OPERABILITY AND COMPATIBILITY CHARACTERISTICS OF ADVANCED TECHNOLOGY DIESEL FUELS

FINAL REPORT

SWRI Project No. 03-02476

CRC Project No. AVFL-2

Prepared for

Coordinating Research Council, Inc.
3650 Mansell Road, Suite 140
Alpharetta, GA 30022

January 2002

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EXECUTIVE SUMMARY

The attached report was prepared for the Advanced Vehicles/ Fuels/ Lubricants (AVFL) Committee of the CRC by Southwest Research Institute (SwRI), the contractor for the subject research program. This Executive Summary has been prepared by the members of the AVFL Committee to explain the purpose of the research program, to explain the choice of fuels and tests used in the study, and to provide the Committee's interpretation of the results.

Background

In 1997, a group called the Ad Hoc Compression Ignition Direct Injection (CIDI) Engine Research Group began a research program intended to identify the benefits of advanced diesel fuel formulations in reducing emissions of oxides of nitrogen and particulates emitted by modern compression ignition engines. The group consisted of the three auto companies that made up the Partnership for a New Generation of Vehicles (DaimlerChrysler, Ford, General Motors), several major oil companies (Arco, BP Amoco, ExxonMobil, Shell), and the Department of Energy. Each auto company selected one of their own engines to evaluate in the program. All of the engines were modern, turbocharged, and equipped with direct injection, common rail, fuel delivery systems.

The advanced diesel fuels selected for the Ad Hoc CIDI engine research program included a variety of fuel technologies that might affect engine out emissions. The first fuel technology selected was a highly hydrocracked petroleum-based fuel with very low levels of sulfur and aromatic compounds (LSLA). It represents an extreme which may be reached using conventional refining to help reduce diesel emissions. The second fuel was the same LSLA base fuel blended with 15 volume percent of the oxygenate, dimethoxymethane (DMM). Although it is doubtful that such a fuel blend would ever be used commercially due to the high volatility of the DMM, this fuel represented an attempt at understanding the benefits of oxygenate additives on reducing diesel emissions. The third test fuel was a sample of synthetic distillate fuel produced from a commercial version of the Fischer-Tropsch process (FT100). This natural-gas-derived fuel provided a zero sulfur, zero aromatic test sample. The fourth fuel was a "typical" southern California, diesel fuel formulation (CA) prepared by a specialty blending refinery. Although the bulk properties were specified to meet those of typical California fuels based on data derived from industry surveys, the actual test fuel was blended using a finite number of blending components. Thus, the specific hydrocarbon composition was not at all typical of fuels manufactured in California.

The properties of the test fuels and the test conditions used in measuring engine out emissions are detailed in a Society of Automotive Engineers (SAE) paper (2001-01-0151). The results of the Ad Hoc CIDI Engine Research program are not the subject of this current report. Statistically different results in engine-out emissions were measured for some of the fuels at some of the test conditions. In general, none of the fuels had a great affect on oxides of nitrogen emissions, but particulate emissions with the DMM15 and FT100 were substantially lower than those for the other fuels. Details of the research project and the emissions results can be obtained from the referenced SAE paper.

During the period in which the Ad Hoc CIDI Engine Research program was being conducted, the AVFL Committee decided that a companion research program was needed. Previous commercial practice had indicated that low sulfur, low aromatic diesel fuels might contribute to fuel system durability problems in service. It was decided that research should be conducted on the physical properties of the fuels used in the Ad Hoc CIDI Engine Research program and that the performance in standardized fuel system durability tests should be evaluated. Thus, the AVFL Committee issued a Request for Proposal identifying several laboratory test procedures to use in determining the effect of the advanced fuels on different aspects of engine durability. Southwest Research Institute was selected to perform the tests based on its proposal response. This report represents the summary of test results collected by SwRI as contractor for the CRC AVFL Committee on this project.

Fuel Pump and Laboratory Wear Tests

Two different laboratory fuel-injection-pump durability-tests were conducted with each of the test fuels. The first test used a relatively low pressure Stanadyne opposed piston pump similar to those used on some current North American engines, and the second test used a relatively high pressure Bosch common rail injection pump such as those used currently on some European engines. The tests were scheduled to operate for 500 hours under severe load conditions that are described in the report.

All of the fuels completed duplicate 500-hour evaluations in the Stanadyne pump tests. Despite completing the tests, there were substantial differences in the condition of the pumps evaluated with each fuel. CA, the baseline fuel, was the only fuel containing a lubricity additive. Even with the presence of this lubricity additive, there was substantial transfer pump wear and poor pump performance presumably as a result of heavy brown deposits that formed in the pump during the tests with the CA fuel. These deposits demonstrated that this simulated commercial fuel had poor oxidation stability characteristics, a finding that was confirmed from failing results in a standard laboratory oxidation test. The conclusions from these tests taken together indicate that the CA fuel should not be used to represent current commercial practice or fuel performance.

Although the Stanadyne pump tests with each of the other test fuels completed 500 hours, all fuels produced high wear. Since none of the other fuels contained a lubricity additive, these results are not surprising. It is encouraging that the fuels did complete the tests and the results with the advanced fuels should be re-evaluated in future test programs when blended with suitable lubricity additives.

In order for the test fuels to complete tests in the Bosch pump, a low load, 2–hour break-in period was required. Even with the break-in period, many of the fuel tests did not complete 500-hours. Pump failures occurred in some of the tests at least once with all of the fuels and appeared to be caused by catastrophic component failures as opposed to high wear rates. Since some of the advanced fuels did finish 500 hours on test (all but FT100), the failures cannot be blamed at this time on the advanced fuels alone. Additional work is needed to determine the benefits of additive treatments to the performance of the advanced fuel formulations. It can be concluded that the Bosch common-rail, high-pressure fuel pump is more sensitive to the advanced fuels than is the Stanadyne pump in this severe duty-cycle test.

Although the laboratory high frequency reciprocating rig (HFRR) tests were able to distinguish between those fuels that contained lubricity additives and those that did not, there was little correlation with pump durability results.

Material Compatibility

Five different elastomers that were identified as being used in current engines or candidates for future engine applications were chosen to assess material compatibility. Three of the materials were nitrile based and two were fluorocarbon based. Elastomeric materials were aged in each test fuel for periods of 72, 216 and 1024 hours at 40C. For each elastomer, the effect of fuel on tensile strength, ultimate elongation, modulus of elongation, hardness, mass change and volume change were determined and compared with recommended values.

A detailed summary included in the attached report shows that none of the four test fuels and five materials went through all of the testing without any negative effects. A composite rating derived from all of the tests and evaluation criteria demonstrates that the LSLA fuel had the least negative effect on the elastomers, followed in order by the FT100, the CA and the DMM15 fuels. In general, the fluorocarbon materials were more compatible with the advanced fuels than were the nitrile materials, although the DMM15 was not compatible with the fluorocarbon elastomers. As with the pump durability tests, future test programs should evaluate the benefits of additive technology in improving performance of commercial elastomers with advanced fuel formulations.

Thermal Stability and Low-Temperature Properties

ASTM D 3241 (JFTOT) and Octel F-21 tests were conducted on each of the advanced fuels to determine their oxidative stability. In the JFTOT test the CA fuel formed substantial deposits as in the Stanadyne pump test. The other fuels performed satisfactorily in the ASTM test.

The DMM15 fuel was not evaluated in the Octel test because of its volatility. All of the other fuels performed satisfactorily in the Octel test. The fact that the CA fuel formed unacceptable deposits in both the pump test and the JFTOT tests but passed the Octel F-21 test may indicate that the CA fuel is sensitive to heated metal surfaces. It's not clear what components of the CA fuel contribute to this tendency to form deposits.

To determine the low-temperature properties of the advanced fuels, four different test procedures were used. These tests included ASTM D 5773 (the Cloud Point), ASTM D 5949 (the Pour Point), ASTM D 4539 (the Low-Temperature Flow Test), and CFPP (the Cold Filter Plugging Point Test). In all of the test procedures, the CA fuel performed as expected for commercial diesel fuels and all of the advanced fuels performed poorly. Since none of the advanced fuels contained low temperature flow additives, these results might be expected. A future test program should evaluate the effect of commercial low-temperature flow modifiers on the properties and performance of the advanced fuels.

Summary

Although the advanced diesel fuel formulations demonstrated limitations with respect to various durability and performance tests, such results might also be expected with current commercial diesel fuels that were not blended with suitable additive technology. Future test programs should be designed to determine if the same additive technology that provides improved performance for petroleum based fuels will also provide improved performance for advanced fuels similar to those evaluated in this test program.

FOREWORD/ACKNOWLEDGEMENTS

This work was performed by the Fuels and Lubricants Research Department, Engine and Vehicle Research Division, located at Southwest Research Institute (SwRI), San Antonio, Texas, during the period January 1999 to September 2001 under Coordinating Research Council (CRC) Contract No. AVFL-2 and SwRI Project No. 03-02476. The work was administered by Mr. Brent Bailey, who served as CRC's technical representative.

TABLE OF CONTENTS

OBJECTIVE 1: PUMP EVALUATIONS

Section **Page**

TABLE OF CONTENTS CONTINUED

OBJECTIVE 1: LIST OF ILLUSTRATIONS

TABLE OF CONTENTS CONTINUED

OBJECTIVE 1: LIST OF ILLUSTRATIONS CONTINUED

OBJECTIVE 1: LIST OF TABLES

TABLE OF CONTENTS CONTINUED

OBJECTIVE 2: MATERIAL COMPATIBILITY

OBJECTIVE 2: LIST OF TABLES

TABLE OF CONTENTS CONTINUED

OBJECTIVE 2: LIST OF ILLUSTRATIONS

TABLE OF CONTENTS CONTINUED

OBJECTIVE 3: THERMAL STABILITY AND LOW-TEMPERATURE PROPERTIES

OBJECTIVE 3: LIST OF TABLES

OBJECTIVE 4: ADDITIONAL FUEL CHARACTERIZATION TESTS

OBJECTIVE 4: LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ACN	Acrylonitrile Content
ASTM	American Society for Testing and Materials
CA	California Reference Diesel Fuel
CFPP	Cold Filter Plugging Point
CIDI	Compression Ignition Direct Injection
CRC	Coordinating Research Council
DMM15	15% Dimethoxymethane (DMM) with 85% LSLA
EVRD	Engine and Vehicle Research Division
FT100	Neat Fischer-Tropsch Diesel
HFRR	High Frequency Reciprocating Rig
HPHFRR	High Pressure HFRR
Hz	Hertz, Cycles per Second
JFTOT	Jet Fuel Thermal Oxidation Tester
LSLA	Low Sulfur, Low Aromatics
LTFT	Low-Temperature Flow Test
PLV	Pump Lubricity Valve
PSIG	Pounds per Square Inch Gauge
RPECS	Rapid Prototyping Engine Control System
SwRI	Southwest Research Institute
WSD	Wear Scar Diameter

OBJECTIVE 1: PUMP EVALUATIONS

I. PURPOSE

Endurance tests were performed using a motorized pump stand to define the effects of diesel fuel composition on full-scale fuel injection equipment durability. The test series attempted to determine the level of fuel injection system degradation due to wear and failure of the boundary film for each of the test fuels. A 500-hour pump operating procedure was utilized. Discussions with Stanadyne Automotive and Bosch indicated 500 hours would be sufficient to see fuel injection pump wear with low lubricity fuels. Both manufacturers also indicated that with insufficient lubricity fuels, a decrease in fuel injector performance can also occur in 500 hours.

Table 1-1 shows the test fuels for this project.

Table 1-1. Test Fuels

Fuel No.	Fuel Code	Fuel Description	SwRI Code
1	CA	California Reference Diesel Fuel	AL-25713
2	LSLA	Low Sulfur, Low Aromatics	AL-25792
3	FT100	Neat Fischer-Tropsch Diesel	AL-25787
4	DMM15	Blend: 15% Dimethoxymethane (DMM) with 85% LSLA	AL-25959

II. APPROACH

A. Fuel Injection Systems

1. Stanadyne

The Stanadyne pump is an opposed-piston, rotary-distributor, fuel-injection pump typical of current diesel vehicle usage. Rotary distributor fuel injection pumps are fuel lubricated, thus sensitive to fuel lubricity. Stanadyne Automotive initially specified the fuel injection pump and injectors for a 2-liter Compression Ignition Direct Injection (CIDI) application. The suggested rotary fuel injection pump was a Stanadyne Model DB4-5116. The DB4 pumps are specified for direct injection diesel applications, have four plungers, and develop higher injection pressures. However, the model DB4 pumps are not rated for speeds above 2800 RPM. It was felt 2800 RPM was too low for an automotive application. Models DB2427 and DB2829 for indirect injection applications, both rated at 3600 RPM, were considered. A Stanadyne Model DB2829-4878 pump from a General Motors application was chosen as the test pump. SwRI has considerable experience and a database of wear results with the DB2829 pumps. The fuel injection pumps and the matching fuel injectors were obtained. The fuel injection pumps were sent to a local commercial vendor for verification of the pump calibrations. The calibration data suggest all eight test pumps exhibit similar performance. The opening pressure, leakdown, chatter, tip dryness, and spray pattern were determined for each of the fuel injectors used for the testing.

2. Bosch

A unique high pressure Common Rail fuel injection system was evaluated. SwRI coordinated with Bosch to obtain the appropriate hardware to evaluate this system on a test stand. Part numbers were obtained from a Mercedes OM611 direct injection diesel engine installed at SwRI for the feed pump, high pressure pump, rail pressure regulator, accumulator rail, and electronically actuated fuel injectors. The part numbers were supplied to various vendors to obtain pricing and availability of the common rail components. The 32 electronic fuel injectors required to complete the program as scoped were purchased. Several other components for the Bosch common rail fuel injection system were obtained, including the high-pressure and fuel feed pumps. All fuel lines, both high and low pressure, were obtained and fitted to the test stand.

Measurements of the drive configuration, and mounting flanges of the injection system components on the OM611 were obtained. The measurements were used to lay out the pump drive adapter for the test stand. The drive adapter eliminated any overhung loads on the feed and high-pressure rail pumps. The fuel feed pump rotates in the opposite direction of the engine and high-pressure rail pump. It was determined upon closer examination of a disassembled OM611 engine that the feed pump turns at camshaft speed, and the high-pressure rail pump turns at 4/3-camshaft speed. Pulley sizes were adjusted to reflect the speed differences.

The design for the pump drive adapter utilized many off-the-shelf components in order to keep custom fabrication to a minimum. The drive adapter features a single synchronous belt, which drives two sets of pumps simultaneously. Belt tension is easily adjustable by shimming of the drive-motor input shaft bearings. Heated collection manifolds containing the fuel injectors fed by each pump were attached to the drive adapter, thereby maintaining the desired fuel injector temperature. This ensured a close reproduction of actual engine operating conditions during the pump testing procedure.

The drive and control electronics for the common rail fuel injection system were more complex than originally anticipated. The injector coils required a special peak and hold driver to obtain fast opening times. The anticipated test condition, 2800-RPM pump speed and 1350-bar rail pressure, does not utilize pilot injection as calibrated by Bosch. The opening time of the injector coils without the peak and hold driver does not adequately represent use on an engine. A peak and hold type driver from a Southwest Research Institute™ (SwRI) Rapid Prototyping Engine Control System (RPECS) control system was utilized to drive the Bosch pump stand injectors. Additional peak and hold drivers were constructed to handle the 16 injectors for each fuel group test. The injection rail pressure was controlled by using pulsewidth modulation at 1000 Hz to vary regulator duty-cycle while using the rail pressure sensor as feedback.

B. Pump Test Stand

The test stand was modified to operate with dual fuel systems, so that either separate fuels or pumps may be evaluated simultaneously. The test stand includes flow and return pipes, lift pumps, filters, flow meters, instrumentation, a fuel pre-heater, and a heat exchanger to reduce the temperature of the fuel before returning to the storage tank. A generalized schematic diagram of the fuel supply system used for the pump stand is shown in Figure 1- 1.

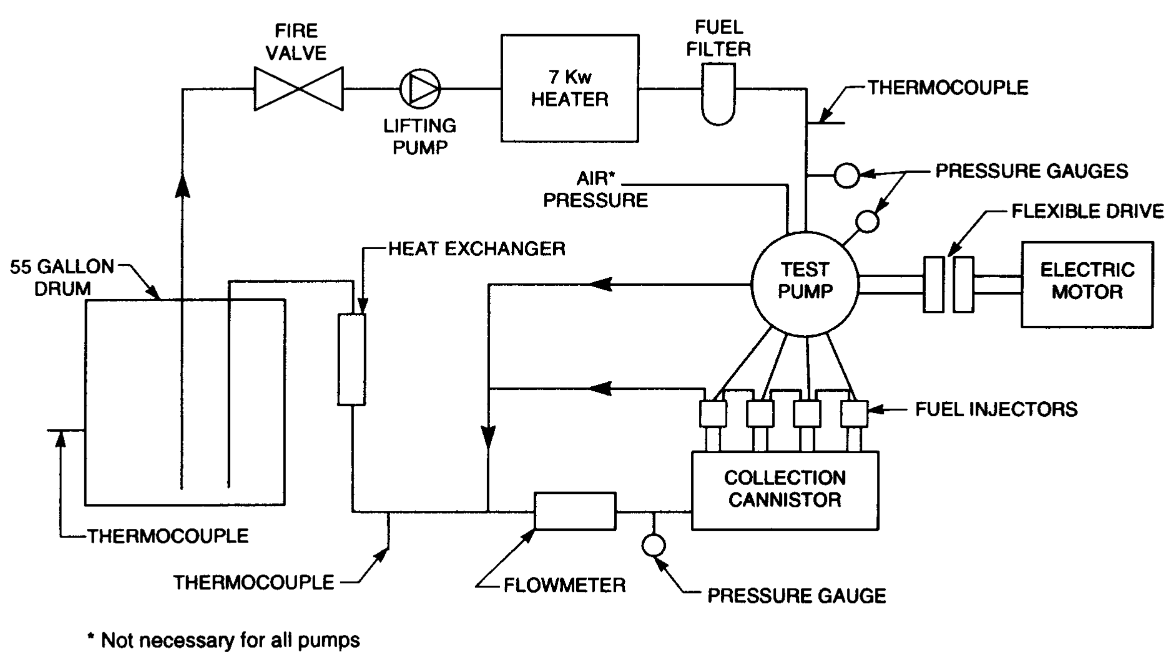


Figure 1-1. Generic Fuel Flow Loop Configuration

III. RESULTS

A. Stanadyne Tests

The Stanadyne drive adapters with gears, pumps, injectors, injection lines, flow meters, and injector collection canisters were mounted on the test stand. The target operating conditions for the Stanadyne pump test are shown in Table 1-2. Table 1-2 also contains the variation in test parameters required to operate the pumps satisfactorily on the DMM15 fuel blend. The decrease in inlet fuel temperature was required to maintain the injection pump fuel inlet pressure. The fuel tank temperature was decreased to avoid volatilization of the DMM in the fuel drums.

Table 1-2. Stanadyne Pump Operating Conditions

Parameter	Value	Value DMM15
Duration, hrs.	500	500
Speed, RPM	1800	1800
Fuel Inlet Temperature, ºF	158	<140
Throttle position	Full	Full
Injector Flange Temperature, ºF	200	200
Fuel-drum temperature, ºF	<110	<90

1. Pump Test Set One

Two fuels were evaluated simultaneously with the Stanadyne fuel injection pumps. The fuels were California Reference Diesel Fuel (CA) and a Low Sulfur, Low Aromatics Diesel Fuel (LSLA). The scheduled 500 hours were accumulated on the test fuels. Initial startup problems included leaks from two of the fuel collection canisters, leaks from rotameter o-rings, a pressure sensor failure, and insufficient cooling capacity for the fuel return on one set of pumps. All leaks were resolved. A replacement pressure sensor was obtained, installed, and calibrated. A larger cooling capacity heat exchanger was installed for the fuel return. Other problems included shutdowns by the external safety system due to power surges and fuel level float bounce. Additionally, a larger horsepower electric motor was installed in the test stand to eliminate motor overload shutdowns, which were occurring. At approximately 420 hours, the computer data acquisition board failed and was replaced.

The pump tests were performed with two pumps operating on fuel CA and two pumps operating on fuel LSLA. The pumps operating on their respective fuels are shown in Table 1-3. The pump and fuel designations for the second pump test set are as shown in Table 1-3. Performance parameters monitored for each fuel injection pump were transfer pump pressure, housing pressure, and rotameter flow reading.

Table 1-3. Stanadyne Pump and Fuel Combinations

Pump Number	Pump Serial Number	Fuel AL Number	Fuel Descriptor
1	8897753	AL-25792-F	Low Sulfur, Low Aromatics
2	8897758	AL-25792-F	Low Sulfur, Low Aromatics
3	8897760	AL-25713-F	California Reference
4	8897761	AL-25713-F	California Reference
5	8897767	AL-25787-F	Fischer-Tropsch
6	8897770	AL-25787-F	Fischer-Tropsch
7	8897768	AL-25959-F	DMM15
8	8897772	AL-25959-F	DMM15

Table 1-4 shows the 0-hour and 500-hour calibration stand measurements for each of the fuel injection pumps evaluated. The return fuel flow at 1000 RPM of the pumps using fuel CA had decreased significantly during the test. This is attributed to the heavy brown deposits found on components throughout these fuel injection pumps. In general, one pump on each of the fuels revealed performance degradation below specification at the 1800-RPM pump speed. The lower 1800-RPM flow would result in lower-rated engine power. The 325-RPM idle flow was below specification for all pumps. Lower idle flow would result in a rough idle. Overall, the calibration stand changes were relatively subtle for each fuel, except for the idle flow and return fuel flow.

The pump disassembly, inspection, and rating of critical components is shown in Table 1-5. A wear level of 5 indicates a component that has failed, seized, or that would be replaced during rebuild because it is worn out of tolerance. The average wear levels suggest more wear was apparent throughout the pumps that operated on the CA fuel. The governor thrust washers from the CA pump revealed a severe circumferential wear groove as shown in Figure 1-2. Upon further inspection of the fuel injection pumps with fuel CA, a dark brown varnish deposit was pervasive throughout the pumps. One area where the deposit was heavy was the orifice that supplies the pressure for the advance piston and subsequently the housing. Deposits in this area affect housing pressure, advance, and return flow. Deposits were also seen on the advance piston. The housing pressure is supplied from a bleed off the advance piston. Figure 1-3 reveals the heavy deposits seen on pump components from the CA fuel test.

Table 1-4. Stanadyne Injection Pump Calibration Stand Data									
Stanadyne Model DB2829-4878 Fuel Injection Pump Serial Number									
RPM	Test Hours	8897753		8897758		8897760		8897761	
		0	500	0	500	0	500	0	500
	Parameter/Specification	Fuel: LSLA				Fuel: CA			
1000	Transfer Pump Pressure, 60 - 62 psi	62	62	62	62	62	58	62	57
	Return Fuel, 225 - 375 cc	300	325	300	315	300	200	300	225
	Fuel Delivery, 56 cc max.	51.9	51	51.9	49	51.9	51.6	51.7	51.8
325	Low Idle, 12 - 16 cc	13.5	9.9	13.5	5.3	13.5	3.6	13.5	10.6
	Housing Pressure, 8 - 12 psi	8	9	8	7.8	8	8	9	8.5
	Cold Advance Solenoid, 1 deg. min.	3	1.5	3	1.5	3	1.75	2.5	1.75
1750	Fuel Delivery, 48 - 53 cc	51	49.5	51	48.1	51	48.9	51	48.6
	Advance, 3.25 - 5.25 deg.	4.5	4.25	4.25	4.25	4.5	3.75	4.5	3.25
750	Fuel Cutoff, 21.5 - 23.5 cc	22	22.8	22	22.6	22	22.7	22	22.1
	Advance, 1.25 - 3.75 deg.	2	2	2	1.75	2	2.75	2	0.75
1800	Fuel Delivery, 48-cc min.	50	48.9	50	47.3	51	48	51	47.3
	Transfer Pump Pressure, report	90	86	90	87	90	80	90	81
	Housing Pressure, report	9	9.1	9	8.5	9	9.2	8	9.3
1900	Fuel Delivery, 33-cc min.	34.9	46.4	35	39.5	34	30.6	34	42
2025	High Idle, 15 cc max.	13	1.8	13	1.6	13	1.7	13	4.3
	Transfer Pump Pressure, 125-psi max.	104	109	104	108	104	104	104	99
200	Fuel Delivery, 45-cc min.	46.1	43.3	46	41.2	46	43.6	46	42.7
	Shut Off 4 cc max.	0	0	0	0	0	0	0	0
75	Fuel Delivery, 28-cc min.	35	35.6	33	32.7	32.4	33.2	36	32.8
	Transfer Pump Pressure, 12-psi min.	25	25	25	26	25	25	25	24

Both pumps on fuel CA had reduced return flow at 1000 RPM after 500 hours, a function of the lower housing pressure. Evident in Table 1-4, the advance at 1750 and 750 RPM shows more of a change with the pumps that operated on CA. Both results confirm the findings of deposits in the pump.

Further, the after-test CA fuel was analyzed for thermal stability characteristics as reported in Section 3 (Thermal Stability and Low-Temperature Properties).

Table 1-5. Subjective Wear Level* on Critical Pump Components: 500 hours

Critical Fuel Injection Pump Component	Fuel Number			
	LSLA		CA	
	Pump Serial Number		Pump Serial Number	
	8897753	8897758	8897760†	8897761†
Distributor Rotor	2‡	2‡	1	1
Delivery Valve	2	2	2	3
Pumping Plungers	1	1	5§	2
Cam Rollers and Shoes	2	2	3	3
Leaf Spring	1	1	1	1
Drive Shaft Tang	1	1	1	1
Cam	1	1	1	1
Governor Weights	1	1	3	3
Governor Thrust Washer	1	1	5	5
Pressure Regulator	1	1	2	2
Pressure Regulator Piston	1	1	2	2
Transfer Pump Blades	2	2	4	5
Liner	1	1	5	5
Rotor Retainers	2	2	3	3
Metering Valve	1	1	1	1
Advance Piston	2	2	2	2
Average Wear:	1.4	1.4	2.6	2.5

* 0= No Wear; 5= Failure
‡ Scratched by Outlet Port
§ Both Plungers Very Scuffed/Scratched
† Brown Stain and Deposits Throughout Pump

Figure 1-2. Governor Thrust Washer Wear Groove with CA Fuel

Figure 1-3. Heavy Deposits from CA Fuel from a Stanadyne Pump

Of interest, the calibration stand housing pressure at 1800 RPM did not show the decrease observed on the durability stand. There are two reasons for this: 1) the calibration stand is operated with 100ºF VISCOR calibration fluid, versus the 158ºF fuel temperature for the durability test stand; and 2) the pump housing relief valve is removed when in the flow loop, because if it remained in the system, the backpressure caused by the plumbing would create too high a housing pressure. When the pumps are run on the calibration stand, the pump housing relief valve is replaced.

The injector performance tests, disassembly, and rating results are shown in Table 1-6 for fuel LSLA. None of the injectors had opening pressures below the minimum after 500 hours. Two injectors for each of the pumps had nonexistent to poor chatter and spray patterns. Several injectors revealed wear scars on the pintle or had a sticking pintle when first pressurized.

The injector performance tests, disassembly, and rating results are shown in Table 1-7 for fuel CA. One of the injectors revealed an opening pressure below the minimum after 500 hours. The opening pressure was so low; the injector components seemed to be defective in hardness. However, all injectors for each of the pumps had fair to good chatter and spray patterns, even the injector with low opening pressure. Several injectors revealed wear scars on their pintles.

A plot of the transfer pump pressures from test initiation to 500 hours is shown as Figure 1-4. The transfer pump pressure is the regulated pressure the metal blade transfer pump supplies to the metering section of the fuel injection pump. With low lubricity fuels, wear occurs in two sections of the transfer pump. The primary area that wear occurs is on the transfer pump blades, blade slot, and eccentric liner. Wear in these areas generally causes the transfer pump pressure to decrease. Because the transfer pump has a pressure regulator, significant wear needs to occur in the transfer pump before the fuel pressure is reduced to below the operating range allowed in the pump specification. The alternate wear area in the transfer pump section is the pressure regulator piston. Wear on the regulating piston is caused by the regulating action and, to some extent, by fretting due to the pumps being operated at a single speed and flow condition. Wear in the pressure regulator may result in reductions in transfer pump pressure due to increased leakage around the regulator piston. Increased or decreased transfer pump pressure may occur due to the regulator piston sticking from fretting. The results in Figure 1-4 indicate that with the LSLA fuel, minimal wear is occurring in the transfer pump section since the pressure did not vary greatly from the start of the test. The results for the California Reference Fuel CA indicate some wear is occurring, manifested by the slight decrease in transfer pump pressure with time.

Table 1-6. Injector Inspections for LSLA Fuel

Injection Pump Serial Number: 8897753
Fuel Number: LSLA

Injector ID Number		1		2		3		4	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1800	1650	1850	1675	1850	1750	1825	1675
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	fair	good	good	good	none	very good	very good
Spray Pattern	Fine Mist	good	fair	good	good	good	poor	good	good
Assembly Leakage	Dry, No Seepage	ok	none	0	none	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	fair, two worn spots	~~	good, 2 slightly worn spots	~~	poor, galled & scuffed	~~	good, 2 slightly worn spots
Lapped Surface Condition	Report	~~	good	~~	~~	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

Injector ID Number		5		6		7		8	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1825	1725, pintle is sticking	1850	1650, pintle sticking	1900	1725	1875	1700
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	none	good	fair	good	pintle sticking at first, good after a few strokes	very good	good
Spray Pattern	Fine Mist	good	poor	good	fair	good	good	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	poor	~~	poor, worn & sticking	~~	fair, small scratches in center of pintle	~~	good, one small worn spot
Lapped Surface Condition	Report	~~	fair	~~	good	~~	fair	~~	fair
Other		~~	groove worn into spring seat	~~	~~	~~	~~	~~	groove worn into spring seat

Injection Pump Serial Number: 8897758
Fuel Number: LSLA

Injector ID Number		9		10		11		12	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1875	1725	1850	1675, sticky pintle	1850	1750	1825	1675
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	very good	good	good	none	good	poor	excellent	good
Spray Pattern	Fine Mist	good	good	good	poor	good	poor	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good, vertical wear spots	~~	poor, badly worn,some scuffing	~~	poor, large worn spot	~~	poor, 2 worn spots
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

Injector ID Number		13		14		15		16	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1800	1675	1850	1675	1900	1750	1825	1775
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	fair	good	good	good	good	good	good
Spray Pattern	Fine Mist	good	fair	good	good	good	good	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	poor, large worn spot	~~	poor, large wear spot	~~	poor, 2 large worn spots	~~	good, no worn spots
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

Table 1-7. Injector Inspections for CA Fuel

Injection Pump Serial Number: 8897760
Fuel Number: CA

Injector ID Number		17		18		19		20	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1775	1675	1800	1700	1850	1675	1825	1700
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	good	good	good	very good	good	good	good
Spray Pattern	Fine Mist	good	good	good	good	good	good	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	fair, one worn spot	~~	good, no wear	~~	good, no worn spots	~~	good, one lightly worn spot
Lapped Surface Condition	Report	~~	fair	~~	good	~~	good	~~	good
Other		~~	slight grove worn into spring seat	~~	~~	~~	~~	~~	~~

Injector ID Number		21		22		23		24	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1850	1750	1900	1775	1825	1700, pintle slightly sticky	1850	1700
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	good	very good	very good	good	good	very good	good
Spray Pattern	Fine Mist	good	good	good	good	good	good	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	poor, large worn spot	~~	good, one lightly worn spot	~~	fair, one large slightly worn spot	~~	fair, 2 large but slightly worn spots
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

Injection Pump Serial Number: 8897761
Fuel Number: CA

Injector ID Number		25		26		27		28	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1925	1700	1825	1700	1850	975, pressure spindle defective	1900	1800
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	?	0	0
Chatter Test	chatter	good	good	good	good	good	good	good	good
Spray Pattern	Fine Mist	good	good	good	good	good	good	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	?	0	0
Pintle Condition	Shiny, No Scratches	~~	good, not worn	~~	good, not worn	~~	good, one small worn spot	~~	good, not worn
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

Injector ID Number		29		30		31		32	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1950	1800	1925	1800	1900	1775	1900	1700
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	very good	very good	good	good	good	fair	good	good
Spray Pattern	Fine Mist	good	good	good	good	good	fair	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good, not worn	~~	good, two worn spots	~~	good, not worn	~~	good, one worn spot
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

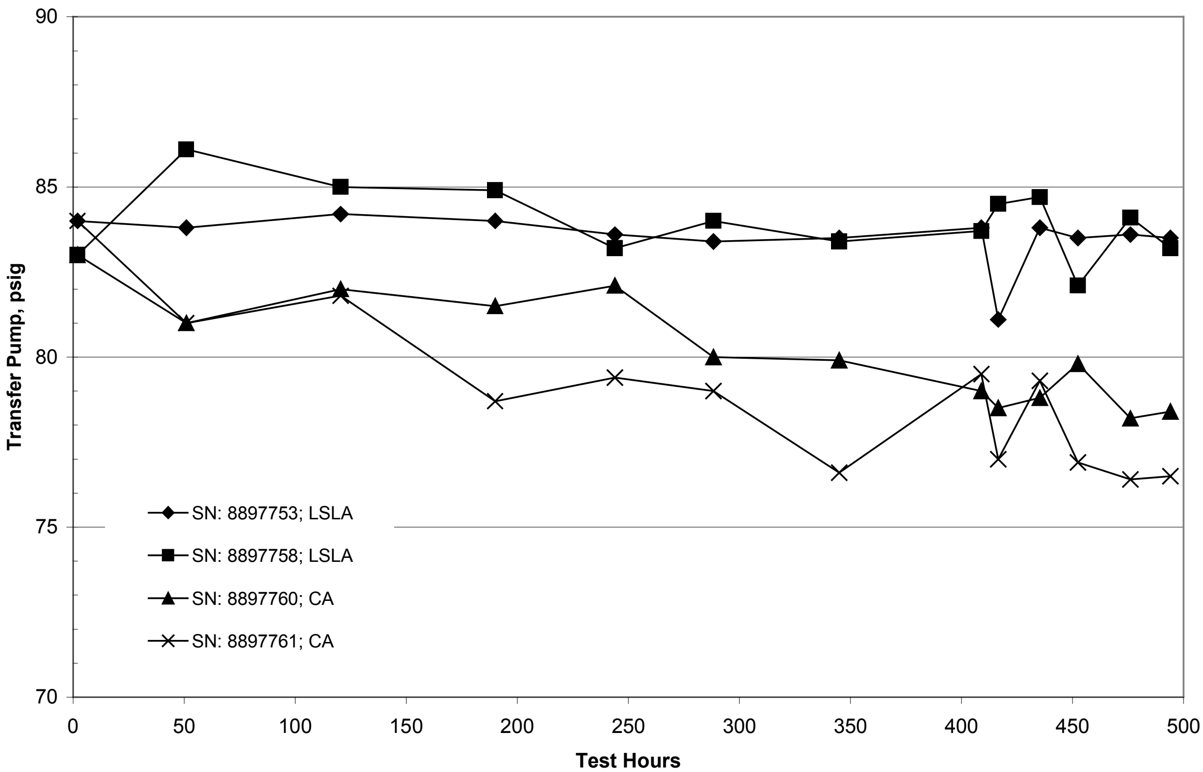


Figure 1-4. Stanadyne Pump Transfer Pump Pressures for LSLA and CA Fuels

A plot of the pump housing pressures from test initiation to 500 hours is shown as Figure 1-5. The housing pressure is the regulated pressure in the pump body that affects fuel metering and injection timing. With low lubricity fuels, wear occurs in high fuel pressure generating opposed plungers and bores, and between the rotor and hydraulic head. Leakage from increased diametrical clearances of the plunger and plunger bores, and the hydraulic head and rotor, results in increased housing pressures. Increased housing pressure reduces metered fuel and retards injection timing. Because of the physical location of the fuel drums, the initial housing pressure for the CA fuel is higher due to flow restrictions. Both sets of pumps are below the specification maximum housing pressure of 12 psig. The results in Figure 1-5 indicate the CA fuel had minimal wear in the high-pressure section because the housing pressure did not increase; however, the housing pressure did decrease slightly. The cause for the decrease in housing pressure with CA fuel is the heavy deposits found in the pumps. The results for the LSLA fuel indicate some wear in the high-pressure section, discernable from the slight increase in housing pressure.

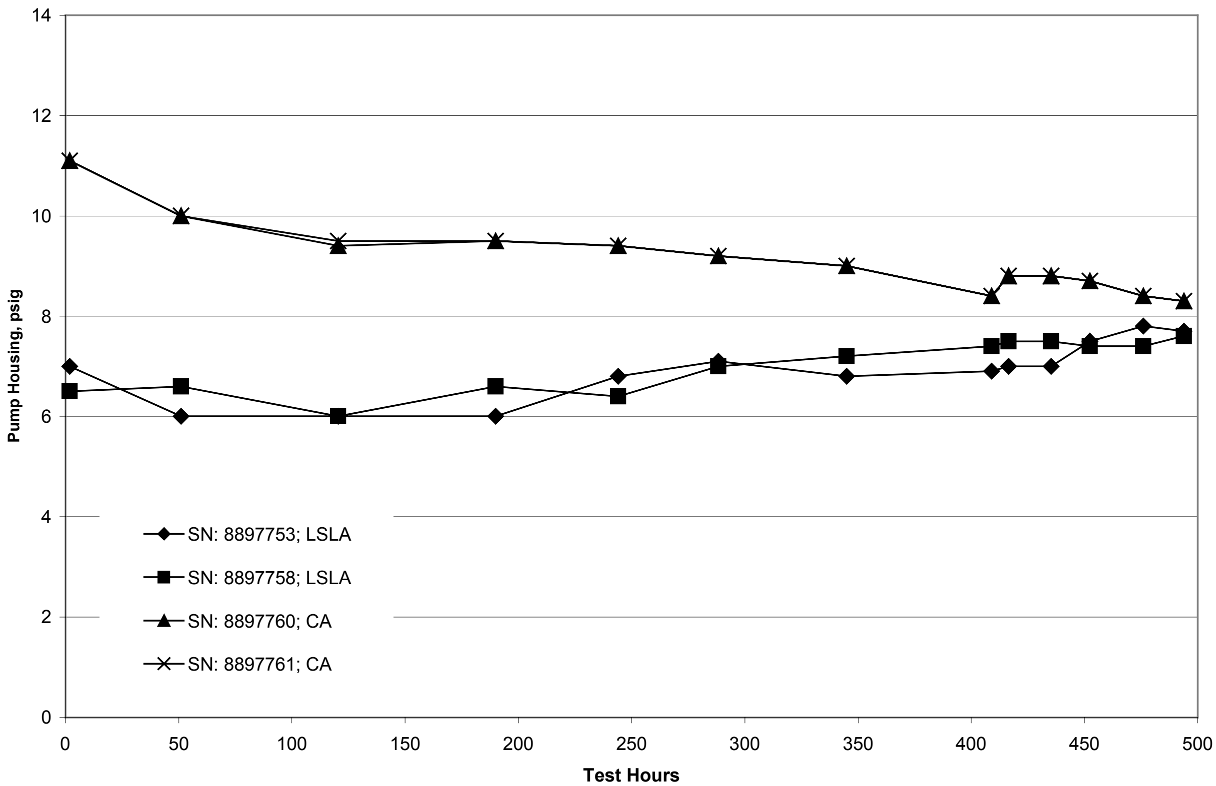


Figure 1-5. Stanadyne Pump Housing Pressures for LSLA and CA Fuels

A plot of the individual pump rotameter flow readings from test initiation to 500 hours is shown as Figure 1-6. The rotameter flow readings reflect the injected flow from the eight fuel injectors in each collection canister. Any wear in the fuel injection pump metering section or the fuel injectors was reflected as a reduced rotameter flow reading. The results in Figure 1-6 indicate that with the LSLA fuel, the injected flow does not show a substantial variation. The results for the CA fuel do not show substantial variation in injected flow for pump 8897761, but reveal a sticking metering valve for pump 8897760. The metering valve sometimes sticks in one position due to fretting and the metering valve always being at the full rack position. When the pump speed or rack setting is reduced, the metering valve may not exhibit a full range of motion. In this case, cycling the fuel rack loosened the sticking metering valve. Disregarding the sticking metering valve, the flow appears consistent for the test duration for pump 8897760.

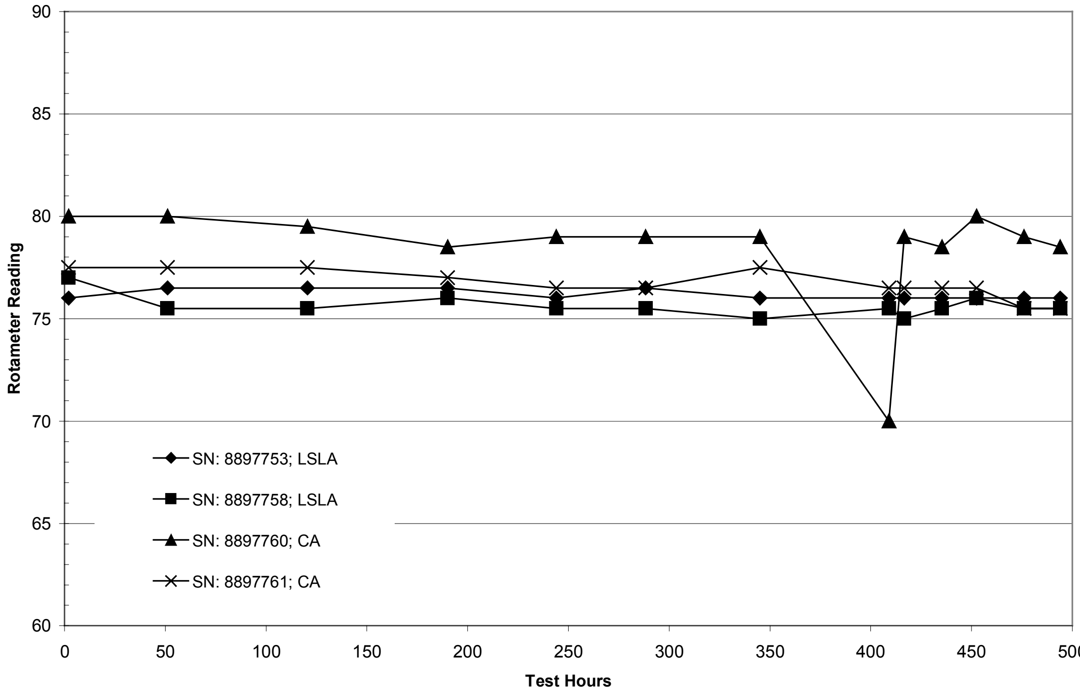


Figure 1-6. Stanadyne Pump Rotameter Flow Readings for LSLA and CA Fuels

2. Pump Test Set Two

Two fuels were evaluated simultaneously with the Stanadyne fuel injection pumps. The fuels were Neat Fischer-Tropsch Diesel Fuel (FT100) and a blend of 15% DMM and 85% Low Sulfur, Low Aromatics Diesel Fuel (DMM15). The scheduled 500 hours were accumulated on the test fuels. An additional heat exchanger was installed for the fuel return of the DMM15 fuel to help condense the DMM so it can recombine with the base fuel.

Table 1-8 shows the check of the volume of DMM in fuel DMM15 during the course of testing. The check was performed by filling a graduated cylinder with 100 ml of fuel, then allowing the DMM to boil off under a fume hood. The volume change was reported as the percent DMM component. The results indicate that the blend remained consistent.

Table 1-8.Percent DMM in Fuel DMM15

Test Hour	DMM Percent
0	16
100	16
200	15
300	15.5
400	15

Table 1-9 shows the 0-hour and 500-hour calibration stand measurements for each of the fuel injection pumps evaluated. The transfer pump pressure at 1000 RPM for all pumps using both FT100 and DMM15 fuel decreased during the test. In general, all pumps on each fuel revealed performance degradation below specification at the 1800-RPM pump speed. The lower 1800-RPM flow would result in lower rated engine power. The 200-RPM fuel flow was below specification for both FT100 pumps and one DMM15 pump. One pump for each fuel revealed a reduced cranking fuel flow. Overall, the calibration stand changes indicate the FT100 and DMM15 fuels affected the rated performance of the injection pumps after 500 hours.

Table 1-9. Stanadyne Injection Pump Calibration Stand Data

Stanadyne Model DB2829-4878 Fuel Injection Pump Serial Number									
RPM		8897767		8897770		8897768		8897772	
	Test Hours	0	500	0	500	0	500	0	500
	Parameter/Specification	Fuel: FT100				Fuel: DMM15			
1000	Transfer Pump Pressure, 60 - 62 psi	62	54	62	58	62	57.5	62	59
	Return Fuel, 225 - 375 cc	300	250	300	235	225	245	225	225
	Fuel Delivery, 56 cc Max.	50	50	49	51	49.2	53.5	49.2	51.3
325	Low Idle, 12 - 16 cc	13.5	16.3	13.5	13.9	13.5	16.9	13.5	20.1
	Housing Pressure, 8 - 12 psi	9	8.4	8	8	8	8.1	9	9.1
	Cold Advance Solenoid, 1 deg. Min.	3	2.5	3	3.25	3	3.75	3	0
1750	Fuel Delivery, 48 - 53 cc	51	45.8	52	49.2	51	49.1	51	48.6
	Advance, 3.25 - 5.25 deg.	4.5	2.5	4.8	3.25	4.5	3.75	4.5	3.5
750	Fuel Cutoff, 21.5 - 23.5 cc	22	22.8	22	22.4	22	22.8	22	22.5
	Advance, 1.25 - 3.75 deg.	2	1.5	2	1.75	2	1.75	2	1.75
1800	Fuel Delivery, 48 cc Min.	50	42.8	50	47.6	50	47.6	51	47.5
	Transfer Pump Pressure, report	90	76	90	79.8	90	83	90	80.5
	Housing Pressure, report	9	9	8	8	9	8.4	9	9.1
1900	Fuel Delivery, 33 cc Min.	37	38.5	34.2	46.4	36.3	44.7	34	45.3
2025	High Idle, 15 cc Max.	13	1	13	3.5	13	10	13	2
	Transfer Pump Pressure, 125 psi Max.	104	95	104	98	104	98	104	99.5
200	Fuel Delivery, 45 cc Min.	46	41.5	45.1	43.7	45.3	45.7	45	35.8
	Shut Off 4 cc Max.	0	0	0	0	0	0	0	0
75	Fuel Delivery, 28 cc Min.	34.2	26.6	37.1	30.5	34	30	32.9	17.6
	Transfer Pump Pressure, 12 psi Min.	24	16	26	24	24	17	24	18

The pump disassembly, inspection, and subjective rating of critical components is shown in Table 1-10. A wear level of 5 indicates a component that has failed, seized, or that would be replaced during rebuild because it is worn out of tolerance. The average wear levels suggest more wear was apparent throughout the pumps operated on FT100 and DMM15 than those operated on the LSLA fuel. Compared across all fuels, the average wear level for the CA fuel (Table 1-5) is similar to the FT100 and DMM15 fuels, which was not anticipated. The CA fuel revealed unusual wear levels on the pumping plungers and governor thrust washers, not seen with the other fuels. The transfer pump wear seen with CA fuel is similar to the FT100 and DMM15 fuels. Inspection of the FT100 and DMM15 fuel injection pumps revealed a light brown discoloration throughout the pumps. This discoloration is due to metal oxidation, and has been seen in other pumps with high wear levels. Of interest with FT100 and DMM15 fuels was the severe drive tang wear scars, wear on the distributor rotor, and high transfer pump component wear. Due to the drive tang wear, the FT100 and DMM15 pumps would probably reveal operational problems on an engine.

