# SYNTHETIC FUEL LUBRICITY EVALUATIONS

SOUTHWEST RESEARCH INST., SAN ANTONIO,
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# Synthetic Fuel Lubricity Evaluations

## INTERIM REPORT
## TFLRF No. 367

by

**Edwin A. Frame**
**Ruben A. Alvarez**
**U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI)**
**Southwest Research Institute**
**San Antonio, TX**

for

**U.S. Army TARDEC**
**National Automotive Center (NAC)**
**Warren, MI**

Under Contract to

**U.S. Army TARDEC**
**Petroleum and Water Business Area**
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Contract No. DAAE-07-99-C-L053 (WD23)
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13. ABSTRACT (Maximum 200 words)

Synthetic fuel, designated S-5, was evaluated for fuel lubricity properties in bench scale and rotary injection pump tests. S-5 fuel was evaluated in the BOCLE, SLBOCLE and HFRR bench tests. The effect of MIL-PRF-25017 additive on S-5 lubricity was determined in the bench tests.

Rotary injection pump tests were conducted for up to 500 hours using S-5 fuel and S-5 fuel additized with MIL-PRF-25017. Neat S-5 fuel exhibited poor lubricity in bench screening and in full-scale rotary injection pump evaluations. The addition of MIL-PRF-25017 at recommended treatment rates improved S-5 lubricity to satisfactory levels in the rotary injection pump tests. The SLBOCLE and HFRR bench tests did not detect the lubricity improvement within test repeatabilities when MIL-PRF-25017 was present. The standard BOCLE fuel lubricity test did show reduced wear scar with the additive present.

14. SUBJECT TERMS

| | | | |
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## EXECUTIVE SUMMARY

The U.S. Army Fuels and Lubricants Research Facility (TFLRF) at Southwest Research Institute conducted bench scale and Rotary Fuel Injection Pump Tests to determine the lubricity properties of S-5 synthetic fuel. In the bench tests, neat S-5 fuel was found to have poor lubricity. Addition of corrosion inhibitor/lubricity enhancer additive (MIL-PRF-25017) did not improve fuel lubricity as measured in the SLBOCLE and HFRR bench tests. The additive did reduce wear scar in the BOCLE test.

Rotary Fuel Injection Pump Tests were conducted using Stanadyne arctic rotary injection pumps from the HMMWV. The pumps were mounted on a test stand and operated at 1800 RPM, with the fuel levers in the wide open throttle position (WOT) for a targeted 500-hour test. All evaluations were conducted using duplicate pumps.

The pump stand evaluation of neat S-5 fuel was stopped at 96 and 151 hours, and both pumps were found to have premature wear. Pump 1 (96 hrs) was out of specification at 6 of the 9 RPM performance check points. The pump had low fuel delivery, and inspection of internal pump parts revealed a chipped rotor shoe, and one seized plunger. Operational problems such as low power output and difficult or non-starting would be expected were Pump 1 used in a vehicle. Pump 2 (151 hrs) had high fuel delivery at some RPM. Increased fuel consumption and exhaust smoke would be expected if Pump 2 were in a vehicle.

S-5 fuel additized with the minimum recommended treatment level (12 mg/L) of material from MIL-PRF-25017 qualified products list (QPL) was evaluated in the pump stand test. Both pumps completed the scheduled 500 test hours. The pumps were slightly outside of fuel flow specifications at various RPM. One pump had a slight fuel leak from the drive shaft seal. Overall, while both pumps had some wear indications, with the exception of the leaking seal, they would be expected to perform adequately if installed in a vehicle.

S-5 fuel additized with the maximum recommended treatment level (22.5 mg/L) of material from MIL-PRF-25017 QPL was evaluated in the pump stand test. Both pumps completed the scheduled 500 test hours, and both pumps were slightly out of specification in only one area, slightly high low idle fuel flow. Overall, both pumps would be expected to perform satisfactorily if installed in a vehicle.

Measured pump wear in the roller-roller area was an order of magnitude greater with neat S-5 fuel as compared to S-5 with the recommended treatment of MIL-PRF-25017.

In summary, neat S-5 fuel exhibited poor lubricity in bench screening tests and in full-scale rotary injection pump evaluations. The addition of MIL-PRF-25017 at recommended treatment rates improved S-5 lubricity to satisfactory levels in the rotary injection pump tests. The SLBOCLE and HFRR bench tests did not detect the lubricity improvement within test repeatabilities with MIL-PRF-25017 present. The standard BOCLE fuel lubricity test did show reduced wear scar with the additive present.

## FOREWORD/ACKNOWLEDGMENTS

This work was performed by the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, during the period February 2003 through September 2003 under Contract No. DAAE-07-99-C-L053. The work was funded by the U. S. Army TARDEC National Automotive Center (NAC). The project was administered by the U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan. Mr. Luis Villahermosa (AMSRD-TAR) served as the TARDEC contracting officer's technical representative. Ms. Pat Muzzell served as the project technical monitor.

The authors would like to acknowledge the technical support provided by Doug Yost and Rodney Grinstead, along with the administrative and report-processing support provided by Wendy Mills.

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## I. BACKGROUND AND OBJECTIVE

Fischer-Tropsch (F-T) process synthetic fuels, first produced in the 1920's (1)*, were used by Germany during WWII and South Africa during its embargoed period to overcome petroleum shortages. Synthetic JP-8 is a clean fuel with no sulfur or aromatics, which has historically cost too much to compete with petroleum fuel. Since the mid-1990s, the world's major energy companies have started to develop updated F-T processes that are less expensive to build and operate. The goal is to produce a sulfur-free product for meeting air quality requirements, and to consume natural gas that can no longer be flared due to environmental rules. However, synthetic fuel chemistry differs significantly from petroleum fuels since F-T synthetic fuels are free of aromatic and sulfur compounds. These differences raise many concerns, particularly in respect to the following:

- Providing adequate lubrication of some engine fuel systems and other equipment.
- Maintaining enough seal swell to avoid leakage when fuel systems are switched between petroleum and synthetic fuels.

This report addresses the lubricity characteristics of a synthetic JP-5 fuel.

## II. TEST FUELS

Synthetic JP-5 fuel, Code No. S-5-03-001 (unadditized), produced by Syntroleum Corporation in Tulsa, OK, was used as the base fuel for the lubricity investigations. This fuel is referred to as S-5. Table 1 presents the properties of the base S-5 fuel (designated AL-26943). Syntroleum provided this information:

*Underscored Numbers in parentheses indicate references at the end of the document

Table 1. Properties of S-5 Test Fuel, AL-26943, S-5X-03-001, non-additized, batch 0001, lot 0003

| Property | Method | Contract Specification | Typical | Actual |
|---|---|---|---|---|
| Kinematic Viscosity -20°C, $mm^2/s$ | D-445 | 8.0 max | 5.6 | 6.2 |
| Aromatics (vol%) | D-1319 | 5.0 max | <1.0 | 0.9 |
| Net Heat of Combustion MJ/kg | D-4529 | 42.8 min | 44.2 | 44.1 |
| Smoke Point, mm | D-1322 | 25.0 min | >43 | >43 |
| Aromatics by $^1H$ NMR mol% | D-5292 | .1% | <0.05 | ND |
| Olefins Vol % (g Br2/100g) | D1319 (D1159) | 1.0 (<1.0) max | <0.5 (0.2) | 0.6 |
| Hydrogen Content wt % | D5291 | 13.4 min | 15.5 | 15.6 |
| Distillation Temp °C | D86 (D2887) | | | |
| Initial Boiling Point | | Report | 193 (Report) | 186 (154) |
| 10% Recovered | | 205 max | 197 (Report) | 196 (172 |
| 20% Recovered | | Report | 202 (Report) | 201 (186) |
| 50% Recovered | | Report | 230 (Report) | 220 (224) |
| 90% Recovered | | Report | 252 (Report) | 254 (272) |
| Final Boiling Point | | 300 max | 274 (Report) | 271 (293) |
| Residue (vol%) | | Report | <2 | 1.1 |
| Loss (vol%) | | Report | <2 | 0.3 |
| Density (kg/L @15°C) | D-4052 | 0.75-0.77 | 0.759 | 0.765 |
| Flash Point °C | D-93 | 60 min | 64 | 64 |
| Total Sulfur, max | D-5453 | 0.3 max | <0.0001 | <0.0001 |
| Freezing Point°C | D-5972 | -47 max | -49 | -53 |
| Saybolt Color | D-156 | Report | +30 | +30 |
| Calculated Cetane Index | D-976 | Report | <60 | 69.3 |
| BOCLE,mm | D-5001 | NR | | 0.95 |
| SLBOCLE, g | D-6078 | NR | | 967 |
| HFRR, µm | D-6079 | NR | | 609 |
| NR=Not Required | ND=Not Determined | | | |

## III. FUEL LUBRICITY BENCH TESTS

Fuel Lubricity Bench Tests were conducted using the neat S-5 fuel, S-5 fuel treated with the minimum recommended level of MIL-PRF-25017F (2), and S-5 fuel treated at the maximum level of the same additive. The following bench lubricity tests were performed:

- Ball-On-Cylinder Lubricity Evaluator (BOCLE) Test, ASTM D5001 (Figure 1)
- Scuffing Load BOCLE Test, ASTM D6078 (Figure 1)
- High Frequency Reciprocating Rig (HFRR) Test, ASTM D6079 (Figure 2)

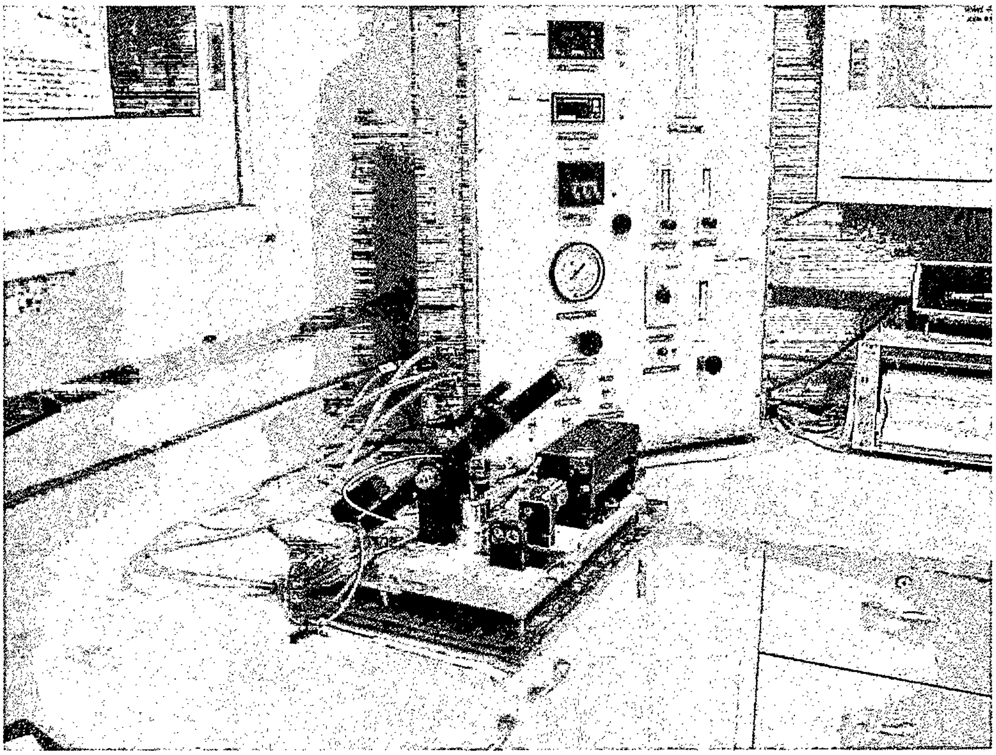

**Figure 1. Instrument for BOCLE and Scuffing Load BOCLE Tests**

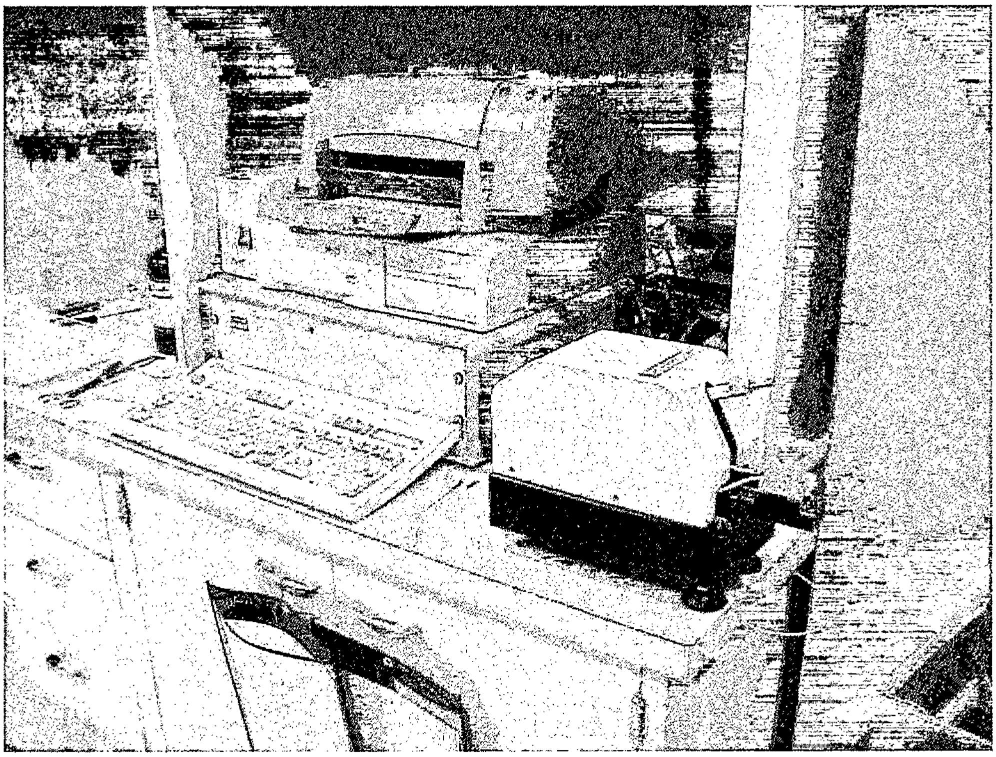

**Figure 2. High Frequency Reciprocating Rig (HFRR)**

The results of fuel lubricity bench tests performed on the neat and additive treated fuel are presented in Table 2. These results confirm the expected low lubricity of the S-5 fuel. Fuel lubricity performance as measured by the SLBOCLE and HFRR was not improved by the addition of MIL-PRF-25017. The results with the additive present were within the test repeatability of the neat S-5 fuel. The MIL-PRF-25017 additive in S-5 fuel did reduce wear scar in the BOCLE test.

**Table 2. TFLRF Fuel Lubricity Bench Test Results**

| Sample Code | AL-26943 | AL-26954 | AL-26953 |
|---|---|---|---|
| Sample Description | S-5 | S-5+min conc of CI (12 mg/L) | S-5+max conc of CI (22.5 mg/L) |
| **Test Methods** | | | |
| **ASTM D6079**<br>HFFR, 60 C, wear in microns | 609 | 662 | 668 |
| **Number of tests** | 6 | 2 | 2 |
| **ASTM D6078:**<br>SLBOCLE, g load | 967 | 1450 | 1333 |
| **Number of tests** | 3 | 3 | 3 |
| **ASTM D5001:**<br>BOCLE, wear scar diameter, mm | 0.95 | 0.76 | 0.68 |
| **Number of tests** | 1 | 1 | 1 |
| **Notes**<br>D6079 repeatability is 80 microns<br>D6078 repeatability is 900 g<br>Corrosion Inhibitor was MIL-PRF-25017 | | | |

## IV. ROTARY INJECTION PUMP TEST STAND EVALUATIONS

Rotary fuel injection pumps are fuel lubricated and sensitive to fuel lubricity. Several pieces of military equipment, including the HMMWV, have rotary injection pumps. Evaluations of S-5 fuel, both neat and with MIL-PRF-25017 additive, were conducted using a rotary injection pump test rig.

