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PORT FUEL INJECTOR FOULING USING THE PFI BENCH RIG – EVALUATION OF FLORIDA GASOLINE, OEM INJECTORS, AND DEPOSIT CONTROL ADDITIVES

September 2005

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Prepared by the

PORT FUEL INJECTOR PROGRAM PANEL

of the

DEPOSIT GROUP

September 2005

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ABSTRACT

CRC conducted a test program whose objectives were to use ASTM D 6421, Standard Test Method for Evaluating Automotive Spark-Ignition Engine Fuel for Electronic Port Fuel Injector Fouling by Bench Procedure, to determine the extent of fuel injector fouling in one region of the U.S. and the adequacy of current deposit control additive dosages to prevent injector fouling. Retail gasoline samples were collected in Florida and properties were measured by standard laboratory tests while injector fouling tendency was evaluated by ASTM D 6421. A subset of these fuels was also evaluated for fouling tendency using injectors obtained from two original equipment manufacturers (OEMs). The effects of deposit control additives and ethanol were investigated using the standard ASTM D 6421 injectors and OEM injectors. Several fuels were obtained that had been run by ASTM D 5598, Standard Test Method for Evaluating Unleaded Automotive Spark-Ignition Engine Fuel for Electronic Port Fuel Injection Fouling, and these were also evaluated by D 6421.

I. INTRODUCTION

Port fuel injector (PFI) deposits were first reported in the mid-1980's, shortly after the mass introduction of PFI fuel systems. Intense effort by the auto, oil, and additive industries cured the problem within a relatively short period of time. In years following, other engine cleanliness issues such as intake valve and combustion chamber deposits became the main areas of interest and concern. With the advent of polymeric detergents, a conventional wisdom arose that if intake valve deposits could be controlled, port fuel injector deposits would automatically be controlled as well.

Anecdotal reports of PFI field problems had been heard for many years, and the first evidence of field problems was presented by an auto manufacturer at the ASTM Subcommittee D2.A meeting in June 2002[1]. Subsequently, another auto manufacturer summarized his findings concerning injector field problems at the CRC Deposit Group meeting in October 2002[2]. In both instances, the problems were reported to be localized and brand specific. The problem was deemed important enough that at the meeting in October 2002, the CRC Deposit Group formed a PFI Panel to investigate regional problems. The PFI Panel held a conference call in March 2003 and outlined a program whose objectives were subsequently defined as: determine the extent of fuel injector fouling in one region of the U.S. and the adequacy of current deposit control additive dosages to prevent injector fouling.

Several areas of the U.S. had experienced injector fouling at times, but Florida was identified by auto manufacturers as a region of persistently high injector fouling rates. Florida is unique in that its gasoline is supplied almost exclusively by marine transport. The west coast of Florida is supplied primarily from US Gulf Coast refineries while its east coast is supplied from the Gulf Coast and from offshore refineries located in the Caribbean, South America, and across the Atlantic Ocean.

The Panel had concerns whether a one-time sampling of retail gasoline would provide fuel with a tendency to foul. Therefore, the Panel decided to use the PFI bench test, ASTM D 6421, as a quicker and much less expensive means of measuring fouling tendency instead of the vehicle injector fouling test, ASTM D 5598. The bench test uses an artificial fuel system in which the fuel injectors are placed in a heater block to simulate the hot-soak portion of the vehicle test. Each test uses screened injectors that are prone to foul. The bench test had been shown to be a predictor of PFI fouling and correlated to the vehicle test[3].

II. CONCLUSIONS

The general objectives of the program were met. The extent of fuel injector fouling in Florida and the adequacy of current deposit control additive dosages to prevent injector fouling should be viewed in relation to performance in ASTM D 6421 only. Performance of any of the sampled fuels or submitted deposit control additives was not determined in vehicles as a part of this program. The following conclusions were drawn from an analysis of the data from the program:

- Retail fuel samples collected in Florida met ASTM D 4814 limits for the properties tested.

- Samples showed a wide range in fouling tendency as measured by ASTM D 6421. Injector fouling was expressed as the percent difference in flow loss between a clean injector and the same injector after the test period. Average fouling for a sample was calculated over the four injectors used in testing the sample. After 44 cycles, samples had average fouling that ranged from -0.5 to 26.7%. Six out of twenty samples showed average fouling above 10%, and two samples were above 20%. An analysis of the maximum fouling level among the four injectors from each test showed values that ranged from 1.4 to 49.6%. Nine out of twenty samples showed maximum fouling above 10%, and six samples had a maximum above 20%. The relationship between injector fouling and fuel properties, including deposit control additive content as measured by unwashed gum, was weak as all correlation coefficients were below ±0.5.

- Six OEM injector sets were provided for testing. OEM1 provided one set of new injectors and two sets of field injectors, all of which were two-hole director plate-type. OEM2 provided one new set each of a pintle-type and an eight-hole director plate-type; also, OEM2 provided one set of pintle-type field injectors. When tested by ASTM D 6421 using reference fouling fuel, OEM-supplied injectors showed varying results with average fouling ranging from nil to over 34%. The level of fouling depended on the type of injector. OEM pintle-type injectors similar in design to those specified in D 6421 showed the highest level of fouling. Also, injectors that reportedly had fouled in the field did not show fouling tendency in the bench rig.

- Three OEM injector sets, representing a two-hole director plate-type, an eight-hole director plate-type, and a pintle-type, were evaluated with a subset of Florida fuels and showed fouling results similar to standard test injectors. Two low fouling fuels showed minimal or no fouling after 44 or 88 cycles. Two high fouling fuels showed higher levels of fouling especially after 88 cycles. One injector set, the six-hole director plate-type, was more resistant to fouling than the other two, especially after 88 cycles.

- Four deposit control additives evaluated at 40, 60, and 100 pounds per thousand barrels (ptb) in reference fouling fuel by ASTM D 6421 exhibited a wide range of performance after 44 cycles. Additive A showed decreased fouling from about 31 to 2% as concentration increased from 40 to 100 ptb. Additive B showed a constant level of about 20% fouling at all concentrations, and even showed an increase in fouling when concentration was increased to 140 ptb. Additive C showed about 21% fouling at 40 ptb and none at 60 ptb. Additive D showed no fouling at 40 ptb and was not tested at higher concentrations. However, Additive D did show about 25% fouling when the concentration was decreased to 20 ptb.

- The presence of 10 volume percent fuel-grade ethanol in reference fouling fuel resulted in lower fouling levels than without ethanol when tested using standard D 6421 injectors. Average fouling decreased from about 53% to 25%. Reference fouling fuel containing Additive A was also tested with and without 10 volume percent ethanol and showed a similar pattern. For example, at 40 ptb, average fouling was about 34% without ethanol compared to about 12% with ethanol.

- Three deposit control additives evaluated using five OEM injector sets showed a wide range of performance. Additives A and C at 40 ptb kept fouling below 10% in all injector sets after 44 cycles and in all but one injector set after 88 cycles. Additive B showed mixed results. It could not control fouling to less than 10% at 100 ptb for two injector sets after 44 cycles and three injector sets after 88 cycles.

- A final phase of the program compared fouling results between ASTM D 6421 bench rig and D 5598 vehicle test. Previous work published by SAE indicated that if each injector in the vehicle test had no more than 5% fouling, average fouling in the bench rig would be no more than 10%. SwRI obtained samples of six fuels (not originally associated with the program) that had been tested by D 5598. These samples were then tested by D 6421. The two test methods showed poor correlation, with the bench test being more severe. Four of the six fuels had greater than 10% average fouling in the bench rig while all but one fuel had less than 5% fouling in any injector in the vehicle test.

III. TEST PROGRAM

A. Fuel Sampling

The PFI Panel developed a pilot program to survey the fouling tendency of commercial Florida gasoline. Sampling from both coasts of Florida was believed to offer the best chance of obtaining gasoline from varied sources, including offshore refineries. The process of selecting sampling sites was intended to maximize the probability of choosing high volume retail stations and stations supplied by their respective branded terminals. Thus, the presence of many retail gasoline stations within a locale assumed that fuel sales volume was high at those stations. Also, for brands with a corresponding supply terminal, retail sites in reasonable proximity to the respective terminal were selected to make the probability of direct supply as high as possible.

Gasoline supply terminal locations were first identified in the Tampa and Miami areas. Terminals for the Tampa area were concentrated in the city; thus, fuel sampling was done within the city proper. Terminals for the Miami area, however, were located in Port Everglades, a port facility about 30 miles north of Miami. Fuel sampling was done in Fort Lauderdale, which is adjacent to Port Everglades.

Service stations of major and minor brands were identified from web-based business directories. Sampling sites were selected in each city using the following process: (1) street names containing at least three stations of any gasoline brand were identified; (2) from this list of street names, brand A was selected from one street, brand B from another street, etc; (3) for those brands not able to be sorted as described above, sites were selected either at random or from available sites.

In each city, a total of ten retail sites (brands) were selected. In July 2003, Southwest Research Institute (SwRI) collected ten gallons of regular grade gasoline from dispensers at each site and sent them to their laboratories in San Antonio, TX. Samples were coded without identifying brands.

B. Initial Fuel Testing

Laboratory analysis of the Florida gasoline samples was done primarily to determine oxidation stability and relative level of deposit control additive. Compositional analysis was also done to potentially point to suspect individual or groups of compounds likely to cause injector fouling or fuel instability. All samples were subjected to the following analyses at SwRI: distillation (ASTM D 86), solvent washed and unwashed gum (ASTM D 381), induction period (ASTM D 525), total sulfur (ASTM D 2622), peroxide number (ASTM D 3703), manganese content (ASTM D 3831), and copper content (atomic absorption). A portion of each sample was sent to ChevronTexaco in Richmond, CA, for detailed hydrocarbon analysis by gas chromatography.

After laboratory testing was completed, all samples were tested in the PFI bench rig according to ASTM D 6421 using the standard pintle style injectors specified by the test method. After all samples had been tested once, five samples were chosen for replicate testing.

C. PFI Tests with OEM Injectors

A second phase of testing was conducted to determine the fouling tendency of current original equipment manufacturer (OEM) injectors. Two OEMs provided both new injectors and several from the field that were reportedly fouled. Testing was done according to D 6421 with the exception that OEM injectors were substituted for the standard pintle injectors.

Before testing started, photos of the injector tips were taken under a magnification sufficient to see surface detail (about 100x). All injectors were then cleaned according to the procedure in D 6421. The bench rig required minimal modification to accommodate the OEM injectors, specifically addition of a bushing at the tip end to ensure snug metal-to-metal contact between injector and heating block. The reference fouling fuel was a volumetric blend of 75% Phillips 65th percentile gasoline and 25% Koch unleaded regular gasoline, which was previously found by SwRI to provide consistent fouling results. The reference fuel was checked for fouling tendency by running a test with standard pintle injectors prior to running the OEM injectors. Photos of injectors were also taken at the end of test. However, a considerably lower magnification level was used than at the start of test, and no analyses of the photos of the injector tips were done.

OEM1 obtained two-hole director plate-type injectors in Florida from four vehicles equipped with V-6 engines that had experienced symptoms of fouling as determined by injector balance tests performed at dealerships. This test procedure calls for firing each injector individually by means of a scan tool. The decrease in pressure for each injector is measured as it fires, and a low change in pressure relative to the average indicates restricted fuel flow.

From the four sets of six injectors, two sets of four injectors were selected for testing, each set containing one injector that had shown a low pressure drop in the injector balance test and three normal injectors. In addition, one set of four new injectors was also tested.

OEM2 provided three sets of injectors, all from four-cylinder passenger car engines. Two of the sets consisted of new injectors obtained from OEM2's local parts warehouse and forwarded directly to SwRI. These injector sets were of two different designs, one a pintle-type and the other an eight-hole director plate-type. The third set consisted of used pintle-type injectors returned by a dealership service department. The vehicle's engine management computer had indicated an injector-related problem. The injectors were removed from the engine and confirmed to be plugged by visual inspection.

OEM field injectors were also evaluated using four Florida fuels that were selected to represent a 2 x 2 matrix of high and low fouling and unwashed gum levels:

- 504626 (low fouling, low unwashed gum)
- 505623 (high fouling, low unwashed gum)
- 504629 (low fouling, high unwashed gum)
- 504625 (high fouling, high unwashed gum)

D. Additive Testing

Members of the PFI Panel submitted four deposit control additives to SwRI for testing in the bench rig. The additive samples were coded by SwRI such that the identities were not known even to the submitters. The four additives were labeled as A, B, C, and D; panel members were not made aware of which chemistries they represented.

Each additive was blended into reference fouling fuel starting at a concentration of 40 pounds per thousand barrels (ptb) and evaluated according to D 6421. If greater than 10% fouling was obtained, the concentration was increased to 60 ptb. If fouling was still greater than 10%, the concentration was increased to 100 ptb.

Subsequently, the following were also tested: (1) Additive A at 40 and 60 ptb in reference fouling fuel containing 10% ethanol; (b) Additive B at 140 ptb in reference fouling fuel; (c) Additive D at 20 ptb in reference fouling fuel; (d) Additives A, B, and C at 40-100 ptb in reference fouling fuel with OEM injectors to compare fouling levels between these and standard test injectors. All additives in (d) started at 40 ptb and progressed to higher concentrations if fouling was greater than 10%. The actual concentrations evaluated were as follows. Additive A: 40 and 60 ptb; Additive B: 40, 60, and 100 ptb; Additive C: 40 ptb.