Table 1-10. Subjective Wear Level* on Critical Pump Components: 500 Hours

Critical Fuel Injection Pump Component	Fuel Number			
	FT100		DMM15	
	Pump Serial Number		Pump Serial Number	
	8897767¥	8897770¥	8897768¥	8897772¥
Distributor Rotor	4	3	3	3
Delivery Valve	1	2	2	2
Pumping Plungers	1	2	1	2
Cam Rollers and Shoes	3	3	2	3
Leaf Spring	2	1	3	2
Drive Shaft Tang	5	5	3	5
Cam	1	1	1	1
Governor Weights	2	2	3	3
Governor Thrust Washer	2	2	3	3
Pressure Regulator	2	1	1	1
Pressure Regulator Piston	2	2	1	1
Transfer Pump Blades	5	4	5	5
Liner	5	5	5	5
Rotor Retainers	3	3	3	3
Metering Valve	1	1	2	2
Advance Piston	2	2	2	2
Average Wear:	**2.6**	**2.4**	**2.5**	**2.7**

* 0= No Wear; 5= Failure
¥ Light Brown Stain Throughout Pump

A plot of the transfer pump pressures for fuels FT100 and DMM15 is shown in Figure 1-7 for the hours accumulated. One pump for both fuels reveals a decrease in transfer pump pressure, which indicates wear is occurring on the transfer pump blades and liner. Of interest is the fact that the heavy wear in the transfer pump section seen during inspection was not revealed as a large transfer pump pressure change. This could be due to the pressure regulator still operating in an effective range. The results for fuel DMM15 appear a little inconsistent because the fuel inlet temperature needed to be adjusted to avoid boiling at the fuel inlet to the pump. The CA (Figure 1-4), FT100, and DMM15 fuels revealed a transfer pump pressure below specification at 1000 RPM during the post-test calibration stand check.

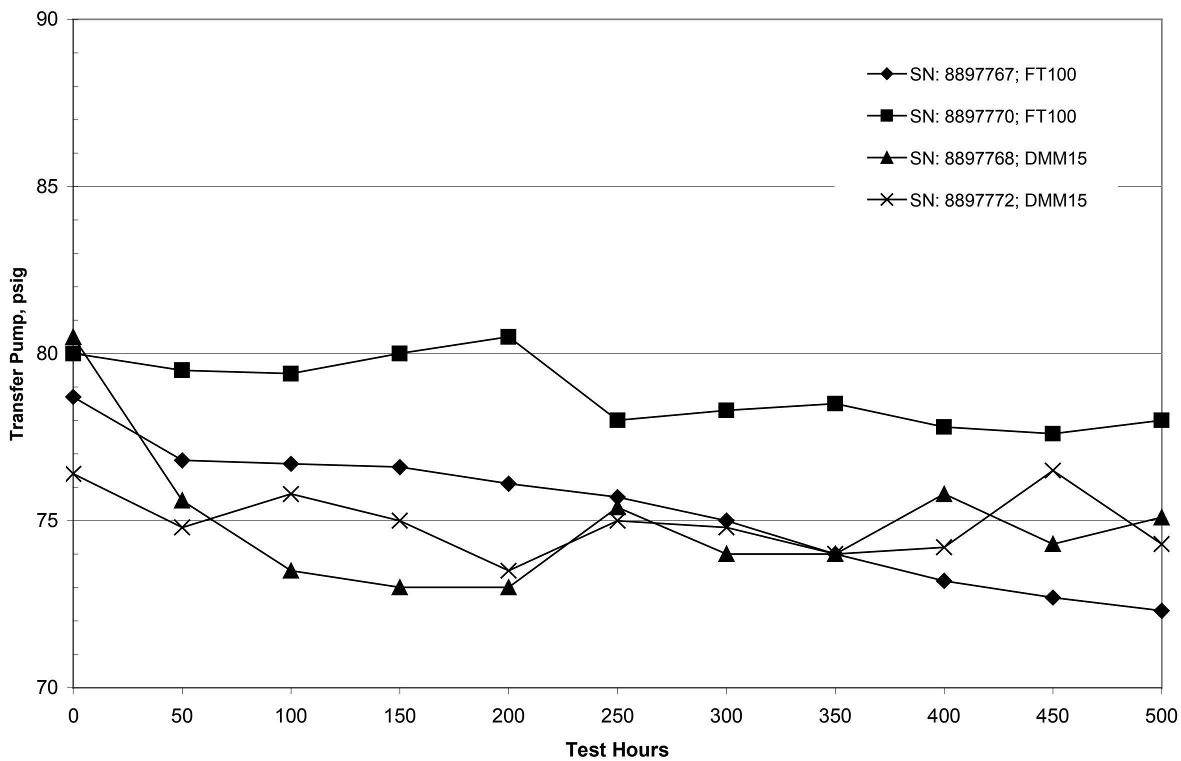


Figure 1-7. Stanadyne Pump Transfer Pump Pressures for FT100 and DMM15 Fuels

The data in Figure 1-8 is for the housing pressures for fuels FT100 and DMM15. Fuel FT100 shows a slight increase in housing pressure, which indicates wear in either the head and rotor or the plungers and bores. Pump component inspections revealed distributor rotor wear scars for FT100. Again, the results for fuel DMM15 appear a little inconsistent because of the need to adjust fuel inlet temperature. Stable fuel inlet conditions to the pump were achieved after 50 hours. A slight increase in housing pressure does appear from 100 hours to the end of test. The distributor rotor ratings revealed wear scars that would be consistent with a housing pressure increase. It should be noted that the wear scars seen on the distributor rotors with FT100 and DMM15 are unusual. Wear in this area can become rapidly catastrophic because the small clearance between the head and rotor is intolerant of wear debris.

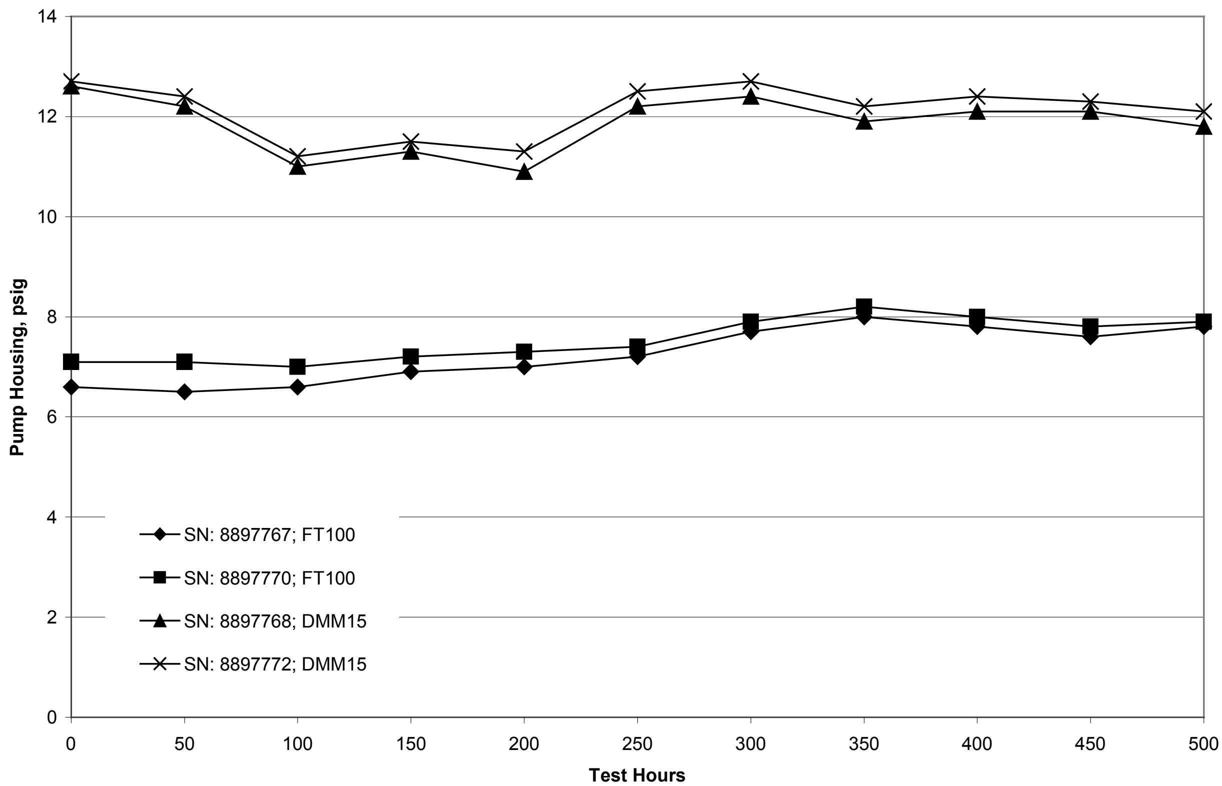


Figure 1-8. Stanadyne Pump Housing Pressures for FT100 and DMM15 Fuels

A plot of the rotameter flow readings is shown in Figure 1-9 for fuels FT100 and DMM15. For the Fischer-Tropsch fuel, there is a decrease of injected quantity over the duration of testing. Pump 8897767 reveals the most change, which is supported by the calibration stand data. The readings for the DMM15 blend are inconsistent due to boiling of the fuel after it leaves the injectors, which are held at 200°F. A decrease in injected flow is seen for the DMM15 pump after stable pump conditions were achieved. A decrease in injected flow is noted for the DMM15 pump on the calibration stand at 1800 RPM.

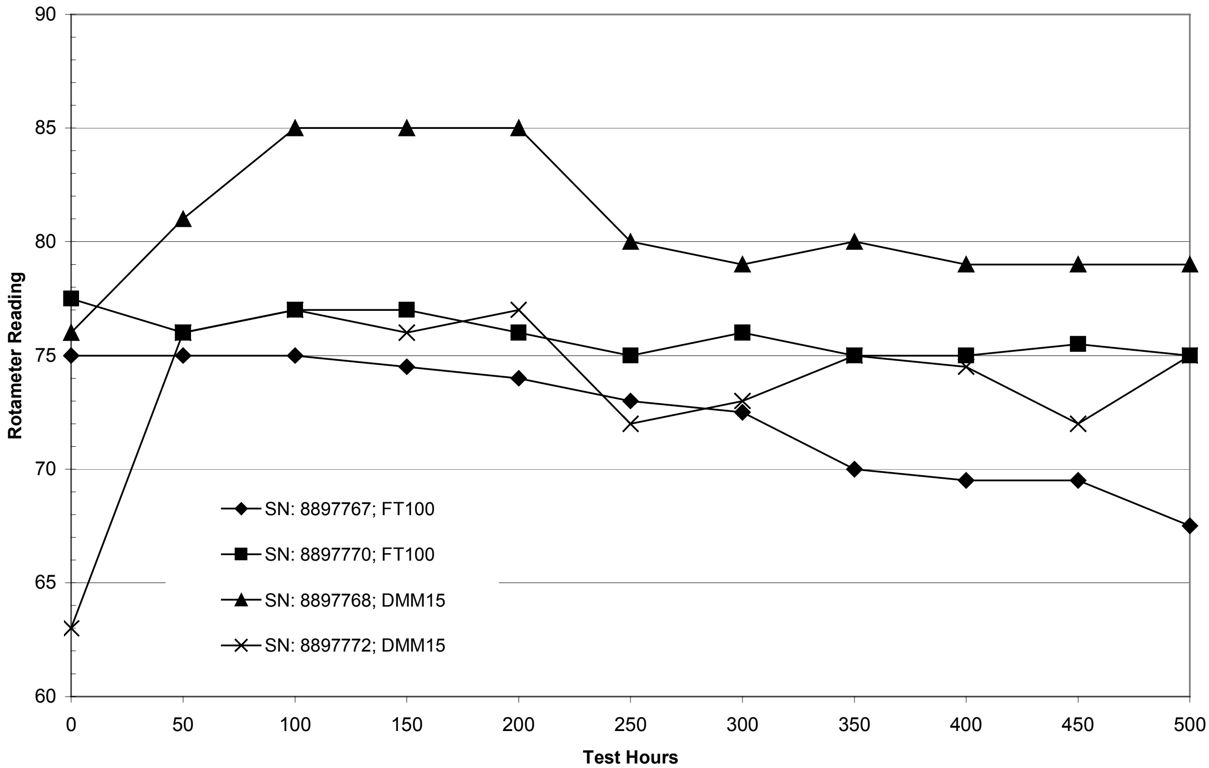


Figure 1-9. Stanadyne Pump Rotameter Flow Readings for FT100 and DMM15 Fuels

The injector performance tests, disassembly, and rating results are shown in Table 1-11 for fuel FT100. Two of the injectors had opening pressures below the minimum after 500 hours and two more were within 50 psig of the minimum. Only one injector from either pump had nonexistent to poor chatter and spray patterns. Several injectors revealed a wear scar on the pintle stem where it mates with the spring seat or had a sticking pintle when first pressurized. Several of the pintles revealed light scratches.

The injector performance tests, disassembly, and rating results are shown in Table 1-12 for fuel DMM15. Three of the injectors revealed an opening pressure at or below the minimum after 500 hours. Several other injectors had opening pressures within 50 psig of the minimum. Two injectors had either poor chatter or a poor spray pattern. Several injectors had a wear scar on the pintle stem at the spring seat mating surface. Several injectors revealed light scratches on their pintles.

Table 1-11. Injector Inspections for FT100

Injection Pump Serial Number: 8897767
Fuel Number: FT100

Injector ID Number		33		34		35		36	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1725	1550	1750	1600	1800	1550	1800	1000
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	exc.	good	very good	very good	exc.	good	very good	good
Spray Pattern	Fine Mist	exc.	good	very good	very good	exc.	good	very good	good
Assembly Leakage	Dry, No Seepage	0	none	0	none	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good	~~	good	~~	good	~~	good
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	wear on stem tip	~~	wear on stem tip	~~	wear on stem tip	~~	wear on stem tip

Injector ID Number		37		38		39		40	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1800	1625	1825	1625	2000	1800	1825	1150
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	good	exc.	very good	good	good	very good	good
Spray Pattern	Fine Mist	good	good	exc.	very good	good	good	very good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good	~~	good	~~	good	~~	worn
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	wear on stem tip	~~	wear on stem tip	~~	wear on stem tip	~~	stem tip & spring seat worn

Injection Pump Serial Number: 8897770
Fuel Number: FT100

Injector ID Number		41		42		43		44	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1850	1625	1850	1625, pintle sticking	1875	1675	1800	1600
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	exc.	very good	very good	fair	exc.	exc.	very good	very good
Spray Pattern	Fine Mist	exc.	very good	very good	good	exc.	exc.	very good	very good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good	~~	good	~~	good	~~	good
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	~~

Injector ID Number		45		46		47		48	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1950	1625, pintle sticking	1850	1650	1900	1700	1825	1650
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	exc.	fair	exc.	poor	good	good	good	good
Spray Pattern	Fine Mist	good	fair	exc.	poor	good	good	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	fair, lt. Scratches	~~	fair, lt. Scratches	~~	fair, lt. Scratches	~~	good
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	wear on stem tip	~~	~~	~~	~~	~~	~~

Table 1-12. Injector Inspections for DMM15

Injection Pump Serial Number: 8897768
Fuel Number: DMM15

Injector ID Number		49		50		51		52	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1800	1600	1750	1600, pintle sticking	1875	1600, pintle sticking	1800	1600
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	exc.	good	good	good	fair	very good	good
Spray Pattern	Fine Mist	good	exc.	good	good	good	fair	very good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good	~~	fair, lt. Scratches	~~	fair, pintle worn	~~	good
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	~~	~~	rust on nozzle

Injector ID Number		53		54		55		56	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1800	1575	1925	1650, pintle sticking	1850	1600	1750	1500
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	drop formed, did not fall
Chatter Test	chatter	exc.	good	exc.	good	good	fair	very good	good
Spray Pattern	Fine Mist	exc.	good	exc.	good	good	poor, unsymetric	good	good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	fair, lt. Scratches	~~	fair, lt. Scratches	~~	good	~~	fair, 2 large but slightly worn spots
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	~~	~~	~~	~~	rust on nozzle	~~	rust on nozzle, worn stem tip

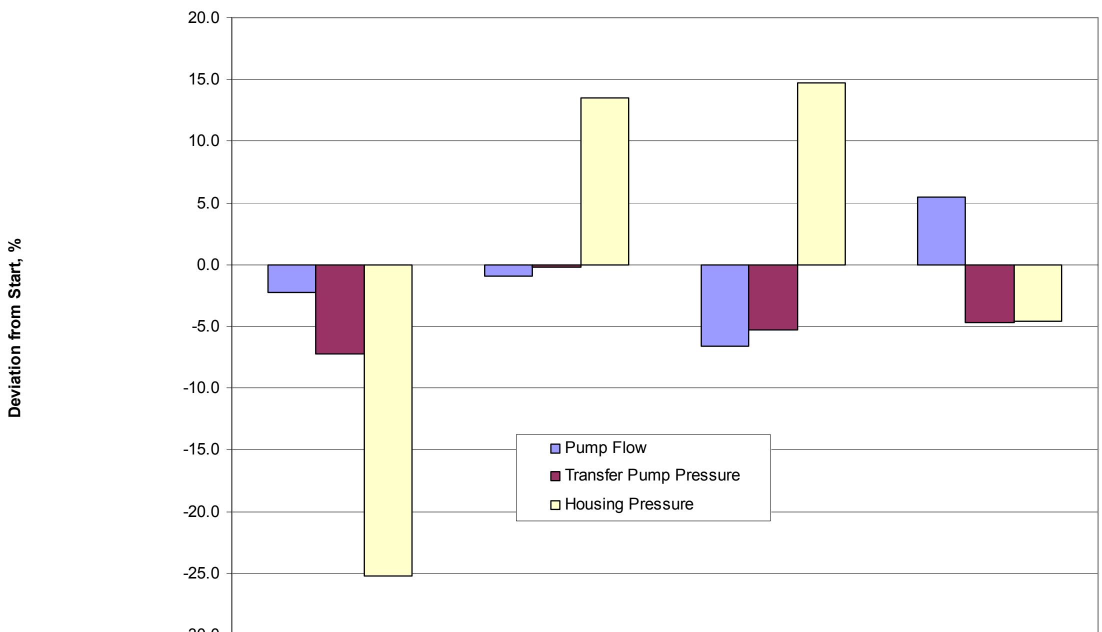
Injection Pump Serial Number: 8897772
Fuel Number: DMM15

Injector ID Number		57		58		59		60	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1700	1450	1925	1675	1925	1675	1800	1525
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	good	exc.	good	exc.	good	good	fair
Spray Pattern	Fine Mist	good	good	exc.	good	exc.	good	good	fair
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	good	~~	fair, lt. Scratches	~~	fair, lt. Scratches	~~	fair, lt. Scratches
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	worn stem tip	~~	worn stem tip	~~	worn stem tip	~~	worn stem tip

Injector ID Number		61		62		63		64	
		Test Hours		Test Hours		Test Hours		Test Hours	
Injector Test	Specification Value	0	500	0	500	0	500	0	500
Opening Pressure Test	1500 Psig Min.	1775	1550, pintle sticking	1775	1600	1800	1500	1950	1675
Leakage Test	No Drop Off in 10 sec. @ 1400 psig	0	0	0	0	0	0	0	0
Chatter Test	chatter	good	fair	good	good	exc.	good	exc.	very good
Spray Pattern	Fine Mist	good	poor	good	good	exc.	good	exc.	very good
Assembly Leakage	Dry, No Seepage	0	0	0	0	0	0	0	0
Pintle Condition	Shiny, No Scratches	~~	poor, large scratch	~~	fair, pintle worn	~~	fair, lt. Scratches	~~	good
Lapped Surface Condition	Report	~~	good	~~	good	~~	good	~~	good
Other		~~	worn stem tip	~~	worn stem tip	~~	worn stem tip	~~	worn stem tip

3. Stanadyne Results Discussion

The average pump performance deviations for the two pumps from the durability stand measurements for each test fuel are shown in Figure 1-10 for the 500-hour tests. The decreasing pump flow variations reflect wear in the transfer pump, plunger and bore, and rotor and housing areas for reduced flow. Increased pump flow with DMM15 indicates an increase of the roller-to-roller dimension due to wear between the roller shoe and leaf spring. Increased roller-to-roller dimension results in a greater injection quantity. The transfer pump pressure for each fuel showed a decrease after 500 hours, due to wear on the pump vanes and pump liner. Reduced transfer pump pressure usually results in reduced metering pressure, and a concomitant decrease in pump flow. The housing pressure increase is due to increased leakage, and is associated with wear between the plunger and bore, and the rotor and housing. The housing pressure decrease with CA fuel is due to the presence of heavy deposits around the housing pressure supply orifice. The decrease in housing pressure with the DMM15 may be related to the increased injected flow, which results in a lower return flow.



	CA	LSLA	FT100	DMM15
Pump Flow	-2.2	-1.0	-6.6	5.4
Transfer Pump Pressure	-7.2	-0.2	-5.3	-4.7
Housing Pressure	-25.2	13.5	14.7	-4.6

Figure 1-10. Average Stanadyne Pump Performance Deviation after 500 Hours with Test Fuels.

The calibration stand summaries are shown in Table 1-13 for each pump and fuel after 500 hours. Bold, underlined areas reflect performance parameters that are below the minimum requirement for the pump specification. The LSLA fuel was the only fuel that did not show any impact at 1000 RPM, which corresponds to the application peak torque. The idle results, 325 RPM, indicate either a rough idle or that stalling may be evident with LSLA or CA fuels, due to low idle injection quantities. Of interest, the FT100 and DMM15 showed increased injection quantity at idle. FT100 fuel showed delivery and timing changes at 1750 RPM not seen with the other fuels. Advance is out of tolerance for one of the CA pumps at 750 RPM, likely due to the deposits seen in the pump. At least one pump for each test fuel showed low fuel delivery at the pump application rated engine speed. The increased injection flow at 1800 RPM on the test stand with DMM15 was not seen on the calibration stand, likely due to the use of a calibration fluid on the calibration stand. The CA fuel was the only fuel that showed an impact at 1900 RPM. The 75-RPM results indicate starting problems due to low cranking flows with one pump from both the FT100 and DMM15 tests.

Table 1-13. Stanadyne Pump Calibration Performance after 500 Hours on Test Fuels

Stanadyne Model DB2829-4878 Fuel Injection Pump Serial Number									
RPM		8897753	8897758	8897760	8897761	8897767	8897770	8897768	8897772
	Test Hours	500	500	500	500	500	500	500	500
	Parameter/Specification	LSLA		CARB		FT100		DMM15	
1000	Transfer Pump Pressure, 60 - 62	62	62	**<u>58</u>**	**<u>57</u>**	**<u>54</u>**	**<u>58</u>**	**<u>57.5</u>**	**<u>59</u>**
	Return Fuel, 225 - 375 cc	325	315	**<u>200</u>**	225	250	235	245	225
325	Low Idle, 12 - 16 cc	**<u>9.9</u>**	**<u>5.3</u>**	**<u>3.6</u>**	**<u>10.6</u>**	16.3	13.9	16.9	20.1
	Housing Pressure, 8 - 12 psi	9	**<u>7.8</u>**	8	8.5	8.4	8	8.1	9.1
1750	Fuel Delivery, 48 - 53 cc	49.5	48.1	48.9	48.6	**<u>45.8</u>**	49.2	49.1	48.6
	Advance, 3.25 - 5.25 deg.	4.25	4.25	3.75	3.25	**<u>2.5</u>**	3.25	3.75	3.5
750	Advance, 1.25 - 3.75 deg.	2	1.75	2.75	**<u>0.75</u>**	1.5	1.75	1.75	1.75
1800	Fuel Delivery, 48 cc Min.	48.9	**<u>47.3</u>**	48	**<u>47.3</u>**	**<u>42.8</u>**	**<u>47.6</u>**	**<u>47.6</u>**	**<u>47.5</u>**
1900	Fuel Delivery, 33 cc Min.	46.4	39.5	**<u>30.6</u>**	42	38.5	46.4	44.7	45.3
200	Fuel Delivery, 45 cc Min.	**<u>43.3</u>**	**<u>41.2</u>**	**<u>43.6</u>**	**<u>42.7</u>**	**<u>41.5</u>**	**<u>43.7</u>**	45.7	**<u>35.8</u>**
75	Fuel Delivery, 28 cc Min.	35.6	32.7	33.2	32.8	**<u>26.6</u>**	30.5	30	**<u>17.6</u>**

4. Stanadyne Injector Performance Summary

The average fuel injector opening pressure loss for each injection pump and fuel is shown in Table 1-14. Fuel CA had one injector that was uncharacteristically poor; the spring seat appeared defective. The averages for CA were calculated with and without the anomalous injector. The average injector opening pressure loss appears to rank the fuels in the order of the new fuel lubricity results.

Table 1-14. Injector Nozzle Opening Pressure Loss after 500 Hours

Fuel	Injection Pump Serial Number	Pump Average Opening Pressure Loss, psig	Fuel Average Opening Pressure Loss, psig
CA	8897760	125	183/137*
	8897761	241/150*	
LSLA	8897753	153	144
	8897758	134	
FT100	8897767	328	273
	8897770	219	
DMM15	8897768	228	239
	8897772	250	

* Averages without spring seat which appeared defective.

5. Stanadyne Pump Drive Tang Wear

The drive tang of the Stanadyne pumps couples the distributor rotor to the engine drive, and is critical for injection timing. Significant wear on the drive tang effectively retards fuel injection timing, and increases backlash. The drive tangs shown in Figures 1-11 through 1-14 are the most worn of the two pumps tested on each fuel. The wear seen on the drive tang for the LSLA fuel shown in Figure 1-11 is minimal and would not likely cause operational problems.

Figure 1-11. Drive Tang from LSLA Pump SN:8897758

Figure 1-12. Drive Tang from CA Pump SN:8897760

The wear seen in Figure 1-12 for the CA fuel is similar to the LSLA pump, and again would not likely cause problems on an engine. Both the DMM15 (Figure 1-13) and FT100 (Figure 1-14) fuels revealed considerable drive tang wear. Both of these fuels revealed more drive tang wear than with any low lubricity fuels previously seen. The level of drive tang wear for the DMM15 and FT100 fuels would likely cause operability problems on an engine.

Figure 1-13. Drive Tang from DMM15 Pump SN:8897772

Figure 1-14. Drive Tang from FT100 Pump SN:8897767

6. Stanadyne Operator Notes

The pumps utilized for the DMM15 testing were operated at inlet conditions of 140°F and 3.5 psig. This was required to avoid vaporization of the fuel at the pump inlet and correct unsteady transfer pump pressures.

The test stand operator upon initial inspection of the test pumps noted the observations shown in Table 1-15.

Table 1-15. Operator Notes from Pump Inspections

Fuel Code	Pump Serial Number	Notes
LSLA	8897753	Normal wear, light metal flakes under top cover
	8897758	Normal wear, light metal flakes under top cover
CA	8897760	Brown gummy build-up throughout pump. More metal under top cover than LSLA pumps.
	8897761	Heavier brown gum build-up throughout pump. Same amount of metal shavings under top cover as other CA pump.
FT100	8897767	Dark brown oxidation film throughout pump. Metal shavings under top cover, similar to CA pumps.
	8897770	Light brown oxidation film throughout pump. Metal shavings under top cover similar to other FT100 pump.
DMM15	8897768	Light brown oxidation film throughout pump. Metal shavings under top cover same as FT100 and CA pumps.
	8897772	Darker brown oxidation film than previous DMM15 pump. Metal shavings under top cover same as FT100 and CA pumps.

7. Manufacturer Ratings

The Stanadyne Automotive Corporation inspection results are included as Appendix A. Stanadyne calculates a Pump Lubricity Value (PLV) based on component wear and pump performance change. Table 1-16 cross-references the pump serial numbers with test fuels. The rankings are based on the average Stanadyne PLV values for each fuel. Stanadyne considers fuels with a PLV above 4 to be unacceptable for their pumps. The SwRI ranking is based on performance, subjective part ratings, and overall pump condition.

Table 1-16. Stanadyne Rotary Fuel Injection Pump Rating Summary					
pump SN	Fuel	Stanadyne PLV	Stanadyne Fuel Rank (PLV avg.)	SwRI Subjective Wear Rating	SwRI Fuel Rank
8897753	LSLA	3	1	1.4	1
8897758	LSLA	3		1.4	
8897760	CA	4	2	2.6	2
8897761	CA	4.5		2.5	
8897768	DMM15	6	3	2.5	3
8897772	DMM15	7		2.7	
8897767	FT100	8	4	2.6	4
8897770	FT100	5.5		2.4	

B. Bosch High-Pressure Common-Rail Tests

The Bosch common-rail drive adapters, transfer pumps, high-pressure rail pumps, fuel rails, injectors, and the injector heating/fuel collection manifolds were mounted to the test stand. All high-pressure fuel lines and fittings were obtained and formed to meet the test stand physical configuration. Figure 1-15 is a photograph of the two Bosch drive adapters mounted to the test stand. The fuel inlet pressure, fuel transfer pump pressure, high-pressure pump housing drain pressure, and common-rail fuel pressure were monitored throughout the testing. Fuel supply, fuel inlet, fuel injector, and fuel return temperatures were monitored.

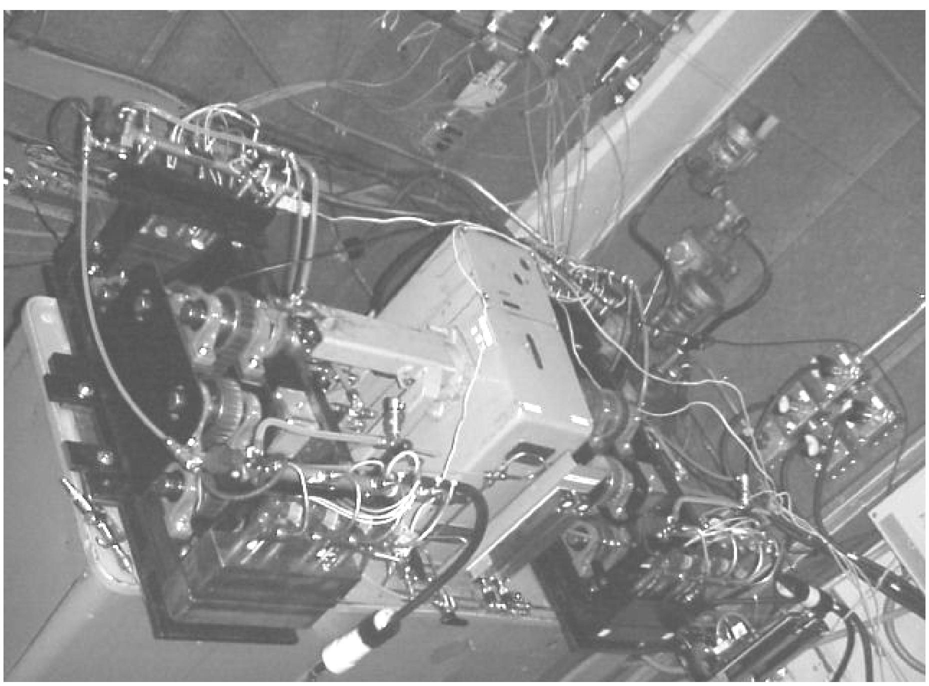


Figure 1-15. Bosch Common-Rail Drive Adapters on Test Stand

Peak-and-hold driver failures were resolved, and the drivers were used successfully to drive the injectors at various pulsewidths and frequencies. The timing and control circuit to generate the timing pulses for the peak and hold drivers, and steer them to the correct channel were verified to work with the injector drivers and injectors. The closed loop pulsewidth modulation circuit for the rail pressure control was verified. As originally configured, the test stand had the capability of driving the common rail system at 1850-RPM camshaft speed, with a rail pressure of 750 bar. A severe vibration at 1900-RPM camshaft speed limited the test stand speed. Miscalculation of the parasitic loss required to control the rail pressure means the belt drive, electric motor, and variable speed drive were undersized for running duplicate test pumps for each fuel at 1350-bar rail pressure. An option considered for the continuation of testing included operating the test at derated conditions, provided Bosch indicated that the condition was severe enough to rank the test fuels.

To ensure that the operating conditions required for showing discrimination between test fuels could be identified, Bosch was contacted concerning the operating conditions and test fuel lubricity. Bosch was supplied with the HFRR wear scar diameters for the test fuels and asked to comment on discrimination in the common-rail fuel system. Bosch indicated engine dynamometer operation would rank the high and low lubricity level fuels in 500 hours; however, they did not indicate a test cycle. Bosch felt it would be hard to discriminate between the two high (or likewise the two low) lubricity fuels because normal wear variability is fairly high, and the sample size is small.

Bosch replied with the following comments on wear areas and test recommendations:

- You may not be able to distinguish between a 0.550 and 0.600 wear scar diameter (WSD) fuel; it will be tough even to distinguish between a 0.325 and 0.550 after 500 hours, due to the small sample size (there are many tolerances that affect wear); you would need to run a very large sample to show a significant difference.
- Look for wear in rotating components (bushings, cam lobes), and also axial components (plungers).
- Run rated speed and pressures, temperature 70°C; do an inspection every 500 hours, and run for 2000 total hours.

The original contact at Bosch during the initial stage of the program is no longer with the company, and these recommendations were different from those originally expressed at program initiation.

The test stand was configured for operating two pumps per fuel, with four 500-hour tests to be scheduled. The fuel system was modified so that each pump used 200L of fuel, consistent with the Stanadyne tests. An additional heat exchanger was added on the test stand to maintain the fuel tank temperature at ambient 38°C temperatures.

The safety shutdown system was configured to handle the special requirements of the electronic controls. A shutdown of the rail pressure controller power is needed in case:

- a rail pressure transducer fails,
- a rail pump fails,
- a drive belt breaks,
- or a drive motor fault is set (includes line power outage).

The shutdown is required so that the rail pressure duty cycle controller does not reach 100%. The coil of the rail pressure regulator will overheat if operated at 100% duty cycle for an extended period of time. A shutdown threshold of 1000 bar rail pressure was set for the system.

1. Bosch Test Set One

Each injection system was evaluated over a nine-point rail pressure and injection pulsewidth matrix prior to test initiation. The inspection tables are shown as Table 1-17, LSLA fuel (Test 1) and Table 1-18, CA fuel (Test 2). The injection system operating on CA fuel had a slightly higher flow per injector. The duty cycle that was required to control the rail pressure was similar for each fuel. It was originally intended to hold the injector heating blocks at 120°F during calibration; however, the fuel compressive heating resulted in increased injector block temperatures. The pre-test and post-test injection system inspection tables for the CA fuel are shown as Table 1-18 and Table 1-19, respectively. Table 1-20 shows the 500-hour injection system deviations with the CA fuel. There were not any substantial injection system calibration changes after 500 hours with the CA (Test 2) fuel. The LSLA fuel injection system stopped generating rail pressure at 482 hours. The test was terminated when metal shavings were found in the fuel rail during inspections to determine the cause of injection pressure loss. Post-test system calibration curves were not generated for the LSLA (Test 1) fuel system due to the inoperative rail pump.

Table 1-17. Bosch Common Rail LSLA Fuel Pre-Test Performance Inspections.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number:	Fuel Description:	Test Hours:	Date:	Operator:
AL-25792-F	**LSLA**	**0**	**7/27/00**	**REG / DMY**

	Test 1	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	9.5	13.5	15	14.5	16.5	18.5	15	18	20.5
	Injector 2 Only	9.5	13.5	15	14	17	18.5	15	18.5	21
	Injector 3 Only	9.5	14	15	15	17.5	19	15.5	19	21.5
	Injector 4 Only	10	14	16	15	17.5	19.5	16.5	19.5	22
Record With All Injectors Connected Only	All Injectors	20	30.5	38.5	38.5	47	54	47.5	58	68
	Actual Rail Pressure, bar	402	402	404	800	800	800	1352	1353	1352
	Rail Pressure Controller Duty Cycle, %	19.9	18.3	18.6	31.5	31.6	31.8	49	49.7	49.6
	Transfer Pump Pressure, psig	67.5	67.2	67.9	67.9	67	68.3	67.7	67.5	67.9
	Drain Pressure, psig	16.8	16.2	15.9	13.6	14.5	14	13.3	12.8	12.2
	Stand Speed, RPM	2100	2100	2100	2100	2100	2100	2100	2100	2100
	Drive Amps	23	22	22	27	26.8	26.7	36	35.7	35.8
	Fuel Inlet Temperature, F	107	104	103	103	102	103	102	100	102
	Fuel Tank Temperature, F	91	87	87	89	89	91	93	93	94
	Injector Block Temperature, F	125	124	126	131	140	142	187	183	184

Table 1-18. Bosch Common Rail CA Fuel Pre-Test Performance Inspections.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: AL-25713-F	Fuel Description: CA	Test Hours: 0	Date: 7/27/00	Operator: REG / DMY

	Test 2	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	11	15	16.5	16.5	18.5	19.5	16.5	19.5	23.5
	Injector 2 Only	10.5	14	16.5	15	18.5	19.5	16	19.5	22.5
	Injector 3 Only	11	15	16.5	16.5	19	19.5	16.5	19.5	22.5
	Injector 4 Only	11.5	15	16.5	16.5	18.5	20	16.5	20	23
Record With All Injectors Connected Only	All Injectors	21.5	32	39.5	38.5	48	54.5	46	58.5	68.5
	Actual Rail Pressure, bar	400	402	403	800	800	800	1350	1351	1350
	Rail Pressure Controller Duty Cycle, %	18.8	18.6	19	30.9	31	31.1	48.9	50	49.3
	Transfer Pump Pressure, psig	61.5	60.7	60.9	61.2	60.9	61.7	61.2	62.3	62
	Drain Pressure, psig	20.6	19.7	19.3	18.9	18.5	18	17.5	16.9	16.5
	Stand Speed, RPM	2100	2100	2100	2101	2100	2100	2099	2100	2100
	Drive Amps	22	22	22	27	26.8	26.7	36	35.7	35.8
	Fuel Inlet Temperature, F	106	99	100	100	99	102	102	101	102
	Fuel Tank Temperature, F	86	88	82	83	81	82	82	82	82
	Injector Block Temperature, F	123	122	121	130	135	137	194	197	190

Table 1-19. Bosch Common Rail CA Fuel Post-Test Performance Inspections.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number:	AL-25713-F	Fuel Description: CA		Test Hours: 500		Date: 8/23/00		Operator: REG	
Test 2	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
Injector 1 Only	11	15	17	16	18.5	20.5	17	19.5	22.5
Injector 2 Only	10	14	16.5	15	17.5	19.5	16	19.5	22.5
Injector 3 Only	11	15	17	15.5	18	20	16.5	19.5	22.5
Injector 4 Only	11.5	15	17	16	18	20.5	17	20	23
All Injectors	21.5	32	40	39.5	47.5	55.5	47.5	58.5	68.5
Actual Rail Pressure, bar	400	400	400	801	800	800	1349	1350	1350
Rail Pressure Controller Duty Cycle, %	18.5	18.8	19	30.9	31.3	31.5	49.9	50.9	51.2
Transfer Pump Pressure, psig	60	59.1	59.3	60.3	59.2	59.9	60.3	60.5	60.1
Drain Pressure, psig	19.3	18.7	18.4	17	16.9	16.5	17.5	16.2	15.7
Stand Speed, RPM	2100	2100	2100	2100	2100	2100	2100	2100	2100
Drive Amps	19	19	18.9	20.3	20.3	20.3	22.5	22.7	22.7
Fuel Inlet Temperature, F	102	98	96	97	97	99	98	99	100
Fuel Tank Temperature, F	90	90	91	91	91	90	89	90	90
Injector Block Temperature, F	130	128	121	133	138	138	192	197	192

Record With All Injectors Connected Only (applies to rows All Injectors through Drive Amps)

Table 1-20. Bosch Common Rail CA Fuel Post-Test Performance Deviations.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: **AL-25713-F**		Fuel Description: **CA**		Test Hours: **500**		Date: **8/23/00**		Operator: **REG**	
Test 2	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
Injector 1 Only	0%	0%	3%	-3%	0%	5%	3%	0%	-4%
Injector 2 Only	-5%	0%	0%	0%	-5%	0%	0%	0%	0%
Injector 3 Only	0%	0%	3%	-6%	-5%	3%	0%	0%	0%
Injector 4 Only	0%	0%	3%	-3%	-3%	3%	3%	0%	0%
All Injectors	0%	0%	1%	3%	-1%	2%	3%	0%	0%
Actual Rail Pressure, bar	0%	0%	-1%	0%	0%	0%	0%	0%	0%
Rail Pressure Controller Duty Cycle, %	-2%	1%	0%	0%	1%	1%	2%	2%	4%
Transfer Pump Pressure, psig	-2%	-3%	-3%	-1%	-3%	-3%	-1%	-3%	-3%
Drain Pressure, psig	-6%	-5%	-5%	-10%	-9%	-8%	0%	-4%	-5%
Stand Speed, RPM	0%	0%	0%	0%	0%	0%	0%	0%	0%
Drive Amps	-14%	-14%	-14%	-25%	-24%	-24%	-38%	-36%	-37%
Fuel Inlet Temperature, F	-4%	-1%	-4%	-3%	-2%	-3%	-4%	-2%	-2%
Fuel Tank Temperature, F	5%	2%	11%	10%	12%	10%	9%	10%	10%
Injector Block Temperature, F	6%	5%	0%	2%	2%	1%	-1%	0%	1%

Record With All Injectors Connected Only (applies to rows All Injectors through Drive Amps)

A plot of the rotameter flow number for each fuel and injection system is shown as Figure 1-16. The CA fuel had a slight drop in injected flow, reached a stable value, then appeared to recover close to the initial flow. The LSLA fuel had a drop in injected flow, around 90 test hours, that recovered and appeared to stabilize till the test was terminated. A plot of the injection rail pressures and rail pressure controller duty cycle is shown in Figure 1-17. Both the CA and LSLA fuels show the rail pressure duty cycle increases to maintain the relatively constant rail pressure, which is probably indicative of break-in wear. The CA fuel duty cycle appears to reach a stable value after 220 hours. The duty cycle drop at the end of the CA data is probably a function of disconnecting the LSLA fuel injectors from the injector driver. Each driver channel fired two injectors in series (e.g., the two injector ones for each test set), which were verified to open for the commanded duration, but at a reduced ballistic opening rate. When one of the serial injectors was replaced with an inactive coil (to maintain resistive load and continuity), the ballistic opening rate of the remaining injector increased. This effectively meant the injector was fully open for a slightly longer time, seen as a slight increase in injected flow for the CA fuel after 482 hours. Two elements effectively control the pressure in the fuel rail; both the pressure regulator and the fuel injectors act as pressure relief valves. Because the CA fuel injectors were fully open longer (relieving pressure), after the LSLA injectors were disconnected, the rail pressure controller rolled back on the duty cycle to maintain constant rail pressure. The item to note is the critical component; the high-pressure pump was still always generating 1350-bar rail pressure. This suggests the tests occurring simultaneously could interact with each other through the injector driver channel; however, during all tests there were no injector failures, other than entire injector sets taken off-line for pump failures. The duty cycle increase is greater for the LSLA fuel, and does not appear to reach a stable value. The increase in duty cycle at constant rail pressure is a measure of wear. At 90 test hours, a drop in the LSLA rail pressure duty cycle is seen that corresponds to the drop in the injected flow at 90 test hours. As injected flow drops, a lower duty cycle is required to maintain the rail pressure.

Post-test inspections revealed the LSLA pump stopped generating rail pressure because the drive coupling failed. The drive coupling failure was attributed to poor lubrication and a material hardness mismatch. The CA and LSLA fuels' drive couplings were lubricated with an oil bath and had the same coupling hardness. Although the CA drive coupling did not fail, there was evidence of severe wear. An inspection of the high pressure rail pump internal components showed drastic wear with the LSLA fuel. Figure 1-18 shows the wear scars from the high-pressure rail pump eccentric follower for both fuels. The pumping plunger follower, which slides on the eccentric follower, is shown for both fuels in Figure 1-19. The eccentric and plunger followers are fuel lubricated.

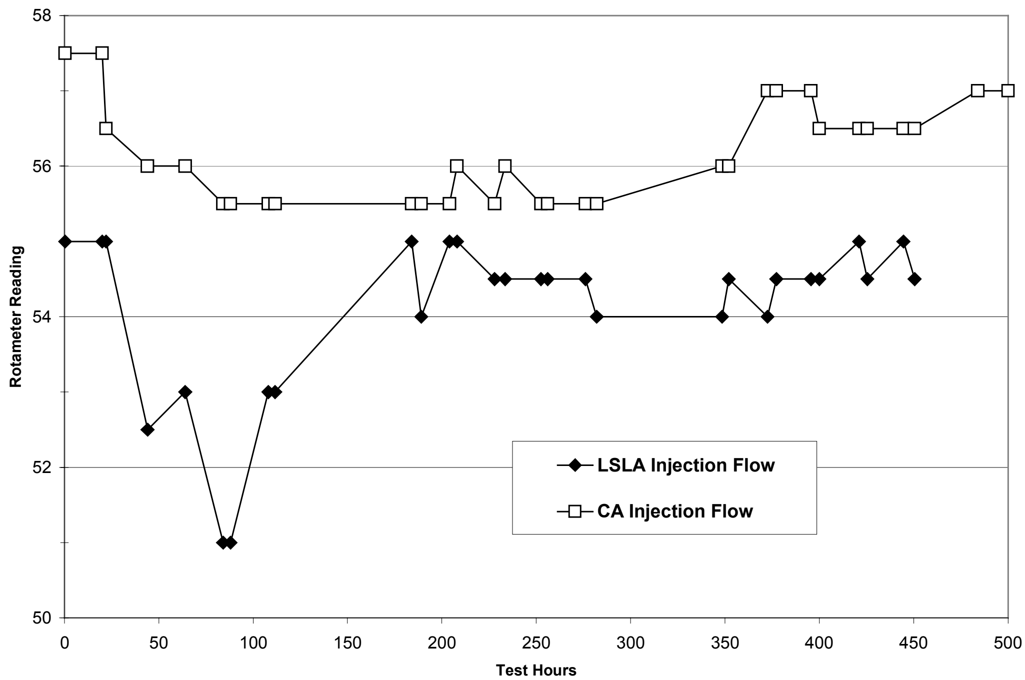


Figure 1-16. Bosch Common Rail Injected Flow Readings.

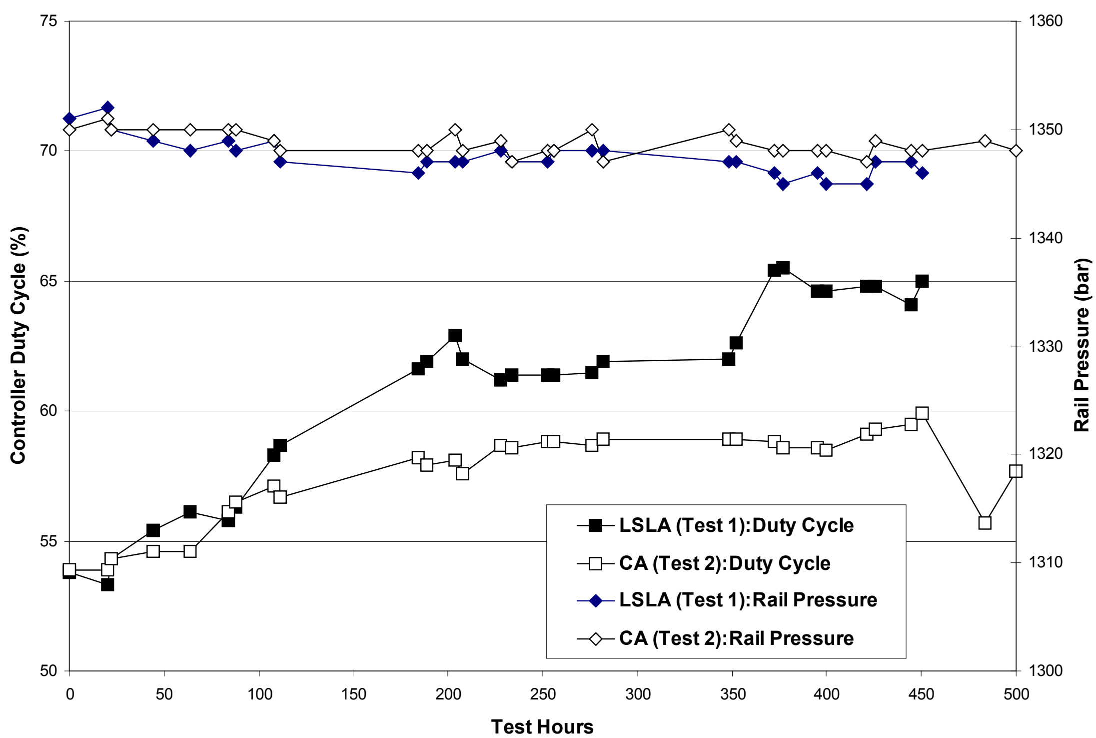


Figure 1-17. Bosch Common Rail Duty Cycles and Rail Pressures for LSLA and CA Fuels.

