinder Pinto; a six-cylinder AMC Gremlin; and an eight-cylinder Chevrolet-Malibu. Additional testing involves a 100-cc two-cycle Yamaha engine.

Figure 7 compares the results obtained with a standard, conventional spark plug and with a FVI installed in a single-cylinder L-head four-cycle engine. The upper curve shows the amount of fuel used at various loads and speeds with the standard spark plug. The lower curve depicts that engine's fuel consumption with FVI rather than a spark plug in use. Total fuel flow including fuel through the carburetor and through the Fuel Vapor Injector/Igniter is recorded. Approximately 20% of the fuel was fed through the FVI in these tests.

The single-cylinder engine was equipped with various designs and configurations of FVIs (in place of spark plugs) for test and evaluation.

purposes. It was operated at A/F ratios ranging from 10:1 to as lean as 80:1* (*No load, idle speed. No measurable differences were observed in exhaust gas temperature or CHT as the mixture was leaned from 32:1 to 80:1.) At 1000 rpm, the engine was run with various throttle settings ranging from partially to fully open and A/F ratios from 15:1 to 45:1. At higher speeds the average ratio was about 22:1, which appeared to be the best specific fuel consumption ratio. Improvement over conventional spark plug ignition was obtained with the FVI at the same loads and speeds.

MULTIFUEL TESTING

One of the byproducts of the Gas Phase Induction and Optimizer developments is a fuel metering system which is inherently multifuel in nature. Since the latent heat of vaporization has no effect on combustion or distribution, and since the Optimizer produces A/F ratios which optimize engine efficiency, fuels with varying properties may be used interchangeably without adjustment of the metering system.

Normally, the Optimizer operates within a range of 12:1 to 24:1 air/fuel ratio. For purposes of multifuel testing, the range was adjusted to approximately 6:1 to 20:1, and the different fuels were introduced into a hot, running engine. The problems of cold starting were not considered in these tests.

Figure 8 details the results obtained in a multifuel test carried out on a 122 CID four-cylinder Pinto. The engine was equipped with Gas Phase Induction, Optimizer and FVI. No exhaust gas recirculation was used. All test data was collected at 35 mph, steady

state road-load on the chassis dynamometer. Fuel economy and emissions were measured at standard timing of 12°BTDC and at an advanced timing of 24°BTDC.

The most significant result of these tests is not the improvement in fuel economy or the reduction in emissions, rather the fact that fuels of varying properties could be compared on an equal basis by a single fuel metering and preparation system—without introducing any pre-programmed air/fuel ratio.

REDUCING NO_x WITHOUT EGR

A series of tests was run with a 232 CID six-cylinder AMC Gremlin. In all of the tests standard spark plugs and carburetor were used. In the first series, data was taken with all adjustments set at factory specifications. The EGR system was operative and the ignition was set at 8°BTDC. Fuel economy and emissions were measured on the dynamometer at 30, 40 and 50 mph at steady state road-load horsepower.

A second series of tests was run under the same conditions using standard spark plugs and standard carburetor. However, the Optimizer was installed and the EGR system deactivated. Also, ignition timing was set at 16°BTDC. The tests with Optimizer installed produced significant improvements in fuel economy, emissions and performance.

Figures 9 and 10 contain the data from this series of tests. It clearly indicates that the Optimizer is more effective than EGR for

controlling oxides of nitrogen emissions and that it is a valuable retrofit item.

To obtain a "Worst Case" verification of the Optimizer's effectiveness, the 232 CID six-cylinder AMC Gremlin was subjected to a Certified Federal Urban Cycle emissions test. This test was performed at Scott Environmental Technology, Inc., Plumsteadville, PA.

To establish base line, the vehicle was set at standard factory specifications and used standard spark plugs, standard carburetor and operational EGR system. Ignition timing was set at 8° BTDC.

In order to minimize changes in operating conditions which might affect evaluation of the Optimizer, the second series of the certified tests involved only the following changes: Installation of the Optimizer, deactivation of the EGR system, and adjustment of ignition timing to 16° BTDC. No changes were made to spark plugs, plug gaps, carburetor settings or other engine systems.

The test results reveal that even under these conditions the Optimizer can control emissions of NO_x more effectively than EGR, and achieve an improvement in fuel economy in the process. The test results follow:

	Standard specifications with EGR	Standard specifications with Optimizer, no EGR
HC %	1.88	2.46
CO %	9.1	7.0
NO _x gm/mile	2.87	2.74
Miles per gal.	16.85	17.29

No after-treatment (catalytic converter) is used on this vehicle.

