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Matthew Warner Hoag

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Effects of Fuel Rail Design and Fuel Injector Durability on the Starting Performance of a Liquid LPG Fuelled PFI Engine

By

Matthew W. Hoag

A Thesis
Submitted to the Faculty of Graduate Studies and Research through Mechanical, Materials and Automotive Engineering in Partial Fulfillment of the Requirements for the Degree of Masters of Applied Science at the University of Windsor.

Windsor, Ontario, Canada

2000

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ABSTRACT

Two important issues for liquid LPG or propane PFI engines were researched: unacceptable HC emissions during cold starts and long hot start times. The poor cold start performance was linked to deposits forming within the fuel injectors and the long hot start times were due to the vapourization of the fuel within the fuel rail during hot soak and hot start. Solutions for both of these problems were developed.

To determine the effects of fuel composition on the formation of deposits, 5 sets of fuel injectors were mileage-accumulated on-road for 6400 km with 40 hot soaks using identical vehicles operating with fuels of different compositions or different injector designs.

Each set of mileage-accumulated injectors was installed in a test vehicle and standard FTP emission tests were performed on a vehicle chassis dynamometer using a standard fuel. When compared to the fuel injectors that were operated on HD-5 LPG an improvement in Bag 1 NMHC FTP emissions of approximately 50% was shown for fuel injectors that were operated on the anti-deposit additive treated fuels.

Following mileage accumulation each set of injectors was leak tested. The leakage rate of all the fuel injectors increased; HD-5 LPG injectors by 1.11 cc/min, Additive-V injectors by 0.22 cc/min and Additive-C injectors by 0.07 cc/min. SEM photographs revealed that sulphur and zinc deposits had formed within the HD-5 LPG fuel injectors, downstream of the sealing band.

In an attempt to improve the long hot start times of this type of vehicle the inner surface of the fuel rail tubing was coated with a thermal coating. This coating appeared to reduce the temperature of the surface that was in contact with the LPG more quickly than a steel surface. It appeared that fuel vapourization was minimized during the hot start and this lead to a 49% decrease in hot start time compared to the uncoated fuel rail. The emissions during hot start showed an average 38% decrease in HC emissions and 25% decrease in CO emissions.
ACKNOWLEDGEMENTS

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The work of many people must be acknowledged, for without their assistance this project would not have been possible. Jim Lanigan, Shawn Yates, Larry Robertson, Mario Miceli, Bob Hofman, Marc Drouillard, Archie Callaby, Remko Brouerius, Lou Degrace, James (Turbo) Cohen and Bob Tattersall.

Many thanks for the resources supplied by Siemens Automotive of Newport News VA, USA, DaimlerChrysler Jeep Truck Engineering Detroit, MI, USA and the University of Windsor - DaimlerChrysler Canada Automotive Research and Development Centre of Windsor, ON, Canada. As well the financial support of the Natural Sciences and Engineering Research Council of Canada, DaimlerChrysler Canada, and the University of Windsor Faculty of Graduate Studies is gratefully acknowledged.
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ABBREVIATIONS AND SYMBOLS

AFR  Air to Fuel Ratio
CH₃CHO  Acetaldehyde.
CH₃OH  Methanol
CH₄  Methane
CO  Carbon monoxide
CO₂  Carbon dioxide
EGR  Exhaust Gas Re-circulation
EPA  Environmental Protection Agency (U.S.)
EPP  Engine Power Pulse
g/mi  Grams per mile
HC  Hydrocarbons
HCHO  Formaldehyde
mg/mi  Milligrams per mile
MPG  Miles Per Gallon
MTBE  Methyl Tertiary Butyl Ether
NMHC  Non-Methane Hydrocarbons
NMOG  Non-Methane Organic Compounds
NOₓ  Oxides of nitrogen
O₂  Oxygen
OMHCE  Organic Material Hydrocarbon Equivalent
OMNMHCE  Organic Matter Non-Methane Hydrocarbon Equivalent
PFI  Port Fuel Injection
THC  Total Hydrocarbons
VOC  Volatile Organic Compounds
DEFINITIONS

To assist in explaining the problems that are to be studied it is necessary to clarify some terms, which will be used in this paper.

**Type-1 Liquid LPG Fuel Rail**
A series feed fuel system that uses a distribution block at the inlet to direct the fuel down the two branches and a T-junction at the fuel outlet to connect the branches to the fuel return line. A solenoid valve and the fuel temperature and pressure sensors are mounted in the distribution block. Two fuel injector pods are mounted on each branch to support the four fuel injectors that supply the one of the engine’s cylinder banks.

**Type-2 Liquid LPG Fuel Rail**
A series feed fuel system that is similar to the Type-1 liquid LPG fuel rail however it uses Y-junctions to join the two fuel rail branches to the fuel inlet and outlet lines. The fuel temperature and pressure sensors are mounted on the fuel inlet tube prior to the supply tube Y-junction.

**Coated Fuel Rail**
A fuel rail design that is identical to that of the Type-2 liquid LPG fuel rail. The only exception is that the inner surface of the tubing used in the fuel rail assembly was coated with a low thermal diffusivity material.

**Fuel Injector Pod**
A manifold that supports two fuel injectors in individual cavities and allows fuel to pass through them. Fuel enters the pod, passes through and around the first injector, travels to the second injector through a small passage, passes through and around the second injector and then exits the pod.

**Liquefied Petroleum Gas (LPG)**
Liquefied petroleum gas is a mixture of hydrocarbons between C1 through C6. The mixture is such that it is a liquid at room temperature when pressurized to approximately
1.07 MPa (160 psia). The composition of LPG varies depending on the production source. HD-5 is a specification that constrains the composition and properties of HD-5 LPG. These are described in Chapter 40 (Environmental) of the U.S. Charter of Federal Regulations Section 79.55 Base Fuel Specifications [1]:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vapour Pressure at 100°F psig, max</td>
<td>208</td>
</tr>
<tr>
<td>Evapourative temperature, 95%, °F, max.</td>
<td>-37</td>
</tr>
<tr>
<td>Propane, vol%, min</td>
<td>92.5</td>
</tr>
<tr>
<td>Propylene, vol%, max</td>
<td>5.0</td>
</tr>
<tr>
<td>Butane and heavier, vol%, max</td>
<td>2.5</td>
</tr>
<tr>
<td>Residue-evaporation of 100mL, max, mL</td>
<td>0.05</td>
</tr>
<tr>
<td>Sulfur (including odorant additive) ppm, max</td>
<td>123</td>
</tr>
</tbody>
</table>

In Canada, HD-5 is defined as fuels meeting the Canadian General Standards Board fuel standard CAN/CGSB-3014-M88 Liquefied Petroleum Gas/Propane, Grade 1. Note, no attempt was made to determine the average Canadian or U.S. HD-5, fuel or commercial fuel composition.

**Aerosol Grade LPG**

This grade of LPG was commonly used as a propellant in aerosol containers. It generally contained fewer long chain hydrocarbons and had a lower sulphur concentration. This fuel was designated as FUEL P for this study. The typical composition for this fuel is described in Chapter 4: Fuel Injector Durability Study Methods and Materials.

**Liquid LPG Injection**

Engines that use this fuel injection system are similar to current fuel injected gasoline engines. Pressurized liquid fuel, in this case liquefied petroleum gas (LPG), is supplied to the fuel injectors from an in-tank fuel pump. The injectors then meter the fuel into the intake manifold where it vapourizes, mixes with air and is then drawn into the combustion chamber through the intake valve.

**Fuel Injector Deposits**

The deposits that were investigated in this study were found on the valve surfaces of the fuel injectors. Fuel injector deposits have been found to contain large amounts of carbon,
nitrogen, sulphur and various metals [2]. It is assumed that deposits near the sealing surfaces lead to increased injector leakage rates.

**Fuel Injector Leakage Rate**

This rate describes the volume of gas that passed through a closed fuel injector over a set period of time. The injector leakage rate is determined by pressurizing a closed injector with nitrogen at 300kPa. The injector was then isolated from the supply of gas and the rate of pressure loss was used to calculate the leakage rate.

**Fuel Injector Pulse Width**

The time, in milliseconds, that a fuel injector is opened to deliver fuel into the intake port.

**Engine Power Pulse (EPP) Count**

The engine power pulse records the length of time that the starter motor is energized in an effort to start the engine. Once the engine fires and exerts a force on the starter motor the engine is considered to be running and the EPP stops increasing and the count is stored in the engine computer memory. If a misfire occurs and the starter must continue to turn the engine, the EPP count is reset to zero and the count will continue to increase until the engine fires.

**Hot Soak**

A hot soak is when a vehicle sits with all systems turned off after the engine had reached operating temperature. Since the radiator fan of the vehicle used in this study does not run when the vehicle is shut down, the cooling system is no longer removing heat from the engine block. Instead, this heat is rejected to the engine bay. This results in a temporary increase in temperature of some engine components after the engine shuts down. It is during the hot soak that the fuel system will reach its maximum temperature. For the vehicle that is being examined in this study, the maximum coolant temperature is reached after 40 minutes of hot soak [23]. However to decrease the testing time a hot soak period of 30 minutes was used for the coated fuel rail analysis and a hot soak period of 10 minutes was used during the FTP tests of the fuel injector durability study. as it is
specified in the FTP standard. Using a shorter hot soak time will result in a decrease in the maximum temperature of engine components following hot soak.

**Hot Start**

A hot start is when an attempt is made to restart a vehicle that has completed a hot soak of any duration.

**Federal Test Procedure (FTP) Exhaust Emissions Test**

The federal test procedure (FTP) is a series of tests that are used to determine a vehicle’s emission performance and fuel economy [3]. These tests include procedures to measure exhaust, refuelling and evapourative emissions. The exhaust emission test of the FTP is based on the Urban Dynamometer Driving Schedule (UDDS) [3] shown in Figure 176. This cycle was developed to model a home to work commute in Los Angeles. The cycle includes three sections: cold, stable and hot. The varying speeds at which the vehicle travels during each section are specified by the U.S. EPA and are shown in Chapter 20: Appendix G: FTP Emissions Test Speed Profile.

The vehicle is prepared, and then soaked at room temperature for at least 12-hours. The first section of the test is a cold start followed by driving at varying speeds for 505 seconds. The second section consists of driving at varying speeds for 866 seconds. These speeds are considered to be representative of the standard operating manner of the vehicle. The vehicle is then hot soaked for 10 minutes before the start of the third section. The third section includes a hot start followed by driving using the same speed profile as the first section, again for 505 seconds.

Emissions from each section are collected into separate plastic bags for analysis. These are referred to as bags one, two and three or cold, stable and hot. A representation of the level of emissions of a vehicle is considered equal to sum of bags 1 and 2 weighted by 43% plus the sum of bags 2 and 3 weighted by 57%. A motor vehicle manufacturer is only permitted to sell a vehicle to the public if its weighted total of emissions is less than the legislated value.
Operating Principals of Fuel Metering for Liquid LPG Injection SI Engines

Similar to a gasoline fuel injected engine, the fuel for a liquid-injection LPG engine is metered into the intake manifold using fuel injectors. By opening the injectors for a specified period of time (pulse width), they can be used to meter a specific quantity of fuel into the intake manifold. However to accurately determine the mass of fuel that passes through the injector, the density of the fuel and pressure difference between the manifold and the fuel rail must be known. To determine these quantities both a pressure and temperature sensor are installed on the inlet line of fuel rail. These inputs are used in conjunction with the manifold pressure, engine speed, air temperature, coolant temperature and acceleration to determine the pulse width required to meter the mass of fuel that will result in a near stoichiometric in-cylinder mixture. Accurate control of the stoichiometry of the in-cylinder mixture is critically important as it has the most significant effect on emissions.

Closed Loop Feedback Fuel Metering System to Optimize Emissions

All modern engines use a feedback system to maintain an air to fuel ratio such that the equivalence ratio is close to unity during operation to insure that the three-way exhaust catalyst works correctly. The input for this system is an oxygen sensor in the exhaust stream. This sensor, referred to as a lambda sensor, sends a signal that indicates whether the exhaust is a result of lean or rich combustion. Based on the signal from the lambda sensor, the engine control computer will vary the pulse width of the injectors such that the mass of fuel injected into the cylinders will produce a mixture with an equivalence ratio close to one. The memory values referred to as the "adaptives" are used to describe how much the optimized pulse width value differs from the standard values based on the inputs mentioned above. The variable "adaptives" are used by the engine control computer to control the fuel injector pulsewidths over a range of engine operation.
CHAPTER 1: INTRODUCTION TO ENERGY USE AND ALTERNATIVE FUELS

1.1 Energy Use and the Motivation for the Use of Alternative Fuelled Vehicles

What is the motivation for moving away from gasoline-powered vehicles? There are a series of concerns with gasoline that can be classified under such diverse headings as environmental, political and public health. These concerns have led the Canadian and U.S. governments to support the use of liquefied petroleum gas, or propane fuel, as alternative fuels to gasoline.

The goals of both governments' policies on alternative fuels are to reduce production of the precursors to ground based ozone or smog (HC and NOx), reduce the dependence of North America on overseas oil, to reduce toxic vehicle emissions such as benzene and reduce carbon dioxide emissions.

The transportation sector is one of the major contributors to pollution in the United States and Canada. In 1994 this sector accounted for 26% of the total U.S. emission of volatile organic compounds (VOCa). 32% of total oxides of nitrogen (NO\textsubscript{X}) and 62% of the total U.S. carbon monoxide (CO) emissions [4]. When all of the other greenhouse gases are considered this sector was responsible for 32% of U.S. greenhouse-gas emissions [4].

In terms of air pollutant production, LPG powered vehicles can offer some benefits when compared against gasoline powered vehicles. The U.S. Clean Fleet alternative fuels demonstration project of 1994 provided an opportunity to compare identical vehicles that were fuelled with either a carburetted gaseous LPG fuel system or a gasoline fuel system using reformulated gasoline. The vehicles used were Chevrolet vans with 5.8L V8 engines.
The FTP Bag-1 emission results that are referenced were all taken while the vehicles’ mileage was between 8,800 and 20,800 accumulated kilometres. The exhaust emission results from these vehicles are shown in Table 1. It can be seen that the use of propane fuel lead to a 64% decrease in total oxides of nitrogen, a 32% decrease in carbon monoxide emissions, and a 38% increase in total non-methane organic (NMOG) emissions [5].

Table 1: FTP Cycle Emissions from 1994 Chevrolet 5.8L V8 Van [g/mi] [5]

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fuel</th>
<th>CO</th>
<th>NMHC</th>
<th>NMOG</th>
<th>NOx</th>
<th>THC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>GM 5.8L V8</td>
<td>Gaseous LPG Carburetion</td>
<td>5.87</td>
<td>3.90</td>
<td>0.56</td>
<td>0.08</td>
<td>0.57</td>
</tr>
<tr>
<td>GM 5.8L V8</td>
<td>California Reformulated</td>
<td>9.10</td>
<td>1.51</td>
<td>0.34</td>
<td>0.06</td>
<td>0.35</td>
</tr>
</tbody>
</table>

However, this increase in NMOG should be interpreted with some explanation. Hydrocarbon emissions (and therefore NMOG) are viewed critically in emission regulations due to their tendency to form ground-based ozone in the presence of NOx and sunlight. Rather than merely analyzing these results in terms of mass, they should be analyzed with regard to the quantity of smog or ground-based ozone created from the mass of NMOG.

NMOG emissions are the mass sum of all measurable organic compounds (excluding methane). These organics can consist of molecules composed of between 2 and 12 carbon atoms. Each of these compounds has a different tendency to produce ground-based ozone. The maximum incremental reactivity (MIR) scale assigns a factor to each compound that represents its tendency to contribute to ground-based ozone formation [6]. By applying these factors to the NMOG emissions, it is possible to determine the ground-based ozone forming potential of the emissions from each vehicle. When the potential ozone formation from NMOG emissions was considered as shown in Table 3 it can be seen that these LPG vehicles showed a clear advantage over the comparable gasoline powered alternatives.
Table 2 and Table 3 show the breakdown of NMOG emissions, and the ozone forming potential for those NMOG emissions for the vehicles used in the Clean Fleet Study.

**Table 2: Composition of NMOG Emissions [mg/mi] [5]**

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fuel</th>
<th>Alcohol</th>
<th>Carbonyls</th>
<th>Light-end HC</th>
<th>Mid-Range HC</th>
<th>Total NMOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM 5.8L V8</td>
<td>Gaseous LPG Fuel Carburetion</td>
<td>0.00</td>
<td>6.23</td>
<td>560.2</td>
<td>2.6</td>
<td>569.0</td>
</tr>
<tr>
<td>GM 5.8L V8</td>
<td>California Reformulated Gasoline</td>
<td>0.00</td>
<td>10.29</td>
<td>122.4</td>
<td>221.5</td>
<td>354.0</td>
</tr>
</tbody>
</table>

**Table 3: Calculated Ozone Forming Potential of NMOG Exhaust Emissions [g/mi] [5]**

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fuel</th>
<th>Alcohol</th>
<th>Carbonyls</th>
<th>Light-end HC</th>
<th>Mid-Range HC</th>
<th>Total OFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM 5.8L V8</td>
<td>Gaseous LPG Fuel Carburetion</td>
<td>0.00</td>
<td>0.039</td>
<td>0.499</td>
<td>0.006</td>
<td>0.544</td>
</tr>
<tr>
<td>GM 5.8L V8</td>
<td>California Reformulated Gasoline</td>
<td>0.00</td>
<td>0.054</td>
<td>0.566</td>
<td>0.757</td>
<td>1.377</td>
</tr>
</tbody>
</table>

The above results from the Clean Fleet study showed that the use of LPG vehicles can lead to a significant decrease in CO, NOx and the ground-ozone forming potential of the NMOG emissions.

This study also showed that the emission of air toxins from LPG powered vehicles are significantly lower than those for gasoline powered vehicles. The results of the air toxins emissions are shown in Table 4.
Table 4: Air Toxics Emissions FTP Phase 1 (mg/mile) [5]

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fuel</th>
<th>Acetaldehyde</th>
<th>Formaldehyde</th>
<th>1,3-Butadiene</th>
<th>Benzene</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>GM 5.8L V8</td>
<td>Gaseous LPG Fuel Carburetion</td>
<td>1.12</td>
<td>0.29</td>
<td>4.32</td>
<td>4.12</td>
</tr>
<tr>
<td>GM 5.8L V8</td>
<td>California Reformulated Gasoline</td>
<td>2.43</td>
<td>0.23</td>
<td>4.56</td>
<td>1.38</td>
</tr>
</tbody>
</table>

The LPG powered vehicle shows a 54% decrease in acetaldehyde emissions, 5% decrease in formaldehyde emissions, an elimination of 1,3-Butadiene emissions and a 100 times reduction in benzene emissions.

These reductions in ozone forming potential and air toxin emissions can be attributed to the composition of LPG fuel. Generally, gasoline is composed of hydrocarbons with carbon chains in the range between C5 to C8 whereas LPG fuel is composed of chains in the range of C1 to C5. In general air toxins 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 [6]. Since LPG composition does not have many of the precursors to air toxins or highly volatile organic compounds, it is obvious that this fuel would lead to low emissions values in these areas.

The emissions benefits of LPG exist for vehicles powered by smaller engines as well. This was demonstrated by a study that compared the emissions of an indolene fuelled Dodge Caravan Minivan against one that was fuelled with a PFI gaseous LPG fuel system [7]. Indolene is a blend of gasoline that is used for emissions certification tests of all gasoline-powered vehicles. The results of the FTP tests that were performed are shown in Table 5 and Table 6.
### Table 5: Weighted FTP EPA-75 Tailpipe Emissions and OFP [g/mi.] [7]

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fuel</th>
<th>CO</th>
<th>NMHC</th>
<th>NMOG</th>
<th>NOx</th>
<th>THC</th>
<th>OFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dodge 3.3L V6</td>
<td>Gaseous LPG Fuel Injection</td>
<td>1.410</td>
<td>0.101</td>
<td>0.099</td>
<td>0.144</td>
<td>0.124</td>
<td>0.115</td>
</tr>
<tr>
<td>Dodge 3.3L V6</td>
<td>Indolene</td>
<td>1.959</td>
<td>0.146</td>
<td>0.143</td>
<td>0.238</td>
<td>0.175</td>
<td>0.500</td>
</tr>
</tbody>
</table>

### Table 6: Air Toxic Species Weighted FTP EPA-75 [mg/mi.] [7]

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fuel</th>
<th>Acetaldehyde</th>
<th>Formaldehyde</th>
<th>1,3-Butadiene</th>
<th>Benzene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dodge 3.3L V6</td>
<td>Gaseous LPG Fuel Injection</td>
<td>0.28</td>
<td>0.76</td>
<td>0.00</td>
<td>0.12</td>
</tr>
<tr>
<td>Dodge 3.3L V6</td>
<td>Indolene</td>
<td>0.64</td>
<td>0.30</td>
<td>0.88</td>
<td>6.50</td>
</tr>
</tbody>
</table>

The results from these tests again show an improvement in both emissions and air toxins for LPG powered vehicles when compared against the same vehicle fuelled with gasoline.

In conclusion, the use of LPG fuelled vehicles can lead to reduced emissions, a reduction in ground-based ozone production and lower air toxin emissions. LPG can be obtained from natural gas deposits, which are plentiful in North America or produced as a byproduct of domestic gasoline production from crude oil. Therefore, the use of this alternative fuel can lower North American dependence on foreign oil production.
CHAPTER 2: MOTIVATION FOR THE STUDY OF FUEL INJECTOR DURABILITY

Although LPG vehicles provide an excellent alternative to gasoline vehicles problems still remain to be solved before LPG systems will be capable of continuing to meet the stringent emission 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 at an unusually quick rate 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 636km, 3860km and 6713km [8]. The emission results from these tests showed a 9% increase in “FTP phase 1” total hydrocarbon (THC) emissions over the first 3000km and another 33% increase in “FTP phase 1” THC over the second 3000km that was accumulated. This phase of the FTP test includes the emissions from a cold start that followed a 12 hour 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 was due to leaking fuel injectors. It was believed that as the mileage of LPG vehicles increased deposits formed within the fuel injector and affected the injector’s ability to form a seal between the injector needle and seat.

A similar 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 and slow or uneven acceleration [9]. 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 [10] 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 would 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) 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 vapourized [11] due to the lack of fuel flow and increased heat flux to the rail during hot soak. As the engine hot soaks the seal within each fuel injector must be maintained to withstand a 10 bar or more pressure difference between the interior of the fuel rail and the intake manifold. This is a much more demanding requirement than that which is found in a gasoline injector. A gasoline fuel injector must maintain a seal between the liquid fuel in the fuel rail and the air in the intake manifold at a pressure difference of only about 3.0 bar when the engine is running.

Since the sealing demands that are placed on the LPG fuel rail are greater than those for gasoline fuel injectors the formation of deposits was first manifested as an increased leakage as opposed to a reduction in injector flow rate. The addition of fuel detergents to gasoline was the solution used to remove deposits from within gasoline fuel injectors in the past. The goal of this study was to apply this solution and 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.
CHAPTER 3: LITERATURE REVIEW FOR THE STUDY OF FUEL INJECTOR DURABILITY

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 and slow or uneven acceleration [9]. These problems were found to be due to flow restriction in the fuel injectors as deposits were forming within the injector. A significant amount of research has been completed on which factors contribute to deposit formation within gasoline-fuelled engines. Other studies have been completed on which additives have been used to hinder the formation of deposits as well as testing procedures to determine if a gasoline blend will lead to deposits within a fuel system.

3.1 Deposits in LPG Fuel Systems

Unfortunately, no work has yet been completed in the study of deposits that result from the use of LPG as an automotive fuel. The California Air Resources Board (CARB) LPG Task Group recently completed [12] an evaluation of the emissions and engine durability of a Ford F-150 gasoline/ LPG bi-fuel pick-up truck as it operated on various blends of LPG. This vehicle used an LPG system that injects LPG vapour through the fuel injectors and is therefore not similar to the liquid LPG injection system that is used on the vehicles in the present study. The durability analysis of the CARB study focused on using engine oil analysis as a measure of engine durability. No analysis was performed to determine the effects of the different fuels on the durability of the vapourizer used to convert the stored liquid fuel. If an analysis of the fuel system of the engine used in the CARB study was performed, this information would complement the present study quite well.

In the absence of any publications in the public domain describing the formation of deposits within the fuel injectors of liquid LPG fuel systems, one can attempt to apply the theories developed from the analysis of deposits within gasoline fuel injectors. All other
sources in this literature review refer to studies on deposit formation within gasoline engines.

3.2 Review of Experimental Procedures Used to Develop and Quantify Gasoline Fuel Injector Deposits

To develop the experimental procedure for this study a number of gasoline fuel injector deposit studies were analyzed. Much of the information that has been gathered from gasoline deposit studies can be applied to a study designed to analyze LPG fuel injector deposits.

The common method of evaluating fuel injector performance was to measure the initial performance of a new injector and the final performance of the injector following a mileage accumulation procedure. For all of the injector performance studies [13][14][15][22] the percent change in fuel injector flow rate was used as a performance measure, as a significant change in fuel injector flow rate would result in the poor driveability and acceleration that indicated injector deterioration.

Two types of mileage accumulation methods were used in the gasoline deposit studies that were reviewed. A fifteen minute drive at 88 km/h followed by a 45-minute hot soak was used when individual vehicles were analyzed in a laboratory environment. This combination of drive and soak times was found to best result in gasoline deposit formation [15]. Alternately when fleet vehicles were analyzed a consistent initial vehicle set up and maintenance schedule was used and vehicles were operated on similar driving profiles.

When developing the experimental procedure for this work one of the concerns was how different weather conditions effect the mileage accumulation of the vehicles. It was necessary to mileage-accumulate five vehicles to a mileage of 6400 km each using on road mileage accumulation. This process took 10 months to complete and involved
operating vehicles at external temperatures that varied between the summer and winter seasons. For this reason, studies that analyzed the effects of exterior temperature were reviewed. Past research has shown that ambient temperature has little effect on injector tip temperature or the degradation of injector flow rates. Injector tip temperatures were measured during a gasoline PFI deposit accumulation program performed by Benson [9] using a 5.0L V8 Camaro operating on gasoline. These experiments showed a variation in injector tip temperatures of only 6°C even though the outdoor temperature varied between 18 and 27°C. A study performed by Tupa [13] showed that gasoline fuel injector flow rates degraded very similarly in two 3.8L V6 vehicles even though one was operated at 0°C and the other at 12°C ambient. Finally when performing a statistical review of 199 PFI “Keep Clean Tests” Whitehead [14] found that when comparing winter/spring mileage accumulation period versus summer/fall the outcome of the keep clean tests were independent of season.

The review of past experimental procedures used to determine the rate of injector degradation due to deposits has lead to the design of the procedure used in this study. Based on past research, the mileage accumulation procedure used in this study is not the most effective for deposit formation but it will provide a good indication of the degree of deposits that are developed during average vehicle use.

3.3 Gasoline Fuel Injector Deposit Formation Mechanism

3.3.1 Physical Deposit Formation Mechanisms for Gasoline Fuel Injector Deposits

All of the work reviewed concluded that deposits within fuel injectors are formed during a prolonged engine shutdown followed by a short period of operation. Taniguchi et al [15] demonstrated that the worst deposit forming conditions for gasoline fuel systems were found to involve operating a vehicle for fifteen minutes followed by a 45-minute soak period.
Deposits that consisted of two distinct layers as observed by Benson and Yaccarino [9] led to their hypothesis that the physical deposit mechanism is a two-stage process. First, during the high fuel injector temperatures of the hot soak period (78-85°C), a thin film of liquid gasoline oxidizes on the internal surfaces of the injector downstream of the sealing area. This sticky varnish type deposit hardens into the first deposit layer. The sticky surface of this layer traps particulate material from the EGR and PCV gases present in the intake manifold, which lead to the formation of the black crusty second deposit layer.

3.3.2 Chemical Deposit Formation Mechanism for Gasoline

Little is known about the true chemical pathway between liquid gasoline fuel and harmful deposits within gasoline fuel injectors, but a few theories have been proposed. Benson and Yaccarino [9] referenced the mechanism of deposit formation in jet fuels as a possible deposit formation process in automotive gasoline. The deposit formation mechanism in jet fuels is initiated by the autoxidation of the fuel from the oxygen present in the fuel. These reactions tend to involve free radicals and therefore any component within an automotive fuel that will easily form these radicals could initiate the degradation of the fuel. This could be true for either LPG or Gasoline. Benson and Yaccarino [9] proposed that the highly reactive diolefin compounds that are present in both LPG and gasoline could be involved in the deposit formation process. These compounds tend to form free radicals and are known to cause deposits in refinery processes. This hypothesis was tested by mileage accumulating two of the same type of vehicles using gasolines of different diolefin content. After operating on the base fuel with 0.016% mass diolefins for 6 080 km the flow rate of the fuel injectors had decreased by an average of 1%. A second fuel was mixed by adding additional diolefin compounds to the base fuel such that the total diolefin content was increased to approximately 0.4% by mass. When operating on this fuel for only 4 650 km the second vehicle experienced a 10% average decrease in injector flow rate. Further tests by Hilden [16] supported the claim that diolefins may be critical to the formation of gasoline fuel injector deposits, but are not sufficient as initiators when other reactive components such as olefins are absent.
Hilden also completed an extensive literature review on deposits and gum produced by the oxidation of gasoline. Although the early steps in gum formation have been studied for many hydrocarbons, a detailed set of reactions that describe the formation of a gasoline deposit from initiation to conclusion was not found during this literature search.