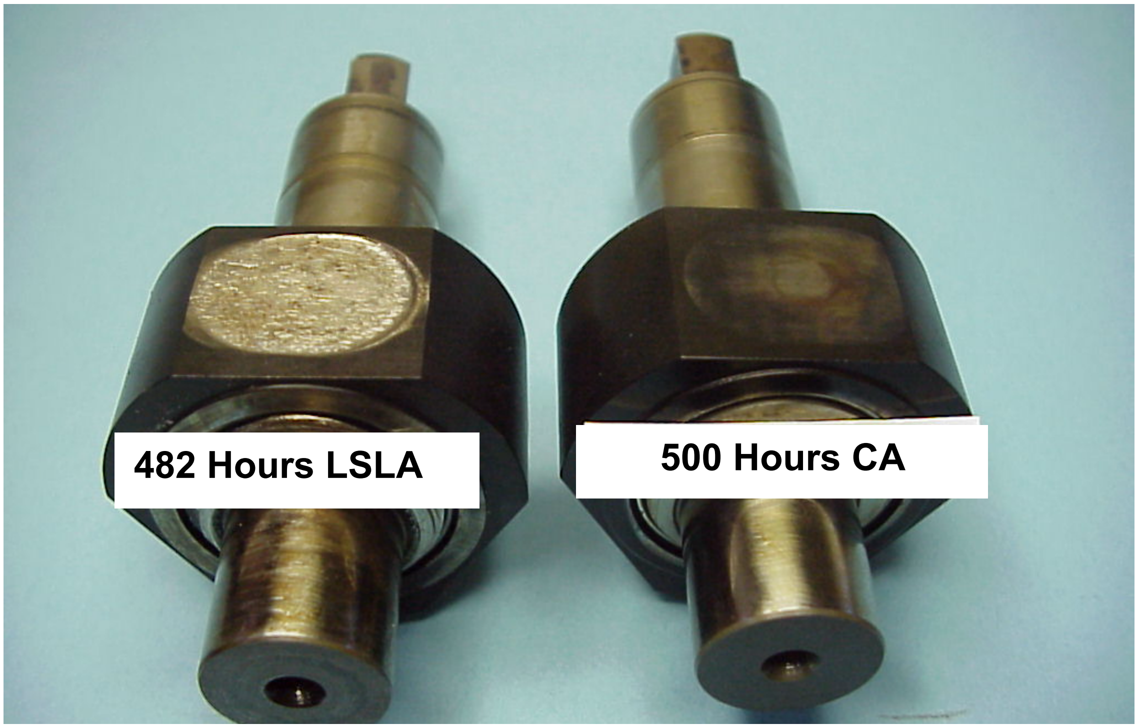


Figure 1-18. Common Rail Pump Eccentric Follower Wear for LSLA (Test 1) and CA (Test 2) Fuels.

Figure 1-19. Rail Pump Plunger Follower Wear for LSLA (Test 1) and CA (Test 2) Fuels.

2. Bosch Test Set Two

Test stand modifications were performed prior to testing the DMM15 (Test 4) and FT100 (Test 3) fuels. New components were machined for the test stand couplings, and the new coupling parts were hardened. There were also modifications made to the coupling lubrication system (from oil bath to flow through). Modifications to the test stand were made to attempt to control the volatility of the DMM15 blend during testing.

Modifications were made to insure the DMM15 fuel remained below the boiling point at the inlet to the high-pressure common rail pump. Fuel cooling was also added to the DMM15 fuel prior to the rotameter in an attempt to attain steady readings.

During the performance inspection phase of the second set of Bosch pump tests, the high-pressure Common Rail pump using the FT100 fuel seized. The seizure occurred during the 1350-bar rail pressure calibration. Initial thoughts were misalignment or contamination. Measurements taken for misalignment showed the FT100 setup to have the same runout as the other pump and fuel setups. The contact pattern on the pump drive tang confirmed this; the contact pattern was evenly distributed across the face of the drive tang. The performance inspections for FT100 (Test 3) that were completed are shown in Table 1-21. The inspection table is shown as Table 1-22 for the DMM15 (Test 4) fuel. The duty cycle that is required to control the rail pressure is similar for each fuel.

Table 1-21. Bosch Test 3 for FT100 Fuel System Pre-Test Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: **AL-25787-F**		Fuel Description: **FT-100**		Test Hours: **0**, *(1.8 cal)*		Date: **9/22/00**		Operator: **REG**	

	Test 3	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	11.5	14	16.5	15	18	20			
	Injector 2 Only	13	15	17	15.5	18.5	20.5			
	Injector 3 Only	12	14.5	16.5	15	18	20.5			
	Injector 4 Only	12	15	17.5	15.5	18.5	20.5			
Record With All Injectors Connected Only	All Injectors	22	32	40	38.5	47.5	55.5			
	Actual Rail Pressure, bar	402	401	402	800	800	800		**SIEZED**	
	Rail Pressure Controller Duty Cycle, %	19.5	19.9	20	32.1	32.3	32.5			
	Transfer Pump Pressure, psig	57.6	58.1	58.1	59	57.5	58			
	Drain Pressure, psig	13.4	13.2	12.7	12.2	13.9	10.5			
	Fuel Inlet pressure, psig	7	7	7	7.3	7.3	7.1	7.5		
	Stand Speed, RPM	2101	2102	2101	2100	2100	2102	2100		
	Drive Amps	22.9	22.3	22.3	27	27	26.7	27.5		
	Fuel Inlet Temperature, F	107	106	108	108	105	103			
	Fuel Tank Temperature, F	83	83	84	84	82	87			
	Injector Block Temperature, F	125	126	126	136	144	148	187		

Table 1-22. Bosch Test 4 for DMM15 Fuel Pre-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: **AL-25959-F**	Fuel Description: **DMM15**	Test Hours: **0**, *(6.4cal)*	Date: **9/28/00**	Operator: **REG**

	Test 4	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	11.5	15.5	17.5	16.5	19	20.5	20	23	25
	Injector 2 Only	11	15	16.5	16.5	18.5	20.5	20	22	25
	Injector 3 Only	11	15	17	16.5	19	21	20.5	23	25
	Injector 4 Only	11.5	15.5	17.5	17	19.5	21	20.5	22	25
Record With All Injectors Connected Only	All Injectors	21.5	34.5	41.5	46.5	50	58	59	65	74
	Actual Rail Pressure, bar	401	400	400	800	800	800	1350	1350	1350
	Rail Pressure Controller Duty Cycle, %	18.6	19.3	19.6	31.6	32	32.2	52.2	53.5	55.2
	Transfer Pump Pressure, psig	49.7	49.2	49.1	49.6	49.6	49.2	50.6	50.2	50.1
	Drain Pressure, psig	22.3	21.9	21	20.3	19.4	17.7	18.8	17.8	16.2
	Fuel Inlet pressure, psig	7	7	7	7	7	7	7.5	7.5	7.5
	Stand Speed, RPM	2100	2100	2100	2100	2100	2100	2100	2100	2100
	Drive Amps	19	19.1	18.9	20.2	20.2	20.3	22.7	22.7	22.7
	Fuel Inlet Temperature, F	97	100	100	100	100	100	100	100	100
	Fuel Tank Temperature, F	86	88	89	90	92	93	90	92	93
	Injector Block Temperature, F	124	125	125	128	133	136	160	178	181/184

Inspection of the seized FT100 pump revealed two seized plungers and one working plunger. One plunger broke when it was removed from the pump. There was no evidence of a third body contaminant. Generally, contaminants result in vertical scratches on the plungers. There were no vertical scratches on any plunger that indicated third body wear. There was burnishing circumferentially at the top and bottom of the plungers. Additionally, there are two plain bearings, which support the pump camshaft, that have a thin overlay that looked brand new. It would have been expected that the plain bearings would reveal scratches in the relatively soft overlay if there was contamination in the pump. There was evidence of a wear scar forming between the cam follower and plunger follower. Figure 1-20 is a photograph of the wear scar forming on the pump cam follower, the associated plunger follower and the plunger. The plunger broke at the keeper groove, due to excessive side thrust. Figure 1-21 is the second seized FT100 plunger with the location of seizure noted. Considering the good condition of the rest of the pump components and the lack of evidence of third-body (contaminant) wear, these failures appear to be fuel lubricity related. The viscosity of FT100 (3.2 cSt@40C) suggests a sufficient strength hydrodynamic film would develop to support pump loads. The pump plungers reciprocate, so boundary and elastohydrodynamic lubrication regimes are also important. The FT100 fuel is parafinic, devoid of polycyclic aromatic compounds that correlate to fuel lubricity, a measure of boundary lubrication. The FT100 result suggests the importance of fuel lubricity during the run-in stage of a high-pressure pump. The boundary lubricating quality of the fuel is always important for durability, but appears to be critical during the run-in period, until the asperities of the mating, sliding surfaces have worn down.

The pump calibrations were started without any prior running in of the test pumps with the test fuels, other than the operation needed to fill the fuel system and check for leaks. The failure could be an infant mortality issue, where the lubricity of the fuel normally provides enough margin to protect the pump during run-in. The calibration procedure steps up through rail pressures starting at 400 bar, 800 bar, then 1350 bar all at 2100-RPM stand speed. The seizure occurred after the rail pressure for the pumps was set and stabilized at 1350 bar. At the time of shutdown the clock showed 1.8 hours of operation.

The pumps for LSLA (Test 1) and CA (Test 2) fuels were not intentionally run-in; however, they were on the test stand during the controller development, controller tuning, and stand operating condition checks. It is estimated the prior pumps may have had 2 to 3 hours of running at relatively low rail pressures and lower speeds prior to performing the calibration matrix.

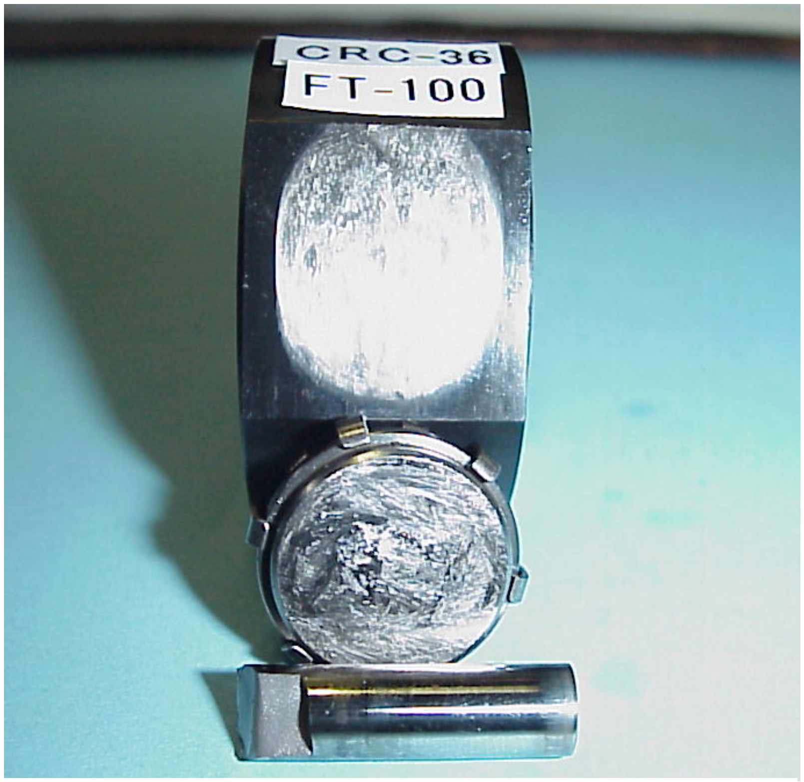


Figure 1-20. FT100 (Test 3) High-Pressure Common Rail Pump Cam Follower and Plunger Follower Wear Scars for Seized and Broken Plunger.

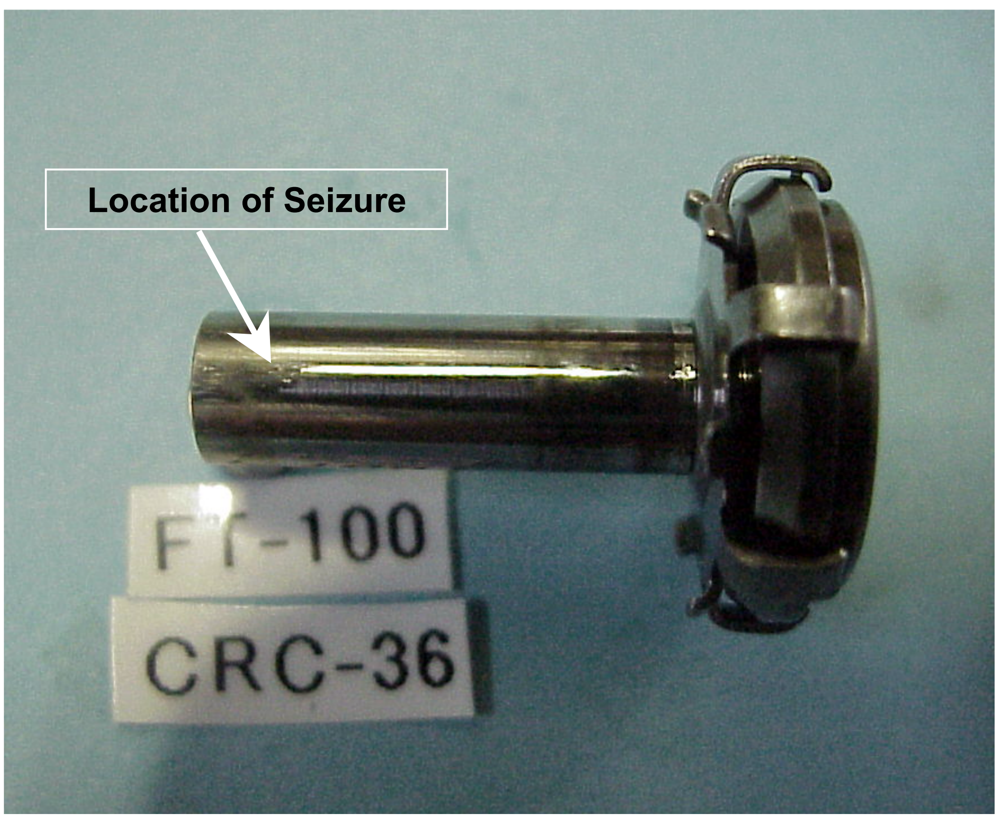


Figure 1-21. Location of Wear Scar for Second Seized FT100 (Test 3) Plunger.

Minor plumbing corrections were made on the DMM setup to try to handle the fuel volatility. The common-rail system runs hot due to the compression work to 1350 bar on the fuel. When the regulator bleeds, the return gets hot, and the DMM comes out of solution. This worked fine when all injectors were firing, but when the individual injector calibrations were tried, the bleed side return pressurized the rotameter exit, suppressing the flow. This only happened at the 1350 bar calibration condition. Plumbing changes made to resolve this issue changed the flow readings at the previous calibrated points. The DMM15 (Test 4) calibration was performed again after the plumbing corrections were made. The run-in mentioned previously was not performed on the DMM15 (Test 4) pump because the calibration check was completed successfully.

The test clock was zeroed and the test initiated. The following test conditions were set, with the fuel inlet temperatures gradually increased to the setpoint values over the first test hour:

- Speed: 2100 RPM
- Pressure: 1350 bar
- Injection Pulsewidth: 1.0 ms
- FT100 Fuel Tank Temperature: 38°C
- FT100 Fuel Inlet Temperature: 70°C
- DMM15 Fuel Tank Temperature: 24°C (to control boiling in return flow and tank)
- DMM15 Fuel Inlet Temperature: 57°C (to control volatility at transfer pump inlet)

At 2.5 hours the test stand shut down with low rail pressure on the DMM15 (Test 4) pump. When the test stand was checked to confirm the pump was not making rail pressure, it was noted that the DMM15 pump was very noisy. The pump was removed and inspected. One seized plunger was found, along with one plunger starting to gall. There were sizable wear scars on the cam follower and plunger followers. Figure 1-22 shows the wear scar on the plunger follower, while Figure 1-23 shows the corresponding wear scar on the cam follower mating surface. Figure 1-24 shows the location of seizure on the pump plunger. Wear debris in the pump housing is shown in Figure 1-25. The wear debris comes from the fuel-lubricated contact between the cam follower and plunger followers. There is evidence some of the wear debris may have caused the plunger seizure. With calibrations and plumbing checks, this pump had about 6 hours on it prior to the start of the test but all at a fuel inlet temperature of 38ºC. Operation at 57°C fuel inlet temperature decreased the fuel viscosity, possibly magnifying the importance of fuel lubricity in the fuel lubricated contacts. As with the FT100 (Test 3) pump, the rest of the DMM15 pump components are in good condition, these failures appear to be fuel lubricity related, or the impact of low lubricity fuels during initial run-in.

Figure 1-22. Wear Scar on DMM15 (Test 4) Plunger Follower.

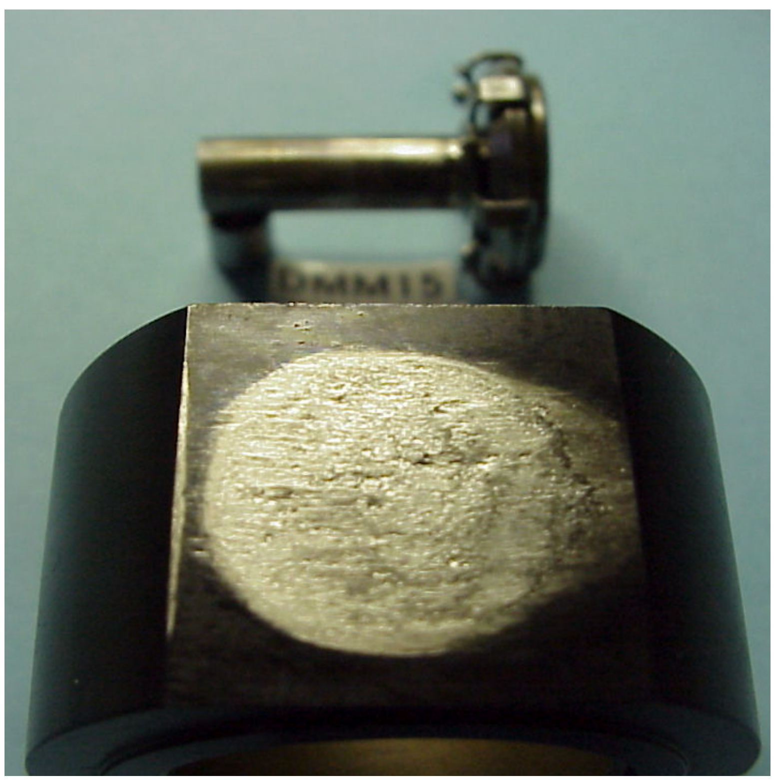


Figure 1-23. Wear Scar on DMM15 (Test 4) Cam Follower.

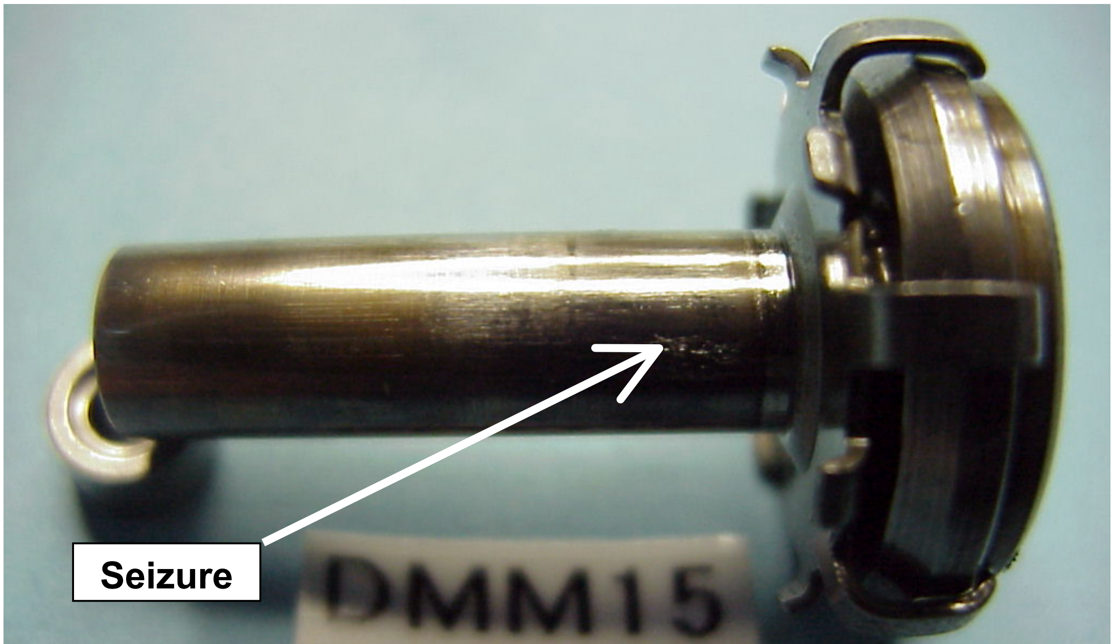


Figure 1-24. Location of Seizure for DMM15 (Test 4) Plunger.

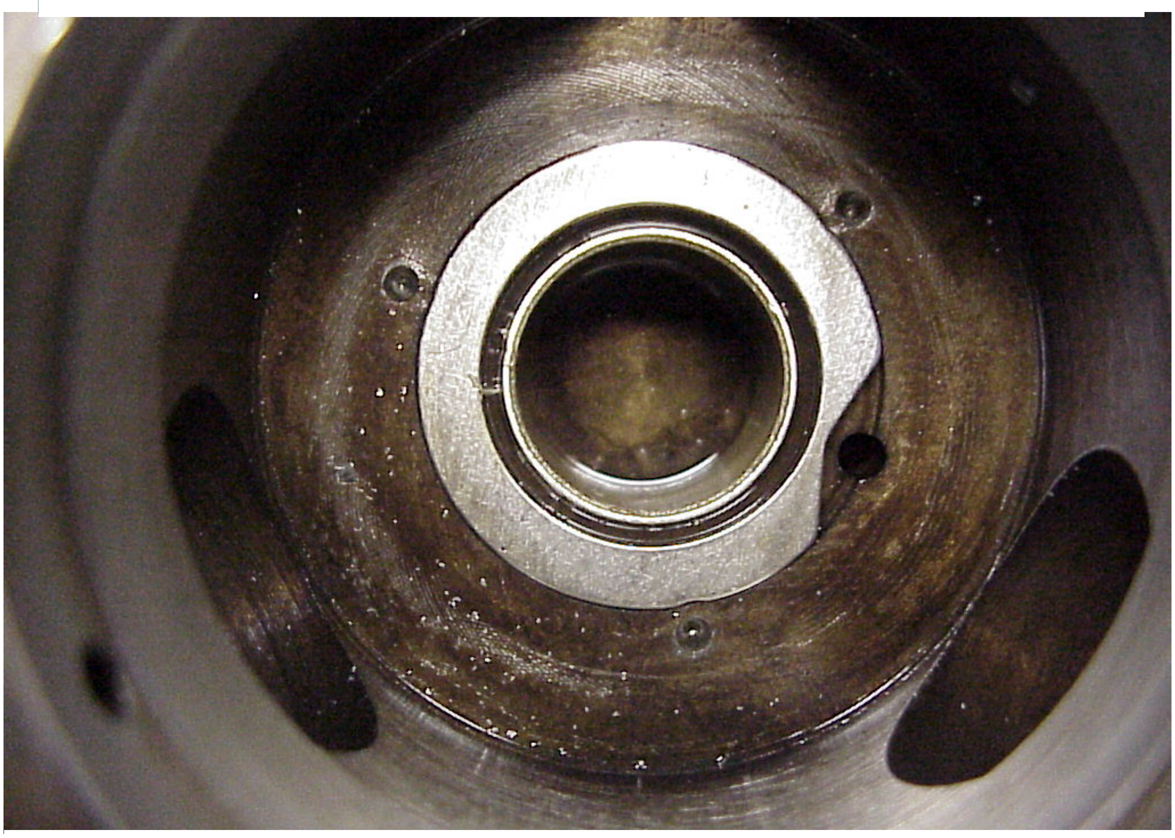


Figure 1-25. Bosch Test 4 with DMM15, Pump Housing Wear Debris.

3. Bosch Test Set Three

The third test set includes the second FT100 (Test 5) pump and the second DMM15 (Test 6) pump and fuel injector sets that were installed on the test stand after the aborted second test set. A brief, 2-hour run-in to adapt the pump to the fuel at a lower rail pressure and speed was recommended to, and approved by, the CRC advisory group. The run-in was performed at the following conditions:

- 38ºC Fuel Inlet Temperature
- 32ºF Fuel Tank Temperature
- 30 minutes at 450 RPM with 300-bar rail pressure (simulates 900-RPM idle)
- 90 minutes at 750 RPM with 450-bar rail pressure (simulates 1500-RPM/2.62-bar BMEP engine operation)

After the run-in was completed, the inspection matrix was performed on the second FT100 pump with no operational problems. Each injection system was evaluated over a nine-point rail pressure and injection pulsewidth matrix prior to test initiation. The system performance tables are shown as Table 1-23, FT100 fuel (Test 5) and Table 1-24, DMM15 fuel (Test 6). The injection system operating on CA fuel has a slightly higher flow per injector. The duty cycle that is required to control the rail pressure is similar for each fuel. The pre-test and post-test injection system calibration tables for the DMM15 fuel are shown as Table 1-24 and Table 1-25, respectively. Table 1-26 shows the 500-hour injection system deviations with the DMM15 fuel. There were no substantial injection system calibration changes after 500 hours with the DMM15 (Test 6) fuel. The FT100 fuel injection system stopped performing at 385 hours. Post-test system calibration curves were not generated for the FT100 (Test 5) fuel system due to the inoperative rail pump.

Table 1-23. Bosch Test 5 for FT100 Fuel Pre-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: **AL-25787-F**	Fuel Description: **FT-100**	Test Hours: **0**, *(2cal)*	Date: **9/29/00**	Operator: **DH**

Test 5 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
Injector 1 Only	11	15	17	15	18	20	17	19	22
Injector 2 Only	11	15	17	16	18	20	17	20	23
Injector 3 Only	11	15	17	16	18	21	18	20	23
Injector 4 Only	12	16	18	16	19	21	18	20	23
Record With All Injectors Connected Only: All Injectors	22	34	41	39	49	57	50	60	69
Actual Rail Pressure, bar	402	402	403	802	803	801	1349	1349	1350
Rail Pressure Controller Duty Cycle, %	19.5	20.3	20.3	32.5	32.8	33	51.9	53.3	54
Transfer Pump Pressure, psig	57.2	57.6	58.1	58	57.8	58.1	57.8	57.4	57.4
Drain Pressure, psig	13.9	13.8	13.5	12.1	11.5	12	11	9.9	9.4
Fuel Inlet pressure, psig	7	7	7	7	7	7	7	7	7
Stand Speed, RPM	2101	2101	2100	2100	2100	2100	2100	2100	2100
Drive Amps	19.7	19.7	19.9	21.4	21.4	21.4	24.7	24.6	24.7
Fuel Inlet Temperature, F	104	104	104	105	105	105	103	103	104
Fuel Tank Temperature, F	88	95	92	91	95	92	87	90	96
Injector Block Temperature, F	118	119	120	131	137	141	160	174	180

Record With All Injectors Connected Only

Table 1-24. Bosch Test 6 for DMM15 Fuel Pre-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: AL-25959-F	Fuel Description: DMM15	Test Hours: 0, *(1.7cal)*	Date: 10/4/00	Operator: REG

	Test 6 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	11.5	15	17	16	19	20	20	22	23
	Injector 2 Only	11	15	17	16	18.5	20	20	21	22
	Injector 3 Only	10.5	14.5	16.5	15.5	18	20	20	20	21.5
	Injector 4 Only	11.5	15	17	16.5	19	20	20	20	22
Record With All Injectors Connected Only	All Injectors	21.5	33.5	40.5	41	49.5	57.7	53	67	75
	Actual Rail Pressure, bar	400	400	400	800	800	800	1350	1350	1349
	Rail Pressure Controller Duty Cycle, %	19.3	19.7	19.9	32.1	32.6	32.7	53.2	55.8	58.4
	Transfer Pump Pressure, psig	47.8	46.8	46.6	41.7	50.5	50	41.7	41.7	41.3
	Drain Pressure, psig	21.5	21.6	20	18.3	18.7	18	19.2	18	16
	Fuel Inlet pressure, psig	7	7	7	7.5	7	7.5	7.9	8	8
	Stand Speed, RPM	2100	2099	2100	2100	2100	2100	2100	2100	2100
	Drive Amps	19.7	19.7	19.7	21.4	21.2	21.2	24	24	23.9
	Fuel Inlet Temperature, F	108	103	100	99	99	101	99	99	99
	Fuel Tank Temperature, F	77	77	77	76	77	78	78	77	79
	Injector Block Temperature, F	120	122	126	128	133	136	164	177	183

Table 1-25. Bosch Test 6 for DMM15 Fuel Post-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number:	AL-25959-F	Fuel Description: DMM15	Test Hours: 500, *(3.6cal)*	Date: 11/8/00	Operator: DH

		Test 6 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
			750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
		Injector 1 Only	12	16	17.5	17	19	21	20.5	22	25.5
		Injector 2 Only	12	15.5	17.5	16.5	19	21	20.5	20.5	26
		Injector 3 Only	10	15	17	16.5	19	21	20	19.5	23.5
		Injector 4 Only	12	16	17.5	17.5	20	22	20	23.5	25.5
Record With All Injectors Connected Only		All Injectors	22	34	42.5	41.5	50.5	58.5	56.5	65	77
		Actual Rail Pressure, bar	400	402	402	800	800	802	1350	1350	1351
		Rail Pressure Controller Duty Cycle, %	19.3	19.6	19.9	31.9	32.1	32.2	52.9	55.1	56.3
		Transfer Pump Pressure, psig	49	48.8	48.6	50.2	50.1	50.4	51.9	50.6	52
		Drain Pressure, psig	22.1	21.1	20	19.7	18.2	18.2	17.7	15.9	15.5
		Fuel Inlet pressure, psig	NR	NR	NR	NR	NR	NR	NR	NR	NR
		Stand Speed, RPM	2100	2100	2100	2100	2100	2100	2100	2100	2100
		Drive Amps	18.9	19.1	19.6	20.3	20.4	20.4	22.8	22.7	22.8
		Fuel Inlet Temperature, F	107	107	108	99	100	99	100	100	99
		Fuel Tank Temperature, F	78	78	78	73	75	75	76	77	75
		Injector Block Temperature, F	114	115	115	135	137	139	161	175	182

Table 1-26. Bosch Test 6 for DMM15 Fuel System Performance Deviations.

Bosch Test Stand/Injector Calibration Worksheet

	Fuel ID Number:	**AL-25959-F**	Fuel Description:	**DMM15**	Test Hours:	**500, (3.6cal)**	Date:	**11/8/00**	Operator:	**REG/DH**
	Test 6 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	4%	7%	3%	6%	0%	5%	3%	0%	11%
	Injector 2 Only	9%	3%	3%	3%	3%	5%	3%	-2%	18%
	Injector 3 Only	-5%	3%	3%	6%	6%	5%	0%	-3%	9%
	Injector 4 Only	4%	7%	3%	6%	5%	10%	0%	18%	16%
Record With All Injectors Connected Only	All Injectors	2%	1%	5%	1%	2%	1%	7%	-3%	3%
	Actual Rail Pressure, bar	0%	1%	1%	0%	0%	0%	0%	0%	0%
	Rail Pressure Controller Duty Cycle, %	0%	-1%	0%	-1%	-2%	-2%	-1%	-1%	-4%
	Transfer Pump Pressure, psig	3%	4%	4%	20%	-1%	1%	24%	21%	26%
	Drain Pressure, psig	3%	-2%	0%	8%	-3%	1%	-8%	-12%	-3%
	Fuel Inlet pressure, psig	NR	NR	NR	NR	NR	NR	NR	NR	NR
	Stand Speed, RPM	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Drive Amps	-4%	-3%	-1%	-5%	-4%	-4%	-5%	-5%	-5%
	Fuel Inlet Temperature, F	-1%	4%	8%	0%	1%	-2%	1%	1%	0%
	Fuel Tank Temperature, F	1%	1%	1%	-4%	-3%	-4%	-3%	0%	-5%
	Injector Block Temperature, F	-5%	-6%	-9%	5%	3%	2%	-2%	-1%	-1%

The FT100 (Test 5) pump stand broke a drive belt at 385 hours of operation. A new drive belt was installed. During installation of the drive belt the technician noted the rail pump appeared to turn hard at one point in the rotation of the pump. The belt was installed, and the stand run up to speed; when pressure was applied to the common rail, the FT100 pump sheared the teeth off the drive belt. The rail pump was removed and opened for inspection. Inspection of the pump revealed one of the plunger followers had broken in half. The broken piece was getting lodged between the cam following and pump body, increasing the torque required to turn the pump. Figure 1-26 is a picture of the pump body with the broken follower indicated. Evident in Figure 1-26 is damage to the cam follower due to the broken plunger follower. The damage to the cam follower and follower pieces is shown clearly in Figure 1-27, along with the developing wear scars on the other two plunger followers. The wear interface between the cam follower and plunger follower for one of the other pump cylinders is shown in Figure 1-28. The wear scar on the plunger follower and the pitting on the cam follower suggest poor lubrication and that the pump failure with FT100 fuel was due to fuel lubricity.

Throughout the FT100 (Test 5) evaluation there were periodic excursions of rail pressure to 1450 bar, thus a high pressure shutdown limit was set for the FT100 pump. It was originally felt the excursion was possibly due to deposits forming in the system. At test completion the rail pressure regulator was removed and inspected. Figure 1-29 shows the FT100 pressure regulator covered with tar-like deposits. It is felt the deposits may have caused an overload condition in the pump, by hindering pressure regulation, which resulted in the fracture of the plunger follower.

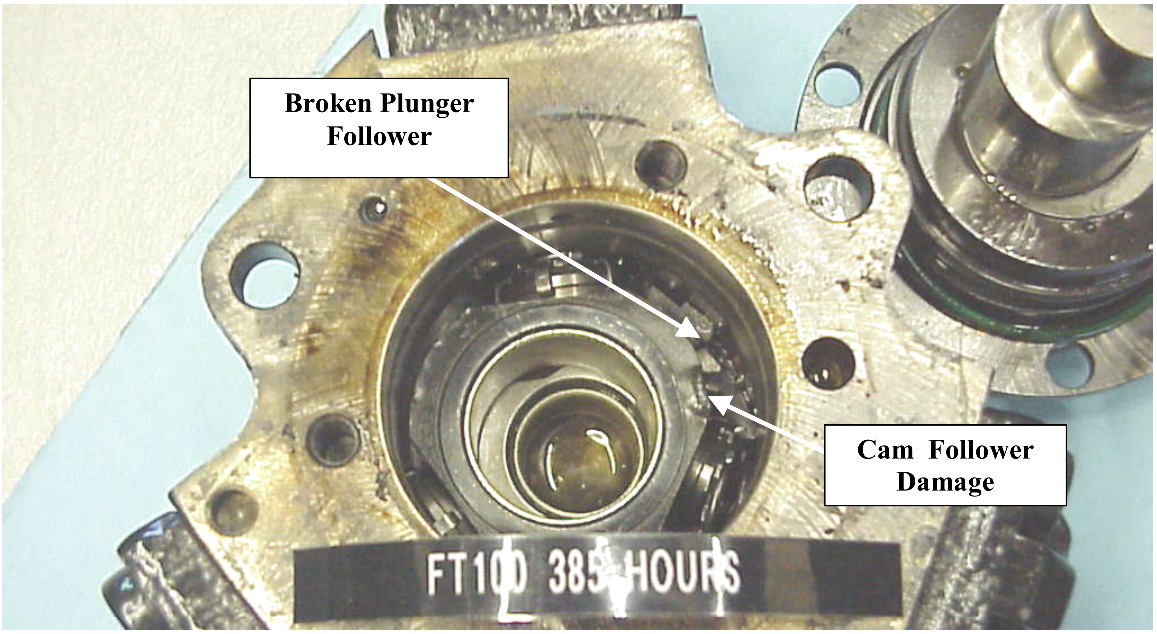


Figure 1-26. FT100 (Test 5) Fuel at 385 Hours Showing Bosch Common Rail Broken Plunger Follower and Cam Damage.

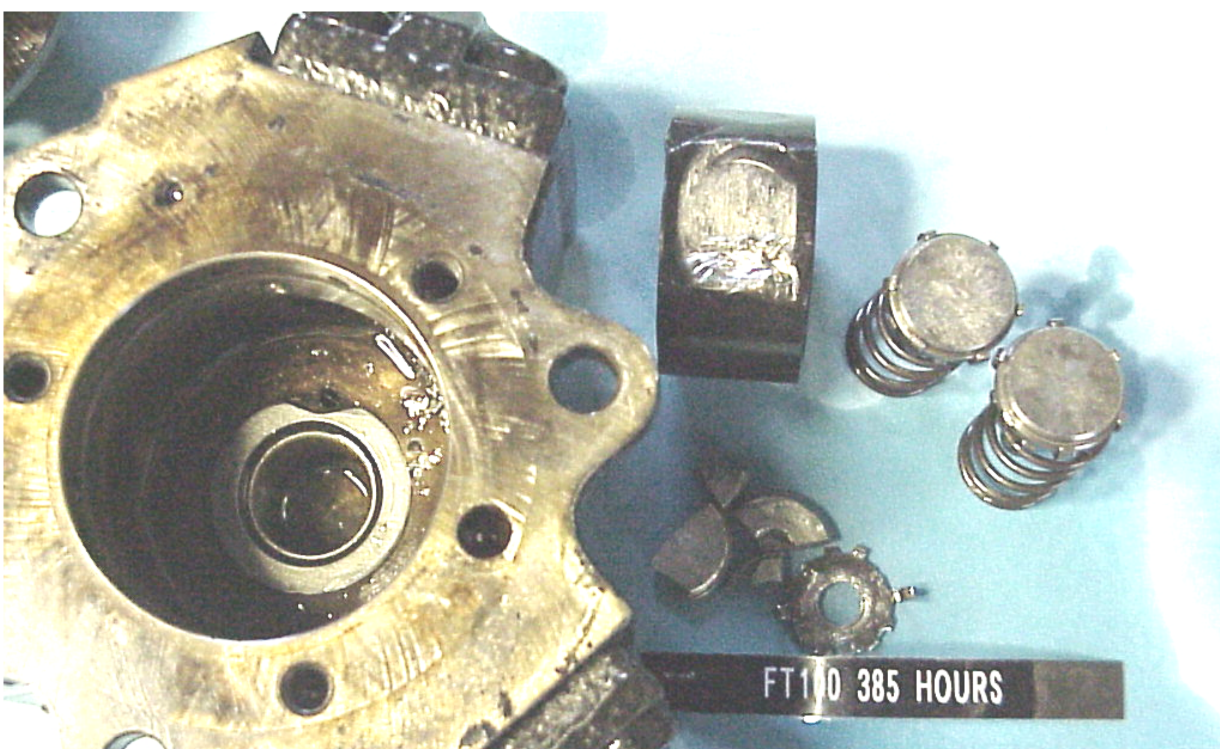


Figure 1-27. FT100 (Test 5) Fuel at 385 Hours Showing Cam Follower Damage and Broken Plunger Follower

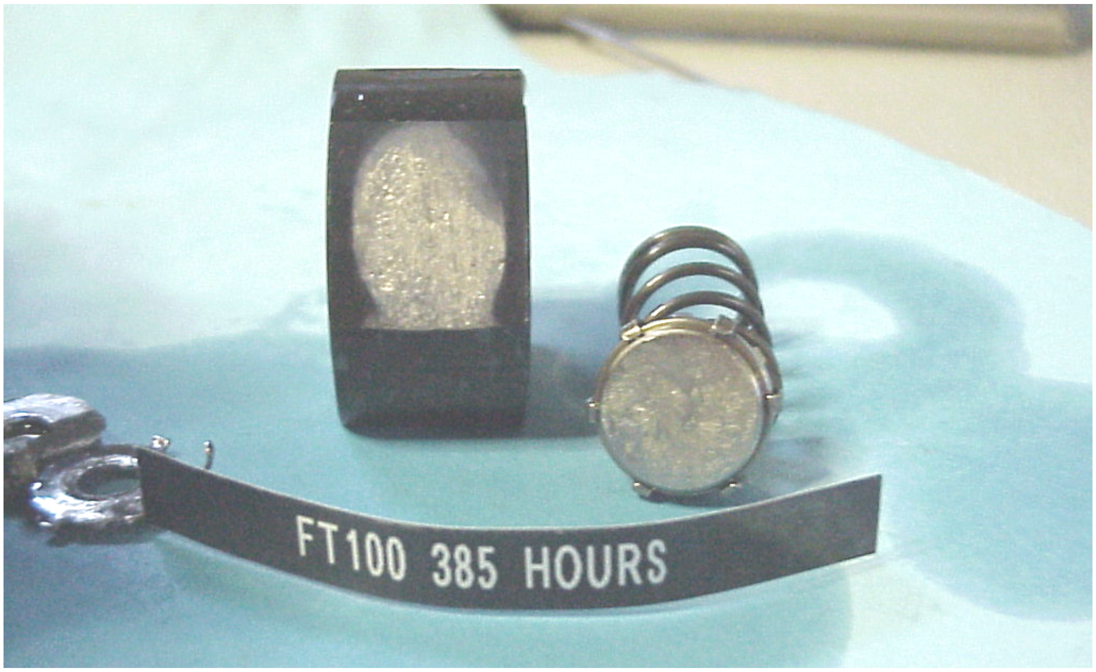


Figure 1-28. FT100 (Test 5) Fuel at 385 Hours with Pitting on Cam Follower and Plunger Follower Wear Scar

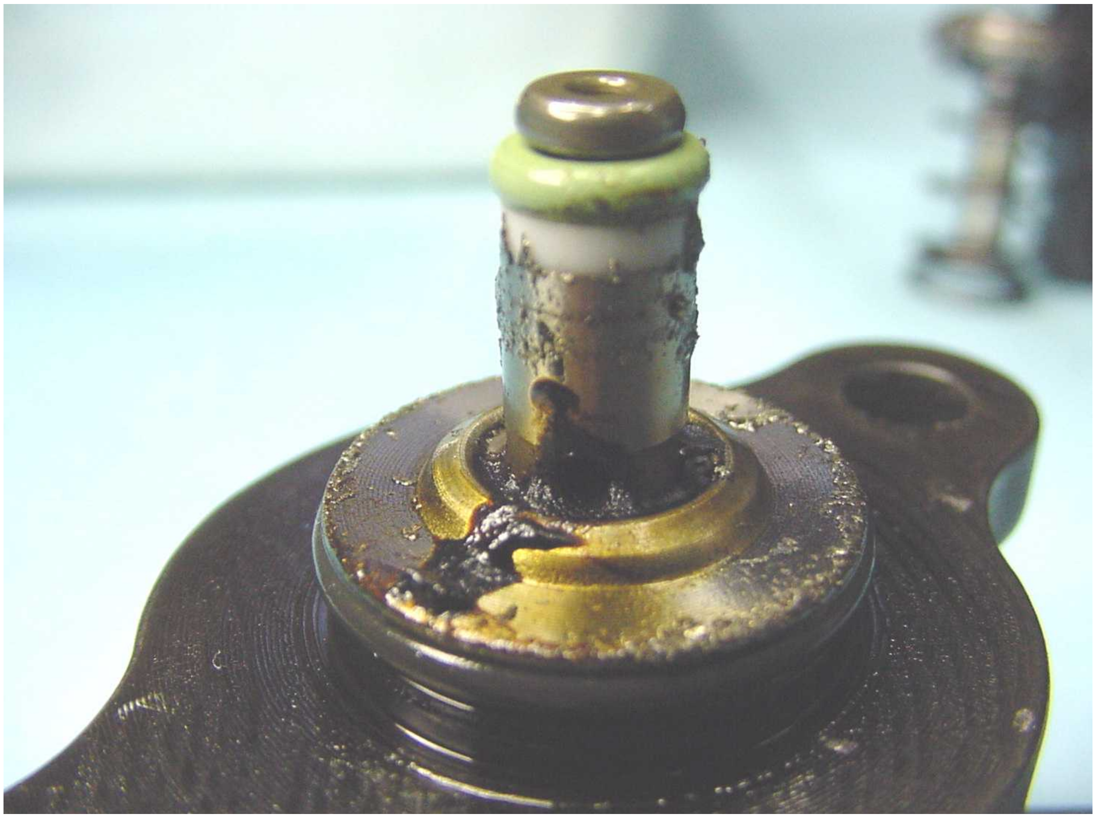


Figure 1-29. FT100 (Test 5) Rail Pressure Regulator with Deposits

The DMM15 common rail pump survived the 500-hour evaluation (Test 6), which was not anticipated due to experience with this fuel on an OM611 engine. This result may have been due to the lower fuel inlet temperatures at the rail pump to avoid cavitation due to DMM boiling. The temperature going into the rail pump ranged from 35-40°C, due to a cooler between the transfer pump and the rail pump. During inspection it was noted one of the seal rings, shown in Figure 1-30, was extremely swollen and falling out of the seal groove. Shown in Figure 1-31, a brown deposit was noted on the rail pump camshaft. It was speculated the lubricant for the drive coupler may have migrated past the front seals and left deposits on the camshaft. The test fuel was analyzed by gas chromatography to see if lubricant had co-mingled with the fuel. There was not any lubricant detected in the test fuel. The camshaft had two wear grooves where the seals may contact. The groove wear was more severe than earlier tests, so it is speculated seal swell may have contributed to the wear grooves with DMM15. Upon inspection of the plungers it was noted all three plungers had polishing and scoring, yet the pump was fully operational. Figure 1-32 indicates the scoring on a representative plunger.

The pump rail pressure performance data for FT100 (Test 5) and the DMM15 (Test 6) fuels are shown in Figure 1-33. Each pump maintained 1350 rail pressure until their respective tests were terminated. The duty cycle to maintain 1350-bar rail pressure at 1-ms injection duration is shown in Figure 1-34 for the fuels. The FT100 curve shows a trend of increasing duty cycle over the test hours operated. The DMM15 curve is relatively consistent, but shows variation that may be attributable to the fuel volatility.

The rotameter flow readings for the injected fuel are shown in Figure 1-35. The FT100 data show minor variations of injected flow, which indicates the increase in duty cycle noted earlier is an indication of wear with the FT100 fuel. The DMM15 injected flow remained relatively consistent. It is suspected the flow number is higher with the DMM15 fuel due to volatilization of DMM in the rotameter. The operator noted it was hard to obtain a stable rotameter reading with the DMM15 fuel because the fuel was two-phase.