E. Correlation Testing with ASTM D 5598

The PFI Panel asked SwRI to solicit fuel samples from their customers who recently had vehicle PFI tests done according to ASTM D 5598 vehicle test. Six samples were obtained, tested according to D 6421, and results from the two test methods were compared. None of the samples were originally associated with the test program. Fuel origin, fuel composition (other than ethanol content), nor additive type or concentration were provided for the samples.

IV. RESULTS AND DISCUSSION

A. Initial Fuel Testing

All fuels met the stability specifications set by ASTM D 4814. Solvent washed gum was consistently 0.5 mg/100 ml or less, while induction period ranged from 363 minutes to no break point after 1440 minutes. Peroxide was not detected in any of the samples. Copper, a known fuel oxidation promoter, was detected at only very low levels ranging from 0.007 to 0.039 mg/kg. Manganese content was measured primarily to identify imported gasoline containing the organometallic octane enhancer, MMT, but was not detected in the samples.

Deposit control additive content was measured indirectly by unwashed gum with higher values inferring higher levels of deposit control additive in the fuel. Unwashed gum values ranged from 8 to 27 mg/100 ml, but samples clustered into two distinct groups: those below 12 mg/100 ml and those above 22 mg/100 ml. Fourteen samples had values of 12 mg/100 ml or less and six samples had values of 22 mg/100 ml or greater. Complete laboratory test results are shown in **Tables 1a and 1b.**

Detailed hydrocarbon analysis provided organic compound class distribution, a carbon number distribution, total volume percent conjugated diolefins, and volume percent of five specific compounds indicative of pyrolysis gasoline. Olefins ranged from 8.4 to 15.7 volume percent and aromatics ranged from 27.8 to 35.6 volume percent. Thirteen samples contained oxygenate levels less than 1 volume percent, and seven samples contained between 1 to 5 volume percent oxygenate with the highest level being 4.7 volume percent. Five samples contained pyrolysis gasoline, defined as containing more than 0.1 volume percent dihydrodicyclopentadiene. Complete DHA results are found in **Tables 2a and 2b.**

For the Florida samples, average fouling in the PFI bench rig ranged from –0.5 to 26.7. Six out of the twenty samples showed fouling above 10%, three from Ft. Lauderdale and three from Tampa. Two samples had average fouling greater than 20%.

Maximum fouling values were also analyzed. While six samples had average fouling greater than 10%, nine samples had maximum individual injector fouling greater than 10%. In general, however, maximum fouling values mirrored average values. Average and maximum fouling values after 44 cycles are shown in Figures 1 and 2, respectively. Complete PFI test results are shown in **Tables 3a and 3b.**

The fact that six samples showed fouling greater than 10% raised questions about the PFI bench rig results. To address concerns about test precision, replicate tests were run on five samples representative of varying levels of unwashed gum, induction period, and fouling levels chosen from both sampling areas. Samples 504621 and 504633 had low unwashed gum, average fouling levels of 10.9 and 13.3%, and induction periods of 993 and greater than 1440 minutes, respectively. Samples 504622 and 504635 had low unwashed gum, average fouling levels of 2.0 and 2.1%, and induction periods of 363 and greater than 1440 minutes, respectively. Sample 504625 had high unwashed gum, an average fouling level of 26.7%, and an induction period of 838 minutes.

Replicate average fouling results for three samples were considerably higher than the original values. Sample 504621 saw a doubling in fouling (10.9 to 21.2%), while samples 504622 and 504635 each saw about a six-fold increase (2.0 to 12.4% and 2.1 to 13.1%, respectively). Sample504625 saw essentially no change (26.7 to 26.5%) while sample 504633 saw a small decrease in fouling (13.3 to 10.9%). Results for replicate test are shown in **Figure 1** and **Tables 3a and 3b.**

The time interval between replicates varied from approximately 4 to 12 weeks, and for four samples, the interval was 8 weeks or longer. The fuels were kept in cold storage during this time; however, none were evaluated prior to running the replicate to see if stability properties had changed during storage.

The reasons for the increase in fouling could not be explained by unwashed gum and induction period. For instance, samples 504633 and 504635 both had low unwashed gum and no break point. The samples were stored for roughly 12 and 11 weeks, respectively, before the replicate was run. Yet 504633 showed a small decrease in fouling while 504635 saw a modest increase.

The statistics function within Microsoft Excel® was used to correlate fuel properties to fouling tendency. The properties used in the correlation analysis were: unwashed gum (mg/100 ml), induction period (minutes), total sulfur (mg/kg), olefins (volume percent), conjugated diolefins (volume percent), pyrolysis gasoline content (volume percent), temperature at 50% percent evaporated (T50 reported as °F), and Driveability Index. Induction periods greater than 1440 minutes were listed as 1440 minutes. In this analysis pyrolysis gasoline content was the sum of styrene, indene, dicyclopentadiene, dihydrodicyclopentadiene, and tetrahydrodicyclopentadiene.

The correlation coefficient between injector fouling and all fuel properties were less than ±0.5; the highest correlations occurred for unwashed gum (0.39) and T50 (-0.44). A complete list of coefficients is found in **Table 4.**

<u>B. PFI Tests with OEM Injectors</u>

Injectors from OEM1 were all of the same design with a flat, circular director plate at the tip containing two centered holes through which fuel flows and is atomized into a spray pattern suitable for mixing with air. Injector fouling occurs when one or both holes become occluded with oxidized fuel, resulting in restricted fuel flow. The new set of injectors was labeled "OEM1-N" and the field injector sets were labeled "OEM1-U1 and "OEM1-U2".

All tests were run using reference fuel to 44 cycles. Prior to running OEM injectors, a test was done with standard pintle injectors and reference fouling fuel. Average fouling was 32.1%, and individual injectors ranged from 23.8 to 39.7% fouled, providing confidence that the bench rig was operating properly.

With OEM1-N, average fouling was 7.1%, ranging from 2.0 to 13.3%. Average fouling with OEM1-U1 was 7.2% with a range from –0.9 to 28.8%. With OEM1-U2, average fouling was 16.9%, ranging from 1.2 to 53.7%. In sets OEM1-U1 and –U2, injector number 4 was the one that had fouled in the field according to the injector balance test. However, in the bench rig, both injectors showed only low levels of fouling.

SwRI also ran OEM1-U2 out to 66, 88, and 110 cycles. Average percent fouling was relatively constant up to 88 cycles, and then it increased sharply after 110 cycles. Also, injector number 2 showed the highest level of fouling after all measurement periods with the exception of after 88 cycles when injector 1 showed the highest level of fouling.

Injectors from OEM2 were of two different designs. One design was a director plate-type similar to that of the injectors submitted by OEM1, but the top contained eight holes in a circular pattern. This set was labeled "OEM2-N2" and consisted of new injectors only. The remaining two injector sets from OEM2 were of the pintle-type design, in which fuel flows through a single orifice and around a concentric, protruding pintle. Injector fouling occurs in this design when deposits form in the space between the pintle and orifice wall. These injector sets were submitted in both new and used condition, and labeled "OEM2-N1" and "OEM2-U1", respectively.

With OEM2-N1, average fouling was 34.4%, ranging from 0.4 to 51.7%. Average fouling with OEM2-N2 was –0.4 with a range from –1.5 to 0.9%. With OEM2-U1, average fouling was 21.9%, ranging from 6.0 to 41.9%.

Average and maximum fouling levels are shown in **Figure 3**, and complete PFI test results are shown in **Table 5.**

C. PFI Tests with OEM Injectors and Florida Fuels

Four Florida fuels (504623, 504625, 504626, and 504629) were evaluated using injector sets OEM1-U2, OEM2-N1, and OEM2-N2. All tests were run on rig E. SwRI felt that extending the test beyond 44 cycles to 88 cycles would improve the chance of a fuel to show fouling tendency since the injectors were not pre-screened for fouling tendency as required by the test method.

With OEM1-U2, OEM2-N1, and OEM2-N2, the two low fouling fuels (504626 and 504629) both showed minimal or no fouling after 44 or 88 cycles. Fuel 504623 (high fouling, low unwashed gum) showed 3.0%, 3.5%, and 0.9% fouling after 44 cycles and 8.3%, 13.3%, and

1.3% fouling after 88 cycles in the three injector sets, respectively. Fuel 504625 (high fouling, high unwashed gum) showed 7.9%, 14.9%, and 4.1% fouling after 44 cycles and 17.2%, 24.0%, and 8.2% fouling after 88 cycles in the three injector sets, respectively..

Average fouling levels are shown in **Figures 4a and 4b** after 44 and 88 cycles, respectively, and complete injector test results are shown in **Tables 6a and 6b.**

D. PFI Tests with Deposit Control Additives

Additives A, B, C, and D were evaluated in reference fouling fuel according to D 6421. Additive A showed a classic response as concentration increased. Fouling was 31.4% at 40 ptb, 12.7% at 60 ptb, and 1.7% at 100 ptb. Additive B at 40 ptb showed 20.3% fouling, but at higher concentrations, percent fouling remained essentially the same: at 60 ptb it was 19.0% and at 100 ptb it was 21.3%. Additive C at 40 ptb showed 20.9% fouling; at 60 ptb, fouling dropped to –1.4%. Additive D showed 0% fouling at 40 ptb.

Additive A had been run on rig A while the other three additives had been run on rig E. The question arose whether the performance of Additives B and D was true or whether test rig variability could have been responsible for the unexpected results. To answer the question of performance, Additive B was rerun at 140 ptb and Additive D was rerun at 20 ptb to see if the fouling levels could be moved. To answer the question of rig variability, both additives were tested at each concentration in rigs A and E.

Additive B at 140 ptb showed approximately double the fouling level of the lower concentrations. Results were comparable in rigs A and E, 42.2 and 45.6%, respectively. Additive D showed a sharp increase in fouling at 20 ptb. Results were comparable in rigs A and E, 26.5 and 23.8%, respectively.

The results indicated the performance of the additives was true and the results were comparable in either test rig. Additive B did not appear to be formulated for optimum fuel injector performance in the bench rig while additive D appeared to be highly tuned to prevent injector fouling, at least in the bench rig.

Average fouling levels after 44 cycles are shown in **Figure 5**, and complete injector test results are shown in **Table 7.**

The effect of ethanol on the performance of additive A in the PFI bench rig was also investigated. Reference fouling fuel was blended with 10 volume percent ethanol and dosed at 40 and 60 ptb additive A. With no additive present, fouling was 25.1% (vs. 53.3% without ethanol); at 40 ptb fouling was 12.2% (vs. 31.4% without ethanol); and at 60 ptb fouling was 2.3% (vs. 12.7% without ethanol).

Average fouling levels after 44 cycles are shown in Figure 6, and complete injector test results are shown **Table 8.**

E. PFI Tests With Deposit Control Additives and OEM Injectors

Additives A, B, and C were evaluated using five OEM injector sets and reference fouling fuel to compare their response to additive concentration relative to standard test injectors. Each additive was blended into reference fouling fuel starting at a concentration of 40 ptb. If fouling greater than 10% was obtained, the concentration was increased to 60 ptb. If fouling was still greater than 10%, the concentration was increased to 100 ptb. Since OEM injectors were not screened for fouling tendency as the standard test injectors were, total test cycles were increased from 44 to 88.

(i) Additive A

Four out of five injector sets showed either no fouling or very low levels at 40 ptb. OEM1-N showed no fouling after 44 or 88 cycles; OEM1-U2 showed no fouling after 44 cycles and 0.8% fouling after 88 cycles; OEM2-N1 showed fouling levels of 1.1% after 44 cycles and 1.8% after 88 cycles; OEM2-U1 showed no fouling after 44 cycles and 2.5% fouling after 88 cycles.

Only OEM1-U1 showed any appreciable fouling. At 40 ptb, fouling was 1.1% after 44 cycles and 12.5% after 88 cycles. When the concentration was increased to 60 ptb, fouling was 1.2% after 44 cycles and 5.6% after 88 cycles.

Average fouling levels after 44 and 88 cycles are shown in **Figures 7a and 7b,** respectively, and complete injector test results are shown **Table 9.**

(ii) Additive B

At 40 ptb, OEM1-N showed 1.0% fouling after 44 cycles and 2.8% fouling after 88 cycles.

At 40 ptb, OEM1-U1 showed 7.1% fouling after 44 cycles and 22.9% after 88 cycles. When the concentration was increased to 60 ptb, fouling was 14.1% after 44 cycles and 9.1% after 88 cycles. At 100 ptb, fouling was 1.1% after 44 cycles and 14.1 % after 88 cycles.

OEM1-U2 showed no fouling after 44 or 88 cycles at 40 ptb.

OEM2-N1 showed 29.8% fouling after 44 cycles and 37.7% fouling after 88 cycles. At 60 ptb, OEM2-N1 showed 21.9% fouling after 44 cycles and 33.1% fouling after 88 cycles. When the concentration was increased to 100 ptb, fouling was 14.0% after 44 cycles and 37.1% after 88 cycles.

