

## **EFFECTS OF FUEL COMPOSITION ON FUEL INJECTORS DURABILITY IN A LIQUID LPG PORT INJECTED SI ENGINE**

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**Summary.** Fleet operators of vehicles that use liquid port injection liquefied petroleum gas (LPG) fuel systems have experienced poor cold start performance and poor vehicle drivability of high mileage vehicles. It was assumed that was due to the formation of deposits within the fuel injectors. To determine the effects of fuels on the severity of deposits, injectors were mileage accumulated on the road using identical vehicles with fuels of different compositions. All of these vehicles repeatedly traveled along a specific 82 km driving route for a total of 6400 km. This driving profile was designed to simulate standard driving conditions and included a minimum hot soak period of 30 min at the conclusion of each 164 km. Four fuels were used in this study. They included; HD-5 LPG with no additives, the same HD-5 LPG with additive C, again the same HD-5 LPG with additive V and finally an LPG with a lower sulphur content and higher isobutane content than HD-5 LPG. All injectors used in this study were bottom feed style with needle and seat type metering orifice. Each set of mileage accumulated injectors were then installed in a test vehicle and emissions tests were performed using the low sulphur LPG fuel. Two types of emissions tests were performed for each set of injectors. These tests included standard FTP emissions tests and cold start steady state tests. Each set of injectors was then flow and leak tested to determine if the static and dynamic flow rates, or the leakage rate of the injectors had changed from the initial values. The results obtained from this research program shows that the use of anti-deposit additives in LPG fuel leads to a significant reduction in FTP cold start hydrocarbon emissions for engines operating with liquid LPG PFI fuel systems.

### **1. Automotive Use of Alternative Fuels**

Automotive industry is encouraged to reduce its dependence on gasoline as a fuel due to a series of diverse concerns such as environmental pollution, public health, and off-shore oil dependence. These concerns have lead the Canadian and US governments to support the use of liquid propane as one of the alternative fuels to gasoline. The transportation sector is one of the major contributors to pollution in Canada and the United States.

The transportation sector is one of the major contributors to pollution in the United States. In 1994 this sector accounted for 26% of the total U.S. emissions of volatile organic compounds, 32% of total oxides of nitrogen and 62% of the total U.S. carbon monoxide emissions [1]. When all of the greenhouse gases are considered this sector was responsible for 32% of U.S. greenhouse gas emissions [1].

In terms of the air pollution that is produced propane powered vehicles can offer some benefits when compared against gasoline powered vehicles. The Clean Fleet alternative fuels demonstration project of 1994 [2], provided an opportunity to compare identical vehicles that were fueled on either a gaseous LPG fuel system or a gasoline fuel system. The vehicles used

were Chevrolet vans with 5.8L V8 engines. The FTP EPA-75 emissions results that are referenced all taken while the vehicles were between 5500 and 13000 accumulated miles. It was demonstrated that the use propane fuel lead to a 64% decrease in total oxides of nitrogen, a 32% decrease in carbon dioxide emissions and an 84% increase in total non-methane organic (NMOG) emissions.

The Clean Fleet study showed that the use of LPG vehicles can lead to a significant decrease in the ozone forming potential of the vehicle emissions. This study also showed that the emissions from LPG powered vehicles are significantly lower than those for gasoline powered vehicles. When comparing the emissions from the above mentioned vehicles a hundred fold reduction in benzene emissions was seen.

These reductions in ozone forming potential and pollutant emissions can be attributed to the composition of LPG fuel. Generally gasoline is composed of hydrocarbons with carbon chains in the range between C4 to C12 where as LPG fuel is composed of chains in the range of C2 to C5. In general the polluting species are long chain hydrocarbons, and the more reactive hydrocarbons in ozone production tend to be those with long carbon chains, functional groups or double bonds [3]. Since LPG composition does not have the many of the precursors to air toxics or highly volatile organic compounds with respect to ozone production it is obvious that this fuel would lead to low emissions values in these areas.

## **2. Cold Start Emissions of Liquid LPG Injected Vehicles**

Although LPG vehicles provide an excellent alternative to gasoline vehicles problems still remain to be solve before LPG systems will be capable of meeting the stringent emissions regulations of the day. The issue that this research addressed was that cold start emissions in vehicles that use liquid fuel injection systems tended to deteriorate as vehicle mileage increased.

This hypothesis was supported by data obtained from three FTP tests that were performed in 1998 on the same vehicle operating on a 5.2L V8 liquid port injection LPG engine at mileage of 636 km, 3860 km and 6713 km [4]. The emissions results from these tests showed an 9% increase in "FTP phase 1" total hydrocarbon (THC) emissions over the first 3000 km and another 33% increase in "FTP phase 1" THC over the second 3000km accumulated. This phase of the FTP test includes the emissions from a cold start that followed a 12 hours cold soak, and 505 seconds of driving at the speeds specified by the FTP driving procedure.