The work of Wallace [17] was referenced by Hilden [16] regarding the role of sulphur in fuel instability. Wallace concluded that of the sulphur compounds, elemental sulphur, thiols, disulfides, and polysulfides posed the greatest problem to fuel instability. With regard to the role of thiols he was quoted by Hilden as noting “Thiols apparently contribute to instability by their ready oxidation to thyl radicals. The latter form disulfides, add to diolefins and mono-olefins to form hydroxy sulfoxides, and initiate polymerization reactions”. Hilden [16] further detailed the complexity of deposit formation by concluding that regarding fuel sulphur content: “It is not possible to predict a fuel’s stability simply on the basis of total sulphur content. The chemistry of the individual sulphur compounds, the presence of other hydrocarbons or heteroatom species, and the test conditions (e.g. temperature, oxygen concentration, mixing, etc.) all play important roles”.

3.4 Chemical Analysis of Gasoline Fuel Injector Deposits

Much of the literature on deposits within gasoline fuel injectors involved studies of their composition. Benson and Yaccarino [9] analyzed deposits that were found on 15 pintle-type gasoline fuel injectors that had been returned from the field. In general, for the bulk of the sample, 40% was carbon by weight, and the remaining 60% of the deposit was composed of inorganic compounds. This analysis was unable to detect the presence of hydrogen or oxygen within the deposits. Taking the average results from the electron dispersion spectrometry (EDS) analysis the relative inorganic elemental concentrations within the deposits were found and are shown in Table 7.
Table 7: Inorganic Composition of Gasoline Fuel Injector Deposits

<table>
<thead>
<tr>
<th>Element</th>
<th>S</th>
<th>Na</th>
<th>Zn</th>
<th>K</th>
<th>Al</th>
<th>Si</th>
<th>Cl</th>
<th>Ca</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>70</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Tupa and Koehler [13] analyzed the composition of gasoline PFI deposits using an x-ray diffraction method. They determined that the major inorganic elements within the deposit were sulphur, silicon and iron as well as minor traces of zinc, calcium and chromium.

Taniguchi [15] et al. used Electron Spectroscopy for Chemical Analysis (ESCA) in combination with infrared spectroscopy to analyze the deposits found on fouled gasoline fuel injectors returned from the field. During this study, it was found that the deposits contained a large amount of organic carbon as aromatics and low levels of metals including sodium, lead and zinc.

Tseregounis [18] used a laboratory-based technique to form films of deposit on the surface of small stainless steel plates. These deposits were formed while the plates were immersed in a gasoline fuel sample that was heated to 100°C, and exposed to a flow of heated air over a 24-hour period. The deposits were then analyzed using Electron Spectroscopy for Chemical Analysis (ESCA).

The composition of these deposits was primarily carbon followed by varying amounts of oxygen, sulphur, and nitrogen and traces of metals including Zn, Pb, Na and Si. Based on the results of the ESCA the carbon was likely bound to oxygen (C=O, C-O, O=C-O) and the sulphur within the deposits was highly oxidized (SO₄, SO₃, RSO₂OR, RSO₂OSOR, ROSO₂OR etc). Since the sulphur compounds within the original fuel were in the form of sulphides, thiophenes and thiols (which do not contain S-O bonds), the oxygenated sulphur compounds must have been formed during the oxidation of the fuel. The total sulphur concentration of the deposits was between 5-10 times greater than the sulphur content of the fuel used.
Experiments performed by Bailey et al [19] to analyze the gasoline deposits formed on aluminum in a laboratory environment at different temperatures produced different results regarding the carbon bonding within the deposits. These experiments used high-resolution ESCA to determine that the dominant (75% of all carbon bonds) carbon bonding structure within the deposits was simple C-C or C-H bonds. The remaining carbon bonds were about two-thirds ether or amine-type linkages and about one third carbonyl bonds. Gel Permeation Chromatography analysis (GPC) of the deposits formed at 135°C was used to determine the apparent molecular weight range of the deposits. The peak outputs of this procedure showed that the majority of molecules present in the deposits were formed by polymerization and had molecular sizes of approximately 1500 or 250 and less than 130 carbon atoms in each molecule.

This literature review has shown that the composition of gasoline fuel injector deposits tend to be composed of approximately 40% by mass of carbon-based compounds and the remaining mass consists of inorganic compounds. Most of analyses were was unable to detect the presence of hydrogen or oxygen within the deposits however it was assumed that a significant number of oxides are present within the deposits. Generally the deposits were formed by the auto-oxidization of the fuel and consist of a combination of long chain hydrocarbons and concentrated sulphur compounds mixed with other inorganic compounds from the fuel and exhaust products.

3.5 Effects of Gasoline Composition on Fuel Injector Deposit Formation

Benson and Yaccarino [9] found that the aromatic concentration within the fuel did not influence deposit formation, but an effect was found due to either the total olefin concentration or the concentration of a specific olefin. Tupa and Koehler [13] found a reasonable correlation between total gasoline olefin content and fuel injector flow restriction following 4 800km of mileage accumulation. However further data from this mileage accumulation showed no correlations between specific gravity of the fuel, total sulphur content or ASTM D 381 gum results (washed or unwashed) and increased fuel injector flow restriction.
Tseregounis' [18] laboratory-based deposit forming experiments showed that fuel sulphur content does not necessarily lead to an increase in sulphur content within the deposit. When 2.5% by volume of either thioanisole or thianaphthene (sulphur based compounds) were added to the base gasoline no significant increase in sulphur content of the deposits was noted between the base fuel and the doped fuel. Taniguchi [15] felt that this implied that these two compounds did not directly affect the deposit formation mechanism. However it is of importance to note that the addition of thioanisole in fact resulted in a thinner deposit layer than that from the base fuel.

3.6 Effects of Additive Chemistry on Gasoline Fuel Injector Deposits

Gasoline anti-deposit additives act as both dispersants and detergents. Since they are polar molecules they assist in keeping deposit precursors suspended within the fuel so that they may not coalesce to form deposits. As well, these additive have some surface-active action that allows them to act as detergents and remove deposits from fuel system surfaces [20].

Tupa and Koehler [13] found that both polymeric dispersant and amine detergent based gasoline additives can provide effective deposit prevention and clean up of gasoline PFI deposits. However, the amine detergent lead to increased intake manifold and valve deposits when the treatment level exceeds 100 PPM.

To insure that additives do not result in the formation of deposits elsewhere within the engine they must be tested for deposit forming tendency using ASTM standards D5500 and D5598 and base fuel that is described in ASTM 5598 [21]: “should be typical of commercial, unleaded automotive spark-ignition engine fuel”. These tests measure the tendency of the fuel-additive combination to form intake valve deposits or port fuel injector deposits respectively. An additive can be approved for use in compliance with the U.S. Environmental Protection Agency’s (EPA) Final Rule for Deposit Control
Additives if both tests described in the above ASTM standards are completed successfully.

To date no standards, other than odorant requirements, have been specified for the use of additives in LPG motor fuel.

### 3.7 Summary of Literature Review

No work has been performed to evaluate the composition or formation mechanism of deposits within LPG liquid fuel injectors. Based on the work that was completed for gasoline, assumptions can be made 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.
CHAPTER 4: FUEL INJECTOR DURABILITY STUDY MATERIALS AND METHODS

Many 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 fuel injector deposit formation 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 [22]. 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 highly volatile fuel such as LPG.

The approach chosen in this work was to operate five sets of injectors on different fuels. The injectors were leak tested prior to use and installed on specified intake ports in each vehicle based on their leakage rates. The injectors were mounted in similar vehicles with 5.2L V8 engines fuelled by liquid LPG PFI fuel systems and were mileage-accumulated to 6 400km following a specified driving profile while operating on their specified fuel. Each set of injectors was then mounted into an emissions testing vehicle, which was operated on the same fuel while testing each set of injectors. Each injector was then leak tested again to evaluate injector performance. A subset of the fuel injector were photographed with a scanning electron microscope to determine if deposits were present. 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.

4.1 LPG PFI 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. Fuel flow is provided using a fuel pump mounted within the fuel tank. The pressure of the fuel
rail is maintained above that of the tank using a pressure sensitive back check and relief valve. A schematic of the Type-1 fuel system is shown in the figure below:

![Fuel System Diagram]

Figure 1: Schematic of Liquid LPG PFI Fuel System Type-1 Fuel Rail

4.2 Initial Fuel Injector Testing and Positioning

For this study a pool of 96 bottom feed LPG fuel injectors were used. These fuel injectors had been manufactured to the specifications required for operation within the liquid LPG PFI fuel system installed on the 5.2L V8 engines that 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 ± 1% of reading and a repeatability of ±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.

The data from the first trial of the initial testing for all fuel injectors was eliminated as the distribution of results from this trial differed significantly from those of the following two
trials. The standard deviation of the leakage rate data of all 96-injectors from the first trial was three times greater than the standard deviations of the second and third trials. A distinct shift in the mean of the first trial relative to the means of the second and third trials was noted. The mean of the first trial was offset from the means of the other two trials by 0.9 standard deviations of the trial 2 and 3 data. Conversely the data from the second trial was within 0.1 standard deviations of the third trial data.

It was felt that this significant shift of the mean value from the first trial was due to the incorrect seating of the O-rings of the test injector seating as the system was first pressurized. Using the averaged raw data from the final two leakage tests each injector was placed in one of three groups, low, medium and high leakage. These three groups were defined by the raw leakage data values using the following leakage rates. Group 1, low leakage: 0.00-0.11 cc/min, group 2 medium leakage: 0.12-0.21 cc/min and group 3 high leakage: 0.22-0.31 cc/min. Since the leakage rate values for groups 1 and 2 are below the minimum accurate reading of the instrument the fuel injectors from these groups are considered to have the same leakage rates of 0.2 cc/min. Four sets of eight injectors were chosen for each engine such that three injectors were of low leakage, three were of medium leakage and finally two injectors were from the high leakage group. The maximum acceptable leakage rate for fuel injectors of this type was 1.0 cc/min. The leakage rate testing was performed at Siemens Automotive Group's fuel injector development facility in Newport News, VA, USA.

The fifth injector set consisted of injectors that were assembled with titanium coated injector valve seats. The eight injectors for this set were selected from a population of 26 injectors. Again the 26 injectors were separated into groups of low, medium and high leakage. The flow rates of the titanium nitride (TiN) injectors were recorded. All met the requirements of having a static flow rate of 3.400g/sec ±3% and a dynamic flow rate of 5.45 mg ± 3% per 2.5 ms injector pulse.
The flow rate data for these injectors was not specifically recorded. However since these injectors were specified to be used for research purposes they had all been flow tested and met the flow specifications that were described above.

From these groups a set of eight injectors were selected such that three fuel injectors were of low leakage, three were of medium leakage and finally two fuel injectors were from the high leakage group. Using these designations the fuel injectors were mounted into the engines of the mileage accumulation vehicles such that injectors from a specific leakage group are mounted in the specified cylinder. The locations and leakage rates of all fuel injectors used in this study are described in Table 8 and Appendix F: Description of Vehicles and Injectors Used in Testing.

Since the TiN coated seat fuel injectors were prototype parts there was a smaller population from which to select the injectors, the subset of titanium coated seat injectors that was used for this study had a significantly lower initial leakage rate. Taking into account that lowest leakage rate that could be accurately measured by the leakage rate instrument was 0.2 cc/min, the average initial leakage rate of the FUEL H-TiN fuel injectors was 0.21 cc/min as opposed to an average of 0.32cc/min for all other fuel injector groups.
Table 8: Initial Fuel Injector Leakage Rate and Engine Location

<table>
<thead>
<tr>
<th>INJECTOR GROUP</th>
<th>Cylinder #</th>
<th>Legend</th>
<th>Firing Order:</th>
<th>1-8-3-6-5-7-2</th>
<th>Coolant flow</th>
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</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>7 5 3 1 8 6 4 2</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INJECTOR GROUP</th>
<th>Cylinder #</th>
<th>G1 0.04 cc/min</th>
<th>Cylinder #</th>
<th>G2 0.12 cc/min</th>
<th>Cylinder #</th>
<th>G3 0.25 cc/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL H</td>
<td>Cy#: 1: Inj# 10</td>
<td>Cy#: 2: Inj# 22</td>
<td>Cy#: 3: Inj# 11</td>
<td>Cy#: 4: Inj# 23</td>
<td>Cy#: 5: Inj# 12</td>
<td>Cy#: 6: Inj# 24</td>
</tr>
<tr>
<td></td>
<td>Cy#: 4: Inj# 24</td>
<td></td>
<td>Cy#: 5: Inj# 15</td>
<td></td>
<td>Cy#: 6: Inj# 26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cy#: 7: Inj# 28</td>
<td></td>
<td>Cy#: 8: Inj# 17</td>
<td></td>
<td>Cy#: 9: Inj# 29</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INJECTOR GROUP</th>
<th>Cylinder #</th>
<th>G1 0.04 cc/min</th>
<th>Cylinder #</th>
<th>G2 0.12 cc/min</th>
<th>Cylinder #</th>
<th>G3 0.25 cc/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL C</td>
<td>Cy#: 1: Inj# 21</td>
<td>Cy#: 2: Inj# 46</td>
<td>Cy#: 3: Inj# 20</td>
<td>Cy#: 4: Inj# 47</td>
<td>Cy#: 5: Inj# 21</td>
<td>Cy#: 6: Inj# 48</td>
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<td>Cy#: 4: Inj# 25</td>
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<td>Cy#: 6: Inj# 27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cy#: 7: Inj# 26</td>
<td></td>
<td>Cy#: 8: Inj# 24</td>
<td></td>
<td>Cy#: 9: Inj# 28</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INJECTOR GROUP</th>
<th>Cylinder #</th>
<th>G1 0.03 cc/min</th>
<th>Cylinder #</th>
<th>G2 0.12 cc/min</th>
<th>Cylinder #</th>
<th>G3 0.22 cc/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL V</td>
<td>Cy#: 1: Inj# 82</td>
<td>Cy#: 2: Inj# 60</td>
<td>Cy#: 3: Inj# 58</td>
<td>Cy#: 4: Inj# 62</td>
<td>Cy#: 5: Inj# 57</td>
<td>Cy#: 6: Inj# 62</td>
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<tr>
<td></td>
<td>Cy#: 4: Inj# 57</td>
<td></td>
<td>Cy#: 5: Inj# 56</td>
<td></td>
<td>Cy#: 6: Inj# 55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cy#: 8: Inj# 54</td>
<td></td>
<td>Cy#: 9: Inj# 53</td>
<td></td>
<td>Cy#: 10: Inj# 52</td>
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</table>

<table>
<thead>
<tr>
<th>INJECTOR GROUP</th>
<th>Cylinder #</th>
<th>G1 0.05 cc/min</th>
<th>Cylinder #</th>
<th>G2 0.14 cc/min</th>
<th>Cylinder #</th>
<th>G3 0.23 cc/min</th>
</tr>
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<tbody>
<tr>
<td>FUEL P</td>
<td>Cy#: 1: Inj# 96</td>
<td>Cy#: 2: Inj# 78</td>
<td>Cy#: 3: Inj# 74</td>
<td>Cy#: 4: Inj# 79</td>
<td>Cy#: 5: Inj# 75</td>
<td>Cy#: 6: Inj# 77</td>
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<tr>
<td></td>
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<td>Cy#: 5: Inj# 72</td>
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<td>Cy#: 6: Inj# 71</td>
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</tr>
<tr>
<td></td>
<td>Cy#: 8: Inj# 69</td>
<td></td>
<td>Cy#: 9: Inj# 68</td>
<td></td>
<td>Cy#: 10: Inj# 67</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>INJECTOR GROUP</th>
<th>Cylinder #</th>
<th>G1 0.01 cc/min</th>
<th>Cylinder #</th>
<th>G2 0.07 cc/min</th>
<th>Cylinder #</th>
<th>G3 0.18 cc/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL H-TiN</td>
<td>Cy#: 1: Inj# 23</td>
<td>Cy#: 2: Inj# 107</td>
<td>Cy#: 3: Inj# 21</td>
<td>Cy#: 4: Inj# 108</td>
<td>Cy#: 5: Inj# 22</td>
<td>Cy#: 6: Inj# 109</td>
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<td>Cy#: 4: Inj# 25</td>
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<td>Cy#: 5: Inj# 26</td>
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<td>Cy#: 6: Inj# 27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cy#: 8: Inj# 29</td>
<td></td>
<td>Cy#: 9: Inj# 30</td>
<td></td>
<td>Cy#: 10: Inj# 31</td>
<td></td>
</tr>
</tbody>
</table>

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min due to the accuracy of the instrument used to determine the leakage rate.

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

4.3 Fuel Properties

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

- **FUEL P** - Low sulphur high purity, aerosol grade LPG
- **FUEL H** - Commercially available LPG
- **FUEL C** - Commercially available LPG with anti-deposit additive C
- **FUEL V** - Commercially available LPG with anti-deposit additive V
The anti-deposit additives were added to the vehicle’s fuel tank as they were filled with fuel. At each refuelling the volume of fuel to be added was determined based on the mileage that the vehicle had run since the last fuelling and the suggested concentration of the additive. The fuel to additive ratio for each of the additives is described in Appendix F: Description of Vehicles and Injectors Used in Testing. Using the amount of fuel that was to be added to the vehicle tank the corresponding volume of anti-deposit additive was determined and measured with an accuracy of 0.5 mL using a 100 mL graduated cylinder. The additive was then poured into a chamber that was mounted inline with the fuel filling system. As the predetermined volume of LPG was pumped into the vehicle the additive was mixed with the fuel and forced into the fuel tank. Each of the additives consisted of a dispersant mixed with petroleum distillates as carrier fluids. The details of the additive chemistry cannot be fully disclosed to protect the confidential composition of these commercial products.

For safety reasons the sulphur based odorant ethyl-mercaptan was added to the otherwise odorless FUEL P in a manner that was identical to the method that was used to add the anti-deposit additive to the fuel. A volume of 2 mL of ethyl mercaptan was measured with an accuracy of 0.5 mL using a 10 mL syringe. This was added and 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.

To determine the hydrocarbon and sulphur compounds that were present in the fuel a third party performed a chemical analysis of the fuel. 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 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 mass PPM of sulphur. Any hydrocarbon or sulphur compounds which are not listed in the analysis summaries of
Table 9 and Table 10 were not present in significant quantities. The results of this analysis are presented in Table 9 and Table 10 below. No analysis was performed to determine the specific composition of FUEL V and FUEL C since the small concentration of additive that was added would not cause a significant change in composition when compared to the FUEL H.

Table 9: Composition of LPG FUEL P Used in This Study

<table>
<thead>
<tr>
<th>Hydrocarbon Content of Fuel</th>
<th>Weight %</th>
<th>Sulphur Content of Fuel</th>
<th>Sulphur mass ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>&lt;0.01</td>
<td>Carbonyl Sulphide (COS)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.11</td>
<td>Methanethiol (Methyl Mercaptan)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Propene</td>
<td>0.05</td>
<td>Ethanethiol (Ethyl Mercaptan)</td>
<td>7</td>
</tr>
<tr>
<td>Propane</td>
<td>96.39</td>
<td>Iso-Propanethiol</td>
<td>0</td>
</tr>
<tr>
<td>IsoButane</td>
<td>3.22</td>
<td>ThioPhene/sec-Butanethiol</td>
<td>0</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.23</td>
<td>DiMethyl Disulphide (DMDS)</td>
<td>0</td>
</tr>
<tr>
<td>IsoPentane</td>
<td>&lt;0.01</td>
<td>Unknown C6 Sulphur Compounds</td>
<td>0</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>&lt;0.01</td>
<td>Unknown C7 Sulphur Compounds</td>
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<td>2-Methylpentane</td>
<td>&lt;0.01</td>
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<td></td>
</tr>
<tr>
<td>n-Hexane</td>
<td>&lt;0.01</td>
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</tr>
</tbody>
</table>

Table 10: Composition of LPG FUEL H Used in This Study

<table>
<thead>
<tr>
<th>Hydrocarbon Content of Fuel</th>
<th>Weight %</th>
<th>Sulphur Content of Fuel</th>
<th>Sulphur mass ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
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<td>Carbonyl Sulphide (COS)</td>
<td>28</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.81</td>
<td>Methanethiol (Methyl Mercaptan)</td>
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<tr>
<td>Propene</td>
<td>0.04</td>
<td>Ethanethiol (Ethyl Mercaptan)</td>
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</tr>
<tr>
<td>Propane</td>
<td>95.79</td>
<td>Iso-Propanethiol</td>
<td>1</td>
</tr>
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<td>IsoButane</td>
<td>1.17</td>
<td>ThioPhene/sec-Butanethiol</td>
<td>1</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.69</td>
<td>DiMethyl Disulphide (DMDS)</td>
<td>2</td>
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<tr>
<td>IsoPentane</td>
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<td>Unknown C5 Sulphur Compounds</td>
<td>7</td>
</tr>
<tr>
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<td>Unknown C7 Sulphur Compounds</td>
<td>1</td>
</tr>
<tr>
<td>2-Methylpentane</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-Hexane</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.4 Fuel Injector Groups

Five fuel injector groups were used in this study to determine the effects of fuel composition or injector construction on the durability or function of LPG fuel injectors. These five groups are described as follows:
FUEL P - Standard seat fuel injectors, mileage-accumulated using FUEL P
FUEL H - Standard seat fuel injectors, mileage-accumulated using FUEL H
FUEL C - Standard seat fuel injectors, mileage-accumulated using FUEL C
FUEL V - Standard seat fuel injectors, mileage-accumulated using FUEL V
FUEL H-TiN - Titanium Nitride seat fuel injectors, mileage-accumulated using FUEL H

The designation describes which fuel was run through the injector during mileage accumulation. All injector sets were emission tested while operating on "FUEL P". This allowed the condition of the fuel injector to be the only variable during the emission tests.

4.5 Vehicles Used in the Study.

The vehicles used for this study were of model years 1998-1999. All vehicles used the 5.2L V8 engine with the Type-1 liquid LPG PFI fuel system installed. The details of these vehicles are summarized in the vehicle information matrix found in the Appendix F: Description of Vehicles and Injectors Used in Testing.

4.6 Mileage Accumulation Procedure

Each set of injectors was mileage-accumulated for a total of 6,400 km on their specified fuels while mounted in similar vehicles with identical engines. These vehicles were driven on a specified driving route of 81.5 km. This route was based on the mileage accumulation route used by Transport Canada for vehicle testing. It is designed to expose the vehicle to speeds and loads similar to those that are typical for fleet type vehicles. The route consisted of both city and highway driving with an average speed 55 km/h. Generally each vehicle was driven through the route twice and was allowed to sit for at least 30 min before being driven again. Although the maximum fuel system hot soak temperature is reached after 45 minutes, 30 minutes was chosen as it would permit an opportunity for the deposits to form and speed up the mileage accumulation procedure. Each vehicle was driven in a similar manner and all vehicles were exposed to the same number of hot soaks.
4.7 Emissions Testing Procedure

To investigate only the effects of the injectors' condition on emission performance a single van was used as a test bed for all injector sets. Vehicle #4 (mileage accumulation vehicle for FUEL P VIN# WK134597) was used as the emission test vehicle.

To determine the baseline emissions for a new set of fuel injectors three EPA-75 FTP tests were performed before the mileage accumulation had begun. These tests were performed with the emission testing vehicle operating on fuel "P" using the fuel injector group FUEL P. The results from these tests are designated 0-KM in all figures. All fuel injector groups, except those of group FUEL H-TiN, had similar average initial leakage rates and flow rates to those of the FUEL P fuel injector group. Due to this it was assumed that the results of the 0-KM emission tests were indicative of the initial FTP emission performance of all of the fuel injector groups.

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 from the mileage accumulation vehicle and mounted in the emission testing vehicle for emission 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 emission testing.

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

Once each fuel injector set was installed in the emission-testing vehicle it was test driven by a technician to insure that it was operating correctly. The vehicle was then driven to the emission 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. This preparation was completed to insure that the vehicle had operated under all of the operating conditions that were expected during the FTP test. This allowed the engine computer to optimize the pulsewidth of the fuel injectors for stoichiometric operation for each engine operating condition. This optimization was required since the flow rates of the new fuel injector group may have differed from the previous group that had been installed and tested. This procedure insured that the vehicle would produce the lowest emissions possible for the given fuel injector group.

4.7.1 FTP EPA-75 Emissions Testing

Each vehicle soaked for at least 12 hours at room temperature prior to the EPA-75 FTP emission test. During the FTP tests both the exhaust emissions and engine variable data were recorded. The soaking and testing procedure was repeated at least twice more to provide at least three independent FTP tests (a total of five FTP were performed for the FUEL P fuel injector set). Each FTP Test involved traveling a total of 17.66 km on the specified speed profile. The speed profile used in the EPA-75 FTP tests is shown in the following figure:
4.7.2 Cold Start and Idle Emissions Tests

Following the EPA-75 FTP emission tests 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 three EPA-75 FTP tests and three “Cold Start and Idle” tests the vehicle was driven back to the research centre at both highway and city speeds to install the next injector set and fuel rail.

It should be re-iterated that all emission tests were performed while the vehicle was operating on FUEL P. The designations within the results of the emission tests designate which fuel was used to mileage-accumulate the fuel injector set. The only variable in the emission tests was the condition of the fuel injectors.
4.8 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.

The standard leak testing method, which is used for new injectors, involves purging the injector with compressed air while cycling the injector before leak testing, and purging and cycling again between each leak testing trial. To provide reliable leakage rate results for new fuel injectors the purging procedure was incorporated to clear any cutting or cooling fluids that may remain from machining operations. If any liquid remains in the injector prior to leak testing it may assist in sealing the injector and affect the leakage rate value observed.

However the purging component of the leakage rate test was eliminated for this study since the purging of a mileage-accumulated fuel injector could result in damage of any deposits that may have formed within the injector. The deposits could be dislodged by the high-speed passage of compressed air over the sealing band of the injector when it is opened or the deposits could be damaged when the injector is cycling dry. Dry cycling results in a greater impact force between the injector needle and seat when compared to normal operation as no liquid is present within the injector to dampen the motion of the needle. The deposits could be at an even greater risk of damage during testing as compared to normal operation as they may have become brittle without the constant contact with fuel once the fuel injector is removed from the fuel system.

The elimination of the purging process 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 results.
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 used to determine a leakage rate with the same Furness Controls FCO90 test rig that was used in the initial leakage rate testing.

For each test two new O-rings were installed on each injector and these were lubricated with light oil. The injector was then mounted into the test rig and held in place with a locking collar and the test cycle was started. This automated procedure involves pressurizing both the test injector and the standard sealed injector with nitrogen at 300 kPa for 5-seconds. The rate of pressure change between the two injectors is then compared during the 5-second test cycle. Using the rate of pressure change a leakage value is calculated by the instrument using the following formula:

\[
\frac{(V + 14\, cc) \cdot \frac{\Delta P}{\Delta t}}{10340} = cc/min
\]

\(V\) = volume of test rig and component [cm\(^3\)]. This value was calculated by others for the fuel injector and test rig that was used. This value was programmed into the instrument and incorporated into the leakage rate calculation that was performed by the instrument.

\(14\, cc\) = Internal volume of leak detector [cm\(^3\)]

\(\frac{\Delta P}{\Delta t}\) = Measured differential pressure [mm H\(_2\)O/min]

10340 = Atmospheric pressure [mm H\(_2\)O]

For each injector the pressurizing and 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 final leakage rate values for each injector.

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4.9 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 and seats of the injectors. For a comparison purposes additional high mileage LPG fuel injectors and high mileage gasoline fuel injectors of the same bottom feed design that had been used in other vehicles were cut open and photographed as well.

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. A schematic of the type of fuel injector that was used in this study is shown in Figure 3.

![Fuel Injector Schematic](image)

Figure 3: Fuel Injector Schematic

All eight injectors from the FUEL H group and three injectors from groups FUEL P, FUEL C, FUEL V and FUEL H-TiN were opened and images of the tips of these injector needles and injector seats were obtained using a Scanning Electron Microscope (SEM). The injectors to be photographed from groups FUEL P, FUEL C, FUEL V and FUEL H-TiN were chosen based on the average leakage rates that were obtained during the final leak testing. The two injectors with the highest final leakage rates and the fuel
injector with the lowest final leakage rate for each fuel injector set were disassembled and their needles were scanned with the SEM.

As a comparison, components from high mileage LPG and gasoline bottom feed fuel injectors that were not mileage-accumulated in this study were scanned as well. The LPG fuel injector needles were removed from a high-mileage a liquid port-injection LPG vehicle that had operated on Southern Ontario LPG for approximately 60,000 km. The gasoline fuel injector needles were removed from a gasoline-fuelled vehicle with 55,000 km. Comparing fuel injectors of the same design that were mileage-accumulated using gasoline against high mileage LPG fuel injectors provided insight into the effect of high mileage operation on fuel injectors that were fuelled with an additive treated fuel.

Images of the fuel injector components were obtained using two different methods. The images that appear as “negatives” (dark background) were obtained using a backscatter electron detector. These images were obtained by collecting the electrons that were emitted from the sample in the direction of the electron source. These electrons tend to be emitted from organics. The other type of image was obtained using a standard detector. This system detects electrons that are glanced off the sample surface in various directions. This type of detection is best for determining the relief of a surface.

Prior to photographing, each needle was cleaned using an ultrasonic bath containing ethanol to remove any contaminating particles that were picked up during the disassembly process. No fuel injector needle was cleaned in the bath for more than 20 seconds. This short cleaning time should not affect the deposits on the injector as ultrasonic baths combined with strong solvents have been shown to remove all fuel injector deposits only after a minimum of 30 minutes of cleaning [22].