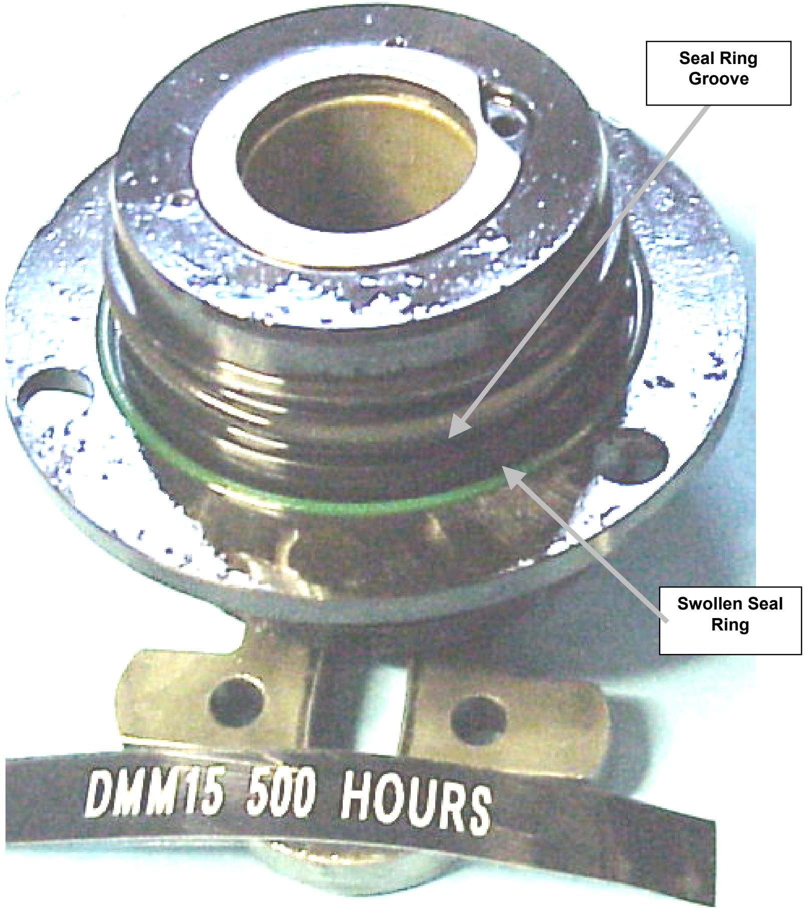


Figure 1-30. DMM15 (Test 6) Pump Bearing Housing with Swollen Seal Ring

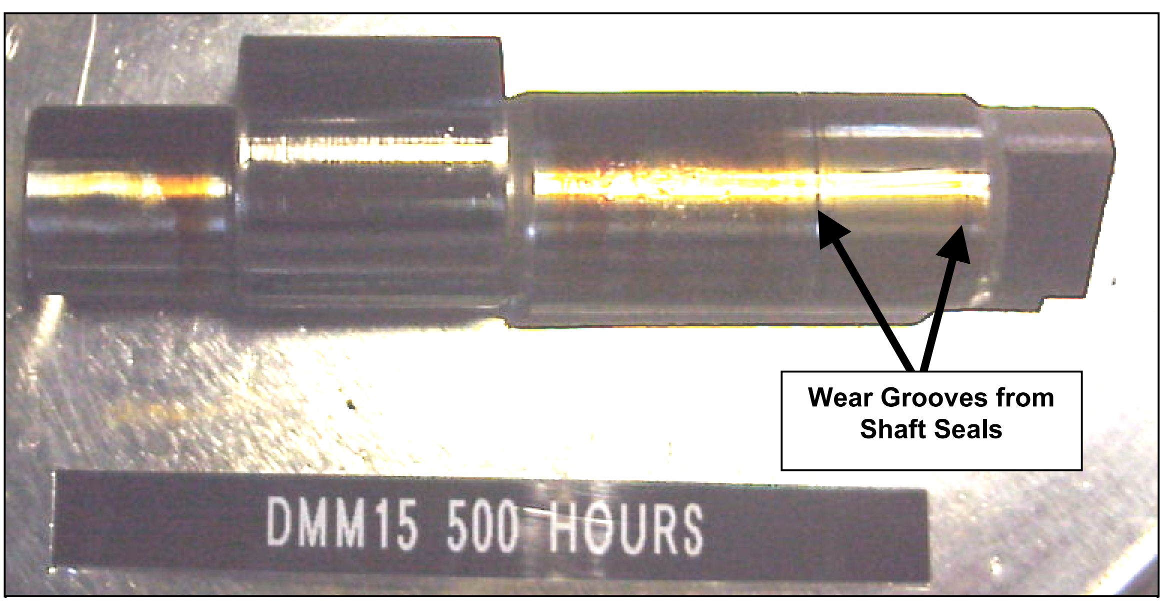


Figure 1-31. DMM15 (Test 6) Pump Camshaft with Deposits

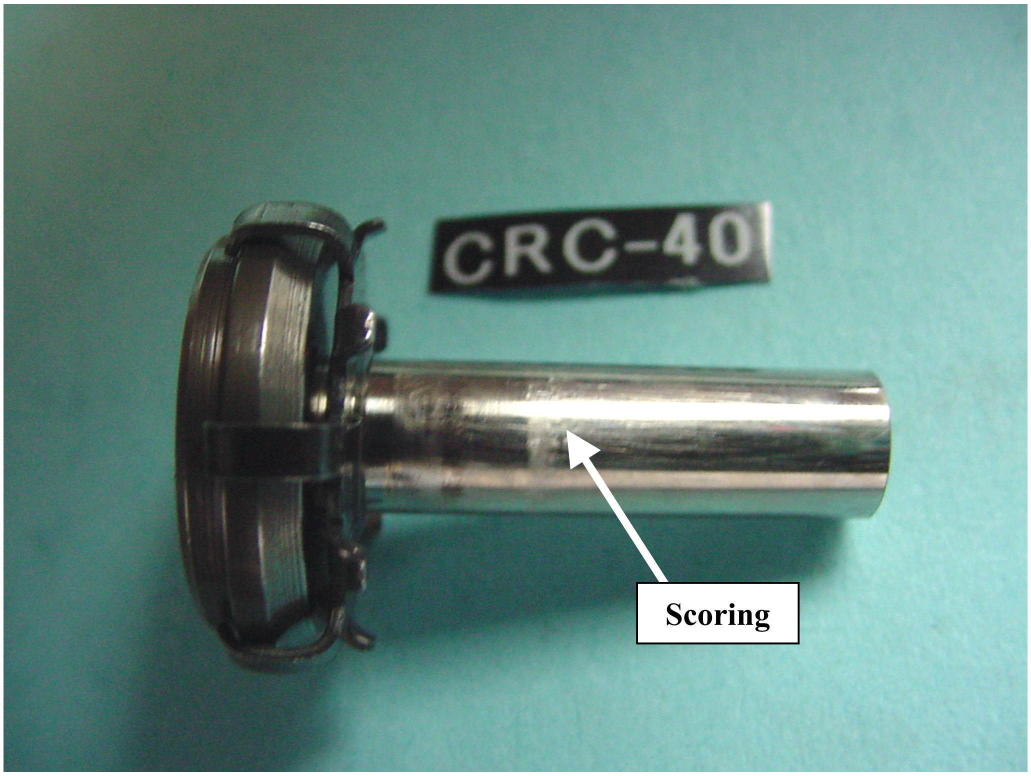


Figure 1-32. DMM15 (Test 6) Plunger with Scoring

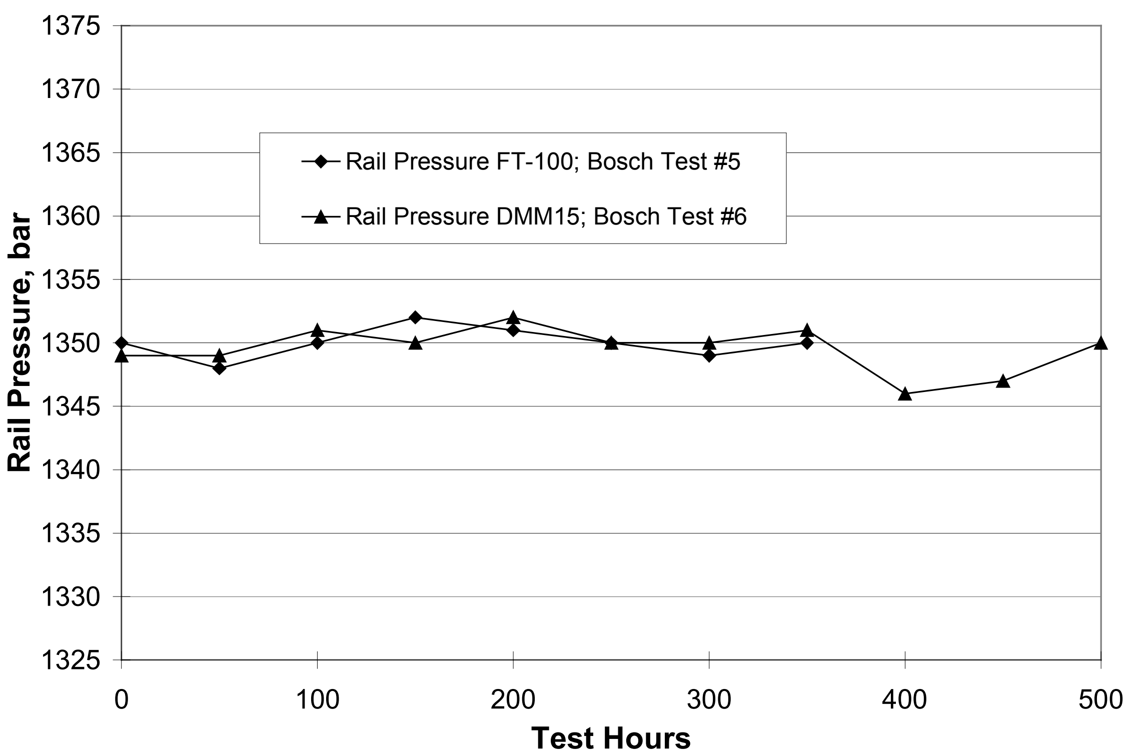


Figure 1-33. FT100 and DMM15 Rail Pressures

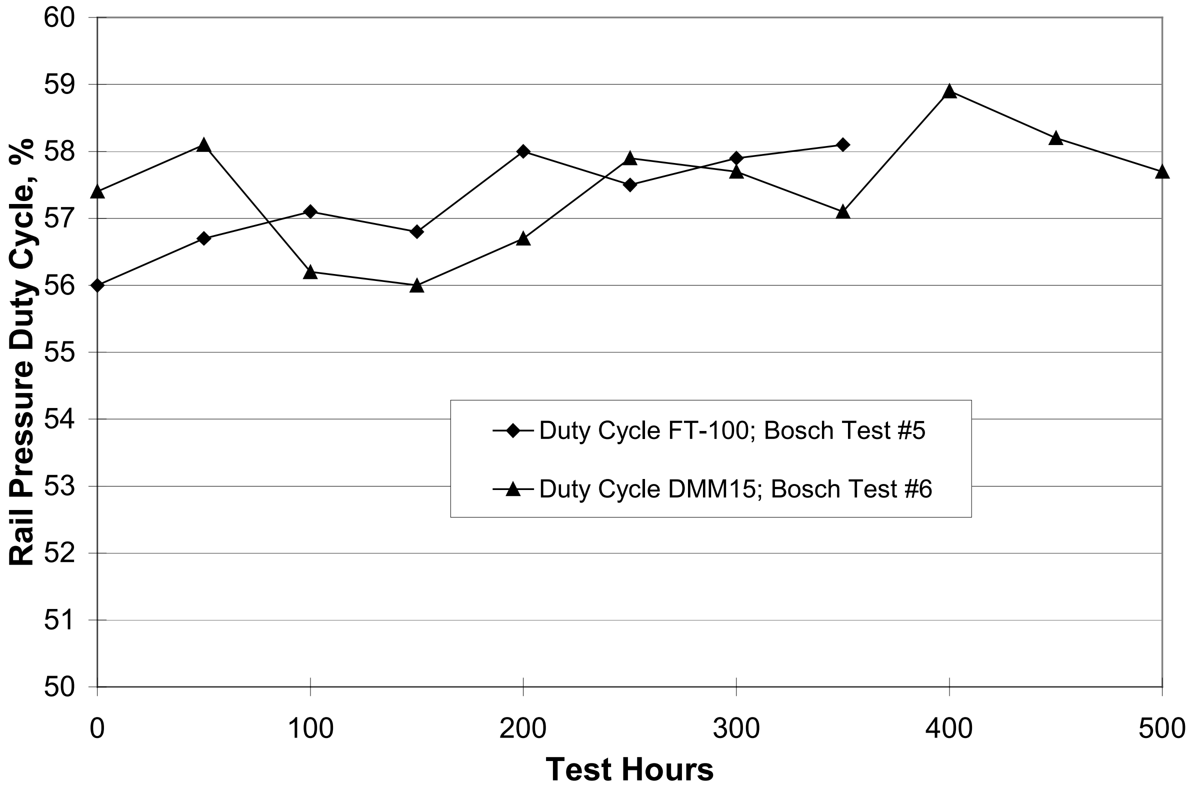


Figure 1-34. FT100 and DMM15 Rail Pressure Duty Cycle

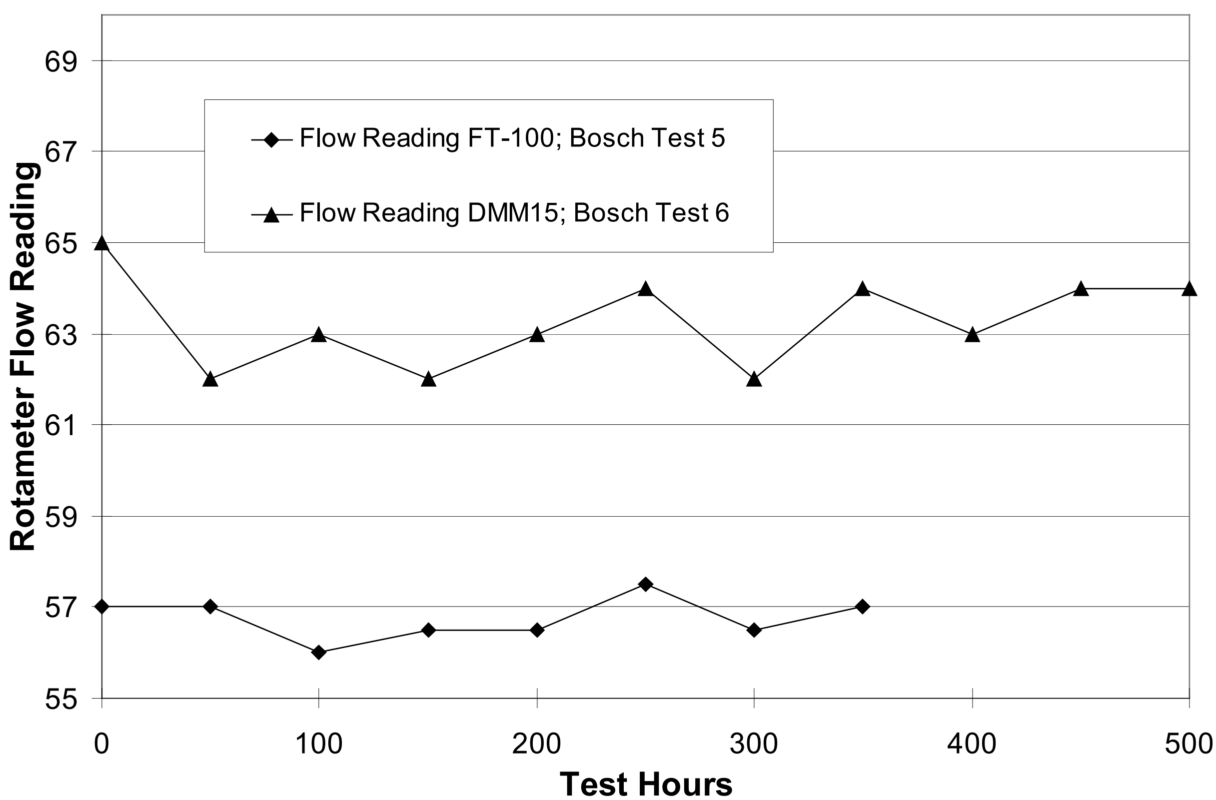


Figure 1-35. FT100 and DMM15 Injected Flow Reading

4. Bosch Test Set Four

The CA (Test 8) and LSLA (Test 7) pumps, along with the appropriate set of fuel injectors, were installed on the test stand. A brief, 2-hour run-in, described previously, was performed to adapt the pumps to the test fuels at a lower rail pressure and speed.

Each injection system was evaluated over a nine-point rail pressure and injection pulsewidth matrix prior to test initiation. The inspection tables are shown as Table 1-27, LSLA fuel (Test 7) and Table 1-28, CA fuel (Test 8). The injection system operating on CA fuel has a slightly higher flow per injector. The duty cycle that is required to control the rail pressure is similar for each fuel. The pre-test and post-test injection system calibration tables for the LSLA fuel are shown as Table 1-27 and Table 1-29, respectively. Table 1-30 shows the 500-hour injection system deviations with the LSLA fuel. The CA fuel injection system stopped generating rail pressure at 233 hours. Post-test system inspections were not generated for the CA (Test 8) fuel system due to the inoperative rail pump and rail pressure regulator.

Table 1-27. Bosch Test 7 for LSLA Fuel Pre-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: AL-25792-F	Fuel Description: LSLA	Test Hours: **0**, *(1.6cal)*	Date: **11/17/00**	Operator: **REG**

	Test 7 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	13	17	18	15	17	19.5	16.5	19	21.5
	Injector 2 Only	13	17	18.5	15	17	19.5	16	18.5	21
	Injector 3 Only	13	18	18.5	15.5	17.5	20	17	19.5	22
	Injector 4 Only	13	17	19	15	17	19.5	16	19.5	21
Record With All Injectors Connected Only	All Injectors	24	35	42	38.5	47	55.5	46.5	59	68
	Actual Rail Pressure, bar	400	403	401	799	803	800	1350	1349	1349
	Rail Pressure Controller Duty Cycle, %	19.1	19.7	19.9	32.8	33.1	31.6	50	50.4	51.7
	Transfer Pump Pressure, psig	55	55	55	55.3	54.4	55	55.2	55.1	55
	Drain Pressure, psig	12.3	11.7	11.9	12.8	11.8	10.9	11.9	10.3	10.2
	Fuel Inlet pressure, psig	7	7	7	7	7	7	7	7	7
	Stand Speed, RPM	2100	2100	2101	2101	2100	2100	2100	2100	2100
	Drive Amps	21.7	21.7	21.7	26.3	26.3	26.3	35.4	35.4	35.4
	Fuel Inlet Temperature, F	100	104	104	104	103	104	104	103	103
	Fuel Tank Temperature, F	75	84	89	90	87	91	88	90	93
	Injector Block Temperature, F	100	110	115	132	140	140	170	183	188

Table 1-28. Bosch Test 8 for CA Fuel Pre-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: AL-25713-F	Fuel Description: CA	Test Hours: **0**, *(1.6cal)*	Date: **11/17/00**	Operator: **REG**

	Test 8 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
		750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
	Injector 1 Only	11.5	15	16.5	15	17	19.5	16.5	19	22
	Injector 2 Only	12	15	16.5	15	17	19.5	16.5	19	21.5
	Injector 3 Only	11.5	15	16.5	15.5	17.5	19.5	17	19.5	22
	Injector 4 Only	12	15.5	17	15	17	19.5	17	19.5	22
Record With All Injectors Connected Only	All Injectors	23.5	34	40.5	39.5	48	55.5	47	60	70
	Actual Rail Pressure, bar	400	400	400	800	800	800	1351	1350	1350
	Rail Pressure Controller Duty Cycle, %	18.8	19.1	19.4	31.6	31.8	31.9	49.7	50.8	51.5
	Transfer Pump Pressure, psig	57	57	57	57.4	56.7	56.5	56.6	56.4	56.5
	Drain Pressure, psig	23	23	22.3	22.3	23.1	20	20.7	18.6	19.2
	Fuel Inlet pressure, psig	7	7	7	7	7	7	7	7	7
	Stand Speed, RPM	2100	2100	2101	2100	2100	2100	2100	2100	2100
	Drive Amps	21.7	21.7	21.7	23.6	23.6	23.6	35.4	35.4	35.4
	Fuel Inlet Temperature, F	103	100	101	99	97	103	102	101	100
	Fuel Tank Temperature, F	75	87	90	88	83	93	89	93	92
	Injector Block Temperature, F	105	112	115	132	140	140	174	187	192

Table 1-29. Bosch Test 7 for LSLA Fuel Post-Test System Performance Inspection.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: **AL-25792-F**	Fuel Description: **LSLA**		Test Hours: **500**, *(1.0cal)*		Date: **1/25/01**		Operator: **REG**		
Test 7 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
Injector 1 Only	13	16.5	17.5	15.5	17.5	19.5	16.5	19	21
Injector 2 Only	11	15.5	18	15.5	18	19.5	16.5	19	20.5
Injector 3 Only	13	17	18.5	16.5	18.5	20	17	19.5	22
Injector 4 Only	9	14	17	14.5	17.5	19.5	16	19	21
Record With All Injectors Connected Only									
All Injectors	22.5	31.5	41.5	38.5	47	55	47.5	58.5	68
Actual Rail Pressure, bar	402	400	401	801	801	801	1350	1350	1350
Rail Pressure Controller Duty Cycle, %	19	19.4	19.7	31.5	32	32.2	50.8	51.4	52.6
Transfer Pump Pressure, psig	52.8	52.3	52.3	53	53	52.7	53.1	52.5	52.3
Drain Pressure, psig	13.1	12.6	12.1	11.5	11	13.2	12.4	10.6	9.3
Fuel Inlet pressure, psig	7	7	7	7	7	7	7	7	7
Stand Speed, RPM	2100	2100	2100	2100	2100	2100	2100	2100	2100
Drive Amps	19.5	19.4	19.6	21	21	21	23.4	23.4	23.3
Fuel Inlet Temperature, F	100	102	101	102	102	105	105	105	106
Fuel Tank Temperature, F	59	67	75	86	88	92	92	86	89
Injector Block Temperature, F	85	93	96	109	120	153	153	169	180

Table 1-30. Bosch Test 7 for LSLA Fuel System Performance Deviations.

Bosch Test Stand/Injector Calibration Worksheet

Fuel ID Number: **AL-25792-F**	Fuel Description: **LSLA**	Test Hours: **500**, *(1.0cal)*	Date: **1/25/01**	Operator: **REG**

Test 7 2-hr run-in	400 Bar Rail Pressure			800 Bar Rail Pressure			1350 Bar Rail Pressure		
	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth	750 microsecond Pulsewidth	1000 microsecond Pulsewidth	1250 microsecond Pulsewidth
Injector 1 Only	0%	-3%	-3%	3%	3%	0%	0%	0%	-2%
Injector 2 Only	-15%	-9%	-3%	3%	6%	0%	3%	3%	-2%
Injector 3 Only	0%	-6%	0%	6%	6%	0%	0%	0%	0%
Injector 4 Only	-31%	-18%	-11%	-3%	3%	0%	0%	-3%	0%
Record With All Injectors Connected Only									
All Injectors	-6%	-10%	-1%	0%	0%	-1%	2%	-1%	0%
Actual Rail Pressure, bar	1%	-1%	0%	0%	0%	0%	0%	0%	0%
Rail Pressure Controller Duty Cycle, %	-1%	-2%	-1%	-4%	-3%	2%	2%	2%	2%
Transfer Pump Pressure, psig	-4%	-5%	-5%	-4%	-3%	-4%	-4%	-5%	-5%
Drain Pressure, psig	7%	8%	2%	-10%	-7%	21%	4%	3%	-9%
Fuel Inlet pressure, psig	0%	0%	0%	0%	0%	0%	0%	0%	0%
Stand Speed, RPM	0%	0%	0%	0%	0%	0%	0%	0%	0%
Drive Amps	-10%	-11%	-10%	-20%	-20%	-20%	-34%	-34%	-34%
Fuel Inlet Temperature, F	0%	-2%	-3%	-2%	-1%	1%	1%	2%	3%
Fuel Tank Temperature, F	-21%	-20%	-16%	-4%	1%	1%	5%	-4%	-4%
Injector Block Temperature, F	-15%	-15%	-17%	-17%	-14%	9%	-10%	-8%	-4%

The test stand was shut down at 233.1 hours because the CA fuel (test 8) rail pump was unable to maintain a rail pressure above 1000 bar. An inspection of the pump revealed polishing and scoring on the pump plungers. A representative plunger is shown in Figure 1-36. Rail pressure performance data for the CA fuel show the CA pump was maintaining 1350 rail pressure up until the last several minutes before the test was terminated as seen in Figure 1-37. The duty cycle to maintain 1350-bar rail pressure at 1-ms injection duration for the CA fuel increased continuously over the test hours operated, with a sudden increase at the end as shown in Figure 1-38. The last CA reading was observed by the operator 5 minutes prior to the stand shutting down. The minor variations of rotameter flow readings seen in Figure 1-39 for the injected CA fuel indicate the increase in duty cycle noted earlier is an indication of wear. The relatively consistent flow readings suggest the low rail pressure with CA fuel was due to pump wear and not a pressure transducer failure. If the pressure transducer registered low, the controller would increase duty cycle, which would ultimately result in a higher fuel flow for the fixed injection pulsewidth. Post test inspection of the CA pump components revealed a cracked barrel. The crack in the barrel was relieving pressure, resulting in the increased duty cycle to maintain the set condition. The cracked CA (Test 8) fuel barrel and associated plunger is shown in Figure 1-40.

Prior to the test stand shut down, the control circuitry for the CA fuel was increasing the duty cycle to the rail pressure regulator. The rail pressure regulator coil overheated due to the large duty cycle and short-circuited. The short circuit in the CA rail pressure regulator coil resulted in an over-current condition of a power transistor circuit. The section of the controller board that failed also included the ground circuitry for the LSLA controller. Operational channels were identified on the power transistor board, and the wiring was reconfigured to have an operational channel to complete testing.

The LSLA pump testing continued after the controller circuit was reconfigured. The LSLA pump completed the 500 hours of testing. The rail pressure for the LSLA pump is also shown in Figure 1-37, and remained consistent throughout the test. The rail pressure controller duty-cycle increased slightly until 400 hours, when there was a 5% duty-cycle increase, Figure 1-38. The injected fuel flow remained consistent throughout the LSLA test as seen in Figure 1-39.

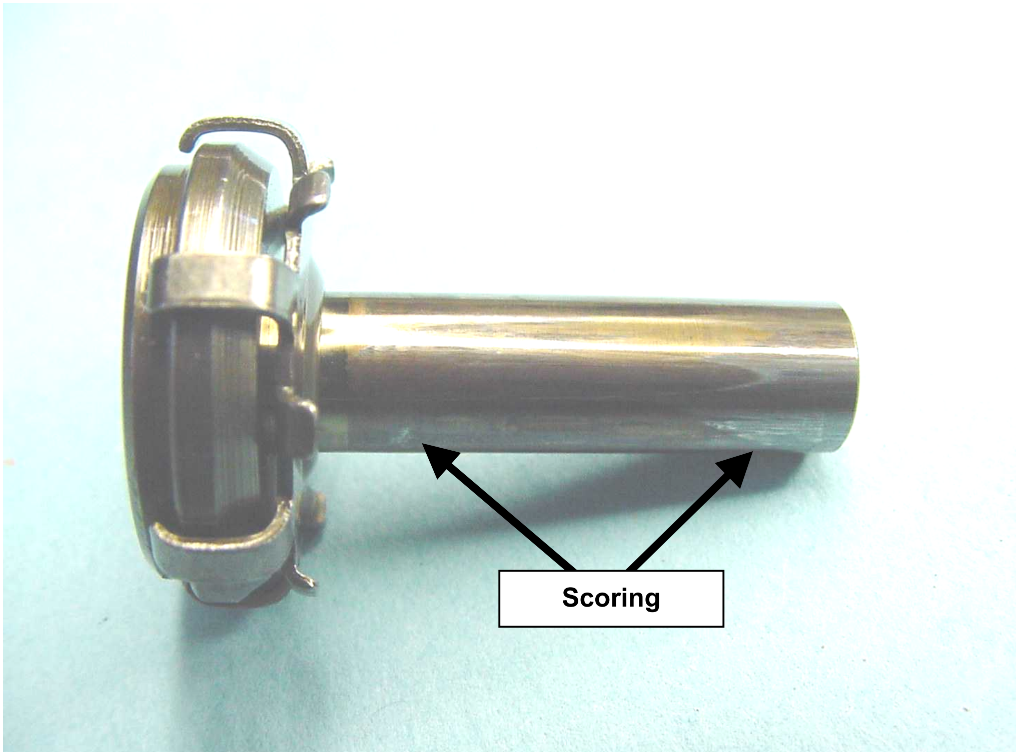


Figure 1-36. Test 8 CA Fuel Plunger with Scoring

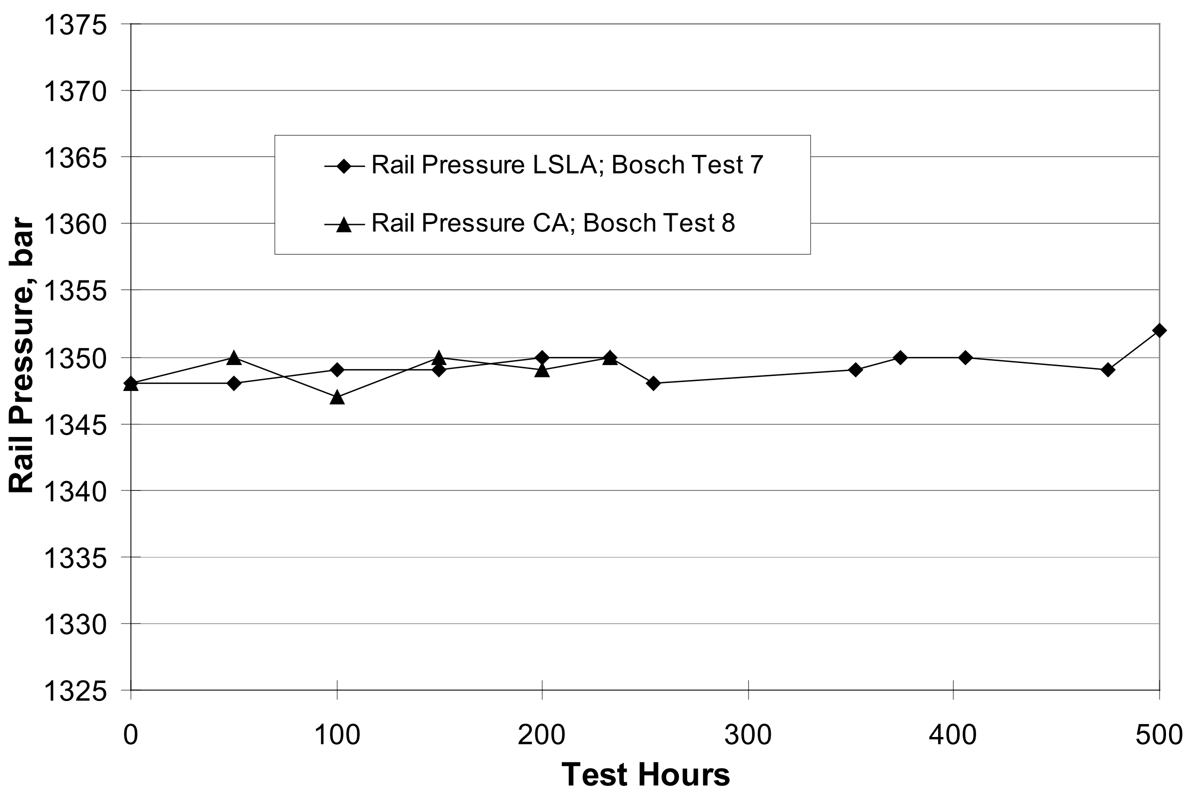


Figure 1-37. Rail Pressure for LSLA and CA Fuels

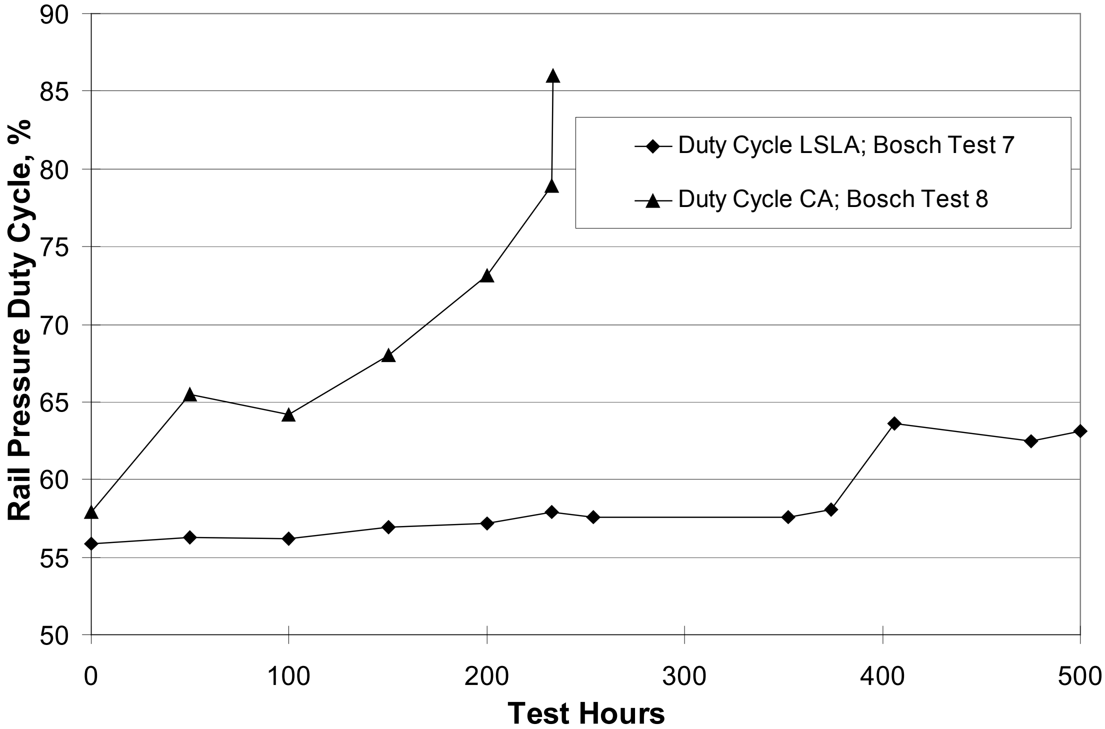


Figure 1-38. Rail Pressure Controller Duty Cycle for LSLA and CA Fuels

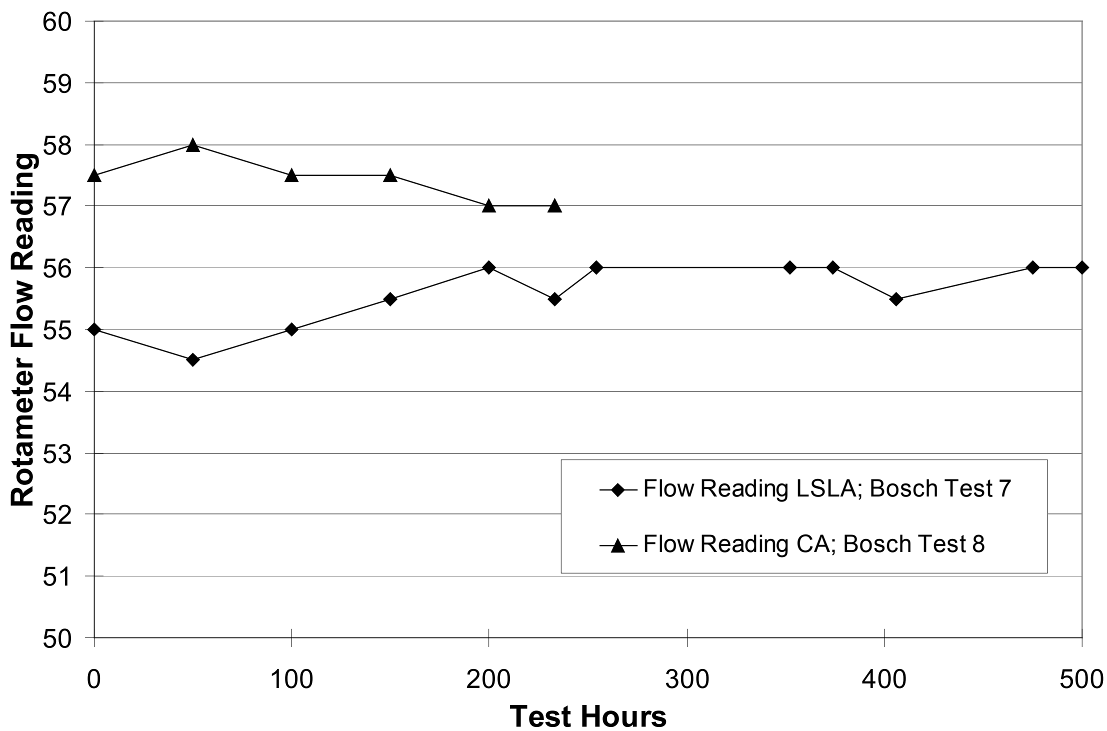


Figure 1-39. Injected Fuel Flow Readings for LSLA and CA Fuels

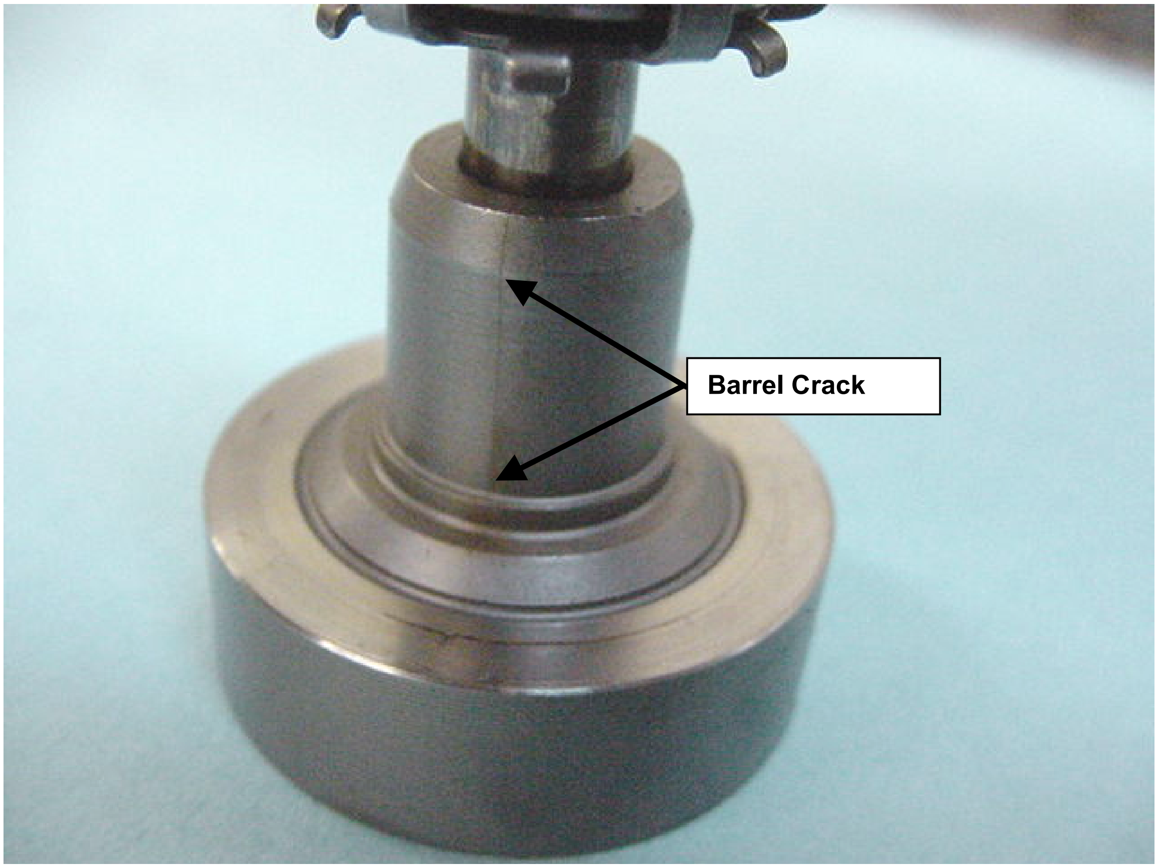


Figure 1-40. CA (Test 8) Fuel Cracked Rail Pump Barrel with Plunger

The injection system performance deviations after 500 hours are shown in Table 1-29 for the LSLA (Test 7) fuel. The injection system flow appeared to deviate the most at lower rail pressures, and shorter injection pulsewidths. The transfer pump pressure revealed a deviation which could be attributed to wear. It was anticipated an increase in drain pressure would reflect wear on the pumping plungers; however, the deposits seen in the pump may have lowered the drain pressure by restricting flow.

Pumping plungers from the test revealed light polish with some scratches and a light brown deposit, a representative plunger is shown in Figure 1-41. The cam follower for the LSLA test revealed pitting of the plain bearing, shown in Figure 1-42, which had not been seen in other tests. The common rail pump cam shaft revealed (Figure 1-43), brown deposits on the support bearing surfaces.

Figure 1-41. LSLA (Test 7) Pump Plunger with Light Polish, Scratches, and Deposition

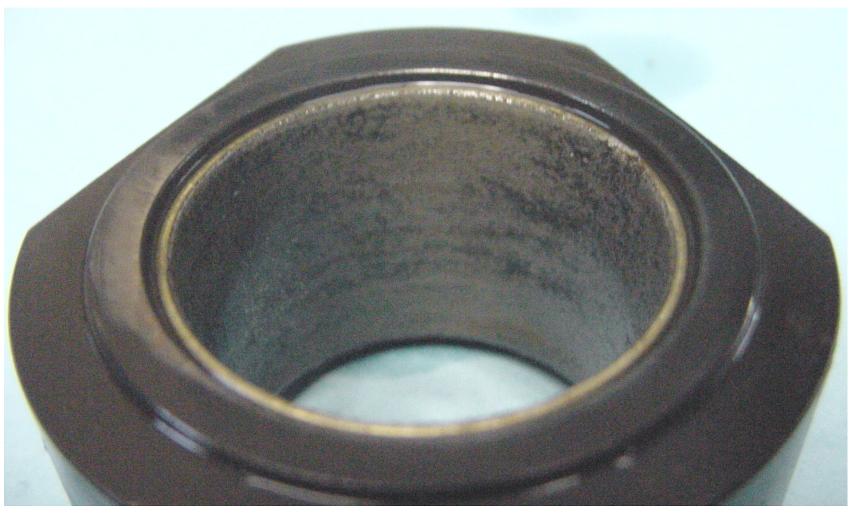


Figure 1-42. LSLA (Test 7) Cam Follower with Bearing Pitting.

Figure 1-43. LSLA (Test 7) Common Rail Pump Shaft with Deposits.

5. Bosch Test Component Inspection Summary and Results

The common rail fuel injection system components for each test and fuel were disassembled and laid out for comparative subjective observations of wear and deposition. The subjective ratings for wear were 0=No Wear, and 5=Failure. The deposition ratings were 0=No Deposits or Brown Film, and 5=Very Heavy Deposits.

Figure 1-44 shows a cross section of the pumping elements in the high-pressure common-rail pump. Item 19/9 in Figure 1-44 is the pumping plunger, shown connected to the plunger foot with a clip. Item 19/5 is the camshaft and item 19/4 is the cam follower. Table 1-31 shows the subjective ratings for each test and pump component. The tests that showed severe wear on the plunger foot (Tests 1,3,4,and 5) also revealed wear on the cam follower. The long duration tests showed a similar level of wear on the plungers, regardless of fuel. Tests in which wear debris was evident in the pump (Tests 1and 5) revealed some camshaft wear. Some camshaft wear was seen with Test 6 for the DMM15 fuel. Test 6 with DMM15 also revealed camshaft wear and heavy deposits. Test 7 with LSLA revealed some pitting of the cam follower bearing. The deposition ratings are based on overall pump component cleanliness. Of interest for FT100 (Test 5) was the observation that pumps and injectors were fairly clean; however, the pressure regulator had severe deposition. Test 6 (DMM15) and Test 7 (LSLA) revealed heavy deposits on the camshaft surfaces. Both tests, which revealed extra heavy deposits, utilized the LSLA fuel, either as a component or neat, and ran for 500 hours.

Figure 1-45 shows a simplified schematic of the common-rail fuel injector. Item 50/18 in Figure 1-45 is the injector pintle that was rated. Also in Figure 1-45 is a blow-up of the vent section of the injector, the ventilator ball (50/12) and seat were inspected under a microscope for each injector but no discernable wear patterns were evident. Table 1-32 shows the subjective ratings for each test and injector pintle. Two pintles from Test 1 with the LSLA fuel showed distinctive wear scars as shown in Figure 1-46 (injector pintles CRC-5 and CRC-6). Wear debris from the pump could have caused the injector pintle wear seen in Test 1. A representative pintle showing minimal wear (injector pintle CRC-17) is also included in Figure 1-46. Injector pintle deposits were moderate for all the tests that completed a significant number of hours.