It has been hypothesized that the increasing THC emissions found in phase 1 of the FTP test is due to leaking fuel injectors. It is believed that as the mileage of LPG vehicles increase, deposits form within the fuel injector and effect the injector's ability to create a seal between the injector needle and seat.

The problem of fuel injector deposits in gasoline vehicles was recognized in the mid 1980s when port fuel injected (PFI) vehicles began developing poor driveability problems such as rough idle, stalling, slow or uneven acceleration [5]. These problems were found to be due to flow restriction in the fuel injectors as deposits were forming within the injector.

Although there have been some cases of LPG fuel injectors failing due to flow restrictions [6] the concern which is more common is that of increasing injector leakage. This leads to poor cold start performance and emissions as opposed to driveability concerns.

The mass of fuel that could leak through an LPG fuel injector is significant due to a combination of two factors that are unique to LPG systems. First, the fuel system of a liquid PFI LPG engine must be operated at high pressures (10 bar gauge) to insure that the fuel is supplied to the injector as a liquid during operation. Second, the fuel that remains in the rail after engine shut down is vaporized [7] due to the lack of fuel flow and increased heat flux to

the rail during hot soak. As the engine soaks the seal within each fuel injector be maintained to withstand a 10 bar pressure differential between two gases. This is a much more demanding requirement than that which is found in a gasoline injector where a seal is maintained between a liquid and a gas at pressures of only 3 bar.

The objective of this study was to determine if the use of fuel additives in liquid PFI LPG engines could lead to a reduction in PFI deposits and cold start (FTP phase 1) emissions.

### **2.1. Deposit Formation Mechanism**

A very limited literature exists regarding composition or formation mechanism of deposits within LPG liquid fuel injectors. According to research that was completed for gasoline we can make assumptions on the general mechanism for deposit formation from hydrocarbon fuels. Deposits are formed by the auto-oxidization of the fuel leading to a polymerization reaction that incorporates a high concentration of the fuel sulphur into the deposit as oxidized sulphur. The only supported correlation between fuel composition and deposit formation appears to be that of olefin or di-olefin content within the fuel. Obviously sulphur compounds play a significant role in deposit chemistry but they have not yet been shown to be the deposit initiator, nor does deposit quantity relate to sulphur content of fuel.

## **3. Experimental Procedure**

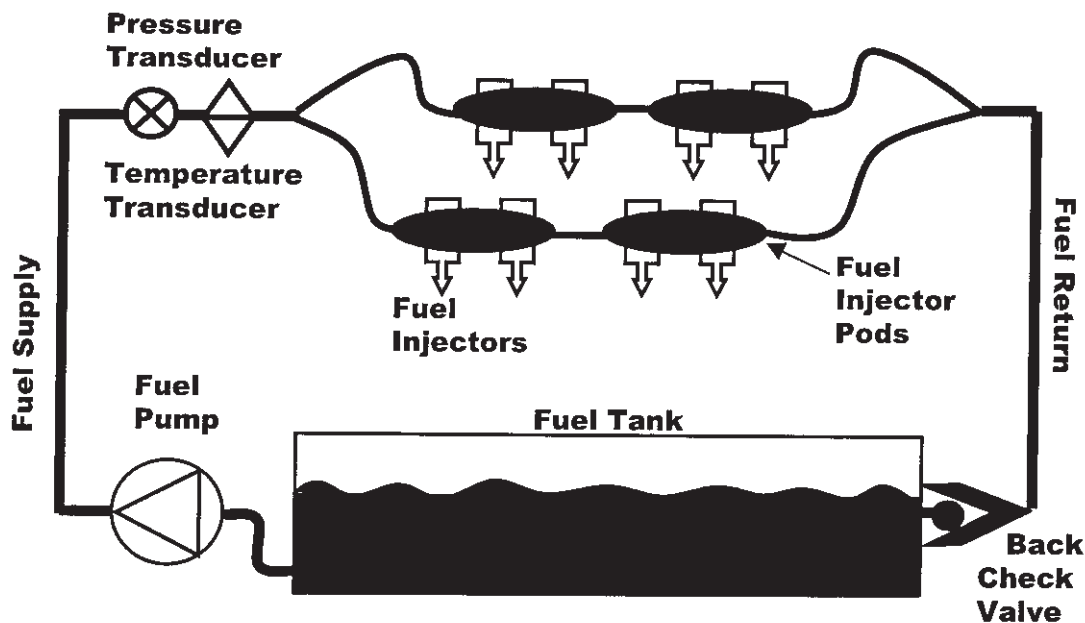
Numerous studies have been completed to develop techniques to quantify the effects of fuel injector deposits in gasoline engines. These included the development of a bench test method that has been shown to correlate well with vehicle tests and the creation of ASTM Test Method D5598 which describes this bench test in detail [8]. However no work has been completed that quantifies the effect or extent of deposits within LPG engines. When considering adopting the ASTM method, it was decided that it would be too time consuming and costly to develop a safe test bench that could be used with a high volatility fuel such as LPG