At 40 ptb, OEM2-U1 showed 16.8% fouling after 44 cycles and 39.2% fouling after 88 cycles. At 60 ptb, fouling was 19.4% after 44 cycles and 28.4% after 88 cycles. When the concentration was increased to 100 ptb, fouling was 19.0% after 44 cycles and 29.1% after 88 cycles.

Average fouling levels after 44 and 88 cycles are shown in **Figures 8a and 8b**, respectively, and complete injector test results are shown **Table 10.**

(iii) Additive C

All injector sets showed low levels of fouling at 40 ptb. OEM1-N showed 3.1% fouling after 44 cycles and 6.2% fouling after 88 cycles. OEM1-U1 showed 0.1% fouling after 44 cycles and no fouling after 88 cycles, while OEM1-U2 showed 0.7 and 1.1% fouling after 44 and 88 cycles, respectively. OEM2-N1 showed 0.1% fouling after 44 cycles and 1.5% fouling after 88 cycles, while OEM2-U1 showed 1.7 and 4.7% fouling after 44 and 88 cycles, respectively.

Average fouling levels after 44 and 88 cycles are shown in **Figures 9a and 9b**, respectively, and complete injector test results are shown **Table 11.**

F. Comparison of Bench Rig and Vehicle Fouling Results

An earlier study reported that a pass in the vehicle test, defined as no one injector having more than 5% fouling, would be predicted if average fouling after 44 cycles in the bench rig was no more than 10%. This same study also reported a higher fouling severity in the bench rig relative to the vehicle test[3]. The current results confirmed higher fouling levels in the bench rig. However, ASTM D 6421 (bench rig) after 44 cycles and D 5598 (vehicle test) after 10,000 miles showed no correlation either for average or maximum fouled injector results. Also, a simple pass-fail outcome could not be predicted.

All six fuel samples showed higher fouling result in the bench rig after both 22 and 44 cycles relative to the vehicle test after 10,000 miles. Samples CRC-03 and CRC-04 showed the greatest disparity in results. Fouling in the bench rig was about 40% for both samples while in the vehicle, the highest fouled injector for CRC-03 was 4.24% and for CRC-04 was -0.16%. SwRI indicated that originally CRC-01 and CRC-04 had been blended with 10 volume percent fuel-grade ethanol by them; CRC-02 and CRC-03 had arrived at SwRI already containing 10 volume percent ethanol; and CRC-05 and CRC-06 had no ethanol. However, with only six samples, it was not clear whether the presence of ethanol affected the correlation. Results from the two test methods are shown graphically in **Figure 10** and complete injector results are shown in **Table 12.**

Additive chemistry and test conditions may have affected the correlation between the two test methods. Based on the variability in performance in the bench rig, Additives A, B, C, and D most likely represented different chemistries and/or formulations. Also, the two methods had quite different injector soak temperatures. D 6421 used a temperature of 160°C ± 5°C for the injector heating block while D 5598 required injector 3 to have a maximum skin temperature of greater than 90°C for more than 95% of the soak cycles. It is possible that an additive formulated for testing in D 5598 is not thermally stable at the soak temperature encountered in D 6421. Thus, an additive could pass D 5598 and perform poorly in D 6421.

G. Acknowledgements

The CRC PFI Panel would like to thank Chevron Products Company for performing detailed hydrocarbon analyses on the gasoline samples from Florida; John Naylon of SwRI for his counsel and conscientious work; and Kevin Brunner and Randy Honc of SwRI for obtaining the gasoline samples used in the comparison work.

V. REFERENCES

(1) ASTM Subcommittee D2.A minutes, June 2002.

(2) CRC Deposit Group minutes, October 2002.

(3) M. Megnin, B. Evans, D. Koehler, K. Kohl, J. Naylon, *The CRC Port Fuel Injector Bench Test Method, Interlaboratory Study, and Vehicle Test Correlation*, SAE paper no. 1999-01-1548.

TABLES AND FIGURES

Table 1a: Laboratory Results – Gasoline Samples from Ft. Lauderdale, FL

		Sample ID	504616	504617	504618	504619	504620	504621	504622	504623	504624	504625
		Proj seq	30519	30520	30521	30522	30523	30524	30525	30526	30527	30528
TEST	PROPERTY	UNITS										
AA	Copper	ppm	0.012	0.012	0.007	0.007	0.007	0.012	0.016	0.002	0.016	0.012
D 2622	Sulfur	ppm	195	67	654	250	128	280	485	384	359	267
Rerun					632							
D 3703	Peroxide	mg/kg	0	0	0	0	0	0	0	0	0	0
D 3831	Manganese	g/gal	0	0	0	0	0	0	0	0	0	0
D 525	Induction period	minutes	643	>1440	634	714	>1440	993	363	496	1289	838
Rerun										517		919
D 86	Distillation	deg F										
	IBP		98.2	96.7	100.0	98.2	97.3	99.7	97.9	98.6	96.3	98.1
	5% evap		118.2	112.9	118.7	120.7	110.5	121.3	120.4	116.6	110.2	119.5
	10% evap		134.5	130.6	130.8	135.1	131.6	133.7	134.7	130.7	126.3	133.4
	15% evap		144.3	141.3	138.0	144.7	142.5	141.8	144.0	137.9	136.0	141.5
	20% evap		152.9	150.4	144.1	153.9	152.2	149.4	152.1	144.7	144.9	149.3
	30% evap		171.3	170.0	158.6	173.0	172.4	165.7	169.7	159.5	163.3	166.2
	40% evap		192.0	191.3	176.6	193.9	194.5	184.6	189.6	176.9	185.8	185.7
	50% evap		214.5	212.4	199.9	216.5	215.7	207.3	212.5	198.7	211.7	208.6
	60% evap		236.8	231.5	228.1	239.5	234.9	233.4	238.7	225.0	240.2	234.9
	70% evap		261.0	251.9	258.5	264.6	255.0	262.1	268.7	255.1	270.4	264.6
	80% evap		292.1	281.1	290.6	295.6	284.6	294.4	303.3	289.4	303.3	299.3
	90% evap		333.3	322.6	332.0	336.6	326.4	334.9	341.5	331.1	345.8	342.0
	95% evap		365.8	354.0	365.4	369.6	357.9	367.8	373.0	361.5	374.1	376.2
	FBP		411.0	400.4	417.5	414.9	403.0	411.3	414.9	402.2	418.2	421.1
	Recovered	ml	96.6	96.5	96.9	96.7	96.2	96.9	97.1	96.3	95.8	96.9
	Residue	ml	0.6	0.6	0.6	0.8	0.8	0.9	0.8	0.9	0.8	0.9
	Loss	ml	2.8	2.9	2.5	2.5	3.0	2.2	2.1	2.8	3.4	2.2
	% evap at 200 °F	vol %	43.60	44.03	50.04	42.75	42.50	46.97	44.72	50.53	45.61	46.42
	% evap at 212 °F	vol %	48.89	49.80	54.45	48.03	48.17	51.89	49.80	55.25	50.11	51.37
	% evap at 300 °F	vol %	82.20	85.05	82.63	81.26	84.10	81.59	79.06	82.83	79.07	80.19
	Driveability Index		1179	1156	1128	1189	1171	1157	1181	1123	1170	1168
D 381	Unwashed gum	mg/100 ml	9	9.5	10.5	12	9.5	9.5	9	11	26.5	25
	Solvent washed gum	mg/100 ml	<0.5	<0.5	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.5	0.5
Rerun	Unwashed gum	mg/100 ml								16.5		28.5
	Solvent washed gum	mg/100 ml								1.5		1
D 873, 4 h	Unwashed precip.	mg/100 ml								32.5		76
	Washed gum	mg/100 ml								6.1		6
	Precipitate	mg/100 ml								<0.5		<0.5

Table 1b: Laboratory Results – Gasoline Samples from Tampa, FL

		Sample ID	504626	504627	504628	504629	504630	504631	504632	504633	504634	504635
		Project seq	30529	30530	30531	30532	30533	30534	30535	30536	30537	30538
TEST	PROPERTY	UNITS										
AA	Copper	ppm	0.007	0.039	0.012	0.012	0.016	0.012	0.012	0.012	0.007	0.007
D 2622	Sulfur	ppm	429	403	470	324	354	348	317	373	351	352
Rerun												
D 3703	Peroxide	mg/kg	0	0	0	0	0	0	0	0	0	0
D 3831	Manganese	g/gal	0	0	0	0	0	0	0	0	0	0
D 525	Induction period	minutes	1403	>1440	915	>1440	>1440	1368	>1440	>1440	1417	>1440
Rerun			>1440			>1440						
D 86	Distillation	deg F										
	IBP		97.0	98.6	98.2	100.1	100.6	98.0	98.4	103.6	104.5	104.7
	5% evap		113.2	115.6	119.4	128.0	113.1	117.1	115.7	122.2	131.8	131.6
	10% evap		131.1	131.4	133.1	140.2	129.2	134.4	133.2	140.0	144.0	145.2
	15% evap		142.2	141.5	143.2	149.6	142.6	144.5	143.8	149.9	152.6	153.9
	20% evap		151.1	150.7	152.6	158.8	151.7	153.5	152.7	157.2	159.9	160.7
	30% evap		170.0	169.7	173.1	177.1	171.1	172.7	172.0	171.4	177.9	175.5
	40% evap		191.3	191.6	196.8	197.7	192.6	194.1	193.5	189.7	196.6	179.4
	50% evap		215.6	215.7	222.7	220.4	216.4	217.6	216.9	212.5	213.3	206.0
	60% evap		243.2	242.6	249.8	245.3	241.9	242.3	241.0	238.6	237.9	238.4
	70% evap		273.5	272.5	278.5	270.6	269.9	269.2	267.8	268.9	268.6	271.2
	80% evap		304.5	305.2	312.6	304.4	304.0	302.1	302.1	306.2	303.5	304.9
	90% evap		346.8	348.9	354.5	347.5	349.7	345.3	346.2	352.5	347.6	346.5
	95% evap		376.5	381.8	383.6	378.2	376.6	378.5	378.9	385.0	380.0	378.7
	FBP		426.0	426.6	416.6	424.4	425.6	420.3	421.6	427.9	432.6	424.2
	Recovered	ml	95.7	96.4	96.8	98.1	95.3	96.5	96.5	96.5	97.5	97.3
	Residue	ml	0.9	0.8	0.9	0.9	0.7	0.8	0.7	0.7	0.9	0.9
	Loss	ml	3.4	2.8	2.3	1.0	4.0	2.7	2.8	2.8	1.6	1.8
	% evap at 200 °F	vol %	43.74	43.58	41.27	41.05	43.21	42.58	42.84	44.72	42.06	52.24
	% evap at 212 °F	vol %	48.60	48.53	45.94	46.42	48.21	47.67	47.94	49.80	49.29	49.43
	% evap at 300 °F	vol %	78.65	78.52	76.51	78.85	78.96	79.42	79.45	78.46	79.07	78.54
	Driveability Index		1190	1193	1222	1219	1193	1200	1197	1200	1204	1182
D 381	Unwashed gum	mg/100 ml	9.5	10	11.5	22	27	12	26	8	24.5	10
	Solvent washed gum	mg/100 ml	<0.5	0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Rerun	Unwashed gum	mg/100 ml	10.5			24						
	Solvent washed gum	mg/100 ml	<0.5			<0.5						
D 873, 4 h	Unwashed precip.	mg/100 ml	11.6			12						
	Washed gum	mg/100 ml	6			0.6						
	Precipitate	mg/100 ml	<0.5			<0.5						

Table 2a: Detailed Hydrocarbon Analysis – Gasoline Samples from Ft. Lauderdale, FL

		Sample ID	504616	504617	504618	504619	504620	504621	504622	504623	504624	504625
		Proj seq	30519	30520	30521	30522	30523	30524	30525	30526	30527	30528
Class Distribution												
n-Paraffins	LV%		11.60	11.88	9.82	11.94	11.49	11.21	9.11	10.50	12.68	11.67
Iso-Paraffins	LV%		36.27	38.78	37.74	36.02	38.36	36.30	33.67	35.09	31.42	33.71
Cyclo-Paraffins	LV%		5.89	5.01	6.02	5.99	4.80	7.62	7.62	6.47	8.38	8.19
Olefins	LV%		10.26	8.40	11.78	10.63	8.50	11.12	15.59	13.11	10.96	12.53
Aromatics	LV%		32.41	33.27	29.76	32.07	34.51	28.55	30.60	27.77	33.66	27.86
Oxygenates	LV%		1.58	1.27	2.30	1.11	0.83	2.46	0.14	4.66	0.06	3.17
Unclassified	LV%		1.98	1.39	2.59	2.24	1.51	2.75	3.27	2.41	2.85	2.87
Total	LV%		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
C# Distribution												
C3-	LV%		0.03	0.03	0.01	0.03	0.04	0.03	0.08	0.01	0.03	0.02
C4	LV%		2.34	2.31	1.00	2.68	2.50	1.91	2.53	1.18	2.38	2.14
C5	LV%		18.38	19.45	22.91	18.51	19.00	19.31	16.35	22.20	19.73	20.06
C6	LV%		19.06	16.18	24.24	18.61	14.89	23.09	21.31	24.87	20.60	22.64
C7	LV%		22.94	26.69	17.50	21.86	27.30	15.36	20.29	16.01	18.71	15.86
C8	LV%		16.55	16.26	15.46	16.94	16.66	19.30	15.74	15.88	16.05	18.12
C9	LV%		11.57	11.40	9.64	11.60	11.42	10.97	11.62	10.98	10.88	10.55
C10	LV%		5.97	5.47	5.20	6.16	5.68	5.90	7.07	5.49	6.78	6.12
C11	LV%		2.00	1.48	2.26	2.24	1.67	2.50	3.01	2.02	2.98	2.79
C12+	LV%		1.16	0.72	1.77	1.36	0.85	1.63	2.00	1.35	1.86	1.69
Total	LV%		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Other Species:												
Conjugated Dienes	LV%		0.107	0.090	0.155	0.112	0.097	0.146	0.185	0.150	0.173	0.189
Pygas present?*			No	No	No	No	No	Trace?	Trace?	No	Yes	Yes
Styrene	LV%		nd	nd	nd	nd	nd	0.049	0.031	nd	0.093	0.062
Indene	LV%		0.029	0.018	0.035	0.031	0.027	0.063	0.042	0.037	0.117	0.073
DCPD	LV%		nd	nd	nd	nd	nd	0.008	nd	nd	0.020	0.011
DihydroDCPD	LV%		nd	nd	nd	nd	nd	0.087	0.014	nd	0.279	0.117
TetrahydroDCPD	LV%		nd	nd	nd	nd	nd	0.028	0.016	nd	0.027	0.041

*"No" assigned where no dihydrodicyclopentadiene (dihydroDCPD) species were identified.
* "Trace" assigned where <1000 ppm dihydroDCPD was identified.
* "Yes" assigned where >1000 ppm dihydroDCPD was identified.