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 injectors 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. All of the EDS analysis’s shown in Appendix E: SEM and EDS Data describe any constituents that were not found in the base metal of stainless steel.
CHAPTER 5: PRESENTATION OF RESULTS FROM THE STUDY OF FUEL INJECTOR DURABILITY

The following are typical results that were obtained during this study. They have been separated into results from: change in fuel injector leakage rate, emissions, scanning electron microscope and electron dispersion spectroscopy. The features of typical results will be discussed in this section. A detailed analysis of the results will be described in Chapter 6: Discussion and Analysis of Results For Fuel Injector Durability Study.

5.1 Change in Injector Leakage Rates

The change in fuel injector leakage rate provided the best data on how each of the fuels affected the fuel injector's performance since the emission data is a secondary method of measuring the performance of the fuel injectors. As shown in Figure 4 the change in leakage rate for all eight of the mileage-accumulated injectors was recorded as the difference between initial and final leakage rates. Data was tabulated in this manner for each fuel injector group. These figures show the change in leakage rate in cubic centimeters per minute as indicated by the solid bar and the left-hand axis. As well each of these figures show the standard deviation of the final leakage rate tests as indicated by the outlined bar and the right hand axis. Below each bar the injector number, injector group letter and cylinder location number provide the specific details of each injector. Detailed tables and plots of all the leakage data that was recorded is included in Appendix A: Fuel Injector Leakage Data.
Some fuel injectors showed a negative change in leakage rate. This was due to the leakage rate of the injector decreasing following the mileage accumulation process. This was a result of the "coining" of the injector. After manufacturing, the surfaces of the valve needle and seat do not mate exactly. This leads to an initial leakage rate. Coining occurs as the fuel injector is operated and these two parts repeatedly contact each other. During this contact the microscopic machining lines on the contact surfaces of the two mating parts wear down into a smooth surface resulting in a superior seal across the valve. This results in a lower leakage rate following some mileage accumulation.

The data for all injector groups showed high standard deviations between each trial. It was assumed that this was due to the fact most of the values that were recorded were quite close to the 0.2 cc/min minimum accuracy limit of the leak rate testing instrument. It should be noted that the above values are changes in leakage rate and thus the values are not limited by the 0.2 cc/min minimum accuracy of the leak testing instrument.
5.2 Emission Results

5.2.1 Bag Average FTP Tailpipe Emissions

Typical results for the average FTP tailpipe emissions that were recorded at DaimlerChrysler's Jeep Truck Engineering Facility in Detroit, MI, USA are shown below in Figure 5. It should be noted that the results of the individual trials have been normalized against the greatest value for each constituent that was recorded in a single trial to protect the confidential emission data.

![Graph showing normalized HC emissions for different fuel injector groups and stages of FTP test.]

Figure 5: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average HC Emissions for all Fuel Injector Groups

The average results for all five mileage-accumulated injector groups are shown on the same figure with the results from the initial 0-KM tests. For injector groups FUEL H, FUEL C, FUEL V, FUEL H-TiN and 0-KM the average results were obtained from three
independent FTP test for each injector group. The average results for the FUEL P injector group were obtained from five independent FTP tests.

For a given fuel injector group the first three bars in the lower section of the figure represent the constituent concentration for “cold bag 1”, “stable bag 2” and “hot bag 3” results respectively. The constituent concentrations found in each bag was determined at the conclusion of the FTP test. The results from the three sections of the test are added together in a weighted average that is represented by the fourth darker colored bar labeled “weighted”. The values for each of the lower bars can be read from the left axis. The wider bars at the top of the figure represent the standard deviations between the tests that were used in the average values below them. All other data that was recorded has been included in Chapter 15: Appendix B: EPA-75 FTP Emissions Results.

5.2.2 Transient Engine Emissions Recorded During FTP Tests

Figure 6 is an example of the transient emission data that was recorded at one-second intervals during the FTP tests. The samples for these emission results were obtained from upstream of the catalytic converter and are thus considered to be a record of “engine-out” emissions. These exhaust samples were analyzed during the FTP test using the same emissions bench that was then used to determine the FTP bag results at the conclusion of the test. The five lines with symbols represent the average emission traces for each fuel injector group (transient values were not recorded during the 0-KM testing). The values of emissions can be read from the left axis. The single dark line represents the average vehicle speed during the FTP test. This value can be read from the right hand axis.

5.2.3 Cold Start and Idle Emissions Tests

Figure 7 is an example of the transient emission data that was recorded at one-second intervals during the “Cold Start and Idle” tests. The samples for these emission results are were obtained from upstream of the catalytic converter and are thus considered to be a record of “engine-out” emissions. The five lines with symbols represent the average emission traces for each fuel injector group. The values of emissions can be read from the left axis.

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Figure 6: Transient Comparison of Engine Out HC Emissions for all Injectors: Hill 1 EPA-75 t=115-140
Figure 7: Transient HC Emissions from Cold Start and Idle Tests t=40-80
5.3 Scanning Electron Microscope Analysis

Figure 8 shows a typical back-scatter scanning electron microscope image of the bottom tip of a fuel injector needle. The fuel injector schematic shown in Figure 3 shown on page 30 describes the location of this component within the fuel injector. These scanning electron microscope photographs were taken at Siemens Automotive Group’s fuel injector development facility in Newport New., VA, USA and The University of Windsor in Windsor, ON, Canada.

Some features of this image are common to all SEM images of fuel injector needles. These features have been detailed in Figure 8.

![Figure 8: Typical FUEL H Injector Needle with Descriptions](image)

The sealing band is the location where the needle contacts the seat to form a seal. It can be identified in the SEM pictures by the absence of machining lines. During the “wearing in” phase of the injector the rough machined surface is worn into a smooth sealing surface as the needle repeatedly contacts the seat of the injector.
As mentioned above the backscatter image of Figure 8 tends to show the organic compounds more clearly. Figure 9 shows a typical standard detector SEM image of an injector needle. Again the deposits and sealing band are visible, but this type of image shows more of the inorganic contaminants and surface relief.

Figure 9: Typical Fuel H-TiN Injector Needle

Figure 10 below shows a typical back-scatter scanning electron microscope image of the inside of a fuel injector seat. The fuel injector schematic shown in Figure 3 describes the location of this component within the fuel injector.

Some features of this image are common to all SEM images of fuel injector seats. These features have been detailed in Figure 10.
Figure 10: Typical FUEL H Injector Seat

Figure 11 shows an SEM image of the inside of a fuel injector seat using a standard electron detector.

Figure 11: Typical FUEL C Injector Seat
5.4 Electron Dispersion Spectrum Analysis

Figure 12 shows the spectrum of energy frequencies that were emitted from the surface of fuel injector needle #11 during electron dispersion analysis. This output spectrum is then interpreted using a computer program and set of tabulated results related to the intensity of each frequency of energy that is produced. These tabulated values provide an estimate of the composition of deposit under analysis. These analyses were unable to accurately measure the presence of carbon or hydrogen. The EDS analyses were performed at Siemens Automotive Group’s fuel injector development facility in Newport New, VA, USA and The University of Windsor in Windsor, ON, Canada.

![Example of Electron Dispersion Spectrum](image)

Figure 12: Example of Electron Dispersion Spectrum

Table 11 below shows the typical tabulated results of an electron dispersion spectrum analysis. This data shows that since the deposit under analysis was very thin much of the EDS signal can be related to the base metal of the needle. To estimate the composition of the deposit elements such as iron, chromium and silicon should be ignored as they are also found in the stainless steel base metal of the needle. Salt components such as
calcium, chlorine, potassium and sodium should be ignored as well as they may have originated from sweat found on the hands of whomever performed the analysis.

Table 11: Average Electron Dispersion Spectrum Analysis of Fuel Injector Needle Ring Deposits

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight%</th>
<th>Element</th>
<th>Weight%</th>
<th>Element</th>
<th>Weight%</th>
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</tbody>
</table>
CHAPTER 6: DISCUSSION AND ANALYSIS OF RESULTS FOR FUEL INJECTOR DURABILITY STUDY

6.1 Change in Fuel Injector Leakage Rate

The change in leakage rate of the fuel injectors following the mileage accumulation is the best indicator of how the different fuels have affected the performance of the injectors. The results presented in Figure 13 through Figure 17 clearly show that operating on FUEL H has lead to the greatest increase in leakage rate. Comparing the average change in fuel injector leakage rates for all injectors in a group as shown Table 12 it can be seen that injectors from FUEL H-TiN resulted in the next largest increase in leakage rate. These were followed by injectors from groups FUEL V, FUEL C, and finally FUEL P in order of decreasing change in leakage rate.

<table>
<thead>
<tr>
<th>Fuel Injector Group</th>
<th>Initial Leakage Rate [cc/min]</th>
<th>Final Leakage Rate [cc/min]</th>
<th>Change in Leakage Rate [cc/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUEL H</td>
<td>0.32</td>
<td>0.79</td>
<td>1.11</td>
</tr>
<tr>
<td>FUEL H-TiN</td>
<td>0.21</td>
<td>0.46</td>
<td>0.25</td>
</tr>
<tr>
<td>FUEL V</td>
<td>0.32</td>
<td>0.54</td>
<td>0.22</td>
</tr>
<tr>
<td>FUEL C</td>
<td>0.32</td>
<td>0.39</td>
<td>0.07</td>
</tr>
<tr>
<td>FUEL P</td>
<td>0.32</td>
<td>0.37</td>
<td>0.05</td>
</tr>
</tbody>
</table>

It was not expected that the fuel injectors from the FUEL P group would result in such small increases in leakage rate. This was unusual as a significant quantity of deposits were found on the needles of these injectors during the SEM analysis as was shown in Section 6.5 on page 72.

Comparing the effects of the type fuel, as opposed to fuel injector design, on average change in fuel injector final leakage rate it can be said that the fuel injectors from group FUEL H were most adversely affected, followed by FUEL V, FUEL C and FUEL P. The change in fuel injector leakage rate data is presented in Figure 13 through Figure 17. Note
that the leakage rate scale of Figure 13 covers a greater range when compared to the other figures.

By comparing the results for injectors in the group FUEL H-TiN against those of group FUEL H it can be seen that the use of the titanium nitride coated seat lead to an improvement in both change in leakage rate and final leakage performance. It should be re-iterated that these injectors were mileage-accumulated using identical fuels and the only differences of the FUEL H-TiN injector group when compared to the FUEL H group are the lower average initial leakage rate and the use of a titanium nitride coated seat.

![Bar Chart]

**Figure 13:** Change in Fuel Injector Leakage Rate Over 6 400km "FUEL H"
Figure 14: Change in Fuel Injector Leakage Rate Over 6 400km "FUEL V"

Figure 15: Change in Fuel Injector Leakage Rate Over 6 400km "FUEL C"
Figure 16: Change in Fuel Injector Leakage Rate Over 6 400km "FUEL H" with TiN Seat Fuel Injectors

Figure 17: Change in Fuel Injector Leakage Rate Over 6 400km "FUEL P"
Since fuel injectors with different initial leakage rates were used in this study the data recorded could provide insight into whether the initial fuel injector leakage rate is related to the final change in leakage rate. The data for each fuel injector group was analyzed individually and showed no trends relating initial fuel injector leakage rate to the change in leakage rate.

In summary, the fuel injectors from group FUEL H showed the greatest leakage rate increase for all injectors tested. The use of a titanium nitride coated seat within an injector, as with injectors from group FUEL H-TiN, improved the sealing ability of the injector following operation of 6 400 km. As well the use of FUEL C, FUEL V or FUEL P lead to an improvement in injector sealing ability following operation for 6 400 km when compared to the results from FUEL H.

6.2 FTP Emission Results

6.2.1 FTP NMHC Emissions Results

All of the fuel injector groups, except the unusual results from the FUEL P injectors, showed an increase in FTP weighted NMHC emission level compared against the 0-KM fuel injector group. Significant differences between the fuel injector groups can be seen as well in the FTP NMHC emission results found in below. The tailpipe emission results from the FTP EPA-75 tests show a clear improvement in non-methane hydrocarbon emissions when the injectors are mileage-accumulated with additive treated FUEL C and FUEL V compared against the non-additive treated FUEL H. Figure 18 below shows the relative FTP NMHC emissions between each of the injector sets that were tested. These results show that the use of additive C or V during mileage accumulation lead to a 53% or 55% reduction respectively in bag 1 non-methane hydrocarbon emissions.
The FUEL P injector group results show that mileage accumulating a set of injectors using a fuel that is composed of simpler hydrocarbons with lower sulphur content can lead to a dramatic reduction in the FTP Bag 1 NMHC emissions. However it must be noted that since the vehicle that was used to mileage-accumulate the FUEL P injectors was also used as the emission testing vehicle, this group of injectors was not removed and reinstalled in the emission testing vehicle as had been done with the other injector groups. It is unknown if or how this could have lead to the dramatic and consistent reduction in FTP Bag 1 NMHC emissions. Since the average final leakage rate of the FUEL P injectors was similar to that from the FUEL C injector group it was expected that the FTP Bag 1 NMHC emissions would have been similar.

Excluding the unusual results from the FUEL P injectors it is believed that the FTP Bag 1 NMHC emissions are related to the fuel injector leakage rate. This weak correlation is demonstrated in Figure 19. It can be seen that it heavily depends on the results from the
FUEL H fuel injector group. The proposed connection is that fuel from leaking fuel injectors accumulates in the intake manifold during the 12-hour cold soak period of the FTP prior to start-up. The procedure of the current study did not include in-cylinder samplings prior to start up to confirm the hydrocarbon concentration at the conclusion of the cold soak. However the data presented in section 6.3: Transient Engine Emissions Recorded During FTP Tests indirectly supports the following hypothesis by tracing a large hydrocarbon peak during the start of the cold start.

Figure 19: Fuel Injector Final Leakage Rate and FTP Bag 1 NMHC Correlation

During start-up some of the fuel that has accumulated in the intake manifold and cylinders was combined with additional fuel metered by the injectors and this is pulled into the cylinder through the intake valve. This rich in-cylinder mixture is beyond flammability limits and will not ignite. With each engine cycle more of the accumulated fuel is removed from the intake manifold resulting in a less-rich in-cylinder mixture. Eventually a flammable in-cylinder mixture is provided, allowing the engine to start. Until the engine catches this raw fuel is pumped through the engine and is recorded in the
NMHC emissions trace. A correlation between bag 1 FTP NMHC emissions and cold start cranking time was found and is demonstrated in Figure 20 below. This supports the hypothesis that the longer time required to remove the accumulated fuel from the intake manifold and provide a combustible mixture to the cylinder results in a greater amount of NMHC concentration in the exhaust.

![Graph showing the correlation between FTP Bag 1 NMHC and engine cranking time](image)

**Figure 20: Cold Start Cranking Time and FTP Bag 1 NMHC Correlation**

### 6.2.2 FTP CO Emissions Results

All of the fuel injector groups except those from the FUEL C group showed an increase in FTP weighted CO emission level compared against the 0-KM fuel injector group. Significant differences between fuel injector groups can be seen in the FTP CO emission results found in Figure 21 shown below:
Figure 21: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average CO Emissions for all Injector Groups

It is important to compare the results of the FUEL H fuel injectors against those that were mileage-accumulated on additive treated fuels to determine the effects of the additives. A 24% decrease in the level of weighted average FTP CO emissions can be seen for the injector group FUEL C relative to the FUEL H injectors. Conversely, the injectors from the FUEL V group showed a 32% increase in the weighted average FTP CO emissions relative to the emissions of the FUEL H injectors.

Comparing the results from injector groups FUEL H and FUEL H-TiN to determine the affect of the titanium nitride coated seat showed that the weighed FTP CO emission level remained within 3% of each other.

Again it should be reiterated that all of these injectors were operated on the same fuel during emissions testing. Thus any variation in the emission results between fuel injector sets is only due to the change in injector performance.
6.2.3 FTP CO₂ Emissions Results

The FTP weighted CO₂ emissions as detailed below in Figure 22 show the emission results for all fuel injector groups.

![Graph showing normalized CO₂ emissions for different fuel injector groups and stages of FTP test.

Figure 22: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average CO₂ Emissions for all Injector Groups

Only the FUEL C fuel injector group showed a significant difference in CO₂ emission levels, showing an 11% decrease in weighted CO₂ compared against those from the 0-KM injector group. The weighted CO₂ emission levels for all other fuel injector groups were all within 5% of the lowest levels.

6.2.4 FTP NOₓ Emissions Results

The FTP weighted NOₓ emissions as detailed below in Figure 23 show the emission results for all fuel injector groups.
Figure 23: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average NOx Emissions for all Injector Groups

All of the fuel injector groups showed an increase in FTP weighted NOx emission level compared against the 0-KM fuel injector group. Significant differences between fuel injector groups can be seen for the FTP NOx emissions from Bag 3. These lead to differences in the weighted NOX results as the results from Bags 1 and 2 are similar. When comparing the results from FUEL H fuel injectors against those that were mileage-accumulated on additive treated fuels. A 122% increase in the level of Bag 3 FTP NOx emissions can be seen for the injector group FUEL C relative to the FUEL H injectors. Conversely, the injectors from the FUEL V group showed a 9% decrease in the Bag 3 FTP NOx emissions relative to the emissions of the FUEL H injectors.

Comparing the results from injector groups FUEL H and FUEL H-TiN showed that the Bag 3 FTP NOx emissions increased 91% with the use of titanium nitride coated seats within the fuel injectors.
The FUEL P injector group results showed that mileage accumulating a set of injectors using a fuel that is composed of simpler hydrocarbons with lower sulphur content lead to a reduction of 32% in the FTP Bag 3 NOₓ emissions.

6.2.5 FTP MHC Emissions Results

The results of the FTP methane hydrocarbon emissions showed no significant variation between each of the fuel injector groups that were tested.

6.3 Transient Engine Emissions Recorded During FTP Tests

The transient emission results described below are the averages from all of the FTP trials that were performed for each fuel injector group.

6.3.1 Transient HC Concentrations Recorded during FTP Tests

The traces of the transient engine exhaust hydrocarbon concentrations at start up all showed large hydrocarbon peaks as shown in Figure 24 below.
Figure 24: Transient Comparison of Engine Out HC Emissions for all Injectors: Hill 1
EPA-75 t=0-35

The widths of these peaks corresponded to the cranking times required to start the engine as shown by the strong correlation in Figure 25. The widths of these peaks were defined as the time required for the engine exhaust HC emissions to drop below 300 PPM after the start of engine cranking.
Figure 25: Correlation Between Transient HC Peak Time and Starting Time

When analyzing the transient traces of the engine exhaust HC concentrations during FTP tests shown in Figure 24 above as well as Figure 26 below it can be seen that the FUEL H injectors consistently result in higher HC concentrations during the first 80-seconds of the trace.
Figure 26: Transient Comparison of Engine Out HC Emissions for all Injectors: Hill 1 EPA-75 t=35-80

These results are consistent with both the high leakage rates and the high FTP Bag 1 HC tailpipe concentrations for this injector group. Comparatively the FUEL P injectors show the lowest transient engine exhaust HC concentrations during the FTP test. Again this is consistent with the both the low leakage rates and the low FTP Bag 1 HC tailpipe emissions for this injectors group. By averaging the pulse width of the injectors during an idle period of the FTP for injector sets FUEL H and FUEL P it was noted that there was no difference in how these injectors were being actuated for a given set of operating conditions. Therefore the engine exhaust HC concentration results are due only to the condition of the injectors, the engine control system is not actuating them at different rates.

When examining the transient engine exhaust HC concentration for the injectors that ran on the two fuel additives, we can see that the injectors from FUEL C resulted in higher HC concentrations when compared against those of FUEL V. This is contradictory to
what is expected based on the final leakage rate 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 transient HC emissions of injectors from FUEL C even though they had lower final leakage rates.

Comparing the transient HC FTP concentrations for the injector groups FUEL H and FUEL H-TiN of Figure 24 and Figure 26 we can again determine the effect of using injectors with titanium nitride coated seats. The results show similar HC peaks but the results from the FUEL H-TiN injectors drop at a faster rate. This is expected based on the leakage data that shows that the injectors from the FUEL H group had a higher final leakage rate than those from the FUEL H-TiN.

6.3.2 Transient Air to Fuel Ratio Recorded during FTP Tests

The values of the air to fuel ratios were calculated based on the exhaust constituent concentrations. The values shown below are not accurate since they were calculated by the emissions test bench assuming that the fuel used was gasoline instead of LPG. However since this practice was consistently applied during all tests the data can be used to compare the AFR values between the fuel injector groups. Thus when comparing two AFR values on the following figures, a lower value is considered to be a richer mixture than any value above it.

The transient AFR trace from the FTP tests shown below in Figure 27, Figure 28 and Figure 29 indicated that the injectors that were operated on FUEL H consistently showed a fuel rich AFR where as all other injector sets showed similar air to fuel ratios throughout the transient data.
Figure 27: Transient Comparison of Engine Out AFR for all Injectors: Hill 1 EPA-75 
\( t=0-35 \)

Figure 28: Transient Comparison of Engine Out AFR for all Injectors: Hill 1 EPA-75 
\( t=35-80 \)
Figure 29: Transient Comparison of Engine Out AFR for all Injectors: Hill I EPA-75 t=115-140

It is believed that this is due to the fact that the high final leakage rate of the FUEL H injectors allowed fuel to leak past the seal while the injectors were closed. This resulted in the supply of excess fuel to the manifold during operation resulting in a more rich mixture being delivered to the combustion chamber.

6.3.3 Transient CO Concentration Recorded during FTP Tests

The transient CO concentration results recorded during the FTP tests show no significant variation in results between fuel injector groups.

6.3.4 Transient NOx Concentration Recorded during FTP Tests

The transient NOx concentration results recorded during the FTP tests show no significant variation in results between fuel injector groups.
6.3.5 Transient CO₂ Concentrations Recorded during FTP Tests

The transient CO₂ concentration results recorded during the FTP tests show no significant variation in results between fuel injector groups.

6.3.6 Transient O₂ Concentrations Recorded during FTP Tests

The transient O₂ concentration results recorded during the FTP tests show no significant variation in results between fuel injector groups.

6.4 Transient Engine Exhaust Emissions Recorded During Cold Start and Idle Tests

To analyze the engine emissions of the vehicle during a cold start a set of cold start and idle tests were performed. These tests eliminated the variation in engine speed required during the FTP tests while the vehicle was following the speed profile. This allows the performance of the injectors to be analyzed when they are operating in a steady state manner.

6.4.1 Transient Engine Exhaust HC Concentrations From Cold Start and Idle Tests

Similar to the transient results from the FTP test results from these tests shown below in Figure 30 and Figure 31 show HC peaks for all fuel injector groups that existed for lengths of time that were related to the cold start times of each fuel injector group.
Figure 30: Transient HC Emissions from Cold Start and Idle Tests t=0-40

Figure 31: Transient HC Emissions from Cold Start and Idle Tests t=40-80
Injectors from FUEL P show the smallest peak and the use of fuel injectors from groups FUEL H and FUEL H-TiN lead to the longest peaks. This was expected as these results relate to the FTP Bag 1 results.

6.4.2 Transient Engine Exhaust CO Concentrations From Cold Start and Idle Tests

The exhaust CO concentrations that were recorded during the cold start and idle tests are shown in below in Figure 32 and Figure 33.

Figure 32: Transient CO Emissions from Cold Start and Idle Tests t=0-40
Figure 33: Transient CO Emissions from Cold Start and Idle Tests t=40-80 seconds

These results show a rise in CO emissions during start up due to initial misfiring before the engine catches. The results show that while operating with the injectors from the FUEL P group the engine started with the least amount of cranking time resulting in the earliest CO concentration increase. The use of this set of injector also resulted in the smallest CO peak implying that there were the fewest misfires before proper engine ignition.

Conversely, the results from the FUEL H injectors required the longest cranking time before a rise in CO was shown. As well, the CO peak for this injector group was quite large showing a high level of misfires during startup. Although the injectors from the FUEL V group showed an early ignition use of these injectors lead to the most significant CO peak demonstrating a great number of misfires during startup. The high CO level for the FUEL V injector group continued until t = 45 s. At this time, there was a sudden drop in CO concentration. It is believed that this was due to the second fuel pump shutting down as it is programmed to do during startup. The results from the transient AFR data
show that while operating with the FUEL V injectors the engine was running rich until the $t = 45$ s. This implies that the use of the two fuel pumps during startup lead to the injectors supplying an excess amount of fuel, leading to rich operation and high CO levels.

6.4.3 Transient Engine Exhaust NO$_X$ Concentrations From Cold Start and Idle Tests

Figure 34 and Figure 35 below detail the cold start and idle test transient engine exhaust NO$_X$ concentrations for all fuel injector groups. Similar to the CO emissions the initial rise in NO$_X$ levels indicated the start of combustion or misfire.

![Graph](Image)

Figure 34: Transient NOx Emissions from Cold Start and Idle Tests $t=0$–40 seconds
Figure 35: Transient NOx Emissions from Cold Start and Idle Tests t=40-80 seconds

Again these results show that the engine started sooner when it was operated using the FUEL P fuel injectors compared to when it was operated using the FUEL H fuel injectors. At $t = 15$ s the NOx levels for each fuel injector group begin to stabilize. The injectors from the FUEL V group tend to lead to high NOx concentrations. Those from the FUEL C group lead to low NOx concentrations. All other fuel injector groups are similar, producing NOx concentrations that are between those of FUEL V and FUEL C. The high NOx concentrations resulting from the use of the FUEL V injectors is unusual as this is combined with high HC, CO and a rich AFR. Conversely, the low NOx concentrations resulting from the operation of the FUEL C fuel injectors are combined with reduced HC, CO and a lean AFR. Again, this is an unusual combination. An engine that is producing low NOx emissions is usually running with a rich AFR and would therefore produce high HC and CO emissions.
6.4.4 Transient Engine Exhaust CO₂ Concentrations From Cold Start and Idle Tests

The CO₂ exhaust concentrations recorded during the cold start and idle tests are presented below in Figure 36 and Figure 37.

Figure 36: Transient CO₂ Emissions from Cold Start and Idle Tests t=0-40 seconds
Figure 37: Transient CO2 Emissions from Cold Start and Idle Tests t=40-80 seconds

The timing of the initial rise in CO2 concentration further supports the hypothesis that the engine operating using the FUEL P fuel injectors started first and with fewer misfires. Conversely, these results show a slow and uneven start when the engine was operated while using the fuel injectors from group FUEL H. From t = 40 s it can be seen that the CO2 concentration is the highest for the FUEL H fuel injector group. It is believed that the excess fuel that these injectors were providing due to their high final leakage rate lead to a rich mixture that produced relatively more CO2 when compared to the other fuel injector groups. It was difficult to recognized this increase in CO2 from the transient FTP data due to the varying engine speeds.

6.4.5 Transient Engine Exhaust O2 Concentrations From Cold Start and Idle Tests
The O2 concentration results from the cold start and idle tests are shown below in Figure 38 and Figure 39.
Figure 38: Transient O$_2$ Emissions from Cold Start and Idle Tests t=0-40 seconds

Figure 39: Transient O$_2$ Emissions from Cold Start and Idle Tests t=40-80 seconds
These results show that the use of the FUEL P injectors lead to an early drop in $O_2$ concentration indicating a faster start. In comparison the results from the use of the FUEL H injectors showed the latest drop in $O_2$ concentration indicating the longest start time. At $t = 45$ s when the second fuel pump shuts down, a sudden drop in $O_2$ concentration for operation using injectors from the FUEL C group coincides with a rise in $O_2$ concentration for the results of the FUEL V fuel injector group. These results are expected since prior to $t = 45$ s the injectors from group FUEL C were operation lean, and those from the FUEL V group were operating rich leading to the corresponding changes in $O_2$ levels.

6.4.6 Transient Engine Exhaust AFR From Cold Start and Idle Tests

The AFR results from the transient cold start and idle test are presented Figure 61 and Figure 62 below.

![Figure 40: Transient AFR from Cold Start and Idle Tests $t=10-50$ seconds](image-url)
Figure 41: Transient AFR from Cold Start and Idle Tests t=40-80 seconds

Following start up it can be seen that the use of the injectors from the FUEL C group lead to the most lean mixture, followed by, in order of increasing richness, FUEL P, FUEL H-TiN FUEL H and FUEL V. Following the shut down of the second fuel pump at t=45s the AFR from the FUEL C group became more rich and the AFR from the FUEL V group leaned out. This lead to all injector groups operating at similar air to fuel ratios with only the injectors from FUEL H group operating consistently rich. It is believed that this consistent rich operation is due to the high final leakage of the FUEL H injector group.

6.5 Scanning Electron Microscope Photographs

Examples of the scanning electron microscope images that were obtained of the fuel injector needles and seats are shown in Figure 42 through Figure 63. Some additional images of fuel injector needles that were mileage-accumulated for other purposes are presented for comparative purposes.
6.5.1 Mileage-accumulated Fuel Injector Needles From this Study

A typical backscatter image of the needle of a fuel injector from the FUEL H group is shown in Figure 42. A deposit ring can be seen just downstream of the sealing band. Some areas of the deposit have been chipped away. It is unclear as to if this damage to the deposit occurred during standard operation of the fuel injector or if this was a result of the disassembly process.