The approach chosen was to operate four sets of injectors on different fuels. The injectors were leak tested prior to use and placed in specified cylinders in each vehicle based on their leakage rates. The injectors were mounted in similar Dodge Ram full sized vans with 5.2L V8 engines with 1998 liquid LPG PFI fuel systems and were mileage accumulated to 6400km. These vehicles were driven on a specified driving route of 81.5 km. This route consisted of both city and highway driving with an average speed 55 km/h. Each vehicle was driven in a similar manner through the route twice and was allowed to sit for at least 30 min before being driven again. All vehicles were exposed to the same number of hot soaks. Each set of injectors were then mounted into a emissions testing vehicle which is operated on the same fuel while testing each set of injectors. All injectors were then leak tested again to evaluate injector performance. This experimental program was designed to provide an estimate of what a customer would experience in the field as opposed to exposing the injectors to conditions that would lead to the greatest deposit formation.

### **3.1. Fuel System Details**

The fuel system, which is used for this experimental program, is a closed loop, series feed system that delivers saturated liquid LPG from the fuel tank to the fuel injectors. A pressure differential between the inlet and outlet of the fuel tank is used to produce a fuel flow through

the injectors. This pressure differential is developed using a fuel pump mounted within the fuel tank and controlled using a pressure sensitive back check and relief valve. A schematic of the system is shown in the figure below:



*Fig. 1. Schematic of the Liquid LPG Injection Fuel System*

### 3.2. Initial Fuel Injector Testing and Positioning

A pool of 96 bottom flow Siemens Deka 2 LPG fuel injectors that had been manufactured to the specifications of the DaimlerChrysler 1998 liquid LPG PFI fuel system were used for this study. Each of these injectors was leak tested using a Furness Controls FCO90 differential pressure leak testing instrument. This instrument is capable of measuring leakage rates between 0.2-19.9 cc/min with an accuracy of  $\pm 1\%$  of reading and a repeatability of  $\pm 0.2\%$  of reading. An injector that has been sealed with an epoxy resin such that there are no leaks, is used in a comparison against the injector tested. The leak test of each injector was repeated 3 times. Using the averaged results from the final two leakage tests each injector was placed in one of three groups, low, medium and high leakage. Eight injectors were chosen for each engine such that three injectors were of low leakage, three were of medium leakage and finally 2 injectors were from the high leakage group. Using these designations the injectors were mounted into the engines of the mileage accumulation vehicles such that injectors from a specific leakage group are mounted in a specific cylinder.

Through the above procedure an attempt was made to insure that each injector used in the program had specific properties and was exposed to the same environment, with fuel type being the only variable.

### 3.3. Fuel Properties

The fuels that were used in this experimental program are listed below:

- Low sulphur high purity LPG (referred to as “FUEL P”)
- Commercially available LPG (referred to as “FUEL H”)
- Commercially available LPG with anti-deposit additive C (referred to as “FUEL C”)
- Commercially available LPG with anti-deposit additive V (referred to as “FUEL V”).

The anti-deposit additives were mixed with the fuel in the as the vehicles were filled with fuel. At each refueling the volume of fuel to be added was determined based on the mileage that the vehicle had run since the last fueling. Using this value the corresponding volume of anti-deposit additive was determine and measured using a 100mL graduated cylinder. The additive was then poured into a chamber that was mounted inline with the fuel filling system. As LPG was pumped into the vehicle the additive was mixed with the fuel and forced into the fuel tank.

For safety reasons the sulphur based odourant ethyl-mercaptan was added to the otherwise odourless “FUEL P” in a manner that was identical to the method that was used for the additive. A volume of 2 mL of ethyl mercaptan was measured using a 10 mL syringe and added mixed with each tank of fuel. The data that describes the composition of the “FUEL P” is based on a sample that was obtained from the vehicle’s fuel tank and therefore included the effect of the ethyl mercaptan on the fuel composition.