Table 2b: Detailed Hydrocarbon Analysis – Gasoline Samples from Tampa, FL

		Sample ID	504626	504627	504628	504629	504630	504631	504632	504633	504634	504635
		Proj seq	30529	30530	30531	30532	30533	30534	30535	30536	30537	30538
Class Distribution												
n-Paraffins	LV%		12.49	12.82	9.68	11.88	11.28	11.48	11.59	11.64	11.61	13.45
Iso-Paraffins	LV%		30.59	32.04	32.05	31.86	33.49	32.43	33.70	33.12	34.08	29.31
Cyclo-Paraffins	LV%		8.42	8.46	7.49	7.79	8.14	8.01	7.98	8.98	8.29	8.94
Olefins	LV%		9.79	10.16	15.68	10.73	10.78	10.46	10.68	11.78	11.03	9.16
Aromatics	LV%		34.86	32.89	29.97	34.60	32.14	33.51	32.38	30.13	31.08	35.63
Oxygenates	LV%		0.09	0.06	0.57	0.64	0.70	0.79	0.48	0.55	0.60	0.14
Unclassified	LV%		3.77	3.56	4.57	2.49	3.47	3.33	3.17	3.81	3.31	3.35
Total	LV%		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
C# Distribution												
C3-	LV%		0.02	0.02	0.04	0.03	0.02	0.02	0.02	0.01	0.02	0.02
C4	LV%		2.36	2.77	2.00	2.75	2.48	2.56	2.53	2.68	2.53	2.72
C5	LV%		16.03	16.93	19.02	18.86	18.08	17.99	18.50	18.41	18.81	16.90
C6	LV%		20.92	20.74	17.08	17.61	19.17	18.48	19.02	20.91	19.88	21.54
C7	LV%		17.19	16.80	15.57	22.28	18.33	19.35	19.55	16.05	17.94	17.55
C8	LV%		18.37	18.49	19.35	16.54	18.34	17.92	17.61	18.08	18.08	16.90
C9	LV%		11.77	11.31	11.90	11.15	11.01	11.22	10.88	10.59	10.63	11.55
C10	LV%		7.30	6.89	8.23	6.57	6.88	6.94	6.65	7.00	6.63	7.18
C11	LV%		3.55	3.58	3.99	2.62	3.36	3.26	3.14	3.78	3.31	3.27
C12+	LV%		2.50	2.47	2.82	1.60	2.33	2.26	2.11	2.49	2.19	2.38
Total	LV%		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Other Species:												
Conjugated Dienes	LV%		0.157	0.166	0.337	0.183	0.179	0.176	0.177	0.198	0.184	0.162
Pygas present?*			Trace?	No	Trace?	Yes	Trace?	Yes	Yes	Trace?	Trace?	Trace?
Styrene	LV%		0.036	nd	0.091	0.109	0.049	0.067	0.055	0.052	0.045	0.039
Indene	LV%		0.052	0.047	0.060	0.118	0.064	0.083	0.069	0.070	0.059	0.057
DCPD	LV%		nd	nd	nd	0.025	0.007	0.139	0.009	nd	nd	nd
DihydroDCPD	LV%		0.015	nd	0.016	0.248	0.078	0.139	0.102	0.091	0.066	0.047
TetrahydroDCPD	LV%		0.016	nd	0.031	0.030	0.048	0.043	0.043	0.051	0.047	0.017

*"No" assigned where no dihydrodicyclopentadiene (dihydroDCPD) species were identified.
* "Trace" assigned where <1000 ppm dihydroDCPD was identified.
* "Yes" assigned where >1000 ppm dihydroDCPD was identified.

Table 3a: ASTM D 6421 PFI Bench Rig Percent Fouling Results After 22 Cycles

Sample ID	504616	504617	504618	504619	504620	504621	504622	504623	504624	504625
Proj seq	30519	30520	30521	30522	30523	30524	30525	30526	30527	30528
Inj 1	-0.7	11.7	-0.3	1.2	-1.1	7.9	-3.0	23.2	2.5	9.5
Inj 2	0.9	1.5	1.0	1.6	-0.2	6.0	2.3	5.2	2.7	9.9
Inj 3	3.3	3.0	1.0	1.2	-0.1	2.0	7.7	16.3	1.6	2.5
Inj 4	2.8	3.5	1.7	3.6	-0.1	1.1	-1.8	1.6	-2.1	0.9
Average	1.6	4.9	0.8	1.9	-0.4	4.3	1.3	11.6	1.2	5.7
Rerun										
Inj 1						2.1	0.1			5.0
Inj 2						5.0	3.3			3.0
Inj 3						5.4	14.4			2.2
Inj 4						4.9	-0.4			2.7
Average						4.4	4.3			3.2
Sample ID	**504626**	**504627**	**504628**	**504629**	**504630**	**504631**	**504632**	**504633**	**504634**	**504635**
Proj seq	30529	30530	30531	30532	30533	30534	30535	30536	30537	30538
Inj 1	5.3	-4.3	1.5	-1.3	9.2	1.3	4.3	8.8	4.9	-0.7
Inj 2	1.2	6.4	2.1	1.3	0.3	1.2	3.2	2.1	6.0	0.2
Inj 3	2.8	0.9	1.3	-2.8	1.9	1.9	3.1	3.5	2.3	0.4
Inj 4	1.6	-2.3	1.3	1.5	3.8	2.9	2.6	3.4	2.4	1.8
Average	2.7	0.2	1.6	-0.3	3.8	1.8	3.3	4.5	3.9	0.4
Rerun										
Inj 1								1.8		8.9
Inj 2								4.9		5.2
Inj 3								4.0		5.0
Inj 4								4.1		10.1
Average								3.7		7.3

Table 3b: ASTM D 6421 PFI Bench Rig Percent Fouling Results After 44 Cycles

Sample ID	504616	504617	504618	504619	504620	504621	504622	504623	504624	504625
Proj seq	30519	30520	30521	30522	30523	30524	30525	30526	30527	30528
Inj 1	2.5	12.5	-0.7	0.8	-0.2	23.6	0.7	49.6	15.3	40.8
Inj 2	0.7	2.8	1.0	2.5	-0.3	10.3	2.3	21.2	10.6	38.5
Inj 3	1.7	5.3	1.4	1.6	-2.9	3.2	7.1	21.6	1.4	12.2
Inj 4	1.0	2.2	-0.4	4.1	5.6	6.6	-2.1	4.0	-1.0	15.2
Average	1.5	5.7	0.3	2.3	0.6	10.9	2.0	24.1	6.6	26.7
Rerun										
Inj 1						20.9	5.3			46.6
Inj 2						14.2	11.6			24.2
Inj 3						22.6	21.8			14.9
Inj 4						27.2	10.8			20.3
Average						21.2	12.4			26.5
Sample ID	**504626**	**504627**	**504628**	**504629**	**504630**	**504631**	**504632**	**504633**	**504634**	**504635**
Proj seq	30529	30530	30531	30532	30533	30534	30535	30536	30537	30538
Inj 1	0.5	2.4	2.3	-1.1	24.4	0.2	19.5	23.7	17.6	2.0
Inj 2	-0.4	1.4	1.9	1.6	5.2	0.9	11.4	8.0	21.4	1.8
Inj 3	1.5	2.3	1.6	-3.8	3.6	1.8	10.6	11.6	4.1	0.7
Inj 4	0.2	-1.0	1.9	1.3	4.3	1.5	5.7	10.1	6.8	3.9
Average	0.4	1.3	1.9	-0.5	9.4	1.1	11.8	13.3	12.5	2.1
Rerun										
Inj 1								8.3		16.9
Inj 2								9.3		7.4
Inj 3								6.0		7.8
Inj 4								20.0		20.2
Average								10.9		13.1

Table 4: Correlation Coefficient Matrix

	% fouled	Unwashed gum	Induction period	Sulfur	Olefins	Conjugated dienes	Pygas	T50	DI
% fouled	1								
Unwashed gum	0.386115	1							
Induction period	-0.167587	0.285599	1						
Sulfur	-0.117531	-0.028714	-0.297276	1					
Olefins	0.246418	0.006106	-0.646585	0.582538	1				
Conjugated dienes	0.079871	0.215631	-0.015684	0.556913	0.713865	1			
Pygas	0.103495	0.615050	0.383588	0.074592	0.067770	0.393116	1		
T50	-0.441355	0.195161	0.437765	-0.234888	-0.047924	0.328393	0.315428	1	
DI	-0.330536	0.247722	0.476178	-0.021777	0.061555	0.513383	0.434544	0.876040	1

Table 5: ASTM D 6421 PFI Bench Rig Percent Fouling Results for OEM Injectors

Sample ID	Reference	OEM1-N	OEM1-U1	OEM1-U2	OEM2-N1	OEM2-N2	OEM2-U1
Inj 1	3.4	5.6	0.4	-0.1	23.0	-3.5	0.5
Inj 2	0.9	-1.3	0.8	34.0	38.1	0.7	2.4
Inj 3	0.6	2.3	-3.9	8.9	1.0	-0.1	18.8
Inj 4	4.9	-1.3	0.7	0.5	17.4	0.2	22.4
Average after 22 cycles	2.5	1.3	-0.5	10.8	19.9	-0.7	11.0
Inj 1	28.5	13.3	28.8	5.6	51.7	-1.5	6.0
Inj 2	23.8	2.9	-0.1	53.7	49.4	-1.1	9.3
Inj 3	36.5	10.1	-0.9	7.1	0.4	0.9	41.9
Inj 4	39.7	2.0	0.8	1.2	36.2	0.0	30.6
Average after 44 cycles	32.1	7.1	7.2	16.9	34.4	-0.4	21.9
Inj 1				15.6			
Inj 2				22.6			
Inj 3				5.4			
Inj 4				6.1			
Average after 66 cycles				12.4			
Inj 1				25.5			
Inj 2				12.3			
Inj 3				8.6			
Inj 4				5.0			
Average after 88 cycles				12.8			
Inj 1				24.6			
Inj 2				52.2			
Inj 3				34.4			
Inj 4				20.5			
Average after 110 cycles				32.9			

Table 6a: ASTM D 6421 PFI Bench Rig Percent Fouling Results for OEM Injectors and Florida Fuels

Fuel ID	504623			504625		
Injector ID	**OEM1-U2**	**OEM2-N1**	**OEM2-N2**	**OEM1-U2**	**OEM2-N1**	**OEM2-N2**
Inj 1	0.3	1.3	0.4	-2.0	-1.6	5.6
Inj 2	0.8	-2.2	1.1	-0.9	16.9	1.4
Inj 3	1.0	-0.2	2.3	-0.7	-0.6	6.3
Inj 4	0.8	0.1	2.3	-0.3	-3.0	4.4
Average after 22 cycles	0.7	-0.2	1.5	-1.0	2.9	4.4
Inj 1	2.1	3.4	0.9	7.4	5.0	2.8
Inj 2	2.3	0.2	-0.3	11.2	48.6	2.6
Inj 3	2.7	8.1	1.4	-0.6	1.5	7.4
Inj 4	5.1	2.1	1.6	13.8	8.9	3.6
Average after 44 cycles	3.0	3.5	0.9	7.9	14.9	4.1
Inj 1	1.6	6.4	3.4	0.8	3.2	6.2
Inj 2	2.6	4.6	0.6	17.6	48.6	5.5
Inj 3	5.8	17.1	2.1	0.7	2.8	10.9
Inj 4	16.3	5.4	3.3	6.6	18.5	6.0
Average after 66 cycles	6.6	8.4	2.3	6.4	18.3	7.1
Inj 1	0.5	11.5	1.2	3.6	6.3	4.1
Inj 2	3.7	8.6	-0.6	33.1	58.5	6.9
Inj 3	7.2	25.6	2.9	0.9	4.7	13.2
Inj 4	21.9	7.3	1.9	31.1	26.6	8.7
Average after 88 cycles	8.3	13.3	1.3	17.2	24.0	8.2