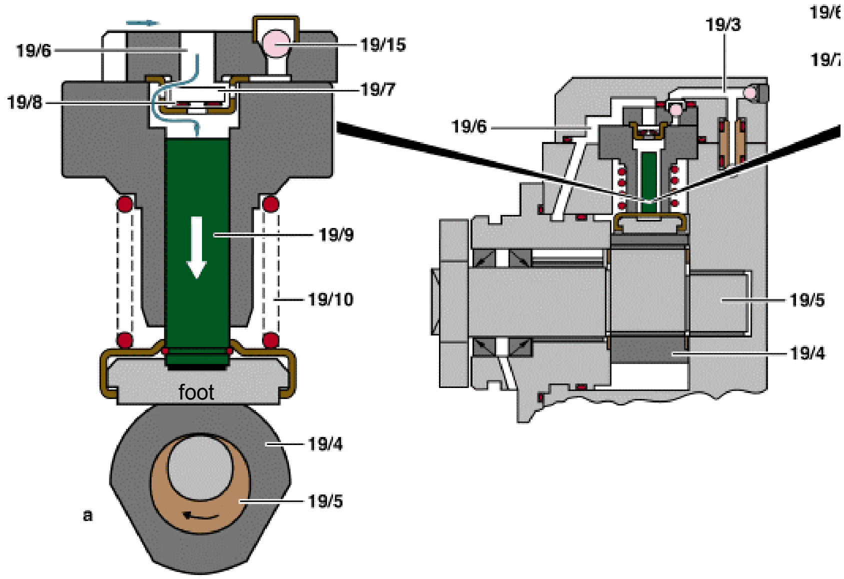


Figure 1-44. Rated Components of High-pressure Common-Rail Pump (Drawin Courtesy of DaimlerChrysler)

Table 1-31. High-Pressure Common-Rail Pump Subjective Ratings

Test Number	Fuel ID	Test Hours	Rail Pump ID	Plunger		Plunger Foot	Camshaft Journals	Cam Lobe	Cam Follower Bearing	Cam Follower	Deposition
1	LSLA	482	CRC-33	1	4.5	5	3	5	5	5	2.5
				2	3	5					
				3	3	5					
2	CA	500	CRC-37	1	3	1	1	1	1	1	2.5
				2	4	1					
				3	4.5	1					
3	FT100	2	CRC-36	1	5	5	1	1	1	5	0
				2	2	1					
				3	5	5					
4	DMM15	9	CRC-38	1	5	5	1	1.5	1	5	0
				2	3	4.5					
				3	5	5					
5	FT100	385	CRC-39	1	5	5	2	2	1	5	1
				2	3.5	5					
				3	3.5	5					
6	DMM15	500	CRC-40	1	2.5	1	2.5	2	1	1	5
				2	3.5	1					
				3	3.5	1					
7	LSLA	500	CRC-34	1	4	1	1	1.5	4 (pitted)	1	5
				2	2.5	1					
				3	2.5	1					
8	CA	233	CRC-35	1	4	1	1	1	1	1	2.5
				2	2.5	1					
				3	2.5	1					

WEAR: 0=No Wear; 5=Failure
DEPOSITS: 0= No Deposits or Brown Film; 5=Very Heavy Deposits

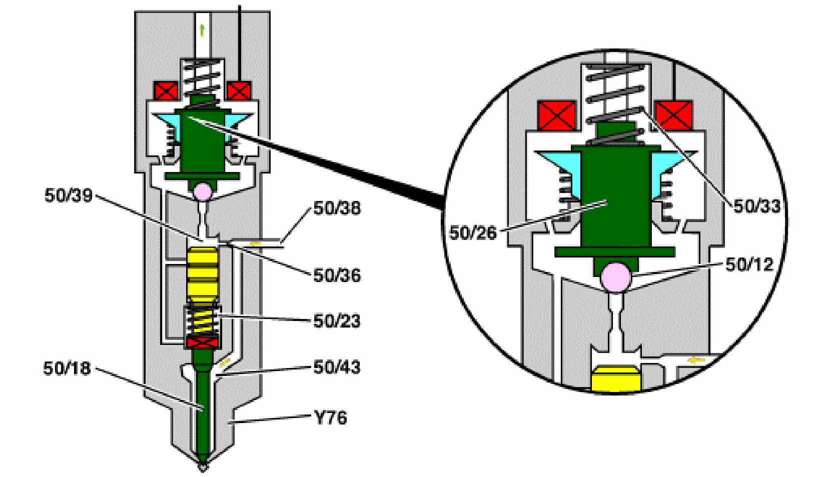


Figure 1-45. Simplified Common-Rail Injector Schematic
(Drawing Courtesy of DaimlerChrysler)

Table 1-32. Common-Rail Injector Ratings

Test Number	Fuel ID	Test Hours	Injector	Pintle	Deposition
1	LSLA	482	CRC-5	4	3
			CRC-6	4	3
			CRC-7	1	3
			CRC-8	1	3
2	CA	500	CRC-9	1	3
			CRC-10	1	3
			CRC-11	1	3
			CRC-12	1	3
3	FT100	2	CRC-17	1	0
			CRC-18	1	0
			CRC-19	1	0
			CRC-20	1	0
4	DMM15	9	CRC-21	1	0
			CRC-22	1	0
			CRC-23	1	0
			CRC-24	1	0
5	FT100	385	CRC-25	1	1
			CRC-26	1	1
			CRC-27	1	1
			CRC-28	1	1
6	DMM15	500	CRC-29	1	0
			CRC-30	1	0
			CRC-31	1	0
			CRC-32	1	0
7	LSLA	500	CRC-1	1	3
			CRC-2	1	3
			CRC-3	1	3
			CRC-4	1	3
8	CA	233	CRC-13	1	1
			CRC-14	1	1
			CRC-15	1	1
			CRC-16	1	1

WEAR: 0=No Wear; 5=Failure
DEPOSITS: 0= No Deposits or Brown Film; 5=Very Heavy Deposits

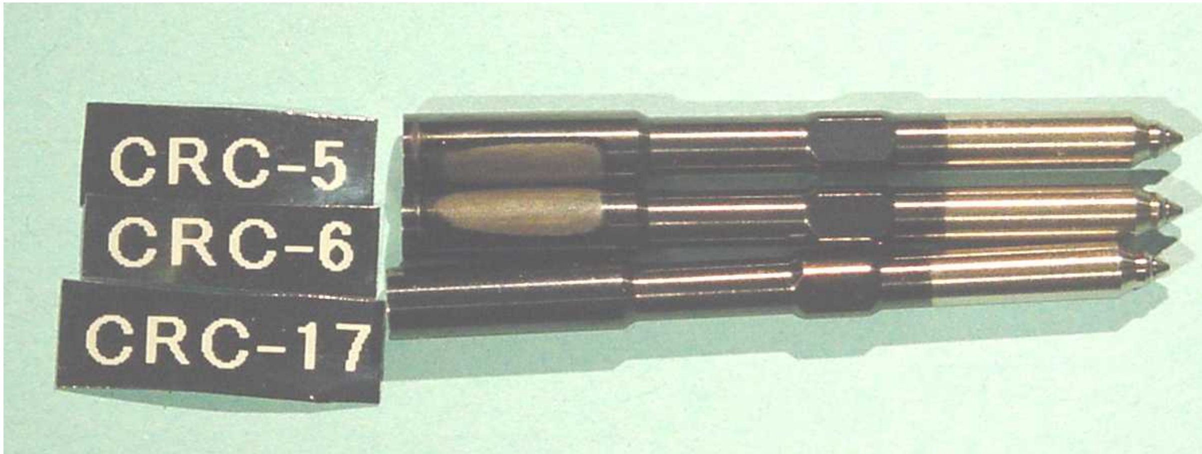


Figure 1-46. Injector Pintle Wear Scars

6. Manufacturer Ratings

The Bosch inspection results are included as Appendix B. Bosch evaluated each component in the injectors and rail pumps and assigned a wear value from 1 to 5, then summed the values for an overall rating for the common rail system. Table 1-33 cross-references the pump tests with test fuels. The rankings are based on the average Bosch wear rating for each fuel. The SwRI ranking was based on performance, test hours completed, subjective part wear ratings, deposition, and overall pump condition.

Table 1-33. Bosch Common Rail Injection System Rating Summary

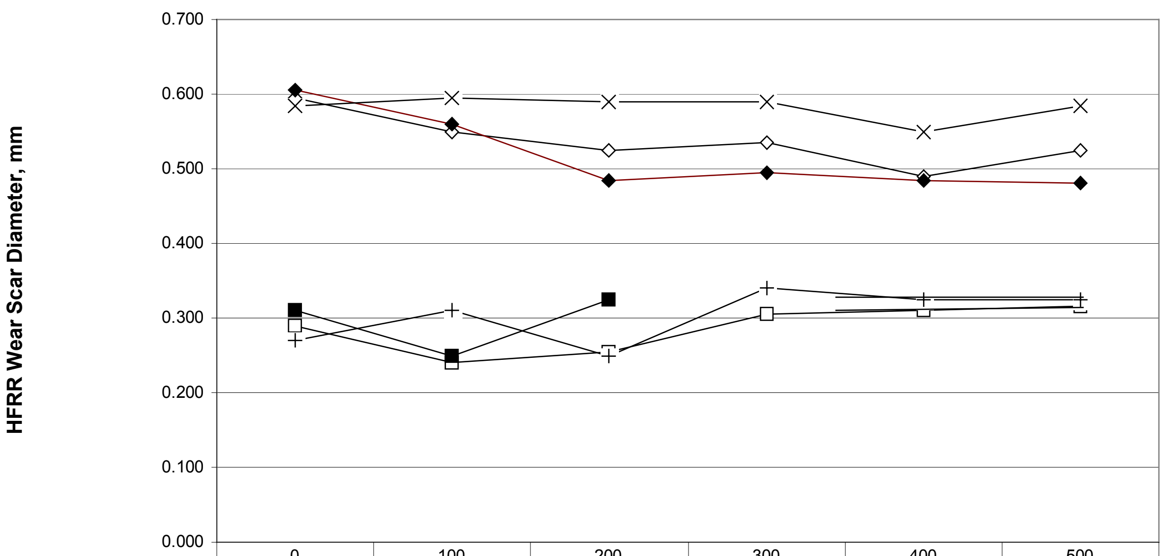
Bosch Test Number/Pump ID	Fuel	Bosch Wear Rating	Bosch Fuel Rank (wear avg.)	SwRI Avg. Subjective Wear Rating	SwRI Fuel Rank
Test 4/CRC-38	DMM15	47	1(47.5)	3.6	3
Test 6/CRC-40	DMM15	48		1.9	
Test 2/CRC-37	CA	57	2(54.5)	1.9	1
Test 8/CRC-35	CA	52		1.6	
Test 3/CRC-36	FT100	47	3(55.5)	3.6	4
Test 5/CRC-39	FT100	64		3.7	
Test 1/CRC-33	LSLA	67	4(62.5)	4.4	2
Test 7/CRC-34	LSLA	58		1.6	

C. Laboratory Scale Wear Tests

Both Stanadyne and Bosch indicated the lubricity of the test fuel should be determined prior to testing. Stanadyne also recommended monitoring the fuel lubricity during the evaluations to determine fuel lubricity changes during testing. The laboratory scale wear test to be performed on the test fuels was the High Frequency Reciprocating Rig (HFRR) procedure described in ASTM D-6079.

Lubricity evaluations were performed on the LSLA fuel, to determine if lubricity additives were present. The HFRR wear scar was 0.585 mm and the BOCLE scuffing load was 1850 grams. These results appear to indicate that a lubricity additive is not present.

HFRR lubricity evaluations at 60ºC were scheduled for every 100 hours of the Stanadyne test for CA and LSLA fuels. The HFRR average wear scar determinations for the Stanadyne test are shown in Figure 1-47. The results indicate the fuel lubricity of the test fuels had not substantially changed during the 500 hours the test operated with Stanadyne pumps.



	0	100	200	300	400	500
CA:Bosch 2	0.290	0.240	0.255	0.305	0.310	0.315
CA:Bosch 8	0.310	0.250	0.325 (233-hrs)			
LSLA:Bosch 1	0.595	0.550	0.525	0.535	0.490	0.525 (482-hrs)
LSLA:Bosch 7	0.605	0.560	0.485	0.495	0.485	0.480
CA:Stanadyne	0.270	0.310	0.250	0.340	0.325	0.325
LSLA:Stanadyne	0.585	0.595	0.590	0.590	0.550	0.585

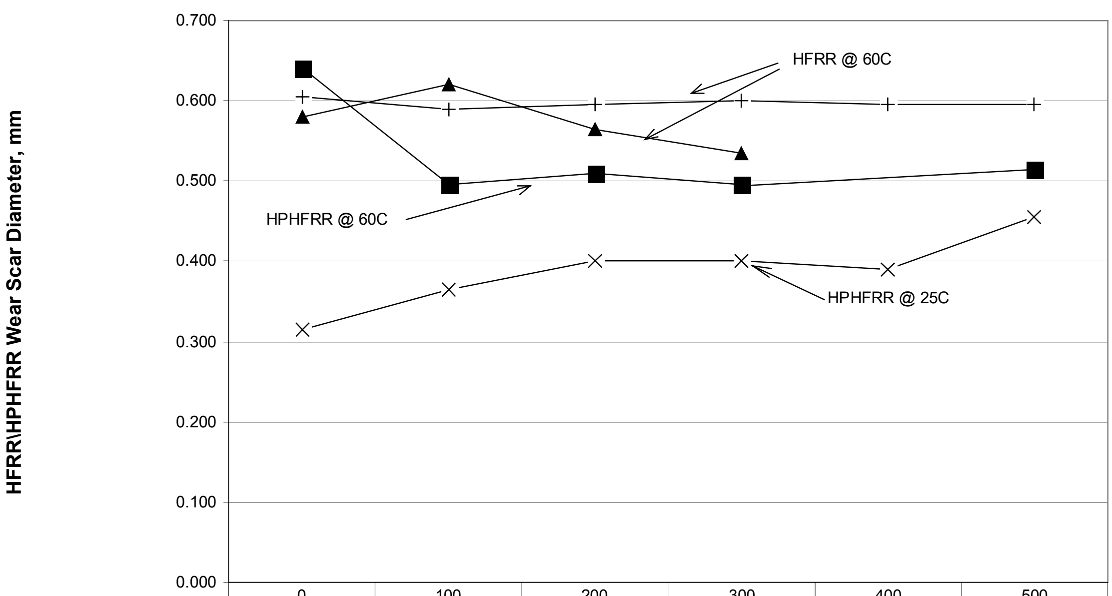
Test Hour

Figure 1-47. HFRR Results for Bosch Common Rail Tests, CA and LSLA Fuels, Compared to Stanadyne Results.

The HFRR wear scar data for the Bosch Common Rail tests are also shown in Figure 1-47 for the LSLA and CA fuels. The HFRR wear scar data shown was performed at 60˚C. The data suggest an improvement in both tests for the LSLA fuel during the test interval, but the lubricity level did not approach the accepted maximum 0.460-mm wear scar for diesel fuels. The CA fuel lubricity remained consistent during the course of testing.

HFRR lubricity evaluations at 60ºC were scheduled for every 100 hours of the test for the Fischer-Tropsch fuel (FT100). The HFRR wear scar determinations for the Stanadyne test is shown in Figure 1-48. The results indicate the fuel lubricity of the test fuel had not substantially changed during the 500-hour test.

For the DMM15 blend a unique high pressure HFRR test apparatus was used to determine the wear scars. The DMM15 blends were evaluated in the HPHFRR apparatus at 25ºC. The HPHFRR results for the Stanadyne test shown in Figure 1-48 appear consistent and indicate the fuel lubricity did not change significantly. The DMM15 wear scar results appear low compared to the base LSLA fuel. This is probably solely due to the temperature difference of the tests, 25ºC for HPHFRR versus 60ºC for HFRR.



	0	100	200	300	400	500
FT100: Bosch 5	0.580	0.620	0.565	0.535 (385-hrs)		
DMM15: Bosch 6	0.640	0.495	0.510	0.495		0.515 (456-hrs)
FT100: Stanadyne	0.605	0.590	0.595	0.600	0.595	0.595
DMM15: Stanadyne	0.315	0.365	0.400	0.400	0.390	0.455

Test Hour

Figure 1-48. HFRR and HPHFRR Results for Bosch Common Rail and Stanadyne Tests, FT100 and DMM15 Fuels.

The HFRR and HPHFRR wear scar data for the Bosch Common Rail tests are also shown in Figure 1-48 for the FT100 and DMM15 fuels. The HFRR wear scar data shown was performed at 60°C. For the Bosch tests the HPHFRR was also performed at 60°C. The data suggest a slight improvement in the FT100 and DMM15 fuels during the test interval, but the lubricity level did not approach the accepted maximum 0.460-mm wear scar at 60°C for good lubricity diesel fuels. The FT100 test was terminated at 385-hrs, with the last HFRR result determined at 300 stand hours. Due to operation over weekends the final wear scar screening at 456 hours supplanted the 400-hour and 500-hour determinations. For the standard HFRR test, the difference attributable to test temperature is approximately 0.070 mm. There is a 0.070-mm greater wear scar for a 60°C test than for a 25°C test for the range of fuel lubricities of interest. It is not certain if the same offset can be applied to the HPHFRR data, but the data suggest, except for the 0-hour reading, there is about a 0.1-mm wear scar offset. It has yet to be determined if the change in lubricity of the DMM15 fuel is due to the nature of the experimental wear test procedure, or a function of the pump testing.

IV. TESTING SUMMARY AND CONCLUSIONS

A. Stanadyne Opposed Piston Fuel Injection System

- All Test Fuels Completed 500 Hours
- Tests Performed in Duplicate
- Fuel Rankings based on Pump Condition, Pump Performance, and Injector Performance

1. LSLA: No Lubricity Additive

- Large HFRR Wear Scar
- Mild Pump Wear
- Minimal Pump Durability Impact
- Minimal Injector Durability Impact

2. CA: Lubricity Additive

- Smallest HFRR Wear Scar
- Heavy Brown Deposits
- Deposits Effect Pump Performance

- Transfer Pump Wear
- Pump Durability Impact
- Minimal Injector Durability Impact

3. DMM15: No Lubricity Additive

- Large HFRR Wear Scar
- Transfer Pump Wear
- Heavy Drive Tang Wear
- Pump Performance Impact
- Pump Durability Impact
- Injector Durability Impact
- High Average Opening Pressure Loss

4. FT100: No Lubricity Additive

- Large HFRR Wear Scar
- Transfer Pump Wear
- Heavy Drive Tang Wear
- Pump Performance Impact
- Pump Durability Impact
- Injector Durability Impact
  - High Average Opening Pressure Loss

B. Bosch Common-Rail Fuel-Injection System

- System Performance Check at Test Initiation and at Test Conclusion if Components Operable
  - 38°C Fuel Inlet Temperature
  - 2100-RPM Transfer Pump Speed and 2800-RPM Rail Pump Speed
  - Three Rail Pressures: 400 bar, 800 bar, and 1350 bar
  - Three Injection Pulsewidths : 750 µs, 1000 µs, and 1250 µs
  - Document: Controller Duty Cycle, Transfer Pump Pressure, and Injection Flow

- Not All Fuels Completed Scheduled 500 hours
- All Tests Conditions Noted
- Tests Fuels Performed in Duplicate
- Substantial Variation of Performance of Duplicate Pumps with Each Fuel
- Fuel Rankings based on Pump Condition, Fuel Lubricated Contact Condition, Pump Performance, Injector Condition, and Injector Performance

1. CA: Lubricity Additive

- Test Condition:
  - 2800-RPM Rail Pump
  - 1350-bar Rail Pressure
  - 1000-µs Injection Pulsewidth
  - 70°C Fuel Inlet Temperature
  - 38°C Fuel Inlet Temperature
- Test 2 Showed Mild Wear at 500 hours
  - No System Run-in
  - Drive Coupling Problems May Have Exacerbated Wear
  - Minimal Pump Durability Impact
  - Minimal Injector Durability Impact
  - Injector Pintle Deposits
- Test 8 Terminated at 233 hours
  - System Run-in
    - 100ºF Fuel Inlet Temperature
    - 90ºF Fuel Tank Temperature
    - 30 minutes at 450 RPM with 300-bar rail pressure
    - 90 minutes at 750 RPM with 450-bar rail pressure
  - Mild Wear on Fuel Lubricated Contacts
  - Cracked Plunger Barrel, Unable to Maintain Rail Pressure
  - Rail Pressure Regulator Failure, Short Circuit
  - Minimal Injector Durability Impact

2. LSLA: No Lubricity Additive

- Test Condition:
  - 2800-RPM Rail Pump
  - 1350-bar Rail Pressure
  - 1000-µs Injection Pulsewidth
  - 70°C Fuel Inlet Temperature
  - 38°C Fuel Tank Temperature

- Test 1 Severe Wear Terminated at 482 hours
  - No System Run-in
  - Drive Coupling Problems May Have Exacerbated Wear
  - Wear Debris, Pump Durability Impact
  - Some Injector Durability Impact, possibly from Wear Debris
  - Injector Pintle Deposits

- Test 7 Mild Pump Wear at 500 hours
  - System Run-in
    - 100ºF Fuel Inlet Temperature
    - 90ºF Fuel Tank Temperature
    - 30 minutes at 450 RPM with 300-bar rail pressure
    - 90 minutes at 750 RPM with 450-bar rail pressure
  - Cam Follower Bearing Pitting
  - Deposits on Pump Driveshaft
  - Minimal Pump Durability Impact
  - Minimal Injector Durability Impact
  - Injector Pintle Deposits

3. DMM15: No Lubricity Additive

- Test Condition:
  - 2800-RPM Rail Pump
  - 1350-bar Rail Pressure

– 1000-µs Injection Pulsewidth
– 57°C Fuel Transfer Pump Inlet Temperature
– 40°C Fuel Rail Pump Inlet Temperature
– 38°C Fuel Tank Temperature

- Test 4 Pump Seizure at 2.5 hours
  – Cooled Fuel Into High Pressure Pump To Avoid Two Phase Flow
  – No System Run-in
  – Heavy Wear in Fuel Lubricated Contacts

- Test 6 Mild Wear at 500 hours
  – Cooled Fuel Into High Pressure Pump To Avoid Two Phase Flow
  – System Run-in
    – 100ºF Fuel Inlet Temperature
    – 90ºF Fuel Tank Temperature
    – 30 minutes at 450 RPM with 300-bar rail pressure
    – 90 minutes at 750 RPM with 450-bar rail pressure
  – Mild Wear on Fuel Lubricated Contacts
  – Pump Driveshaft Deposits
  – Minimal Injector Durability Impact

4. FT100: No Lubricity Additive

- Test Condition:
  – 2800-RPM Rail Pump
  – 1350-bar Rail Pressure
  – 1000-µs Injection Pulsewidth
  – 70°C Fuel Transfer Pump Inlet Temperature
  – 38°C Fuel Tank Temperature

- Test 3 Pump Seizure During Performance Check
  – No System Run-in
  – Heavy Wear in Fuel Lubricated Contacts

- Test 5 Pump Seizure at 385 hours
  - System Run-in
    - 100ºF Fuel Inlet Temperature
    - 90ºF Fuel Tank Temperature
    - 30 minutes at 450 RPM with 300-bar rail pressure
    - 90 minutes at 750 RPM with 450-bar rail pressure
  - Heavy Wear on Fuel Lubricated Contacts
  - Tar-like Deposits on Pressure Regulator
  - Broken Plunger Foot Possibly due to Over Pressure
  - Minimal Injector Durability Impact

- The variability in the data and the small sample size make it difficult to assess the impact of fuel lubricity.
- Bosch High Pressure Common Rail Pumps Appear To Be More Sensitive To Fuel Lubricity
- Substantially More Severe Duty-Cycle and Loading

V. Fuel Pump and Injector Bibliography

1. Lacey, P.I., and Westbrook, S. R., "Diesel Fuel Lubricity," SAE Technical Paper 950248, 1995.

2. Lacey, P.I., "Wear Mechanism Evaluation and Measurement in Fuel Lubricated Components," Interim Report 286, Belvoir Fuels and Lubricants Research Facility, SwRI, Texas, AD A 284870, September 1994.

3. L.L. Stavinoha, J.G. Barbee, D.M., Yost, "Thermal Oxidative Stability of Diesel Fuels," Interim Report BFLRF 205, Belvoir Fuels and Lubricants Research Facility (BFLRF) Southwest Research Institute (SwRI), February 1986.

4. J.N. Bowden, D. L. Present, D. M. Yost, "Evaluation of a Coal-Derived Mid-Distillate Fuel (U)," Interim Report BFLRF 227, Belvoir Fuels and Lubricants Research Facility (SwRI), December 1986.

5. J.N. Bowden, D.M. Yost, A.F. Montemayor, L.L. Stavinoha, "Technology for Use of Variable Quality Fuels (U)," Interim Report BFLRF 239, Belvoir Fuels and Lubricants Research Facility (SwRI), December 1987.

6. Lacey, Paul I., and Lestz, Sidney J., “Failure Analysis of Fuel Injection Pumps From Generator Sets Fueled with Jet A-1,” Interim Report BFLRF 268, Belvoir Fuels and Lubricants Research Facility (SwRI), January 1991.

7. Lacey, Paul I., “Wear Analysis of Diesel Engine Fuel Injection Pumps from Military Ground Equipment Fueled With Jet A-1,” Interim Report BFLRF 272, Belvoir Fuels and Lubricants Research Facility (SwRI), May 1991.

8. Lacey, Paul I., “The Relationship Between Fuel Lubricity and Diesel Injection System Wear,” Interim Report BFLRF 275, Belvoir Fuels and Lubricants Research Facility (SwRI), January 1991.

9. Stavinoha, Leo L., Yost, Douglas M., and Lestz, Sidney J., “Diesel Injector Fouling Bench Methodology,” Interim Report BFLRF 267, Belvoir Fuels and Lubricants Research Facility (SwRI), June 1992.

10. Yost, D.M., “Effect of JP-8 fuel on Material-handling Engines,” Interim Report BFLRF 285, Belvoir Fuels and Lubricants Research Facility (SwRI), November 1992.

11. Lacey, P.I., “Wear Mechanism Evaluation and Measurement in Fuel-Lubricated Components,” Interim Report BFLRF 286, Belvoir Fuels and Lubricants Research Facility (BFLRF), Southwest Research Institute, September 1994.

12. Lacey, P.I., Frame, E.A., and Yost, D.M., “Bench Wear and Single-Cylinder Engine Evaluations of High-Temperature Lubricants for U.S. Army Ground Vehicles,” Interim Report BFLRF 291, Belvoir Fuels and Lubricants Research Facility (BFLRF), Southwest Research Institute, September 1994.

13. Lacey, Paul I. and Westbrook, Steven R., “Effect of Fuel Composition and Prestressing on Lubricity,” Interim Report TFLRF 307, TARDEC Fuels and Lubricants Research Facility (TFLRF), Southwest Research Institute, August 1995.

14. Westbrook, S.R., Stavinoha, L.L., McInnis, L.A., Likos, W.E., and Yost, D.M., “Fuels and Requirements for Low-Heat Rejection Military Diesel Engines,” Interim Report TFLRF 297, TARDEC Fuels and Lubricants Facility (TFLRF), Southwest Research Institute, January 1996.

15. Lacey, P.I., and Westbrook, S.R. “The Effect of Increased Refining on the Lubricity of Diesel Fuel,” Proceedings of the Fifth International Conference on Stability and Handling of Liquid Fuels, October 1994.

16. Lacey, P.I., “Development of a Lubricity Test Based on the Transition from Boundary Lubrication to Severe Adhesive Wear in Fuels,” Lubrication Engineering, 50, No. 10, October 1994.

17. Lacey, P.I., and Westbrook, S.R., “Diesel Fuel Lubricity,” SAE Technical Paper No. 950248, February 27-March 2, 1995.

18. Lacey, P.I., and Lestz, S.J., "Effect of Low-Lubricity Fuels on Diesel Injection Pumps-Part I: Field Performance," SAE Technical Paper No. 920823, February 24-28, 1992.

19. Lacey, P.I., and Lestz, S.J., "Effect of Low-Lubricity Fuels on Diesel Injection Pumps-Part II: Laboratory Evaluation," SAE Technical Paper No. 920824, February 24-28, 1992.

20. Lacey, P.I., "Wear With Low Lubricity Fuels, Part I: Development of a Wear Mapping Technique," *Wear,* 160, 1993; pp. 325-343.

21. Lacey, P.I., "Evaluation of Oxidative Corrosion in Diesel Fuel Lubricated Contacts," Tribology Transactions, 37, No. 2, 1994; pp. 253-260

OBJECTIVE 2: MATERIAL COMPATIBILITY

I. BACKGROUND

In October 1993, new diesel fuels were mandated for use throughout the United States that were designed to reduce emissions of nitrogen oxides and particulate matter from diesel-powered equipment. With the introduction of these fuels, fuel leaks and other failures occurred in a portion of the U. S. diesel population. Fuel system leakage from O-rings and hoses were the most commonly reported problems. These problems appeared to affect primarily O-rings and seals made of nitrile (or Buna N) rubber. While this is a common seal material used in automotive applications, another common type of automotive seal material, a fluorocarbon elastomer, was not experiencing seal failures (Reference 1).

II. PURPOSE

The purpose of Objective 2 was to determine the material compatibility of the four test fuels with five elastomers representative of today's diesel fuel systems and advanced technology diesel systems.

III. APPROACH

The four fuels selected by the Coordinating Research Council (CRC) to be used in this study are listed in Table 2-1 below:

Table 2-1. Test Fuels

Fuel No.	Fuel Code	Fuel Description	SwRI Code
F1	CA	California Reference Diesel Fuel	AL-25713
F2	LSLA	Low Sulfur, Low Aromatics	AL-25792
F3	FT100	Neat Fischer-Tropsch Diesel	AL-25787
F4	DMM15	Blend: 15% Dimethoxymethane (DMM) with 85% LSLA	AL-25959

Five elastomers were chosen to assess material compatibility. These elastomers were chosen after reviewing previous work performed in this area (References 2, 3 & 4), as well as discussions with technical representatives from engine and elastomer manufacturers. Three of the selected elastomers are made out of an acrylonitrile butadiene rubber (commonly referred to as "nitrile"), while the other two are fluorocarbon materials (Viton). The following five different types of elastomers were included in this investigation:

Sample Code	Sample Description
Sx1	N 674 is a 70-durometer general-purpose nitrile;
Sx2	N 497 is a 70-durometer high Acrylonitrile Content (ACN) nitrile that is considered more fuel resistant than N 674;
Sx3	N 741 is a 75-durometer peroxide cured nitrile;
Sx4	V 747 is a 75-durometer, black filled fluorocarbon, and;
Sx5	V 884 is a 75-durometer, non-black filled fluorocarbon.

All tests were performed at 40ºC (104ºF) for testing periods of 72 hours (three days), 216 hours (nine days), and 1024 hours (43 days). The specimens of a particular type of material were stored in 3.5-liter vessels containing one test fuel. Upon completion of the 72-hour, 216-hour and 1024-hour test periods the material samples were pulled and the following test procedures were conducted:

For each test period, three 2.54 cm x 5.1 cm (1" x 2") sections were tested for the following:

- % weight change by ASTM D471 (Rubber Property-Effect on Liquids),
- % volume and mass change by ASTM D471, and
- hardness (pts.) by ASTM D2240 (Rubber Property-Durometer Hardness).

Also, for each test period as well as initial baseline measurements, five dumbbell specimens were tested for the following:

- modulus at 100% elongation (psi),
- ultimate tensile strength (psi), and
- ultimate elongation (%),

All tests were conducted using ASTM D412 (Vulcanized Rubber and Thermoplastic Rubbers and Thermoplastic Elastomers-Tension) Test Method.

IV. TEST RESULTS

The results will be discussed covering the effects of the four fuels on each of the five materials for each test method. The scope of each of the six tests is described below:

- The ultimate tensile strength is the ability to resist pulling apart.
- The ultimate elongation is how well the sample resists stretching.
- As the modulus @ 100% elongation increases, the material is more brittle.
- As the durometer points increase, the sample is harder; when they decrease, the sample is softer.
- The mass change is a change in weight
- The volume change is a change in size.

All the test results are reported at 0-hour (baseline), 72 hours (three days), 216 hours (nine days) and 1024 hours (43 days).

The test results are presented in Table 2-2, which shows the actual test data results for ultimate tensile strength, psi; ultimate elongation, % and modulus at 100% elongation, psi. Table 2-3 shows the percentage change of the results in Table 2-2 and the percentage change for the standard deviation from the mean. Table 2-4 shows the durometer points change and the percentage change. Table 2-5 shows the percentage change in mass and volume. Figures 2-1 through 2-5 show the actual data curves for ultimate tensile strength, psi. Figures 2-6 through 2-10 show the data curves of ultimate elongation, %. Figures 2-11 through 2-15 show the data curves of modulus @ 100% elongation, psi. Figures 2-16 through 2-20 show the data curves of durometer points change and Figures 2-21 through 2-25 show the data curves of mass and volume % change.

A. Tension Results

The tension data including Ultimate Tensile Strength, psi (Figures 2-1 through 2-5); Ultimate Elongation, % (Figures 2-6 through 2-10); and Modulus @ 100% Elongation, psi (Figures 2-11 through 2-15); are presented in Table 2-2. Table 2-3 shows the percentage change of the actual results compared to the baseline and the percentage change of the %Std. Dev. when compared to the baseline.

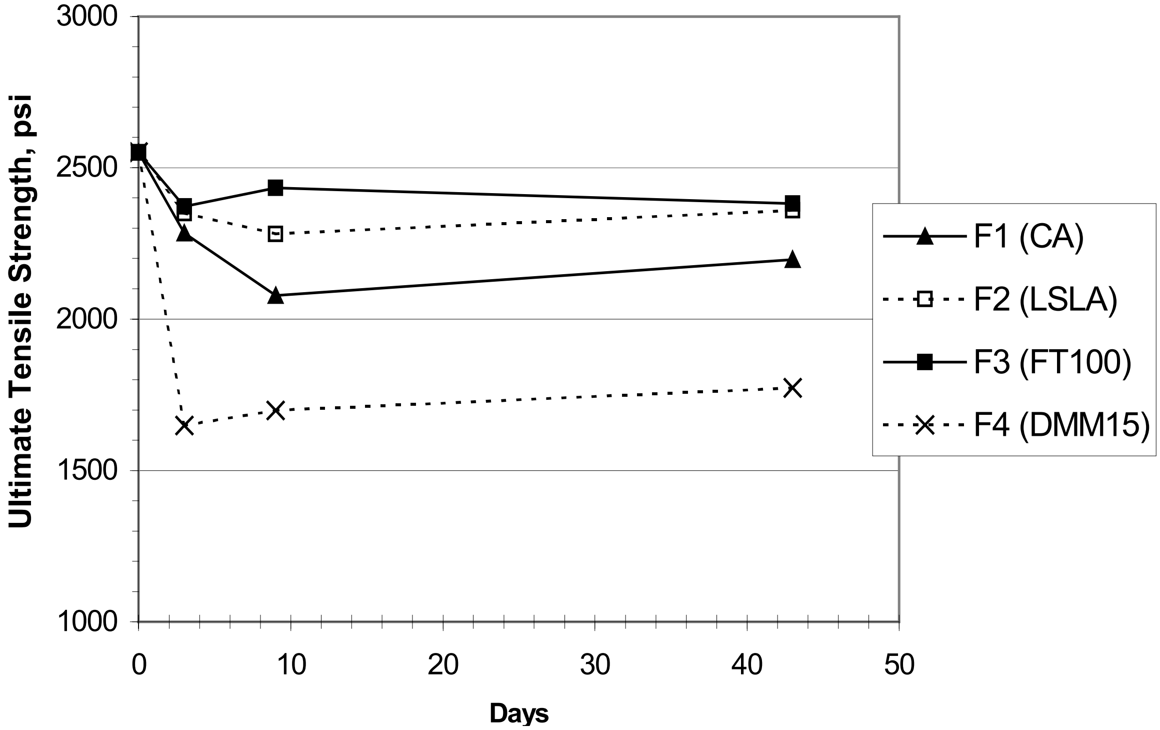


Figure 2-1. Ultimate Tensile Strength, PSI, Sx1 (N674)

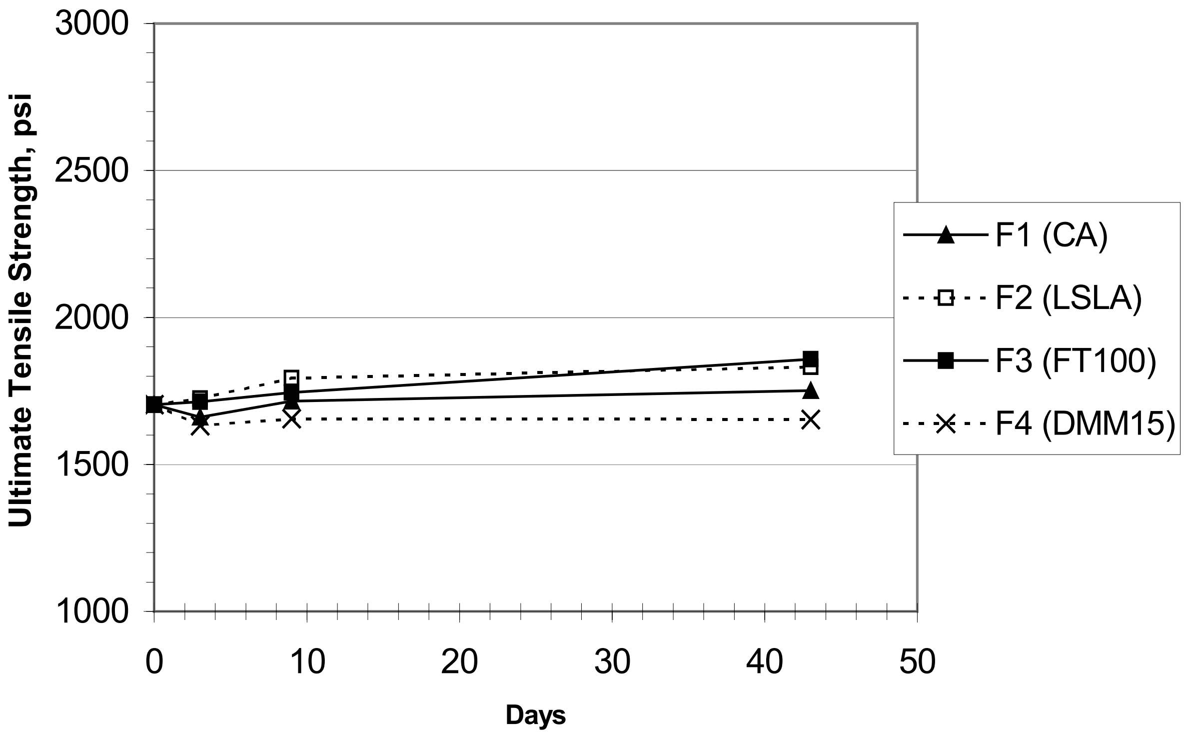


Figure 2-2. Ultimate Tensile Strength, PSI, Sx2 (N497)

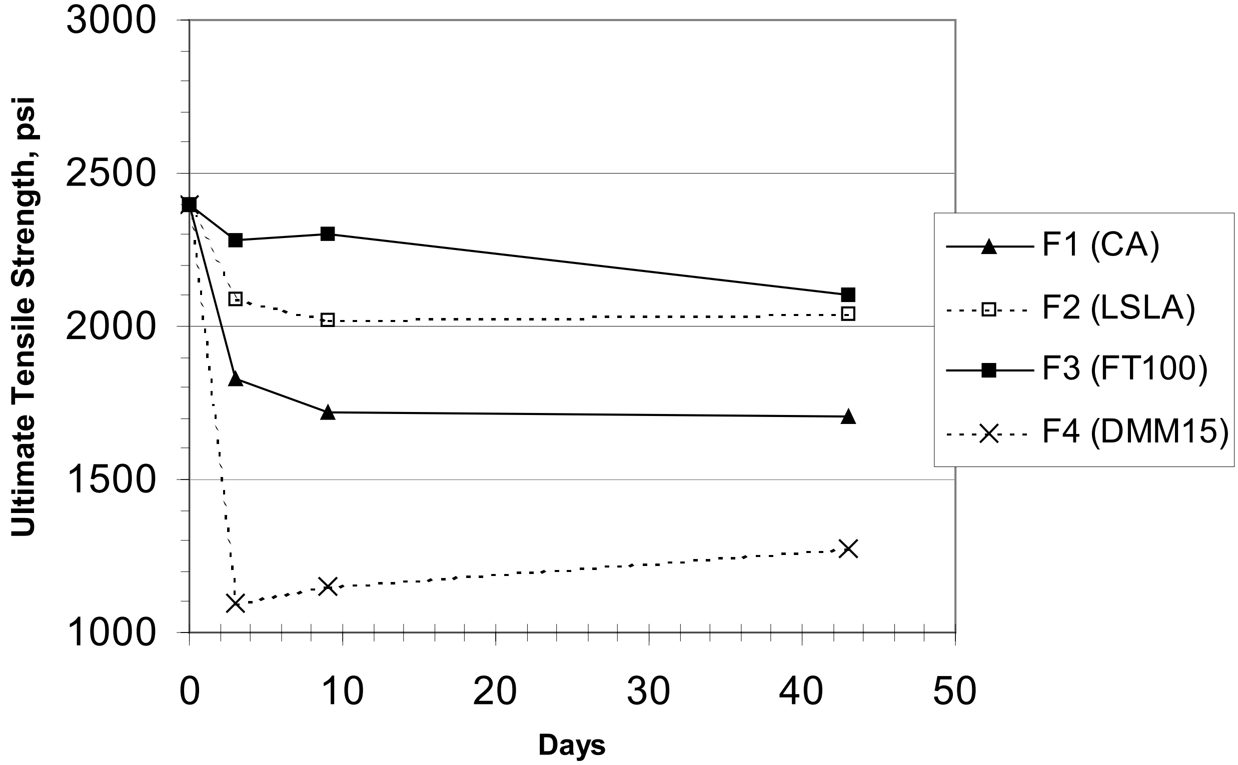


Figure 2-3. Ultimate Tensile Strength, PSI Sx3 (N741)

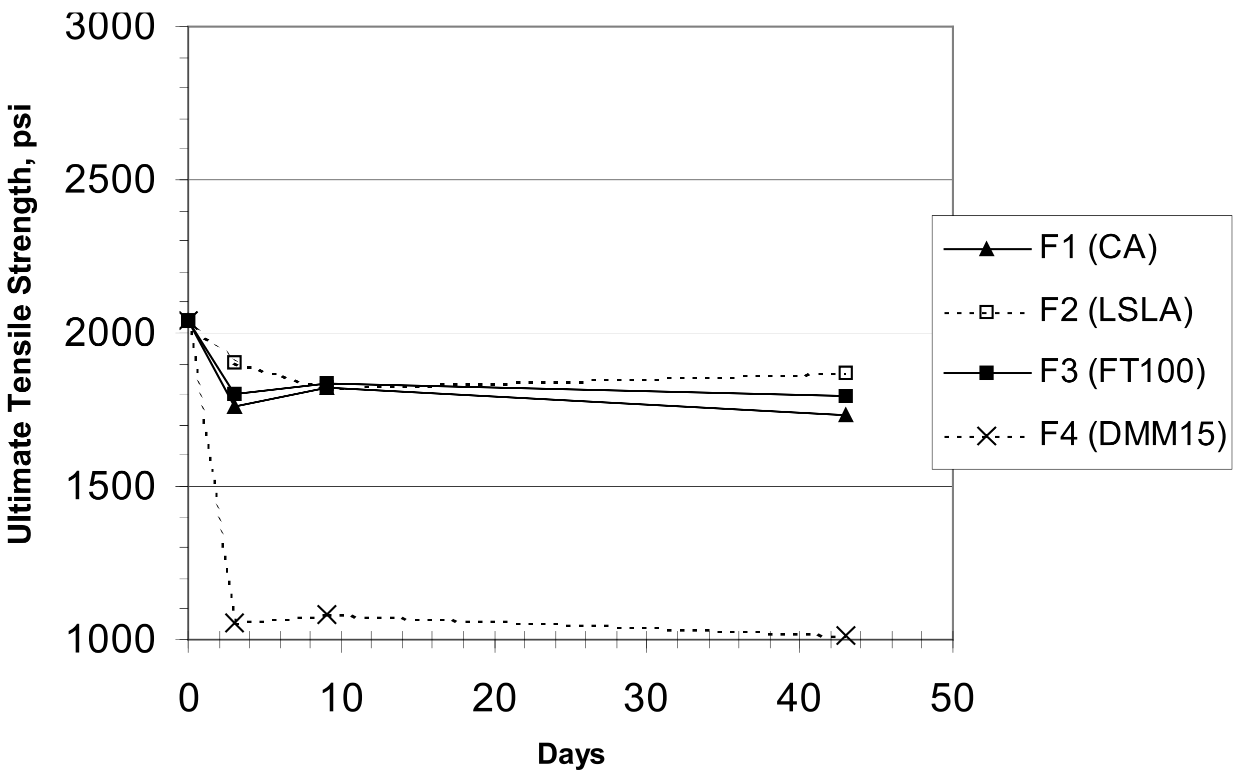


Figure 2-4. Ultimate Tensile Strength, PSI, Sx4 (V747)

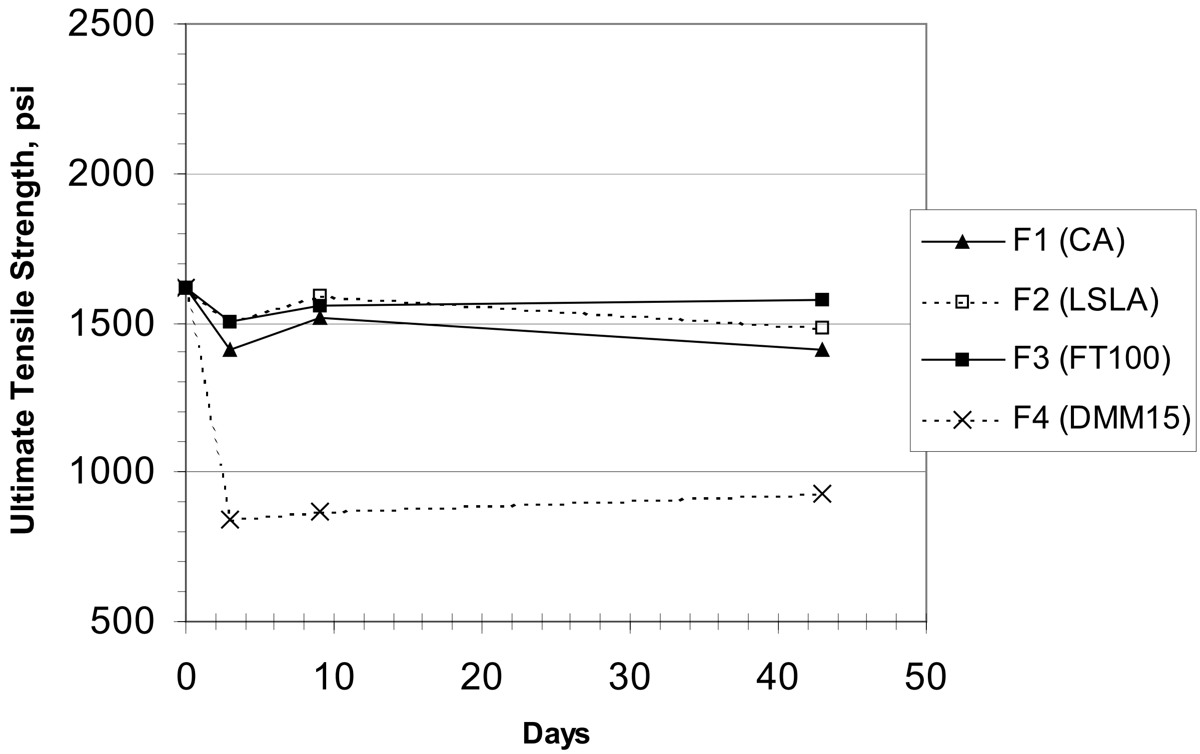


Figure 2-5. Ultimate Tensile Strength, PSI, Sx5 (V884)

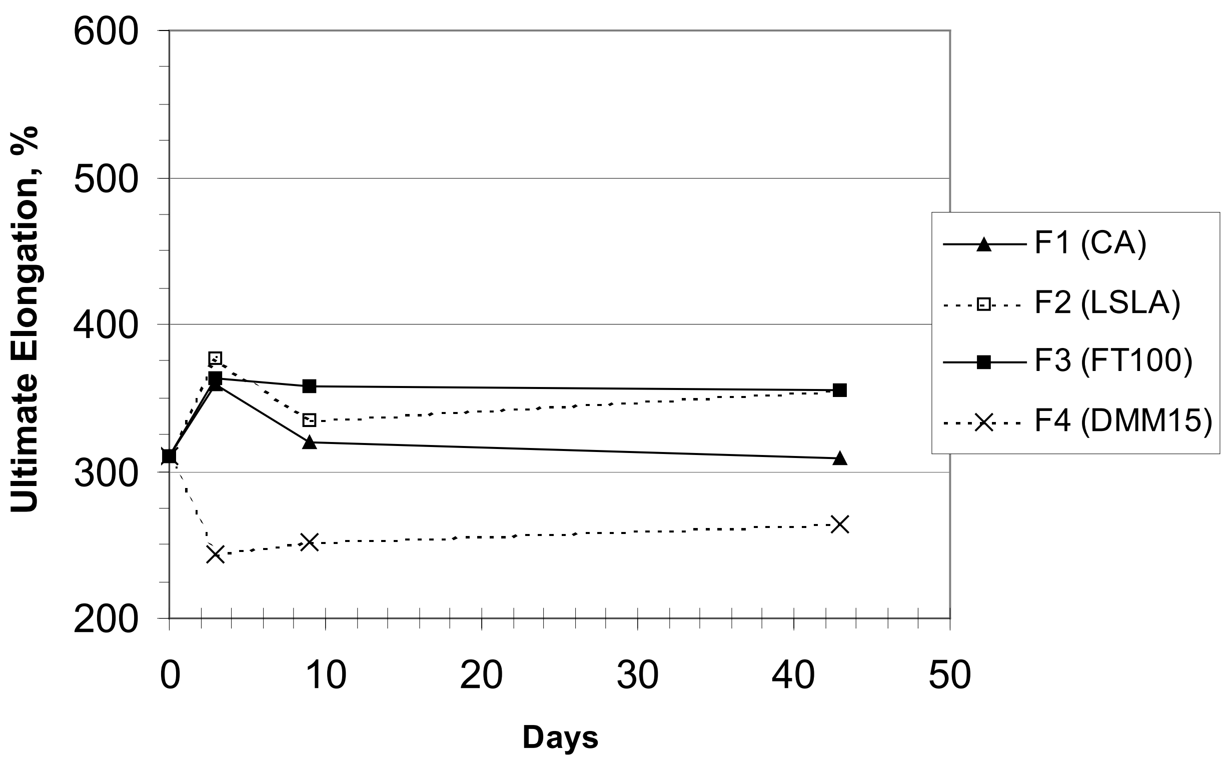


Figure 2-6. Ultimate Elongation, %, Sx1 (N674)