	Weight %	Weight %		Sulphur mass ppm	Sulphur mass ppm
	FUEL H	FUEL P		FUEL H	FUEL P
Methane	0.02	<0.01	Carbonyl Sulphide (COS)	28	<1
Ethane	1.81	0.11	Methanethiol (Methyl Mercaptan)	3	<1
Propene	0.04	0.05	Ethanethiol (Ethyl Mercaptan)	8	7
Propane	95.79	96.39	Iso-Propanethiol	1	0
IsoButane	1.17	3.22	ThioPhene/sec-Butanethiol	1	0
n-Butane	0.69	0.23	DiMethyl Disulphide (DMDS)	2	0
IsoPentane	0.2	<0.01	Unknown C6 Sulphur Compounds	7	0
n-Pentane	0.19	<0.01	Unknown C7 Sulphur Compounds	1	0
2-Methylpentane	0.03	<0.01			
n-Hexane	0.07	<0.01			

*Table 1. Fuel Composition*

To determine the hydrocarbon and sulphur compounds that were present in the fuel a chemical analysis was performed by a third party. The CGSB (Canadian General Standards Board) method 14-3 PONA(U) (Parafins, Olefins, Naphthenes, Aromatics and Unknowns), which uses gas chromatography, was used to determine all of the listed hydrocarbons between C1 and C12 to an accuracy of 0.01 wt%. Gas chromatography with a sulphur chemiluminescent detector was used to determine the possible presence of 17 different sulphur compounds to an accuracy of 1 ppm of sulphur. Any hydrocarbon or sulphur compounds that are not listed in Table 1 were not present in significant quantities.



### **3.4. Emissions Testing Procedure**

To test only the effects of the injectors on emissions performance a single van was used as a test bed for all injector sets. In an attempt to use fewer vehicles, vehicle #4 (mileage accumulation vehicle for "FUEL P" VIN# WK134597) was used as the emissions test vehicle. Each set of injectors was mileage accumulated in their respective vehicles, operating on their particular fuel. The fuel rail and installed injectors were then removed and mounted in the emissions testing vehicle for emissions testing using "FUEL P". The only exception to this procedure involved the injector set for "FUEL P". Emissions testing for this injector set began without removing and reinstalling the injectors as the fuel rail and injectors were already installed in the vehicle that was used for emissions testing.

The motivation for transferring the injectors and the fuel rails as an assembly was to insure that the injector o-rings would not be damaged as the injectors were removed and reinstalled within the fuel rail.

Once each injector set was installed in the vehicle it was test driven by a technician to insure that it was operating correctly. The vehicle was then driven to the emissions test site. These two activities combined both highway and city driving for a distance between 38km and 54km. The vehicle was driven on the dynamometer using a preparation speed profile for a total distance of 24km. The vehicle was then allowed to sit or soak for at least 12 hours at room temperature and then an EPA-75 FTP test was performed while exhaust emissions and engine variables were recorded. The soaking and testing procedure was repeated twice more to provide three independent FTP tests each involving traveling a total of 17.66 km on the specified speed profile.

The vehicle was soaked again for at least 12 hours at room temperature and a "Cold start and Idle" test was performed while exhaust emissions and engine variables were recorded. This combination of soak and test were again repeated twice more to provide results of three independent "Cold start and idle" tests. The vehicle was not driven during these tests, only started, and therefore did not accumulate any mileage. These "Cold Start and Idle" tests were performed to observe how the vehicle performed without any inputs such as acceleration or deceleration. Following the completion of all six tests the vehicle was driven back to the research center at both highway and city speeds to install the next injector set and fuel rail.

### **3.5. Final Injector Leak Testing**

To determine the degree to which the injectors had deteriorated during the mileage accumulation each injector was leak tested. A procedure was developed that differs from the standard leak testing procedure in order to preserve the integrity of any deposits that had formed so scanning electron microscope (SEM) images of the injector needles could be obtained.

Since the injectors were to be disassembled to photograph any deposits using a scanning electron microscope (SEM) it was decided that the purging process should be eliminated from the final leak testing procedure to insure that any deposits remain intact. This was deemed to be reasonable as the only fluids that the injector had been exposed to prior to testing was LPG fuel during operation. Due to the high volatility of this fuel it would have evaporated prior to the injector leak testing and would therefore not effect the leak testing.

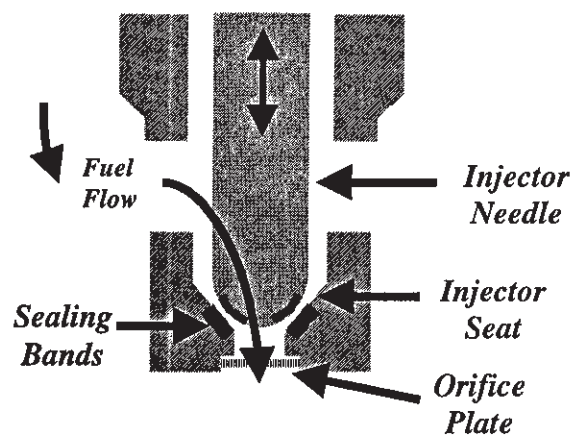
The final leak testing process was similar to the initial injector leak testing. Each injector was compared against a standard sealed injector. The rate of pressure change between the test and sealed injector was compared using the same Furness Controls FCO90 test rig to determine a leakage rate.