![Figure 42: Typical FUEL H Injector Needle](image)

The worst example of fuel injector deposits was found on injector number 87 from the FUEL H injector group. Two types of deposit existed on this injector, which is shown in a standard detector SEM image below in Figure 43. Both the ring type deposit and a larger circular deposit were present on this fuel injector needle. The larger circular deposit was not found on any other fuel injectors. Part of this larger deposit extends into the sealing band area and extends upstream of the sealing band in one location.
This fuel injector was considered to have had a high initial leakage of 0.24 cc/min but even with this large deposit the average final leakage rate of this injector was only 0.92 cc/min. The worst final leakage rate that was recorded during this study was 2.34 cc/min for fuel injector #11, an injector with only a ring deposit.

Figure 44 below shows the typical SEM image of a fuel injector from the FUEL P group. Again this fuel injector needle shows a ring deposit downstream of the sealing band. Some sections of the deposit have been chipped away. It is not clear how this ring deposit affects the fuel injector leakage. Based on the appearance of the deposit it was expected that this injector would have a similar final leakage rate to the injector presented in Figure 42. However this is not the case, the injector below has a final leakage that is 77% less than the final leakage of the fuel injector shown in Figure 42.
Figure 44: Typical FUEL P Injector Needle

Figure 45 and Figure 46 below are images that were taken of fuel injector from groups FUEL C and FUEL V respectively. Both of these injectors show the smoothed sealing band area, but no deposits can be seen. This shows the effectiveness of the anti-deposit additives that were mixed with the fuel that was used to mileage-accumulate these fuel injectors. The slight color difference between the two images is due to different contrast settings used while obtaining the images.
Figure 45: Typical FUEL C Injector Needle

Figure 46: Typical FUEL V Injector Needle

Figure 47 below shows a typical standard detector SEM image of a fuel injector from the FUEL H-TiN group. The ring deposit is visible downstream of the sealing band as well as some staining on the downstream surfaces of the needle.
6.5.2 Mileage-accumulated Fuel Injector Seats From this Study

The fuel injector seat is the opposing part to the fuel injector needle that is used to form a seal with the needle of the fuel injector. Figure 48 shows a backscatter image of a typical fuel injector seat from the FUEL H group. Similar to the fuel injector needle a ring deposit can be seen down stream of the sealing band of the fuel injector seat. This image of the seat shows some deposit within the sealing band of the seat. Deposit in this area could significantly affect the sealing ability of the fuel injector and could be the explanation for the high final leakage rate for fuel injectors that were operated on this fuel during mileage accumulation.
Similar to the fuel injector needle from the FUEL P group the seat from this group shown in Figure 49 has a ring deposit downstream of the sealing band. However compared against the results from the fuel injectors from the FUEL H group the FUEL P injectors did not have any deposits within the sealing band. This may have contributed to lower final leakage rates that were found for the fuel injectors from group FUEL P.
Figure 50 and Figure 51 below show typical backscatter detector SEM images of fuel injector seats from groups FUEL C and FUEL V respectively. Both images show the distinct sealing band. However there was not a consistent ring deposit downstream of the band for either of these groups of fuel injectors. Similar to the fuel injector needles shown for these injector groups the seats from the FUEL C groups showed some deposits upstream, downstream and within the sealing band of the fuel injector seat. Comparatively the seats from the FUEL V group showed no deposits.

Figure 50: Typical FUEL C Injector Seat
Below, Figure 52 shows an example of a typical fuel injector seat from the FUEL H-TiN group. Again fuel injector seats from this group showed some deposits downstream of the sealing band similar to those found on the fuel injector seats from FUEL H.
What role did the fuel injector needle 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 fuel 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.

The hypothesis is that large deposits such as those found on the worst-case FUEL H fuel injector Figure 43 are in fact the primary source of the leakage that leads to poor start times and poor emission performance. However this hypothesis is not supported by the leakage data of these injectors. The fuel injector that appeared to have the greatest amount of deposits from Figure 43 showed a final leakage rate of only 1.02 cc/min following 6 400 km of driving. This was significantly smaller when compared to the worst final leakage rate of 2.99 cc/min found for injector 11. The needle of injector 11 appeared quite similar to the typical FUEL H fuel injector shown in Figure 42, no dramatic deposit was found. The leakage rate data of the FUEL H and FUEL P injectors and the emission data show that that there is little correlation between the extent of a deposit on an injector needle and its performance.

The next consideration would be that of the fuel injector seat. Ring deposits were found on the fuel injector seats that corresponded with those found on the injector needles. These can be seen in Figure 48 through Figure 52. The SEM photographs of the fuel injector seats provided the second half of the information that detailed the condition of the injector sealing band. The objective was to correlate the condition of the sealing band with the leakage rate increase and performance. The results of Figure 53 through Figure 57 show that no such correlation exists.
Figure 53: Clean Contact Band Fuel Injector 22, FUEL H, 0.38 cc/min

Figure 53 above shows an example of a clean contact band with no debris. Final leakage for this injector #22 is 0.38 cc/min. The next two injectors shown below in Figure 54 and Figure 55 have extensive debris within the contact band. These injectors also had high final leakage rates of 1.02 cc/ min and 2.99 cc/min respectively.

Figure 54: Contact Band with Debris Fuel Injector 87, FUEL H, 0.92 cc/min
The possibility of a correlation between contact band condition and leakage rate is eliminated when the results of Figure 56 are considered. This photograph shows injector 90 with extensive debris within the contact band however the final leakage rate of this injector is only 0.20 cc/min following 6 400 km of operation. This injector is from the FUEL P group, which also showed the lowest HC cold start emissions. To further support this lack of correlation Figure 57 shows the clean contact band of injector 10, however this injector showed a final leakage rate of 1.95 cc/min and this injector was from the FUEL H group, which was shown to have the highest cold start emissions of all the groups tested.
No correlation was found between the performance of an injector and the appearance of deposits on the needle, seat or contact band.

6.5.3 Fuel Injector Metering Orifice

Deposits on the external surface of the fuel injector-metering orifice were found only for those injectors that were operated on FUEL P. The deposits appeared hard and yellow
and were distributed across the entire area of the metering orifice plate. SEM pictures shown in Figure 58 and Figure 59 show details of these deposits. No such deposits were found on the orifice plate of the injectors that were operated on FUEL H, FUEL V or FUEL C. An EDS analysis of these deposits showed that they were composed almost entirely of sulphur. This was unexpected as the fuel that was used to mileage-accumulate these injectors had a concentration of sulphur that was approximately 80% less than that which was used to mileage-accumulate the fuel injectors of all other groups.

Figure 58: Fuel P Injector #68 Exterior of Orifice Plate

Figure 59: Fuel P Injector #68 Exterior of Orifice Plate Close Up
The proposed explanation for these abnormal deposits is that the longer chain hydrocarbons that are found in FUEL H but are absent in FUEL P dissolve the sulphur within the fuel. When the injectors were operated using FUEL H the longer chain hydrocarbons carried the sulphur within the fuel past the injector's metering orifice and into the intake manifold. It was within the intake manifold where these higher hydrocarbons would vapourize thus releasing the sulphur compounds on the manifold surfaces or within the combustion chamber. However since FUEL P was composed of lighter hydrocarbons that would have all vapourized immediately after the fuel exited the fuel injector orifice, it was at this location where the sulphur was deposited, as opposed to within the combustion chamber as with the FUEL H injectors.

6.5.4 High Mileage LPG and Gasoline Injectors

Figure 60 through Figure 63 are examples of SEM photographs of high mileage LPG injectors and high mileage gasoline injectors. These images are shown to demonstrate the situation of LPG fuel injectors compared against that of gasoline. The additives that are included in gasoline keep injectors clean and operating properly. Comparatively this study has shown that deposits begin to form within LPG injectors after only 6 400 km and continue to worsen as the injector ages further as shown by the high mileage LPG fuel injector needle pictures.

Figure 60: High Mileage Gasoline Injector #62 Standard Detector Overall
Figure 61: High Mileage Gasoline Injector #62 Back Scatter Detector Overall

Figure 62: High Mileage LPG Injector #1 Standard Detector Overall

Figure 63: High Mileage LPG Injector #1 Back Scatter Detector Overall
6.6 **Electron Dispersion Spectrum Analysis**

The average results from the Electron Dispersion Spectrum (EDS) Analysis of the composition of the deposits that were found on the fuel injector needles are shown below in Table 13. These analyses were unable to accurately measure the presence of carbon or hydrogen.

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<th>FUEL H AVG</th>
<th>FUEL P AVG</th>
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The source of this data is presented in Appendix E: SEM and EDS Data as Figure 174. As mentioned earlier in this paper due to the extremely thin nature of the deposits found on the fuel injector components the exact composition of the deposits cannot be determined using EDS analysis. However this data can provide some qualitative analysis of the deposit composition.

EDS analyses were not performed on injectors from the FUEL H-TiN injector group as they were operated on the identical fuel as those from FUEL H and should show similar deposit composition. Due to the lack of deposits on the fuel injectors that were operated on FUEL V it was impossible to perform an EDS analysis.
Due to the uneven distribution of the deposits a spot analysis was used to estimate the composition at points of substantial deposit. This method was chosen over an area averaging method, as it would provide more data from the deposits as opposed to the metal of the component.

The data presented should be interpreted with caution. Although care was taken to clean the injector components prior to SEM analysis some salts from the hands of the technicians may be present on the samples. This could account for the presence of trace quantities of such elements as calcium, chlorine, sodium and potassium. Again due to the thin nature of the deposits the source of much of the EDS signal was in fact from the base metal of the component. The deposits that were analyzed were all found on the fuel injector needles. This component of the injector was made of stainless steel. Composition of this steel can be composed of 75-88 wt % iron, 12-26 wt % chromium, 0.2-0.5 wt % carbon and a max of 1 wt % silicon.

An EDS Analysis was taken of an area of the fuel injector needle that was free from visible deposits. The results from that analysis show that the fuel injector needle is manufactured from a stainless steel with approximately 85 wt % iron, 13.6 wt % chromium, 0.58 wt % magnesium and 0.72 wt % silicon. Any signals from the components of this alloy can be disregarded in the deposit composition analysis, as they are most likely due to the base metal of the component. The EDS analysis of fuel injector #69 showed a 3 wt % signal for bismuth (Bi). Since this is a rare element, this was most likely a misinterpretation of the spectrum by the analysis system. Cadmium was only present on injector #44 and is therefore considered to be an anomaly.

Once all of these exclusions have been made the remaining elements of interest are sulphur and zinc. Zinc is present in higher concentrations in the deposits of fuel injectors that were mileage-accumulated on FUEL P then from those run on FUEL H or FUEL C, which were similar. The most significant difference in deposit composition was the sulphur content. Deposits within injectors operated on either FUEL C or FUEL
H showed similar sulphur compositions of approximately 1 wt %. These deposits contained a much smaller percentage of sulphur compared to those from FUEL P, which were composed of between 5.4 and 9.0 wt %.

This high concentration of sulphur in the ring deposits on the injectors from the FUEL P group correlated well with the composition of deposits that were found on the exterior of the orifice plate of all of the injectors that were operated on FUEL P. SEM pictures of these deposits are shown in Figure 58 and Figure 59. An EDS analysis of these deposits provided the following results: 71.1 wt % sulphur, 5.96 wt % chromium, 0.4 wt % magnesium, 18.45 wt % iron, 2.3 wt % nickel and 1.78 wt % silicon. Again this orifice is manufactured from a stainless steel and therefore the elements that cannot be accounted for in the base metal include a significant amount of sulphur as well as nickel and zinc.

Based on the results of the EDS analysis the deposits within injectors that were operated on FUEL H or FUEL C consisted of sulphur and zinc. These two elements were shown to be present in gasoline injector deposits by past researchers. However deposits within the injectors that were operated on FUEL P differed significantly. It appears that either the deposits are thicker leading to a more accurate EDS signal or the deposits contain a significantly greater fraction of sulphur.

The increased sulphur content of the FUEL P deposit within the injector and the significant sulphur based deposit on the external of the orifice plate is unusual. The fuel analysis shows that there is in fact more than 80% less sulphur within FUEL P when compared against FUEL H.
CHAPTER 7: MOTIVATION FOR THE STUDY OF FUEL RAIL DESIGN TO IMPROVE HOT START PERFORMANCE

The goal of this study was to determine if an improvement in fuel rail cooling and hot start performance could be achieved by assembling the fuel rail for an LPG (propane) fuel rail from tubing that had been internally coated with a low thermal diffusivity material. Vehicle emissions and hot start time were the variables used to measure any change in performance.

7.1.1 Previous Work Supporting Proposed Hot Start Performance Solution

Fuel temperature and pressure measurements from past studies [23] have shown that high LPG fuel system temperatures during vehicle hot soaks lead to the vaporization of fuel within the fuel rail resulting in long hot starts and poor emission results.

Past studies [23] have shown that during a hot soak, the temperature of the fuel within a fuel rail increased by as much as 25 K above the average operating fuel temperature. The fuel system of the vehicles used in this study was a variable pressure system where the pressure of the fuel rail was kept above the vapor pressure of the fuel tank by a set "delta" value. When the engine was running the system used pumps and a back-check valve to increase the fuel rail pressure to a level that was only 105 kPa (15 psi) above the vapor pressure of the fuel at fuel tank temperature. When the engine was shut down and hot soaked, the fuel pumps were automatically stopped. The pressure of the fuel rail dropped and during the hot soak the fuel rail temperature increased by 25 K. This increase in temperature combined with the pressure drop lead to a vaporization of the fuel within the rail during the hot soak process. This process is shown in Figure 64 on a pressure, temperature and specific volume graph for propane.
Data from the earlier study showed that following a hot soak the fuel temperature and pressure was 340K and 1.2 MPa. Since the LPG used in this study was 97% propane we can safely use the properties of pure propane as an estimate of how the LPG fuel behaved. Based on the temperature and pressure recorded during hot soak the thermophysical properties [24][25][26][27][28] of propane show that the fuel within the fuel rail was a vapour at the end of the hot soak. Once the fuel within the fuel rail vapourized the hot start time increased.

The fuel injectors for this system were sized to supply a mass of liquid fuel that, when mixed with the intake charge or air, resulted in an in-cylinder mixture that had an equivalence ratio near unity. Following an extended hot soak the fuel in the rail was vapourized and the fuel injectors were supplied with lower density gaseous LPG during hot start. At hot start system temperatures and pressures the mass of gaseous LPG fuel that can pass through a fuel injector during a given pulse width is approximately 6% of the mass of liquid LPG fuel that would pass through the fuel injector for the same pulse width. Thus while the fuel within the rail is in a vapour state, such as during early hot
start, the engine is receiving approximately 94\% less fuel than is required and will not start.

As the hot start progressed, liquid fuel was supplied to the hot fuel rail where a fraction of it vapourized. At this point in the start-up the fuel injectors were supplied with a fuel of a mixed-phase. This resulted in the fuel injectors metering a mixture of both liquid and gaseous LPG. However the mass of fuel delivered to the engine was still only a fraction of what was required and thus the engine did not start. After the fuel rail had been cooled to the point where the majority of fuel supplied to the injectors was free of gaseous LPG an adequate mass of fuel was supplied to the engine resulting in an in-cylinder mixture that was combustible, thus allowing the engine to start.

The motivation for this study was to investigate a method of reducing the time required to cool the fuel rail to the point where only liquid fuel is supplied to the fuel injectors. This required fuel rail temperature is the liquid saturation temperature of LPG at hot start fuel rail pressure. The liquid saturation temperature of the LPG used in this study should be similar to that of pure propane, approximately 305 K using a hot start fuel rail pressure of 1.2 MPa [24]. Otherwise stated, for a system at a pressure of 1.2 MPa liquid LPG will vapourize if it comes in contact with a surface that is at a temperature greater than 305 K. When considering the time required to purge the fuel rail of all vapour or bubbles during hot start, we can assume that only mixed phase LPG will flow through the fuel rail until its inner surfaces are cooled from the average hot soak fuel rail temperature of 320 K to 305 K or less.

This leads to the question of how can the fuel rail be designed such that the interior surfaces will cool down as quickly as possible during a hot start to permit liquid fuel to run through the rail without vapourizing.

The current fuel rail is constructed from steel tubing with steel junction blocks where the tubing branches meet. This design provided excellent structural strength against the high system pressures, but lead to problems when the heat transfer issues of the fuel rail were
considered. The primary heat transfer requirement was to cool the inner surface to below 305 K as quickly as possible to allow liquid fuel to flow to the fuel injectors. This is a considerable challenge considering that the temperature of the engine components surrounding the fuel rail could reach 365 K (maximum hot soak coolant temperature as recorded by [23]).

All metals, including the stainless steel used in the construction of this fuel rail, have high thermal diffusivities ($\alpha$). Thermal diffusivity is a measure of how quickly the temperature difference between two points of a material will equalize once an initial temperature gradient is imposed between them. Since this equalization occurs very quickly for metals, the entire thickness of the tubing wall would need to be cooled from 320K to 305K before the inner surface of the tubing reached the desired temperature of 305K.

Thermal diffusivity is defined as:

$$\alpha = \frac{k}{\rho c}$$

Where:

- $\alpha$  Thermal Diffusivity [m$^2$/s]
- $k$  Thermal Conductivity [W/m.K]
- $\rho$  Density [kg/m$^3$]
- $c$  Specific Heat [J/kg.K]

Thermal diffusivity ($\alpha$) relates the rate of temperature change to the spatial temperature gradient. This is described by the following equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

For a material with a large $\alpha$, the spatial temperature gradient will be reduced more quickly when compared to a material with a small $\alpha$. 
Since the original fuel rail was constructed entirely of high α steel tubing, the entire cross-section of the tube must be cooled to a temperature near LPG’s saturated liquid temperature (at the rail pressure) before the inner surface of the tube will reach this temperature. The rail would be cooled by either cool LPG vapour or mixed phase LPG flow removing heat from the tubing’s surface by convection or latent cooling due to LPG vapourization. A schematic of the fuel rail purging process is shown in Figure 65.

![Fuel Rail Cooling Due to Vaporization and Convection]

**Figure 65: Schematic of Fuel Rail Purging Process During Hot Start**

An ideal alternative to the all-steel design would be to construct the fuel rail entirely from a low thermal diffusivity material such as plastic. This material would permit the surface that is in contact with the fuel to cool relatively quickly to a temperature below the liquid saturation temperature without having to cool all of the fuel rail material. The low thermal diffusivity of this material would permit the thermal gradient between the inner and outer surface to exist for a longer period of time relative to the all steel design. Based on the understanding of what factors effect hot start times it appears that this would result in shorter hot start times.

A qualitative test of this theory occurred during the last redesign of the fuel rail. Originally the injector pods for this fuel rail were constructed from aluminum, a material
with a high thermal diffusivity ($\alpha = 97.1 \times 10^{-6}$ m$^2$/s). The pods that are currently in use are molded from plastic, a material with a lower thermal diffusivity (if the plastic used has similar properties to Nylon6 $\alpha=98.7 \times 10^{-9}$ m$^2$/s). Although not documented, it is reported [29] that when using pods constructed of plastic as opposed to aluminum a 50% improvement in hot start time was observed. We can assume that the use of the plastic pods permitted the fuel to flow, without vapourizing, through the pods sooner resulting in fuel with fewer bubbles reaching the fuel injectors.

Unfortunately due to the high cost of the tooling required to produce an all-plastic fuel rail this option is not viable for the low number of LPG powered vehicles produced each year.

7.1.2 Proposed Hot Start Performance Solution
The alternative to the all steel design or all plastic design, and the subject of this paper, was to construct a composite fuel rail. The exterior of the rail was constructed of steel tubing to provide the structural integrity required of a pressurized system. However the internal surface of the steel tubing was coated with a low thermal diffusivity material. This material was not thick enough to insulate the fuel from the heat of the engine bay and prevent vapourization. However it should allow the inner surface of the tubing to be cooled below the saturation temperature of LPG without the requirement of cooling all of the tubing material to that temperature. Since less heat is removed from the tubing, the inner surface should reach LPG saturation temperature sooner, allowing liquid fuel to quickly reach the injectors, ideally decreasing the hot start time.

The low thermal diffusivity coating that was used for this application is Conductive Xylan, a product produced by Whitford (Frazer PA, USA). This coating was an electrically conductive coating composed of a combination of Teflons and conductive graphite supported in an epoxy resin matrix. All are resistant to chemical attack from propane and butane liquid and gas. The Teflons include flourinated ethylene propylene (FEP), tetrafluoroethylene (TFE) and perfluoroalkoxy (PFA). This material provided a
low thermal diffusivity ($\alpha = 0.208 \times 10^{-6} \text{ m}^2/\text{s}$); lining for the inner surface of the fuel rail. The thermal diffusivity of this coating is almost 20 times less when compared to stainless steel ($\alpha = 3.974 \times 10^{-6} \text{ m}^2/\text{s}$). This lower thermal diffusivity allowed thermal gradients to exist longer between the inner and outer fuel rail surface.

An electrically conductive coating was used to reduce the risk of a static charge building up on the inner surface of the tubing as the fuel flowed through the system.

A coating of between 25 $\mu$m and 50 $\mu$m was applied by flooding the internal passages of the assembled fuel rail with the coating. To cure the coating the part was placed in a $548\text{K}$ oven for 10 minutes as per the manufacturer's instructions.

The coated fuel rail was installed into a vehicle and the hot start results were compared against those of a vehicle that used an identical all steel fuel rail. Any performance improvements between the two fuel rail setups were quantified.
CHAPTER 8: LITERATURE REVIEW FOR THE STUDY OF FUEL RAIL DESIGN

The solution that was proposed for the hot start problem applies theories from flow boiling, steady state and transient pool boiling, transient conduction and the effects of thermal coatings. No literature was found on transient flow boiling over coated surfaces. Thus a combination of theories from other areas as applied where they were considered reasonable. The results from pool boiling studies will underestimate the rate of heat transfer, or cooling times relative to the flow boiling that occurs within the LPG fuel rail during hot start.

The solution to the long hot starts in propane-powered vehicles was to coat the internal surface of the steel tubing with a low thermal diffusivity material. This fuel rail coating will reduce the mass that must be cooled in a given time. This will increase the rate of temperature drop of the hot inner surface of the fuel rail as was shown with a simple transient thermal model in Chapter 9: Computational Analysis of Proposed Fuel Rail Design Solution. This allowed the internal passages of the tubing to be cooled below the saturation temperature of LPG sooner allowing liquid fuel to reach the injectors sooner, and decreasing the hot start time.

8.1 Overview of Pool Boiling Heat Transfer.

Pooling boiling is the simplest type of boiling. After establishing the fundamentals of boiling they will be applied to flow boiling, which will be discussed in the following section.

Boiling will occur when a liquid comes in contact with a surface that has a temperature that is greater than the saturation temperature of the liquid for the pressure of the system. The difference between the surface temperature and the saturation temperature is referred to as superheat. Three distinct types of boiling heat transfer exist as the magnitude of the
superheat increases. These three types are nucleate, transition and film boiling, shown in the following Figure 66.

![Diagram of boiling heat transfer curve](image)

**SURFACE TEMP. – LIQUID SATURATION TEMP.**

Figure 66: Boiling Heat Transfer Curve, Heat Flux Versus Superheat

This figure shows that as the superheat increases the heat flux from the surface to the liquid increases as well until film boiling occurs. The heat flux increases linearly with superheat during pure convection shown in Figure 66 by Region I. Nucleate boiling begins as small bubbles are formed on the surface shown in Figure 66 by Region II. As these enlarge and break away from the surface liquid will fill in the site of the bubble and new bubbles will begin to form. As the magnitude of the superheat increases the heat flux due to nucleate boiling increases to the maximum value as shown in Figure 66 between Regions III and IV. As the magnitude of the superheat continues to increase a
transition towards film boiling begins. During transition boiling the heat flux from the surface is less than that of the maximum of the nucleate boiling regime as shown in Figure 66 by region IV. As the superheat continues to increase, film boiling develops. When a continuous film of vapour exists between the heated surface and the liquid indicates this boiling mode. This boiling mode tends to have lower heat flux than nucleate boiling and is considered the most inefficient modes of boiling heat transfer. The heat flux of this mode is described by region V in Figure 66. From this point the heat flux continues to rise as the superheat increases and radiation becomes the dominant heat transfer mechanism as shown in Figure 66 by region VI.

8.2 Overview of Flow Boiling Heat Transfer.

Most of the boiling heat transfer modes that occur in pool boiling exist in flow boiling. When we consider a section of tubing that is quenched by flow boiling each boiling mode will occur at the section of tubing for a period of time until a transition occurs to the next boiling mode as that particular section cools. The boiling modes of flow boiling are shown in Figure 67 below.

If we assume that a hot tube is full of vapour and a flow of liquid flows into it to cool a section of the tube. Initially some of the liquid at the walls will vapourize and the bubbles from this process will migrate towards the mainstream of the flow, coalesce and form a vapour core surrounded by liquid coating the walls of the tube. The liquid layer on the tubing walls will continue to vapourize adding more bubbles to the flow. Eventually this vapour core will break into vapour slugs (irregularly shaped combinations of bubbles). As time progresses these slugs will form into distinct bubbles and eventually these bubbles will condense allowing a single-phase liquid flow to pass through the tube.

Similar to the pool boiling heat transfer the greatest heat flux occurs when nucleate boiling is occurring during the transition between vapour and annular flow regimes.
Figure 67: Flow Regimes of Force Convection Boiling Inside a Tube.
8.3 Review of Literature of Pool Boiling at Coated Surfaces

Some literature has been found on the effects of composite wall construction on the rate of surface cooling. Much of the work found was performed by Yoshihiro Kikuchi at the Hiroshima University, Japan. One of his papers [30] involved modelling and analyzing the quenching of heated metals with pool boiling to determine if applying a thin low thermal conductivity coating the surface could reduce the cooling time of the metal. This study showed that using a Teflon coating lead to lower surface temperatures resulting in an earlier transition from film boiling to transition and nucleate boiling. Since the latter are more efficient modes of boiling heat transfer the bulk metal temperature decreased more rapidly.

These experiments involved using a 3 mm copper plate with one surface coated with Teflon and the opposite surface instrumented with a thermocouple and insulated from any contact with the cooling liquid. This plate was heated to a super heat of 210K above the saturation temperature of the quenching fluid, liquid nitrogen at atmospheric pressure. The plate was then submerged into the quenching fluid and the signal from the thermocouple was used to record the bulk temperature of the plate.

The experimental and theoretical results agreed quite well. By interpreting the results as the time required for the copper plate bulk temperature to cool from a superheat of 210 K to the saturation temperature of quenching liquid, it was shown that the coating improved the cooling time. The bare copper plate cooled by 200 K in a time of 320 seconds when quenched with liquid nitrogen. The same plate required only 200 seconds to cool 200 K when coated with 14 μm of Teflon. As the coating thickness was increased the cooling time decreased. A copper plate with a 52μm thick Teflon coating required only 150 seconds for the bulk temperature to cool by 200 K.
This work shows that the use of a coating can improve the cooling time of a metal surface that was heated to a point where film boiling would occur. A correlation for the minimum film boiling temperature proposed by Berenson [31] and referenced in Kikuchi's [30] paper was used in this study to calculate the minimum film boiling temperature for an uncoated surface immersed in saturated propane. This calculation, described in Appendix H: Minimum Film Boiling Temperature Calculation, showed that the minimum film boiling surface temperature for these conditions was approximately 200°C. This temperature was significantly above the maximum temperatures that were recorded during the hot soak of the vehicle for this study. The average maximum fuel rail external surface temperature was 75°C and the average maximum fuel temperature was 74°C. Since the fuel rail temperature was not at a level that lead to film boiling the work by Kikuchi cannot be directly applied to support a more rapid cooling of the fuel rail. However the decreased minimum film boiling temperature for the coated plate shows that the surface that is exposed to the quenching fluid is cooled more quickly when compared to an uncoated plate. Applying this idea to the LPG fuel rail problem we can see that coating the fuel rail passages with Teflon may lead to a faster cooling of the internal surface of the rail. If the internal surfaces of the fuel rail cool to the saturation temperature of liquid propane faster this could result in less vapourization and therefore improved hot start performance.

Kikuchi further expanded his model in 1991 [32] and found that when a coating of low thermal conductivity was used to coat a surface the minimum film boiling temperature decreases as the coating thickness increases. It was believed that this was due to the transient contact of liquid followed by the evaporation of a thin microlayer of liquid that resulted in a rapid decrease in local surface temperature even though the average wall temperature remained elevated.

Pan and Lin [33] developed a theoretical model to predict the effects of a series of parametric factors. Their results show that coating the boiling substrate would result in a shifting of the boiling curve to the right. This would lead to the requirement of higher superheats for each boiling transition point. When considering the problem of vapour
generation within the fuel system during a hot start this would lead to less vapour generation as the transition to boiling would occur at a higher superheat temperature.

Pan, Hwang and Lin [34] modeled the liquid-solid contract region including the cyclical effects of bubble departure, transient conduction, boiling incipience, microlayer evaporation and vapour covering. It was found that a surface coating lead to an improvement in transitional boiling heat transfer as well as a shifting of the boiling curve to the right at the points of critical heat flux and minimum film boiling points.

Ramilison and Lienhard [35] performed experiments to determine the heat flux from a heated copper surface immersed in n-pentane and other liquids. The surface of the copper that was in contact with the n-pentane was either coated with Teflon (25.4μm thick), polished to a mirror finish or roughened with emery paper. The data from their study, plotted in Figure 68, again shows that the teflon coating leads to a shift of the boiling curve to the right at the critical heat flux and minimum film boiling points.