### A. Rotary Pump Description

The Stanadyne arctic pumps used for this program are opposed-piston, inlet-metered, positive-displacement, rotary-distributor, fuel-lubricated injection pumps, model

DB2829-4879, for a General Motors application. The arctic pump is equipped with the following hardened components to reduce wear in critical pump areas:

- transfer pump blades
- transfer pump liner
- governor thrust washer
- drive shaft tang

A schematic diagram of the principal pump components is provided in Figure 3.

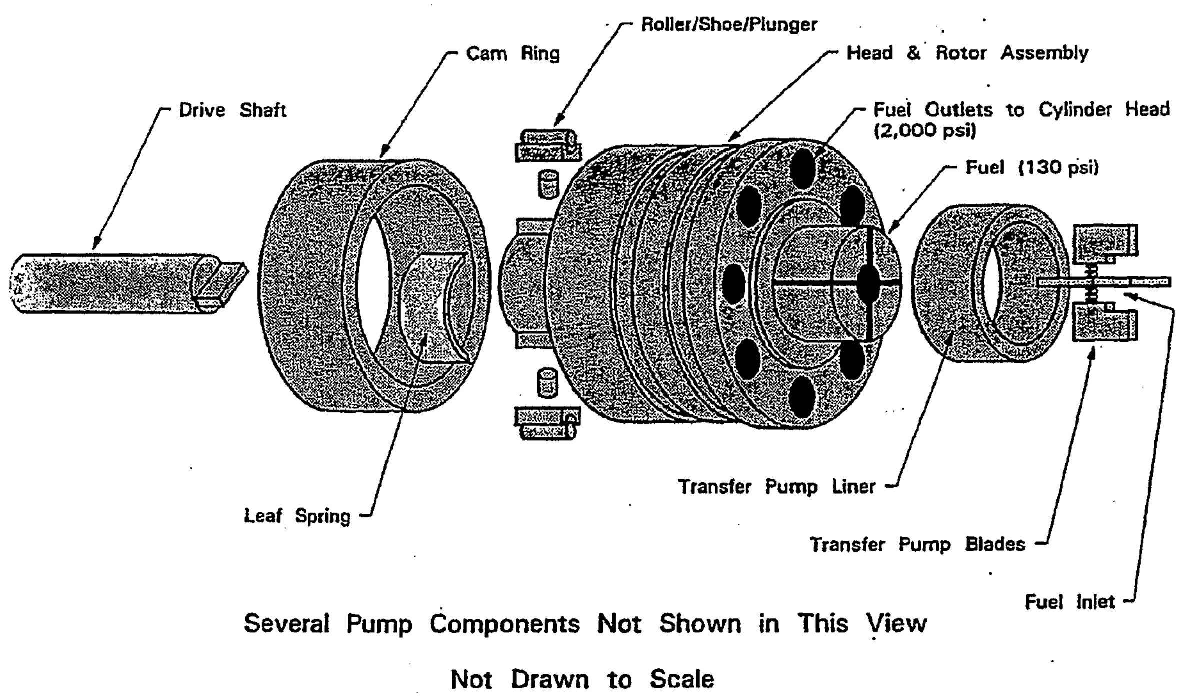


**Figure 3. Schematic Diagram of Principal Pump Components**

Roller-to-roller dimensions on the rotary pumps are pre-set per Stanadyne Diesel Systems Injection Pump Specifications for the DB2829-4879 model, edition 4, dated 05-02-95. The specification calls for a roller-to-roller dimension setting of 1.975 inches ± .0005 inches. Although there are no min-max specifications other than initial assembly values, wear calculation of the roller-to-roller dimension can be used for determining fuel lubricity effects.

## B. Rotary Injection Pump Test Procedure

The test procedure used was similar to a proposed ASTM method entitled "Evaluating Diesel Fuel Lubricity by an Injection Pump Rig." Upon receipt, the pumps were performance tested in preparation for the test-stand evaluations. The injection pumps were paired off for duplicate testing based on closely matched low idle fuel output in cc/1000 strokes. The pumps were mounted on the test stand and operated at 1800 RPM, with the fuel levers in the wide open throttle position (WOT) for a targeted 500-hour (or less) test.

Fuel flow, fuel inlet and outlet temperatures, transfer pump, pump-housing pressures, and RPM were tracked and recorded. Rotameter flow readings reflect the injected fuel from the eight fuel injectors in each collection canister. Any wear in the fuel injection pump metering section is reflected as an increased or reduced rotameter flow reading.

The fuel inlet temperature was controlled at temperatures ranging from 100 to 106°F. Inlet temperature variations directly affect the fuel return temperature, which is a function of accelerated pump wear.

The transfer pump pressure is the regulated pressure the metal blade transfer pump supplies to the pump metering section. With low lubricity fuels, wear may occur in the transfer pump blades, blade slot, and eccentric liner. Wear in these areas generally causes the transfer pump pressure to decrease. However, because the transfer pump has a pressure regulator, significant wear needs to occur in the transfer pump before the fuel pressure drops below the operating range allowed in the pump specification.

The housing pressure is the regulated pressure in the pump body that affects fuel metering and timing. With low lubricity fuel, wear occurs in high-fuel-pressure-generating opposed plungers and bores, and between the hydraulic head and rotor. Leakage from the increased diametrical clearances of the plunger bores and the hydraulic head and rotor results in increased housing pressures. Increased housing pressure reduces metered fuel and retards injection timing.

## C. Pump Test Stand

The rotary pumps were tested on a Unitest stand with a common fuel supply. The fuel system used for the tests is depicted in Figure 4 and the test stand is shown in Figure 5.

To insure a realistic test environment, the mounting arrangement and drive gear duplicate that of the 6.2L engine. The fuel was maintained in a 55-gallon epoxy-lined drum and continuously recirculated throughout the duration of each test. A centrifugal pump provided a positive head of 3 psi at the inlet to the test pumps. A cartridge filter corresponding to that used in the 6.2L engine in the HMMWV was used to remove wear debris and particulate contamination. Finally, a 5-kW Chromalox explosion-resistant circulation heater produced the required fuel inlet temperature.

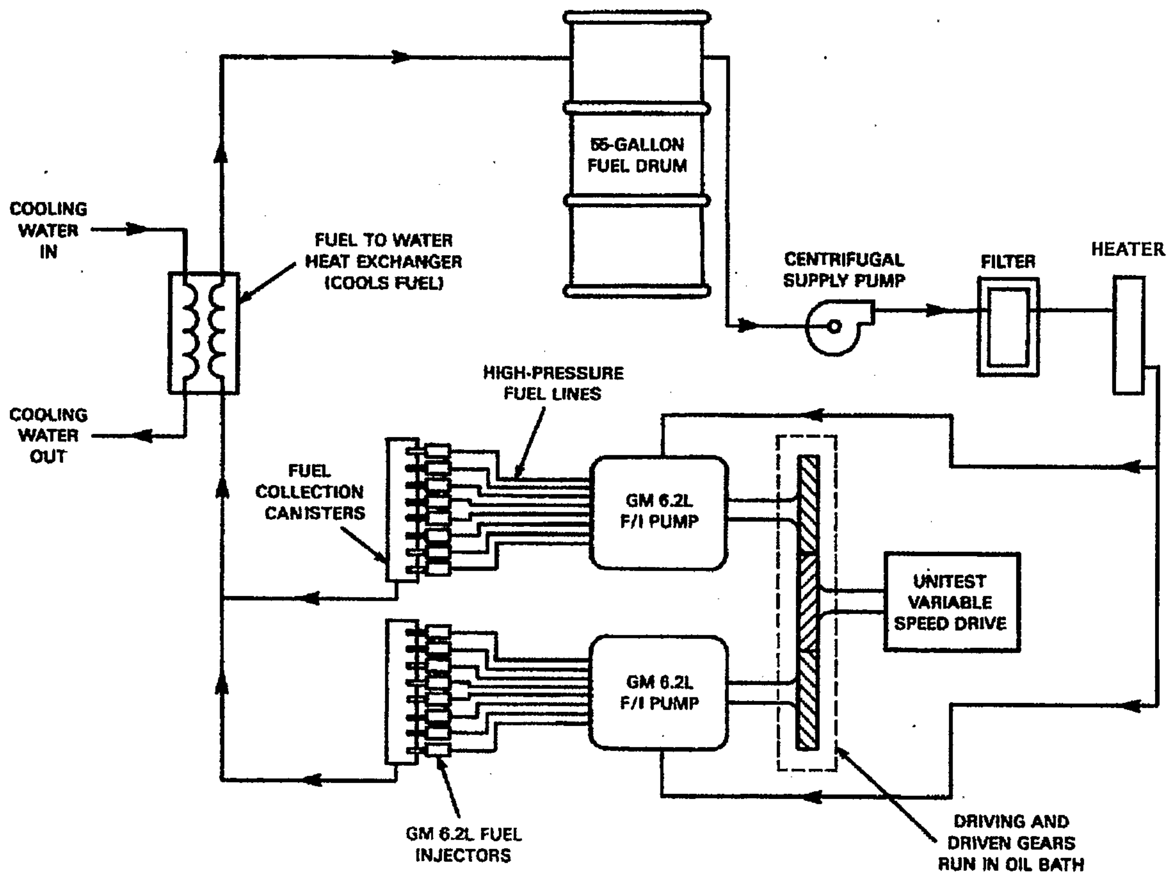


**Figure 4. Fuel System Schematic**

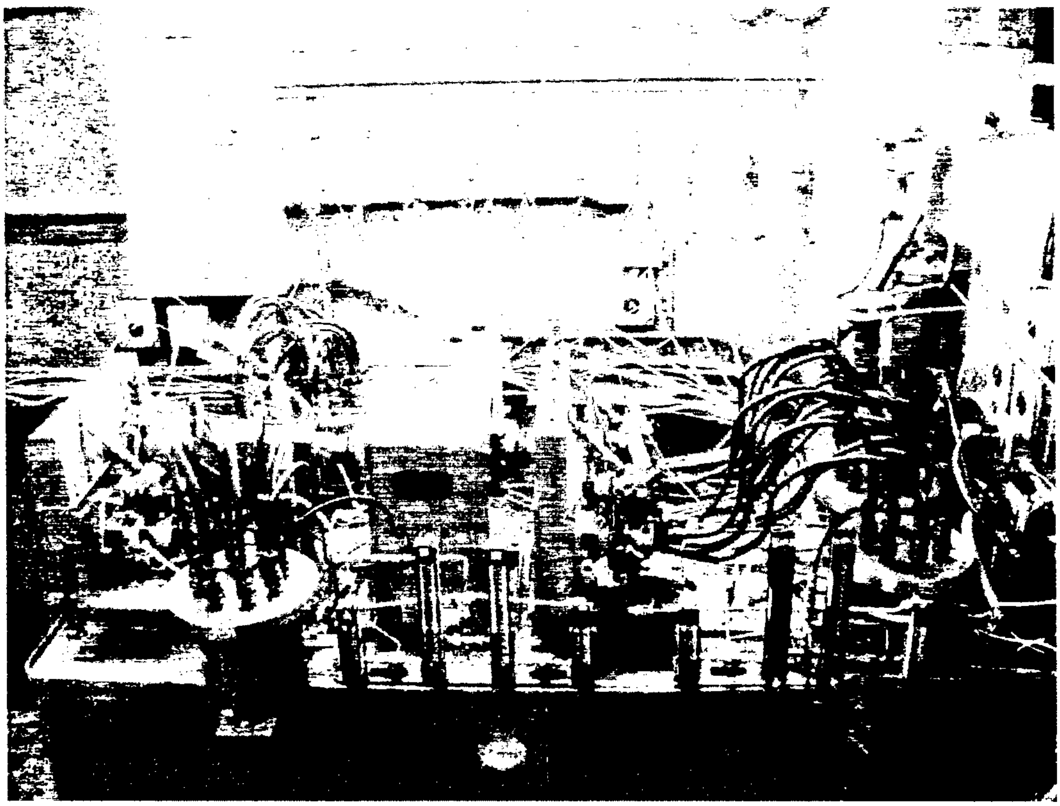

**Figure 5. Pump Stand**

The high-pressure outlets from the pumps were connected to eight Model NA52X fuel injectors for a 6.2L engine and assembled in a collection canister. Fuel from both canisters was then returned to the 55-gallon drum. A separate line was used to return excess fuel from the governor housing to the fuel supply. Fuel-to-water heat exchangers on the return lines from the injector canisters and the governor housing were used to cool the fuel.

Data logger recorded pump stand RPM, fuel inlet pressure, fuel inlet and return temperature, transfer pump, and pump housing pressures. Fuel flow rotameter readings were obtained manually three times during working days and one time daily on weekends and holidays. The entire rig was equipped with safety shutdowns that would turn off the drive motor in the event of low fluid level in the supply drum, high inlet and return fuel temperature (150° F), low or high transfer pump and housing pressure, or fire. The intent of the emergency shutdown capability was to allow the test stand to run unattended during non-working hours. Since high-return fuel temperature is a precursor of accelerated wear, this failsafe feature reduced the possibility of head and rotor seizure.

# V. ROTARY PUMP EVALUATIONS AND RESULTS

## A. Test Fuels

Test 1, pumps 1 and 2, was conducted using the neat non-treated S-5 fuel. The scuffing load BOCLE (SLBOCLE) value of the non-treated S-5 fuel, (AL-26943), was 967 grams. Test 2, pumps 3 and 4, and Test 3, pumps 5 and 6, were conducted using S-5 fuel (AL-26943) blended with ONDEO NALCO 5403 Inhibitor, Corrosion/Lubricity Improver additive at the minimum and maximum concentration rate of 12 and 22.5 mg/L, as per QPL-25017-19, 15 March 2001 (2). The SLBOCLE of the blended fuels, (AL-26854 and Al-26953) were 1400 and 1330 grams, respectively. Table 3 presents specifics on Tests 1 through 3.

**Table 3. Tests 1 through 3**

| Test | Pump | Rig | Pump Type | Fuel Description |
|---|---|---|---|---|
| 1 | 1 | 3 | New Arctic | Neat Synthetic S-5 Fuel AL-26943 |
| 1 | 2 | 4 | New Arctic | Neat Synthetic S-5 Fuel AL-26943 |
| 2 | 3 | 1 | New Arctic | Neat Synthetic S-5 Fuel treated with 12mg/L NALCO 5403 Corrosion/Lubricity Improver AL-26959 |
| 2 | 4 | 2 | New Arctic | Neat Synthetic S-5 Fuel treated with 12mg/L NALCO 5403 Corrosion/Lubricity Improver AL-26959 |
| 3 | 5 | 3 | New Arctic | Neat Synthetic S-5 Fuel treated with 22.5 mg/L NALCO 5403 Corrosion/Lubricity Improver AL-26970 |
| 3 | 6 | 4 | New Arctic | Neat Synthetic S-5 Fuel treated with 22.5 mg/L NALCO 5403 Corrosion/Lubricity Improver AL-26970 |

## B. Rotary Pump Tests

### 1. Test 1 Neat S-5 Fuel (Pumps 1 & 2)

Two new arctic pumps were mounted on pump stand Rigs 3 and 4, and the test stand was slowly ramped to 1000 RPM and operated for five minutes. For the next five minutes the test stand was then incrementally ramped to 1800 RPM until the inlet fuel temperature reached the specified temperature of 104°F, and the first temperature, flow, and pressure readings were recorded.