FUEL ECONOMY

Several thousands of miles of highway driving yield data indicative of substantial improvement in fuel economy. The following results have been recorded:

	Ford Pinto 122 CID	Chevrolet 350 CID	AMC Gremlin 232 CID
Standard engine	26.0	16.0	22.0
Engine with FVI and Optimizer			24.5
Engine with FVI, Optimizer and Gas Phase Induction	32.0	18.8	
Improvement	23%	17.5%	11.4%

Figures above are in miles per gallon.

Referring to Figure-11, the benefits available through the installation of all three subsystems become apparent. In this test the 122 CID Pinto is equipped with all three subsystems: FVI, Optimizer, Gas Phase Induction. However, before they were installed, base line fuel consumption was recorded at steady state road load conditions. While the steady state dynamometer figures do not translate directly into highway mpg, they do provide a reliable comparison of the two systems of fuel management. And they provide a reasonable basis for projecting improvements in operating economy.

TWO-CYCLE APPLICATION

FVI was fitted to a 100 cc Yamaha motorcycle engine. All of the fuel is delivered through the FVI in this configuration, the throttle in the carburetor controls only air. Fuel supply and control is

achieved by means of a regulated pressure source variable from 5 to 50 psig. The engine could be made to idle at 5.0 psig fuel pressure and wide open throttle, indicating true stratified charge operation.

A fuel pressure of 50.0 psig was adequate to bring the no-load engine speed up to 6000 rpm. Hydrocarbon emissions at this speed were on the order of 1500 to 2000 ppm. When running on its original carburetor, hydrocarbons were measured in the range of 4000 to 6000 ppm.

After several weeks of development, the same engine was made to run at 35 ppm hydrocarbons using a modified FVI. Instead of performing the dual function of injector and igniter, the FVI was modified to inject fuel vapor into the vicinity of a standard spark plug which is used for ignition. Figure 12.

~~Lubrication is often supplied by mixing lube oil with the fuel for two-cycle engines. However, the Yamaha engine employs an auto-lube pump to spray minute quantities of oil to mix with the intake air to achieve adequate lubrication. This feature made it practical to cut off all fuel flow through the carburetor and crankcase. Thus, fuel admitted by injection only when the intake and exhaust ports are closed eliminates the fuel loss through those ports as experienced in normal operation of the engine.~~

INITIAL TWO-CYCLE TEST RESULTS

Engine operation through a speed range of 800 to 6000 rpm was achieved at wide open throttle with speed regulated only by changing the fuel pressure in stratified charge operation. Hydrocarbons emissions

varied from 2000 ppm under "Worst Case" maladjustment, to 35 ppm on several runs. The following emissions were recorded at 4000 rpm, unthrottled, no-load operation. (Air/fuel ratio was not measured in this test.)

	Measured at tailpipe	Measured at exhaust port
HC	35 ppm	2000 ppm
CO	.05%	0.5%
NO _x	100 ppm	40 ppm
EGT	725°C	725°C

In this test sequence, the exhaust system was red hot, and the excess air in the exhaust was reacting with almost all of the HC emissions.

The following emissions were measured at the exhaust port at a 20:1 A/F ratio:

	No-load			Road load (1.5 hp)
RPM	6200	5200	3000	1500
HC	200ppm	400ppm	1600ppm	1100ppm
CO	0.38%	0.45%	0.47%	0.30%
EGT	625°C	650°C	600°C	425°C

CONCLUSIONS

1. The Fuel Vapor Injector/Igniter (FVI) has been shown to be more reliable as a source of ignition than a spark plug in lean burn systems.
2. At any given air/fuel ratio, the FVI produces improvements in emissions and specific fuel consumption.

3. By enabling the use of leaner mixtures, an additional fuel consumption improvement can be attributed to the FVI.
4. The FVI shows potential for operating two-cycle engines at emission and efficiency levels comparable with those of four-cycle engines.
5. Gas Phase Induction overcomes the problems of mixture distribution and vaporization associated with two-phase induction systems.
6. By reducing the variations in air/fuel ratios between cylinders, the average air/fuel ratio can be maintained leaner and close control of the A/F ratio becomes meaningful.
7. The Optimizer is an effective means to attain close control of A/F ratios and may be adapted for use with any type of A/F metering system.
8. Since the Optimizer holds the engine at the edge of the lean limit, dramatic reductions in emissions of NO_x are achievable.
9. ~~By removing EGR and allowing timing to be advanced to MBT, the Optimizer improves economy, drivability and performance while emissions are held to statutory limits.~~
10. By employing a lean bias in the Optimizer circuitry, NO_x reduction superior to that achieved through EGR is demonstrable in the Federal-Urban Test Cycle, with acceptable drivability and improved fuel economy.
11. In combination, the Gas Phase Induction system and the Optimizer allow the use of fuels with varying properties without adjustment.
12. ~~All of the devices described are designed to be retrofitted to existing vehicles. Simplicity and low-cost have been retained while all of the items can be manufactured using current methods and materials.~~

Footnotes

(1) Obert, E. F., Internal Combustion Engines and Air Pollution, Intext.