504623: high fouling, low unwashed gum
504625: high fouling, high unwashed gum

Table 6b: ASTM D 6421 PFI Bench Rig Percent Fouling Results for OEM Injectors and Florida Fuels

Fuel ID	**504626**			**504629**		
Injector ID	**OEM1-U2**	**OEM2-N1**	**OEM2-N2**	**OEM1-U2**	**OEM2-N1**	**OEM2-N2**
Inj 1	-0.2	-1.0	1.1	-0.4	-0.2	1.4
Inj 2	-0.2	-0.1	-1.6	3.9	-0.2	-0.2
Inj 3	1.5	-2.4	-0.3	0.2	0.0	-0.2
Inj 4	0.8	-2.4	-2.0	-0.4	1.7	0.3
Average after 22 cycles	0.5	-1.5	-0.7	0.8	0.3	0.3
Inj 1	0.9	0.0	2.6	-1.0	-0.2	2.1
Inj 2	-1.4	-2.1	-0.8	3.4	0.6	-0.5
Inj 3	1.2	-3.6	-0.3	-0.8	0.4	-0.2
Inj 4	0.4	-4.2	5.9	-1.1	1.8	-0.9
Average after 44 cycles	0.3	-2.5	1.9	0.1	0.6	0.1
Inj 1	1.8	0.3	-1.5	-3.1	1.5	0.0
Inj 2	-2.2	-1.4	-2.2	3.7	2.1	-1.6
Inj 3	1.1	-3.2	-0.4	-0.3	-0.5	-1.4
Inj 4	0.4	-2.7	0.0	0.8	0.3	-0.2
Average after 66 cycles	0.3	-1.8	-1.0	0.3	0.8	-0.8
Inj 1	-0.4	-1.4	1.1	-2.9	2.2	3.4
Inj 2	-3.1	-1.1	-2.4	3.8	1.3	-0.9
Inj 3	1.0	-3.2	-0.6	-2.1	0.7	1.2
Inj 4	0.8	-3.0	1.3	-0.5	-0.2	-1.9
Average after 88 cycles	-0.4	-2.2	0.1	-0.4	1.0	0.5

504626: low fouling, low unwashed gum
504629:low fouling, high unwashed gum

Table 7: ASTM D 6421 PFI Bench Rig Percent Fouling Results for Deposit Control Additives

Additive	A	A	A	B	B	B	B	B	C	C	D	D	D
PTB	40	60	100	40	60	100	140	140	40	60	20	20	40
Rig	A	A	A	E	E	E	E	A	A	A	A	E	E
Inj 1	13.7	20.2	0.9	-1.0	-0.3	2.3	46.1	23.9	3.0	-2.9	12.4	4.7	-2.0
Inj 2	25.4	11.4	5.4	1.0	1.5	3.7	16.3	14.5	23.8	2.4	5.3	14.1	4.4
Inj 3	1.0	-5.2	-2.5	3.9	9.4	12.2	28.9	9.6	6.0	0.6	6.2	10.5	-0.6
Inj 4	7.3	1.3	4.3	3.7	0.3	3.1	12.9	8.9	9.7	-0.1	11.6	9.4	-1.6
Average after 22 cycles	11.8	6.9	2.0	1.9	2.7	5.3	26.0	14.2	10.6	0.0	8.9	9.7	0.1
Inj 1	44.1	32.2	2.1	11.8	9.1	6.0	56.0	60.2	16.0	-1.8	36.7	9.9	-3.6
Inj 2	60.0	17.7	6.4	27.1	13.7	30.4	44.4	46.1	35.9	0.1	26.7	38.9	5.9
Inj 3	8.9	-4.1	-1.9	37.9	52.7	39.2	55.2	33.5	19.5	-0.8	20.3	22.9	-2.3
Inj 4	12.7	5.2	0.1	4.5	0.6	9.2	26.9	29.0	12.1	-3.4	22.2	23.4	-0.2
Average after 44 cycles	31.4	12.7	1.7	20.3	19.0	21.1	45.6	42.2	20.9	-1.4	26.5	23.8	0.0

Table 8: ASTM D 6421 Percent Fouling Results for Additive A in 10% Ethanol

Fuel	Reference	Ref+10% ETOH	Reference	Ref+10% ETOH	Reference	Ref+10% ETOH
PTB	0	0	40	40	60	60
Rig	A	A	A	A	A	A
Inj 1	22.2	13.1	13.7	1.9	20.2	-0.6
Inj 2	16.9	3.7	25.4	0.2	11.4	-0.3
Inj 3	5.8	6.2	1.0	6.5	-5.2	1.1
Inj 4	16.2	4.0	7.3	2.1	1.3	0.0
Average after 22 cycles	15.2	6.8	11.8	2.7	6.9	0.1
Inj 1	73.5	33.2	44.1	10.2	32.2	-1.2
Inj 2	56.0	22.1	60.0	3.1	17.7	0.4
Inj 3	28.2	23.3	8.9	21.0	-4.1	5.4
Inj 4	55.4	22.2	12.7	14.5	5.2	4.6
Average after 44 cycles	53.3	25.1	31.4	12.2	12.7	2.3

Table 9: ASTM D 6421 Percent Fouling Results for Additive A and OEM Injectors

Injector ID	OEM1-N	OEM1-U1	OEM1-U1	OEM1-U2	OEM2-N1	OEM2-U1
PTB	40	40	60	40	40	40
Rig	E	E	E	E	E	E
Inj 1	2.9	-1.4	-0.4	2.5	2.9	-0.1
Inj 2	-0.8	2.1	-0.5	0.0	-0.1	-0.5
Inj 3	0.5	-0.5	0.3	-0.6	-0.4	1.5
Inj 4	-0.4	0.4	0.0	0.3	0.1	-2.0
Average after 22 cycles	0.6	0.1	-0.1	0.5	0.6	-0.3
Inj 1	-0.2	-1.2	2.8	2.1	3.9	-2.7
Inj 2	-2.8	3.9	-1.0	-2.0	-0.5	-1.0
Inj 3	0.3	2.2	1.4	-1.6	0.3	2.0
Inj 4	-0.4	-0.3	1.7	-0.4	0.7	-0.6
Average after 44 cycles	-0.8	1.1	1.2	-0.5	1.1	-0.5
Inj 1	2.5	1.2	-0.7	4.2	0.7	0.4
Inj 2	-0.9	11.7	-0.2	-0.6	-0.3	-1.4
Inj 3	0.2	3.9	12.0	-0.7	3.8	1.8
Inj 4	-1.5	1.5	1.4	3.5	-1.4	4.5
Average after 66 cycles	0.1	4.6	3.1	1.6	0.7	1.3
Inj 1	-0.7	15.3	4.5	1.3	1.6	-3.1
Inj 2	-1.9	23.1	6.6	-1.8	-0.4	0.3
Inj 3	-2.3	5.4	11.2	-0.7	6.4	5.0
Inj 4	-1.4	6.1	0.2	4.5	-0.3	7.8
Average after 88 cycles	-1.6	12.5	5.6	0.8	1.8	2.5

Table 10: ASTM D 6421 Percent Fouling Results for Additive B and OEM Injectors

Injector ID	OEM1-N	OEM1-U1	OEM1-U1	OEM1-U1	OEM1-U2	OEM2-N1	OEM2-N1	OEM2-N1	OEM2-U1	OEM2-U1	OEM2-U1
PTB	40	40	60	100	40	40	60	100	40	60	100
Rig	E	E	E	E	E	E	E	E	E	E	E
Inj 1	-0.1	2.1	0.8	4.8	-1.7	10.6	17.4	12.0	0.4	2.9	1.4
Inj 2	-0.1	1.0	0.4	0.7	-1.3	-1.3	19.7	0.8	0.7	0.7	0.5
Inj 3	-1.1	-0.1	-2.6	0.0	0.0	24.9	7.4	16.6	9.2	18.1	7.1
Inj 4	0.3	13.0	0.8	0.2	1.1	31.4	0.0	1.5	0.8	13.8	4.5
Average after 22 cycles	-0.3	4.0	-0.1	1.4	-0.5	16.4	11.1	7.7	2.8	8.9	3.4
Inj 1	-0.1	2.4	25.1	6.0	1.4	32.9	35.0	21.5	2.8	4.3	1.6
Inj 2	0.8	1.5	24.0	2.1	-0.9	4.4	33.2	1.1	7.2	5.4	0.4
Inj 3	3.2	-1.8	-0.7	-2.3	-0.4	38.6	10.9	25.1	41.4	41.1	56.7
Inj 4	-0.1	26.1	8.2	-1.5	-1.0	43.5	8.5	8.5	15.8	26.6	17.4
Average after 44 cycles	1.0	7.1	14.1	1.1	-0.2	29.8	21.9	14.0	16.8	19.4	19.0
Inj 1	2.9	25.9	34.7	15.5	-1.8	50.9	48.1	39.1	7.8	2.3	5.7
Inj 2	0.5	11.8	4.0	11.7	-1.9	13.4	32.4	9.1	24.6	17.0	1.6
Inj 3	6.7	-0.7	9.2	-1.9	-0.3	35.4	23.0	54.3	36.7	52.2	46.3
Inj 4	3.2	35.9	25.1	-0.1	4.0	36.8	27.8	23.3	27.1	27.8	33.7
Average after 66 cycles	3.3	18.2	18.3	6.3	0.0	34.1	32.8	31.4	24.1	24.8	21.8
Inj 1	-0.7	35.5	13.6	24.6	-1.0	51.6	45.4	45.8	20.6	6.6	9.6
Inj 2	4.4	42.3	6.2	22.6	-2.1	14.0	31.9	14.5	44.5	19.7	4.9
Inj 3	-0.8	2.0	3.0	0.4	0.1	45.8	17.0	56.3	48.7	46.4	61.0
Inj 4	8.2	11.7	13.3	8.9	-0.1	39.4	38.1	31.6	43.0	41.0	41.1
Average after 88 cycles	2.8	22.9	9.1	14.1	-0.8	37.7	33.1	37.1	39.2	28.4	29.1

Table 11: ASTM D 6421 Percent Fouling Results for Additive C and OEM Injectors

Injector ID	OEM1-N	OEM1-U1	OEM1-U2	OEM2-N1	OEM2-U1
PTB	40	40	40	40	40
Rig	E	E	E	E	E
Inj 1	2.9	-0.8	3.7	-2.9	4.0
Inj 2	1.1	1.1	-1.3	0.8	2.0
Inj 3	-0.2	0.8	-1.5	2.0	1.0
Inj 4	1.2	2.1	2.7	-0.4	0.4
Average after 22 cycles	1.3	0.8	0.9	-0.1	1.9
Inj 1	-1.4	-2.3	4.7	-1.7	2.5
Inj 2	2.5	2.0	-1.4	1.4	1.6
Inj 3	2.6	0.1	-2.2	-1.3	1.8
Inj 4	8.5	0.5	1.9	-0.3	0.7
Average after 44 cycles	3.1	0.1	0.7	0.1	1.7
Inj 1	2.4	-2.1	4.2	-1.0	0.7
Inj 2	2.5	1.2	-1.4	1.3	0.4
Inj 3	2.4	0.1	-3.3	8.7	-0.6
Inj 4	12.4	1.9	1.8	-0.8	0.6
Average after 66 cycles	4.9	0.3	0.3	2.1	0.3
Inj 1	1.0	-2.6	3.2	-1.0	3.3
Inj 2	2.3	1.8	0.0	1.3	1.6
Inj 3	6.5	0.9	-1.2	5.2	3.0
Inj 4	14.9	-0.5	2.6	0.3	11.0
Average after 88 cycles	6.2	-0.1	1.1	1.5	4.7

Table 12: Comparison of ASTM D 6421 and D 5598 Injector Fouling Results

Fuel ID	**CRC-01**	**CRC-02**	**CRC-03**	**CRC-04**	**CRC-05**	**CRC-06**
10% Ethanol	Yes	Yes	Yes	Yes	No	No
D 6421 rig	A	A	A	A	A	A
Inj 1	-0.8	12.7	23.1	46.8	6.8	4.3
Inj 2	-0.2	2.5	8.8	13.2	5.1	-1.8
Inj 3	2.4	6.3	4.7	21.0	4.5	3.2
Inj 4	1.8	3.0	15.9	4.9	-1.0	0.1
Average after 22 cycles	0.8	6.1	13.1	21.5	3.8	1.5
Inj 1	-0.3	12.1	68.7	78.5	23.2	10.6
Inj 2	2.0	5.4	17.6	40.1	18.0	5.7
Inj 3	1.9	18.5	18.8	34.0	12.5	10.6
Inj 4	3.2	8.9	49.1	11.0	1.2	1.5
Average after 44 cycles	2.0	11.2	38.6	40.9	13.7	7.1
D 5598						
Inj 1	1.09	-0.64	4.24	-0.39	1.74	-1.85
Inj 2	0.47	4.93	-0.70	-0.34	-0.10	-3.49
Inj 3	-0.82	2.70	-0.32	-0.60	0.85	-1.67
Inj 4	0.13	5.11	-0.07	-0.16	-1.16	-2.73
Average after 10K miles	0.22	3.02	0.79	-0.37	*0.33	-2.44

* D 5598 run to 9654 miles.