Early into the test, the pump outlet temperatures increased slightly, and a corresponding rise in rotameter flows was noted, which indicated accelerated wear. Twenty-four hours into the test, rotameter flows increased from 81.5 to 100cc on Pump 1 and from 77.5 to 90cc on Pump 2. As the fuel flow increased, the inlet pressure fell to 0 psi and was adjusted back to 3 psi.

Approximately 46 hours into the test, recorded data revealed that the inlet fuel pressure on Pump 1 increased to 11 psi and fuel flow decreased to 43cc, indicating that some event was causing extreme accelerated wear. Fuel flow continued to increase on Pump 2, indicating accelerated wear on this pump also. All other parameters remained at normal ranges; however, in order to preclude a complete seizure of the head and rotor assembly on Pump 1, the test stand was shut down at 95.6 hours of testing. The top cover on Pump 1 was removed for inspection. Slight metal debris was observed in the top chamber of the pump (Figure 6). Metal debris was also found in the top cover electric shut-off solenoid (Figure 7). Pump 1 was removed from the test stand, and testing resumed with Pump 2.

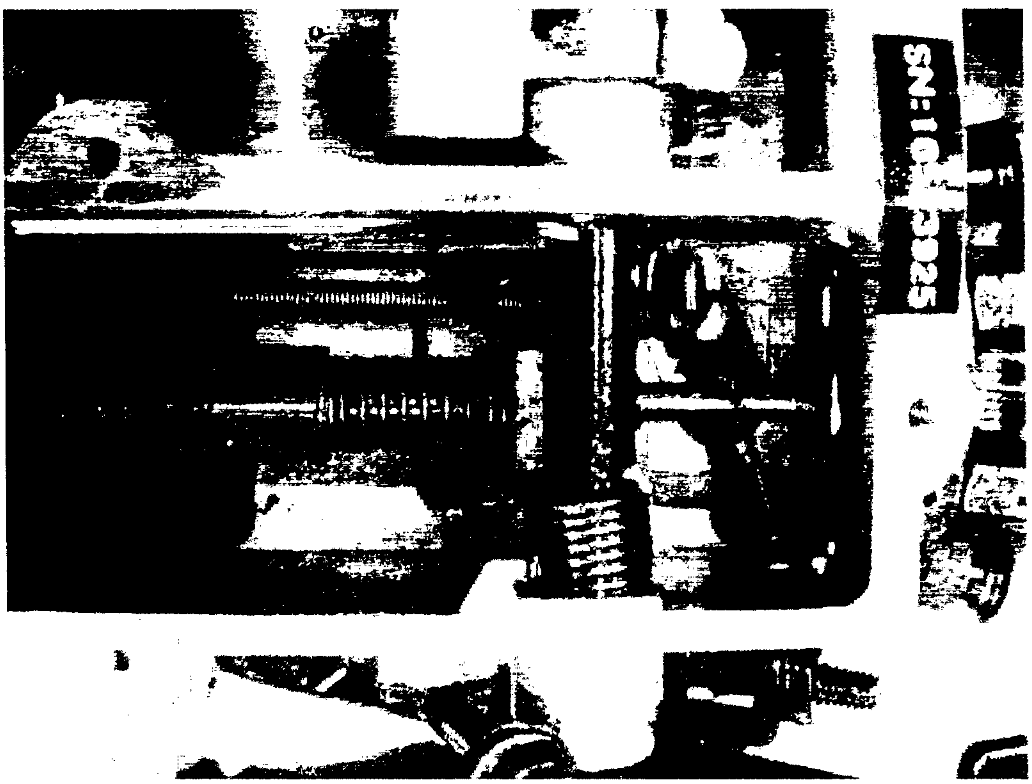


**Figure 6. Test 1 Pump 1: Pump Chamber Wear Debris**

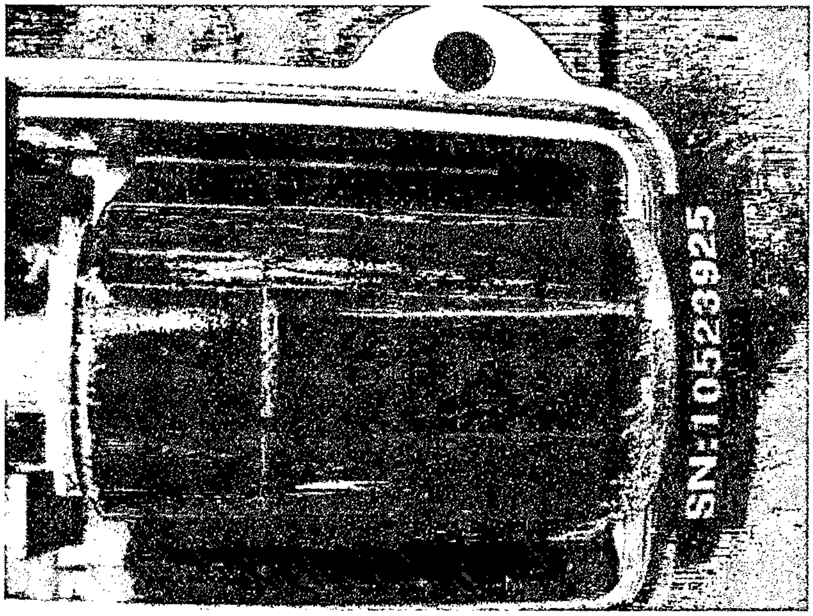


**Figure 7. Test 1 Pump 1: Metal Shavings on Solenoid**

The test progressed until the test stand shut down after 151 hours. Logged data revealed that increased fuel outlet temperature triggered the automatic shutdown of the test stand solenoid, which is used to prevent imminent seizure of the head and rotor assembly. The top cover was removed from Pump 2; however, there was no evidence of wear debris in the chamber or the electric shut-off solenoid (Figures 8 and 9).

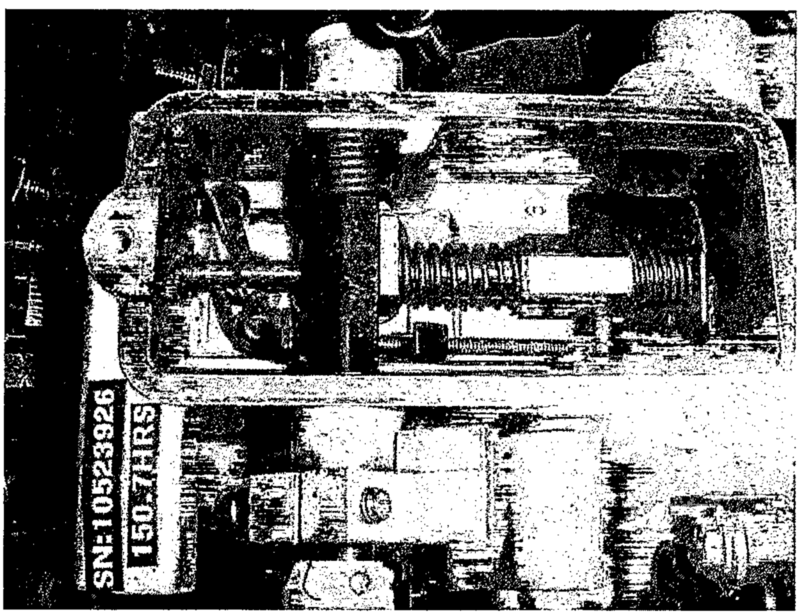


**Figure 8. Test 1 Pump 2: Debris Free Pump Chamber**

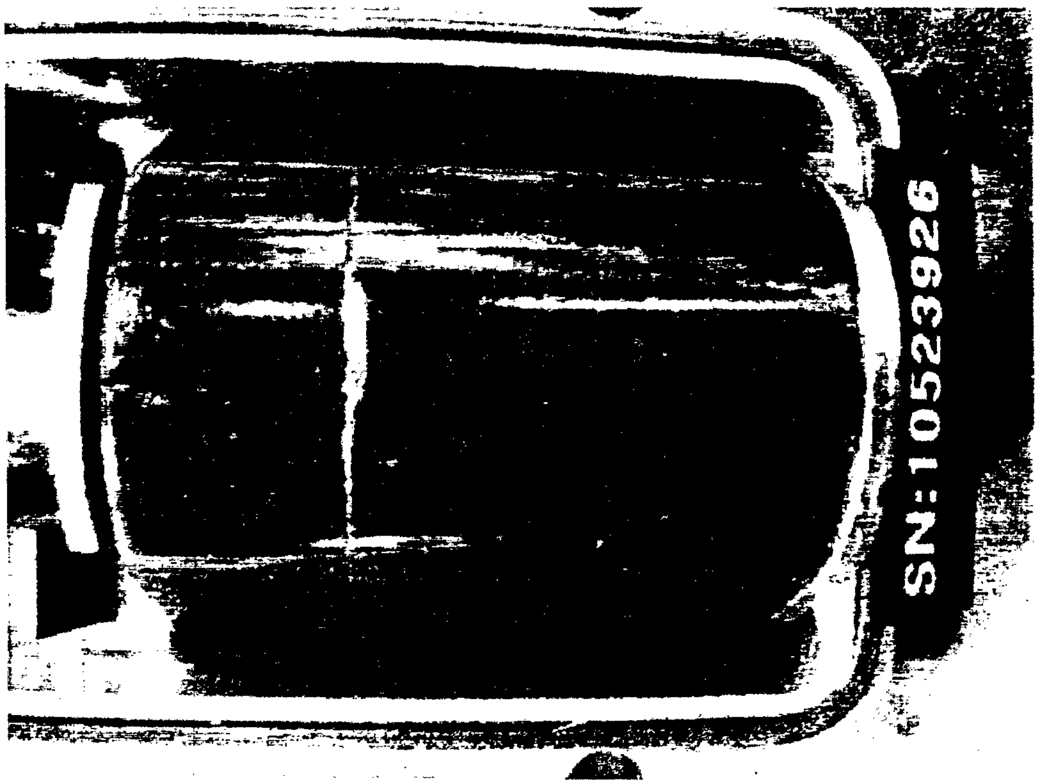


**Figure 9. Test 1 Pump 2: Debris Free Solenoid**

Test stand parameter plots in Appendix A (Figures A-1 through A-4) show that both pumps exhibited a marked increase in rotameter fuel flow readings and a corresponding increase of fuel-return temperatures at the onset of the test. These parameters are precursors in accelerated pump wear. Pump 1 shows a significant increase in transfer pump pressure when the rotameter fuel flow decreases.

Pump 2 was removed from the test stand, rinsed, and prepared for post-test performance evaluations. Results of these evaluations are shown in Table 4. Differences occurred between pre- and post- test results on 9 of 18 performance sequences for Pump 1. Decreased fuel delivery at 750, 1800, 200, and 75 RPM were the most critical of the out-of-specification performance checks. This pump would not be expected to perform adequately in a typical vehicle application. The very low fuel flow delivered at cranking speed would probably not be sufficient to start the engine. Pump 2 exhibited an increase in fuel flow at 1000 and 1750 RPM; in a typical vehicle application, rough idle and visible smoke emissions would be expected.

**Table 4. Rotary Pump Performance Checks Test 1**

| Pump Model: DB2829-4879 Arctic | Test Fuel: S-5 AL-26943 | Pump No.1 Rig 3 SN10523925 | | | Pump No. 2 Rig 4 SN10523926 | | |
|---|---|---|---|---|---|---|---|
| | | Date: 04/07/03 | | Hours: 95.6 | Date: 4/10/03 | | Hours: 150.7 |
| **RPM** | **Specification** | **Pre-Test** | **Post-Test** | **Change** | **Pre-Test** | **Post-Test** | **Change** |
| 1000 | Trans Pump Pres. 60-62 psi | 61 | **66** | 5 | 61 | 60 | -1 |
| | Return Fuel 225-375 cc | 325 | **395** | 70 | 225 | 275 | 50 |
| | Fuel Delivery 56 cc max. | 50.2 | 34 | -16.2 | 50.4 | **78.5** | 28.1 |
| 325 | Low Idle 12-16 cc | 14 | 14.1 | 0.1 | 13.5 | 14.9 | 1.4 |
| | Housing Pres. 8-12 psi | 8 | 8 | 0 | 8 | **7.75** | -0.25 |
| | C.A.S. 0-1 Degree | 0 | 0 | 0 | 0 | 0 | 0 |
| 1750 | Fuel Delivery 48-53 cc | 50 | **35** | -15 | 49 | **70.7** | 21.7 |
| | Advance 1.25-5.25 Degrees | 4.5 | **6.5** | 2 | 4.5 | 4 | -0.5 |
| 750 | F.C. 21.5-23.5 cc | 22 | **31.4** | 9.4 | 22.1 | 21.5 | -0.6 |
| | Advance 1.25-3.75 Degrees | 2.2 | **0** | -2.2 | 2 | 2.25 | 0.25 |
| 1800 | Fuel Delivery 48 cc min. | 49 | **34.8** | -14.2 | 48.7 | 67.4 | 18.7 |
| | Transfer Pump Pressure | 90 | 94 | 4 | 89 | 85 | -4 |
| | Housing Pressure psi. | 6 | 5 | -1 | 6.5 | 7 | 0.5 |
| 1900 | Fuel Delivery 33 cc min. | 42 | 34.8 | -7.2 | 36 | 59.6 | 23.6 |
| 2025 | High Idle 15 cc max. | 1.2 | 2.6 | 1.4 | 1.4 | 2.5 | 1.1 |
| | Trans. Pump Pres.125psi max. | 116 | 116 | 0 | 117 | 120 | 3 |
| 200 | Fuel Delivery 45 cc min. | 45 | **21.6** | -23.4 | 46 | 74.7 | 28.7 |
| | Shut-Off 4 cc max. | 0 | 0 | 0 | 0 | 0 | 0 |
| 75 | Fuel Delivery 28 cc min. | 28 | **8.8** | -19.2 | 37.2 | 52.8 | 15.6 |
| | Trans. Pump Pres. 12 psi min | 19 | 18 | -1 | 20 | 20 | 0 |
| **Bold Values are out of specification** | | | | | | | |

Post-test inspection of Pumps 1 and 2 revealed that the transfer pump blades had light wear at the liner contact and that each had a broken blade spring. The transfer pump liner had slight wear on 5 to 10% of the contact surface area for Pump 1 and 30% for Pump 2. Both liners were functional. The rotor shafts on both pumps exhibited varying degrees of scarring from the broken transfer pump blade springs.

Shoe and roller assemblies were excessively worn at the contact point with the leaf spring. The surface where the rollers make contact in the shoe assemblies on both pumps showed a galled surface, and the rollers were pitted and abraded. The back of the shoes (where the plunger contacts) showed excessive wear. One of the shoes on Pump 1 wore so excessively at the contact point with the leaf spring that it traveled away from the holder until it made contact with the cam ring assembly, causing a piece to chip off the end of the shoe.

Normally a metal chip would create a binding condition, which would immediately seize the head and rotor assembly and shear the drive shaft. However in this instance, the metal chip pulverized, creating highly accelerated wear throughout the pump that ultimately caused the right plunger to seize and to chronically reduce the fuel flow to the transfer pump.

Figures 10 through 15 show the shoe and roller assemblies, the back of the shoe holders, and the fuel plunger assemblies. The chipped shoe assembly can be seen in Figure 10 while the seized plunger is shown in Figure 14. Figure 16 shows deep scarring at the upper ports of the rotor shaft on Pump 1, and light scarring can be seen at the bottom of the rotor shaft in Figure 17.