Acknowledgements:

The authors wish to thank G. Hagey, M. D. Starr and J. Brogan for recognizing the potential of Fuel Vapor Injection in its early stages, and securing sponsorship for its continuing development via ERDA contract number E-(04-3)-1237.

Symbols used:

A/F-air/fuel ratio

BTDC-before top dead center

CHT-cylinder head temperature

CID-cubic inch displacement

CO-carbon monoxide

~~EGR-exhaust gas recirculation~~

~~EGT-exhaust gas temperature~~

FVI-fuel vapor injector/igniter

HC-hydrocarbons

MBT-mean best timing

mpg-miles per gallon

mph-miles per hour

NO_x-oxides of nitrogen

ppm-parts per million

Figure 1

Fuel Vapor Injector/Igniter with fuel supply tube.

Figure 2. Hydrocarbon emissions vs. air/fuel ratio for a standard spark plug and a Fuel Vapor Injector/Igniter.

Figure 3. Oxides of nitrogen emissions vs. air/fuel ratio for a standard spark plug and a Fuel Vapor Injector/Igniter.

Figure 4. The trend of efficiency and hydrocarbon emissions in the vicinity of the lean limit, for three different engine operating conditions.

Figure 5. Adaptor plate for introducing air into the induction system. It replaces the thermal spacer between carburetor and manifold in a retrofit application. Note swirl inducing vanes which enhance mixing.

Figure 6. Exhaust gas temperature measurements for each cylinder of a 350 CID engine with production manifold. Comparison is made between operation with stock carburetion and Gas Phase Induction (vaporized fuel) at 35 mph, road load horsepower.

Figure 7. Fuel flow vs. load for a single-cylinder L-head engine, comparing a standard spark plug with a Fuel Vapor Injector/Igniter.

(lb/hr = .453 Kg/hr, watts = .01434 Kg-cal/minute)

	HC (PPM)	CO %	NO _x (PPM)	MILES GAL.	MILES 1000BTU
TIMING 12° BTDC					
GASOLINE	140	.75	500	35.3	.277
KEROSENE	120	.75	200	38.6	.285
DIESEL FUEL	110	.80	200	46.9	.325
METHANOL	80	.70	170	25.0	.400
TIMING 24° BTDC					
GASOLINE	400	1.20	140	39.2	.308
KEROSENE	250	.75	110	44.1	.326
DIESEL FUEL	150	1.0	140	42.3	.293
METHANOL	80	.13	50	24.3	.389

Figure 8. Results of multifuel testing in a 122 CID four-cylinder engine equipped with Gas Phase Induction, Optimizer, and Fuel Vapor Injector/Igniters at steady state 35 mph road load.

(mpg = 6.09 Km/liter, Mi/10³ BTU = 14.97 Km/Kg-m.)

Figure 9. Fuel economy vs. speed at road load for a 232 CID six-cylinder engine, comparing standard configuration with EGR operating with performance recorded when equipped with Optimizer and deactivated EGR. (mpg = 6.09 Km/liter, mph = 1.61 Km/hr)

Figure 10

MILES PER GALLON

○ FVI + OPTIMIZER + GAS PHASE
△ CARBURETOR

42
40
38
36
34
32
30
28

30

40

50

SPEED

MPH

Figure 11: Fuel economy vs. speed at steady state road load for a 122 CID four-cylinder engine, comparing standard carburetion with a configuration using Gas Phase Induction, Optimizer and Fuel Vapor Injector/Igniter systems.

(mpg = 6.09 Km/liter, mph = 1.61 Km/hr)

Figure 12. Yamaha 100-cc engine cylinder head with modified FVI and spark plug both fitted. The fuel supply tube is attached to the heat exchanger tube which is normally located in the exhaust system in this modification.

Figure 13. The Gas Phase Induction fuel metering and air regulating unit is seen with a large exhaust system heat exchanger fuel vaporizer and a Fuel Vapor Injector/Igniter.