For each injector the pressurizing test cycle was consecutively run four times. The injector was then removed from the rig and the o-rings were inspected. This procedure was repeated 3 times for each injector. This provided 12 leakage values for each injector.

### 3.6. SEM Imaging Procedure

Following the final leak testing a subset of the injectors were cut open and scanning electron microscope pictures were taken of the needles of the injectors.

When studying the leakage of the fuel injectors the most critical area to look at is the sealing band. This is the annulus shaped area of contact between the needle and seat of the injector. When a fuel injector opens, the needle is lifted up from the seat, and fuel flows through the injector. The general layout of the type of fuel injector that was used in this study is shown in the following figure.



*Fig. 2. Fuel Injector Schematic*

Since it was impossible to obtain a clear SEM image of the needle by shooting through the hole in the orifice plate it was necessary to cut open the injector to remove and scan the injector needle. All eight injectors from “FUEL H” and three injectors from fuels “P”, “C” and “V” were opened and images of the tips of these injector needles were obtained using a Scanning Electron Microscope (SEM). The three injectors from fuels “P”, “C” and “V” were chosen based on the average leakage rates that were obtained during the final leak testing. The two injectors with the highest leakage rates and the injector with the lowest leakage rate for each injector set were disassembled and their needles were scanned with the SEM.

Prior to photographing, each needle was cleaned using an ultrasonic bath to remove any contaminating particles that were picked up during the disassembly process.

When deposits were found on the injector needles tips an Electron Dispersion Spectrum Analysis (EDS) was taken to estimate the composition of these deposits. Since these deposits were found to be very thin the EDS analysis tended to show the composition of the base metal of the injector needle. An estimate of the deposit composition was made by comparing the EDS analysis results from an area of deposit against the analysis of an area of exposed metal.

## 4. Results and Discussion

### 4.1 Total Unburned Hydrocarbon Emissions

The results from the FTP EPA-75 emissions tests show a clear improvement in total hydrocarbon emissions for the fuel injectors that were operated using both FUEL C and FUEL V. Figure 3 shows the relative FTP HC emissions between each of the injectors tested. When the cold bag hydrocarbon emissions data is compared with the cold start cranking time a correlation was found. Once engine cranking begins, the fuel injectors begin supplying fuel at a pulse width that has been determined based on the coolant temperature at start up.

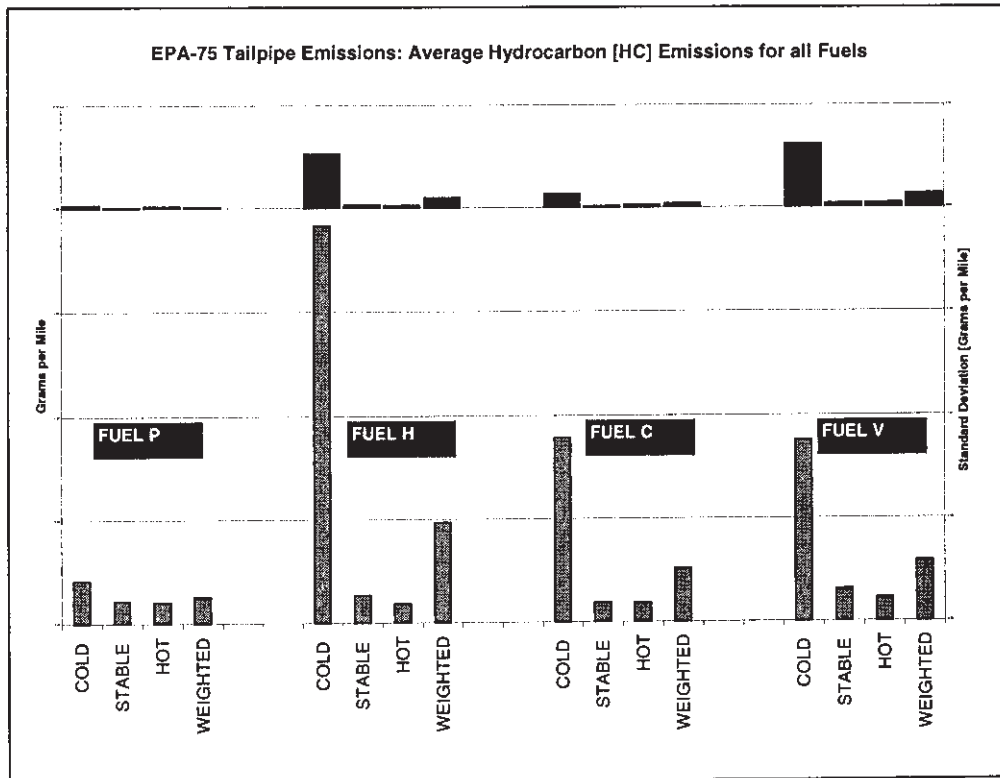


Fig. 3. Unburned hydrocarbon (HC) emissions for all fuel type tested.