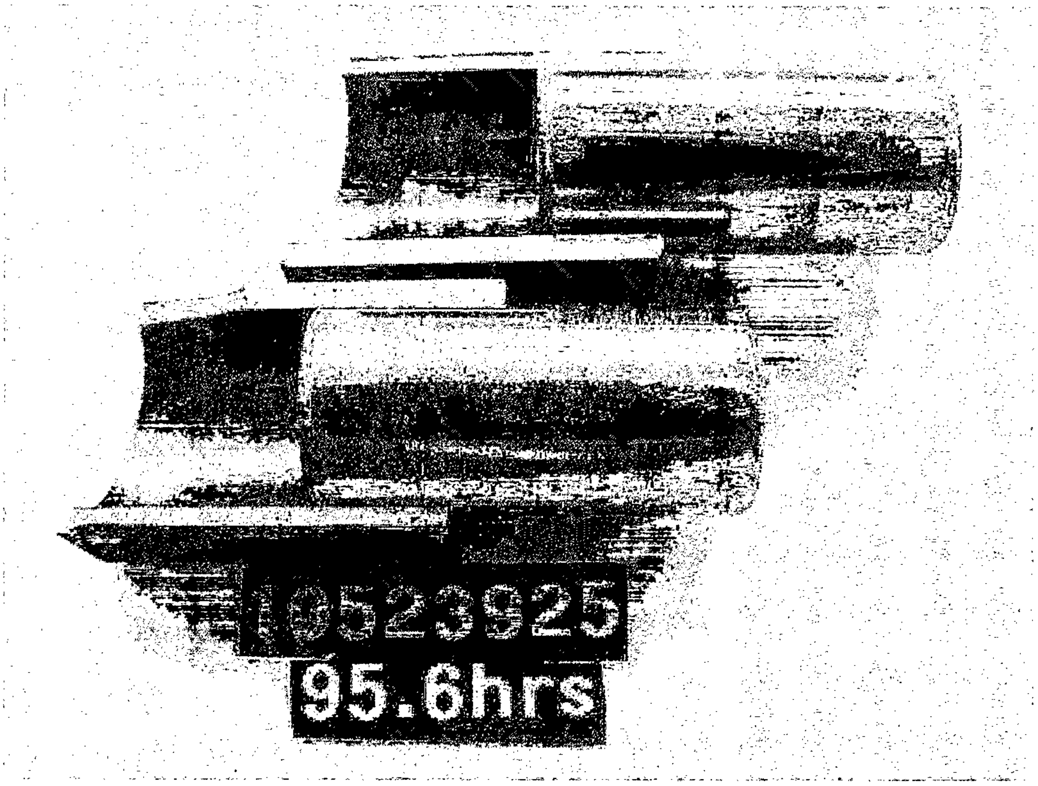


**Figure 10. Test 1 Pump 1: Chipped Shoe Wear**

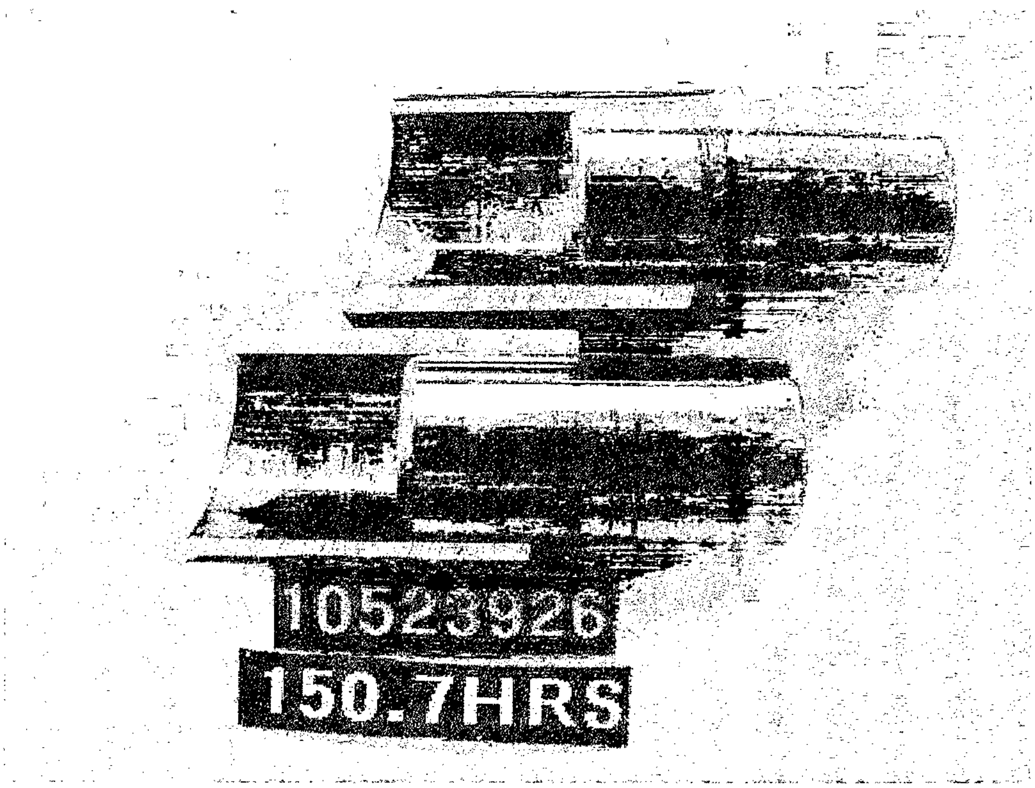


**Figure 11. Test 1 Pump 2: Shoe and Roller Wear**


Figure 12. Test 1 Pump 1: Shoe Back and Roller Wear

Figure 13. Test 1 Pump 2: Shoe Back and Roller Wear

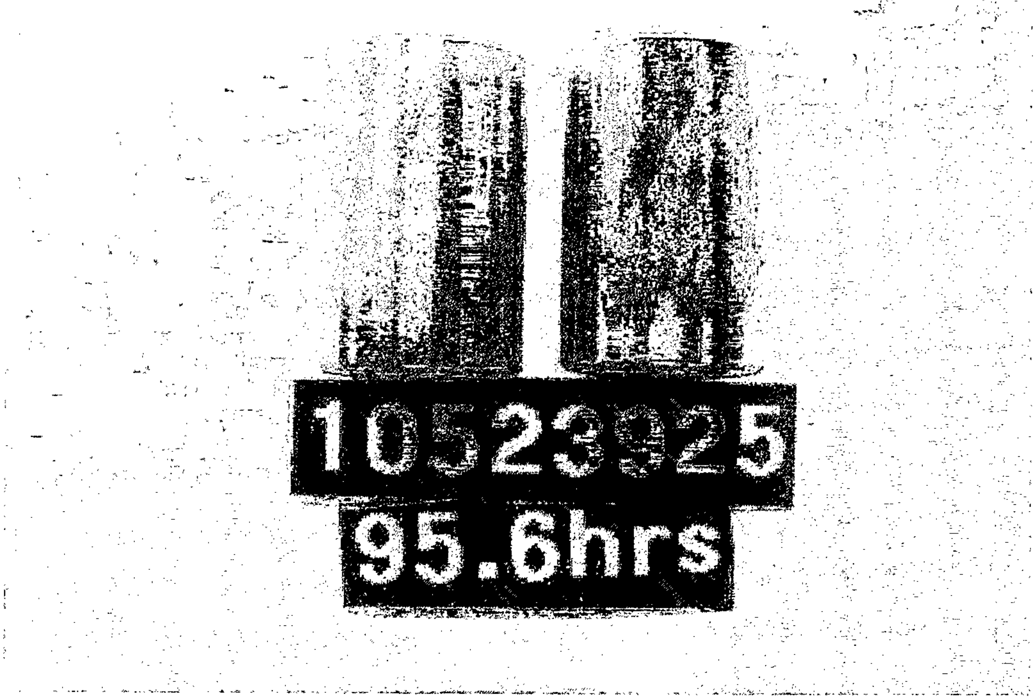


Figure 14. Test 1 Pump 1: Plunger Assembly Wear

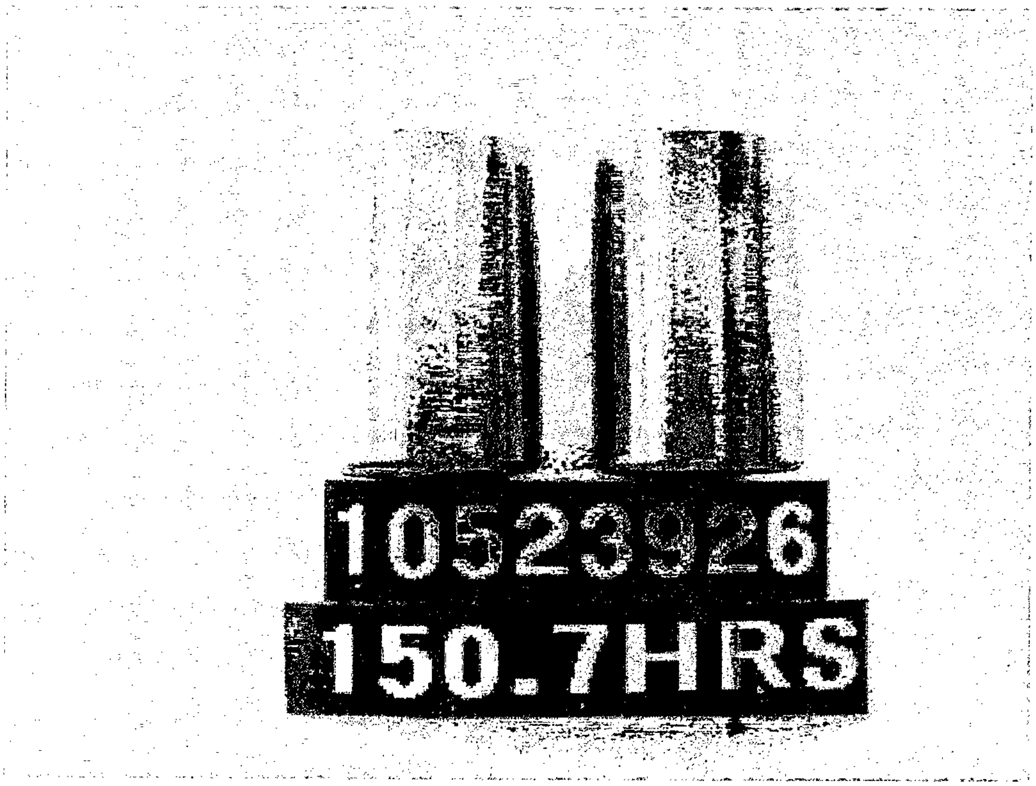


Figure 15. Test 1 Pump 2: Plunger Assembly Wear

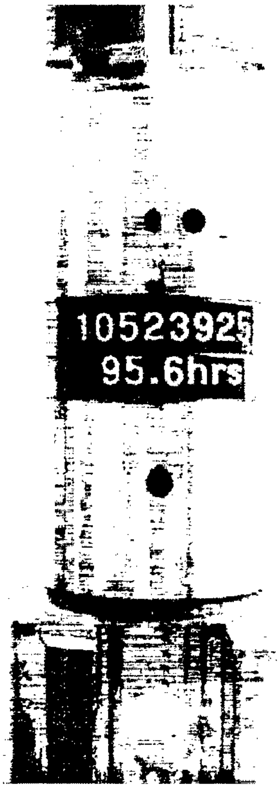


**Figure 16. Test 1 Pump 1: Rotor Shaft Wear**

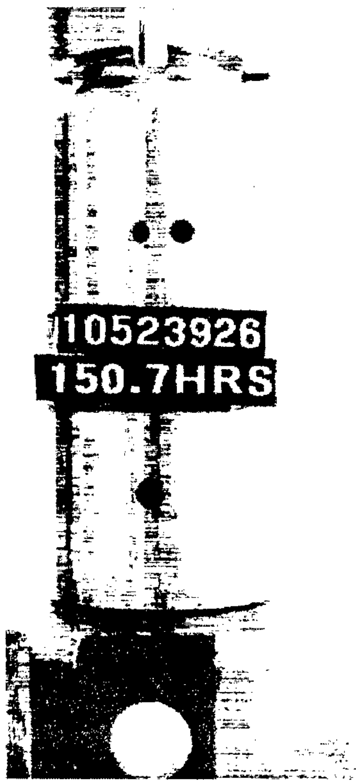


**Figure 17. Test 1 Pump 2: Rotor Shaft Wear**

## 2. Test 2 (Pumps 3 & 4) S-5 Fuel with 12 mg/L MIL-PRF-25017 and Test 3 (Pumps 5 & 6) S-5 Fuel with 22.5 mg/L MIL-PRF-25017

Tests 2 and 3 were run simultaneously with Pumps 3 and 4 mounted on rigs R1 and R2. Pumps 5 and 6 were mounted on rigs L3 and L4. Tests 2 and 3 were initiated using Neat Synthetic S-5 Fuel treated with ONDEO NALCO 5403 Corrosion/Lubricity Improver additive at the minimum and maximum concentration rate of 12mg/L and 22.5 mg/L, respectively, as per QPL-25017-19, 15 March 2001. The tests progressed with no problems, and after 250 hours of operation, all pump parameters were operating normally. The test stand was manually shut down to change to new batches of treated fuel for the second 250-hour segment.

The test stand was again slowly ramped to 1800 RPM until the inlet fuel temperature reached the specified temperature of 104°F. The first temperature, flow, and pressure readings were then recorded. Testing progressed without incident throughout the second 250-hour segment.

Figures A-5 through A-12 (Appendix A) are plots from initiation to 500 hours of the fuel flow, fuel return, inlet temperatures, transfer pump, and pump housing pressures. The only notable difference from start to finish of testing can be seen in Figure A-8 where the pump housing pressure in Pump 3 shows a slight increase at approximately 400 hours. Elevated pump housing pressure results when clearances in plunger and bores and the hydraulic head and rotor assemblies increase due to wear and allow internal pump leakage. High housing pressure can reduce metered fuel and retard engine timing.

The pumps were removed from the test stand after 500 hours of operation, and the top housing covers were removed on all four pumps. No wear debris was found in any of the pumps. Figure 18 presents a representative view of the top chamber of all of the pumps. The pumps were flushed and prepared for post-test performance evaluations. As shown in Tables 5 and 6, only slight performance degradation occurred with each pump. Each of the pumps had out-of-specification fuel flow at low idle speed, which resulted from wear in the metering valve. However, the elevated fuel flow would probably not be apparent in a typical vehicle application.

Pump 3 also exhibited out-of-specification fuel flows at 1750 and 200 RPM, which were the result of a broken transfer blade spring. Neither anomaly would be apparent in a typical vehicle application. The most significant change in performance parameters was the increase in fuel flow at 2025 RPM (high idle) on Pump 4, which indicates wear in the governor weight and linkage assemblies. The reduced fuel flow at maximum engine speed protects against engine over-speed, which can lead to engine and/or drivetrain damage under certain operating conditions. This parameter can be corrected by an external adjusting screw.