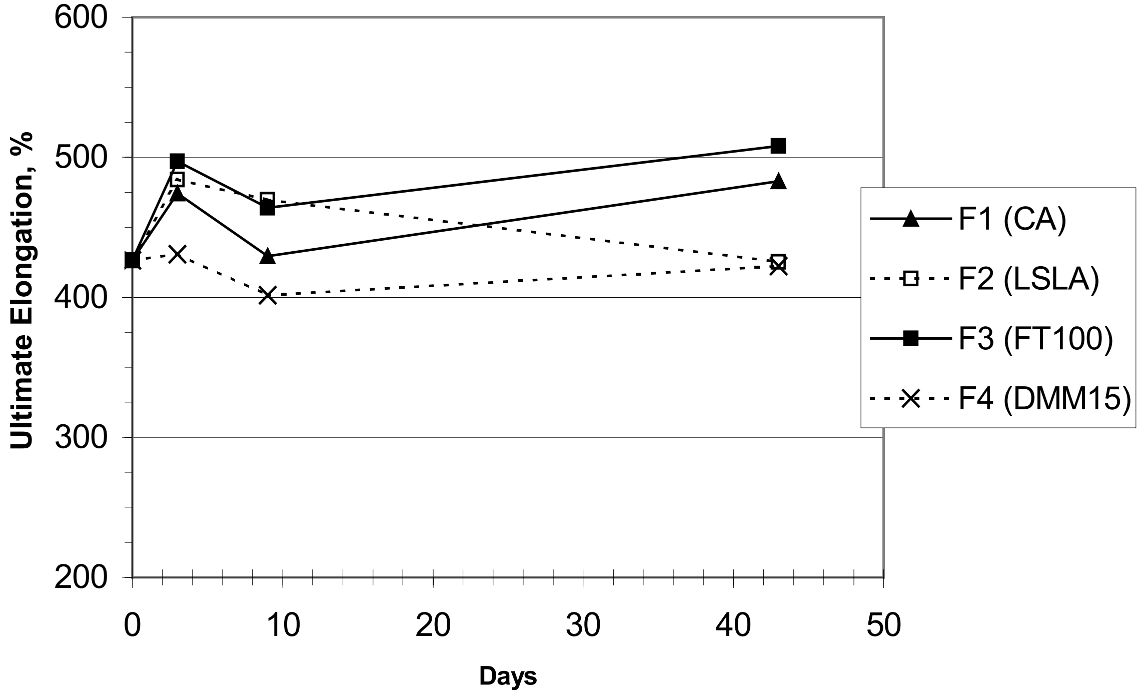


Figure 2-7. Ultimate elongation, %, Sx2 (N497)

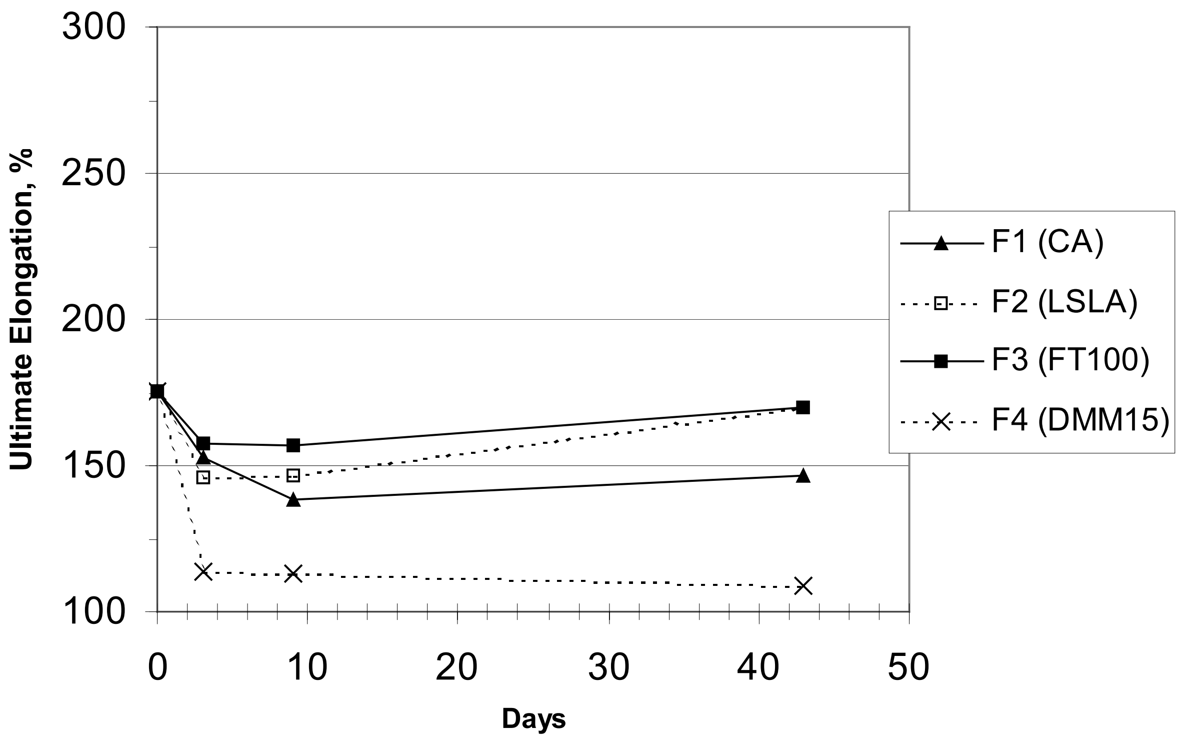


Figure 2-8. Ultimate Elongation, %, Sx3 (N741)

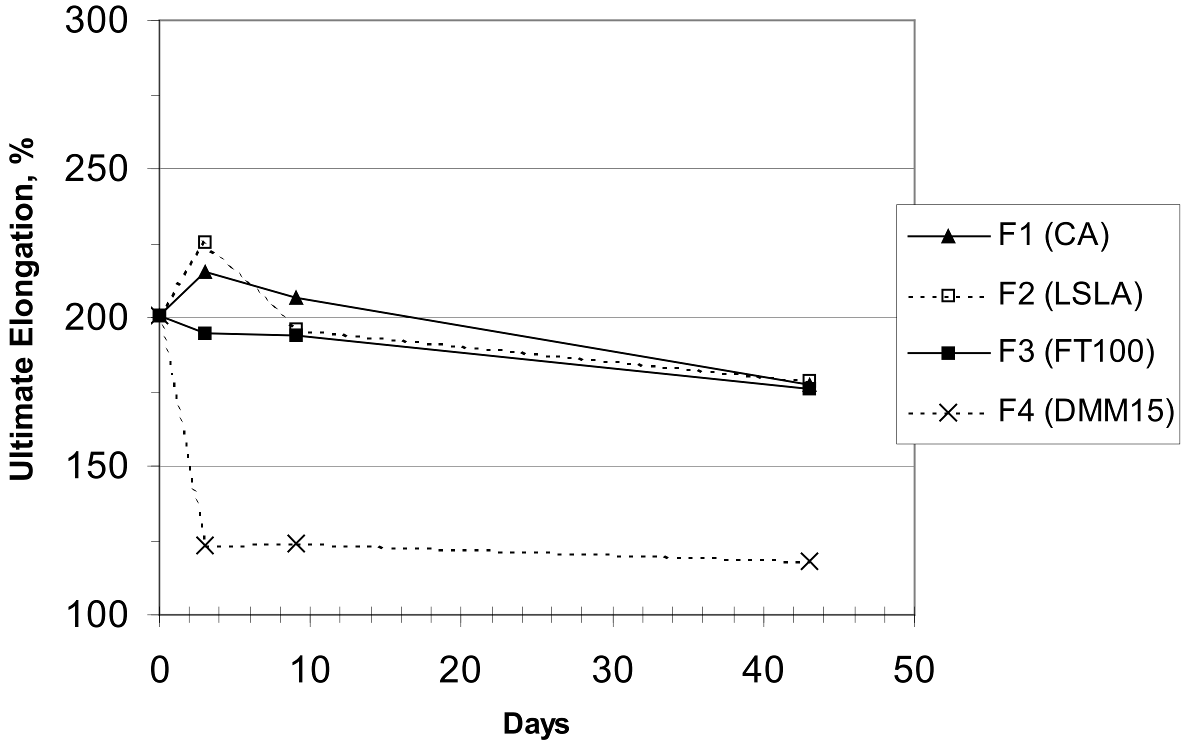


Figure 2-9. Ultimate Elongation, %, Sx4 (V747)

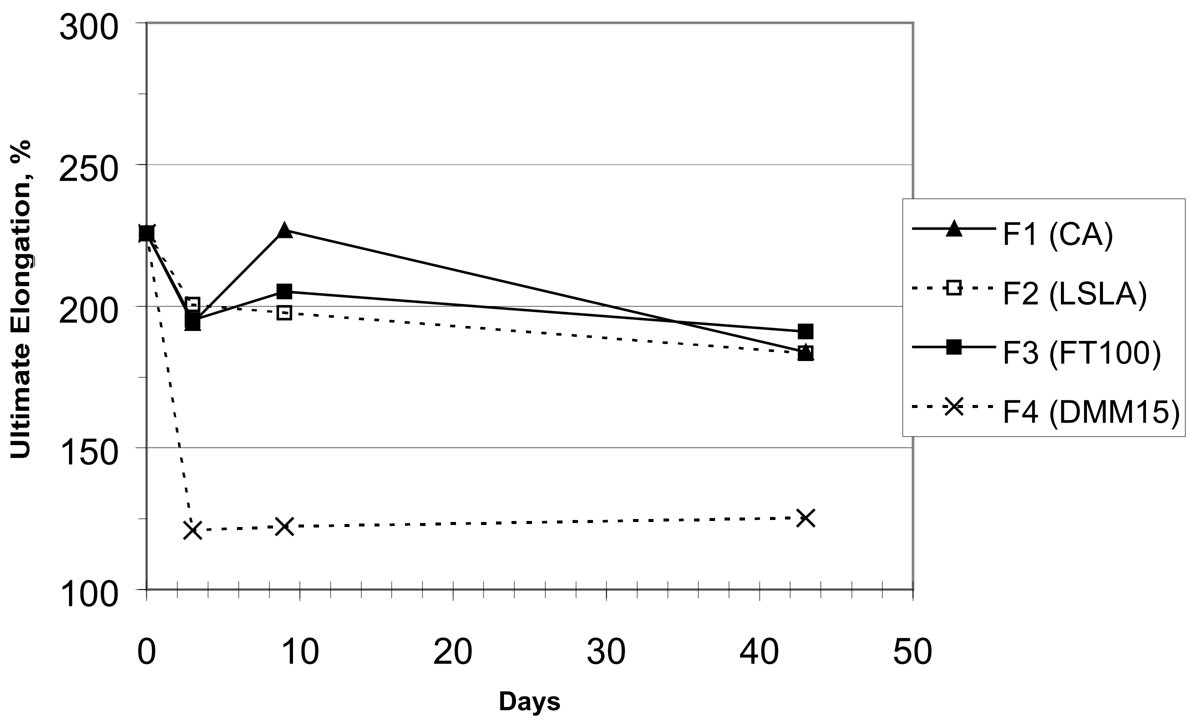


Figure 2-10. Ultimate Elongation, %, Sx5 (V884)

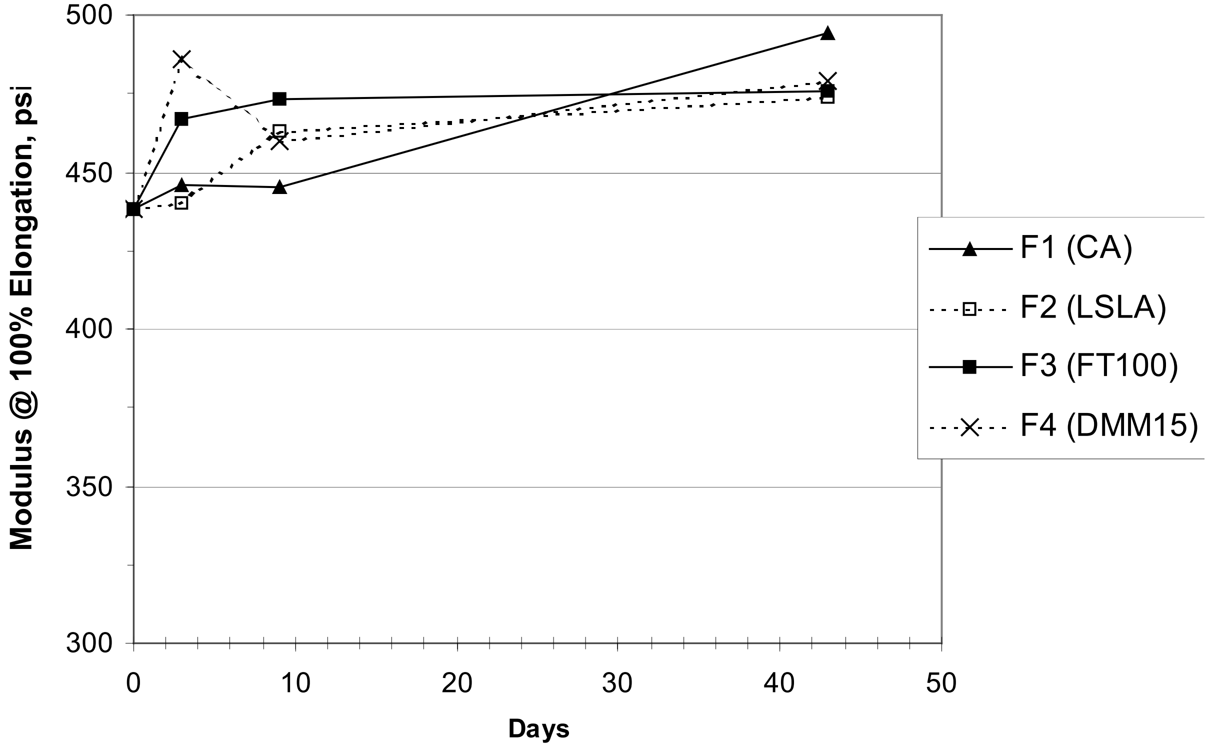


Figure 2-11. Modulus @100% Elongation, PSI, Sx1 (N674)

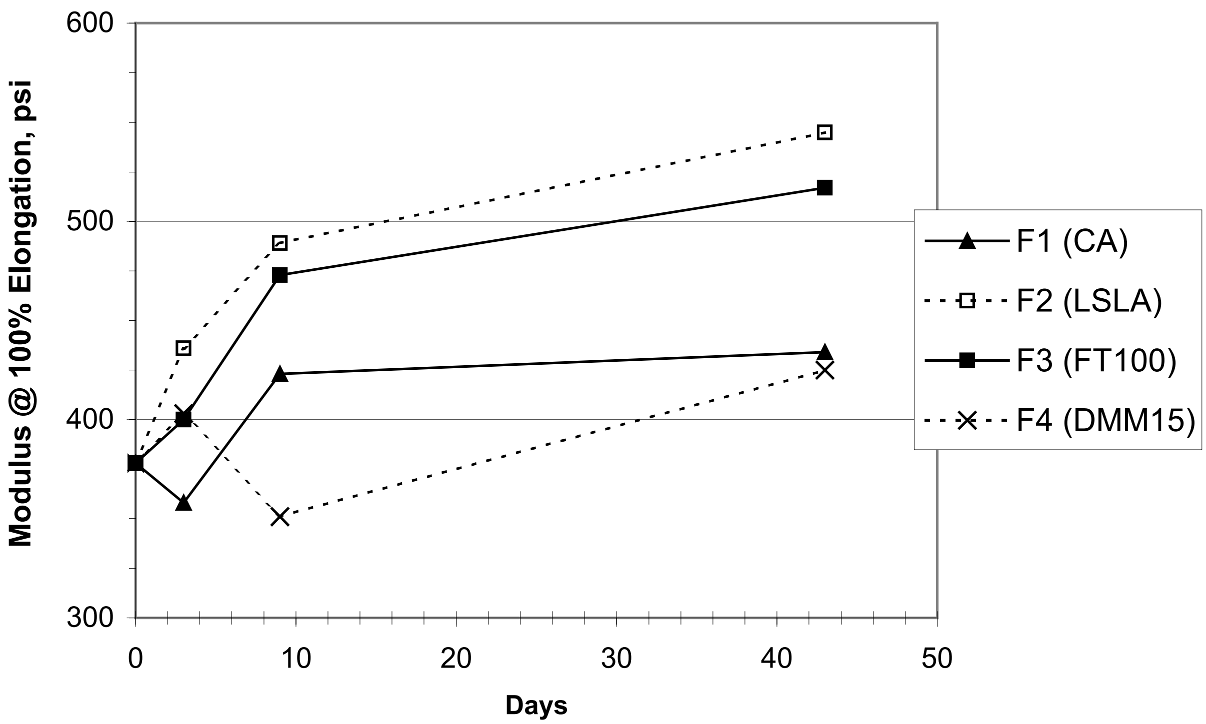


Figure 2-12. Modulus @100% Elongation, PSI, Sx2 (N497)

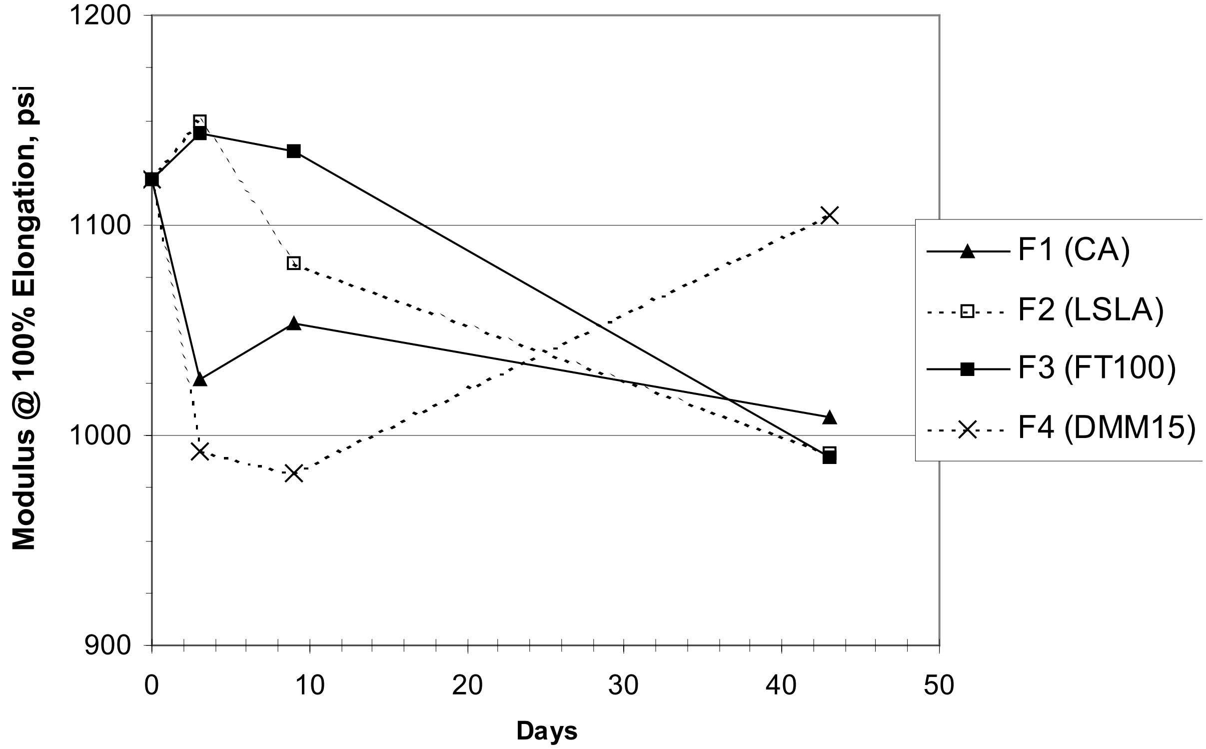


Figure 2-13. Modulus @100% Elongation, PSI, Sx3 (N741)

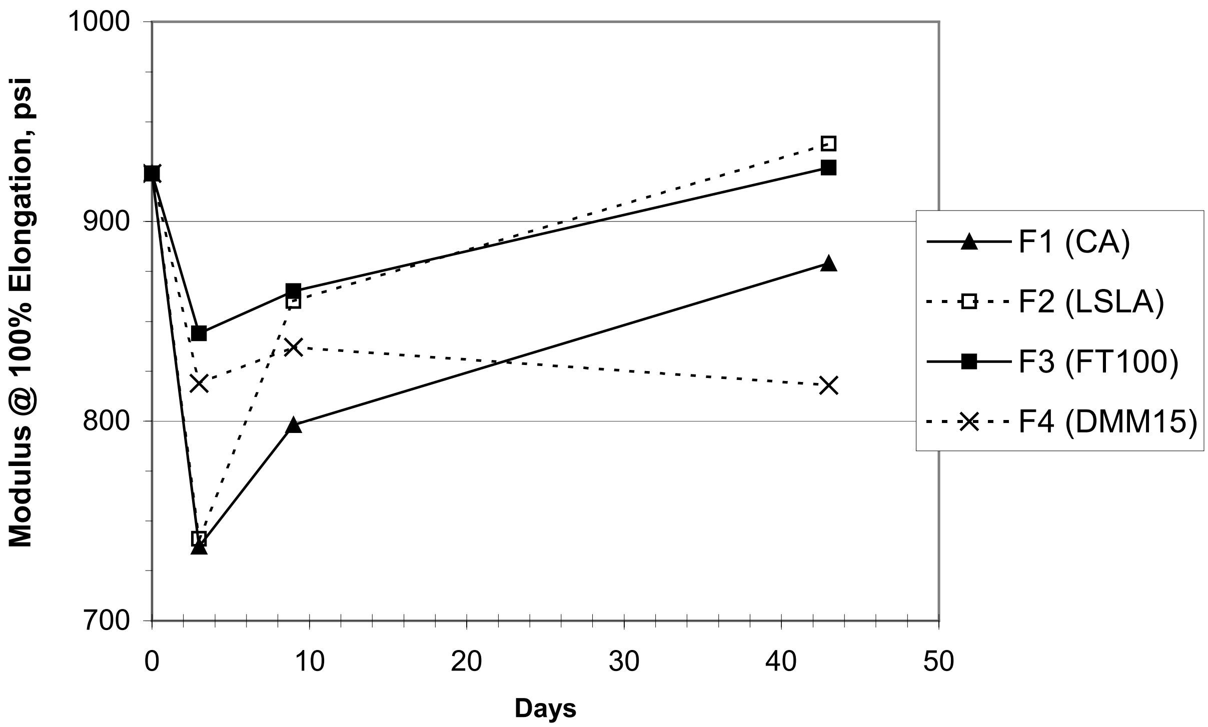


Figure 2-14. Modulus @100% Elongation, PSI, Sx4 (V747)

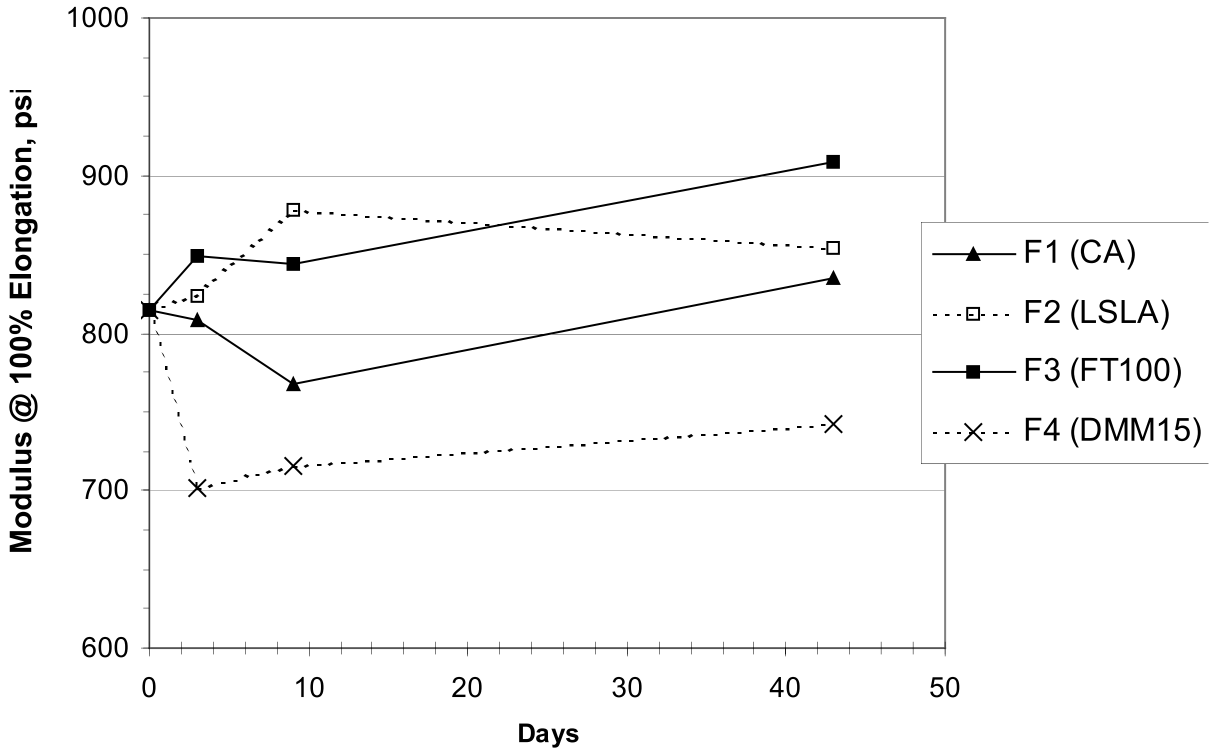


Figure 2-15. Modulus @100% Elongation, PSI, Sx5 (V884)

Table 2-2. ASTM D412 Tension Data						
Fuel	**Storage Time, Hrs**	**Ultimate Tensile Strength, Psi**				
		Sx1 (N674)	**Sx2 (N497)**	**Sx3 (N741)**	**Sx4 (V747**	**Sx5 (V884)**
Air	Baseline	2551	1703	2398	2040	1617
F1 (CA)	72	2285	1661	1829	1762	1409
F1 (CA)	216	2078	1716	1716	1825	1514
F1 (CA)	1024	2197	1751	1704	1735	1410
F2 (LSLA)	72	2350	1724	2086	1902	1506
F2 (LSLA)	216	2282	1794	2018	1820	1590
F2 (LSLA)	1024	2359	1831	2043	1871	1484
F3 (FT100)	72	2373	1714	2278	1798	1504
F3 (FT100)	216	2434	1744	2298	1838	1556
F3 (FT100)	1024	2381	1858	2101	1797	1580
F4 (DMM15)	72	1648	1632	1099	1055	842
F4 (DMM15)	216	1699	1655	1152	1079	867
F4 (DMM15)	1024	1733	1653	1271	1015	928
		Ultimate Elongation, %				
Air	Baseline	309.6	426.4	175.1	200.7	225.7
F1 (CA)	72	359.1	474.1	152.7	215.6	194.1
F1 (CA)	216	319.7	429.4	138.4	206.7	226.9
F1 (CA)	1024	309.1	483.0	146.3	177.6	183.8
F2 (LSLA)	72	376.8	484.0	146.2	225.3	200.6
F2 (LSLA)	216	334.2	469.7	146.5	195.8	197.7
F2 (LSLA)	1024	354.9	425.2	170.0	178.6	183.3
F3 (FT100)	72	363.8	497.0	157.2	194.7	195.1
F3 (FT100)	216	358.2	464.0	156.8	194.0	205.2
F3 (FT100)	1024	355.6	508.0	170.2	175.8	191.0
F4 (DMM15)	72	244.2	430.7	113.4	123.1	120.9
F4 (DMM15)	216	251.4	401.2	112.7	123.9	122.3
F4 (DMM15)	1024	264.6	422.2	109.2	117.7	125.3
		Modulus @ 100% Elongation, PSI				
Air	Baseline	438	378	1122	924	814
F1 (CA)	72	446	358	1027	737	808
F1 (CA)	216	445	423	1053	798	767
F1 (CA)	1024	494	434	1009	879	835
F2 (LSLA)	72	440	436	1150	741	824
F2 (LSLA)	216	463	489	1082	860	878
F2 (LSLA)	1024	474	545	991	939	854
F3 (FT100)	72	467	400	1144	844	849
F3 (FT100)	216	473	473	1135	865	844
F3 (FT100)	1024	476	517	990	927	909
F4 (DMM15)	72	486	403	992	819	701
F4 (DMM15)	216	460	351	982	837	716
F4 (DMM15)	1024	479	425	1105	818	742

Table 2-3. ASTM D412 Tension Data % Change											
		Sx1 (N674)		Sx2 (N497)		Sx3 (N741)		Sx4 (V747)		Sx5 (V884)	
Fuel	Storage Hours	% Change	% ST. DV.	%Change	% ST. DV.	% Change	%ST.DV.	% Change	%ST. DV.	% Change	%ST. DV.
TENSILE STRENGTH, PSI											
AIR	BASELINE		6.3		3.8		2.7		7.2		4.9
FI (CA)	72	-10 4	6.2	-0.4	2.6	-23.7	15.6	-13.6	15.9	-12.9	8.2
FI (CA)	216	-18.5	8.1	+0.8	9.0	-28.4	8.2	-10.5	9.9	-6.4	1.8
F1 (CA)	1024	-13.9	1.3	+2.8	1.3	-29.0	6.1	-14.9	16.2	-12.8	6.9
F2 (LSLA)	72	-7.9	5.8	+1.2	3.0	-13.0	20.8	-6.8	6.9	-6.9	8.5
F2 (LSLA)	216	-10.5	6.8	+5.3	2.9	-15.8	8.3	-10.8	6.8	-1.7	4.5
F2 (LSLA)	1024	-7.5	5.0	+7.5	4.5	-14.8	8.6	-8.3	4.0	-8.2	3.6
F3 (FT100)	72	-7.0	4.8	+0.6	4.0	-5.0	7.9	-11.9	3.8	-7.0	6.4
F3 (FT100)	216	-4.5	6.0	+2.4	3.8	-4.2	4.4	-9.9	18.4	-3.8	1.5
F3 (FT100)	1024	-6.7	4.3	+9.0	1.7	-12.0	14.0	-11.9	7.1	-2.3	5.6
F4 (DMM15)	72	-35.4	6.5	-4.1	4.4	-54.2	11.4	-48.3	3.5	-47.9	2.5
F4 (DMM15)	216	-33.4	3.3	-2.8	2.0	52.0	17.3	-45.6	7.7	-46.4	3.3
F4 (DMM15)	1024	-30.5	6.6	-2.9	4.8	-47.0	18.5	-50.2	5.2	-42.6	4.8
ULTIMATE ELONGATION, %											
FUEL	BASELINE		3.7		16.6		5.8		10.2		3.4
FI (CA)	72	+16.0	4.9	+11.1	5.9	-12.8	12.7	+7.4	10.8	-14.0	9.3
FI (CA)	216	+3.3	4.6	+0.7	20.1	-20.9	7.4	+3.0	10.3	+0.5	4.5
FI (CA)	1024	-0.2	6.5	+13.3	6.4	-16.4	8.3	-11.5	11.5	-18.5	2.1
F2 (LSLA)	72	+21.7	5.6	+13.5	4.5	-16.5	7.0	+12.3	5.1	-11.1	10.2
F2 (LSLA	216	+7.9	4.4	+10.1	14.5	-16.3	5.0	-2.4	7.8	-12.4	5.4
F2 (LSLA)	1024	+14.6	3.2	+0.3	13.9	-2.9	9.1	-11.0	8.8	-14.1	3.4
F3 (FT100)	72	+18.1	4.0	+16.7	12.6	-10.2	2.9	-3.0	8.6	-13.6	10.8
F3 (FT100)	216	+15.7	5.3	+8.8	2.5	-10.4	3.6	-3.3	10.2	-9.1	9.1
F3 (FT100)	1024	+14.9	3.5	+19.1	2.2	-2.8	12.3	-12.4	4.8	-15.4	6.6
F4 (DMM15)	72	-21.1	7.7	+1.0	6.7	-35.2	9.6	-38.7	4.5	-46.4	2.0
F4 (DMMI5)	216	-18.7	4.2	-5.9	5.8	-35.6	7.5	-38.3	8.1	-45.8	4.8
F4 (DMM15)	1024	-14.5	2.8	-1.0	15.0	-37.6	11.0	-41.3	4.8	-44.5	3.3

Table 2-3. ASTM D412 Tension Data % Change											
		Sx1 (N674)		Sx2 (N497)		Sx3 (N741)		Sx4 (V747)		Sx5 (V884)	
Fuel	Storage Hours	% Change	% ST. DV.	%Change	% ST. DV.	% Change	%ST.DV.	% Change	%ST. DV.	% Change	%ST. DV.
MODULUS @ 100% ELONGATION, PSI											
FUEL	BASELINE		9.1		1.3		14.3		5.0		12.4
FI (CA)	72	+1.8	5.6	-5.3	4.7	-8.5	12.1	-20.2	7.9	-0.7	9.3
FI (CA)	216	1.6	7.4	+11.9	13.9	-6.5	4.6	-13.6	10.4	-5.8	5.1
FI (CA)	1024	+12.8	10.8	+14.8	12.0	-10.1	7.6	-4.8	7.4	+2.6	8.0
F2 (LSLA)	72	+0.5	5.9	+15.3	9.6	+2.5	31.0	-19.8	6.9	+1.2	3.9
F2 (LSLA	216	+5.7	5.6	+29.4	17.87	-3.6	6.2	-6.9	9.3	+7.9	6.1
F2 (LSLA)	1024	+8.2	3.8	+44.2	17.6	-11.7	9.4	+1.6	6.9	+4.9	3.6
F3 (FT100)	72	+6.6	7.7	+5.8	17.5	+2.0	13.1	-8.7	8.6	+4.3	10.0
F3 (FT100)	216	+8.0	5.5	+25.1	15.2	+1.2	5.5	-6.4	14.4	+3.7	6.9
F3 (FT100)	1024	+8.7	3.8	+36.8	6.0	-11.8	7.2	+0.3	9.7	+11.7	3.3
F4 (DMM15)	72	+11.0	2.1	+6.6	13.1	-11.6	7.4	-11.4	4.1	-13.9	1.7
F4 (DMMI5)	216	+5.0	5.4	-7.1	9.4	-12.5	11.6	-9.4	3.6	-12.0	2.8
F4 (DMM15)	1024	+9.4	7.1	+12.4	16.5	-1.5	11.2	-11.5	3.2	-8.8	4.6

1. Ultimate Tensile Strength, PSI

Material 1 (N674) decreased in all four fuels, with only a slight decrease for fuels CA, LSLA and FT100 while DMM15 had a substantial decrease of between 25 to 30%.

Material 2 (N497) had a slight increase with LSLA and FT100 while CA and DMM15 remained the same.

Material 3 (N741) decreased in all four fuels but LSLA and FT100 had only a slight decrease while CA decreased approximately 10 to 15% and DMM15 had a substantial decrease of approximately 30 to 40%.

Material 4 (V747) had a slight decrease with CA, LSLA and FT100 while DMM15 had a substantial decrease of between 40 to 45%.

Material 5 (V884) had a slight decrease in the decreasing order of FT100, LSLA, and CA while DMM15 had a substantial decrease of between 38 to 45%.

Fuel 4 (DMM15) had a substantial effect on Materials 1, 3, 4 and 5 but had no real effect on Material 2. The largest tensile effect took place during the first 72 hours of storage.

2. Ultimate Elongation, %

Material 1 (N674) had no real change with CA and had only a slight increase of 4-17% with LSLA, FT100 and DMM15.

Material 2 (N497) had a slight increase with CA and FT100 of 5-17% while LSLA and DMM15 remained essentially the same.

Material 3 (N741) had slight decreases of approximately 7-13% with CA, while it had a substantial decrease of 26 to 28% with DMM15.

Material 4 (V747) had a substantial decrease of 30 to 37% with DMM15.

Material 5 (V884) had a slight effect of approximately 9 to 16% decrease with CA, LSLA and FT100 while DMM15 had a substantial effect of 40 to 44% decrease.

Fuel 4 (DMM15) had a substantial effect on ultimate elongation of N741 and V747 and had a slight effect on N647 and no effect on N497.

3. Modulus @ 100% Elongation, PSI

When the modulus goes up the material gets more brittle.

Material 1 (N674) all fuels had only a slight increase.

Material 2 (N497) had only a slight increase with fuels CA and DMM15 but it had a substantial increase for LSLA and FT100 with a change of 27-30% at 1024 hours.

Material 3 (N741) there appears to be only a slight decrease with all four fuels.

Material 4 (V747) all four fuels had a decrease at 72 hours but CA, LSLA and FT100 increased until they were back at the starting point. Only DMM15 showed a slight decrease of 6 to 8%.

Material 5 (V884) had an 8% increase with FT100 and a slight increase with CA and LSLA, and a 5 to 12% decrease with DMM15.

Only **LSLA and FT100** had a substantial effect on Material 2 at the 1024-hour (43-day) period. The rest of the materials did not appear to be substantially affected with the four fuels.

B. Durometer Hardness Results

The durometer data are presented in Table 2-4 and in Figures 2-16 through 2-20.

Table 2-4. Durometer Hardness Data					
DUROMETER HARDNESS, PTS.					
	STORAGE	Sx1 (N674)			
FUEL CODE	TIME, HRS.	PRE-	POST-	CHANGE	% CHANGE
F1 (CA)	72	67.5	61.5	-6.0	8.8
F1 (CA)	216	65.0	60.0	-5.0	7.7
F1 (CA)	1024	66.5	56.2	-10.3	15.4
F2 (LSLA)	72	63.0	62.0	-1.0	1.6
F2 (LSLA)	216	63.0	61.0	-2.0	3.2
F2 (LSLA)	1024	65.0	60.8	-4.2	6.5
F3 (FT100)	72	67.0	65.5	-1.5	2.2
F3 (FT100)	216	67.0	66.0	-1.0	1.5
F3 (FT100)	1024	65.0	62.5	-2.5	3.8
F4 (DMM15)	72	63.0	54.0	-9.0	14.3
F4 (DMM15)	216	67.0	54.5	-12.5	18.6
F4 (DMM15)	1024	64.0	55.2	-8.8	13.7
		Sx2 (N497)			
F1 (CA)	72	66.0	67.0	+1.0	1.5
F1 (CA)	216	67.5	70.0	+2.5	3.7
F1 (CA)	1024	67.5	70.3	+2.8	4.1
F2 (LSLA)	72	69.5	70.0	+0.5	0.7
F2 (LSLA)	216	69.5	73.0	+3.5	5.0
F2 (LSLA)	1024	66.5	74.5	+8.0	12.0
F3 (FT100)	72	70.0	72.0	+2.0	2.9
F3 (FT100)	216	67.0	72.0	+5.0	7.5
F3 (FT100)	1024	65.0	75.8	+10.8	16.6
F4 (DMM15)	72	69.5	61.5	-8.0	11.5
F4 (DMM15)	216	69.5	63.0	-6.5	9.3
F4 (DMM15)	1024	69.0	63.0	-6.0	8.7
		Sx3 (N741)			
F1 (CA)	72	73.5	69.5	-4.0	5.4
F1 (CA)	216	72.0	69.0	-3.0	4.2
F1 (CA)	1024	72.5	67.3	-5.2	7.2
F2 (LSLA)	72	73.0	72.0	-1.0	1.4
F2 (LSLA)	216	73.5	71.3	-2.2	3.0
F2 (LSLA)	1024	71.5	69.7	-1.8	2.5
F3 (FT100)	72	74.5	74.5	0.0	0
F3 (FT100)	216	74.0	71.6	-2.4	3.2
F3 (FT100)	1024	72.0	70.8	-1.2	1.7

Table 2-4. Durometer Hardness Data					
DUROMETER HARDNESS, PTS.					
	STORAGE	Sx1 (N674)			
FUEL CODE	TIME, HRS.	PRE-	POST-	CHANGE	% CHANGE
F4 (DMM15)	72	71.0	65.0	-6.0	8.4
F4 (DMM15)	216	74.5	66.7	-7.8	10.5
F4 (DMM15)	1024	72.0	66.5	-5.5	7.6
		Sx4 (V747)			
F1 (CA)	72	73.0	73.0	0.0	0
F1 (CA)	216	74.0	74.3	+0.3	0.4
F1 (CA)	1024	74.7	74.5	-0.2	0.3
F2 (LSLA)	72	74.7	74.2	-0.5	0.7
F2 (LSLA)	216	74.7	75.0	+0.3	0.4
F2 (LSLA)	1024	74.5	74.2	-0.3	0.4
F3 (FT100)	72	74.3	73.2	-1.1	1.5
F3 (FT100)	216	72.0	72.0	0.0	0.0
F3 (FT100)	1024	74.0	74.3	+0.3	0.4
F4 (DMM15)	72	74.5	64.0	-10.5	14.1
F4 (DMM15)	216	74.3	64.2	-10.1	14.1
F4 (DMM15)	1024	71.8	65.3	-6.5	9.0
		Sx5 (V884)			
F1 (CA)	72	72.0	71.7	-0.3	0.4
F1 (CA)	216	74.0	72.8	-1.2	1.6
F1 (CA)	1024	74.5	73.0	-1.5	2.0
F2 (LSLA)	72	74.0	73.6	-0.4	0.5
F2 (LSLA)	216	73.0	72.3	-0.7	1.0
F2 (LSLA)	1024	73.8	72.5	-1.3	1.8
F3 (FT100)	72	72.5	71.3	-1.2	1.6
F3 (FT100)	216	74.0	73.6	-0.4	0.5
F3 (FT100)	1024	74.2	72.7	-1.5	2.2
F4 (DMM15)	72	74.0	61.3	-12.7	17.1
F4 (DMM15)	216	71.2	60.0	-11.2	15.7
F4 (DMM15)	1024	74.0	62.5	-11.5	15.5
*The durometer has repeatability ± of two durometer points					

.