![Boiling Curves for Various Surface Treatments of Heated Copper in n-Pentane](image)

**Figure 68:** Boiling Curves for Various Surface Treatments of Heated Copper in n-Pentane
The studies mentioned above by Pan, Lin and Hwang [34] as well as those by Ramilison [35] obtained data for the boiling curves by setting a wall superheat condition as a set value and measuring the steady state heat flux for that boiling regime. These experiments were analyzing a steady state phenomena. The hot start process for an LPG fuel rail involves the transient flow cooling of the fuel rail material. It must be determined if data that has been obtained using steady state experiments can be applied to transient cooling with flow phenomena.

Huang et al. [36] determined boiling curves for a heated copper pipe cooled by flowing water at various pressures and mass flow rates. Some differences were found between the transient results and those determined by others using steady state analysis. These differences were found for parameter values of mass flux greater than 300 kg/(m$^2$ s), pressures higher than 0.70 MPa or inlet sub-cooling greater than 15K. Based on the output of the two fuel pumps that are used in the present system the mass flux of the LPG fuel system under analysis is equal to 53.68 kg/(m$^2$ s) in the 6.35 mm lines and 26.84 kg/(m$^2$ s) in the 12.7 mm lines during the startup sequence. The system pressure at startup is about 1.40 MPa, well above the pressure limit. However LPG has a significantly higher vapour pressure than the water that was used to determine this data. The sub-cooling of the fresh fuel as it is pumped into the fuel rail during startup is only approximately 5K.

Other than the pressure of the system, which can be justified by the higher vapour pressure of LPG when compared against water, the parameters of this system appear to be within the range specified by Huang et al. This allows steady state boiling data to be applied to the transient phenomena that is under study.

Evidence was found during the literature search that supported the use of a coating to improve the rate of cooling for the inner surface of the fuel rail. The application of a coating would shift the boiling curve towards the right resulting in an earlier transition to free convection heat transfer during hot start. This would result in a lower level of vapour production, and an earlier elimination of vapour from the fuel system. This would allow sufficient liquid fuel to pass though the fuel
injectors earlier in the hot start resulting in a shorter start time and a more stoichiometric in-cylinder mixture.
CHAPTER 9: COMPUTATIONAL ANALYSIS OF PROPOSED FUEL RAIL DESIGN SOLUTION

Transient thermal analyses of both all steel and Xylan coated steel fuel rail designs were completed using a one-dimensional finite element analysis and an accepted calculation scheme. The goal of this analysis was to provide further support to the hypothesis that the hot start performance would improve if the interior surfaces of the fuel rail were to be coated with a low thermal diffusivity material. This simple model neglects the effects of fuel vapourization but accounts for the initial convection across the inner surfaces and transient conduction. This model also neglects how the convection coefficient would vary with the change in surface and fluid temperature. Although this is not an exact analysis of the heat transfer conditions within the fuel rail, it does describe the worst-case heat transfer scenario to a reasonable approximation. If the effects of fuel vapourization were included, the tubing surface would cool more quickly than what has been shown in the mathematical model. In summary, this model is designed to compare the two fuel rail wall constructions while keeping the heat transfer conditions constant. A description of the model is included below.

The system was treated as a one dimensional plane wall system as opposed to a radial system. The calculation domain is shown in Figure 69:
Figure 69: Calculation Domain Setup for Transient Thermal Analysis

Node #1 was subjected to convective heat transfer as cool gaseous fuel is forced past the interior surface of the tubing and conduction with node #2. The convection coefficient, \( h \), was determined by using a correlation for the Nusselt number (Nu) which is valid for fully developed turbulent internal flows with Prandtl numbers (Pr) between 0.5 and 2000 and Reynolds numbers (Re\(_D\)) between 3000 and \( 5 \times 10^6 \). This correlation was developed by Gnielinski [37] and is given by the following equation:

\[
Nu_D = \frac{(f/8)Re_D Pr}{1.07 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}
\]

For our application \( Re_D = 38.8 \times 10^3 \), \( f = 0.022 \) and \( Pr = 2.992 \). The friction factor, \( f \), was determined using the Moody diagram with \( Re_D \) and the smooth pipe criteria.

For this case the convective heat transfer coefficient was chosen for propane vapour flow and determined to be \( h = 2479 \text{ W/m}^2\text{K} \).

Using energy conservation about each node with positive direction of heat flow chosen as into the node, the following explicit finite difference equation was developed to model the behavior of each node. By discretizing time with \( p \) (\( t = p \times \Delta t \)) and space with \( m \) (\( x = \))
\( m \times \Delta x \) the governing equations for nodes 1 and 2 that describe transient convection and conduction can be reduced to:

\[
Ah(T_\infty - T_1^p) + \frac{Ak}{\Delta x}(T_2^p - T_1^p) = \rho c A \frac{\Delta x}{\Delta t}(T_1^{p+1} - T_1^p)
\]

Solving for \( T_1 \) at the next time step (\( p+1 \))

\[
T_1^{p+1} = h \frac{\Delta t}{\Delta x c \rho} (T_\infty - T_1^p) + \frac{\Delta t}{\Delta x^2 c \rho} (T_2^p - T_1^p) + T_1^p
\]

Using the Fourier and Biot number and thermal diffusivity definitions:

\[
\alpha = \frac{k}{c \rho}, \quad Fo = \frac{\alpha \Delta t}{\Delta x^2}, \quad Bi = h \frac{\Delta x}{k} \quad \text{and rearranging}
\]

\[
T_1^{p+1} = Bi \cdot Fo \cdot T_\infty + (1 - Bi \cdot Fo - Fo)T_1^p + FoT_2^p
\]

The above equation is valid for solving the temperature of node #1 based on past node temperatures of nodes 1 and 2.

The temperatures of all other nodes are determined by solving the partial differential equation for transient heat conduction.

\[
\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2}
\]

By discretizing time with \( p \). Therefore \( t = p \times \Delta t \) and space with \( x = m \times \Delta x \) and using a forward in time and central in space (FTCS) numerical scheme, the following finite difference equations are developed:
\[ \frac{\partial T}{\partial t} \bigg|_m = \frac{T_{m-1}^\rho - T_m^\rho}{\Delta t} \quad \text{Forward in time} \]
\[ \frac{\partial^2 T}{\partial x^2} \bigg|_m = \frac{T_{m+1}^\rho + T_{m-1}^\rho - 2T_m^\rho}{\Delta x^2} \quad \text{Central in space} \]

Transient conduction equation becomes
\[ \frac{1}{\alpha \Delta t} (T_{m-1}^{\rho+1} - T_m^{\rho}) = \frac{1}{\Delta x^2} (T_{m+1}^{\rho} + T_{m-1}^{\rho} - 2T_m^{\rho}) \]

Solving for \( T_{m-1}^{\rho+1} \) and again using Fo and Bi
\[ T_{m-1}^{\rho+1} = FoT_{m+1}^{\rho} + (1 - 2Fo)T_m^{\rho} + FoT_{m-1}^{\rho} \]

The above equation is valid to solve for temperature at the next time step for all nodes exposed to only transient conduction except for those on the boundary between each material. For the nodes on the boundary between the two materials the following equations that account for the different properties were used to calculate the effects of transient conduction.

\[ T_m^{\rho+1} = T_m^{\rho} + \left[ \frac{k_1}{\Delta x} (T_{m-1}^{\rho} - T_m^{\rho}) + \left( \frac{\Delta x}{2k_1} + \frac{\Delta x}{2k_2} \right)^{-1} \right] \left( T_{m+1}^{\rho} - T_m^{\rho} \right) \left( \frac{\Delta t}{\rho_c_1 \Delta x} \right) \]

\[ T_{m+1}^{\rho+1} = T_{m+1}^{\rho} + \left[ \frac{k_2}{\Delta x} (T_{m+2}^{\rho} - T_{m+1}^{\rho}) + \left( \frac{\Delta x}{2k_1} + \frac{\Delta x}{2k_2} \right)^{-1} \right] \left( T_m^{\rho} - T_{m+1}^{\rho} \right) \left( \frac{\Delta t}{\rho_2 c_2 \Delta x} \right) \]

---

Material #1

Material #2

---

Figure 70: Node Setup at Material Interface

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By solving these equations in a time march scheme, it was possible to determine the temperatures of all nodes as time progresses.

For accuracy a small $\Delta x$ of 5$\mu$m was chosen. Due to the stability criterion of the FTCS numerical scheme this lead to the requirement of a very small $\Delta t$ value of 2.8308$\mu$sec. Due to the large number of calculations required, the total analysis time was limited to 140 ms (this required 55600 iterations). Although this is a short analysis period, the results from the model show the expected behavior. The details of code used to calculate the temperature profiles is given in Appendix I: Explicit Calculation of Transient Temperature Distribution.
CHAPTER 10: MATERIALS AND METHODS FOR FUEL RAIL DESIGN STUDY

The performance of the all steel fuel rail was analyzed to determine the start time, temperature at different points along the fuel rail, the state of the fuel, exhaust temperature and the total vehicle emissions. Each of these variables were studied during the hot start and idle following start. This baseline was used to determine if the modifications to the fuel system will result in an improvement in performance.

The second stage of this study was to perform the same analysis using a fuel rail that has been internally coated with Xylan. In this stage all of the variables mentioned in the above stage will be traced to determine what quantifiable benefits have been obtained by using the coated fuel rail.

The performance variables of one bank of cylinders that were measured for this study include:

- Fuel temperature at two points within the fuel rail
- Fuel pressure between the two fuel injector pods.
- External fuel rail material temperature at three locations along a single branch of the fuel rail.
- Total emissions from the vehicle.
- Exhaust temperatures of each cylinder

These variables were measured while the engine was run in a vehicle on a chassis dynamometer within an emission test cell.

10.1 Fuel System Details

The fuel system, which was used for this experimental program, was a closed loop series feed system that delivered liquid LPG from the fuel tank to the fuel injectors. A pressure
difference between the inlet and outlet of the fuel tank is used to produce a fuel flow through the injectors. This pressure difference is developed using a fuel pump mounted within the fuel tank and controlled using a pressure sensitive back check and relief valve which is shown on the figure below. All of the fuel rail tubing that passes through the engine compartment was enclosed in a 0.5 cm thick insulation. The effects of this insulation were ignored to simplify the analysis of this problem. A schematic of the system is shown in Figure 71:

![Diagram of fuel system](image)

Figure 71: Schematic of Liquid PFI LPG Fuel System Type-2 Fuel Rail

10.2 Initial Vehicle Setup

A vehicle equipped with a 5.2L V8 Liquid LPG PFI engine was used in this study. The fuel rail used was a Type-2 Liquid LPG fuel rail. The injectors used were low flow calibration bottom feed injectors with 30 000 km of accumulated miles.

One branch of the fuel rail that supplied fuel to the drivers side bank of cylinders, was instrumented with three surface thermocouples, two internal fuel temperature
thermocouples and one fuel pressure transducer. The exhaust manifold of the same bank of cylinders was instrumented with exhaust gas temperature thermocouples providing data on the temperature of the exhaust gases exiting each of the four cylinders of that bank.

10.3 Fuel Properties

To determine the hydrocarbon and sulphur compounds that were present in the fuel a chemical analysis was performed by a third party and the results have been summarized in Table 14. 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 mass ppm of sulphur. Any hydrocarbon or sulphur compounds which are not listed in the analysis summary were not present in significant quantities.

Table 14: Composition and Sulphur Content of HD-5 LPG Fuel Used in this Study

<table>
<thead>
<tr>
<th>Hydrocarbon Content of Fuel</th>
<th>Weight %</th>
<th>Sulphur Content of Fuel</th>
<th>Sulphur mass ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>0.02</td>
<td>Carbonyl Sulphide (COS)</td>
<td>28</td>
</tr>
<tr>
<td>Ethane</td>
<td>1.81</td>
<td>Methanethiol (Methyl Mercaptan)</td>
<td>3</td>
</tr>
<tr>
<td>Propene</td>
<td>0.04</td>
<td>Ethanethiol (Ethyl Mercaptan)</td>
<td>8</td>
</tr>
<tr>
<td>Propane</td>
<td>95.79</td>
<td>Iso-Propanethiol</td>
<td>1</td>
</tr>
<tr>
<td>IsoButane</td>
<td>1.17</td>
<td>Thiophene/sec-Butanethiol</td>
<td>1</td>
</tr>
<tr>
<td>n-Butane</td>
<td>0.69</td>
<td>DiMethyl Disulphide (DMDS)</td>
<td>2</td>
</tr>
<tr>
<td>IsoPentane</td>
<td>0.20</td>
<td>Unknown C6 Sulphur Compounds</td>
<td>7</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>0.19</td>
<td>Unknown C7 Sulphur Compounds</td>
<td>1</td>
</tr>
<tr>
<td>2-Methylpentane</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-Hexane</td>
<td>0.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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10.4 Data Acquisition System

The data acquisition system used during these experiments consisted of a laptop computer running specialized data acquisition software. This system recorded the signals from the pressure and temperature transducers as well as engine variable data that was recorded by the engine control unit (ECU).

Data from the ECU were obtained by interrogating the ECU using a direct connection between a laptop computer and the ECU service port. The signals from the thermocouples and pressure transducers were passed through a set of signal conditioners and amplifiers to a 12-bit analogue to digital converter. This converted the analogue signal to a digital signal for the laptop to record.

10.4.1 Transducers

Temperature Transducers

Three types of temperature transducers were used in this experiment; type-J surface mounted thermocouples, type-J sheathed thermocouples and type-K sheathed thermocouples. The details of these transducers are described in Table 15.

<table>
<thead>
<tr>
<th>Transducer Type</th>
<th>Time Constant</th>
<th>Standard Deviation of 200 Random Measurements of Constant Value</th>
<th>First Order Uncertainty</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-J Surface TS 1,2 &amp; 3</td>
<td>0.60 sec.</td>
<td>0.970°C</td>
<td>±1.94°C @95%</td>
<td>Omega</td>
</tr>
<tr>
<td>Type-J Sheathed TF 1 &amp; 2</td>
<td>0.22 sec.</td>
<td>0.847°C</td>
<td>±1.69°C @95%</td>
<td>Omega</td>
</tr>
<tr>
<td>Type-K Sheathed EGT 2.4,6,8</td>
<td>1.8 sec.</td>
<td>0.479°C</td>
<td>±0.96°C @95%</td>
<td>Omega</td>
</tr>
</tbody>
</table>
Pressure Transducers

The pressure transducer used for this work was a model 5550 manufactured by Precise Sensors Inc (Monrovia, CA, USA). This transducer used a strain gauge bonded to a stainless steel diaphragm and had a working range of 0-500 psig. The transducer was calibrated at the DaimlerChrysler Proving Grounds Instrumentation Lab on September 13, 1999 and is traceable to the National Institute of Standards and Technology. The details of the transducer and the calibration data are shown in Table 16.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bridge</strong></td>
<td>Four active arm bonded strain gage.</td>
</tr>
<tr>
<td>Resistance</td>
<td>350 Ohms nominal</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>1 to 10 VDC Regulated</td>
</tr>
<tr>
<td>Full scale output</td>
<td>3.0 mV/V nominal</td>
</tr>
<tr>
<td>Full scale pressure input</td>
<td>500 psig</td>
</tr>
<tr>
<td>Zero offset at 500 psig</td>
<td>0.0991 mV</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>0.14 % of full scale</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.15% of full scale</td>
</tr>
<tr>
<td>Output at capacity</td>
<td>33.7153mV</td>
</tr>
<tr>
<td>Units per mV</td>
<td>14.830 psi/mV</td>
</tr>
<tr>
<td><strong>Standard Deviation of 200 Random Measurements of Constant Value</strong></td>
<td>5.783 kPa</td>
</tr>
<tr>
<td><strong>First order Uncertainty</strong></td>
<td>+/- 11.566 kPa @ 95%</td>
</tr>
</tbody>
</table>

10.4.2 Signal Conditioning and Amplification

The signal from each of the temperature and pressure transducers was filtered, isolated and amplified so that the signal could be used as an input to the A/D converter. The signal conditioning was achieved by using Dataforth SCM5B37J and SCM5B37K analogue modules for the type-J and type-K thermocouples respectively.
Each thermocouple signal conditioning module was electronically cold-junction compensated for the parasitic thermocouples formed by the thermocouple wires and the screw terminals on the module using an internal RTD temperature sensor. These modules incorporates a filter that rejected interference signals at 60Hz and 50Hz. These modules were powered by a 5 VDC input and provide a 0-5VDC output.

When non-linearity, hysteresis and repeatability were accounted for, the accuracy of the type-J module provided an accuracy of ± 0.07% over an input range of -100°C to 760°C or ±0.61°C. The type-K module provided an accuracy of ± 0.07% over an input range of -100°C to 1350°C or ±0.97°C.

A Dataforth SCM5B38 strain gage input signal conditioning module was used to filter, isolate and amplify the strain gage signal. The pressure transducer strain gage is excited by a fully isolated stable 10V source providing a sensitivity of 3 mV/V. The full scale input range of ± 30mV produces a ± 5V full-scale output. Accuracy of 0.08% of span (+/- 2.758 kPa), non-linearity of ± 0.02% of span (+/- 0.689 kPa) and a response time to 90% of full scale of 0.2 seconds. This resulted in an uncertainty of +/- 2.843 kPa at the sensor.

10.4.3 Analogue to Digital Conversion

The amplified signals from the conditioning modules were fed to a laptop PCMCIA card. A National Instruments DAQCard-700 was used as the analogue to digital converter and interface with the laptop computer. This card permits 16 single-ended analogue input channels, which are converted to discrete digital signals using a 12-bit A/D converter. The maximum rate of data acquisition for this card is 100 000 Hz for a single channel, and decreases with increasing number of interrogated channels.

Each of the channels is sampled sequentially. This leads to a dependence of the sampling frequency on the number of channels sampled. For this work data from 10 channels were sampled. Based on the data acquisition card's maximum sampling frequency each
channel could have been sampled at a maximum of 10 000 Hz. Data was recorded at 333 Hz for the all steel fuel rail testing and at 500 Hz for the coated fuel rail. The lower data acquisition rate was used during the all steel fuel rail testing as any greater rate resulted in a computer failure. During the coated fuel rail testing the limitation on the rate of acquisition during the previous tests were traced to the computer cooling. When the computer was kept inside the vehicle during hot soak the system was limited to acquiring data at 333 Hz. However for the trials presented in this study the data acquisition rate was stable at the listed value. Once this problem was solved the data acquisition rate was increased to 500 Hz which was considered reasonable due to the time constants of the thermocouples.

The data acquisition software that was used designated that the input to the A/D converter would be voltages in the range of ±5 V. These voltages being the outputs of the thermocouple and strain gauge signal conditioning modules. With these input voltages the resolution of the A/D converter was ±2.44 mV of the signal from the conditioning modules or ±1.682 kPa for the pressure transducer.

The dynamic characteristics of this card show that the settling time to 0.024% accuracy for a ±5 V input is a maximum of 25 μsec.

10.4.4 Engine Control Unit Variables

During this study, data was recorded from transducers that were mounted on the fuel system as well as input and output variables of the engine control unit (ECU). The ECU tracks information from a series of pressure, temperature and timing sensors. Based on these inputs the ECU determines the control values for various engine components such as injector pulse width and spark timing. The variables that were recorded include from this system were; coolant temperature, battery temperature, EPP count, engine RPM and injector pulse width. Although this data is not of a high resolution nor are the vehicle’s transducers of a research quality the data does provide an excellent estimation of how the vehicle is operating.
10.4.5 Data Acquisition Software

Data acquisition software was used to record data from the vehicle during testing. This software permits interrogation of the ECU computer with the simultaneous acquisition of data from the external analogue transducers. The data is displayed graphically while it is recorded and is saved as data files.

10.4.6 Laptop Computer

The laptop computer used for the data acquisition was a Toshiba 320CDT with 64MB of Ram and a Pentium 233MHz MMX processor.

10.5 All Steel Fuel Rail Setup

Data was recorded from one bank of cylinders of the engine and at six locations along a single branch of the all steel fuel rail to determine the baseline performance of this setup.

10.6 Description of Fuel Rail Transducer Setup

Figure 72 shows a schematic of one branch of the fuel rail and the bank of cylinders that it services. The location of the transducers are shown by the red text and arrows. The legend is given in Table 17.

<table>
<thead>
<tr>
<th>Transducer Number</th>
<th>Transducer Type</th>
<th>Transducer Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF1</td>
<td>Type J Thermocouple</td>
<td>In pressure fitting on inlet tubing</td>
</tr>
<tr>
<td>TF2</td>
<td>Type J Thermocouple</td>
<td>In pressure fitting on outlet tubing</td>
</tr>
<tr>
<td>TS1</td>
<td>Surface Mounted Type J Thermocouple</td>
<td>Exterior surface of inlet tube</td>
</tr>
<tr>
<td>TS2</td>
<td>Surface Mounted Type J Thermocouple</td>
<td>Exterior surface of cross tube</td>
</tr>
<tr>
<td>TS3</td>
<td>Surface Mounted Type J Thermocouple</td>
<td>Exterior surface of outlet tube</td>
</tr>
<tr>
<td>P1</td>
<td>0-500psi Gage Pressure</td>
<td>In pressure fitting on cross tubing</td>
</tr>
<tr>
<td>EGT1</td>
<td>Type K Thermocouple</td>
<td>Exhaust Outlet Cylinder #2</td>
</tr>
<tr>
<td>EGT2</td>
<td>Type K Thermocouple</td>
<td>Exhaust Outlet Cylinder #4</td>
</tr>
<tr>
<td>EGT3</td>
<td>Type K Thermocouple</td>
<td>Exhaust Outlet Cylinder #6</td>
</tr>
<tr>
<td>EGT4</td>
<td>Type K Thermocouple</td>
<td>Exhaust Outlet Cylinder #8</td>
</tr>
</tbody>
</table>

Table 17: Legend for Figure 72
Figure 72: Details of Fuel Rail and Transducer Location

- Fuel Inlet (I1)
- Fuel Exit (I2)
- Fuel Injectors
- Direction of Coolant Flow
- Cylinders 2 and 4
- Cylinders 6 and 8
10.7 Accuracy of Hot Start Emissions Data

The emission results for these hot start tests were obtained using a Horiba emissions bench. The concentrations of CO, CO₂ and HC species were determined using an infrared absorption detector. A chemiluminescence detector was used to determine the concentration of NOₓ within the exhaust. A magnetopneumatic detector was used to determine the concentration of O₂ and gas chromatography was used to determine the concentration of CH₄. The analyzer is zeroed and tested at full scale prior to each test using gases of known concentration. The accuracy of the zero and full scale is within 3% of full scale for each test. The accuracy of the readings for each gas is described in Table 18. During the hot start tests data was recorded at 10-second intervals. This was necessary, as the system required the 10 seconds to purge the system between samples for this type of testing.

Table 18: Accuracy of Exhaust Gas Results

<table>
<thead>
<tr>
<th>Exhaust Constituent</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>± 0.01</td>
</tr>
<tr>
<td>CO</td>
<td>± 0.1</td>
</tr>
<tr>
<td>NOₓ</td>
<td>± 0.01</td>
</tr>
<tr>
<td>CO₂</td>
<td>± 0.0001</td>
</tr>
<tr>
<td>O₂</td>
<td>± 0.001</td>
</tr>
<tr>
<td>AFR</td>
<td>± 0.01 of Ratio</td>
</tr>
</tbody>
</table>

10.8 Fuel Rail Coating

The fuel rail coating that was used for this work is an epoxy matrix mixed with polytetrafloroethylene (Teflon) and carbon particles. The primary use of this product is as coating that will provide dry lubrication with electrical conductivity. It was chosen for this work for its thermal and electrical properties. This material had a lower thermal
diffusivity than stainless steel but can be used in environments where the temperature is up to 260°C. In addition it provided a degree of electrical conductivity that would reduce the likelihood of a static build up on the internal surfaces of the fuel rail due to the flow of the fuel.

Based on the information available [38] the three primary components of this coating (epoxy resin, PFTE and carbon) all show excellent resistance against chemical attack from the components of LPG (methane, ethane, propane, propene, butane, pentane and hexane)

The original fuel rail material was cleaned and degreased. The coating was then applied to the internal passages of the fuel rail by flooding the rail with the coating. The excess coating was then drained from the tubing. Finally, the tubes were hung inside an oven to be cured at 232°C for 10 minutes. This process resulted in a 50 μm thick coating of Xylan covering the inner passages of the fuel rail.

10.9 Coated Fuel Rail Setup and Testing

Following the coating of the fuel rail the rail was inspected to insure that the flow passages were not blocked. The fuel rail was reassembled and mounted on the same vehicle that was used for the all steel fuel rail testing. The vehicle was then tested using the same procedure that was used to obtain the all steel fuel rail results.
CHAPTER 11: PRESENTATION OF FUEL RAIL DESIGN STUDY RESULTS

Typical data sets are presented and described in the following section as an introduction to the type of data that was recorded. A detailed comparative analysis of the results will be included in Chapter 12: Discussion and Analysis of Fuel Rail Results.

11.1 Computational Analysis of Fuel Rail

The following plots show typical results of the computational transient thermal analysis. The model used was a simplified model of a section of the fuel rail tubing. To simplify the calculation the radial system was reduced to a linear wall representing a sector of the tube cross section and the convection coefficient was kept constant as described in Chapter 9: Computational Analysis of Proposed Fuel Rail Design Solution.

The results presented in Figure 73 are the outputs for a steel wall and those shown in Figure 74 are for a coated steel wall with a 50 μm (2 mil or 0.002") coating of conductive Xylan coating.
Figure 73: Transient Temperature Distribution Across Non-coated Steel Wall, Calculation Output

Figure 74: Transient Temperature Distribution Across Steel Wall With a 2 mil Xylan Coating
Each line shown in the above figures represents the temperature profile within the cross section of the fuel rail tubing. The x-axis describes the location of the point relative to the inner surface of the fuel rail. The y-axis details the temperature of the point described. The upper most line on both figures shows that at $t = 0$ s all of the material within the fuel rail is at a uniform temperature of 325 K. As time progresses the temperature of the material is described by the next line down. The results shown in Figure 73 show a gradual reduction in temperature at the inner surface of the fuel rail. The results shown in Figure 74 show a more sudden reduction in temperature, particularly within the coated inner surface of the fuel rail. The inner coating of the fuel rail is represented by the 0 to $50 \times 10^{-6}$ m region of the x-axis. As well these results showed that for any given time the inner surface of coated wall was cooler than that of the all steel wall.

11.2 Experimental Fuel Rail Results

11.2.1 Hot Start Exhaust Temperatures and EPP Data.

The data presented in this section is a sample of all that was recorded. The plots of both the coated and all steel fuel rail results that are not presented below are shown in Appendix K: Fuel System Temperature and Pressure Data Recorded During Hot Start Tests. Figure 75 and Figure 76 show the exhaust gas and EPP count data recorded during one of the hot start trials of the all steel fuel rails. The features that were found in these figures were similar to those that were recorded during the coated fuel rail hot start trials and thus these plots are used to describe the common features of these two fuel rail setups. A detailed comparison between the results of the coated and all steel fuel rail is detailed in Chapter 12: Discussion and Analysis of Fuel Rail Results.
Figure 75: All Steel Fuel Rail, EGT and EPP Count Hot Start Trial 1

Figure 76: All Steel Fuel Rail, t = 29 – 33 s  EGT and EPP Count Hot Start Trial 1

The above figures show the hot start test exhaust gas temperatures and EPP count for trial 1 of the all steel fuel rail and trial 6 of the coated fuel rail. The x-axis details the time that has elapsed since the start of engine cranking.
Figure 75 shows an increase in both exhaust temperature and EPP count at \( t = 4 \) s. It can be seen that this is a false start as the exhaust temperature starts to decline at \( t = 6 \) s. These false starts are common amongst all hot start data. The starting motor was run continuously during the false starts to insure that each trial was similar. From \( t = 6 \) s to \( t = 28 \) s the engine is turned over without any combustion occurring as shown by the gradual reduction in exhaust temperature. At \( t = 28 \) s combustion occurs in cylinders 8 and 6 as shown by the increases in exhaust temperature. Following a 2-second delay combustion occurs in cylinders 4 and 2. At \( t = 28 \) s the EPP count stopped its rise indicating that the engine was turning under its own power and no longer requires the assistance of the starter motor. The details of the delay in ignition times between the two pairs of cylinders are shown in Figure 76.

11.2.2 Fuel Temperature and Pressure Results

![Graph showing fuel temperature and pressure over time](image)

Figure 77: All Steel Fuel Rail, Fuel Temperatures and Pressure Hot Start Trial 5

Figure 77, above, shows an example of the fuel temperature and pressure data that was recorded during the hot start tests. The x-axis details the time that has elapsed since the
start of engine cranking. A detailed analysis of the fuel temperature and pressure data will be presented in Chapter 12: Discussion and Analysis of Fuel Rail Results

11.2.3 Fuel Rail Surface Temperature Data

![Graph showing temperature variations](image)

Figure 78: All Steel Fuel Rail External Surface Temperatures Hot Start Trial 5

Figure 78, above, shows the data from the surface thermocouples mounted on the exterior of the fuel rail tubing. The data above shows an initial discrepancy in external temperatures at different points along the fuel rail at \( t = 0 \) s. This is due to an uneven temperature distribution at different points around the engine. The path of coolant flow through the head is such that coolant exiting the engine block enters the cylinder head near TS3 and flows towards the radiator. The flow passages then carry the coolant near the location of TS2 and then TS1 before passing through a hose to the radiator. Although there is no coolant flow during the hot soak period prior to the hot start the temperature of any point on the cylinder head will be related to the coolant path length to the radiator. Since during the hot soak the coolant within the engine block will be absorbing heat and the coolant at the radiator will be losing heat the temperature of the coolant will vary along a gradient between these two points. Thus the temperature of the engine components near the coolant passages, such as the fuel rail, will based on the proximity
of the component to the coolant flow passages and the location of that coolant passage relative to the cooling system radiator. Since the cross tube thermocouple is located closer to the cylinder head compared to the thermocouples for the supply and return fuel rail surface temperature the expected relative fuel rail material temperatures are TS2 > TS3 > TS1.