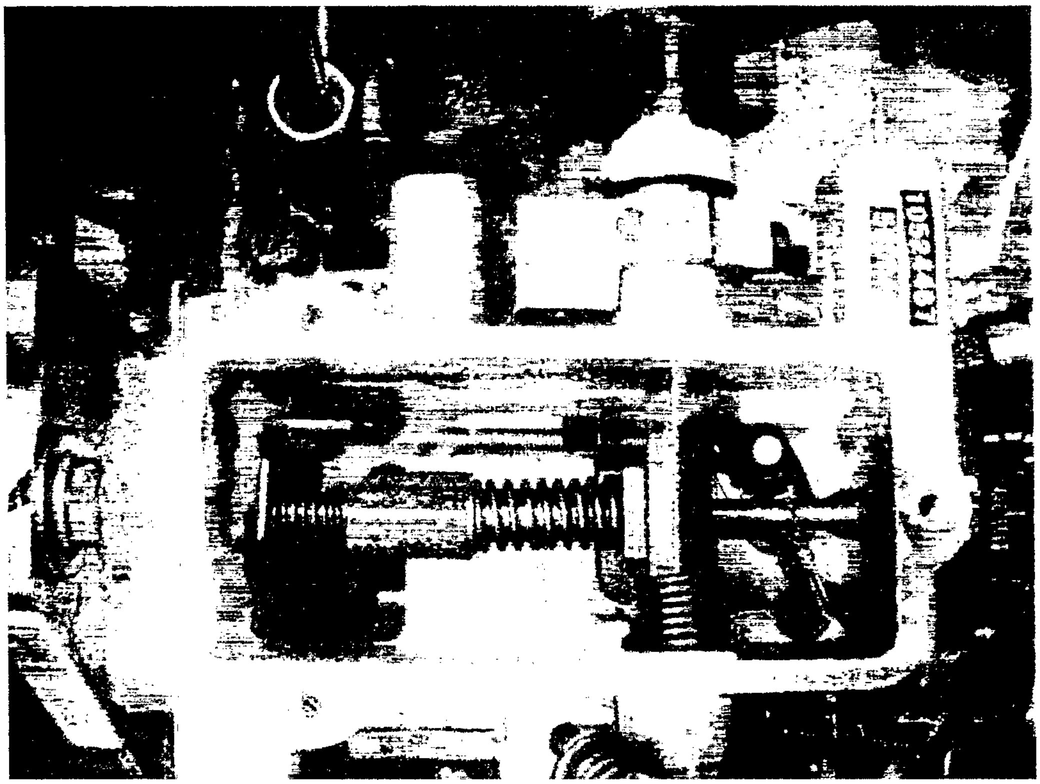

**Figure 18. Test 2 Pump 4: Pump Chamber**

**Table 5. Rotary Pump Performance Checks Test 2**

| Pump Model: DB2829-4879 Arctic | Test Fuel: S-5 Fuel w/ Min CI Treatment AL-26959, AL-26972 | Pump 3 Rig 1 SN10523924 | | | Pump 4 Rig 2 SN10524467 | | |
|---|---|---|---|---|---|---|---|
| | | Date: 5/19/03 | Hours: 500 | | Date: 5/19/03 | Hours: 500 | |
| **RPM** | **Specification** | **Pre-Test** | **Post-Test** | **Change** | **Pre-Test** | **Post-Test** | **Change** |
| 1000 | Trans. Pump Pres. 60-62 psi | 61 | 61 | 0 | 61 | 61 | 0 |
| | Return Fuel 225-375 cc | 225 | 228 | 3 | 250 | 275 | 25 |
| | Fuel Delivery 56 cc max. | 50.7 | 46.4 | -4.3 | 50.4 | 55.4 | 5 |
| 325 | Low Idle 12-16 cc | 12 | **21.8** | 9.8 | 12.5 | **17.2** | 4.7 |
| | Housing Pres. 8-12 psi | 8 | **7.5** | -0.5 | **7.5** | **6.75** | 0.75 |
| | C.A.S. 0-1 Degree | 0 | 0 | 0 | 0 | 0 | 0 |
| 1750 | Fuel Delivery 48-53 cc | 50.8 | **47.5** | -3.3 | 49 | 51.5 | 2.5 |
| | Advance 1.25-5.25 Degrees | 3.75 | 4.5 | 0.75 | 5.25 | 5.25 | 0 |
| 750 | F.C. 21.5-23.5 cc | 22 | 22.1 | 0.1 | 22 | 22.2 | 0.2 |
| | Advance 1.25-3.75 Degrees | 1.75 | 2 | 0.25 | 2 | 2.5 | 0.5 |
| 1800 | Fuel Delivery 48 cc min. | 50 | 48 | -2 | 48.8 | 50.8 | 2 |
| | Transfer Pump Pressure | 89 | 82 | -7 | 88 | 87 | -1 |
| | Housing Pressure psi. | 6.5 | 6.5 | 0 | 6.5 | 6 | -0.5 |
| 1900 | Fuel Delivery 33 cc min. | 36.8 | 47.2 | 10.4 | 44.3 | 50.2 | 5.9 |
| 2025 | High Idle 15 cc max. | 1 | 2.5 | 1.5 | 1 | **23.2** | 22.2 |
| | Trans.Pump Pres.125psi max. | 117 | 104 | -13 | 116 | 99 | -17 |
| 200 | Fuel Delivery 45 cc min. | 48 | **35.6** | -12.4 | 48 | 50.6 | 2.6 |
| | Shut-Off 4 cc max. | 0 | 0 | 0 | 0 | 0 | 0 |
| 75 | Fuel Delivery 28 cc min. | 39.4 | 30 | -9.4 | 40 | 41 | 1 |
| | Trans. Pump Pres. 12 psi min | 19 | 22 | 3 | 19 | 21.5 | 2.5 |
| **Bold Values are out of specification** | | | | | | | |

**Table 6. Rotary Pump Performance Checks Test 3**

| Pump Model: DB2829-4879 Arctic | Test Fuel: S-5 Fuel w/ Max CI Treatment AL-26970, AL-26973 | Pump No. 5 Rig 3 SN10524469 | | | Pump No. 6 Rig 4 SN10524470 | | |
|---|---|---|---|---|---|---|---|
| | | Date: 5/19/03 | Hours: 500 | | Date: 5/19/03 | Hours: 500 | |
| **RPM** | **Specification** | **Pre-Test** | **Post-Test** | **Change** | **Pre-Test** | **Post-Test** | **Change** |
| 1000 | Trans. Pump Pres. 60-62 psi | 61 | 61 | 0 | 61 | 61 | 0 |
| | Return Fuel 225-375 cc | 225 | 225 | 0 | 225 | 225 | 0 |
| | Fuel Delivery 56 cc max. | 51.2 | 55.3 | 4.1 | 50.2 | 55.6 | 5.4 |
| 325 | Low Idle 12-16 cc | 15 | **16.5** | 1.5 | 15.4 | **19.6** | 4.2 |
| | Housing Pres. 8-12 psi | 8 | 8 | 0 | 8 | 8.25 | 0.25 |
| | C.A.S. 0-1 Degree | 0 | 0 | 0 | 0 | 0 | 0 |
| 1750 | Fuel Delivery 48-53 cc | 49.4 | 51 | 1.6 | 50 | 51.9 | 1.9 |
| | Advance 1.25-5.25 Degrees | 4 | 4.75 | 0.75 | 4.75 | 5.25 | 0.5 |
| 750 | F.C. 21.5-23.5 cc | 22.7 | 22.5 | -0.2 | 21.9 | 22 | 0.1 |
| | Advance 1.25-3.75 Degrees | 2.25 | 2.25 | 0 | 2 | 3 | 1 |
| 1800 | Fuel Delivery 48 cc min. | 49.3 | 50.1 | 0.8 | 50.1 | 51 | 0.9 |
| | Transfer Pump Pressure | 84 | 89 | 5 | 87 | 84 | -3 |
| | Housing Pressure psi. | 6 | 7 | 1 | 7 | 7.5 | 0.5 |
| 1900 | Fuel Delivery 33 cc min. | 42 | 49.9 | 7.9 | 38 | 49.5 | 11.5 |
| 2025 | High Idle 15 cc max. | 2.3 | 15 | 12.7 | 1 | 12.1 | 11.1 |
| | Trans. Pump Pres.125psi max. | 117 | 104 | -13 | 117 | 100 | -17 |
| 200 | Fuel Delivery 45 cc min. | 45 | 48.6 | 3.6 | 45.2 | 49 | 3.8 |
| | Shut-Off 4 cc max. | 0 | 0 | 0 | 0 | 0 | 0 |
| 75 | Fuel Delivery 28 cc min. | 32.6 | 39.3 | 6.7 | 32.3 | 38.1 | 5.8 |
| | Trans. Pump Pres. 12 psi min | 20 | 26 | 6 | 17 | 23 | 6 |

**Bold Values are out of specification**

Post-test inspection of Pump 3 (S-5 with min CI/LI) revealed light wear on the transfer pump blades and decreased fuel flow at 200 and 1750 RPM (seen in Table 5 above) caused by one broken blade spring. The transfer pump liner had slight wear on 50 to 75% of the contact surface area, and it was still functional. The rotor was scarred at inlet and outlet ports from the broken blade spring's debris. Very light wear was found on opposing plungers, and some scarring was found in the shoes from the roller contact. The rollers had pit marks from the broken blade spring's debris, and light wear was found in the cam ring.

On Pump 4 (S-5 with min CI/LI), the transfer pump blades had light wear in usual spots, and no springs were broken. The transfer pump liner had wear on 75 to 80% of the contact surface area and was still serviceable. The rotor had light wear marks at the inlet and outlet ports. The left opposing plunger is polished at shoe contact and shows slight wear. The shoes were lightly worn at the leaf spring contact, and the roller area looked very good. The rollers had some discoloration but were otherwise in very good condition. Finally, the cam ring had a very light wear pattern.

Pump 5 (S-5 with max CI/LI) had light wear in the transfer pump blades and springs; the transfer pump liner had wear on 75 to 80% of the surface area and was still serviceable. The rotor had light wear marks at the outlet port, and the opposing plungers were lightly worn. The right shoe assembly had a small dimple at the plunger contact and light scratches at roller contact. The rollers had minute flakes of metal imbedded in the surface and were not smooth. The cam ring had polished spots at the roller contacts.

On Pump 6 (S-5 with max CI/LI), the transfer pump blades and springs were lightly worn. The transfer pump liner had wear on 80% of the surface area and was still in serviceable condition. The rotor showed wear at the outlet ports, and the opposing plungers were lightly worn and in good condition. In the shoe assemblies, light scratches were found in area of roller contact, and small dimples were evident at plunger contact. The rollers, as in Pump 5, had imbedded metal flakes that were hard to see but could be felt. Polished spots could be seen on the cam ring where the rollers made contact.

The effects of the light wear observed after 500 hours of testing would not be expected to be discernable in a typical vehicle installation. These pumps would be expected to operate normally at all sequences. Figures 19 through 22 are representative of the condition of components for all four aforementioned pumps. The shoe and roller assembles for Pump 3 are shown in Figure 19. Figure 20 shows the back of the shoe assemblies of Pump 5 where the opposing plungers make contact. The opposing plungers for Pump 4 are shown in Figure 21, and the rotor shaft for Pump 6 is shown in Figure 22.

## C. Rotary Pump Wear Measurements

The transfer pump and plunger assemblies are integral to the fuel-metering system in the Stanadyne rotary pump, and by function are the most affected with low lubricity fuel. Accelerated wear in either the transfer pump blades or the roller-to-roller dimension results in a change of fueling condition that jeopardizes the quantity of fuel injected into the hydraulic head assembly. Wear in the transfer pump blades limits the amount of pressure necessary to maintain the proper amount of fuel in the chamber where opposing plungers, actuated by the rollers and cam, inject the metered fuel into the hydraulic head assembly. Roller-to-roller dimension variations alter the travel distance of the plungers, effectively changing metered fuel, injector pressure, and injection timing.

Table 7 presents the end-of-test, roller-to-roller dimension measurement results. There were no out-of-specification transfer blade measurements; conversely, all of the roller-to-roller dimensions were greater than the 1.9750 ± 0.0005-inch assembly specification. As shown in Table 7, the post-test differences between the neat S-5 fuel and the S-5 fuel treated with MIL-PRF-25017 are substantial.