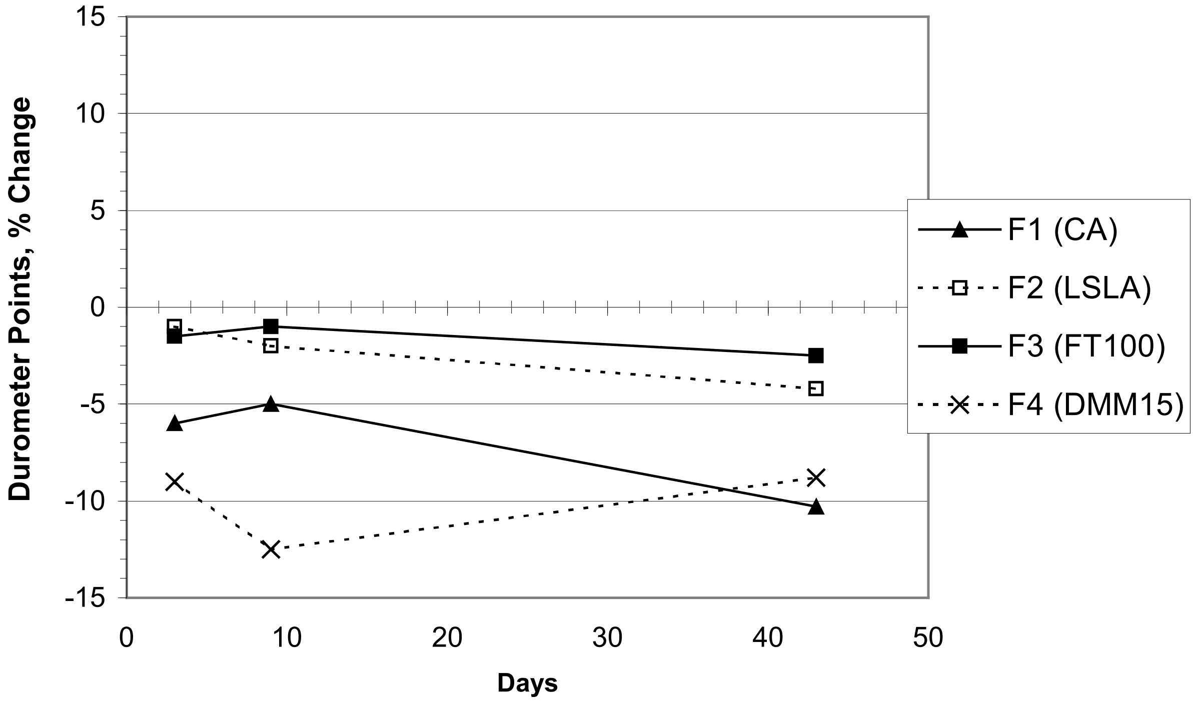


Figure 2-16. Durometer Points, Change, Sx1 (N674)

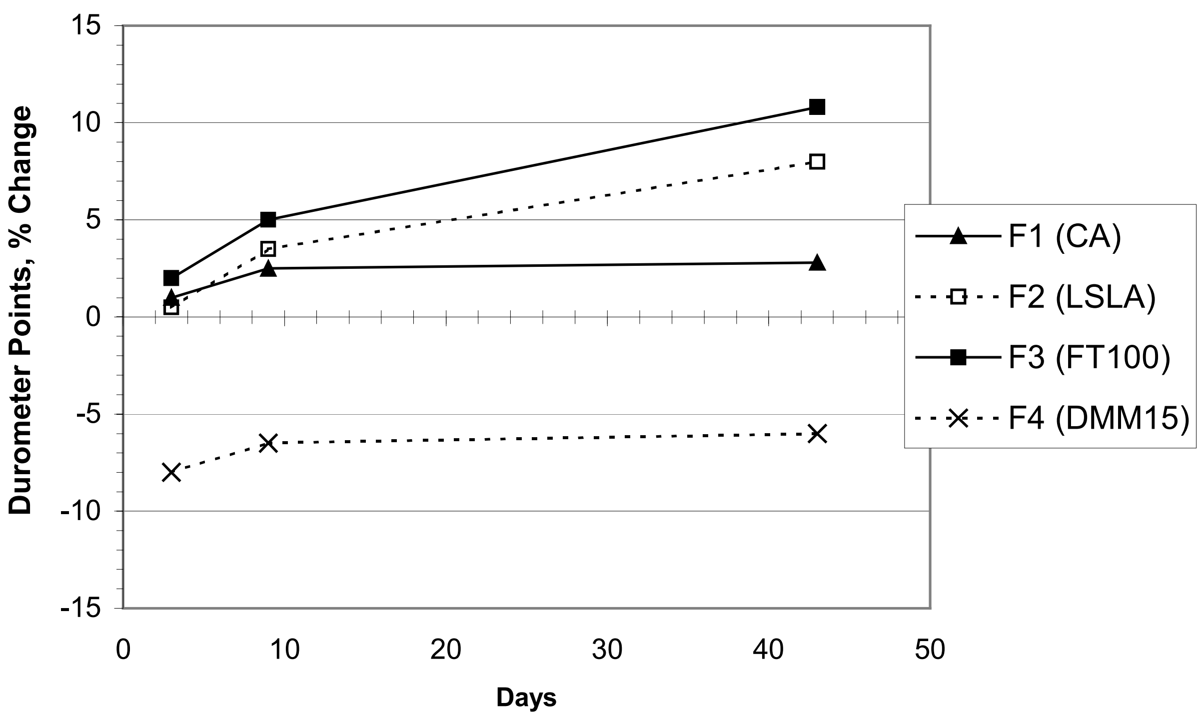


Figure 2-17. Durometer Points, Change, Sx2 (N497)

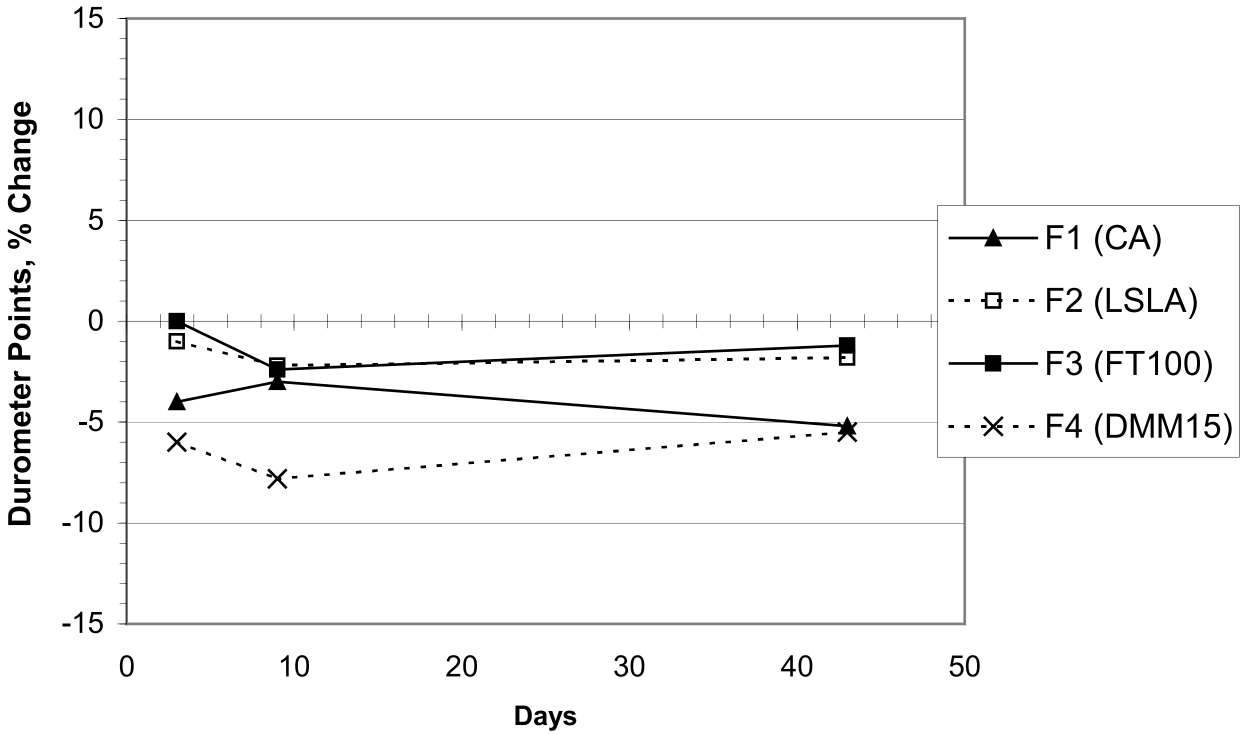


Figure 2-18. Durometer Points, Change, Sx3 (N741)

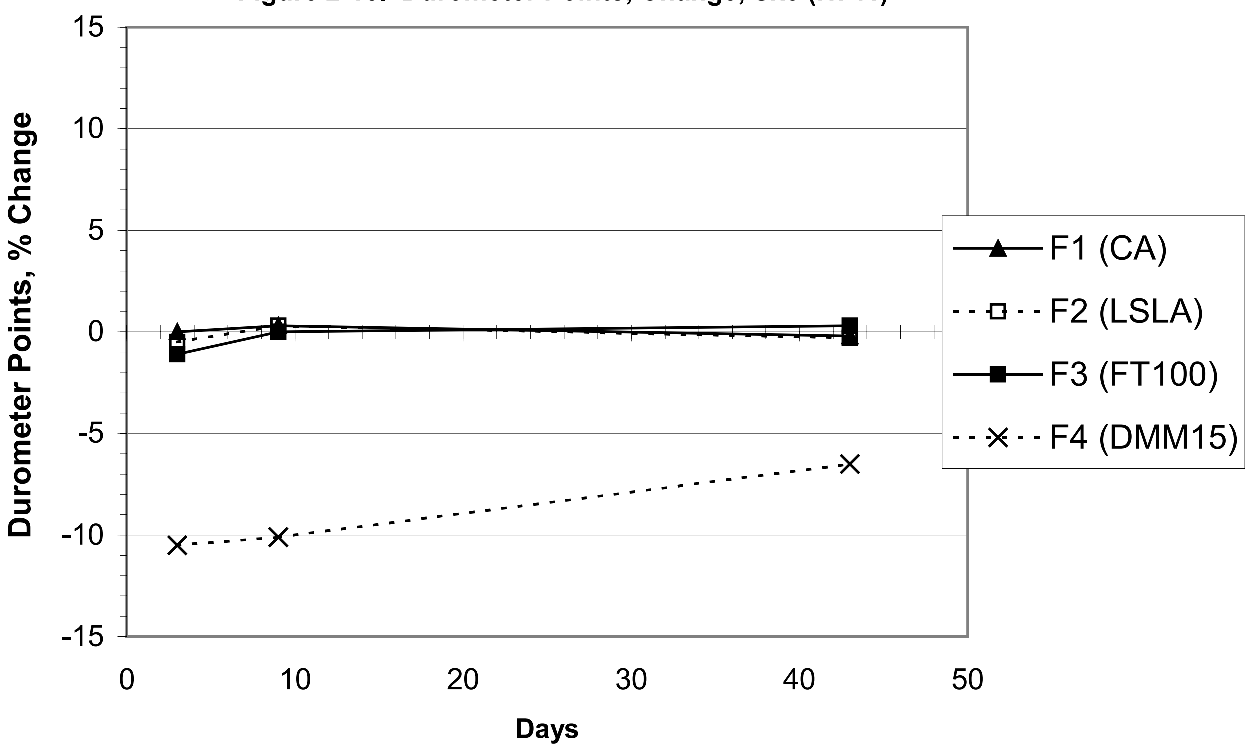


Figure 2-19. Durometer Points, Change, Sx4 (V747)

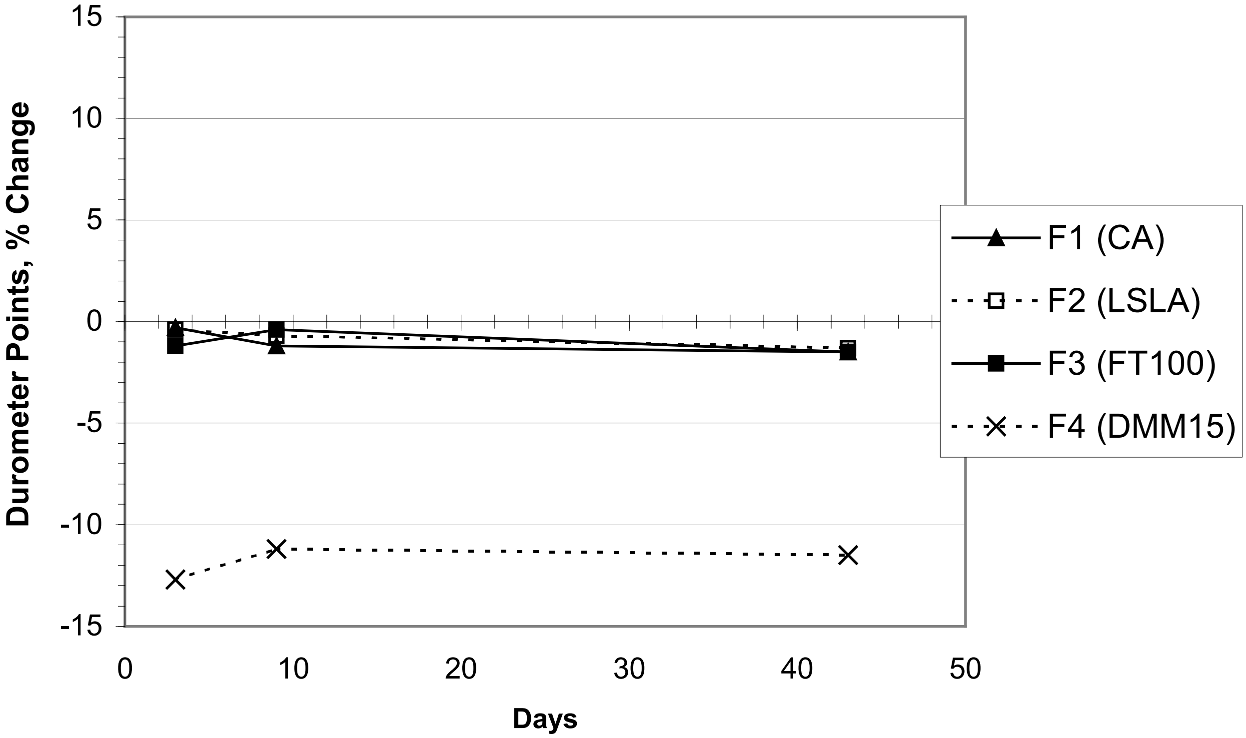


Figure 2-20. Durometer Points, Change, Sx5 (V884)

1. <u>**Durometer Points, % Change**</u>

An increase in durometer points indicates that the material is harder, and a decrease indicates that the material is softer.

Material 1 (N674) had no real effect from LSLA and FT100, but had approximately +14% change with CA and DMM15.

Material 2 (N497) had no real effect from CA, but LSLA and FT100 produced +12 and +16% at 1024 hours (43 days) period and DMM15 produced an average of 10% decrease (softer).

Material 3 (N741) had no real effect from LSLA and FT100, but CA and DMM15 resulted in an average 7% decrease.

Material 4 (V747) had no effect from CA, LSLA and FT100, but DMM15 resulted in an average 12% decrease (softer).

Material 5 (V884) had no effect from CA, LSLA and FT100 but DMM15 produced an average decrease of 16%.

Fuel 4 (DMM15) produced an average decrease effect of 8 to 16% on the five materials; LSLA and FT100 produced an increase of 12 to 16%. On Material NH97; CA produced 14% decrease on N67A.

C. Mass and Volume Results

The percentage change for mass and volume are presented in Figures 2-21 through 2-25 and Table 2-5.

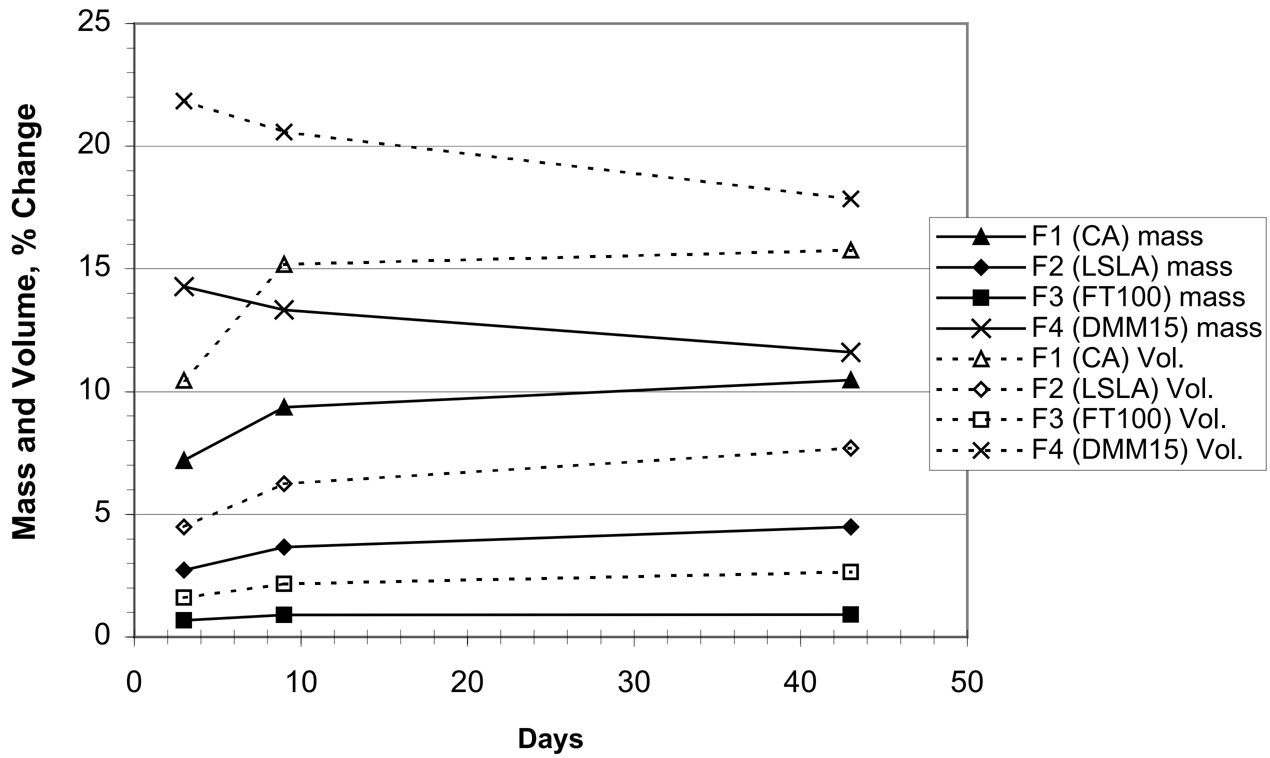


Figure 2-21. Percent Change in Mass and Volume, Sx1 (N674)

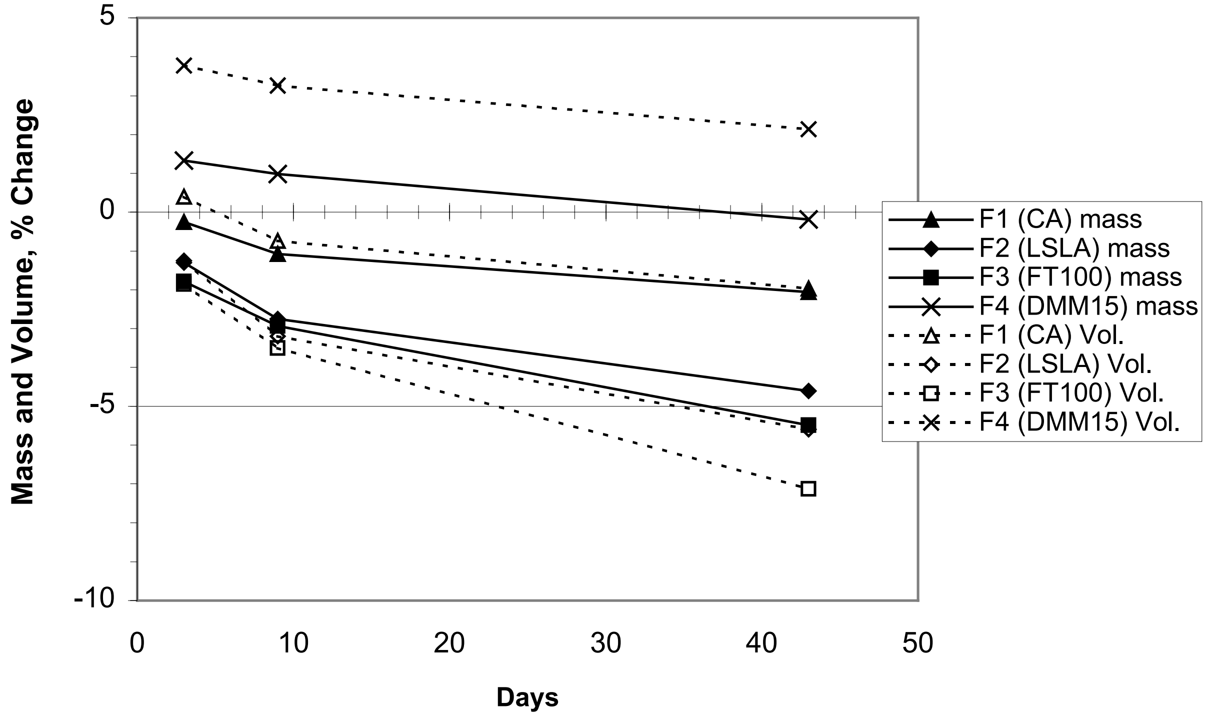


Figure 2-22. Percent Change in Mass and Volume, Sx2 (N497)

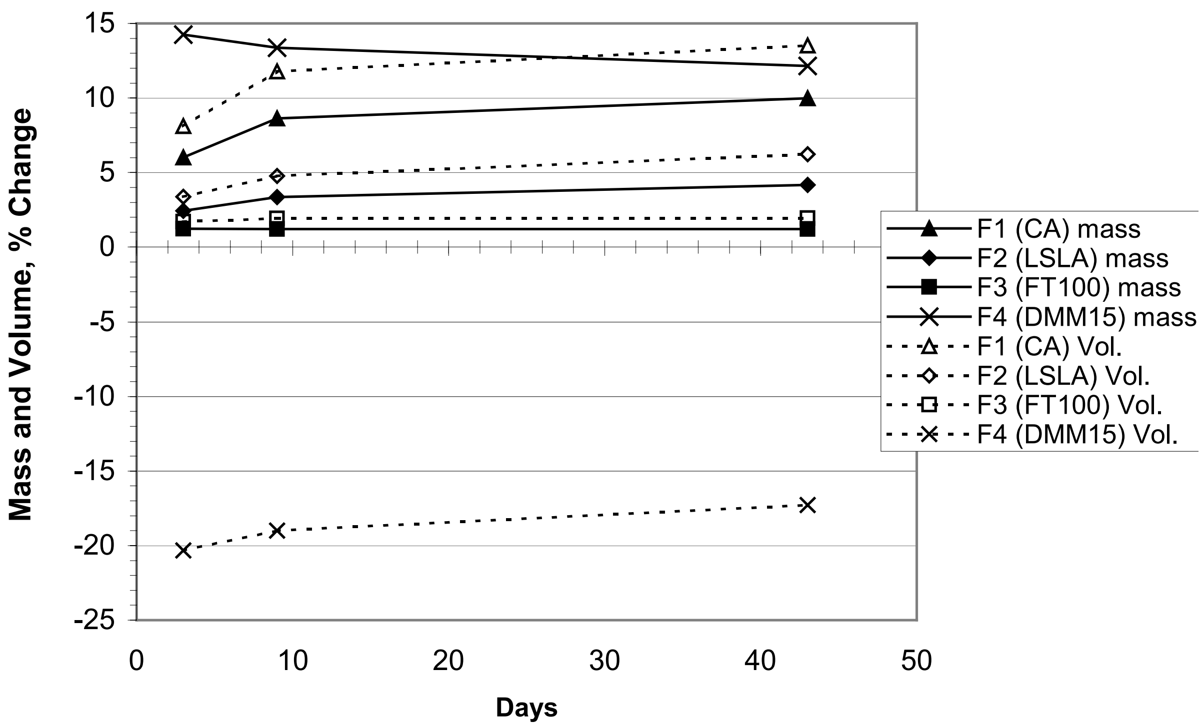


Figure 2-23. Percent Change in Mass and Volume, Sx3 (N741)

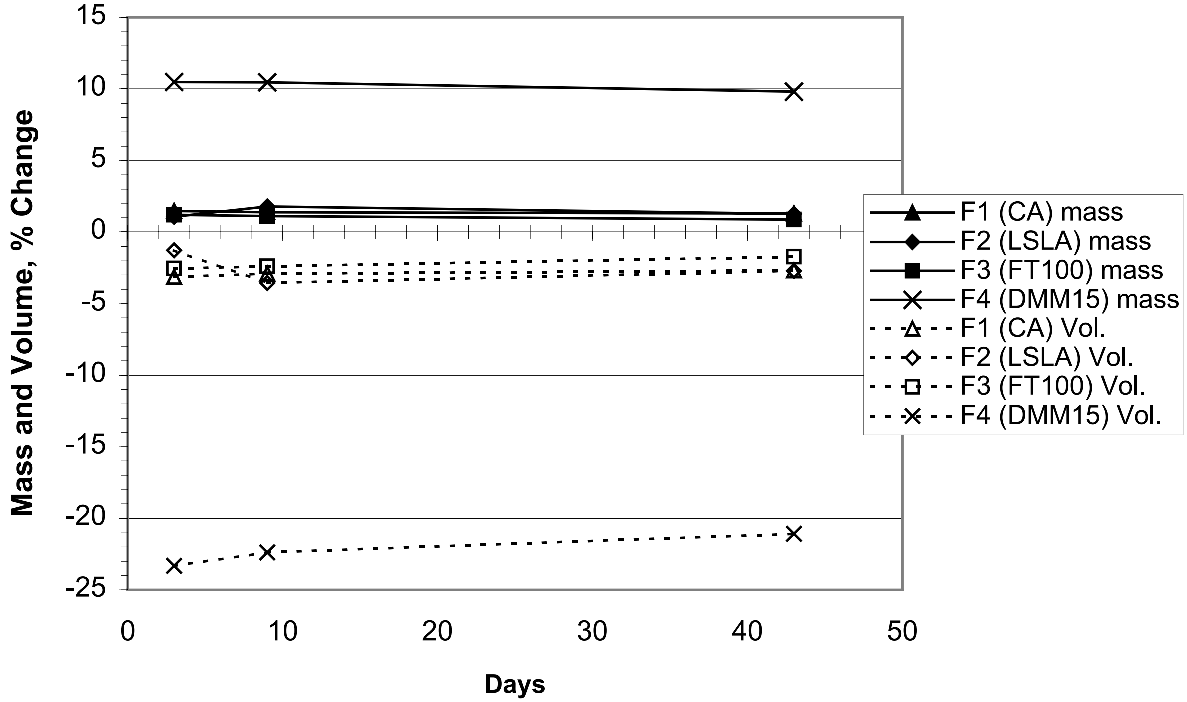


Figure 2-24. Percent Change in Mass and Volume, Sx4 (V747)

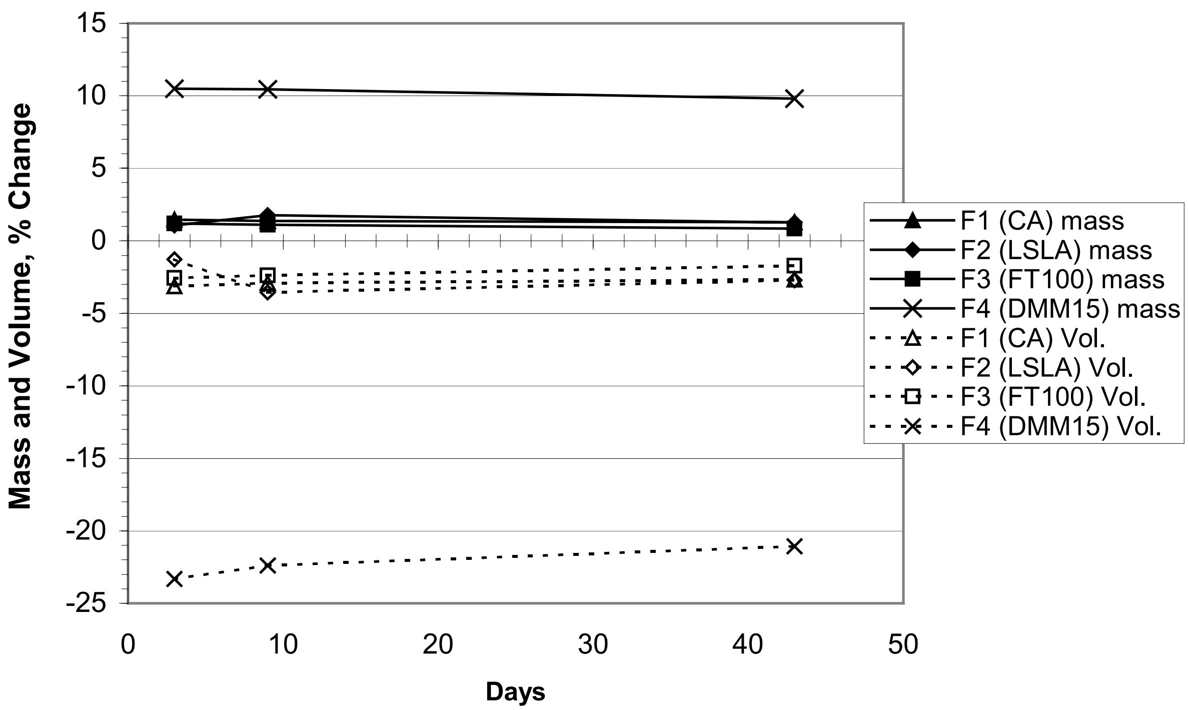


Figure 2-25. Percent Change in Mass and Volume, Sx5 (V884)

Table 2-5. Percent Change in Mass and Volume											
Fuel Code	Storage Time, Hours	Sx1 (N674)		Sx2 (N497)		Sx3 (N741)		Sx4 (V747)		Sx5 (V884)	
		% Mass Change	% Vol. Change	% Mass Change	% Vol. Change	% Mass Change	% Vol. Change	% Mass Change	% Vol. Change	% Mass Change	% Vol. Change
FI (CA)	72	+7.19	+10.46	-0.25	+0.40	+6.01	+8.11	+1.46	-3.14	+1.13	-2.72
FI (CA)	216	+9.36	+15.19	-1.08	-0.74	+8.63	+11.79	+1.37	-2.90	+1.20	-2.87
F1 (CA)	1024	+10.48	+15.76	-2.06	-1.97	+9.99	+13.51	+1.28	-2.67	+1.26	-3.05
F2 (LSLA)	72	+2.73	+4.49	-1.30	-1.25	+2.43	+3.38	+1.06	-1.27	+0.83	-2.03
F2 (LSLA)	216	+3.66	+6.25	-2.75	-3.20	+3.36	+4.77	+1.77	-3.65	+0.83	-2.13
F2 (LSLA)	1024	+4.49	+7.70	-4.61	-5.60	+4.17	+6.22	+1.26	-2.71	+0.96	-2.27
F3 (FT100)	72	+0.68	+1.60	-1.79	-1.85	+1.23	+1.71	+1.20	-2.55	+0.94	-2.28
F3 (FT100)	216	+0.90	+2.17	-2.93	-3.50	+1.20	+1.91	+1.11	-2.38	+0.76	-1.81
F3 (FT100)	1024	+0.92	+2.65	-5.49	-7.13	+1.21	+1.93	+0.85	-1.72	+0.92	-2.23
F4 (DMM15)	72	+14.28	+21.84	+1.33	+3.77	+14.25	-20.33	+10.84	-23.32	+9.61	-23.56
F4 (DMM15)	216	+13.33	+20.58	+0.98	+3.26	+13.37	-18.99	+10.44	-22.38	+8.75	-21.87
F4 (DMM15)	1024	+11.60	+17.85	-0.19	+2.14	+12.15	-17.28	*+9.80*	-21.07	+8.58	-21.27

1. Mass and Volume Change, %

Material 1 (N674) all four fuels caused an increase in both mass and volume, DMM15 produced its highest change at the 72-hour (three-day) period but then decreased for the 216-hour (nine-day) and 1024 hours (43-day) periods. FT100 caused a very slight change in mass and volume; LSLA resulted in a slight increase in mass and volume. DMM15 and CA produced mass changes of 13% and 9%. The volume change produced by DMM15 was +19%; and CA caused a 14% change.

Material 2 (N497) DMM15 and CA produced slight mass and volume changes. DMM15 caused an increase and CA a decrease. LSLA and FT100 caused a volume decrease of 4 to 7%.

Material 3 (N741) all four fuels caused an increase in mass change. FT100 produced a very slight increase, LSLA a 4% increase, CA and DMM15 produced substantial increases of 10 and 12%. FT100 produced a very slight volume increase; LSLA and CA produced 6 and 13% increases, which are substantial. DMM15 caused a substantial volume decrease of 17%. Here we see that DMM15 caused substantial mass increase while causing a substantial decrease in volume.

Material 4 (V747) all four fuels caused an increase in mass change, but CA, LSLA and FT100 produced only a very slight change, while DMM15 caused a substantial increase of 10%.

Also, all four fuels caused a decrease in volume change, again CA, LSLA and FT100 caused a slight change while DMM15 caused a substantial decrease of 22%.

Material 5 (V884) all four fuels caused an increase in mass and a decrease in volume. But CA, LSLA and FT100 resulted in only slight mass increases. DMM15 produced a mass increase of 9% and a volume decrease of 22%.

D. Effect of Fuel on Materials

Fuel 1 (CA) had a slight effect on ultimate tensile strength with N674 and N741 and had a slight durometer effect on N741 (became slightly softer) but had a substantial durometer effect on N674 (became softer). It also had a substantial effect on mass and volume with N674 and N741. Overall, CA appeared to have an effect on N674 and N741.

Fuel 2 (LSLA) had a slight effect on ultimate elongation (resistance to stretching) with N674. It had a substantial effect on N497 with the modulus at 100% elongation (brittle). It had a slight effect on the durometer points (slightly softer) on N674 and a substantial effect on N497; also, it had a slight effect on mass and volume of N674, N497, and N741.

Fuel 3 (FT100) had a slight effect on ultimate elongation with materials N674 and N497. It had a substantial effect on modulus at 100% elongation with N497. FT100 had a substantial effect on the durometer points of N497. There was a slight effect on the mass and volume with N497.

Fuel 4 (DMM15) had a substantial effect on ultimate tensile strength with N674, N741, V747, and V884. It had a light effect with the ultimate elongation on N674, but it had a substantial effect on N741, V747, and V884. It had only a slight effect on V884 modulus at 100% elongation. DMM15 had a substantial effect on durometer points of N674, N741, V747, and V884, but had only a slight effect on N497. It also substantially affected mass and volume change on N674, N741, V747, and V884.

V. CONCLUSIONS

A detailed summary of the general test results in Table 2-6 shows that none of the four fuels and five materials went through all the testing without any negative effects. In Table 2-6, NAC means no apparent change (≤10%); LC means limited change (11-20%); SC means substantial change (≥20%). As shown below, LSLA and FT100 had the least overall effect on the materials. DMM15 had the most effect on the five test materials.

TEST RESULTS	RATING
CA Fuel had 18- NAC, 11- LC and 1- SC	3
LSLA Fuel had 22- NAC, 7- LC and 1- SC	1
FT100 Fuel had 21- NAC, 8- LC and 1- SC	2
DMM15 Fuel had 9- NAC, 12- LC and 9- SC	4

Table 2-6. Detailed Summarized Test Results

Material	Sx1		Sx2		Sx3		Sx4		Sx5	
Ultimate Tensile Strength	F1	-LC	F1	NAC	F1	SC	F1	LC	F1	NAC
	F2	NAC	F2	NAC	F2	LC	F2	NAC	F2	NAC
	F3	NAC	F3	NAC	F3	NAC	F3	LC	F3	NAC
	F4	-SC	F4	NAC	F4	-SC	F4	-SC	F4	-SC
Ultimate Elongation, %	F1	NAC	F1	NAC	F1	-LC	F1	LC	F1	LC
	F2	+LC	F2	NAC	F2	-LC	F2	LC	F2	LC
	F3	+LC	F3	+LC	F3	NAC	F3	LC	F3	LC
	F4	+LC	F4	NAC	F4	-SC	F4	-SC	F4	-SC
Modulus@100%Elongation, PSI	F1	NAC	F1	LC	F1	NAC	F1	NAC	F1	NAC
	F2	NAC	F2	+SC	F2	LC	F2	NAC	F2	NAC
	F3	NAC	F3	+SC	F3	LC	F3	NAC	F3	LC
	F4	NAC	F4	LC	F4	NAC	F4	LC	F4	NAC
Durometer Points	F1	LC	F1	NAC	F1	NAC	F1	NAC	F1	NAC
	F2	NAC	F2	LC	F2	NAC	F2	NAC	F2	NAC
	F3	NAC	F3	LC	F3	NAC	F3	NAC	F3	NAC
	F4	LC	F4	-LC	F4	NAC	F4	LC	F4	LC
Mass, % Change	F1	LC	F1	NAC	F1	LC	F1	LC	F1	NAC
	F2	NAC	F2	NAC	F2	NAC	F2	NAC	F2	NAC
	F3	NAC	F3	NAC	F3	NAC	F3	NAC	F3	NAC
	F4	LC	F4	NAC	F4	LC	F4	LC	F4	LC
Volume, % Change	F1	LC	F1	NAC	F1	LC	F1	NAC	F1	NAC
	F2	NAC	F2	NAC	F2	NAC	F2	NAC	F2	NAC
	F3	NAC	F3	NAC	F3	NAC	F3	NAC	F3	NAC
	F4	LC	F4	NAC	F4	LC	F4	NAC	F4	-SC
TOTAL by Material	1 SC;10 LC		2 SC;6 LC		3 SC;9 LC		2 SC;8 LC		4 SC;5 LC	
	13 NAC		16 NAC		12 NAC		14 NAC		15 NAC	

LEGEND:
NAC = NO APPARENT CHANGE (<10%)
LC = LIMITED CHANGE (11-20%)
SC = SUBSTANTIAL CHANGE (21+ %)

Table 2-7 presents an overall fuels/materials compatibility summary. In this table, OK means adequate compatibility; P means slight compatibility problems are possible; N means compatibility is inadequate. It has been observed in the field that N674 had fuel compatibility problems. This study confirmed this, while the other four materials show overall better results. It appears V747 and V887 had the best overall material compatibility, with V747 having a slight edge over N497 because it did not get as brittle and remained softer. But N497 was the only material that had no problems with DMM15.

From these data it appears that V747 and V884 could be used with CA, LSLA and FT100 with no major problems, but should not be used with DMM15. N497 could be used with CA and DMM15, but with LSLA and FT100 there would be some brittleness and volume loss of the material. N741 can be used with FT100 with no major problems and possibly with LSLA, but with CA there is a possibility of some problems on mass change; but N741 should not be used with DMM15. It does appear that N674 could be used with LSLA and FT100 without any major problems, but should not be used with CA and DMM15.

Table 2-7. Overall Fuel/Material Compatibility

	Materials				
	1 (N674)	2 (497)	3 (N741)	4 (V747)	5 (V884)
Fuel 1 (CA)	N	OK	P	OK	OK
Fuel 2 (LSLA)	OK	P	OK	OK	OK
Fuel 3 (FT100)	OK	P	OK	OK	OK
Fuel 4 (DMM15)	N	OK	N	N	N

Legend
OK=Fuel/Material Compatibility is Adequate
P=Fuel/Material Compatibility could have slight problems
N=Fuel/Material Compatibility is inadequate

VI. MATERIALS COMPATIBILITY REFERENCES

1. Cusano, C.M., Stafford, R.J., and Lucas, J.M., "Changes in Elsastomer Swell with Diesel Fuel Composition," SAE Paper No. 942017.

2. Commercial Confidential Reports covering fuel system materials compatibility:

   - SwRI Report No. 6748-1, November 1995
   - SwRI Report No. 7526-1, February 1996
   - SwRI Report No. 7526-4, July 1996
   - SwRI Report No. 7526-5, September 1996
   - SwRI Report No. 8367, July 1997
   - SwRI Report No. 1209, September 1998

3. Frame, E. A., Bessee, G. B., Marbach, H. W., Jr. Biodiesel Fuel Technology for Military Application, Interim Report TFLRF No. 317, December 1997, AD A332922.

4. Bessee, G. B., and Fey, Joseph P., "Compatibility of Elastomers and Metals in Biodiesel Blends." SAE Paper No. 971690.

OBJECTIVE 3: THERMAL STABILITY AND LOW-TEMPERATURE PROPERTIES

I. INTRODUCTION

Objective 3 was to determine the thermal stability and low-temperature operability characteristics of the four test fuels using accepted test methods. Two separate test methods were conducted to assess the thermal stability characteristics of the test fuels. These tests were the Octel F-21 test and ASTM D 3241. Bacha and Lesnini recently demonstrated the relevance of the F-21 test results (Reference 1). Using the F-21 test results, they concluded, "inadequate thermal stability is the primary cause of premature fuel filter plugging experienced by certain diesel fuel customers." Under the F-21 test, the fuel sample is heated in an open test tube for 90 minutes at 150ºC. The aged fuel was filtered and the amount of material on the filter was rated by visual comparison to a set of standards or measurement with a reflectance meter. The standard test method was modified to include a gravimetric measurement of particulates. This was because particulate color is not a consistent, reliable quantitation of particulates.

To evaluate the hot-surface, deposit-forming tendencies of each fuel, and to reduce possible errors from fuel evaporation, each fuel was tested using a modified ASTM D3241, Thermal Oxidation Stability of Aviation Turbine Fuels (JFTOT) Procedure. Under this test procedure, the fuel sample is flowed over an electrically heated tube. Throughout the test, the entire system is sealed, thereby preventing fuel evaporation. Both the metallurgy and the temperature profile of the heated tube are variable. The essential data derived are the amount of deposits on the heated tube and the rate of plugging of a 17-µm, nominal-porosity filter downstream of the heated tube. Tests were conducted at 260°C. Stainless steel tubes were used for these tests. The tube deposits were rated using the standard visual methods found in the test procedure.

A. Thermal Stability

Two separate test methods are recommended for assessing the thermal stability characteristics of the test fuels (Octel F-21 test and ASTM D3241). The standard Octel F-21 test method was modified to include a gravimetric measurement of particulates. This was done because particulate color is not a consistent, reliable quantitation of particulates. The JFTOT, D3241 data are shown in Table 3-1.

Table 3-1. Results for Jet Fuel Thermal Oxidation Test, JFTOT, ASTM D 3241				
Test	**FT100**	**CA**	**LSLA**	**DMM15**
0 Hour (Neat Fuel)	ASTM Code: 1 TDR Spun: 0	ASTM Code: 4P TDR Spun: 15 @ 25 mm	ASTM Code: 1 TDR Spun: 0	ASTM Code:1 TDR Spun: 0
After 500 hr Stanadyne Test	ASTM Code: 1 TDR Spun: 0	ASTM Code: 4P TDR Spun: 15 @ 19 mm	ASTM Code: <2 TDR Spun: 0	ASTM Code:1 TDR Spun: 0

The CA fuel produced unsatisfactory results on the JFTOT test. This corresponds with the fact that this fuel produced deposits in the Stanadyne test as previously reported. SwRI completed JFTOT tests on the 500-hour (end-of-test) samples from the Stanadyne test. With the exception of the CA fuel, the 500-hour samples also gave acceptable JFTOT results, with very little or no change from the fresh fuel.

Thermal stability was determined by the modified Octel F-21 test. The results are presented in Table 3-2. Only three of the fuels were analyzed because the DMM in the DMM15 fuel boiled out of the sample so rapidly that fuel was sprayed into the air and surrounding samples. Some tests were repeated because of cross-contamination. For the three samples that were tested, all the results were acceptable. Also included in Table 3-2 are the 150ºC test data for the 500-hour pump test samples. All of the test results were in the acceptable range; however, the 180-minute filter pad ratings for the CA fuel were substantially lower than the others.

In the original statement of work, fuel stability additives were to be evaluated in the four test fuels using D3241 and Octel F-21 test procedures. During the course of the project, it was decided to test the four fuels after 500 hours in the Stanadyne Pump Test in D3241 and Octel F-21. These tests were done in lieu of fuel additive tests.

Table 3-2 Thermal Stability Test, F-21				
Fuel	**FT100**	**CA**	**LSLA**	**DMM15**
90 min. @ 150°				
Filter pad rating, % Reflectance	96.5	95.8	96.8	*BSOM
Particulates, mg/100ml	0.7	0.4	<0.1	
180 min. @ 150°C				
Filter pad rating, % Reflectance	95.7	93.6	96.8	*BSOM
Particulates, mg/100ml	0.7	1.0	<0.1	
90 min. @ 150°C: After 500 hr Stanadyne pump Test				
Filter pad rating, % Reflectance	95.7	92.5	95.3	*BSOM
Particulates, mg/100 ml	2.5	2.5	2.3	
180 min. @ 150°C; After 500 hr Stanadyne Pump Test				
Filter pad rating, % Reflectance	95.5	84.3	95.0	*BSOM
Particulates, mg/100 ml	2.2	1.9	1.2	
*BSOM – Beyond Scope of Method				

The fact that the CA fuel formed unacceptable deposits in both the pump stand test and the JFTOT tests, but passed the F-21 test, may indicate that the CA fuel is sensitive to heated metal surfaces.

B. Low-Temperature Properties

As a measure of their low-temperature operability characteristics, each fuel was tested by the following four test methods:

1. Cloud Point, ASTM D5773, Cloud Point of Petroleum Products (Constant Cooling Rate Method) and Pour Point,
2. ASTM D5949, Pour Point of Petroleum Products (Automatic Pressure Pulsing Method),
3. ASTM D4539, Filterability of Diesel Fuels by Low-Temperature Flow Test (LTFT), and
4. Cold Filter Plugging Point (CFPP).

The first two methods provide the historically accepted measures of the low-temperature characteristics of diesel fuel but do not specifically address the filterability of these fuels. The LTFT and CFPP tests estimate the filterability of diesel fuels in some automotive equipment.* There remains some disagreement among users as to the relevance of the results of the LTFT and CFPP; therefore, both tests were conducted.

The laboratory low-temperature data obtained are presented in Table 3-3.

Table 3-3. Results of Low-Temperature Characteristics Testing

Test	FT100	CA	LSLA	DMM15
Cloud Point, °C, ASTM D 5773	0.4	-25.0	-2.9	-3.6
Pour Point, °C, ASTM D 5949	0.0	-31.0	-6.0	-3.0
Low-Temperature Flow Test, LTFT, Min. Pass Temp., °C, ASTM D 4539	0	-24.0	-3	-6
Cold Filter Plugging Point, °C	-11	-25.0	-6	-8

As expected, the FT100, LSLA and DMM15 blend had poor low-temperature properties compared to the CA fuel.

* Additional information is contained in Coordinating Research Council Report No. 528, "1981 CRC Diesel Fuel Low-Temperature Operability Field Test," Coordinating Research Council, Inc., Atlanta, GA, Sept. 1983.

II. REFERENCES

1. Bacha, J.D. and Lesnini, D. G., “Diesel Fuel Thermal Stability at 300°F: Proceedings of the 6th International Conference on Stability and Handling of Liquid Fuels,” H.N. Giles, ed., U.S. Department of Energy, Washington, DC, February 1998.

III. FUEL STABILITY, CLEANLINESS, AND HANDLING BIBLIOGRAPHY

1. Westbrook, S. R, and Hutzler, S. A., "The Use of AOTF-NIR Spectrometers to Analyze Fuels, Phase I. Instrument Selection and Preliminary Calibrations," Interim Report TFLRF No. 313, April 1996.

2. Stavinoha, L. L., "Storage Stability Evaluation of Reformulated Gasoline," Letter Report No. TFLRF-96-001, April 1996.

3. Westbrook, S. R., Stavinoha, L. L, Mclnnis, L. A., Likos, W. E., and Yost, D. M., "Fuel Requirements for Low-Heat Rejection Military Diesel Engines," Interim Report TFLRF No. 297, January 1996

4. Lacey, P. 1. and Westbrook, S. R., "Effect of Fuel Composition and Prestressing on Lubricity," Interim Report TFLRF No. 307, August 1995.

5. Westbrook, S. R, Lacey, P. I., and McInnis, L. A., "Low-Sulfur Diesel Fuel Survey – II (Winter and Summer Samples)," Letter Report No. TFLRF-95-004, September 1995.

6. Westbrook, S. R., "Low-Sulfur Diesel Fuel Survey – I (Summer Samples)," Letter Report No. TFLRF-95-001, January 1995.

7. Stavinoha, L. L., Westbrook, S. R., and McInnis, L. A., "Mechanism of Deposit Formation on Fuel-Wetted Hot Metal Surfaces," Interim Report BFLRF No. 290, January 1995.

8. Fodor, G. E. and Westbrook, S. R., "Best Technical Approach for the Petroleum Quality Analysis (PQA) System," Interim Report BFLRF No. 300, August 1994.

9. Westbrook, S. R., "Analysis of Oxygenated Gasolines Using an AOTF-Based Near-Infrared Spectrophotometer," Letter Report No. BFLRF-93-002, September 1993.

10. Butler, W. E., Alvarez, R. A., Yost, D. M., Westbrook, S. R., Buckingham, J. P., Lestz, S. J., "Final Report on Field Demonstration of Aviation Turbine Fuel MIL-T-83133C, Grade JP-8 (NATO Code F-34) at Fort Bliss, Texas," Interim Report No. BFLRF-278, September 1992.

11. Stavinoha, L. L., Yost, D. M., and Lestz, S. J., "Diesel Injector Fouling Bench Test Methodology," Interim Report BFLRF No. 267, June 1992.

12. Frame, E. A., Westbrook, S. R., and Wright, B. R., "Analysis of Fluid and Foam Samples From Helicopters," Interim Report No. BFLRF-284, April 1992.

13. Bessee, G. B., Westbrook, S. R., and Stavinoha, L. L., "Automotive Diesel Fuel Filter Qualification Methodology and Preliminary Screening Results," January 1992.

14. Butler, W. E., Alvarez, R. A., Yost, D. M., Westbrook, S. R., Buckingham, J. P., Lestz, S. J., "Field Demonstration of Aviation Turbine Fuel MIL-T-83133C, Grade JP-8 (NATO Code F- 34) at Ft. Bliss, TX," Interim Report No. BFLRF-264, December 1990.

15. Bowden, J. N., Westbrook, S. R., and LePera, M. E., "A Survey of JP-8 and JP-5 Properties," Interim Report No. BFLRF-253, September 1988.

16. Westbrook, S. R., Stavinoha, L. L., and Present, D. L., "Studies of Diesel Fuel Insolubles Formation and Fuel Stabilizer Additives," Interim Report No. BFLRF-255, August 1988.

17. Westbrook, S. R., Stavinoha, L. L., and Bundy, L. L., "Worldwide Survey of Automotive Diesel Fuel Quality - Phase I," Interim Report No. BFLRF-236, July 1987.

18. Westbrook, S. R., Stavinoha, L. L., Owens, E. C., Bundy, L. L., and Butler Jr., W. E., "Establishment of Procedural Methodology and Data Interpretation for Fuel Quality Evaluation," Interim Report No. BFLRF-212, March 1986.

19. Westbrook, S. R, Stavinoha, L. L., Burkes, J. M., Barbee, J. G., and Bundy, L. L., "Development of the Captured Fuels Test Kit," Interim Report No. BFLRF-211, December 1985.

20. Giles, H. N., Bowden, J. N., and Stavinoha, L. L., "Overview on Assessment of Crude Oil and Refined Product Quality During Long-Term Storage," Department of Energy Report No. DOE/FE-0048, June 1988.

21. Westbrook, S. R. and Stavinoha, L. L., "Development of the Field Fuel Quality Monitor," Interim Report No. AFLRL-184, September 1984.

22. Westbrook, S. R, Stavinoha, L. L., and Bundy, L. L., "Summary of Stability Additive Package Evaluation in Partially Fueled Vehicles On Board USMC Ships at Diego Garcia," Letter Report No. AFLRL-174, March 1984.

23. Westbrook, S R, Stavinoha, L. L., and Bundy, L. L., "Final Report on Fully Fueled TACOM Vehicle Storage Test Program," Interim Report No. AFLRL-154, December 1981.

24. Bowden, J. N., "Stability Characteristics of Some Shale and Coal Liquids," Department of Energy Report No. DOE/BETC/4162-10, November 1980.

25. Westbrook, S R., Stavinoha, L. L., Barbee, J. G., and Mengenhauser, J. V., "A Field Monitor for the Stability and Cleanliness of Distillate Fuel," Interim Report No. AFLRL-137, December 1981.

26. Westbrook, S. R., Stavinoha, L. L., and Mengenhauser, J. V., "Final Report on Fully Fueled POMCUS Vehicle Storage Test Program," Interim Report No. AFLRL-139, July 1981.

27. Stavinoha, L L. and Westbrook, S. R., "Optimization of Accelerated Stability Test Techniques for Diesel Fuels," Department of Energy Report No. DOE/BC/10043-25, June 1981.

28. Stavinoha, L. L. and Westbrook, S. R., "Accelerated Stability Test Techniques for Diesel Fuels," Department of Energy Report No. DOE/BC/10043, October 1980.

29. Stavinoha, L. L., Westbrook, S. R., and LePera, M. E., "Army Experience and Requirements for Stability and Cleanliness of Diesel Fuels," Interim Report No. AFLRL-128, July 1980.

30. Stavinoha, L. L., Bowden, J. N., Westbrook, S. R., and Giles, H. N., "Final Report on Assessment of Crude Oil and Refined Petroleum Product Quality During Long-Term Storage," Interim Report No. AFLRL-121, December 1979.

31. Westbrook, S. R., "Free Wax in Burner Fuel Oils," Letter Report No. AFLRL-126, October 1979.

32. Westbrook, S. R., "Laboratory Procedure for Sedimentation Tendency of Burner Fuel Oils," Letter Report No. AFLRL-124, September 1979.

33. Westbrook, S R. and Stavinoha, L. L., "Field Fuel Quality/Stability Testing Device," Letter Report No. AFLRL-123, September 1979.