Until the engine catches this fuel is pumped through the engine and is recorded in the HC emissions trace. This shows that longer cold cranking times will lead to higher FTP phase one HC emissions.

The question remains, why does one set of injectors led to longer start up times than others? The current hypothesis is that fuel from leaking fuel injectors can accumulate into the intake manifold during the 12-hour cold soak period. During start up this accumulated fuel, combined with the additional fuel that is supplied by the injectors results in such a rich in-cylinder mixture that it is beyond flammability limits and will not ignite. The injector sets with the greatest leakage rates will lead to the longest start up times and therefore the highest hydrocarbon emissions. No direct measurements were made of hydrocarbon concentration in cylinders prior to ignition. However, by examining at the average leakage rate of the injectors that was taken following the emissions test it can be seen that the injectors that were mileage accumulated on FUEL H had the highest leakage rate, longest start time and highest FTP Phase 1 HC emissions.



## 4.2. Scanning Electron Microscope (SEM) Photographs

Scanning electron microscope photographs were taken of the tip of the injector needles. All eight injectors from FUEL H were photographed, and three injectors for each of the other two fuels were photographed as well. Typical images from these sets of have been included in as Figure 4. Image (b) shows the worst case injector that from FUEL H. The injectors from FUEL H and FUEL P (images a, b, and c) show a deposit ring that is located just downstream of the sealing band of the needle. The sealing band is the location where the needle contacts the seat to form a seal. Injectors that were operated on either FUEL C (image d) or FUEL V (image e) showed no deposits of any kind.

What role these deposits play in the sealing of the injectors is uncertain. Injectors that were operated on FUEL H showed extensive ring deposit, high leakage rates, long start up times and high FTP hydrocarbon emissions. However injectors that were operated on FUEL P also showed extensive ring deposits but did not show the corresponding high leakage rates, long start up times and high FTP HC emissions.

## 4.3. Transient Total Unburned Hydrocarbons Emissions

The trace of the transient hydrocarbon emissions at start up all showed large hydrocarbon peaks that have widths that correspond to the cranking times. Injectors that were mileage accumulated on FUEL P show an HC peak width of 16 seconds, those from FUEL H show an HC peak width of 70 seconds, injectors from FUEL C show an HC peak width of 40 seconds and finally injectors from FUEL V show a hydrocarbon peak width of 45 seconds.

When analyzing the transient traces of the HC emissions during FTP tests shown in Figure 5 it can be seen that the FUEL H injectors consistently result in higher HC emissions. This is consistent with both the high leakage rates and the high total HC emissions for the data from Phase 1 of the FTP for this injector group. Comparatively the FUEL P injectors show the lowest transient HC emissions during the FTP test. Again this is consistent with the both the low leakage rates and the low total HC emissions for Phase 1 of the FTP for these injectors. By averaging the pulse width of the injectors during an idle period of the FTP for these two injector sets it was noted that there was little difference in how these injectors were being actuated for a given set of operating conditions. Therefore the emissions results are due only to the condition of the injectors, not that the engine control system is actuating them at different rates.