![Graph showing temperature and pressure over time](image)

Figure 79: Hot Start Supply Tubing and Fuel Temperature Steel Fuel Rail #1

A difference between the fuel and fuel rail surface temperatures at the beginning of the hot start is clearly shown at the supply tube location are shown above in Figure 79. The difference in temperature is due to the temperature gradient that exists between the fuel and the engine compartment. Heat travels from the engine compartment through the insulation on the fuel rail, through the fuel rail tubing and then to the fuel. Each of these materials acts as a resistance to the passage of heat. Since these temperatures do not reach an equilibrium during the 30 minute hot soak, the fuel within the rail will always be cooler than the external temperature of the fuel rail following a 30 minute hot soak.

Figure 78 shows that as the fuel pumps start during the start of engine cranking the external surface temperature of the fuel rail decreases at the TS1 location. Fuel that is cooler than the fuel rail is pumped from the fuel tank at the start of engine cranking. This
results in a cooling of the fuel rail material due to a combination of convection of latent cooling. As expected since the fuel first arrives at the TS1 location this location shows the first drop in temperature followed by TS2 and TS3 as the cool liquid fuel reaches these locations.

11.2.4 Hot Start Emissions Data

Emissions data was recorded during the hot starts to determine if there was an emissions advantage to using an internal coating on the fuel rail. The concentration of the exhaust species was analyzed following each 10 seconds of engine operation. Thus the first emission data point was recorded 10 seconds after the start of engine cranking as shown on the following figures. The features of the emission traces were similar for both the all steel and coated fuel rail, however the magnitude of the features differed between the two set ups. The details of the all steel fuel rail emission traces shown in Figure 80 though Figure 84 are discussed below. Since the features of the emission data were similar for both fuel rail setups only the all steel fuel rail results are explained in this section. The hot start emissions that were obtained while the vehicle was operated using the coated fuel rail were recorded as well and this data can be found in Chapter 25: Appendix L: Transient Emissions Data Recorded During Hot Start Tests. The average all steel and coated fuel rail results are compared in Chapter 12: Discussion and Analysis of Fuel Rail Results.

Only the first four data points of the all steel emission tests trial 4 was recorded due to a data acquisition error. As well, no emission data was recorded for the 6th hot start trial of the coated fuel rail due to a malfunction of the emission analysis equipment.
Figure 80: All Steel Fuel Rail, Hot Start HC Emissions

Figure 80, above, shows the hydrocarbon exhaust concentration from all of the all steel fuel rail hot start trials. The x-axis shows the time after the start of engine cranking. The y-axis described the HC concentration in parts per million (ppm). All of the trials shown in Figure 80 and those from the coated fuel rail (shown in Appendix L: Transient Emissions Data Recorded During Hot Start Tests) showed a peak in hydrocarbon emissions following the start of engine cranking. This was the expulsion of fuel that accumulated in the intake manifold during the hot soak combined with the gaseous fuel that was injected during startup. This peak dropped off at $t = 50$ s and leveled off once the engine started.
Figure 81: All Steel Fuel Rail, Hot Start CO Emissions

Figure 81, above, shows the CO exhaust concentration for the all steel fuel rail hot start trials. The initial peak shown in the above results was present in the coated fuel rail results as well. This peak was due to the misfires that occurred during the starting of the engine. The rise of CO emissions that occurs after $t = 60s$ is again due to misfires following engine shut down.
Figure 82: All Steel Fuel Rail, Hot Start CO₂ Emissions

Figure 82, above, shows the CO₂ exhaust concentration for all of the all steel hot start trials. As expected these results show a rise in CO₂ concentration following engine ignition. The results from trials 1 and 2 of the all steel fuel rail hot start tests show a later rise in CO₂ concentration. This correlates with the longer start times for these trials.
Figure 83: All Steel Fuel Rail, Hot Start O₂ Emissions

Figure 83, above, shows the O₂ exhaust concentration for all of the all steel hot start trials. As expected these results show a drop in O₂ concentration following engine ignition. The results from trials 1 and 2 of the all steel fuel rail hot start tests show a later drop in O₂ concentration. This correlates with the longer start times and later ignition times for these trials.
Figure 84: All Steel Fuel Rail, Hot Start NOx Emissions

Figure 84, above, shows the NOx exhaust concentration for all of the all steel hot start trials. The NOx concentration shows an early peak due to the higher initial production of NOx during slow engine speeds when some combustion was occurring but the engine still required the starter motor to keep the engine turning. This peak is followed by a gradual rise in NOx concentration following engine ignition in all cylinders and the resulting increase in cylinder temperature.

11.2.5 Hot Start Times, EPP Counts and Fuel System Pressures

The following table presents a summary of the data obtained from the hot start testing. The time required to start the engine is detailed by the EPP count and the start time columns. The tank pressure is the value of fuel pressure that was recorded before the fuel pumps were started. The final rail pressure is the fuel maximum fuel pressure recorded during the hot start. Delta pressure is the difference between these two
pressures. The starter motor was stopped for 2 seconds following the false starts of the coated fuel rail trials 1, 2 and 3 due to operator error. Since the start procedure differed from that used for the all steel fuel rail all results from these trials were not included in the results analysis.

A significant amount of temperature, pressure and EPP data from the all steel fuel rail trials 2, 3 and 4 was lost due to data acquisition failures. The starting procedure was correctly followed during these trials and therefore the start time and emission data were valid and will be included in the analysis.

Table 19: Summary of Hot Start Test Data

| TRIAL | ALL STEEL FUEL RAIL |  |  |
|-------|---------------------|---|---|---|
|       | EPP COUNT | START TIME | TANK PRESSURE | FINAL RAIL PRESSURE | DELTA PRESSURE |
| 1     | 255       | 29.43 s    | 1.073 MPa     | 1.147 MPa           | 0.074 MPa     |
| 2     | 255       | 25.24 s    | 1.215 MPa     | 1.373 MPa           | 0.158 MPa     |
| 3     | 157       | 1.343 MPa  | 1.458 MPa     | 0.115 MPa           |
| 4     | 182       | 18.28 s    | 1.431 MPa     | 1.504 MPa           | 0.073 MPa     |
| 5     | 189       | 16.69 s    | 1.482 MPa     | 1.637 MPa           | 0.155 MPa     |

| TRIAL | COATED FUEL RAIL |  |  |
|-------|------------------|---|---|---|
|       | EPP COUNT | START TIME | TANK PRESSURE | FINAL RAIL PRESSURE | DELTA PRESSURE |
| 1     | 117       | 11.68 s    | 1.263 MPa     | 1.482 MPa           | 0.219 MPa     |
| 2     | 70        | 8.65 s     | 1.126 MPa     | 1.459 MPa           | 0.333 MPa     |
| 3     | 90        | 10.62 s    | 1.206 MPa     | 1.476 MPa           | 0.270 MPa     |
| 4     | 120       | 11.51 s    | 1.221 MPa     | 1.476 MPa           | 0.255 MPa     |
| 5     | 122       | 11.25 s    | 1.263 MPa     | 1.489 MPa           | 0.226 MPa     |
| 6     | 126       | 11.63 s    | 1.230 MPa     | 1.491 MPa           | 0.261 MPa     |
CHAPTER 12: DISCUSSION AND ANALYSIS OF FUEL RAIL RESULTS

12.1 Computational Results

The computational analysis was run for coating thickness of 25 μm, 50 μm and 100 μm to test that the computational model behaved in the manner expected, as the coating became thicker. The results of these analyses are included in Appendix J: Output of Explicit Transient Conduction Analysis of this paper. These figures show that the degree of coated surface cooling increased with an increase in coating thickness.

The point of interest of the results of the computational analysis is the temperature of the inner surface node (x = 0.0 m). This surface must cool to the liquid saturation temperature of propane (at fuel rail pressure) as quickly as possible so that liquid propane can pass through the tubing without vapourizing.

Figure 73 of the results section 11.1. show the temperature distribution of a section of the steel fuel rail as it is subjected to convection and transient conduction. It can be seen that after a time of 140 ms the minimum temperature of the inner surface of the fuel rail has decreased from 325 K to approximately 321.5 K.

Figure 74 of the results in Section 11.1 show the temperature distribution of a fuel rail with an inner surface that has been coated with 50 μm of Xylan. This coating thickness was chosen, as it is the thickest coating that can be applied for this application. (Data that describe the outcome of using coatings of other thickness have been included in Appendix J: Output of Explicit Transient Conduction Analysis). It can be seen that when a coating of 50 μm of Xylan is used the inner surface of the fuel rail cools to approximately 317.5 K after 140 ms of cooling.

This model showed that by applying a coating, the internal surface temperature of the fuel rail will be almost 4.0 K cooler than an all steel design after only 140 ms of exposure.
to transient conduction and convection. The limitations of the model were mentioned earlier, however the trend that was predicted supports the hypothesis that an internal coating of Xylan lead to an increased rate of cooling of the internal surface of the fuel rail.

12.2 Experimental

The complete results from the hot start testing are shown in Appendix K: Fuel System Temperature and Pressure Data Recorded During Hot Start Tests. Specific examples of these results were presented in Chapter 11: and will be referred to in this section. The exhaust gas temperature traces shown in Figure 75 from the hot start show a rise in temperature at $t = 4$ s of for all four cylinders. This phenomenon is a misfire that can be attributed to leaking fuel injectors as opposed to the normal function of the fuel system. Research in fuel injector deposits presented in this thesis shows that operating a vehicle on HD-5 LPG for as little as 6 400 km will result in the formation of deposits within the injectors. These deposits will degrade the sealing ability of an injector. The fuel injectors that were installed in this vehicle had been operating for approximately 35 000 km and would have developed deposits within. Therefore, it is hypothesized that during the 30-minute hot soak used during this test some fuel leaked into the manifold. Upon startup this rich mixture within the intake manifold was supplied to the cylinders and ignited. The engine was turned with the power from this combustion. However since the fuel within the rail is in a gaseous state following a 30 minute hot soak [23], an insufficient amount of fuel was supplied to the cylinder such that combustion that resulted from the fuel that had accumulated during hot soak could not be supported by the lean mixture that was supplied. This lead to the engine faltering and the action of the starter motor was required to continue turning the engine until consistent mixture could be supplied to the cylinder. Since there was no combustion the exhaust temperature slowly dropped as the starter motor turned the engine pumping air through to the exhaust.

As the starter continued to crank the engine, the fuel rail and injectors were cooled by the convective and latent cooling of the liquid fuel that was pumped to the rail from the tank.
Once the rail and fuel injectors had cooled sufficiently, liquid could be metered through the injectors. Ignition within the lead two cylinders occurred as noted by the increase in EGT temperature for cylinders 8 and 6 as shown in Figure 76 of the results section 11.2.5.

The fuel that is supplied to the final two injectors on each branch of the fuel rail must first pass through the lead set of injectors and cross tube. During this process the fuel absorbs more heat from these parts resulting in a degree of fuel vapourization leading to the final two injectors attempting to meter fuel that is again not in a liquid state. The final two cylinders will continue to be supplied with a lean mixture for an additional few seconds after the lead cylinders have fired. This is shown in the lag between the rise in EGT temperatures of cylinders 2 and 4 compared against cylinders 6 and 8 as shown in Figure 76.

Approximately 40 seconds following initial engine cranking the engine was running and the exhaust gas temperature began to stabilize as shown in Figure 75. Cylinder 2 has the highest temperature followed by similar but lower temperatures of cylinders 6 and 4. Finally cylinder 8, the first cylinder to be supplied with fuel from the rail had the lowest exhaust gas temperature as shown in Figure 75.

The discrepancy in EGT temperatures between each cylinder is due to some boiling within the fuel as it absorbs heat while traveling between injectors and an injector attempting to meter a two-phase flow. This results in a richer mixture supplied to cylinder 8 and leaner mixture supplied to cylinder 2. This accounts for the higher exhaust gas temperatures of cylinder 2 and cooler exhaust gas temperatures of cylinder 8.
12.2.1 Hot Start Time Results Comparison

When comparing the hot start performance of the two fuel rail setups a significant improvement in hot start time was observed for the fuel rail with the internal coating of Xylan. Figure 75 and Figure 75 show typical EGT temperatures and EPP counts for hot starts with the all steel and coated fuel rail. Table 20 summarizes the valid data that was obtained during the hot start tests.

Table 20: Summary of Valid Hot Start Data

<table>
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<tr>
<th>TRIAL</th>
<th>ALL STEEL FUEL RAIL</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EPP COUNT</td>
<td>START TIME</td>
<td>TANK PRESSURE</td>
<td>FINAL RAIL PRESSURE</td>
<td>DELTA PRESSURE</td>
</tr>
<tr>
<td>1</td>
<td>255</td>
<td>29.43 s</td>
<td>1.073 MPa</td>
<td>1.147 MPa</td>
<td>0.074 MPa</td>
</tr>
<tr>
<td>2</td>
<td>255</td>
<td>25.24 s</td>
<td>1.215 MPa</td>
<td>1.373 MPa</td>
<td>0.158 MPa</td>
</tr>
<tr>
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<td>18.28 s</td>
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<td>1.458 MPa</td>
<td>0.115 MPa</td>
</tr>
<tr>
<td>4</td>
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<td>16.69 s</td>
<td>1.482 MPa</td>
<td>1.637 MPa</td>
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</table>

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>EPP COUNT</td>
<td>START TIME</td>
<td>TANK PRESSURE</td>
<td>FINAL RAIL PRESSURE</td>
<td>DELTA PRESSURE</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>11.51 s</td>
<td>1.221 MPa</td>
<td>1.476 MPa</td>
<td>0.255 MPa</td>
</tr>
<tr>
<td>5</td>
<td>122</td>
<td>11.25 s</td>
<td>1.263 MPa</td>
<td>1.489 MPa</td>
<td>0.226 MPa</td>
</tr>
<tr>
<td>6</td>
<td>126</td>
<td>11.63 s</td>
<td>1.230 MPa</td>
<td>1.491 MPa</td>
<td>0.261 MPa</td>
</tr>
</tbody>
</table>

The above results show that when the vehicle was operated using the coated fuel rail setup resulted an average 11-second improvement in hot start time.

The above table shows that the tank pressure increased with successive trials for each setup. The tank pressure depends on tank temperature and will tend to increase with increasing number of tests as the temperature of the fuel within the tank increases. During operation, the mass of fuel that is pumped through the fuel rail is greater than the mass that is injected into the engine. The excess fuel that passes through the fuel rail absorbs heat from the engine in transit. This warm fuel is then dumped into the fuel tank, thereby increasing the average temperature of the fuel within the tank. The tank
temperature increase and its relation to the running time following cold start was predicted by a simple model of a liquid LPG PFI fuel system developed by Lutz et al. [39]. Since the fuel tank can be treated as a closed system containing an equilibrium of liquid and gaseous LPG, the increase in fuel temperature leads to an increased tank pressure. This trend is clear for the all steel fuel rail data shown in Table 20.

It was noted that the average fuel tank pressures varied significantly between the two fuel rail setups. This is due to the different times of year that the two sets of test were performed. Prior to testing the vehicles were parked in the outdoors for 8 hours, and the exterior temperature affected the fuel tank temperature. The all steel set of tests was performed in April at a temperature of 8°C and the coated fuel rail tests were performed in September at a temperature of 13°C. Although the fuel tank temperature was not recorded, it is believed that between the testing of the two fuel rail setups the increase in soaking temperature lead to an increase in fuel temperature and therefore a corresponding increase in average fuel tank pressure. Lutz et al. [39] developed a simple hot start time model that was based on a liquid LPG system similar to one studied in this paper. The results of this model demonstrated that an increase in fuel tank temperature (and therefore fuel tank pressure) lead to a decrease in hot start time. The increased fuel tank pressure noted during the coated fuel rail tests certainly contributed to the decrease in hot start time for this fuel rail setup.

The coated fuel rail showed an increase in the pressure difference between the fuel tank and the fuel rail. This pressure difference is normally caused by the resistance of the back check valve and is referred to as the boost pressure. However this increase in boost pressure between each fuel rail set may be due to the effects of the internal coating. The application of the xylan coating resulted in less than a 2% decrease in the flow area of the fuel rail which can be viewed as an insignificant change. However the coating surface roughness was not consistent throughout the rail. Prior to installation of the coated fuel rail all internal surfaces were checked and any excess coating was removed to insure that the flow passages were as smooth as possible. Generally it can be assumed that the flow
passages of the coated fuel rail were not as smooth as the all steel fuel rail this lead to an increased resistance to flow within the fuel rail passages.

Data presented in Table 20 showed that the average boost pressures for the for the all steel and coated fuel rail were 0.115MPa and 0.247MPa respectively. The fuel system model developed by Lutz et al. [39] demonstrated a relation between boost pressure and start time for the pump curve that was used in the modeled system. The results from the model showed that due to the lower flow rates that the pump can provide at the higher boost pressure, the increased boost pressure lead to a longer hot start time. These results show that the effect of the increased boost pressure that was noted during the testing of the coated fuel was to increase the hot start time.

The above arguments suggest that the decreased hot start time that was noted with the use of the coated fuel rail setup was due to either the coating or the increase in fuel tank pressure. By comparing results from the two fuel rail setups that were tested at the same tank pressure the effect of the fuel rail coating can be evaluated. The results of the second trial for the all steel fuel rail and those from the fourth trial from the coated fuel rail show the effect of the coating. When the fuel tank pressure was kept constant the use of coating on the inner surface of the fuel rail resulted in a 13.7 second decrease in start time following a 30-minute hot soak.

The improvement in hot start time demonstrated by the coated fuel rail, was most likely due to a faster cooling of the inner surfaces of the fuel rail. This faster cooling allowed liquid fuel to reach the fuel injectors sooner: with less boiling. This lead to earlier ignition.

12.2.2 Comparison of Fuel System Pressure and Temperature Traces

Figure 85 and Figure 86 show the traces of the fuel rail surface and fuel temperatures for the supply section of the fuel rail. This data was recorded by the thermocouples in the
fuel and mounted on the external surface of the fuel rail tubing. The data from the supply section of the fuel rail shows the clearest difference between the two fuel rails. All other fuel and surface temperature data is presented in Appendix K: Fuel System Temperature and Pressure Data Recorded During Hot Start Tests.

Figure 85: Hot Start Supply Tubing and Fuel Temperature Steel Fuel Rail #1
The supply tube fuel rail external temperature (TS1) data from trial #1 (29.4 s hot start time) of the all steel fuel rail tests presented in Figure 85 showed a distinct two stage cooling process. The fuel rail material temperature dropped by $\Delta T = -7^\circ C$ in a slow negative exponential at $t = 0$ s until $t = 11$ s during trial five. Then at $t = 11$ s the temperature then dropped at a strong negative exponential rate for $\Delta T = -20^\circ C$ over the following 40 s. This rate of the exponential temperature drop was that of the fuel and was not limited by the time constant of the thermocouple based on data from step input tests of the thermocouples.

Results of the supply tube external temperature (TS1) from the fourth trial (11.5 s hot start time) of the coated fuel rail are shown in Figure 86. These results showed a much shorter period of slow temperature drop during $t = 0$ s to $t = 5$ s that only cooled the fuel rail by $\Delta T = -4^\circ C$. This was followed by a more dramatic temperature drop of $\Delta T = -30^\circ C$. 

Figure 86: Hot Start Supply Tubing and Fuel Temperature Coated Fuel Rail #4
These results would suggest that for both equipment setups the cooling process was the same, but the time periods of each cooling phase varied significantly. Initially the fuel rail material temperature decreased in a slow exponential that described the transient convection of cool gaseous LPG (from upstream vapourization) that cooled the local fuel rail tubing. The temperature then dropped suddenly when the liquid LPG reached the thermocouple location and transition nucleate boiling heat transfer takes over as the liquid LPG vapourizes on the hot surface.

The shorter gaseous LPG convective cooling period of the coated fuel rail can be explained by the results of the computer model. The coating of the internal surfaces lead to a faster cooling of the surfaces that are in contact with the liquid LPG. Since there was a shorter period when a section of tubing was hot enough to vapourize the LPG, less gaseous LPG was created. Thus for the coated fuel rail the convection cooling process was significantly shorter as there was a lower volume of vapour passing each point within the system. This lead to liquid LPG reaching each point in the system much faster for the coated fuel rail when compared to the all steel fuel rail resulting in a shorter hot start time.

Figure 87: Hot Start Return Tubing and Fuel Temperature Steel Fuel Rail #5
The fuel temperature, fuel rail surface temperature and pressure traces on the return section of the fuel rail are shown as TS3, TF2 and P1 on Figure 87 and Figure 88. These data give further indicators of how the inner surface of the coated fuel rail cooled more quickly. Similar to the external fuel rail temperatures the coated fuel rail showed an earlier drop in fuel temperature when compared to the all steel fuel rail.

A point of interest is that the return fuel temperature (TF2 Figure 89) recorded from the coated fuel rail test shows a significant increase in fuel temperature immediately after initial engine cranking followed by a sudden drop at 6 seconds. Comparatively the fuel return temperature (TF2 Figure 90) of the all steel fuel rail rises only slightly following initial engine cranking and remains relatively constant before suddenly dropping at 13 seconds. If the coating does result in a faster decrease in the inner surface temperature, less vapourization of liquid fuel would occur within the fuel rail upstream of the return fuel temperature thermocouple. This would result in less cooling of the gaseous LPG that is purged from the system during startup, leading to an increased temperature of the
purged LPG gas that is forced past the return fuel thermocouple when compared against the results of the all steel fuel rail.

The pressure traces of the two types of fuel rail show that there is almost twice the pressure difference between the tank and the rail for the coated fuel rail. The greater pressure difference of the coated fuel rail most likely resulted in a higher flow rate for the coated fuel rail condition, but this could be limited by the characteristics of the fuel pump. Although flow rate within the fuel rail was not measured due to the difficulty of installing a two-phase flow meter on a running engine, it can be estimated using the fuel temperature data shown in Figure 89 and Figure 90 below. Assuming that the sudden drop in fuel temperature defines the point when liquid LPG reaches the thermocouple and begins to boil due to the high local surface temperatures. With this assumption we can state that the time difference between the sudden drop in supply fuel temperature and return fuel temperature describes the time required for the liquid LPG to travel between the two points. Comparing this time difference shows that the time is 3.0 seconds difference for the all steel fuel rail and 1.8 seconds for the coated fuel rail. This increased flow rate certainly resulted in higher convection heat transfer rates, which may be one of the factors that account for the improvement in hot start.

However if less LPG liquid is lost to vapour production liquid LPG will move through the system with greater speed. This could be working in conjunction with the greater pressure difference to lead to a faster start time for the coated fuel rail.
Figure 89: Coated Fuel Rail Cooling Delay Details Hot Start 4

Figure 90: All Steel Fuel Rail Cooling Delay Details Hot Start 1
The supply fuel temperature for both the coated and all steel fuel rail results presented above in Figure 89 and Figure 90 show two distinct cooling stages that are separated by a temperature plateau. The supply fuel temperature of the coated fuel rail and all steel fuel rail leveled off at 44°C and 56°C respectively during the cooling of the hot start. These temperatures were between 8°C and 13.5°C less than the saturation temperatures at the test pressures. The pressure transducer was downstream of the supply fuel temperature thermocouple and could have underestimated the value of the pressure at the thermocouple location. Thus it could be assumed that these plateaus were indicators of the liquid LPG vapourizing when it came in contact with the hot fuel rail tubing.

12.2.3 Hot Start Emission Results Comparison

The emission results from the two fuel rail setups show similar trends for all species. Figure 91 through Figure 95 compare the average emission values for each fuel rail setup. The area under each transient emission curve was integrated to develop an estimate of the cumulative emissions for each fuel rail setup. The integrated results are shown in the figures.
Figure 91: Comparison of Hot Start HC Emissions

Figure 92: Comparison of Hot Start CO Emissions
Figure 93: Comparison of Hot Start CO2 Emissions

Figure 94: Comparison of Hot Start O2 Emissions
The average HC emissions are shown in Figure 91, results from the all steel fuel rail showed a wider HC peak when compared to the peak from the coated fuel rail. This wide peak was most likely due to the longer starting times of the all steel fuel rail setup. While the engine is cranking without firing unburned fuel is pumped through the engine to the exhaust. By integrating the average HC results over the 70-second steady state idle period of emission recording it was determined that the use of the coated fuel rail resulted in a 38% decrease in HC emissions over the testing period.

Compared to the coated fuel rail the all steel fuel rail showed higher initial CO emissions as shown in Figure 92. This was due to the longer starting times of the all steel fuel rail could have resulted in a greater number of engine misfires that produce CO. By integrating the average CO emission results over the 70-second steady state idle period of emission recording it was determined that the use of the coated fuel rail resulted in a 25% decrease in CO emissions over the testing period.
The CO\textsubscript{2} and O\textsubscript{2} emission results are very similar between the two fuel rails, the only
difference being the distinct time shift of the all steel results to the right due to the longer
start up time the all steel fuel rail setup as shown in Figure 93 and Figure 94. By
integrating the average CO\textsubscript{2} results over the 70-second steady state idle period of
emission recording it was determined that the use of the coated fuel rail resulted in a
8.4\% increase in CO\textsubscript{2} emissions over the testing period. By integrating the average O\textsubscript{2}
results over the 70-second steady state idle period of emission recording it was
determined that the use of the coated fuel rail resulted in a 21\% decrease in O\textsubscript{2} emissions
over the testing period.

The NO\textsubscript{x} emissions from the two vehicle setups varied to some degree as shown by
Figure 95. Both fuel rail types lead to low initial NO\textsubscript{x} values in the first 10 seconds
followed by a peak at 20 seconds that returns to a low point at 30 seconds. At the times
of 40 and 50 seconds the emission results of the two setups deviate. Use of the coated
fuel rail lead to NO\textsubscript{x} emissions that were approximately 20 PPM greater than the all steel
fuel rail over this period.

By integrating the average NO\textsubscript{x} results over the 70-second steady state idle period of
emission recording it was determined that the use of the coated fuel rail resulted in a
2.6\% decrease in NO\textsubscript{x} emissions over the testing period.

12.3 Relation of Computational Analysis to Hot Start Results

Based on the output of the computer model of the transient heat transfer problem, the
interior of the coated fuel rail tubing should cool at a faster rate when compared to the all
steel fuel rail. This was supported by the increased rate of cooling of the fuel rail material
as explained in the external temperature section.

Since the coating acts to insulate the inner surface from the thermal mass of the steel fuel
rail tubing the exterior of the tubing should show a slower cooling rate. The fuel and
fuel rail material temperature data from the supply section of the fuel rail was presented earlier in Figure 85 and Figure 86. The results from these figures indeed show a more gradual cooling of the fuel rail material (TS1) for the coated fuel rail when compared to the near vertical temperature drop shown for the all steel fuel rail setup.
CHAPTER 13: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

13.1 Fuel Injector Durability Study

The data obtained from this research program shows that the use of anti-deposit additives in LPG fuel will lead to a significant reduction in fuel injector deposits and fuel injector leakage. Operating an LPG vehicle on these additive treated fuels will improve the FTP exhaust emission levels for mileage-accumulated engines operating with liquid LPG PFI fuel systems. The deposits that were found within the fuel injectors were shown to be composed of sulphur and zinc. Although the exact deposit formation mechanism is unknown the use of surfactant or dispersant type fuel additives can lead to the elimination of deposits within the fuel injectors.

Operating fuel injectors on FUEL H lead to a significant increase in the average fuel injector leakage rate compared against fuel injectors that operated on additive treated or low sulphur fuels. This reduction in leakage rate lead to superior FTP emission performance. An improvement in bag 1 NMHC FTP emissions of approximately 50% was shown for fuel injectors that were operated on the additive treated fuels, FUEL V and FUEL C relative to those that were operated on additive-free FUEL H. The use of additive treated FUEL V lead to 32% increase in weighted FTP CO emissions when compared against the additive-free FUEL H. Conversely the alternate additive treated FUEL C lead to 24% decrease in weighted FTP CO emissions when compared against the additive-free FUEL H.

The FTP Bag 1 NMHC emission results from the FUEL P fuel injectors of this study showed a strong improvement over those from FUEL H. However since deposits were found within the FUEL P injectors, and this fuel rail was not removed and reinstalled prior to emission testing it is questionable if these FTP emission results can be compared against those from the other fuel injector groups.
Significant differences in the FTP NOx emissions of each fuel injector group were found during this study. The most significant differences were seen in the FTP NOx emissions from Bag 3. When comparing the results from FUEL H fuel injectors against those that were mileage-accumulated on additive treated fuels. A 122% increase in the level of Bag 3 FTP NOx emissions were recorded for the injector group FUEL C relative to the FUEL H injectors. Conversely, the injectors from the FUEL V group showed a 9% decrease in the Bag 3 FTP NOx emissions relative to the emissions of the FUEL H injectors.

This study has shown that the use of fuel injectors with titanium coated seats can improve the bag 1 NMHC FTP emissions. However further research should be competed to further support to the conclusion.

It is recommended that further research be performed to develop a laboratory based LPG fuel injector deposit formation technique similar to the current ASTM method used for gasoline fuel injectors. Research should be performed to determine if the sulphur deposits that were found on the exterior of the orifice plate of the FUEL P fuel injectors are a result of a lower solubility of ethyl mercaptain within the LPG composed of lighter components. If the specifications of HD-5 were altered to eliminate the heavier components sulphur deposits may become a new issue with LPG vehicles.