OBJECTIVE 4: ADDITIONAL FUEL CHARACTERIZATION TESTS

I. DISCUSSION

Table 4-1 is a listing of the recommended fuel characterization tests, along with additional comments as necessary. These analyses were recommended because they are the most generally accepted characterization/specification tests for commercial diesel fuel. In addition, SwRI planned to report the odor of each fuel as compared to commercial diesel fuel. This was not possible because of a SwRI policy that prohibits using human subjects for exposure tests. Conductivity and other measurements were made on each fuel as presented in Table 4-2. Since fuel conductivity is so sensitive to trace contaminants, temperature, and conductivity additives, the conductivity results should not be considered representative of all fuels of each type. Conductivity measurements are most appropriately taken at time of transfer or point of use. Additional tests were conducted to complete the analysis of DMM15 blend in LSLA fuel, as presented in Table 4-3.

The results for the water separation test on the CA fuel were unsatisfactory. Other fuel analyses are presented in Table 4-4.

Table 4-1. Fuel Characterization Tests		
Fuel Property	**Test Method (s)**	**Additional Comments**
Density	D 4052, for Density and Relative Density of Liquids by Digital Density Meter	
Distillation	1) D 86, for Distillation of Petroleum Products 2) D 2887, for Boiling Range Distribution of Petroleum Fractions by Gas Chromatography	While the D 86 data are the generally accepted distillation results, the gas chromatography data will provide additional information for evaluation of the test fuels.
Ignition Quality	3) D 613, for Ignition Quality of Diesel Fuels by the Cetane Method 4) Ignition Quality by Constant Volume Combustion Apparatus (CVCA)	The CVCA tests can provide detailed information on the ignition quality of the fuels.
Aromatics	D 5186, for Determination of Aromatic Content and Polynuclear Aromatic Content of Diesel Fuels and Aviation Turbine Fuels by Supercritical Fluid Chromatography	
Flash Point	D 93, for Flash point by Pensky-Martens Closed Cup Tester	Recent testing with DMM blends at SwRI has shown that the flash point of such blends is below room temperature
Kinematic Viscosity at 40°C	D 445, for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)	
Total Sulfur Content	D 2622, for Sulfur in Petroleum Products by X-Ray Spectrometry	Sulfur detection limit is 0.0010%w (wavelength dispersive x-ray fluorescence)
Net Heat of Combustion	D 240, for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter	
Water Separation	D 3948, for Determining Water Separation Characteristics of Aviation Turbine Fuels by portable spectrometer	
Fuel Lubricity	D 6078, for Evaluating Lubricity of Diesel Fuels by the Scuffing Load Ball-on-Cylinder Lubricity Evaluator (SLBOCLE)	The lubricity of these fuels is being evaluated, under a separate project, using the High Frequency Reciprocating Rig. However, the SLBOCLE provides additional information about the lubricity of the fuel.

Table 4-2. Additional Fuel Properties				
Test Method	**FT100**	**CA**	**LSLA**	**DMM15**
Water Separation Characteristics, ASTM D 3948	100	0	89	71
Electrical Conductivity, pS/M, ASTM D 2624	0	30	0	BSOM
Total Sulfur, ASTM D 5453, ppm	<1.0	150.6	1.4	1.0
Ignition Quality by CVCA	a	a	a	a
a= equipment not available during project time frame				

Table 4-3. Results of Additional Testing to Confirm Composition of DMM15		
Test Method	**DMM15**	
Density, D 4052, kg/m^3	818.8	
Distillation, D 86, °C, D 2887	**ASTM D 86**	**ASTM D 2887**
Initial Boiling Point	41	58
10% Distilled	58	179
50% Distilled	262	273
90% Distilled	316	344
95% Distilled	327	360
End Point	335	413
Residue, vol%	1.1	—
Kinematic Viscosity @ 40°C, D445, mm^2/s	1.65	
Cetane Number, D 613	59	
Ignition Quality by CVCA	a	
Aromatics, D 5186, mass%	9.5	
Flash Point, D 93, °C	Below Room Temperature	
Total Sulfur, D 2622, mass%	1.0 ppm by ASTM D 5453	
Net Heat of Combustion, D 240, MJ/kg	40.1	
Fuel Lubricity, D 6078, SLBOCLE, kg	1.950	
a=equipment not available		

Table 4-4. Test Fuel Properties

Fuels Analyses			FISCHER TROPSCH (FT100)	FISCHER TROPSCH (FT100)	California Reference (CA)[1]	California Reference (CA)	LSLA	LSLA	DMM/LSLA Blend (ADMM15)	DMM/LSLA Blend (ADMM15)
			AL25323F	AL25323F	AL25713F	AL25713F	AL25383F	AL25383F	AL25469F	AL25959
PROPERTY	UNITS	ASTM	SwRI	Core	SwRI	Core	SwRI	Core	SwRI	Core
Density @ 15C	g/ml	D4052	0.7812		0.8378		0.8160		0.8201	
Distillation		D2887								
IBP	°C		145		145		140		58	
10%	°C		266		192		202		179	
50%	°C		302		251		280		273	
90%	°C		351		325		344		344	
95%	°C		359		339		362		360	
End point	°C		377		372		416		413	
Distillation		D86								
IBP	°C		215	233	189	192	207	210	42	40
10%	°C		258	256	215	214	232	232	73	61
50%	°C		289	287	255	253	276	275	264	261
90%	°C		325	323	309	308	322	321	319	312
95%	°C		332	330	321	321	334	334	332	325
End Point	°C		337	336	331	331	344	344	342	338
Cetane Number		D613	84	87	45	49	63	62	59	
Cetane Index		D976	78		48		61		57	
Kinematic Viscosity at 40°C	cSt	D445	3.2	3.1	2.4	2.3	2.9	2.9	1.9	1.7
Flash Point	°C	D93	98	99	72	70	87	87	<2(D56)	<24
Hydrogen	wt%	D5291	15.1		13.4		14.4		13.7	
Carbon	wt%	D5291	84.8		86.4		85.6		81.6	
Oxygen	wt%	difference	0.1		0.2		0.0		4.7	
Nitrogen	mg/g	D4629	7.8		<1.0		<1		<1	
Sulfur	ppm	D5453	1.0				1.0		1.0	
Sulfur	ppm	D2622	<10		176		<10		<10	
Sulfur by X-ray Spect	wt%	D4294				0.021				
Hydrocarbon Type:										
Total Aromatics	wt%	D5186	0.2	<0.1	18.9	18.6	9.0	9.1	8.2*	9

Table 4-4. Test Fuel Properties

Fuels Analyses			FISCHER TROPSCH (FT100)	FISCHER TROPSCH (FT100)	California Reference (CA)[1]	California Reference (CA)	LSLA	LSLA	DMM/LSLA Blend (ADMM15)	DMM/LSLA Blend (ADMM15)
			AL25323F	AL25323F	AL25713F	AL25713F	AL25383F	AL25383F	AL25469F	AL25959
Mono	wt%	D5186	0.2		15.1		8.5		7.8*	
Poly(Di+Tri)	wt%	D5186	<0.1		3.8		0.5		0.4*	
Paraffins	wt%	D2425	97.1		44.2		54.5		54.2*	
Naphthenes	wt%	D2425	2.9		37.8		36.9		31.9*	
Water	ppm	D4928	45.0		105.0		77.0		368.0	
Color		D1500	LO.5		L0.5		L0.5		L0.5	
Clear and Bright		D4176	PASS		PASS		PASS		PASS	
Particulates	mg/L	D6217	4.3		<0.01		0.8		0.7**	
Copper Strip Corrosion		D130	1a		1a		1a(50C)		1a	
Cloud Point	°C	D2500	-1		-27		-4		-7	
Pour Point	°C	D976	-2		-32		-5		-9	
Carbon Residue	%	D524	0.071		0.220		0.080		0.038	
Acid Number	mgKOH/g	D664	0.03		0.02		0.02		0.02	
Oxidation Stability		D2274	0.20		0.20		<0.01		0.25***	
Net Heat of Combustion	MJ/kg	D240	43.9		42.7		43.3		40.8	
Gross Heat of Combustion	MJ/kg	D241		47.2		46.0		46.8		42.0
Lubricity, HFRR	mm	D6079	0.59		0.27		0.57		0.49	
BOCLE Scuff	grams	D6078	1900		4300		1600		1950	

[1]The CA fuel contained 200 ppm by vol. lubricity additive
*The DMM is interfering with these results
**DMM altered shape of filter and may be interfering with results
***Vigorous boiling occurred as sample came to temperature

APPENDIX A
PARTS INSPECTION REPORT BY STANADYNE

STANADYNE®
Automotive

May 23, 2001

TEST REPORT

OBJECTIVE: The objective of this test was to conduct a post-test inspection on eight DB2 8-cyl injection pumps (from SwRI) and to determine the **P**ump **L**ubricity **V**alue (PLV) for each pump.

BACKGROUND: PLV is defined in an ASTM **P**roposed **T**est **M**ethod (PTM) as, "an assessment of the lubricating property of a fluid used in a diesel fuel injection pump". The PLV is normally determined by running a DB4 pump 500 hours at rated speed and fuel flow conditions and calculating the PLV by using a formula that applies weighted factors to R-R (roller to roller) dimension change, fuel flow change, T.P. blade wear, and T.P. pressure change following a 500 hour endurance test.

The ASTM PTM further states that a PLV greater than 5 is considered unacceptable fuel lubricity. A PLV of 4 or less considers the fuel to be "fit for purpose" from a lubricity standpoint, and lastly, a PLV in the 4 to 5 range is an indication of a fuel that is marginally fit for purpose.

TEST CONDITIONS: The eight pumps used in this test were 8-cyl DB2 pumps and not the DB4 pump specified in the ASTM PTM. The R-R dimension and fuel delivery in an 8-cyl DB2 pump does not react the same as a DB4 pump in a poor lubricity environment. Pre-test measurements were not available for certain critical parts. It was therefore necessary, given these test conditions, to attempt to simulate a PLV by reviewing limited quantitative data and observing the condition of certain components after test.

DISCUSSION: Some pre-test and post-test performance data were made available with the delivery of the pumps, after test, to Stanadyne. T.P. pressure at 2050 rpm and fuel delivery at 1750 rpm were the performance data used to simulate a PLV. A differential dimension (measurement of wear) was derived by measuring the most worn area compared to an unworn surface on all T.P. blades and driveshaft tangs. The T.P. blades, T.P. liner, roller shoes, and driveshafts of each tested pump were displayed for visual inspection. Three Stanadyne experts viewed and subjectively accessed the condition of each set of parts.

The above data was tabulated by pump S/N and a PLV for each was estimated.

SUMMARY: The estimated PLV for each tested pump by S/N was as follows:

pump S/N	PLV	pump S/N	PLV
8897753	3	8897767	8
8897758	3	8897770	5.5
8897760	4	8897768	6
8897761	4.5	8897772	7

CONCLUSIONS: From the above stated estimated PLVs, the following conclusions can be made.

1. The fuels used in pump S/Ns 8897767, 8897770, 8897768, and 8897772 are considered unacceptable from a lubricity standpoint.

2. The fuels used in pump S/Ns 8897753, 8897758, and 8897760 are considered "fit for purpose" from lubricity standpoint.

3. The fuel used in pump S/N 8897761 has marginal lubricity.

Test Report Reviewed and Submitted by:

P. T. Henderson

Paul T. Henderson
Manager, Quality Management Systems

APPENDIX B
PARTS INSPECTION REPORT BY BOSCH

AP/EHD2 Investigation Report
Number: F00HP10182

BOSCH

Department	From	Telephone number	Fax number	Farmington Hills
AP/EHD2	N. Karwande NK	248-848-2939	248-324-7288	19-Oct-01

CC: AP/EHD2-Fabis, Korte, Southwest Research-Yost

Customer:	Southwest Research	**RA Number:**	
Project:		**Customer No.:**	
Component:	CR pump and injector	**ASMUS-No.:**	
Component No.:	See below	**IBAS-No.:**	
Serial No.:		**SPI No.:**	

1. Subject

Evaluation of Mercedes Common Rail (CR) injectors, CP1 pumps, and ZP18 feed pumps returned from Southwest Research Institute for analysis.

2. Scope

- **Customer input:** Southwest ran 8 CR systems with 4 different types of fuel. A preliminary analysis was made by Southwest and was sent to Bosch for further investigation.

  - Injector - **0 445 110 012**
  - CP1 pump – **0 445 010 008**
  - ZP18 feed pump – **0 440 020 003**

3. Evaluation

The systems were tested at Southwest Research Institute and the results are listed on page #2.
The parts were sent to Bosch for further investigation. The disassembled components were ranked from a scale of 1 (No wear) to 5 (Extreme wear/broken/damaged) for each set. The total number was added for each system to determine the most critical and least critical fuel in terms of effect of the CR system. However, since some ZP18 feed pump components were missing, these values were not included in the analysis. See page #5.
The fuels data sheet and specifications are listed on page #6.
The systems were compared and the fuels were ranked (#1 Lowest Wear, #4 Highest Wear) by both Southwest Research and Bosch:

Southwest Research Rankings

#1: CA: Lubricity Additive
#2: LSLA: No Lubricity Additive
#3: DMM15: No Lubricity Additive
#4: FT100: No Lubricity Additive

Bosch Rankings

#1: DMM15: No Lubricity Additive
#2: CA: Lubricity Additive
#3: FT100: No Lubricity Additive
#4: LSLA: No Lubricity Additive

4. Conclusion / Recommendations

The rankings for fuel comparisons of a Common Rail system from Southwest Research and Bosch are listed above.

-+Checked:	UO/EHD2-VF	Tele:	1113	Date: 10/22/01	Signed: [signature]

Department	From	Telephone number	Fax number	Farmington Hills
AP/EHD2	N. Karwande	248-848-2939	248-324-7288	19-Oct-01

Bosch Common-Rail Components Testing Summary and Conclusions

Bosch Common Rail Fuel Injection System

- System Performance Check at Test Initiation and at Test Conclusion if Components Operable
  - 38°C Fuel Inlet Temperature
  - 2100-RPM Transfer Pump Speed and 2800 RPM Rail Pump Speed
  - Three Rail Pressures: 400-bar, 800-bar, and 1350-bar
  - Three Injection Pulsewidths : 750-µs, 1000-µs, and 1250-µs
  - Document: Controller Duty Cycle, Transfer Pump Pressure, and Injection Flow
- Not All Fuels Completed Scheduled 500 Hours
- All Tests Conditions Noted
- Tests Fuels Performed in Duplicate
- Substantial Variation of Performance of Duplicate Pumps with Each Fuel
- Fuel Rankings based on Pump Condition, Fuel Lubricated Contact Condition, Pump Performance, Injector Condition, and Injector Performance:

Fuels information:

1. CA: Lubricity Additive

- Test Condition:
- 2800-RPM Rail Pump
- 1350-bar Rail Pressure
- 1000-µs Injection Pulsewidth
- 70°C Fuel Inlet Temperature
- 38°C Fuel Inlet Temperature

- Test 2 Showed Mild Wear at 500-hours
- No System Run-in
- Drive Coupling Problems May Have Exacerbated Wear
- Minimal Pump Durability Impact
- Minimal Injector Durability Impact
- Injector Pintle Deposits

- Test 8 Terminated at 233-hours
- System Run-in
- 100ºF Fuel Inlet Temperature
- 90ºF Fuel Tank Temperature
- 30 minutes at 450 rpm with 300-bar rail pressure
- 90 minutes at 750 rpm with 450-bar rail pressure
- Mild Wear on Fuel Lubricated Contacts
- Cracked Plunger Barrel, Unable to Maintain Rail Pressure
- Rail Pressure Regulator Failure, Short Circuit
- Minimal Injector Durability Impact

Department	From	Telephone number	Fax number	Farmington Hills
AP/EHD2	N. Karwande	248-848-2939	248-324-7288	19-Oct-01

2. LSLA: No Lubricity Additive

- Test Condition:
- 2800-RPM Rail Pump
- 1350-bar Rail Pressure
- 1000-μs Injection Pulsewidth
- 70°C Fuel Inlet Temperature
- 38°C Fuel Tank Temperature

- Test 1 Severe Wear Terminated at 482-hours
- No System Run-in
- Drive Coupling Problems May Have Exacerbated Wear
- Wear Debris, Pump Durability Impact
- Some Injector Durability Impact, possibly from Wear Debris
- Injector Pintle Deposits

- Test 7 Mild Pump Wear at 500-hours
- System Run-in
- 100ºF Fuel Inlet Temperature
- 90ºF Fuel Tank Temperature
- 30 minutes at 450 rpm with 300-bar rail pressure
- 90 minutes at 750 rpm with 450-bar rail pressure
- Cam Follower Bearing Pitting
- Deposits on Pump Driveshaft
- Minimal Pump Durability Impact
- Minimal Injector Durability Impact
- Injector Pintle Deposits

3. DMM15: No Lubricity Additive

- Test Condition:
- 2800-RPM Rail Pump
- 1350-bar Rail Pressure
- 1000-μs Injection Pulsewidth
- 57°C Fuel Transfer Pump Inlet Temperature
- 40°C Fuel Rail Pump Inlet Temperature
- 38°C Fuel Tank Temperature

- Test 4 Pump Seizure at 2.5-hours
- Cooled Fuel Into High Pressure Pump To Avoid Two Phase Flow
- No System Run-in
- Heavy Wear in Fuel Lubricated Contacts

- Test 6 Mild Wear at 500-hours
- Cooled Fuel Into High Pressure Pump To Avoid Two Phase Flow

Department	From	Telephone number	Fax number	Farmington Hills
AP/EHD2	N. Karwande	248-848-2939	248-324-7288	19-Oct-01

- System Run-in
- 100ºF Fuel Inlet Temperature
- 90ºF Fuel Tank Temperature
- 30 minutes at 450 rpm with 300-bar rail pressure
- 90 minutes at 750 rpm with 450-bar rail pressure
- Mild Wear on Fuel Lubricated Contacts
- Pump Driveshaft Deposits
- Minimal Injector Durability Impact

4. FT100: No Lubricity Additive

- Test Condition:
- 2800-RPM Rail Pump
- 1350-bar Rail Pressure
- 1000-μs Injection Pulsewidth
- 70°C Fuel Transfer Pump Inlet Temperature
- 38°C Fuel Tank Temperature

- Test 3 Pump Seizure During Performance Check
- No System Run-in
- Heavy Wear in Fuel Lubricated Contacts

- Test 5 Pump Seizure at 385-hours
- System Run-in
- 100ºF Fuel Inlet Temperature
- 90ºF Fuel Tank Temperature
- 30 minutes at 450 rpm with 300-bar rail pressure
- 90 minutes at 750 rpm with 450-bar rail pressure
- Heavy Wear on Fuel Lubricated Contacts
- Tar-like Deposits on Pressure Regulator
- Broken Plunger Foot Possibly due to Over Pressure
- Minimal Injector Durability Impact

- Bosch Claim That Sample Size Is Too Small For Fuel Lubricity Impact Determination Appears To Be Substantiated
- Bosch High Pressure Common Rail Pumps Appear To Be More Sensitive To Fuel Lubricity
  - ➢ Substantially More Severe Duty-Cycle and Loading

Attachment #1.

Department	From	Telephone number	Fax number	Farmington Hills
AP/EHD2	N. Karwande	248-848-2939	248-324-7288	19-Oct-01

Wear Comparison Table

	LSLA: No lubricity additive		CA Lubricity additive		FT100: No lubricity		DMM 15: No lubricity	
Component								
Injector (0 445 110 012)	Test 1	Test 7	Test 2	Test 8	Test 3	Test 5	Test 4	Test 6
Nozzle	3	2	2	3	4	3	3	2
Needle	4	3	2	3	2	1	2	2
Intermediate pin	2	2	2	2	1	2	1	1
Nozzle spring	1	1	1	1	1	1	1	1
Injector body	1	1	2	2	1	1	1	2
Push rod	1	2	2	2	1	1	1	1
HP sealing ring	2	2	2	2	2	3	2	2
Valve piece	3	3	3	2	2	2	2	2
Valve ball	1	1	1	1	1	1	1	1
Armature pin	2	2	1	1	2	2	1	1
Armature plate	1	1	2	1	1	1	1	1
Armature spring	1	1	1	1	1	1	1	1
Valve spring	1	1	1	1	1	1	1	1
Magnet core	2	3	3	3	1	3	2	2
Injector Total	**25**	**25**	**25**	**25**	**21**	**23**	**20**	**20**
Pump (0 445 010 008)	Test 1	Test 7	Test 2	Test 8	Test 3	Test 5	Test 4	Test 6
Housing	4	3	3	3	2	5	2	2
Eccentric shaft	5	3	4	4	2	4	3	3
Flange	3	3	3	2	2	4	2	2
Plunger	4	3	3	2	5	5	3	3
Barrel	4	3	4	3	2	4	3	3
Cylinder head	3	3	3	2	2	3	2	3
Polygon	5	3	3	3	3	5	4	3
Thrust ring	5	3	2	2	2	2	2	2
Valve assembly	4	4	3	2	2	5	2	3
Shaft sealing ring	3	3	2	2	2	2	2	2
Spring	2	2	2	2	2	2	2	2
CP1 Total	**42**	**33**	**32**	**27**	**26**	**41**	**27**	**28**
SYSTEM TOTAL	**67**	**58**	**57**	**52**	**47**	**64**	**47**	**48**
ZP18 (0 440 020 003)	Test 1	Test 7	Test 2	Test 8	Test 3	Test 5	Test 4	Test 6
Housing	2	5	2	1	*	1	1	2
Cover	2	3	*	1	*	*	1	1
Gears	2	2	3	3	*	2	2	3
Shaft	5	2	5	1	*	2	2	2
Driver	*	2	*	1	*	2	2	2
ZP18 Total	**11**	**14**	**10**	**7**	**0**	**7**	**8**	**10**
*Parts not available								

Department	From	Telephone number	Fax number	Farmington Hills
AP/EHD2	N. Karwande	248-848-2939	248-324-7288	19-Oct-01

Wear Comparison Table, Cont'd

Scale:	
1	No Wear
2	Light Wear
3	Moderate Wear
4	Heavy Wear
5	Extreme Wear/Damaged/Broken

Attachment #2.

Fuel Properties Table

Bosch CR Fuels Analysis	FISCHER-TROPSCH (FT100)	FISCHER-TROPSCH (FT100)	California Reference (CA)	California Reference (CA)	LOW S (LSHC)	LOW S (LSHC)	DMM/LSHC BLEND (DMM15)	DMM/LSHC BLEND (DMM15)		
PROPERTY	UNITS	ASTM	SwRI	Core	SwRI	Core	SwRI	Core	SwRI	Core
Density @ 15C	g/ml	D4052	0.7812		0.8378		0.816		0.8201	
Distillation		D2887								
IBP	°C		145		145		140		58	
10%	°C		266		192		202		179	
50%	°C		302		251		280		273	
90%	°C		351		325		344		344	
95%	°C		359		339		362		360	
End point	°C		377		372		416		413	
Distillation		D86								
IBP	°C		215	233	189	192	207	210	42	40
10%	°C		258	256	215	214	232	232	73	61
50%	°C		289	287	255	253	276	275	264	261
90%	°C		325	323	309	308	322	321	319	312
95%	°C		332	330	321	321	334	334	332	325
End Point	°C		337	336	331	331	344	344	342	338
Cetane Number		D613	84	87	45	49	63	62	59	
Cetane Index		D976	78		48		61		57	
Kinematic Viscosity at 40°C	cSt	D445	3.2	3.1	2.4	2.3	2.9	2.9	1.9	1.7
Flash Point	°C	D93	98	99	72	70	87	87	<2(D56)	<24
Hydrogen	wt%	D5291	15.1		13.4		14.4		13.7	
Carbon	wt%	D5291	84.8		86.4		85.6		81.6	
Oxygen	wt%	difference	0.1		0.2		0		4.7	
Nitrogen	microg/g	D4629	7.8		<1.0		<1		<1	
Sulfur	ppm	D2622	1		176		1		1	

BOSCH

Department: AP/EHD2 | From: N. Karwande | Telephone number: 248-848-2939 | Fax number: 248-324-7288 | Farmington Hills

Fuel Properties Table, cont'd

Bosch CR Fuels Analysis	FISCHER-TROPSCH (FT100)	FISCHER-TROPSCH (FT100)	California Reference (CA)	California Reference (CA)	LOW S (LSHC)	LOW S (LSHC)	DMM/LSHC BLEND (DMM15)	DMM/LSHC BLEND (DMM15)		
PROPERTY	UNITS	ASTM	SwRI	Core	SwRI	Core	SwRI	Core	SwRI	Core
Hydrocarbon Type:										
Total Aromatics	wt%	D5186	0.2	<0.1	18.9	18.6	9	9.1	8.2*	9
Mono	wt%	D5186	0.2		15.1		8.5		7.8*	
Poly(Di+Tri)	wt%	D5186	<0.1		3.8		0.5		0.4*	
Parafins	wt%	D2425	97.1		44.2		54.5		54.2*	
Napthenes	wt%	D2425	2.9		37.8		36.9		31.9*	
Water	ppm	D4928	45		105		77		368	
Color		D1500	LO.5		L0.5		L0.5		L0.5	
Clear and Bright		D4176	PASS		PASS		PASS		PASS	
Particulates	mg/L	D6217	4.3		<0.01		0.8		0.7**	
Copper Strip Corrosion		D130	1a		1a		1a(50C)		1a	
Cloud Point	°C	D2500	-1		-27		-4		-7	
Pour Point	°C	D976	-2		-32		-5		-9	
Carbon Residue	%	D524	0.071		0.22		0.08		0.038	
Acid Number	mgKOH/g	D664	0.03		0.02		0.02		0.02	
Oxidation Stability		D2274	0.2		0.2		<0.01		0.25***	
Net Heat of Combustion	MJ/kg	D240	43.9		42.7		43.3		40.8	
Gross Heat of Combustion	MJ/kg	D241		47.2		46		46.8		42
Lubricity at 60degC	mm	D6079	0.59		0.27		0.57		0.49	
Lubricity at 60degC (pressurized)	mm	HPHFRR							0.64	
BOCLE Scuff	grams	D6078	1900		4300		1600		1950	
Detergent	yes/no	unknown								
Sulfur by X-ray Spect	wt%	D4294				0.021				

*The DMM is interfering with these results
**DMM altered shape of filter and may be interfering with results
***Vigorious boiling occurred as sample came to temperature.

Attachment #3.

APPENDIX C
INVENTION DISCLOSURE

SOUTHWEST RESEARCH INSTITUTE™

6220 CULEBRA ROAD • POST OFFICE DRAWER 28510 • SAN ANTONIO, TEXAS 78228-0510, USA • (210) 684-5111 • WWW.SWRI.ORG

Refer to: 03.02476
May 31, 2001

Coordinating Research Council, Inc.
3650 Mansell Road
Alpharetta, GA 30022-8246

Attention: Mr. Timothy C. Belian
Executive Director

Sent Via: Mr. Ed Frame, SwRI

Subject: Contract/Grant No. AVFL-2-98-1/2
SwRI Project No. 03.02476
Final Patent Report

Dear Mr. Belian:

This is to certify that, with the exception of Invention Disclosure Docket No. 2810 entitled "Adjustable Sealing Boot for Rotating Shafts" reported to you on 06/19/2000 (copy attached), no other inventions reasonably believed to be patentable were conceived or first actually or constructively reduced to practice in performance of subject grant/contract. This therefore constitutes a final patent report for this program.

Should additional information be required, please do not hesitate to contact the undersigned of Contract Administration at 210/522-3026 (fax 801/760-0999; email vparr@swri.org) or Mr. Louis Rodriguez of the Legal Department at 210/522-2210.

Sincerely,

Vicki Parr

Vicki Parr
Contract Specialist

VLP/mm
Attachment (1)
cc: E. Owens, SwRI (via email)
L. Rodriguez, Legal (via email to S. McDonald)

2810

SOUTHWEST RESEARCH INSTITUTE™

6220 CULEBRA ROAD • POST OFFICE DRAWER 28510 • SAN ANTONIO, TEXAS, USA 78228-0510 • (210) 684-5111 • WWW.SWRI.ORG

Refer to: 03.02476
June 19, 2000

Coordinating Research Council, Incorporated
210 Perimeter Center Parkway, Suite 400
Atlanta, Georgia 30346-1301

Attention: Mr. Timothy C. Belian
Executive Director

Subject: SwRI Project No. 03.02476
CRC Contract No. AVFL-2
Invention Disclosure Docket No. 2810
Adjustable Sealing Boot for Rotating Shafts

Dear Mr. Belian:

We are pleased to enclose Invention Disclosure Docket No.2810 entitled ***Adjustable Sealing Boot for Rotating Shafts*** which was conceived as a result of work under subject program.

Should additional information be required, please contact the undersigned at 210/522-3948, by facsimile at 810/461-5301, or via e-mail stwilligear@swri.org.

Sincerely,

Sherry A. Twilligear
Senior Contract Specialist

SAT/js
Enclosure
cc: G. L. Phillips, SwRI
K. E. Stoecklein, SwRI
L. Rodriguez, SwRI-Legal

INVENTION DISCLOSURE*

1. Title: Adjustable Sealing Boot for rotating shafts. Docket No. 2810

Date Rec'd 01/11/2000

2. Object: To provide a quick and simple solution in sealing a lubricated rotating shaft or rotating through-shaft to an adjoining surface, with the ability to adjust for different coverage-area length requirements, if desired.

3. Name of inventor(s) (typed): Gregory Lynn Phillips, Karl Eugene Stoecklein

4. Date first constructed or formulated (if applicable): November 8, 1999

5. Previous or planned publication or public disclosure:

Title

Name of Publication Vol. Issue Page(s) Date

6. INVENTOR(S): (I) (We), the undersigned, certify that (I)(We) first conceived the within invention on ______ and that it is fully described in the attached disclosure on pages numbered consecutively 1 through ______

Signature in full Karl Eugene Stoecklein Date 1-7-2000

Signature in full Gregory L. Phillips Date 1-7-2000

Signature in full ______ Date ______

7. WITNESSES: We, the undersigned, certify that the invention described in the attached disclosure was explained to us and that we understand the same.

Signature in full Scott Alan Hutzler Date 1-7-00

Signature in full Dan Paxton Mann Date 01-07-00

FOR DEPARTMENT DIRECTOR ONLY

8. ☐ The described invention *was not* conceived or first reduced to practice as the result of work on a sponsored research project.

☒ The described invention *was* conceived or first reduced to practice as the result of work on a sponsored research project.

Project No. 03-02476 Contract No. AVFL-2

Sponsor: Coordinating Research Council

9. Summary recommendation to Patent Committee: request guidance from sponsor

Ed Owens Date 1/11/00

Department Director

*(See Instructions on Reverse)

(SwR-35)
FORM OP-2
REV 12/82

INSTRUCTIONS

1. Items 1 through 7 to be completed and forwarded to Department Director to complete Items 8 and 9 before transmitting to Patent Committee.

2. For Item 5, if the transmitted new technology has been or will be described, in full or in part, in a conference or seminar; or in a published report, journal, patent application or patent; or in a paper submitted for publication in any of the above, the appropriate blanks should be completed and the indicated source of information supplied. The earliest such publication or disclosure establishes a statutory bar; therefore, this date should be given where indicated.

3. Original must be signed, but required copies may be prepared by conforming (typing or printing signatures exactly as they appear on original) or by other means of reproduction. Transmit original and three copies to Chairman of Patent Committee unless invention was result of work on a sponsored research project, in which case submit one additional copy for commercially sponsored projects and four additional copies for government sponsored projects.

4. Strike all inapplicable words.

5. Use Invention Disclosure Description sheets (Form OP-2A) to describe invention. Freehand sketches may be used to help describe invention if desired. Each page of description must be signed and dated by inventor and by witnesses. Number each page in sequence. **(Leave at least one-inch margin to left for binding.)** Please use black ink for best reproduction results.

6. Include a summary at beginning of description. At the end of the description, set forth what you consider to be the invention, i.e., the new, useful, and unique concept when compared with the prior art of which you are aware in the specific field to which it relates and the results or benefits of its application.

7. Director's recommendation refers to action to be taken by Institute, i.e., apply for patent, assign to sponsor, retain commercial rights, file, etc. In this connection, attention is invited to Institute's normal policy that, excepting special cases, patent and publication rights resulting from sponsored research (other than SwRI-sponsored projects) belong to the sponsor.

8. Treat internal research projects as SwRI-sponsored.

9. Each inventor's signature must show full first, middle and last name. This is a Patent Office requirement. Initials only in lieu of first name are not accepted. In those cases, show middle name as first name. In cases of no middle name, write "(NMN)."

INVENTION DISCLOSURE DESCRIPTION

This invention was conceived for the purpose of providing a quick and convenient means to enclose a lubricated power-transfer coupling in order to prevent unwanted slinging and loss of the lubricant. Using commonly available seal sizes, it can be adapted to various shaft diameters as required for a specific application. The sealing boot could be manufactured in incremental sizes to accommodate different applications. The design also offers the flexibility of joining two boots together in order to provide sealing on a completely through-shaft application.

This device basically consists of a sealed housing which can be flush-mounted to a plate or flat surface on one end, and utilizes a lip-type seal on the other end for sealing to a rotating shaft. The actual material and configuration used to construct the boot body section is open to various options, three of which are described in this disclosure statement.

<u>Concept No. 1</u>
The first possibility is a bellows-shaped rubber boot made with an integral spring, which provides resistance to torsional loading on the seal. The boot is molded to a steel mounting flange on one end, which provides a means of bolting to a flat surface. The other end accepts a standard sized seal by incorporating a housing for the same. The bellows-shaped boot can allow for variations in required sealing length through its capability to be expanded and compressed along the shaft axis.

<u>Concept No. 2</u>
The second possibility for boot body construction consists of the same basic concept as with the rubber boot, but utilizing thin, formed aluminum. This aluminum housing would likewise be able to expand and contract axially, maintaining the desired length in a manner similar to a commonly available aluminum dryer duct connector.

<u>Concept No. 3</u>
The third possibility is a clam-shell style housing made of molded polymer material. This housing can be of one-piece construction, with a molded hinge integrated into the unit for low manufacturing cost. Snap-together flanges on the housing allow the two clam-shell halves to be fastened and sealed together, facilitating simple and quick installation. Again, a standard size seal is accommodated in the molded retainer grooves, and a flange provides for mounting to a plate or flat surface.

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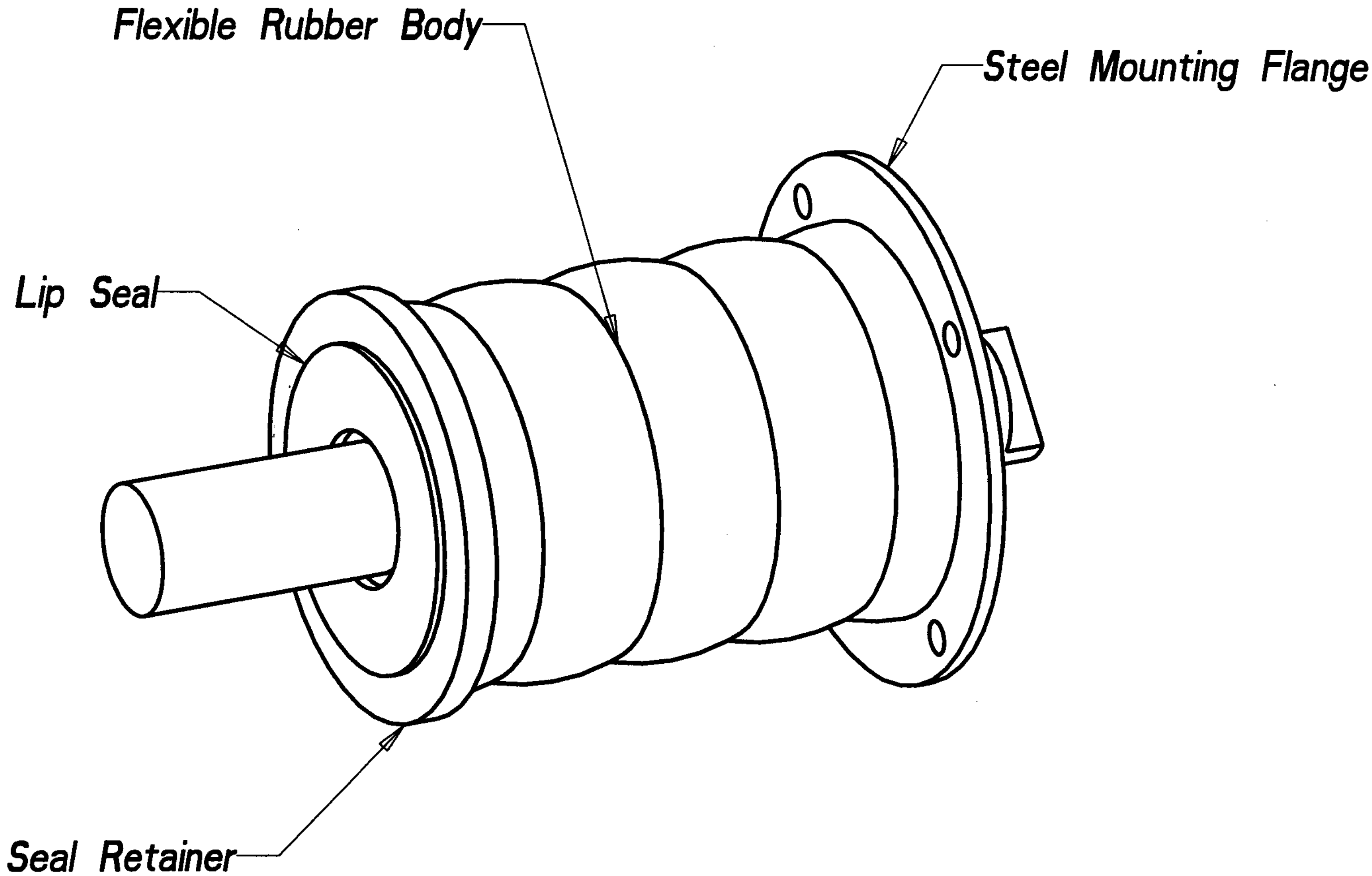
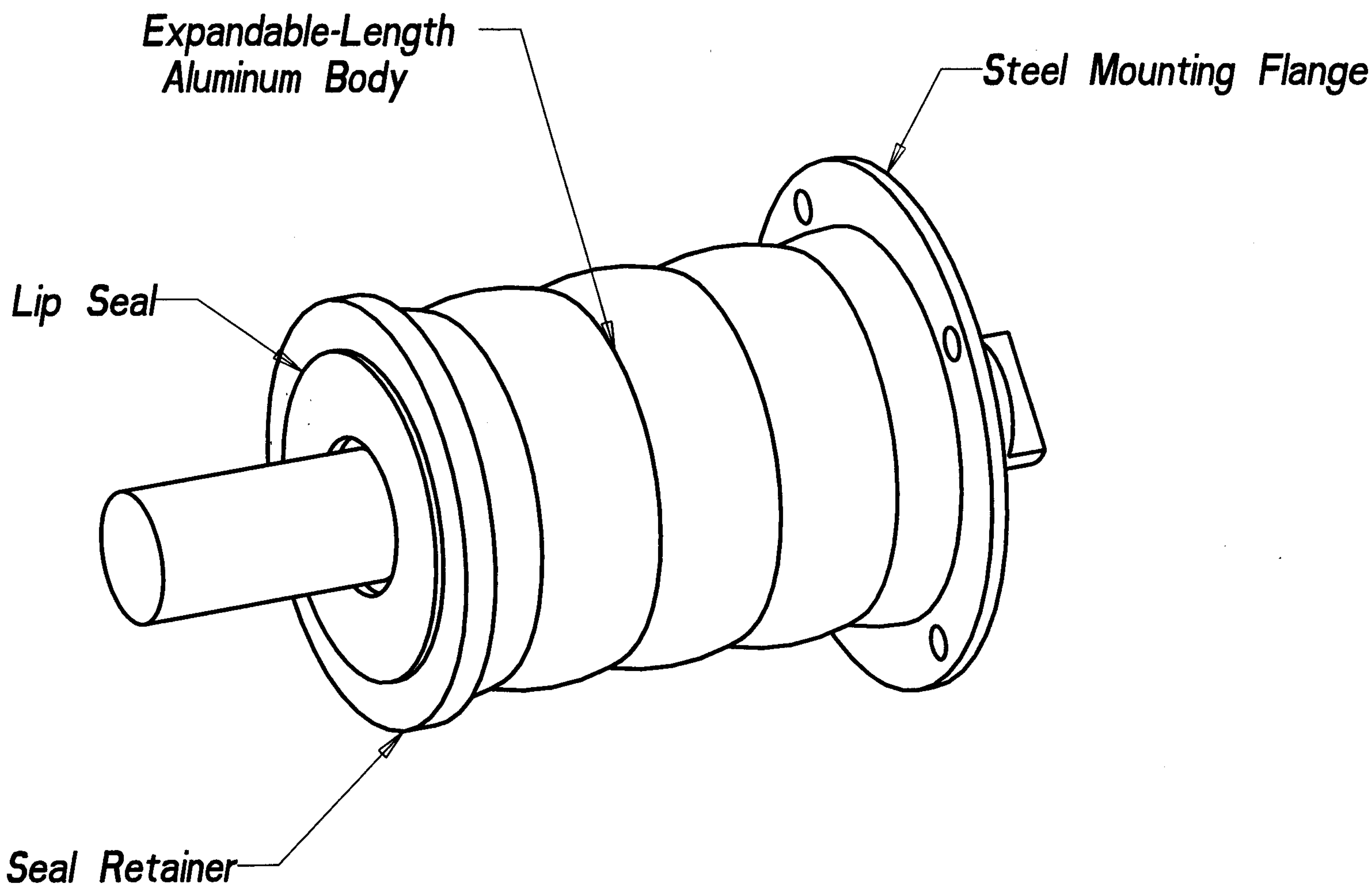
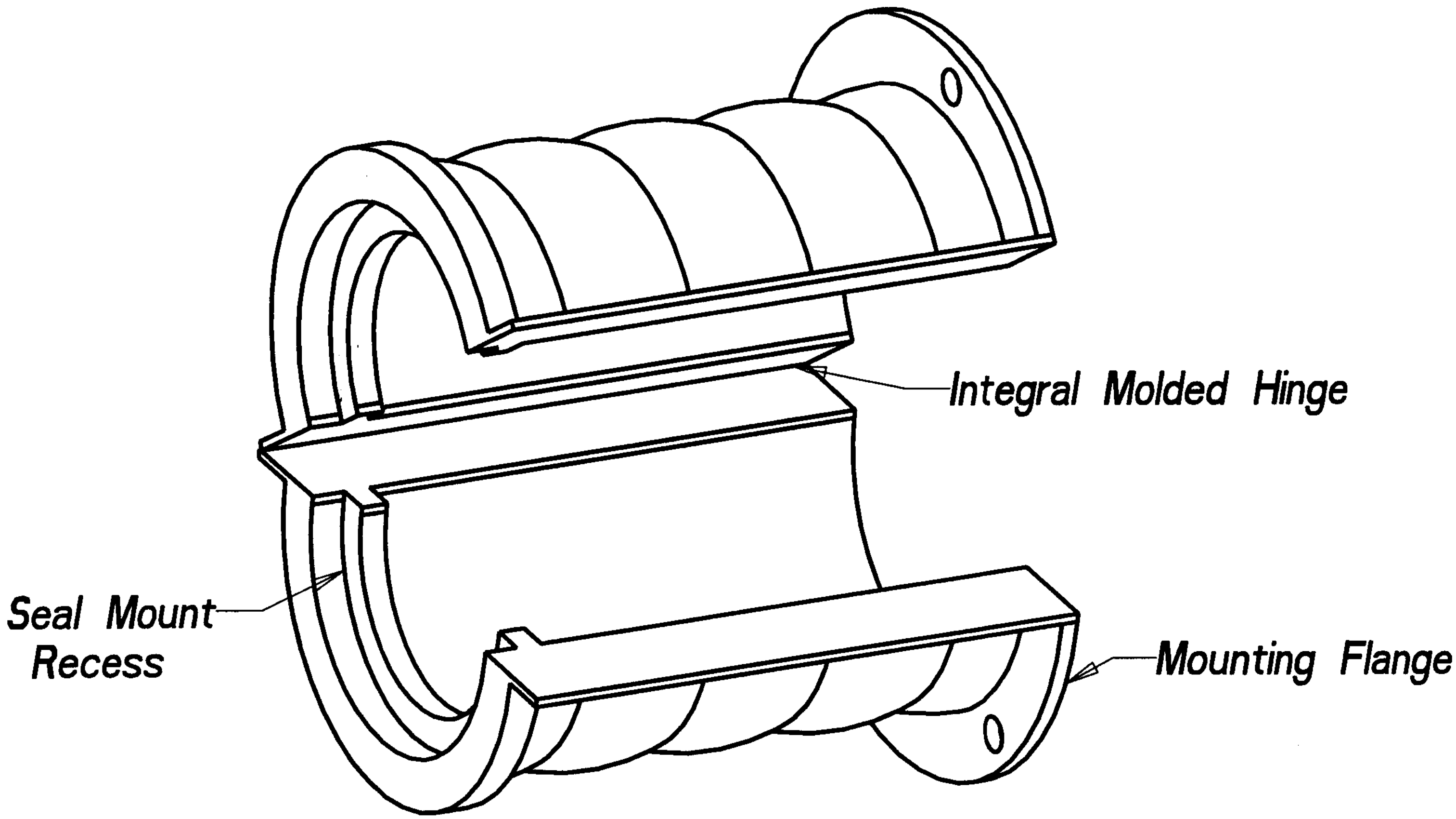


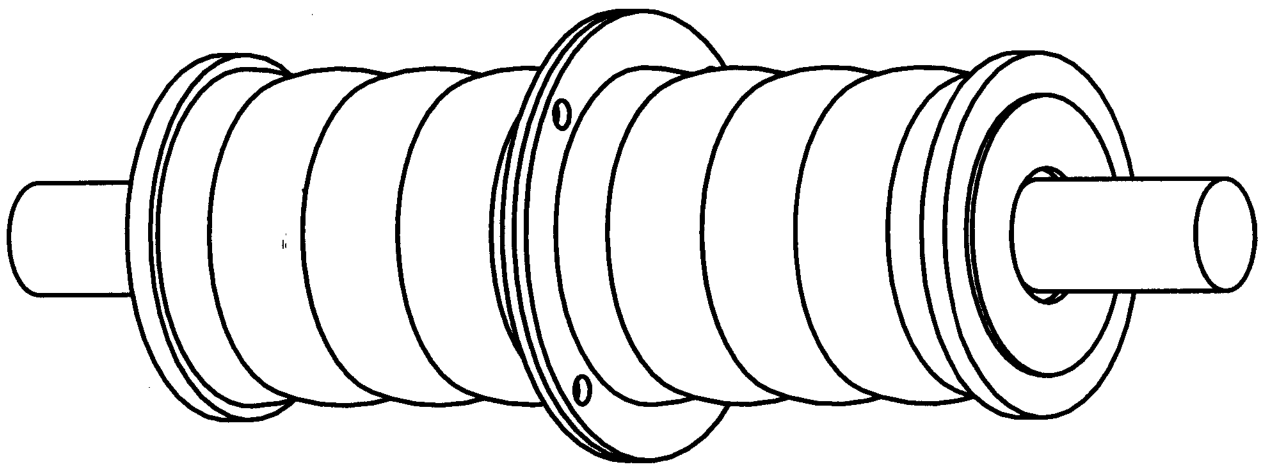
Quick Attach Seal Boot - Conceptual Drawing #1		KES	
Wire-Reinforced Rubber Design		01/06/00	



Quick Attach Seal Boot - Conceptual Drawing #2		KES	
Expandable Aluminum Design		01/06/00	



Quick Attach Seal Boot - Conceptual Drawing #3		KES	
Clam-Shell Design of Molded Polymer		01/06/00	



Quick Attach Seal Boot - Conceptual Drawing #4		KES	
Through-Shaft Application		01/06/00	