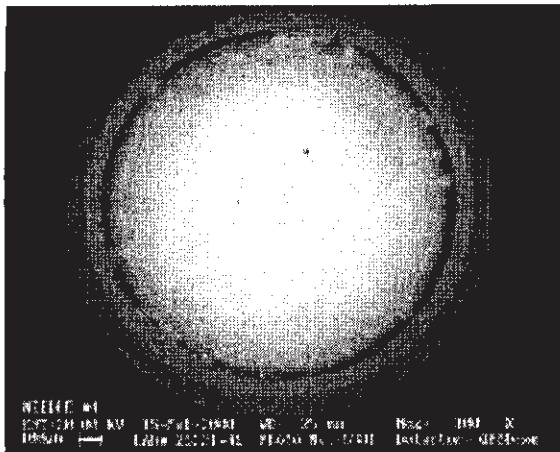


Image a: Typical FUEL H Injector Needle

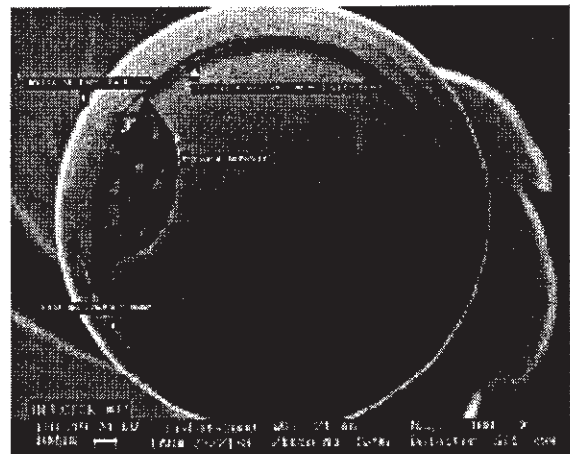


Image b: Worst Case FUEL H Injector Needle

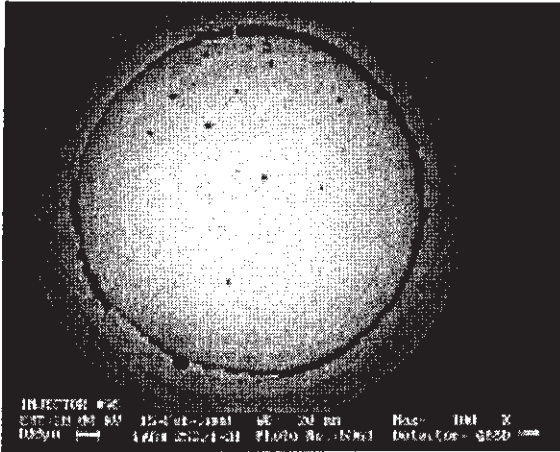


Image c: Typical FUEL P Injector Needle

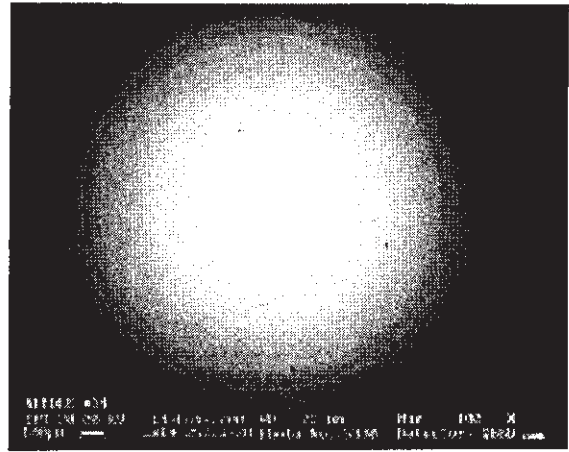


Image e: Typical FUEL V Injector Needle

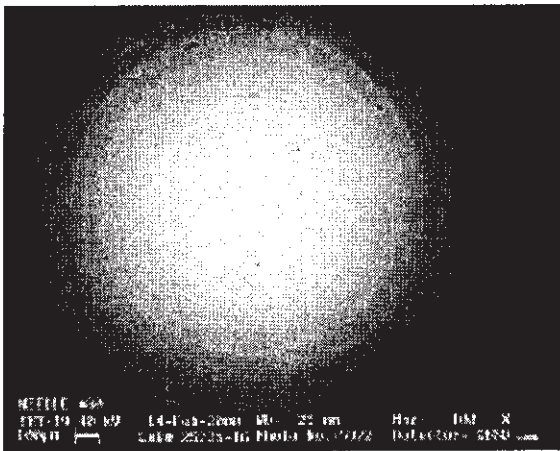


Image d: Typical FUEL C Injector Needle

Fig. 4. Scanning electron microscope (SEM) images of the injector tips.