13.2 Fuel Rail Design Study

This study demonstrated that the hot start time of a liquid port injection LPG fuelled engine can be reduced by approximately 49% by coating the internal passages of the fuel rail with Xylan coating.

The transient emission results over the 70-second emission recording period showed a decrease in all of the exhaust emissions that are currently controlled by North American environmental legislation. This included a 38% decrease in HC emissions, 25% decrease in CO emissions and a 2.6% decrease in NOx emissions.
Further studies must be performed to confirm that these results are a result of the coating as opposed to the significant increase of the fuel tank / fuel rail pressure difference or increased tank pressure that was recorded between the coated and all steel fuel rail trials.

No literature was found on the cooling and purging of vapour filled coated tubing with a low vapour pressure fluid. A well-designed laboratory based study using liquid and gaseous nitrogen could clearly determine if a thin coating could improve the purging time of vapour filled tubing with a liquid. This type of study would eliminate the additional variables that were encountered while performing test on a vehicle.

Further research must be performed to develop a cost-effective method of manufacturing lined tubing for this type of solution to be viable.
CHAPTER 14:  APPENDIX A: FUEL INJECTOR LEAKAGE DATA
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Initial Leak 1</th>
<th>Initial Leak 2</th>
<th>Initial Leak 3</th>
<th>Initial Avg T2 &amp; T3</th>
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<th>Final Leak 2</th>
<th>Final Leak 3</th>
<th>Final Leak 4</th>
<th>Final Avg T2, T3, T4</th>
<th>Std Dev</th>
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<th>Final Leak 6</th>
<th>Final Leak 7</th>
<th>Final Leak 8</th>
<th>Final Avg T6, T7, T8</th>
<th>Std Dev</th>
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<th>Std Dev</th>
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<th>Avg Final Leakage</th>
<th>Avg Final StdDev</th>
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Figure 96: FUEL C Injector Group Initial and Final Leakage Data and Comments

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min.
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<th>Final Leak 1</th>
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Figure 97: FUEL H Injector Group Initial and Final Leakage Data and Comments

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min.
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<th>Final Leak 1</th>
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<th>Final Leak 3</th>
<th>Final Leak 4</th>
<th>Final Avg T2, T3, T4</th>
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<td>0.01</td>
<td>0.01</td>
<td>0.09</td>
<td>0.17</td>
<td>0.16</td>
<td>0.14</td>
<td>0.04</td>
<td>0.14</td>
<td>0.12</td>
<td>0.10</td>
<td>0.13</td>
<td>0.12</td>
<td>0.02</td>
<td>yellow deposits at injector tip</td>
<td>0.26</td>
<td>0.15</td>
<td>0.0582</td>
<td>39.38</td>
</tr>
<tr>
<td>Inj #64c P Cyl #7</td>
<td>0.00</td>
<td>0.12</td>
<td>0.16</td>
<td>0.14</td>
<td>0.03</td>
<td>0.21</td>
<td>0.21</td>
<td>0.23</td>
<td>0.22</td>
<td>0.01</td>
<td>-0.04</td>
<td>0.22</td>
<td>0.24</td>
<td>0.25</td>
<td>0.24</td>
<td>0.02</td>
<td>0.01</td>
<td>0.17</td>
<td>0.20</td>
<td>0.23</td>
<td>0.20</td>
<td>0.02</td>
<td>yellow deposits at injector tip</td>
<td>0.14</td>
<td>0.22</td>
<td>0.0239</td>
<td>10.96</td>
</tr>
<tr>
<td>Inj #44c P Cyl #6</td>
<td>0.13</td>
<td>0.25</td>
<td>0.21</td>
<td>0.23</td>
<td>0.32</td>
<td>0.77</td>
<td>0.76</td>
<td>0.76</td>
<td>0.77</td>
<td>0.01</td>
<td>0.40</td>
<td>0.67</td>
<td>0.67</td>
<td>0.66</td>
<td>0.67</td>
<td>0.01</td>
<td>0.38</td>
<td>0.52</td>
<td>0.57</td>
<td>0.56</td>
<td>0.55</td>
<td>0.03</td>
<td>yellow deposits at injector tip</td>
<td>0.23</td>
<td>0.66</td>
<td>0.0964</td>
<td>14.56</td>
</tr>
</tbody>
</table>

Figure 98: FUEL P Injector Group Initial and Final Leakage Data and Comments

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min.
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Initial Leak 1</th>
<th>Initial Leak 2</th>
<th>Initial Avg T2 &amp; T3</th>
<th>Final Leak 1</th>
<th>Final Leak 2</th>
<th>Final Leak 3</th>
<th>Final Avg T2, T3 &amp; T4</th>
<th>Std Dev</th>
<th>Final Leak 5</th>
<th>Final Leak 6</th>
<th>Final Leak 7</th>
<th>Final Avg T6, T7 &amp; T8</th>
<th>Std Dev</th>
<th>Final Leak 9</th>
<th>Final Leak 10</th>
<th>Final Leak 11</th>
<th>Final Leak 12</th>
<th>Final Avg T10, T11 &amp; T12</th>
<th>Std Dev</th>
<th>Comments</th>
<th>Avg. Initial Leakage</th>
<th>Avg Final Leakage</th>
<th>Std Dev</th>
<th>%Dev</th>
<th>CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inj #T23 H Cyl #1</td>
<td>0.01</td>
<td>0.01</td>
<td>0.79</td>
<td>0.50</td>
<td>0.47</td>
<td>0.36</td>
<td>0.48</td>
<td>0.12</td>
<td>0.31</td>
<td>0.33</td>
<td>0.25</td>
<td>0.24</td>
<td>0.28</td>
<td>0.05</td>
<td>0.30</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.00</td>
<td>0.01</td>
<td>0.32</td>
<td>0.1433</td>
<td>45.36</td>
<td>0.31</td>
</tr>
<tr>
<td>Inj #T7 H Cyl #2</td>
<td>0.07</td>
<td>0.07</td>
<td>0.13</td>
<td>0.47</td>
<td>0.51</td>
<td>0.51</td>
<td>0.50</td>
<td>0.02</td>
<td>0.36</td>
<td>0.45</td>
<td>0.51</td>
<td>0.54</td>
<td>0.50</td>
<td>0.05</td>
<td>0.29</td>
<td>0.45</td>
<td>0.49</td>
<td>0.53</td>
<td>0.49</td>
<td>0.04</td>
<td>0.07</td>
<td>0.50</td>
<td>0.0328</td>
<td>6.592</td>
<td>0.42</td>
</tr>
<tr>
<td>Inj #T12 H Cyl #3</td>
<td>0.01</td>
<td>0.01</td>
<td>0.20</td>
<td>0.30</td>
<td>0.29</td>
<td>0.30</td>
<td>0.30</td>
<td>0.01</td>
<td>0.30</td>
<td>0.32</td>
<td>0.36</td>
<td>0.38</td>
<td>0.36</td>
<td>0.03</td>
<td>0.23</td>
<td>0.27</td>
<td>0.31</td>
<td>0.30</td>
<td>0.30</td>
<td>0.02</td>
<td>0.01</td>
<td>0.32</td>
<td>0.0347</td>
<td>10.94</td>
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<tr>
<td>Inj #T21 H Cyl #4</td>
<td>0.04</td>
<td>0.04</td>
<td>0.42</td>
<td>0.10</td>
<td>0.18</td>
<td>0.18</td>
<td>0.16</td>
<td>0.05</td>
<td>0.42</td>
<td>0.10</td>
<td>0.16</td>
<td>0.18</td>
<td>0.15</td>
<td>0.04</td>
<td>0.36</td>
<td>0.10</td>
<td>0.14</td>
<td>0.16</td>
<td>0.14</td>
<td>0.03</td>
<td>0.04</td>
<td>0.15</td>
<td>0.0357</td>
<td>24.33</td>
<td>0.11</td>
</tr>
<tr>
<td>Inj #T8 H Cyl #5</td>
<td>0.02</td>
<td>0.02</td>
<td>0.40</td>
<td>0.51</td>
<td>0.60</td>
<td>0.60</td>
<td>0.57</td>
<td>0.05</td>
<td>0.55</td>
<td>0.57</td>
<td>0.63</td>
<td>0.64</td>
<td>0.62</td>
<td>0.04</td>
<td>0.55</td>
<td>0.49</td>
<td>0.55</td>
<td>0.57</td>
<td>0.54</td>
<td>0.04</td>
<td>0.02</td>
<td>0.58</td>
<td>0.0507</td>
<td>6.812</td>
<td>0.56</td>
</tr>
<tr>
<td>Inj #T14 H Cyl #6</td>
<td>0.15</td>
<td>0.15</td>
<td>-0.03</td>
<td>0.22</td>
<td>0.27</td>
<td>0.25</td>
<td>0.25</td>
<td>0.03</td>
<td>0.12</td>
<td>0.12</td>
<td>0.15</td>
<td>0.13</td>
<td>0.14</td>
<td>0.02</td>
<td>0.11</td>
<td>0.09</td>
<td>0.13</td>
<td>0.16</td>
<td>0.13</td>
<td>0.04</td>
<td>0.15</td>
<td>0.17</td>
<td>0.0627</td>
<td>36.61</td>
<td>0.02</td>
</tr>
<tr>
<td>Inj #T5 H Cyl #7</td>
<td>0.09</td>
<td>0.09</td>
<td>0.77</td>
<td>0.26</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.01</td>
<td>0.45</td>
<td>0.18</td>
<td>0.20</td>
<td>0.18</td>
<td>0.19</td>
<td>0.01</td>
<td>0.48</td>
<td>0.17</td>
<td>0.18</td>
<td>0.20</td>
<td>0.19</td>
<td>0.02</td>
<td>0.09</td>
<td>0.21</td>
<td>0.0421</td>
<td>19.59</td>
<td>0.12</td>
</tr>
<tr>
<td>Inj #T15 H Cyl #5</td>
<td>0.18</td>
<td>0.18</td>
<td>1.09</td>
<td>0.26</td>
<td>0.17</td>
<td>0.16</td>
<td>0.20</td>
<td>0.06</td>
<td>0.50</td>
<td>0.18</td>
<td>0.14</td>
<td>0.14</td>
<td>0.16</td>
<td>0.02</td>
<td>0.51</td>
<td>0.16</td>
<td>0.12</td>
<td>0.13</td>
<td>0.14</td>
<td>0.02</td>
<td>0.18</td>
<td>0.16</td>
<td>0.0415</td>
<td>25.17</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Figure 99: FUEL H-TiN Injector Group Initial and Final Leakage Data and Comments

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min.
<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ini/Leak 1</th>
<th>Ini/Leak 2</th>
<th>Ini/Leak 3</th>
<th>Ini Ave T2 &amp; T3</th>
<th>Ini Ave T2, T3, T4</th>
<th>Ini Ave T6, T7, T8</th>
<th>Ini Ave T9, T10, T11, T12</th>
<th>Std Dev</th>
<th>Comments</th>
<th>Avg Ini Leakage</th>
<th>Avg Final Leakage</th>
<th>Std Dev</th>
<th>%Dev</th>
<th>CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inj #28 V Cyl #1</td>
<td>-0.28</td>
<td>0.01</td>
<td>0.05</td>
<td>0.03</td>
<td>1.69</td>
<td>0.77</td>
<td>0.69</td>
<td>0.68</td>
<td>0.71</td>
<td>0.05</td>
<td>1.13</td>
<td>0.71</td>
<td>0.66</td>
<td>0.70</td>
</tr>
<tr>
<td>Inj #60 V Cyl #2</td>
<td>-0.09</td>
<td>0.11</td>
<td>0.16</td>
<td>0.14</td>
<td>-0.24</td>
<td>0.02</td>
<td>0.06</td>
<td>0.08</td>
<td>0.06</td>
<td>0.03</td>
<td>0.36</td>
<td>0.57</td>
<td>0.67</td>
<td>0.63</td>
</tr>
<tr>
<td>Inj #2 V Cyl #3</td>
<td>0.11</td>
<td>0.02</td>
<td>0.09</td>
<td>0.06</td>
<td>-0.18</td>
<td>0.24</td>
<td>0.21</td>
<td>0.16</td>
<td>0.20</td>
<td>0.04</td>
<td>0.00</td>
<td>0.21</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>Inj #36 V Cyl #4</td>
<td>-0.06</td>
<td>0.12</td>
<td>0.17</td>
<td>0.15</td>
<td>0.11</td>
<td>0.33</td>
<td>0.44</td>
<td>0.40</td>
<td>0.39</td>
<td>0.06</td>
<td>0.10</td>
<td>0.34</td>
<td>0.40</td>
<td>0.41</td>
</tr>
<tr>
<td>Inj #17 V Cyl #5</td>
<td>-0.17</td>
<td>0.02</td>
<td>0.09</td>
<td>0.06</td>
<td>0.27</td>
<td>-0.06</td>
<td>0.01</td>
<td>0.03</td>
<td>-0.01</td>
<td>0.05</td>
<td>0.21</td>
<td>-0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Inj #14 V Cyl #6</td>
<td>0.17</td>
<td>0.28</td>
<td>0.26</td>
<td>0.27</td>
<td>-0.53</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.31</td>
<td>-0.05</td>
<td>-0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Inj #57 V Cyl #7</td>
<td>-0.24</td>
<td>0.10</td>
<td>0.13</td>
<td>0.12</td>
<td>-0.48</td>
<td>0.00</td>
<td>0.20</td>
<td>0.03</td>
<td>0.08</td>
<td>0.11</td>
<td>1.30</td>
<td>1.79</td>
<td>1.90</td>
<td>1.90</td>
</tr>
<tr>
<td>Inj #83 V Cyl #8</td>
<td>-0.02</td>
<td>0.19</td>
<td>0.24</td>
<td>0.22</td>
<td>0.28</td>
<td>0.68</td>
<td>0.90</td>
<td>0.02</td>
<td>0.90</td>
<td>0.02</td>
<td>-0.37</td>
<td>0.05</td>
<td>0.00</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 100: FUEL V Injector Group Initial and Final Leak Data and Comments

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min.
Figure 101: Change in Fuel Injector Leakage Rate Over 6 400 km "FUEL C"

Figure 102: Change in Fuel Injector Leakage Rate Over 6 400 km "FUEL H"
Figure 103: Change in Fuel Injector Leakage Rate Over 6 400 km "FUEL H" with TiN Seat Fuel Injectors

Figure 104: Change in Fuel Injector Leakage Rate Over 6 400 km "FUEL P"
Figure 105: Change in Fuel Injector Leakage Rate Over 6 400 km "FUEL V"
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Figure 107: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average CO Emissions for all Injector Groups
Figure 109: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average NOx Emissions for all Injector Groups
Figure 110: EPA-75 FTP Emissions: Bags 1-3 and Weighted Average MHC Emissions for all Injector Groups
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Figure 114: Transient Comparison of Engine Out HC Emissions for all Injectors: Hill 1 EPA-75 t=35-80
Figure 115: Transient Comparison of Engine Out HC Emissions for all Injectors: Hill 1 EPA-75 t=115-140
Figure 117: Transient Comparison of Engine Out AFR for all Injectors: Hill 1 EPA-75 t=35-80
Figure 119: Transient Comparison of Engine Out CO Emissions for all Injectors: Hill 1 EPA-75 t=0-35
Figure 120: Transient Comparison of Engine Out CO Emissions for all Injectors: Hill 1 EPA-75 t=35-80
Figure 121: Transient Comparison of Engine Out CO Emissions for all Injectors: Hill 1 EPA-75 t=115-140
Figure 122: Transient Comparison of Engine Out NOx Emissions for all Injectors: Hill I EPA-75 t=0-35
Figure 123: Transient Comparison of Engine Out NOx Emissions for all Injectors: Hill 1 EPA-75 t=35-80
Figure 124: Transient Comparison of Engine Out NOx Emissions for all Injectors: Hill 1 EPA-75 t=115-140
Figure 125: Transient Comparison of Engine Out CO2 Emissions for all Injectors: Hill 1 EPA-75 t=0-35
Figure 127: Transient Comparison of Engine Out CO2 Emissions for all Injectors: Hill 1 EPA-75 t=115-140 sec.
Figure 128: Transient Comparison of Engine Out O2 Emissions for all Injectors: Hill 1 EPA-75 t=0-35
Figure 129: Transient Comparison of Engine Out O2 Emissions for all Injectors: Hill 1 EPA-75 t=35-80 sec.
Figure 130: Transient Comparison of Engine Out O2 Emissions for all Injectors: Hill 1 EPA-75 t=115-140 sec.
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Figure 132: Transient HC Emissions from Cold Start and Idle Tests t=40-80
Figure 133: Transient CO Emissions from Cold Start and Idle Tests t=0-40
Figure 134: Transient CO Emissions from Cold Start and Idle Tests t=40-80 seconds
Figure 135: Transient NOx Emissions from Cold Start and Idle Tests $t=0$-40 seconds
Figure 136: Transient NOx Emissions from Cold Start and Idle Tests t=40-80 seconds
Figure 137: Transient CO2 Emissions from Cold Start and Idle Tests t=0-40 seconds
Figure 138: Transient CO2 Emissions from Cold Start and Idle Tests t=40-80 seconds
Figure 139: Transient O2 Emissions from Cold Start and Idle Tests t=0-40 seconds
Figure 140: Transient O2 Emissions from Cold Start and Idle Tests \( t=40-80 \) seconds
Figure 141: Transient AFR from Cold Start and Idle Tests $t=10-50$ seconds
Figure 142: Transient AFR from Cold Start and Idle Tests $t=40-80$ seconds
CHAPTER 18:  APPENDIX E: SEM AND EDS DATA
<table>
<thead>
<tr>
<th>INJ #</th>
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</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>1</td>
</tr>
<tr>
<td>Initial</td>
<td>-0.08</td>
</tr>
<tr>
<td>Final</td>
<td>0.27</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.08</td>
</tr>
<tr>
<td>Difference</td>
<td>0.34</td>
</tr>
<tr>
<td>Fuel</td>
<td>C</td>
</tr>
<tr>
<td>T</td>
<td>0746Y</td>
</tr>
</tbody>
</table>

**SEM NOTES**

<table>
<thead>
<tr>
<th>Contact Band Loc</th>
<th>Some Relief</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Band</td>
<td></td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.5</td>
</tr>
<tr>
<td>Width of Deposit Ring (um)</td>
<td>10</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>no</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>no</td>
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</tbody>
</table>

**Element Weight% of Deposit—**

- Si: 3.35%
- P: 0.14%
- S: 1.26%
- Ca: 0.24%
- Cr: 15.77%
- Fe: 76.58%
- Zn: 2.66%

*Fe, Si and Cr are signals from base metal of needle.*

**Figure 143: Fuel Injector #21 Data**
<table>
<thead>
<tr>
<th>INJ #</th>
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</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Initial</td>
<td>0.16</td>
</tr>
<tr>
<td>Final</td>
<td>0.18</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.12</td>
</tr>
<tr>
<td>Difference</td>
<td>0.02</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>1998X</td>
</tr>
</tbody>
</table>

**SEM NOTES**

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<th>Contact Band</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Contact Band Loc</td>
<td>no</td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>no</td>
</tr>
<tr>
<td>Width of Deposit Ring (um)</td>
<td>0</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>0</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>no</td>
</tr>
</tbody>
</table>

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Figure 144: Fuel Injector #80 Data
Figure 145: Fuel Injector #3 Data
<table>
<thead>
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<th></th>
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<tbody>
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<td></td>
</tr>
<tr>
<td>Initial</td>
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<td></td>
</tr>
<tr>
<td>Final</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Difference</td>
<td>1.18</td>
<td></td>
</tr>
</tbody>
</table>

**Fuel: H**

<table>
<thead>
<tr>
<th>T</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

**SEM NOTES**

<table>
<thead>
<tr>
<th>Contact Band Loc Band</th>
<th>Smooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.85</td>
</tr>
<tr>
<td>Width of Deposit Ring (um)</td>
<td>50</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>stained</td>
</tr>
</tbody>
</table>

Figure 146: Fuel Injector #4 Data
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Band Loc Band</td>
<td>Some relief</td>
</tr>
<tr>
<td>Contact Band Loc Band</td>
<td></td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.5</td>
</tr>
<tr>
<td>Width of Deposit Ring</td>
<td>50</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>Stained</td>
</tr>
</tbody>
</table>

Figure 147: Fuel Injector #7 Data
<table>
<thead>
<tr>
<th>INJ #</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>1</td>
</tr>
<tr>
<td>Initial</td>
<td>-0.08</td>
</tr>
<tr>
<td>Final</td>
<td>1.95</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.07</td>
</tr>
<tr>
<td>Difference</td>
<td>2.02</td>
</tr>
</tbody>
</table>

**Fuel**

H

0746Y

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Contact Band Loc</td>
</tr>
<tr>
<td>Deposit Ring</td>
</tr>
<tr>
<td>Fraction of Total Ring Circ</td>
</tr>
<tr>
<td>Width of Deposit Ring</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
</tr>
<tr>
<td>Other Deposits</td>
</tr>
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</table>

Figure 148: Fuel Injector #10 Data
<table>
<thead>
<tr>
<th>INJ #</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>4</td>
</tr>
<tr>
<td>Initial</td>
<td>0.04</td>
</tr>
<tr>
<td>Final</td>
<td>2.34</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.49</td>
</tr>
<tr>
<td>Difference</td>
<td>2.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>0746Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>3</td>
</tr>
</tbody>
</table>

**SEM NOTES**

- Contact Band: Smooth
- Contact Band Loc:
- Deposit Ring: Yes
- Fraction of Total Circ: 0.75
- Width of Deposit Ring [μm]: 50
- Chipped Deposit Ring: Yes
- Other Deposits: Stained

**Element Weight% of Deposit**

- Si: 2.38
- S: 2.26
- Cl: 2.66
- K: 0.73
- Ca: 0.82
- Cr: 20.12
- Fe: 68.78
- Zn: 2.26

Fe, Si and Cr are signals from base metal of needle.

---

**Figure 149: Fuel Injector #11 Data**
<table>
<thead>
<tr>
<th>INJ #</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>2</td>
</tr>
<tr>
<td>Initial</td>
<td>0.03</td>
</tr>
<tr>
<td>Final</td>
<td>0.38</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.05</td>
</tr>
<tr>
<td>Difference</td>
<td>0.36</td>
</tr>
</tbody>
</table>

**Fuel:** H  
**T:**  0746Y

**SEM NOTES**

<table>
<thead>
<tr>
<th>Contact Band</th>
<th>Some relief</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Band Loc</td>
<td></td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.75</td>
</tr>
<tr>
<td>Width of Deposit Ring [um]</td>
<td>50</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>No</td>
</tr>
</tbody>
</table>

**Element**  
**Weight% of Deposit:**
- Na 0.17
- Mg 0.00
- Si 1.58
- S 0.68
- Cr 13.41
- Fe 84.16

**Figure 150: Fuel Injector #22 Data**
<table>
<thead>
<tr>
<th>INJ #</th>
<th>69</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>8</td>
</tr>
<tr>
<td>Initial</td>
<td>0.14</td>
</tr>
<tr>
<td>Final</td>
<td>1.70</td>
</tr>
<tr>
<td>FinalDev</td>
<td>1.53</td>
</tr>
<tr>
<td>Difference</td>
<td>1.56</td>
</tr>
<tr>
<td>Fuel</td>
<td>H</td>
</tr>
<tr>
<td>T</td>
<td>1998X</td>
</tr>
<tr>
<td>T</td>
<td>2</td>
</tr>
</tbody>
</table>

### SEM NOTES

| Contact Band | Some relief |
| Contact Band Loc | |
| Deposit Ring | No |
| Fraction of Total Circ | |
| Width of Deposit Ring [um] | 0 |
| Chipped Deposit Ring | No |
| Other Deposits | Stained |

### Element Weight% of Deposit

- Si: 0.99
- C: 0.50
- Cr: 23.60
- Fe: 69.58
- Au: 2.25
- Bi: 3.07

Fe, Si and Cr are from base metal.

Figure 151: Fuel Injector #69 Data
<table>
<thead>
<tr>
<th>INJ #</th>
<th>87</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>6</td>
</tr>
<tr>
<td>Initial</td>
<td>0.13</td>
</tr>
<tr>
<td>Final</td>
<td>1.02</td>
</tr>
<tr>
<td>Final&quot; Dev</td>
<td>0.13</td>
</tr>
<tr>
<td>Difference</td>
<td>0.89</td>
</tr>
<tr>
<td>Fuel</td>
<td>H</td>
</tr>
<tr>
<td>T</td>
<td>1998X</td>
</tr>
</tbody>
</table>

**SEM NOTES**

<table>
<thead>
<tr>
<th>Contact Band Loc</th>
<th>Some relief</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit Ring</td>
<td>yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.6</td>
</tr>
<tr>
<td>Width of Deposit Ring [um]</td>
<td>30</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>yes</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>Large Deposit Signal</td>
</tr>
</tbody>
</table>

**Element Weight% of Deposit**

- Si: 0.73
- S: 0.84
- K: 0.15
- Ca: 0.11
- Cr: 20.81
- Fe: 77.36
- Fe, Si and Cr are signals from base

---

*Figure 152: Fuel Injector #87 Data*
Figure 153: Fuel Injector #44 Data
<table>
<thead>
<tr>
<th>INJ #</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>6</td>
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<tr>
<td>Initial</td>
<td>0.15</td>
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<tr>
<td>Final</td>
<td>0.18</td>
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<tr>
<td>Final Dev</td>
<td>0.05</td>
</tr>
<tr>
<td>Difference</td>
<td>0.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>1998X</td>
</tr>
</tbody>
</table>

**SEM NOTES**

<table>
<thead>
<tr>
<th>Contact Band Loc</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Deposit Ring</td>
<td>yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>.9</td>
</tr>
<tr>
<td>Width of Deposit Ring [um]</td>
<td>30</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>yes</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>no</td>
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Figure 154: Fuel Injector #90 Data
<table>
<thead>
<tr>
<th>INJ #</th>
<th>96</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>1</td>
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<tr>
<td>Initial</td>
<td>-0.07</td>
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<tr>
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<td>Final Dev</td>
<td>0.04</td>
</tr>
<tr>
<td>Difference</td>
<td>0.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>3</td>
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</tbody>
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**SEM NOTES**

<table>
<thead>
<tr>
<th>Contact Band</th>
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<tbody>
<tr>
<td>Contact Band Loc</td>
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</tr>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.65</td>
</tr>
<tr>
<td>Width of Deposit Ring (um)</td>
<td>50</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>stained</td>
</tr>
<tr>
<td>Element Weight% of Deposit—</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>1.14</td>
</tr>
<tr>
<td>Si</td>
<td>9.03</td>
</tr>
<tr>
<td>Cr</td>
<td>15.11</td>
</tr>
<tr>
<td>Fe</td>
<td>65.12</td>
</tr>
<tr>
<td>Zn</td>
<td>9.60</td>
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</table>

*Fe, Si and Cr are signals from base metal of needle.*

Figure 155: Fuel Injector #96 Data
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>POSITION</td>
<td>6</td>
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<tr>
<td>Initial</td>
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<tr>
<td>Difference</td>
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</tbody>
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| Fuel | V |

<table>
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<tr>
<td>Contact Band Local Smooth</td>
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<tr>
<td>Deposit Ring</td>
<td>no</td>
</tr>
<tr>
<td>Fraction of Total Width of Deposit Ring [um]</td>
<td>0</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>no</td>
</tr>
<tr>
<td>Other Deposit</td>
<td>no</td>
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Figure 156: Fuel Injector #14 Data
<table>
<thead>
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<tbody>
<tr>
<td>POSITION</td>
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</tr>
<tr>
<td>Initial</td>
<td>-0.08</td>
</tr>
<tr>
<td>Final</td>
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<tr>
<td>Final Dev</td>
<td>0.04</td>
</tr>
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<td>Difference</td>
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<table>
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<th>Fuel</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>1998X</td>
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**SEM NOTES**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Contact Band Loc Band</td>
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</tr>
<tr>
<td>Contact Band</td>
<td></td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>no</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0</td>
</tr>
<tr>
<td>Width of Deposit Ring [um]</td>
<td>0</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
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</tr>
<tr>
<td>Other Deposits</td>
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Figure 157: Fuel Injector #82 Data
<table>
<thead>
<tr>
<th>INJ #</th>
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</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>8</td>
</tr>
<tr>
<td>Initial</td>
<td>0.11</td>
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<tr>
<td>Final</td>
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<tr>
<td>Final Dev</td>
<td>0.43</td>
</tr>
<tr>
<td>Difference</td>
<td>0.45</td>
</tr>
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**SEM NOTES**

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Contact Band Loc</td>
<td></td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>No</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td></td>
</tr>
<tr>
<td>Width of Deposit Ring [μm]</td>
<td>0</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>No</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>No</td>
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Figure 158: Fuel Injector #83 Data
<table>
<thead>
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<tbody>
<tr>
<td>POSITION</td>
<td>1</td>
</tr>
<tr>
<td>Initial</td>
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<tr>
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<tr>
<td>Final Dev</td>
<td>0.14</td>
</tr>
<tr>
<td>Difference</td>
<td>0.12</td>
</tr>
</tbody>
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**Fuel**

<table>
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</thead>
<tbody>
<tr>
<td>Contact Band Loc Band</td>
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<td>Contact Band</td>
</tr>
<tr>
<td>Deposit Ring</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
</tr>
<tr>
<td>Width of Deposit Ring (um)</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
</tr>
<tr>
<td>Other Deposits</td>
</tr>
</tbody>
</table>