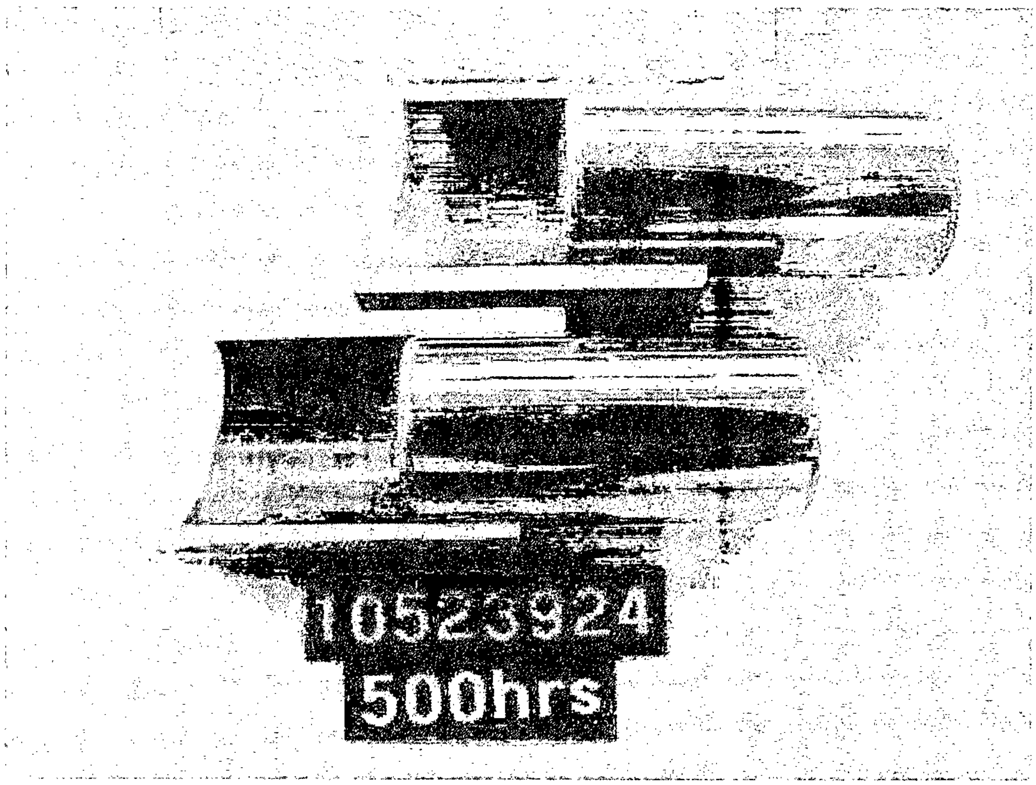


Figure 19. Test 2 Pump 3: Shoe and Roller Assembly

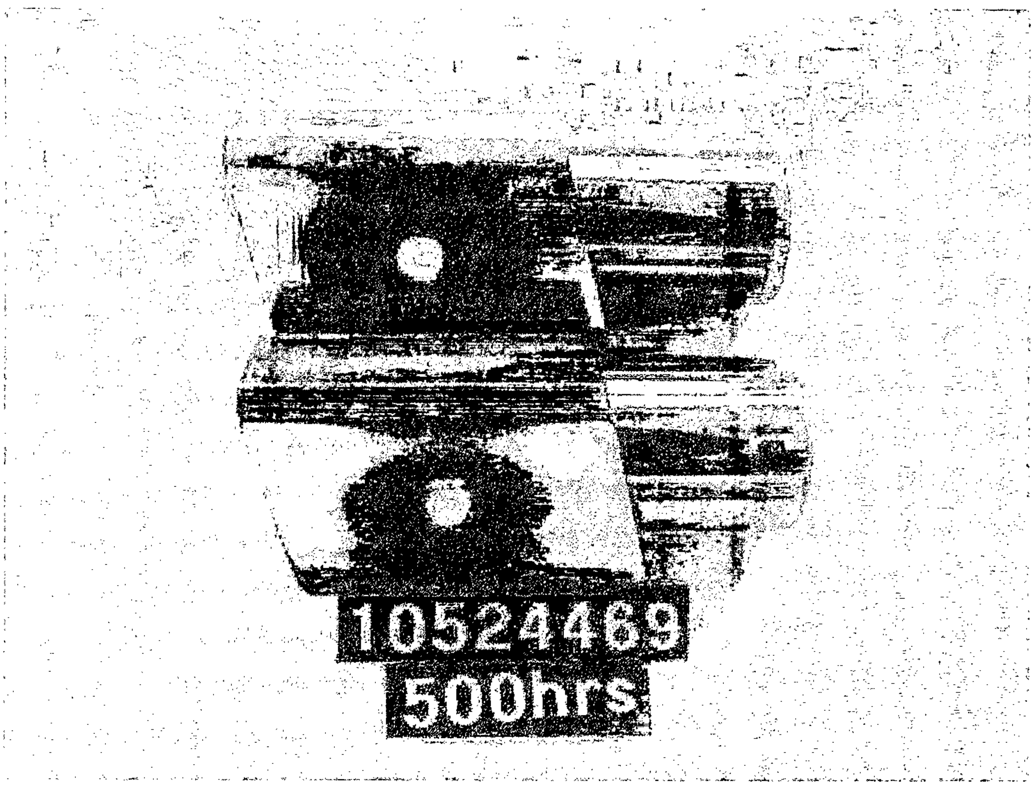


Figure 20. Test 3 Pump 5: Back of Shoe and Roller Assembly

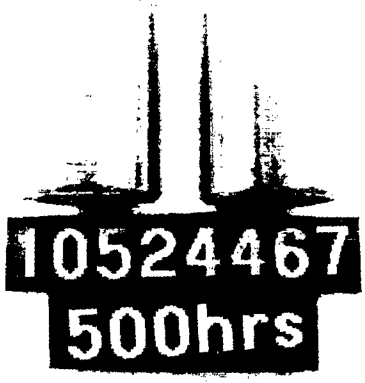


**Figure 21. Test 2 Pump 4: Plunger Assembly**

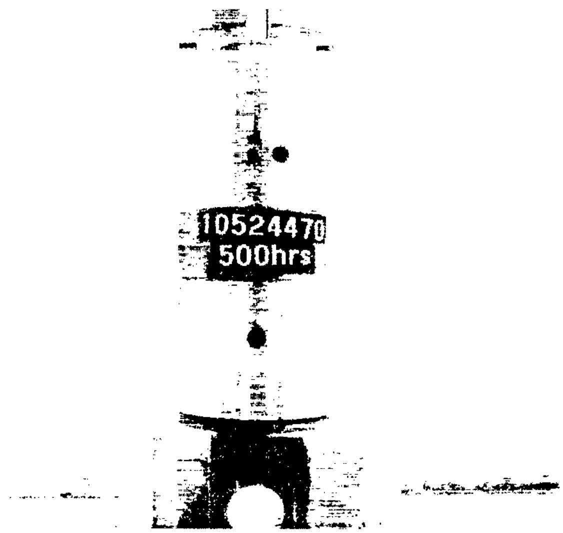


**Figure 22. Test 3 Pump 6: Rotor Shaft Assembly**

| Table 7. Roller-to-Roller Dimension Measurements | | | | | | |
|---|---|---|---|---|---|---|
| **Test No** | **Pump No.** | **Test Hours** | **Pre- Test** | **Post-Test** | **Change** | **Fuel Type** |
| 1 | 1 | 95.6 | 1.975* | 2.013 | 0.038 | Neat S-5 |
| 1 | 2 | 150.7 | 1.975 | 2.002 | 0.027 | Neat S-5 |
| | | | | | | |
| 2 | 3 | 500 | 1.975 | 1.978 | 0.003 | Neat S-5 + Minimum Additive |
| 2 | 4 | 500 | 1.975 | 1.973 | 0.002 | Neat S-5 + Minimum Additive |
| | | | | | | |
| 3 | 5 | 500 | 1.975 | 1.977 | 0.002 | Neat S-5 + Maximum Additive |
| 3 | 6 | 500 | 1.975 | 1.976 | 0.001 | Neat S-5 + Maximum Additive |
| *= Roller-to-Roller Dimension Pump Assembly Specification – 1.975 in ± 0.0005 in | | | | | | |

## VI. FUEL INJECTOR RESULTS

Fuel injector nozzle tests were performed in accordance with procedures set forth in an approved 6.2L diesel engine manual using diesel nozzle tester J 29075-B. Nozzle testing is comprised of the following checks:

- Nozzle Opening Pressure
- Leakage
- Chatter
- Spray Pattern

Each test is considered independent of the others, and if any one of the tests is not satisfied, the injector should be replaced.

The normal opening pressure specification for these injectors is 1500 psig minimum. The specified nozzle leakage test involves pressurizing the injector nozzle to 1400 psig and holding for 10 seconds – no fuel droplets should separate from the injector tip. The chatter and spray pattern evaluations are subjective. A sharp audible chatter from the injector and a finely misted spray cone are required.

New Model NA52X injectors were used for each test. The injector performance tests and rating results are shown in Tables 8 through 10. Table 8, shows injectors used with neat S-5 fuel. Twelve of the 16 injectors passed the requirements. Only one injector failed to meet the opening pressure specification and also failed the leakage, chatter, and spray pattern checks. Three other injectors had satisfactory opening pressure, but did not satisfy the requirements of the other checks. All the injectors tested with S-5 fuel plus MIL-PRF-25017 additive at the minimum required treatment level satisfied all of the required checks. Injectors used with S-5 fuel plus MIL-PRF-25017 additive at the maximum allowed treatment level are shown in Table 10. The three injectors shown in bold characters failed all of the required checks.

**Table 8. Injector Nozzle Test**

**Test 1, , Neat S-5 Fuel, AL-26854**

**Pump 1, Test Hours-95.6 (17-03 - 24-03) – Pump 2, Test Hours – 150.7 (25-03 – 32-03)**

| Injector No. | Opening Pressure 1500 psig min | | Leakage Test No drops for 10 sec. @ 1400 psig. | | Chatter Test Audible Chatter | | Spray Pattern Fine Spray | |
|---|---|---|---|---|---|---|---|---|
| | Pre-Test | Post- Test | Pre-Test | Post-Test | Pre-Test | Post-Test | Pre-Test | Post-Test |
| 17-03 | 1850 | 1625 | Pass | Pass | Pass | **Fail** | Pass | **Fail** |
| 18-03 | 1825 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 19-03 | 1850 | 1675 | Pass | Pass | Pass | **Fail** | Pass | **Fail** |
| 20-03 | 1875 | 1700 | Pass | Pass | Pass | Pass | Pass | Pass |
| 21-03 | 1850 | 1675 | Pass | Pass | Pass | **Fail** | Pass | **Fail** |
| 22-03 | 1850 | 1675 | Pass | Pass | Pass | Pass | Pass | Pass |
| 23-03 | 1825 | 1650 | Pass | Pass | Pass | Pass | Pass | Pass |
| 24-03 | 1850 | 1700 | Pass | Pass | Pass | Pass | Pass | Pass |
| 25-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 26-03 | 1850 | 1550 | Pass | Pass | Pass | Pass | Pass | Pass |
| 27-03 | 1825 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 28-03 | 1825 | 1550 | Pass | Pass | Pass | Pass | Pass | Pass |
| 29-03 | 1825 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 30-03 | 1850 | 1550 | Pass | Pass | Pass | Pass | Pass | Pass |
| 31-03 | 1850 | **1000** | Pass | **Fail** | Pass | **Fail** | Pass | **Fail** |
| 32-03 | 1850 | 1600 | Pass | Pass | Pass | Pass | Pass | Pass |

**Pass Rate: 12 of 16**

**Bold Characters = Fail**

**Table 9. Injector Nozzle Test**

**Test 2, Neat S-5 Fuel Treated with 12mg/L Corrosion/Lubricity Improver AL-26959 – AL-26972**
**Pump 2, Test Hours-500 (1-03 - 16-03) – Pump 4, Test Hours – 500 (9-03 – 16-03)**

| Injector No. | Opening Pressure 1500 psig min | | Leakage Test No drops for 10 sec. @ 1400 psig. | | Chatter Test Audible Chatter | | Spray Pattern Fine Spray | |
|---|---|---|---|---|---|---|---|---|
| | Pre-Test | Post- Test | Pre-Test | Post-Test | Pre-Test | Post-Test | Pre-Test | Post-Test |
| 1-03 | 1875 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 2-03 | 1825 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 3-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 4-03 | 1825 | 1550 | Pass | Pass | Pass | Pass | Pass | Pass |
| 5-03 | 1850 | 1600 | Pass | Pass | Pass | Pass | Pass | Pass |
| 6-03 | 1875 | 1600 | Pass | Pass | Pass | Pass | Pass | Pass |
| 7-03 | 1850 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 8-03 | 1850 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 9-03 | 1825 | 1525 | Pass | Pass | Pass | Pass | Pass | Pass |
| 10-03 | 1850 | 1525 | Pass | Pass | Pass | Pass | Pass | Pass |
| 11-03 | 1825 | 1525 | Pass | Pass | Pass | Pass | Pass | Pass |
| 12-03 | 1850 | 1550 | Pass | Pass | Pass | Pass | Pass | Pass |
| 13-03 | 1900 | 1600 | Pass | Pass | Pass | Pass | Pass | Pass |
| 14-03 | 1875 | 1600 | Pass | Pass | Pass | Pass | Pass | Pass |
| 15-03 | 1850 | 1600 | Pass | Pass | Pass | Pass | Pass | Pass |
| 16-03 | 1875 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |

**Pass Rate: 16 of 16**

**Bold Characters = Fail**

**Table 10. Injector Nozzle Test**

**Test 3, Neat S-5 Fuel Treated with 22.5mg/L Corrosion/Lubricity Improver AL-26970 –AL-26973**
**Pump No. 3, Test Hours-500 (1-03 - 16-03) – Pump 4, Test Hours – 500 (9-03 – 16-03)**

| Injector No. | Opening Pressure 1500 psig min | | Leakage Test No drops for 10 sec. @ 1400 psig. | | Chatter Test Audible Chatter | | Spray Pattern Fine Spray | |
|---|---|---|---|---|---|---|---|---|
| | Pre-Test | Post- Test | Pre-Test | Post-Test | Pre-Test | Post-Test | Pre-Test | Post-Test |
| 33-03 | 1850 | 1650 | Pass | Pass | Pass | Pass | Pass | Pass |
| 34-03 | 1850 | **1000** | Pass | **Fail** | Pass | **Fail** | Pass | **Fail** |
| 35-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 36-03 | 1850 | 1650 | Pass | Pass | Pass | Pass | Pass | Pass |
| 37-03 | 1875 | 1650 | Pass | Pass | Pass | Pass | Pass | Pass |
| 38-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 39-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 40-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 41-03 | 1875 | **150** | Pass | **Fail** | Pass | **Fail** | Pass | **Fail** |
| 42-03 | 1850 | **850** | Pass | **Fail** | Pass | **Fail** | Pass | **Fail** |
| 43-03 | 1850 | 1525 | Pass | Pass | Pass | Pass | Pass | Pass |
| 44-03 | 1825 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 45-03 | 1850 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |
| 46-03 | 1875 | 1675 | Pass | Pass | Pass | Pass | Pass | Pass |
| 47-03 | 1850 | 1575 | Pass | Pass | Pass | Pass | Pass | Pass |
| 48-03 | 1875 | 1625 | Pass | Pass | Pass | Pass | Pass | Pass |

**Pass Rate: 13 of 16**

**Bold Characters = Fail**

The injectors used for these pump tests are subjected to wide open throttle operation for the duration of the test. Post-test fuel injector condition and performance test results may not be indicative of typical in-vehicle field operation. An injector with decreased opening pressure will probably "fail" the chatter test and more than likely "fail" the spray pattern test. In a typical vehicle application, this condition could cause erratic engine operation, increased smoke emission, or decreased power, which may actually go unnoticed depending on the severity of the condition. Likewise, a leakage test failure would cause increased smoke emission upon engine start, which may also go unnoticed.

# VII. SUMMARY

## A. Lubricity Bench Tests

- Neat S-5 fuel exhibited poor lubricity in the BOCLE, SLBOCLE and HFRR tests.
- S-5 blends containing the recommended treatment levels of MIL-PRF-25017 had improved lubricity in the standard BOCLE test.
- Considering test repeatability of the SLBOCLE and HFRR tests, no improvement in fuel lubricity was detected for the S-5 fuel treated with additive per MIL-PRF-25017 QPL.

## B. Rotary Injection Pump Tests

- Fuel lubricity of neat S-5 fuel was not adequate. The pumps completed 96 and 151 hours of a scheduled 500-hour test.
  - Pump performance was degraded as one pump failed 9 of 17 post-test performance checks with low fueling rates.
  - The second pump had high fueling rates that are a precursor to extensive wear and low fueling rates.
  - Both pumps had excessive roller-to-roller measured wear.
  - If either of these pumps were used in typical vehicle applications, performance problems would be expected.

- Fuel lubricity of S-5 fuel was improved by addition of either the minimum or maximum recommended treatment rate of additive per MIL-PRF-25017 QPL. All pumps completed the scheduled 500-hour test.
  - At the minimum recommended treatment level, only slight degradation of pump performance checks was observed in three or four areas.
  - At the maximum recommended treatment level, only one post-test performance check was out of specification.
  - Roller-to-roller measured wear was an order of magnitude less than when the neat S-5 fuel was used.

### C. Fuel Injector Condition

- Overall, fuel injector condition was not strongly affected by the S-5 fuel or S-5 with the MIL-PRF-25017 QPL additive.

## VIII. CONCLUSION

In conclusion, neat S-5 fuel exhibited poor lubricity characteristics. The addition of the maximum recommended concentration of MIL-PRF-25017 QPL additive improved the lubricity performance to a satisfactory level in the rotary injection pump test. The SLBOCLE and HFRR bench tests were not sensitive to the minimum and maximum treatment levels of MIL-PRF-25017 QPL additive.

## IX. RECOMMENDATIONS

- S-5 fuel should be treated with lubricity improver for use in military ground equipment. If MIL-PRF-25017 QPL additive is used, it should be at the maximum recommended treatment.
- The additive response of other additives per MIL-PRF-25017 QPL additive in S-5 fuel should be investigated.
- The effect of added aromatics on the lubricity of S-5 fuel should be determined.
- The additive response of various additives per MIL-PRF-25017 QPL in the S-5 with added aromatics should be determined.
- The additive response of commercial, diesel fuel lubricity improvers should be determined in S-5 fuel with and without added aromatics.
- An improved fuel lubricity bench test is needed that is sensitive to small quantities of lubricity improver additives.

## X. REFERENCES


1. Fischer, F., and Tropsch, H., 1926. "Jerfahren zur Gewinnung Mehrgliedriger Paraffinkohlenwasserstofle aus Kohlenoxyden und Wasserstoff auf Katalystischem Wege," German Patent, DRP 484337.

2. Qualified Products List, MIL-PRF-25017, "Inhibitor, Corrosion/Lubricity Improver, Fuel Soluble," QPL-25017-19, 15 March 2001.

3. Alvarez, R.A. and Frame, E.A., "Component Time to Failure Using Jet A/Jet A-1," Draft Report to Defense Energy Support Center (DESC), DESC contract No. SPO60099 D5944, Delivery Order 0006, June 2002.