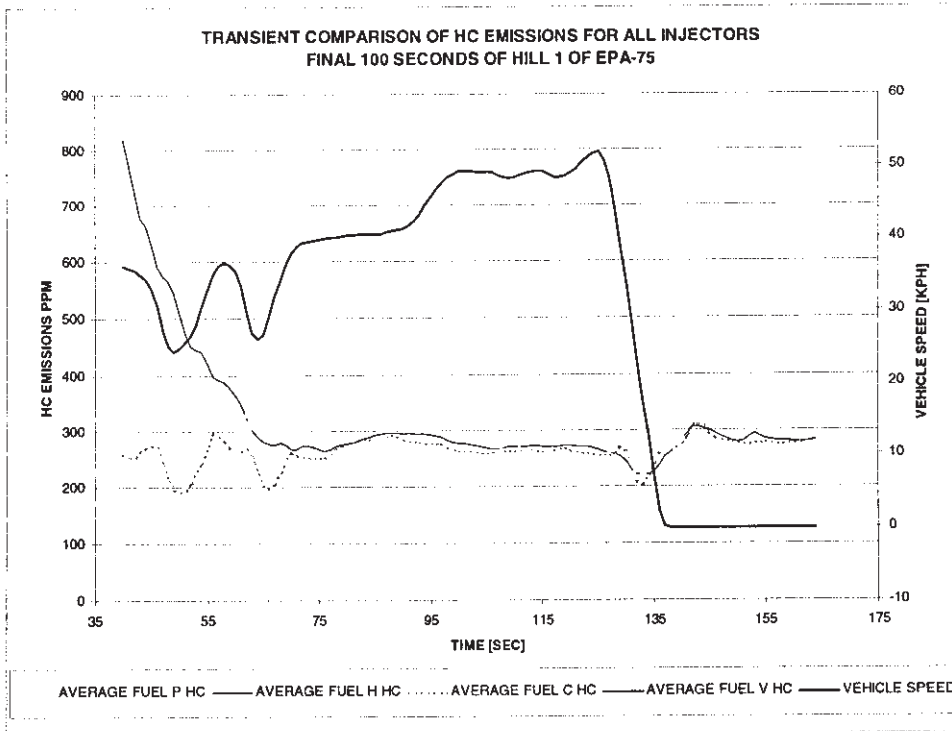


Fig. 5. Transient HC emissions for all fuel type tested.

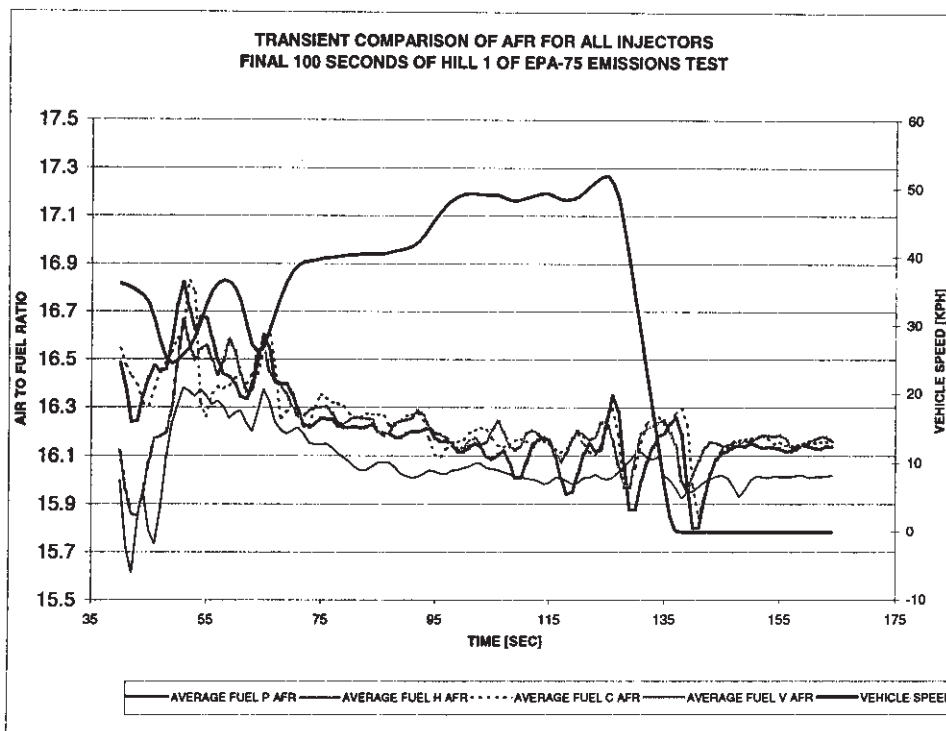


Fig. 6. Transient AFR for all fuel type tested.

When examining the transient HC emission traces for the injectors that ran on the two fuel additives, we can see that the injectors from FUEL C are resulting in higher HC emissions when compared against those of FUEL V. This is contradictory to what is expected based on the leakage data. However the pulse width data for these injectors shows that generally the injectors of FUEL C are open longer than those of FUEL V for a given set of operating conditions. This may account for the higher HC transient HC emissions of injectors from FUEL C even though they have lower leakage rates.

#### 4.4. Transient Air to Fuel Ratio

The transient trace of the air to fuel ratio (AFR) as shown in Figure 6 indicates that the injectors that were operated on FUEL H consistently showed a rich AFR where as all other injector sets show similar air to fuel ratios throughout the transient data. It is believed that this is due to the fact that these injectors have a high leakage rate leading to poor control of the amount of fuel that is delivered.

### 5. Conclusions

The results obtained from this research program shows that the use of anti-deposit additives in LPG fuel leads to a significant reduction in FTP cold start hydrocarbon emissions for engines operating with liquid LPG PFI fuel systems. This work will be continued to develop a complete understanding of the effects of the ring deposits.

## **6. Acknowledgments**

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