Figure 1: Average Fouling of Florida Gasoline Samples After 44 Cycles

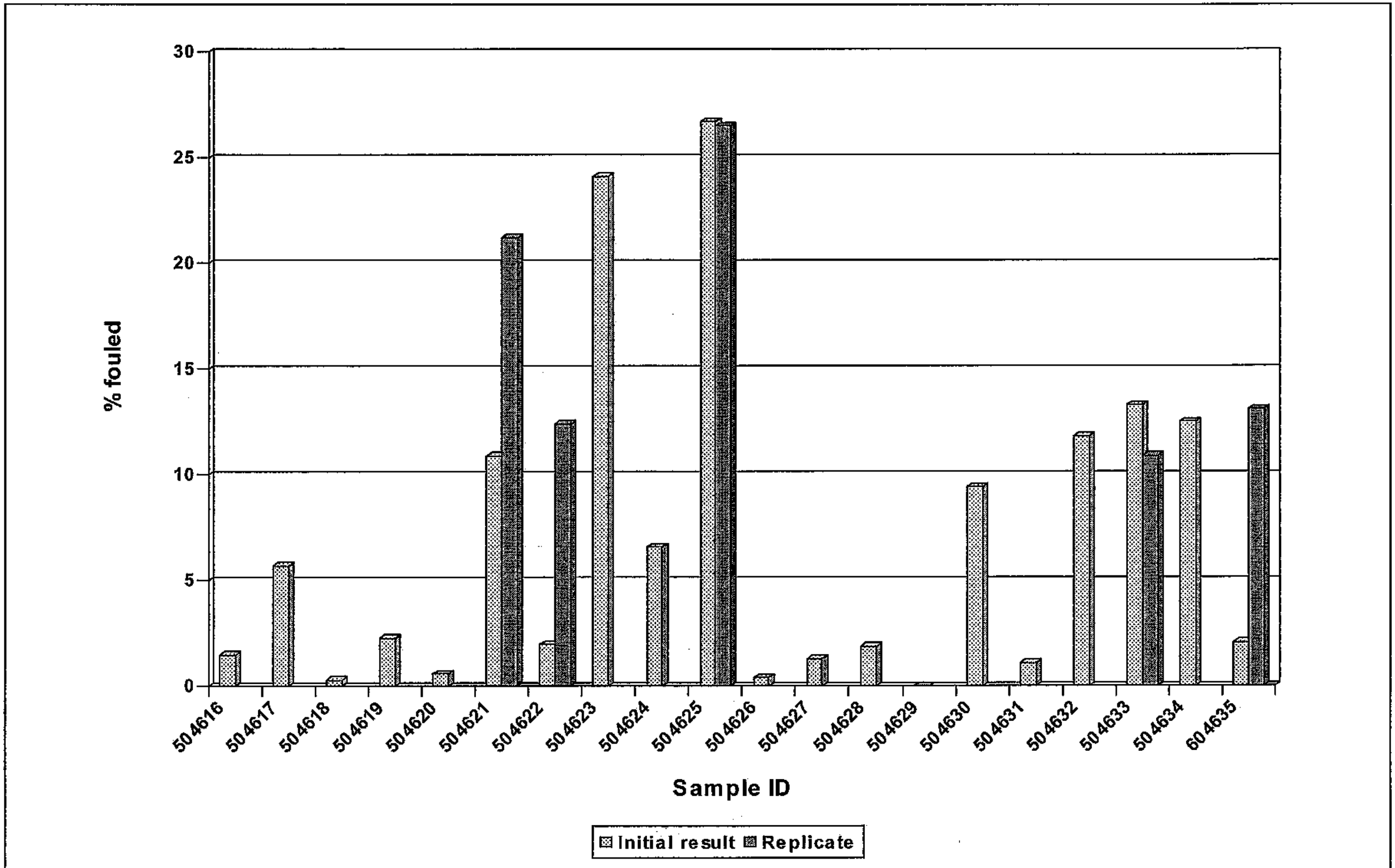


Figure 2: Maximum Fouling of Florida Gasoline Samples After 44 Cycles

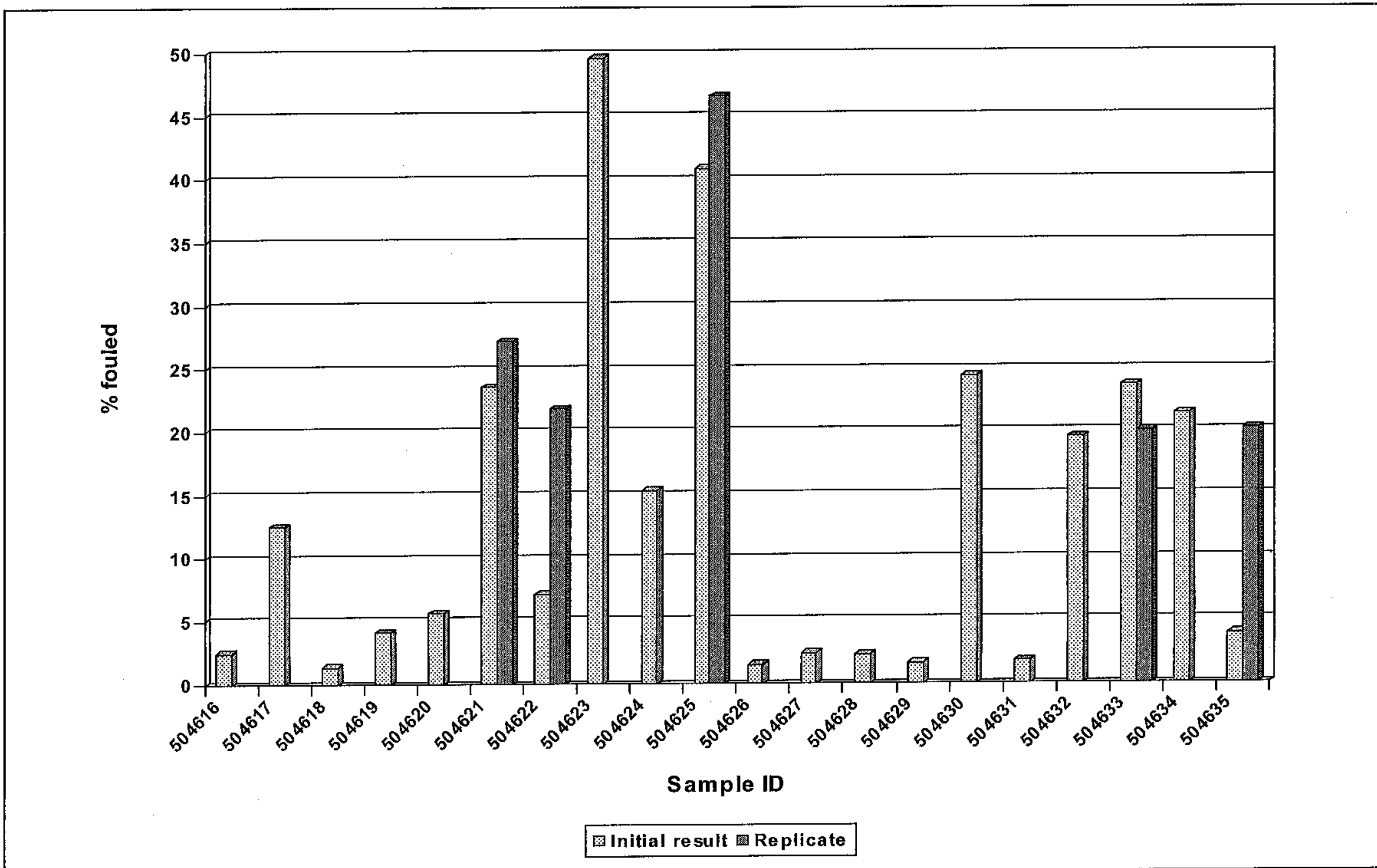


Figure 3: Average and Maximum Fouling of OEM Injectors After 44 Cycles

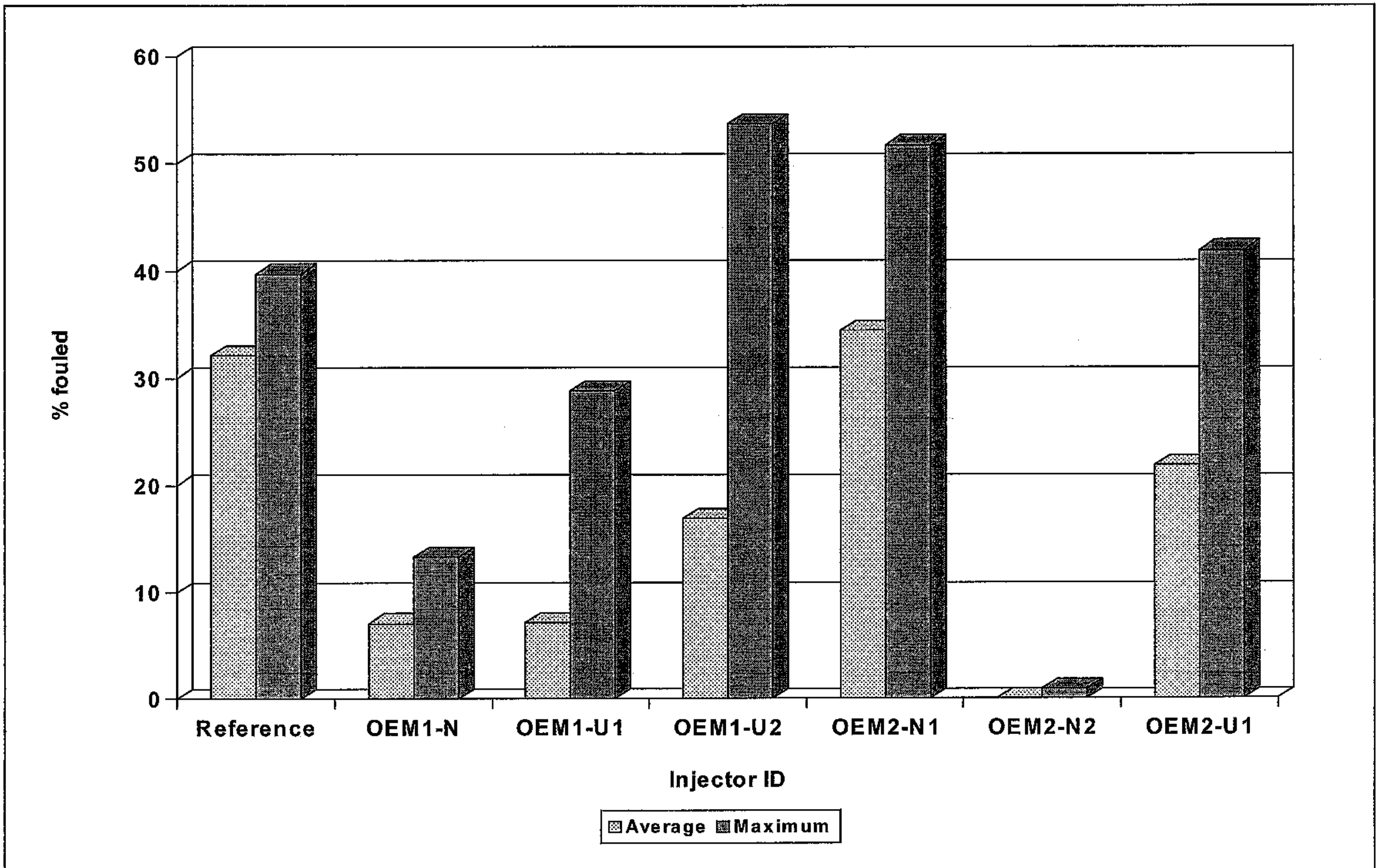
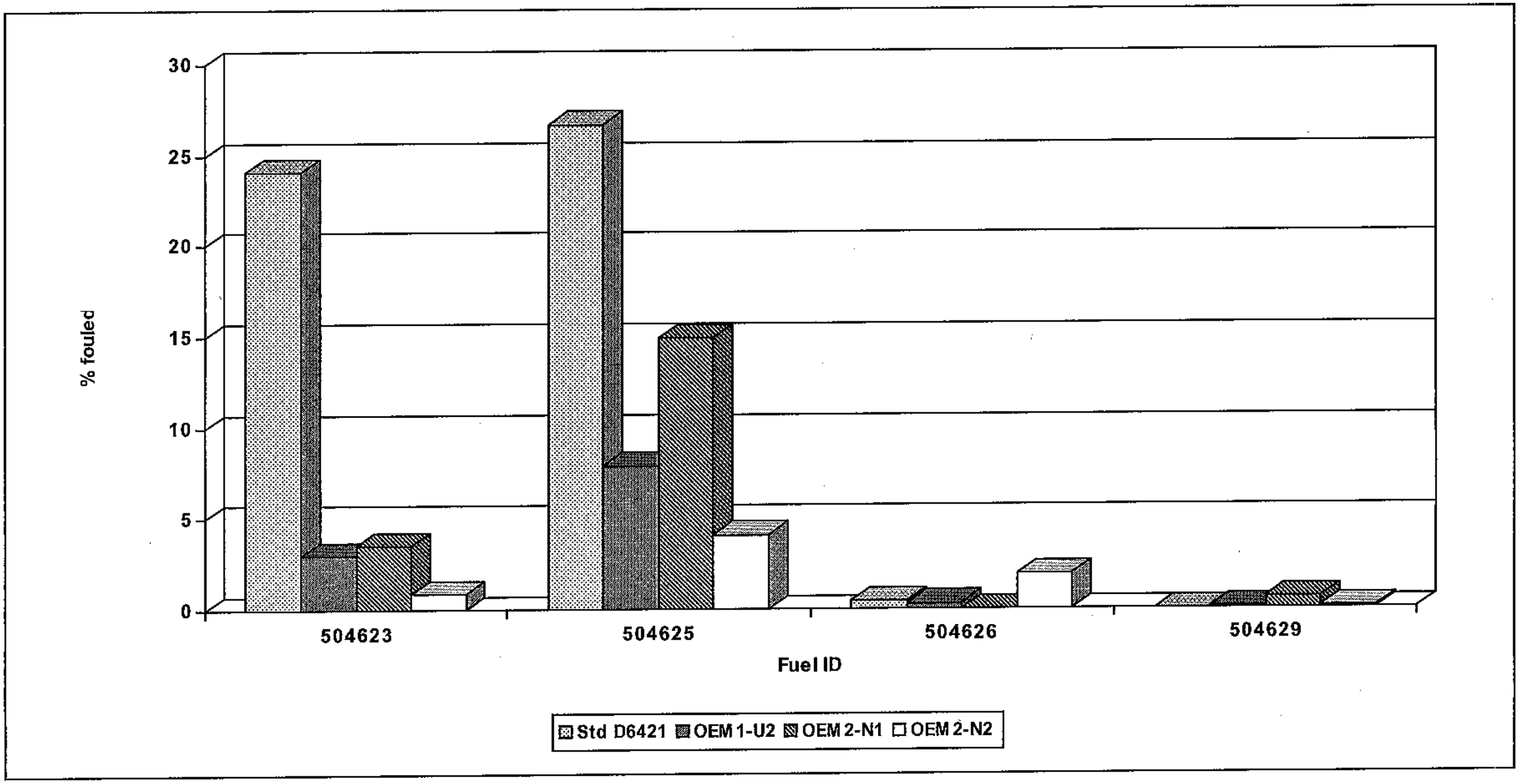
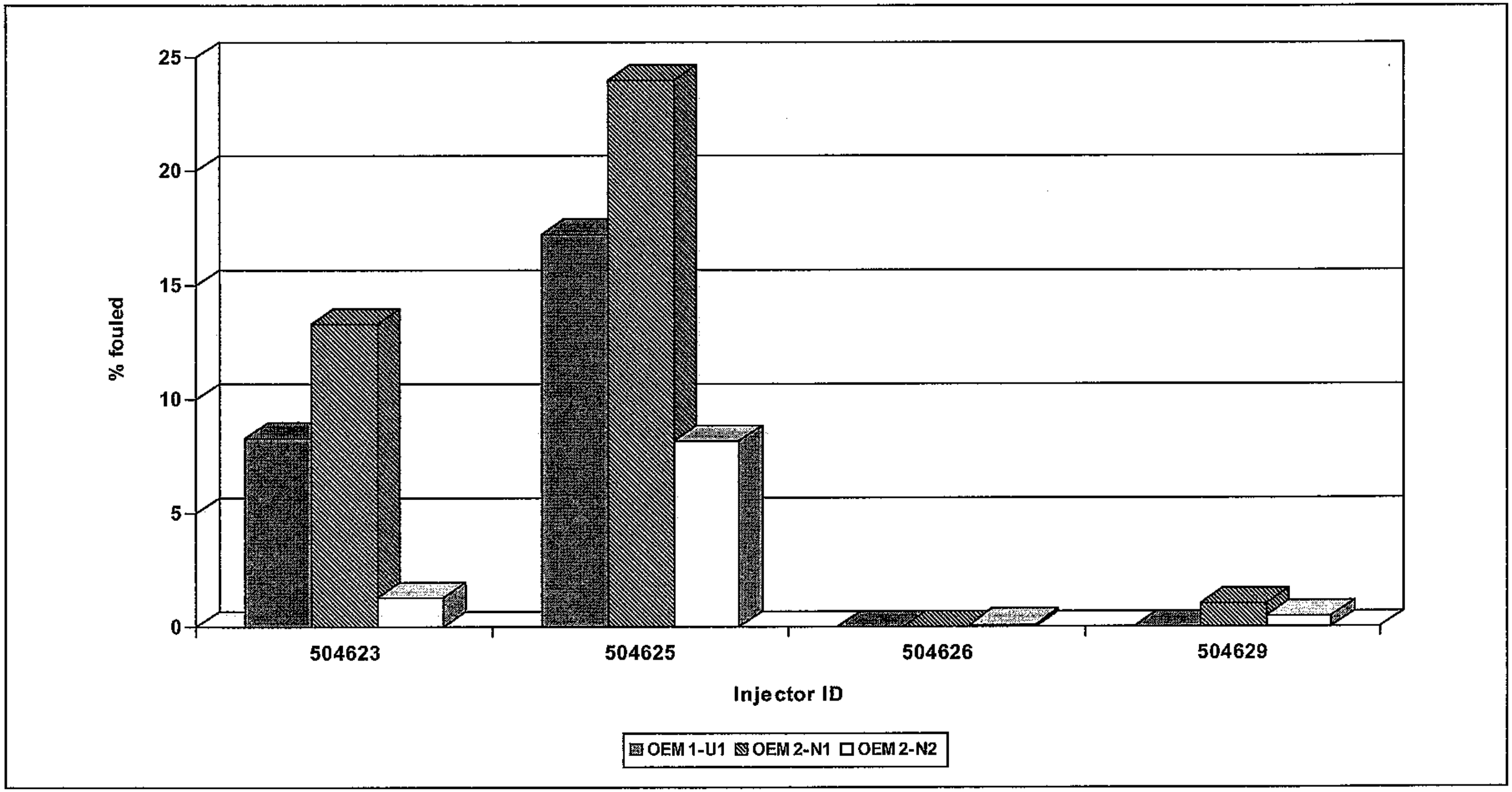


Figure 4a: Average Fouling Results for OEM injectors and Florida Gasoline After 44 Cycles



504623: high fouling, low unwashed gum
504625: high fouling, high unwashed gum
504626: low fouling, low unwashed gum
504629: low fouling, high unwashed gum
Fouling results less than zero are shown as zero.

Figure 4b: Average Fouling for OEM Injectors and Florida Gasoline After 88 Cycles



504623: high fouling, low unwashed gum
504625: high fouling, high unwashed gum
504626: low fouling, low unwashed gum
504629: low fouling, high unwashed gum
Fouling results less than zero are shown as zero. Standard test injectors were not run out to 88 cycles.