# APPENDIX A
# TEST STAND PARAMETER PLOTS

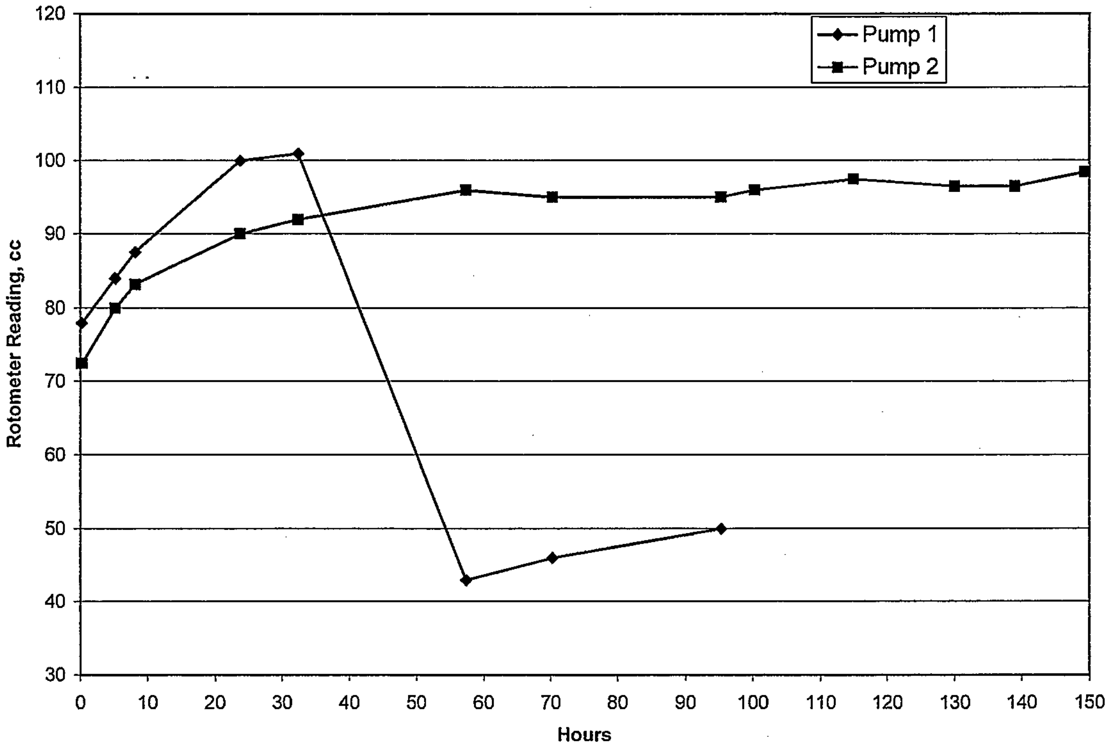


**Figure A-1. Test 1 - Rotameter Readings**

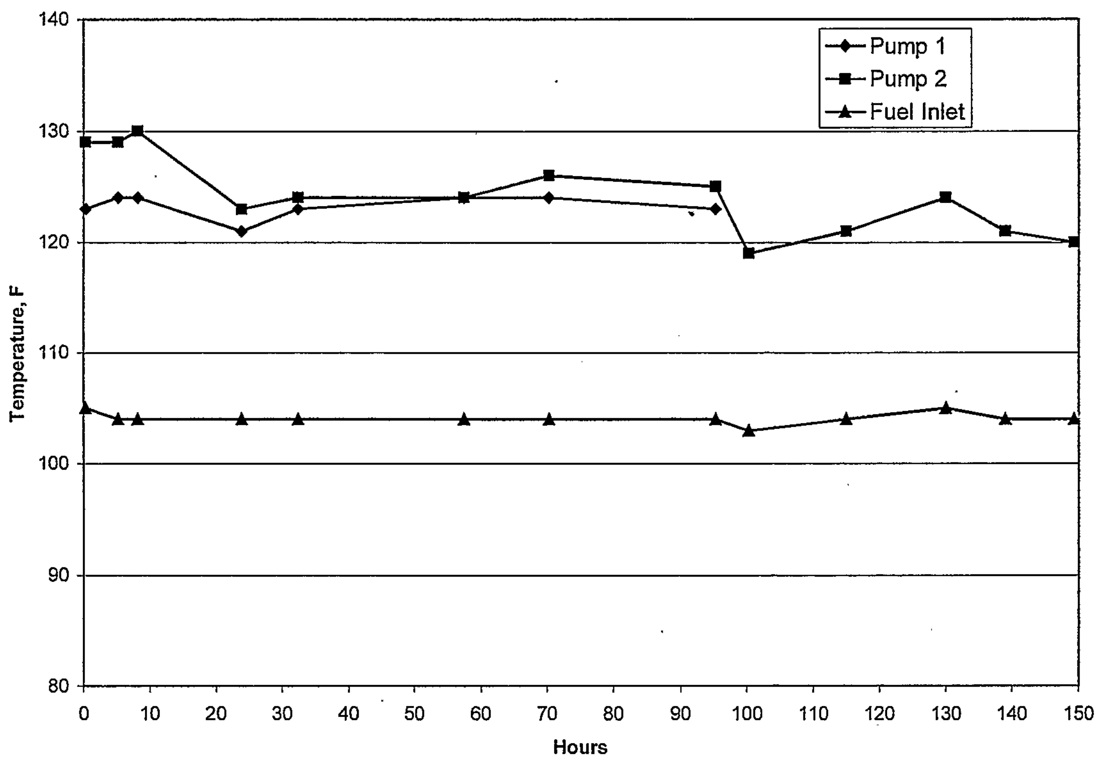


**Figure A-2. Test 1 - Fuel Return and Inlet Temperatures**

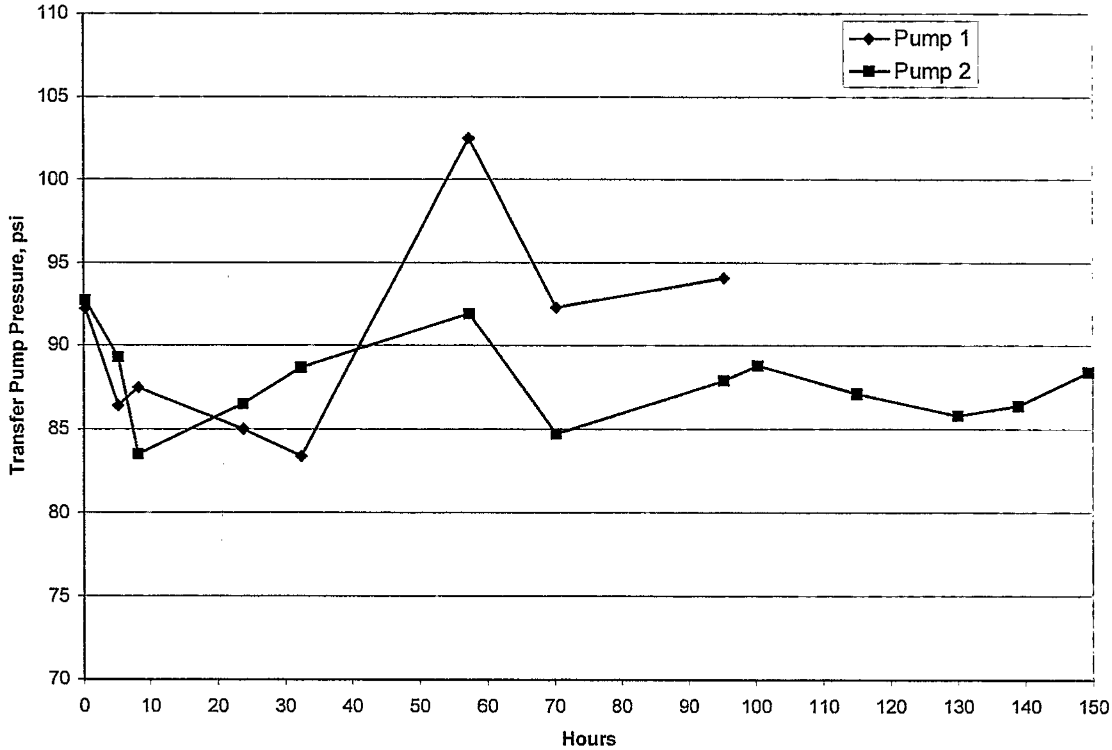


**Figure A-3. Test 1 - Transfer Pump Pressures**

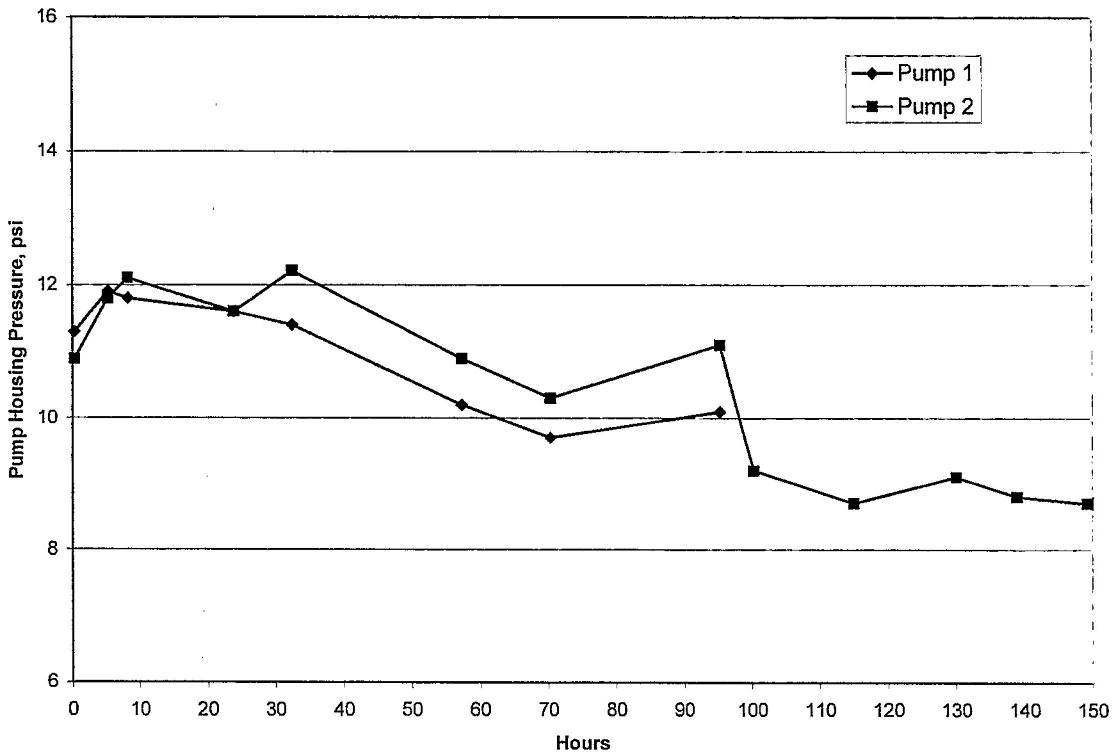


**Figure A-4. Test 1 - Pump Housing Pressures**

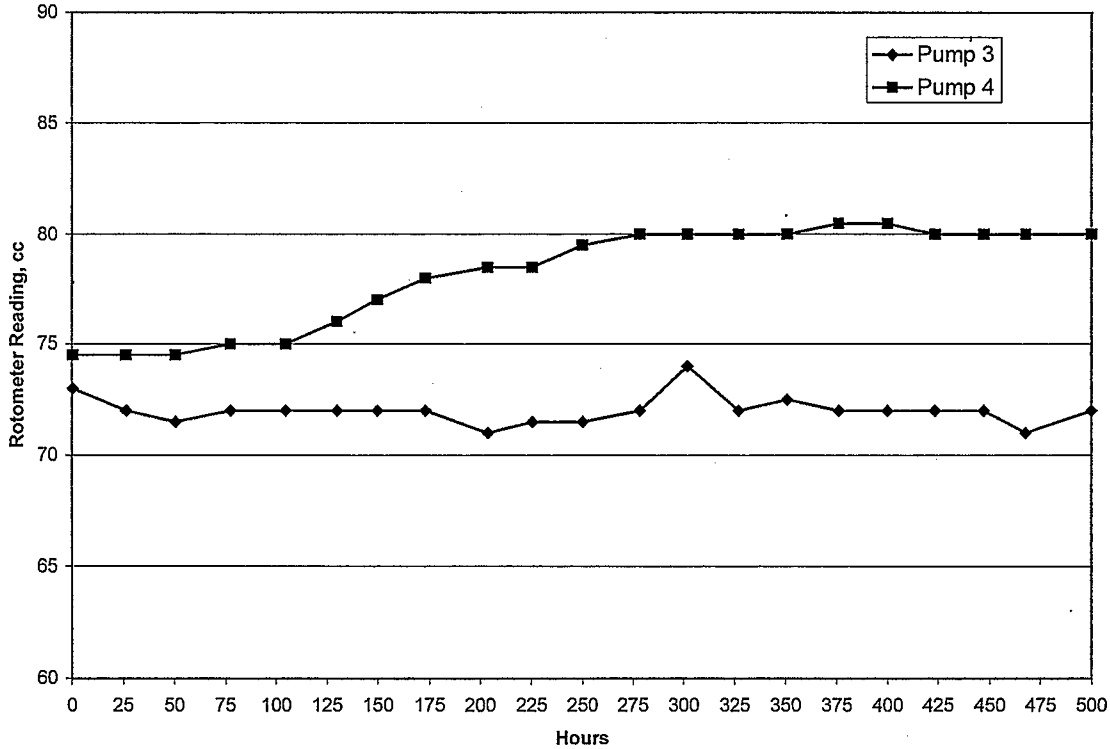


**Figure A-5. Test 2 - Rotameter Readings**

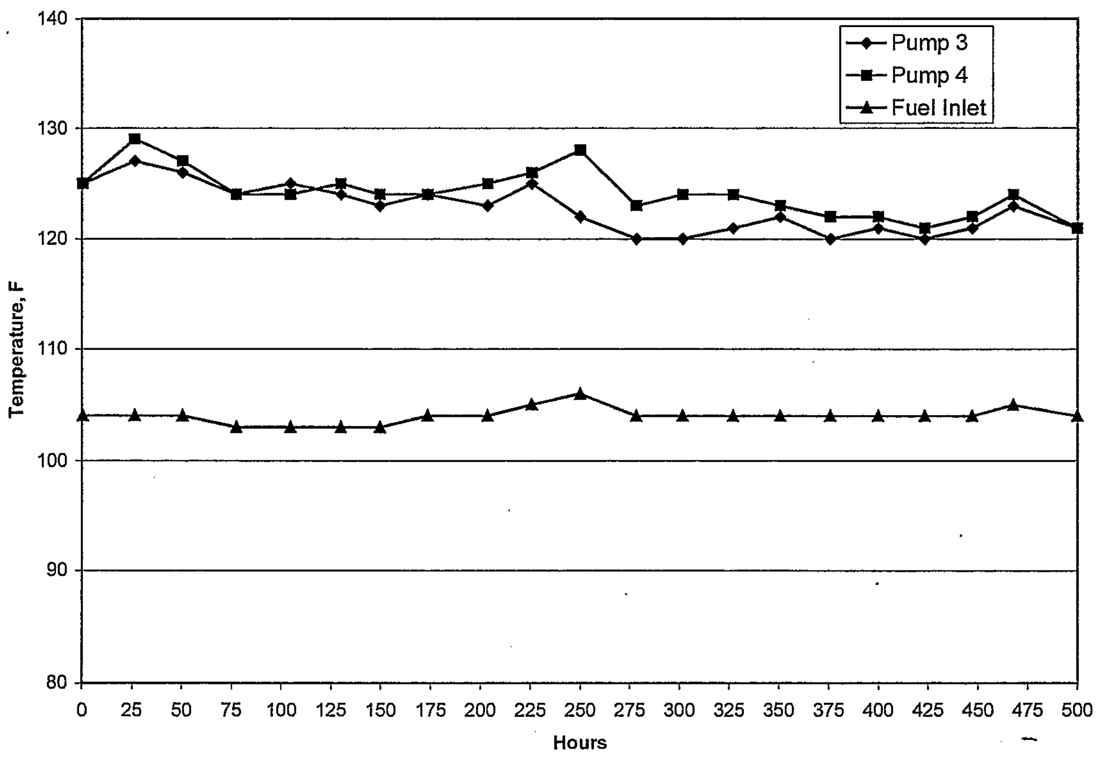