Figure 159: Fuel Injector #T23 Data
<table>
<thead>
<tr>
<th>INJ #</th>
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</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>2</td>
</tr>
<tr>
<td>Initial</td>
<td>0.07</td>
</tr>
<tr>
<td>Final</td>
<td>0.32</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.03</td>
</tr>
<tr>
<td>Difference</td>
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<td>Fuel</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>1998</td>
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**SEM NOTES**

<table>
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<tr>
<th>Contact Band</th>
<th>Smooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Band Loc</td>
<td>Centered</td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total</td>
<td>0.8</td>
</tr>
<tr>
<td>Width of Deposit Ring (um)</td>
<td>40</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>No</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>Tip Deposits</td>
</tr>
</tbody>
</table>

Figure 160: Fuel Injector #T07 Data
Figure 161: Fuel Injector #T14 Data
<table>
<thead>
<tr>
<th>INJ #</th>
<th>T15</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSITION</td>
<td>8</td>
</tr>
<tr>
<td>Initial</td>
<td>0.18</td>
</tr>
<tr>
<td>Final</td>
<td>-0.02</td>
</tr>
<tr>
<td>Final Dev</td>
<td>0.04</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

**Fuel**

T 1996

**SEMNOTES**

<table>
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<th>Smooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Band</td>
<td>Centered</td>
</tr>
<tr>
<td>Deposit Ring</td>
<td>Yes</td>
</tr>
<tr>
<td>Fraction of Total Circ</td>
<td>0.95</td>
</tr>
<tr>
<td>Width of Deposit Ring</td>
<td>50</td>
</tr>
<tr>
<td>Chipped Deposit Ring</td>
<td>No</td>
</tr>
<tr>
<td>Other Deposits</td>
<td>Tip Deposits</td>
</tr>
</tbody>
</table>

---

Figure 162: Fuel Injector #T15 Data

---

227
Figure 163: High mileage LPG Injector #1 Standard Detector Overall

Figure 164: High mileage LPG Injector #1 Back Scatter Detector Overall
Figure 165: High mileage LPG Injector #1 Back Scatter Detector Close-up

Figure 166: High mileage Gasoline Injector #62 Standard Detector Overall
Figure 167: High mileage Gasoline Injector #62 Back Scatter Detector Overall

Figure 168: High mileage Gasoline Injector #62 Standard Detector Close-up
Figure 169: High mileage Gasoline Injector #243 Standard Detector Overall
Figure 170: High mileage Gasoline Injector #243 Back Scatter Detector Overall

Figure 171: High mileage Gasoline Injector #243 Back Scatter Detector Close-up
Figure 172: Fuel P Injector #68 Exterior of Orifice Plate

Figure 173: Fuel P Injector #68 Exterior of Orifice Plate Close Up
Figure 174: Summary of EDS Data from SEM Analysis

Figure 175: Average EDS Data From SEM Analysis By Fuel
CHAPTER 19: APPENDIX F: DESCRIPTION OF VEHICLES AND INJECTORS USED IN TESTING
<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>Fuel Composition</th>
<th>Vehicle Description</th>
<th>Emission and Fuel Systems Component Description</th>
<th>Initial Mileage</th>
<th>VIN#</th>
<th>Injector Serial # at Cylinder #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FUEL H</td>
<td>Bronze AB2L52</td>
<td>Used Catalytic Conv. Used Fuel Rail Used Fuel Tank Used Fuel Pump Fuel Pumps: 1 Walbro, 1 Bosch</td>
<td>10,660 km</td>
<td>WK134596 LIC# WR4 839</td>
<td>Cylinder # 7: Inj# 7 G1 0.04 cc/min Cylinder # 8: Inj# 8 G1 0.14 cc/min</td>
</tr>
<tr>
<td>2</td>
<td>FUEL H + Additive C</td>
<td>Red AB2L12</td>
<td>Used Catalytic Conv. Used Fuel Rail Used Fuel Tank Used Fuel Pump Fuel Pumps: 2 Walbro</td>
<td>7,124 km</td>
<td>WK100190 LIC# ZX2 949</td>
<td>Cylinder # 1: Inj# 1 G1 0.04 cc/min Cylinder # 2: Inj# 21 G1 0.04 cc/min</td>
</tr>
<tr>
<td></td>
<td>Additive Conc.: 10 mL / 12.8 L 7.81 mL / 10 L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cylinder # 3: Inj# 6 G1 0.05 cc/min Cylinder # 4: Inj# 20 G1 0.15 cc/min</td>
</tr>
<tr>
<td>3</td>
<td>FUEL H + Additive V</td>
<td>Green AB1L12</td>
<td>Used Catalytic Conv. Used Fuel Rail Used Fuel Tank Used Fuel Pump Fuel Pumps: 1 Walbro</td>
<td>26,472 km</td>
<td>WK100124 LIC# 941 6AW</td>
<td>Cylinder # 5: Inj# 17 G1 0.06 cc/min Cylinder # 6: Inj# 14 G1 0.15 cc/min</td>
</tr>
<tr>
<td></td>
<td>Additive Conc.: 25 mL / 60 L 4.17 mL / 10 L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cylinder # 7: Inj# 57 G2 0.12 cc/min Cylinder # 8: Inj# 8 G3 0.22 cc/min</td>
</tr>
<tr>
<td>4</td>
<td>FUEL P 2 mL Ethyl Mercaptan added at each fill up</td>
<td>Red AB2L52</td>
<td>New Catalytic Conv. New Fuel Rail New Fuel Tank New Fuel Pump Fuel Pumps: 2 Walbro</td>
<td>640 km</td>
<td>WK134597 LIC# ACLR 318</td>
<td>Cylinder # 96 G1 0.05 cc/min Cylinder # 97: Inj# 64 G2 0.14 cc/min</td>
</tr>
<tr>
<td>5</td>
<td>FUEL H with Titanium Nitride Seat Injectors</td>
<td>Green AB2L52</td>
<td>New Catalytic Conv. New Fuel Rail New Fuel Tank New Fuel Pump Fuel Pumps: 2 Walbro</td>
<td>8,524 km</td>
<td>WK100108 LIC# Dealer plate</td>
<td>Cylinder # 7: Inj# TIN 08 G2 0.02 cc/min Cylinder # 8: Inj# TIN 15 G3 0.18 cc/min</td>
</tr>
</tbody>
</table>

* Note that raw data is shown in the table above. All leakage rate values shown as less than 0.20 cc/min should be interpreted as equal to 0.20 cc/min.
CHAPTER 20: APPENDIX G: FTP EMISSIONS TEST SPEED PROFILE

Figure 176: Speed Profile of EPA-75 FTP Emissions Test
CHAPTER 21: APPENDIX H: MINIMUM FILM BOILING TEMPERATURE CALCULATION

Kikuchi reprinted the minimum film boiling superheat correlation of Berenson. Using this formula we are able to predict if the film boiling conditions exist within the fuel rail of this liquid LPG system during hot start conditions.

\[ \Delta T_{\text{min}} = 0.127 \frac{\rho_v h_{fg}}{k_v} \left[ \frac{g (\rho_i - \rho_v)}{\rho_i + \rho_v} \right]^{2/3} \times \left[ \frac{\sigma}{g (\rho_i - \rho_v)} \right]^{1/2} \times \left[ \frac{\mu_v}{g (\rho_i - \rho_v)} \right]^{1.3} \]

Where for Propane at \( T = 340K \) and \( P = 1.45 \) MPa

\( \rho_v = \text{density of vapor} = 27.7 \text{ kg/m}^3 \) @340K 14.5 bar [26]
\[ \text{= 27.1 kg/m}^3 \text{ @ 340K and 14.5 bar [24]} \]
\[ \text{AVERAGE = 27.4 kg/m}^3 \text{ @ 340K and 14.5 bar} \]

\( \rho_l = \text{density of sat liquid} = 419.2 \text{ kg/m}^3 \) [24]
\[ \text{= 412 kg/m}^3 \text{ @ 340K [28]} \]
\[ \text{= 411.5 kg/m}^3 \text{ @ 340K and 24.36 bar [25]} \]
\[ \text{= 415.2 kg/m}^3 \text{ @ 340K and 24.3 bar [24]} \]
\[ \text{AVERAGE = 414.5 kg/m}^3 \text{ @ 340K} \]

\( h_{fg} = \text{latent heat of vaporization} = 240.80 \times 10^3 \text{ J/kg @ 340K [24]} \)
\[ \text{= 242.06 \times 10^3 J/kg @340K [28]} \]
\[ \text{= 239.54 \times 10^3 J/kg @340K and 24.36 bar [25]} \]
\[ \text{AVERAGE = 240.8 J/kg @340K} \]
\( k_v \) = thermal conductivity of vapor = \( 25.2 \times 10^{-3} \) W/m \( \cdot \) K @340K
\[ = 22.81 \times 10^{-3} \) W/m \( \cdot \) K @340K \[28] \]
\[ \text{AVERAGE} = 24.0 \times 10^{-3} \) W/m \( \cdot \) K @340K \]

\( g \) = acceleration due to gravity = 9.807 m/s

\( \sigma \) = surface tension of liquid = \( 15.15 \times 10^{-3} \) N/m @233K [26] (Disregarded)
\[ = 2.4675 \times 10^{-3} \) N/m @340K [28] \]

\( \mu_v \) = viscosity of vapor = \( 9.24 \times 10^{-6} \) N s/m\(^2\) @340K and 1 bar [26]
\[ = 9.30 \times 10^{-6} \) N s/m\(^2\) @ 340K [27] \]
\[ = 9.366 \times 10^{-6} \) N s/m\(^2\) @ 340K [28] \]
\[ \text{AVERAGE} = 9.30 \times 10^{-6} \) N s/m\(^2\) @ 340K \]

\[ \Delta T_{min} = 0.127 \frac{27.4 \text{ kg/m}^3 \cdot 239.54 \times 10^3 \text{ J/kg}}{24.0 \times 10^{-3} \text{ W/m} \cdot \text{K}} \left[ \frac{g(414.5 \text{ kg/m}^3 - 27.4 \text{ kg/m}^3)}{414.5 \text{ kg/m}^3 + 27.4 \text{ kg/m}^3} \right] \]
\[ \times \left[ \frac{2.4675 \times 10^{-3} \text{ N/m}}{g(414.5 \text{ kg/m}^3 - 27.4 \text{ kg/m}^3)} \right]^{\frac{1}{2}} \times \left[ \frac{9.30 \times 10^{-6} \text{ N s/m}^2}{g(414.5 \text{ kg/m}^3 - 27.4 \text{ kg/m}^3)} \right]^{\frac{1}{2}} \]

\[ \Delta T_{min} = 158 K \]

\[ T_{sat@14.5bar} = 315.70K \ [24] \]
\[ = 315.08K \ [26] \]
\[ = 315.34K \ [25] \]
\[ \text{Average} = 315.37K \]

\[ T_{surface \ for \ film \ boiling} = \Delta T_{min} + T_{sat@14.5bar} = 158K + 315.37K = 473K \ or \ 200 \ ^\circ \text{C} \]
CHAPTER 22: APPENDIX I: EXPLICIT CALCULATION OF TRANSIENT TEMPERATURE DISTRIBUTION

Details of Calculation:
\[ \text{dt} = 2.8308e-6 \text{ sec} \]
\[ \text{dx} = 5.0e-6 \text{ m} \]
\[ h = 2479 \text{ W/m}^2 \text{K} \]
\[ T_1 = 325 \text{ K} \]
\[ T_\infty = 295 \text{ K} \]
Total Analysis Time: 11.3 ms
Total number of time steps: 4001
Number of points used in calculation: 647
11 points in coating
636 points in steel

Computer Code (MATLAB):

```
% CHAPTER
% Appendix I. Explicit
% Chapter 22
%
% This problem is designed to solve a 1-D conduction transient surface convection problem through a steel material. Initial material is heated by a constant temperature difference on the two ends of the steel material. Due to heat transfer at the fluid material, the problem is solved to observe the transient conduction and determine new temperatures.

% Outline
% 1. Define time steps
% 2. Define material properties
% 3. Material properties
% 4. Apply boundary conditions
% 5. Calculate new temperatures

% Defining time steps
dt=2.8308e-6;
% Defining distance
dx=5*10^(-6);
% Defining convection coefficient
h=2479;

% Defining material properties
coefficient file = 'hyper4mat.dat';

% Material 1: Conductive Pipe metal
dens1=2130;
cond1=0.62;
hcapi=1400;
thick1=50*10^(-6);
pts1=thick1/dx+1;
alpha1=cond1/dens1/hcapi;

% Material 2: Stainless Steel
dens2=7860;
cond2=14.9;
hcap=477;

thick2=3.175*10^(-3);
pts2=thick2/dx+1;
alpha2=cond2/dens2/hcap;

% Total number of time steps
p_tot=pts1+pts2;
int_temp=325;
```

240
flu_temp=295;

while temperature not in limits do
  # Calculate the Fick's law for the first material
  dt1=dx^2/2/alpha1;
  dt2=dx^2/2/alpha2;

  if dt1<dt2
    if dt>dt1
      dt=0.9*dt1;
    end
  else if dt2<dt1
    if dt>dt2
      dt=0.9*dt2;
    end
  end

  # Calculate the Fick's law for the second material
  B1=dt*dx/cond1;
  F1=alpha1*dt/dx^2;
  B2=dt*dx/cond2;
  F2=alpha2*dt/dx^2;

  # Create Bi and Fourier Number Arrays
  B1(n)=Bi(n); Bi(n+1)=B1(n+1);
  F1(n)=Fo(n); Fo(n+1)=F1(n+1);

  # Calculate temperature for the first material
  T1(n)=T(n-1);

  # Open files
  id1=fopen('coarsefile', 'w');
  fclose(id1);
  id2=fopen('coarsefile', 'a');

  # Set initial number of lines
  max_steps=55600;
  file_step=100;
  file_dt=file_step*dt;

  # Calculate number of lines to store
  data_lines=0;

  for m=1:max_steps/file_step
    added1=fwrite(id1,T1,:)', 'uint16');
    added1=1; // Add initial data to file
    data_lines=data_lines+1
  end

  for n=2: file_step // Steps in time
    T(n,1)=B1(1)*Fo(1)*flu_temp(1-B1(1)*Fo(1-Fo(1))*T(n-1,1)+Fo(1)*T(n-1,2));
  end

  # Increment time
  t=t+dt;
end
T(n,p_tot)=int_temp;
for k=2:1:p_tot-1
    for m=1:1:n-1 pt
        T(n,m)=T(n,m)+(dx/2)*((cond1/dx)*(T(n-1,m)-T(n,m))+
        (dx/2)*((cond2/dx)*(T(n,m+1)-T(n,m)));
    end
end
end
end

if k==ptsl+1 then i=1 i Material E
    T(n,k)=T(n-1,k)+dt/dens1/ncapi*(T(n-1,k-1)-T(n-1,k))+(dx/2)*((cond2/dx)*(T(n,k+1)-T(n,k)));
else
    T(n,k)=T(n-1,k)+dt/dens2/ncapi*(T(n-1,k+1)-T(n-1,k))+(dx/2)*((cond2/dx)*(T(n,k+1)-T(n,k)));
end
end
end
end

T(TempT)=T(file_step,); clear T;
T(1,:)=TempT; % Create temp file a use it
T=NaN; % Set the initial value of T

if T(1,1)<300 % If temperature at time 1 reaches 300 set initial to 1
    break
end

figure
the following section will plot the simulated temperature distribution graph
plotlines=10;
plot_step=floor(datalines/plotlines);
plot_max=plot_step*plotlines;
plot_dt=file_dt=plot_max/plotlines;
plot([0:(p_tot-1)].*dx,T(1:plot_step:plot_max,));

title('Transient Temperature Distribution Across Steel Wall. Plot Number: Temperature K')
xlabel('Distance from Inner Surface m')
ylabel('Temperature K')
axis([0 3.5e-3 295 326])

create legend
for g=1:1:plotlines
    textmat(g)=[' fontsize=10; t= num2str((g-1)*plot_dt) sec ];
end
ltext=char(textmat);
text1=[' fontsize=10; dt= num2str(dt) sec'];
text2=[' fontsize=10; dx= num2str(dx) m'];
figure
plot((0:(p_tot-1)).*dx,T(1:plot_step:plot_max,:))
%Plot data with surface plot
with contour distance file
title('Numerical Transient Temperature Distribution Across Steel. Wall. Value = K. At 4.56
Soak Time')
xlabel('Distance from inner Surface ,m ,')
ylabel('Temperature ,K ,')
axis([0 0.7e-3 295 326])
%Create legend
for g=1:1:plotlines
    textmat(g)=['fontsizer']=num2str((g-1)*plot_dt) sec];
end
text1=['fontsizer']=num2str(dt) sec ];
text2=['fontsizer']=num2str(dx) m ];
text3=['fontsizer']=num2str(datalines*file_step) cont1text(1).txt '] ];
legend(ltext,text1,text2,text3,4);
set(gcf, position ,{0 25 800 530}) makes clear
fclose( a.. );
clear all
CHAPTER 23: Appendix J: Output of Explicit Transient Conduction Analysis
Figure 177: Transient Temperature Distribution Across Non-coated Steel Wall, Calculation Output

Figure 178: Zoomed Transient Temperature Distribution Across Non-coated Steel Wall, Calculation Output
Figure 179: Transient Temperature Distribution Across a Steel Wall with a 25μm Xylan Coating, Calculation Output

Figure 180: Zoomed Transient Temperature Distribution Across a Steel Wall with a 25μm Xylan Coating, Calculation Output
Figure 181: Transient Temperature Distribution Across a Steel Wall with a 50 µm Xylan Coating, Calculation Output

Figure 182: Zoomed Transient Temperature Distribution Across a Steel Wall with a 50 µm Xylan Coating, Calculation Output
Figure 183: Transient Temperature Distribution Across a Steel Wall with a 100µm Xylan Coating, Calculation Output

Figure 184: Zoomed Transient Temperature Distribution Across a Steel Wall with a 100µm Xylan Coating, Calculation Output
CHAPTER 24: APPENDIX K: FUEL SYSTEM TEMPERATURE AND PRESSURE DATA RECORDED DURING HOT START TESTS

24.1 All Steel Fuel Rail Hot Start Results

Figure 185: Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #1
Figure 186: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #1

Figure 187: Hot Start Fuel Temperature and Pressure, Steel Fuel Rail Trial #1
Figure 188: Hot Start External Fuel Rail Temperature, Steel Fuel Rail Trial #1

Figure 189: Hot Start Supply Tubing and Fuel Temperature Steel Fuel Rail #1
Figure 190: Hot Start Return Tubing and Fuel Temperature Steel Fuel Rail #1

Figure 191: Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #2
Figure 192: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #2

Figure 193: Hot Start Fuel Temperature and Pressure, Steel Fuel Rail Trial #2
Figure 194: Hot Start External Fuel Rail Temperature, Steel Fuel Rail Trial #2

Figure 195: Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #3
Figure 196: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #3

Figure 197: Hot Start Fuel Temperature and Pressure, Steel Fuel Rail Trial #3
Figure 198: Hot Start External Fuel Rail Temperature, Steel Fuel Rail Trial #3

Figure 199: Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #4
Figure 200: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #4

Figure 201: Hot Start Fuel Temperature and Pressure, Steel Fuel Rail Trial #4
Figure 202: Hot Start External Fuel Rail Temperature, Steel Fuel Rail Trial #4

Figure 203: Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #5
Figure 204: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Steel Fuel Rail Trial #5

Figure 205: Hot Start Fuel Temperature and Pressure, Steel Fuel Rail Trial #5
Figure 206: Hot Start External Fuel Rail Temperature, Steel Fuel Rail Trial #5

Figure 207: Hot Start Supply Tubing and Fuel Temperature Steel Fuel Rail #5
Figure 208: Hot Start Return Tubing and Fuel Temperature Steel Fuel Rail #5

24.2 Coated Fuel Rail Hot Start Results
Figure 209: Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #1

Figure 210: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #1
Figure 211: Hot Start Fuel Temperature and Pressure, Coated Fuel Rail Trial #1

Figure 212: Hot Start External Fuel Rail Temperature, Coated Fuel Rail Trial #1
Figure 213: Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #2

Figure 214: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #2
Figure 215: Hot Start Fuel Temperature and Pressure, Coated Fuel Rail Trial #2

Figure 216: Hot Start External Fuel Rail Temperature, Coated Fuel Rail Trial #2
Figure 217: Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #3

Figure 218: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #3
Figure 219: Hot Start Fuel Temperature and Pressure, Coated Fuel Rail Trial #3

Figure 220: Hot Start External Fuel Rail Temperature, Coated Fuel Rail Trial #3
Figure 221: Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #4

Figure 222: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #4
Figure 223: Hot Start Fuel Temperature and Pressure, Coated Fuel Rail Trial #4

Figure 224: Hot Start External Fuel Rail Temperature, Coated Fuel Rail Trial #4
Figure 225: Hot Start Supply Tubing and Fuel Temperature Coated Fuel Rail #4

Figure 226: Hot Start Supply Tubing and Fuel Temperature Coated Fuel Rail #4
Figure 227: Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #5

Figure 228: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #5
Figure 229: Hot Start Fuel Temperature and Pressure, Coated Fuel Rail Trial #5

Figure 230: Hot Start External Fuel Rail Temperature, Coated Fuel Rail Trial #5
Figure 231: Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #6

Figure 232: Zoomed Hot Start Exhaust Gas Temperature and EPP Count, Coated Fuel Rail Trial #6
Figure 233: Hot Start Fuel Temperature and Pressure, Coated Fuel Rail Trial #6

Figure 234: Hot Start External Fuel Rail Temperature, Coated Fuel Rail Trial #6
CHAPTER 25: APPENDIX L: TRANSIENT EMISSIONS DATA
RECORDED DURING HOT START TESTS

Figure 235: All Steel Fuel Rail, Hot Start HC Emissions

Figure 236: All Steel Fuel Rail, Hot Start CO Emissions
Figure 237: All Steel Fuel Rail, Hot Start CO2 Emissions

Figure 238: All Steel Fuel Rail, Hot Start O2 Emissions
Figure 239: All Steel Fuel Rail, Hot Start NOx Emissions

Figure 240: Coated Fuel Rail, Hot Start HC Emissions
Figure 241: Coated Fuel Rail, Hot Start CO Emissions

Figure 242: Coated Fuel Rail, Hot Start CO2 Emissions
Figure 243: Coated Fuel Rail, Hot Start O2 Emissions

Figure 244: Coated Fuel Rail, Hot Start NOx Emissions
CHAPTER 26: APPENDIX M: FUNCTIONAL ANALYSIS

A functional analysis of the liquid propane fuel injection system has been completed to assist in developing a solution to the hot start performance problem.

Figure 245: Functional Block Diagram of Liquid Propane Fuel System
CHAPTER 27: APPENDIX N Step Input Thermocouple Calibration Data

Figure 246: Surface Thermocouple Time Constant Determination Trial #1
Figure 247: EGT Thermocouple Time Constant Determination Trial #1

Figure 248: Fuel Probe Thermocouple Time Constant Determination Trial #2
Table 21: Summary of Thermocouple Time Constant Data, 0-100 °C 90% Rise Time

<table>
<thead>
<tr>
<th>Trial</th>
<th>Surface</th>
<th>Fuel Probe</th>
<th>EGT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TS1, TS2 &amp; TS3</td>
<td>TF1 &amp; TF2</td>
<td>EGT1, EGT2, EGT3 &amp; EGT4</td>
</tr>
<tr>
<td>1</td>
<td>0.35</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>0.70</td>
<td>0.24</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>0.55</td>
<td>0.21</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>0.65</td>
<td>0.19</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>0.70</td>
<td>0.19</td>
<td>1.8</td>
</tr>
<tr>
<td>6</td>
<td>0.65</td>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>0.65</td>
<td>0.21</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>0.50</td>
<td>0.28</td>
<td>1.8</td>
</tr>
<tr>
<td>9</td>
<td>0.70</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>0.60</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>11</td>
<td>0.60</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>12</td>
<td>0.60</td>
<td>0.18</td>
<td>1.7</td>
</tr>
<tr>
<td>AVG</td>
<td>0.60</td>
<td>0.22</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 22: Uncertainties of Thermocouples

<table>
<thead>
<tr>
<th></th>
<th>Time Constant</th>
<th>Standard Deviation of 200 Random Measurements of Constant Value</th>
<th>First Order Uncertainty</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-J Surface TS 1,2 &amp; 3</td>
<td>0.60 sec.</td>
<td>0.970°C</td>
<td>±1.94°C @95%</td>
<td>Omega</td>
</tr>
<tr>
<td>Type-J Sheathed TF 1 &amp; 2</td>
<td>0.22 sec.</td>
<td>0.847°C</td>
<td>±1.69°C @95%</td>
<td>Omega</td>
</tr>
<tr>
<td>Type-K Sheathed EGT 2,4,6&amp;8</td>
<td>1.8 sec.</td>
<td>0.479°C</td>
<td>±0.96°C @95%</td>
<td>Omega</td>
</tr>
</tbody>
</table>
CHAPTER 28: REFERENCES


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[29] Personal Communication with Drouillard, M. DaimlerChrysler Canada, 1999


[38] Cole and Parmer Chemical Resistance Guide, 1999
VITA AUCTORIS

Matthew W. Hoag

Birth
June 4th, 1975 Toronto, ON Canada

Education
1998 - 2000 University of Windsor, Windsor, ON, Canada.
Masters of Applied Science, Mechanical Engineering [GPA: 3.75]
Working with DaimlerChrysler Research and Development, Alternate Fuels Group

1994 - 1998 University of Windsor, Windsor, ON, Canada.
Honors Bachelor of Applied Science, Mechanical Engineering Co-op [GPA: 2.81]

1989 – 1994 Jarvis Collegiate Institute, Toronto, ON, Canada
Ontario Secondary School Diploma

Engineering Related Work Experience
1998 – 2000 DaimlerChrysler Canada, Automotive R&D Centre, Windsor, ON, Canada
Engineering Research Assistant, Alternative Fuels Group
☑ Analyzed and solved fuel injector deposit problems.
☑ Developed new fuel rail concept to address starting issues.

1997 Ford Motor Company, Windsor Aluminum Casting Plant, Windsor, ON, Canada
Co-op Engineering Assistant
☑ Independently designed and supervised fabrication of a material handling system.
☑ Designed ergonomic workstation for continuous process operation.
☑ Developed strong understanding of lean manufacturing practices and applications.

1997 Fulerum Consulting, Consulting Mechanical Engineers, London, United Kingdom
Co-op Engineering Assistant
☑ Directed the design of the vent mechanism for a thermal mass cooling system.
☑ Worked closely with clients to develop solutions to defective mechanical systems.

1996 The Mitchell Partnership Inc., Consulting Mechanical Engineers, Toronto, ON, Canada
Co-op Engineering Assistant
☑ Assisted with design of Niagara Falls Casino drainage and cooling piping systems.
☑ Performed heating and cooling load calculations.

Engineering Related Skills
Technical
- MIT product design and development process
- Plastic part design
- Geometric Dimensioning and Tolerancing (GD&T)
- Design for Manufacturing and Assembly (DFMA)
- Metallurgy and casting processes
- Experimental stress analysis
- Statistical Process Control, SPC
- Stress analysis calculations

Computer Skills
- AutoCAD v12, 3D
- CATIA design drafting
- ANSYS and ALGOR Finite Element Analysis (FEA)
- PRO-ENGINEER 3D Design
- Microsoft Office Suite

Interpersonal Skills
- 5 day course on group and team development
- Fluent conversational French language skills
- Extensive instruction skills
- Conflict resolution courses
Awards and Achievements

1998  Deans List. University of Windsor
1996  American Society of Mechanical Engineers Outstanding Student Award
1994  Received Seventh Place in Ontario Finals of DECA Competition
(A Multinational Association of Marketing and Management Students)
1994  Recipient of the Garfield J. Lorimar Award for Student Leadership.

Additional Employment Experience

1996  
Duke's Bicycles, Toronto, ON
Bicycle Mechanic - Part time
☐ Solved repair problems.
☐ Assembled and tested new bicycles.

1992-94  
YMCA Camp PineCrest, Torrance, ON
Counselor - Summer employment
☐ Responsible for the instruction and group development of children.
☐ Developed and implemented windsurfing instruction program.
☐ Published a 14-page windsurfing course manual.

Volunteer Activities

Events Coordinator, University of Windsor Rock Climbing Club, Windsor, ON
☐ Organized rock climbing excursions for club members.

Treasurer, La Salle Rowing Club, La Salle, ON
☐ Responsible for $200,000.00 in assets.
☐ Analyzed the situation of an organization in transition and developed an annual
financial and investment strategy to address long term goals.
☐ Developed new programs and an organizational plan which lead to the doubling of
membership.

Chairman, American Society of Mechanical Engineers Student Chapter, Univ. of Windsor, Windsor, ON
☐ Organized and promoted ASME events for engineering students.

Volunteer, YMCA Camp PineCrest, Torrance, ON
☐ Developed a skill recognition program for campers.

Personal Interests

Mountain Biking (Competing in weekly race series)
Competitive Rowing
Windsurfing
Acoustical Guitar
Rock Climbing (Consistent 5.11 climber).
Completed Outward Bound Leadership Course.
Triathlon (Completed five triathlons to date).
Camping (Logged 64 days of leading canoe trips).
Alpine Skiing (Level 1 Instructor).
Travel (Turkey, Syria, Jordan, Egypt, Morocco, Denmark, Germany, France, Scotland, Italy, and Spain).