**Figure A-6. Test 2 - Pump Return Fuel and Inlet Temperature**

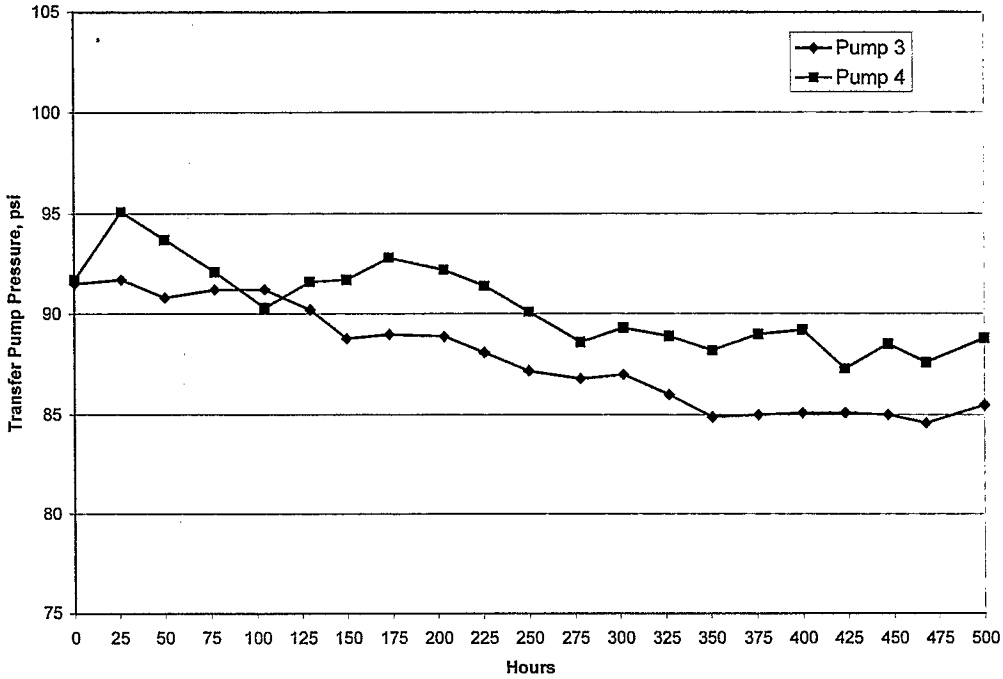


**Figure A-7. Test 2 - Transfer Pump Pressures**

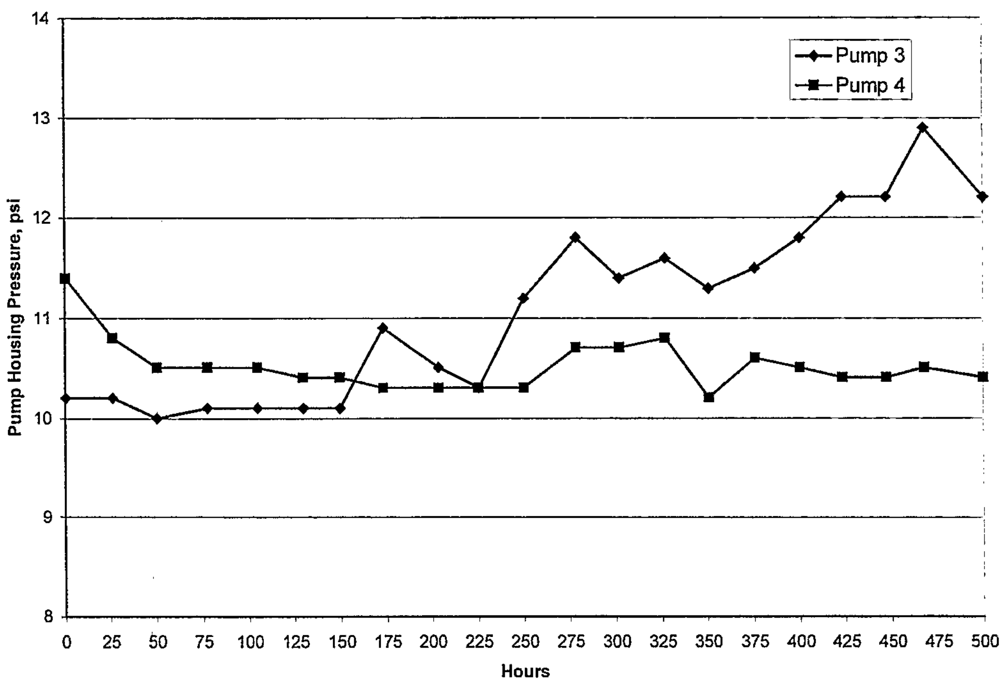


**Figure A-8. Test 2 - Pump Housing Pressures**

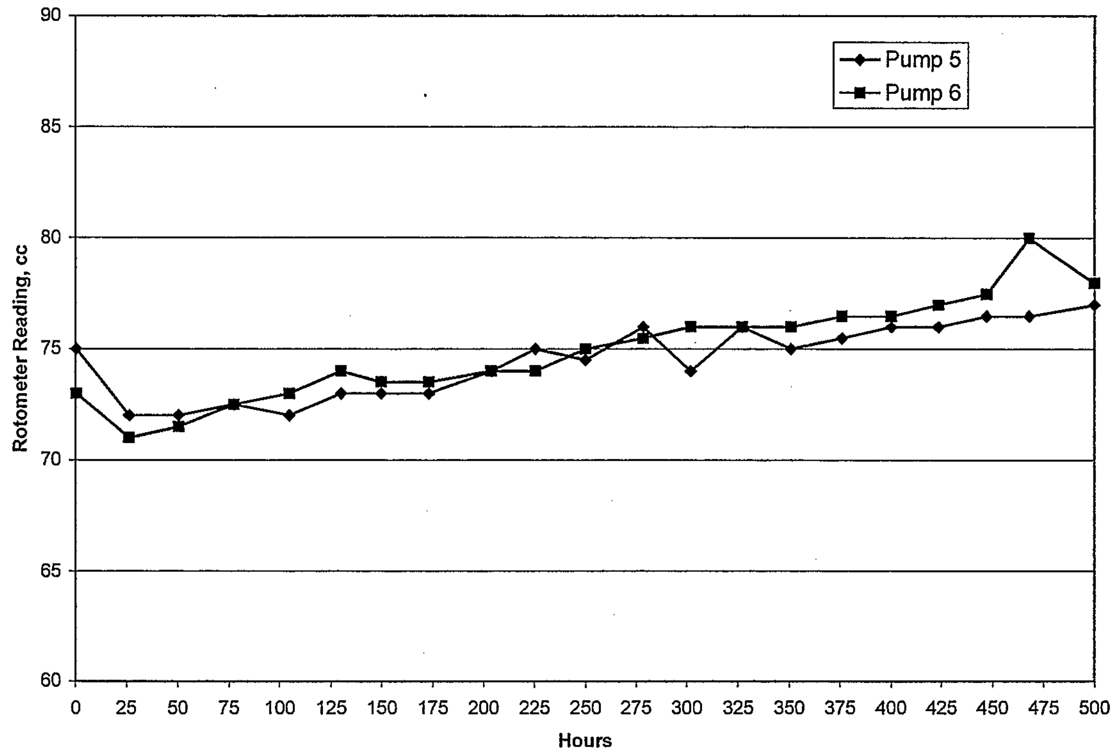


**Figure A-9. Pump Test No. 3 - Rotameter Readings**

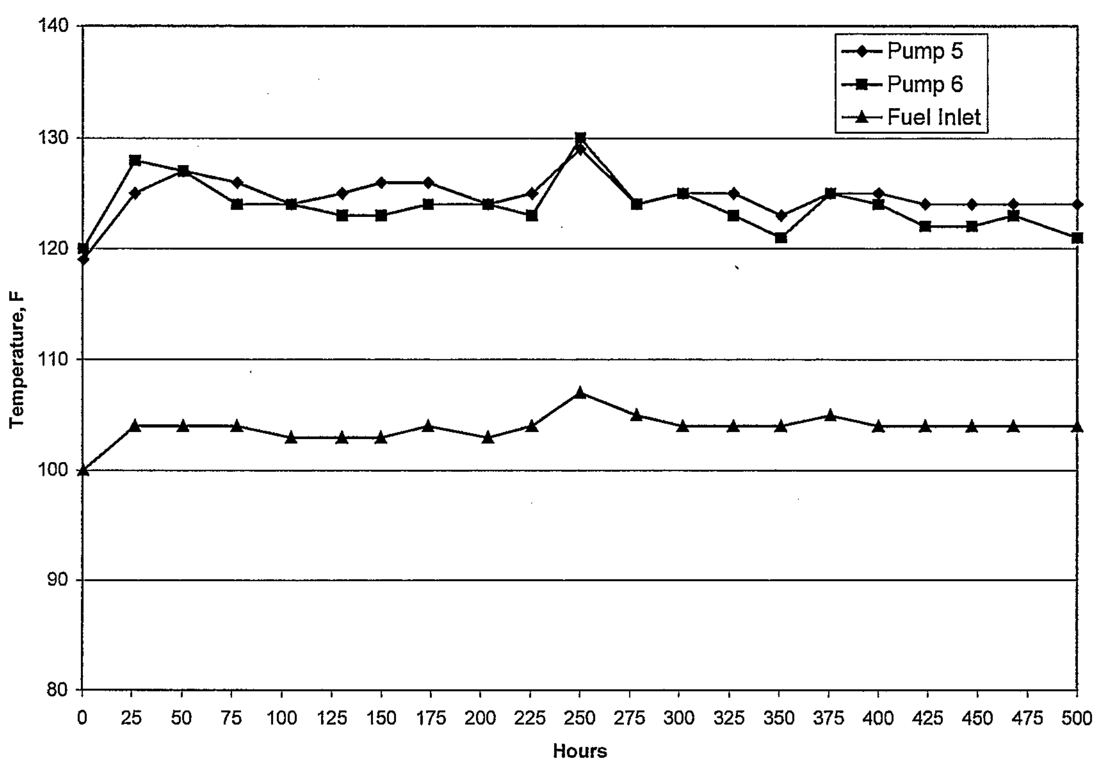


**Figure A-10. Test 3 - Pump Return Fuel and Inlet Temperatures**

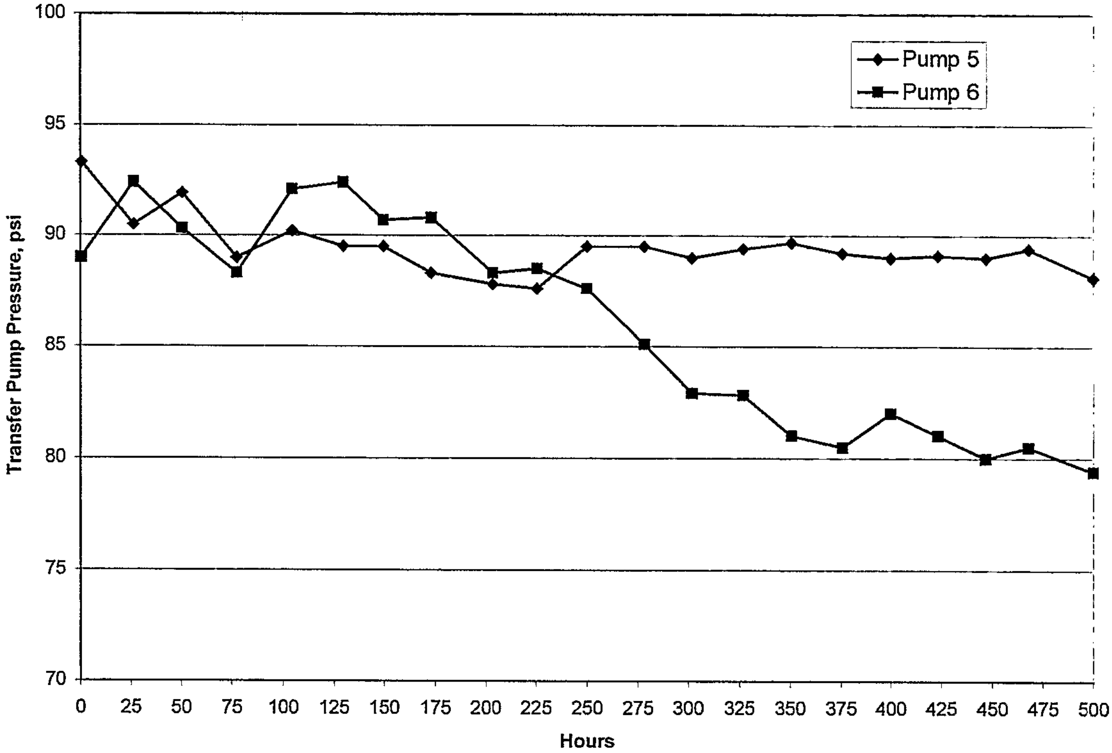


**Figure A-11. Test 3 - Transfer Pump Pressures**

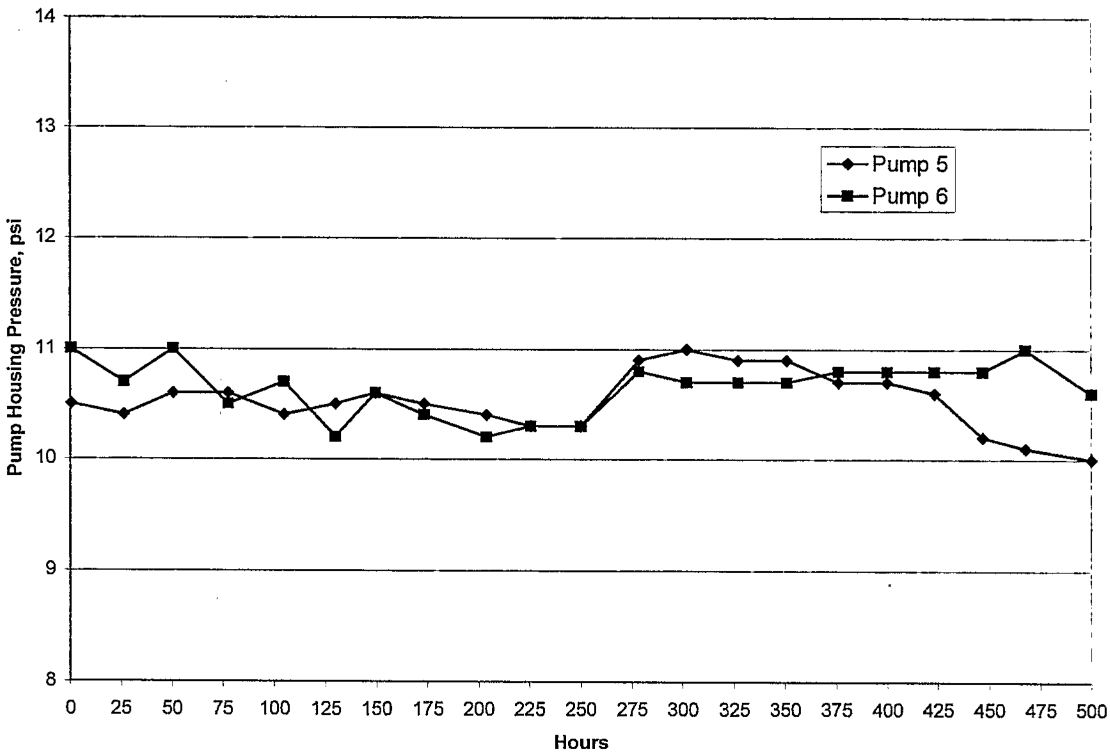


**Figure A-12. Pump Test 3 - Pump Housing Pressures**