Figure 5: Average Fouling Results for Additives A, B, C, and D After 44 Cycles

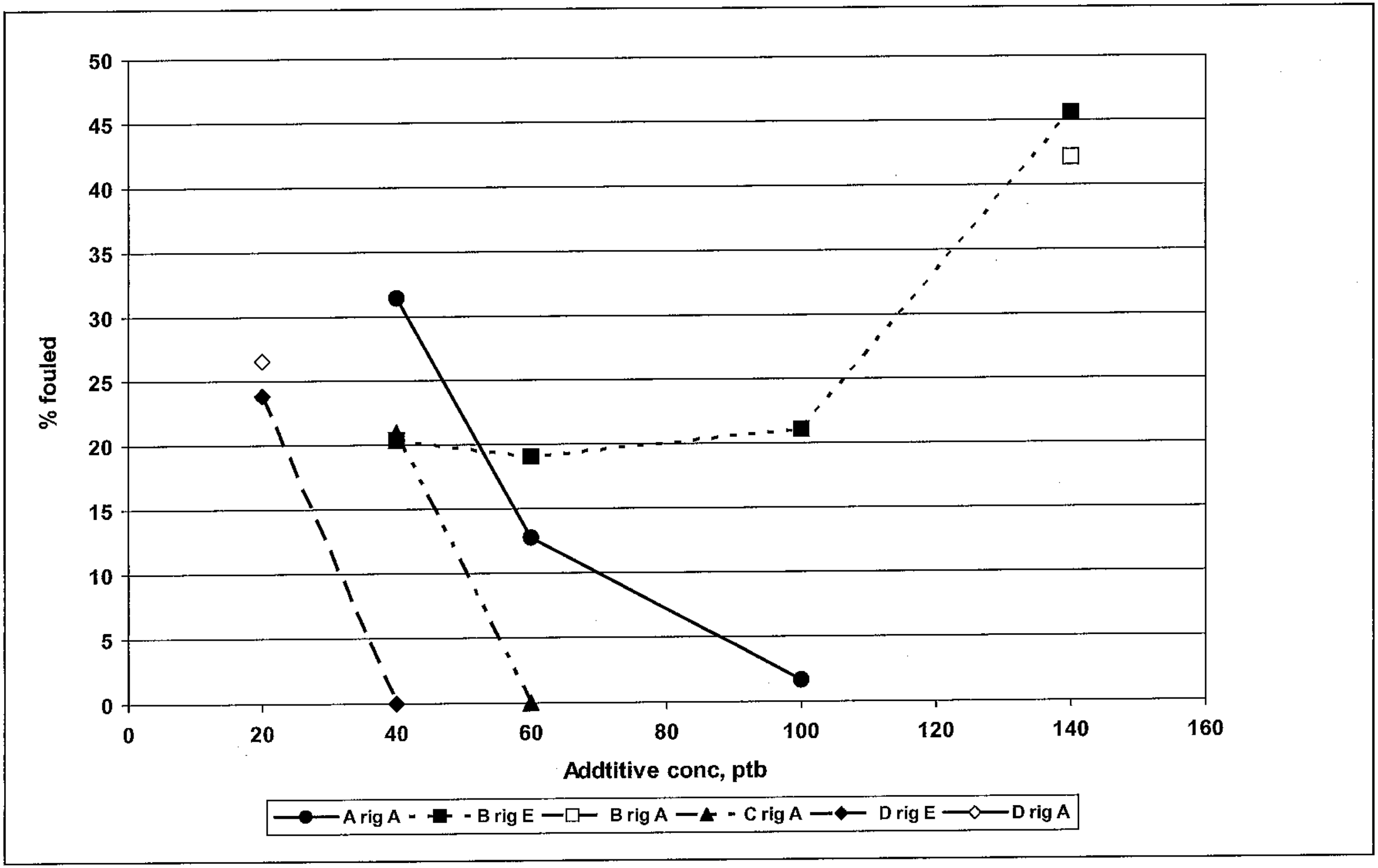


Figure 6: Average Fouling for Additive A in 10% Ethanol After 44 Cycles

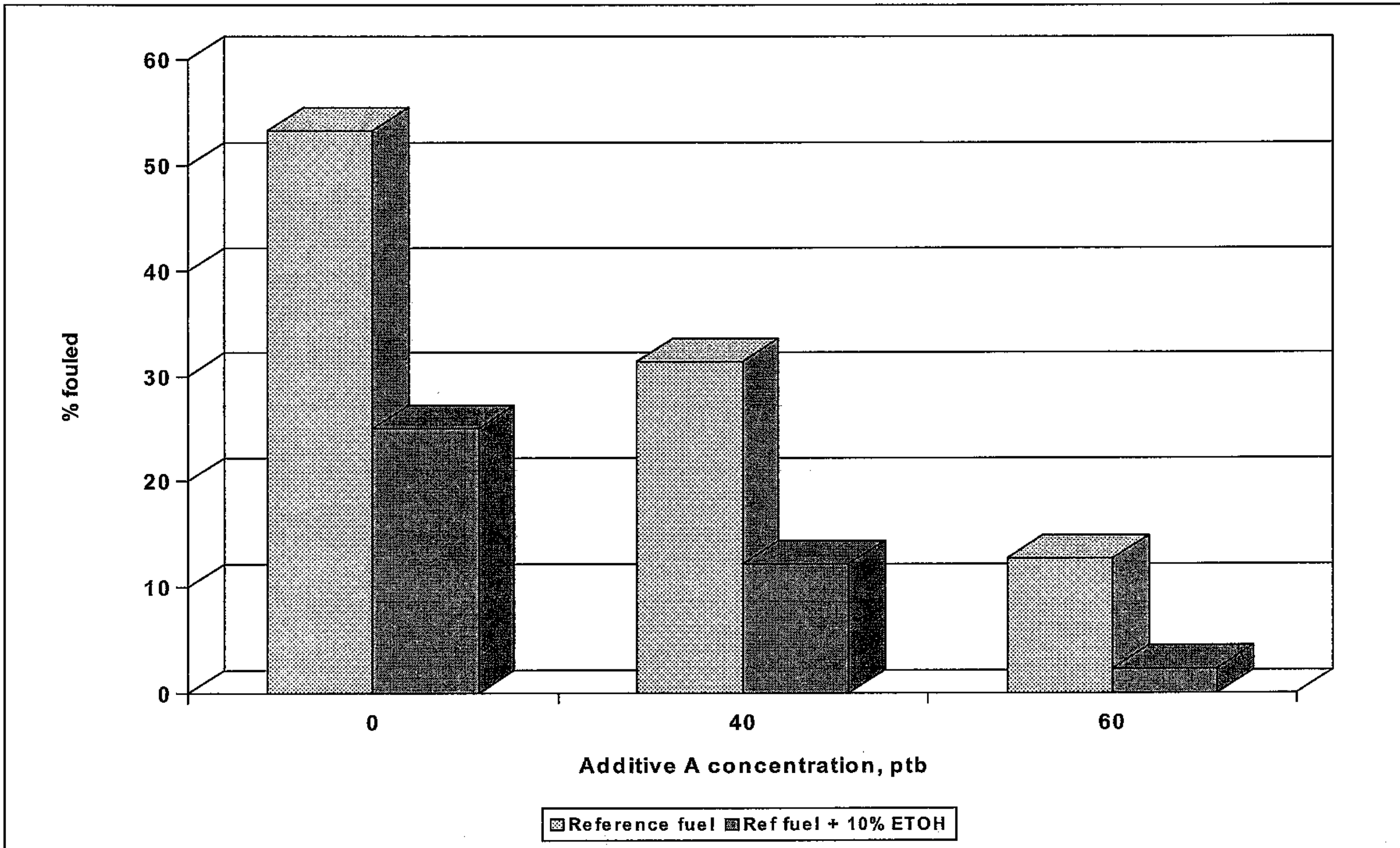
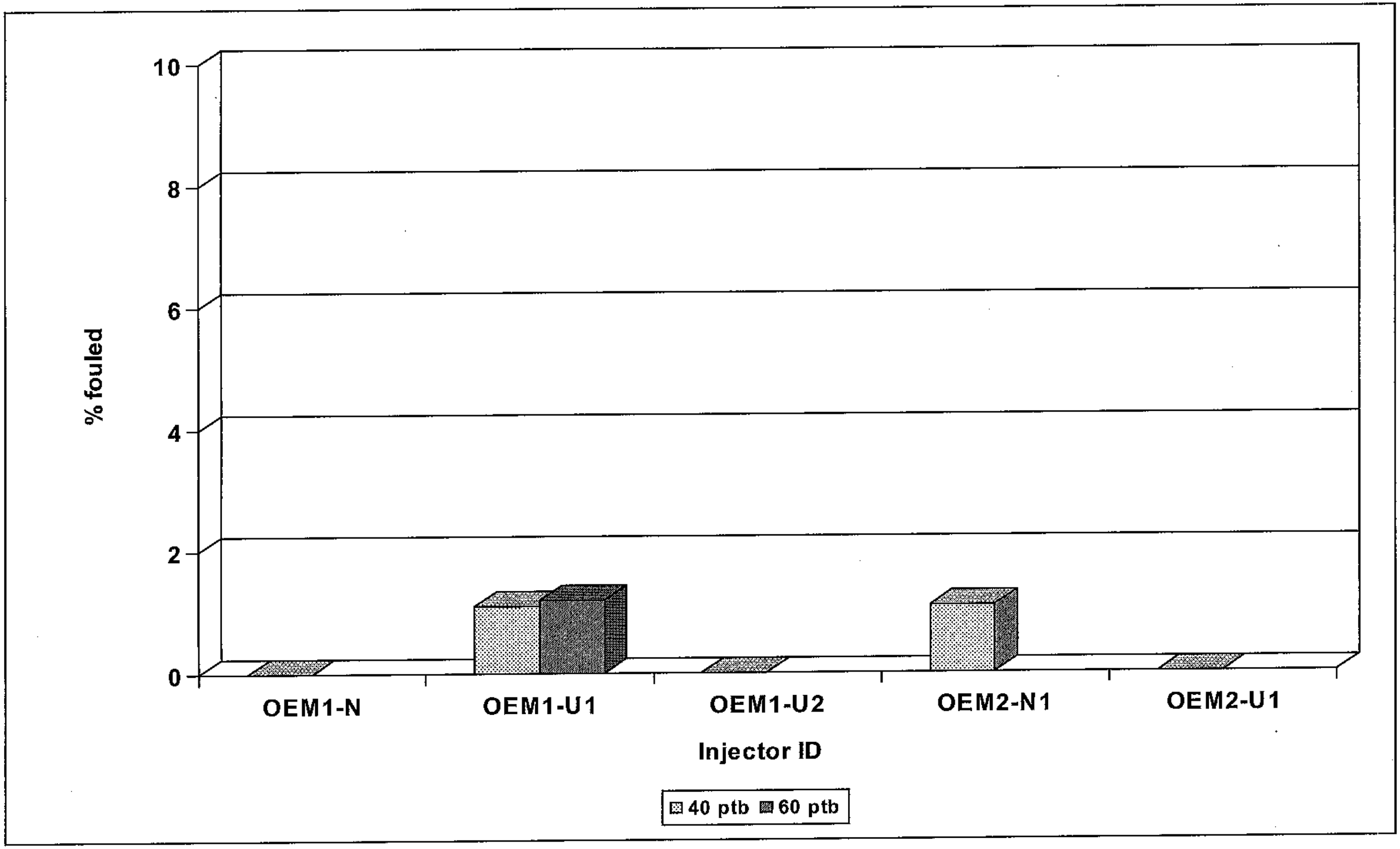
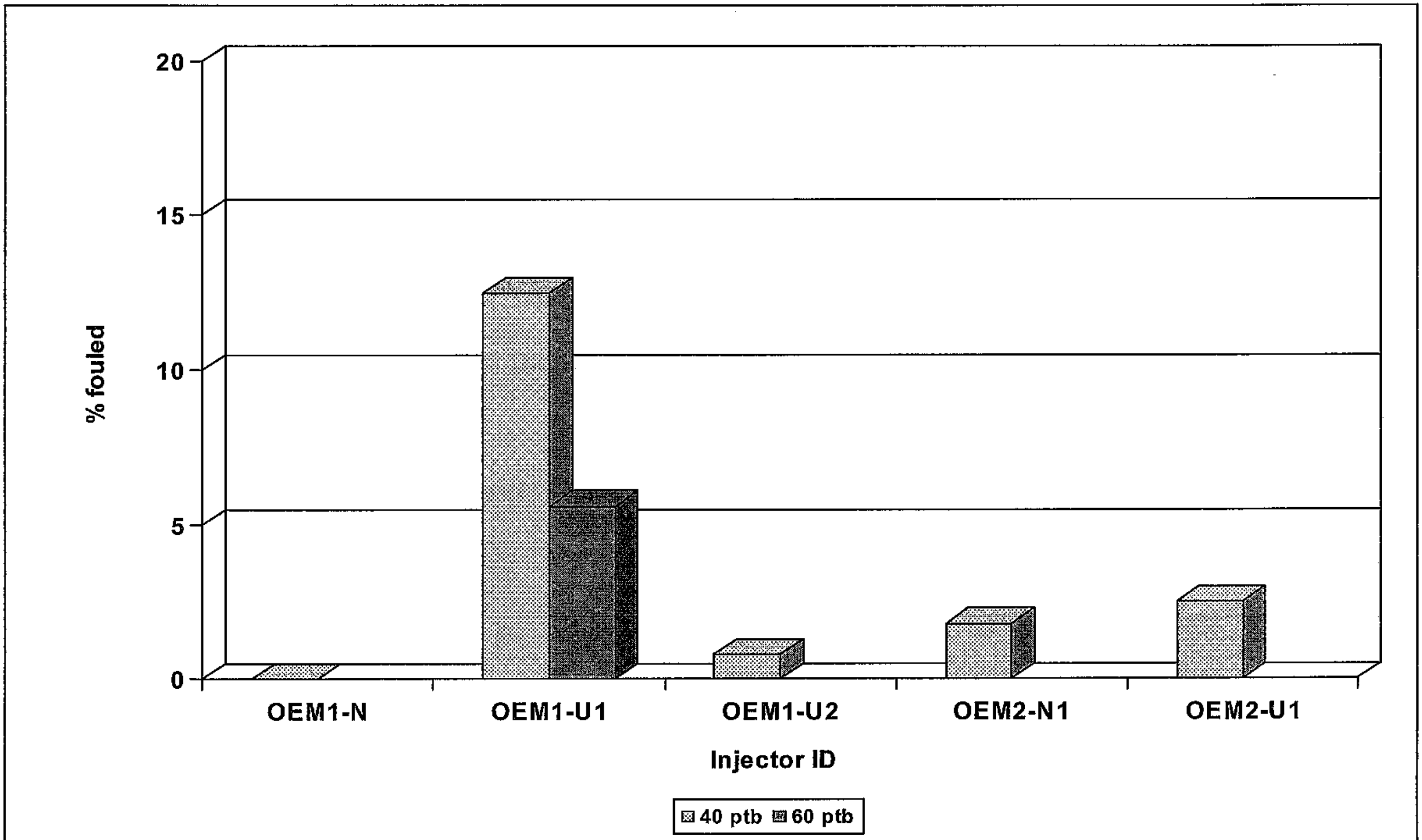


Figure 7a: Average Fouling Results for Additive A and OEM Injectors After 44 Cycles



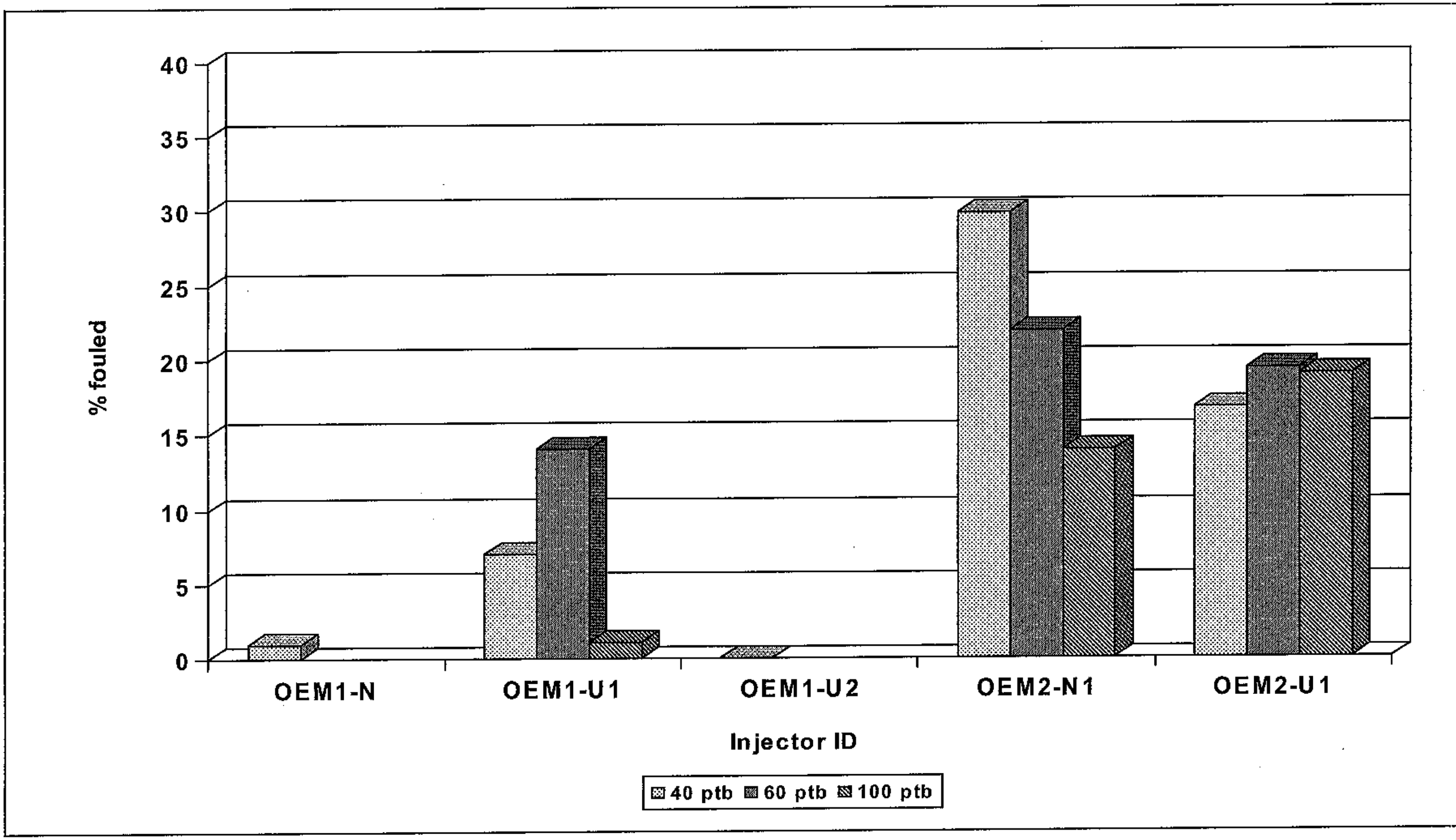
Fouling results less than zero are shown as zero.

Figure 7b: Average Fouling Results for Additive A and OEM Injectors After 88 Cycles



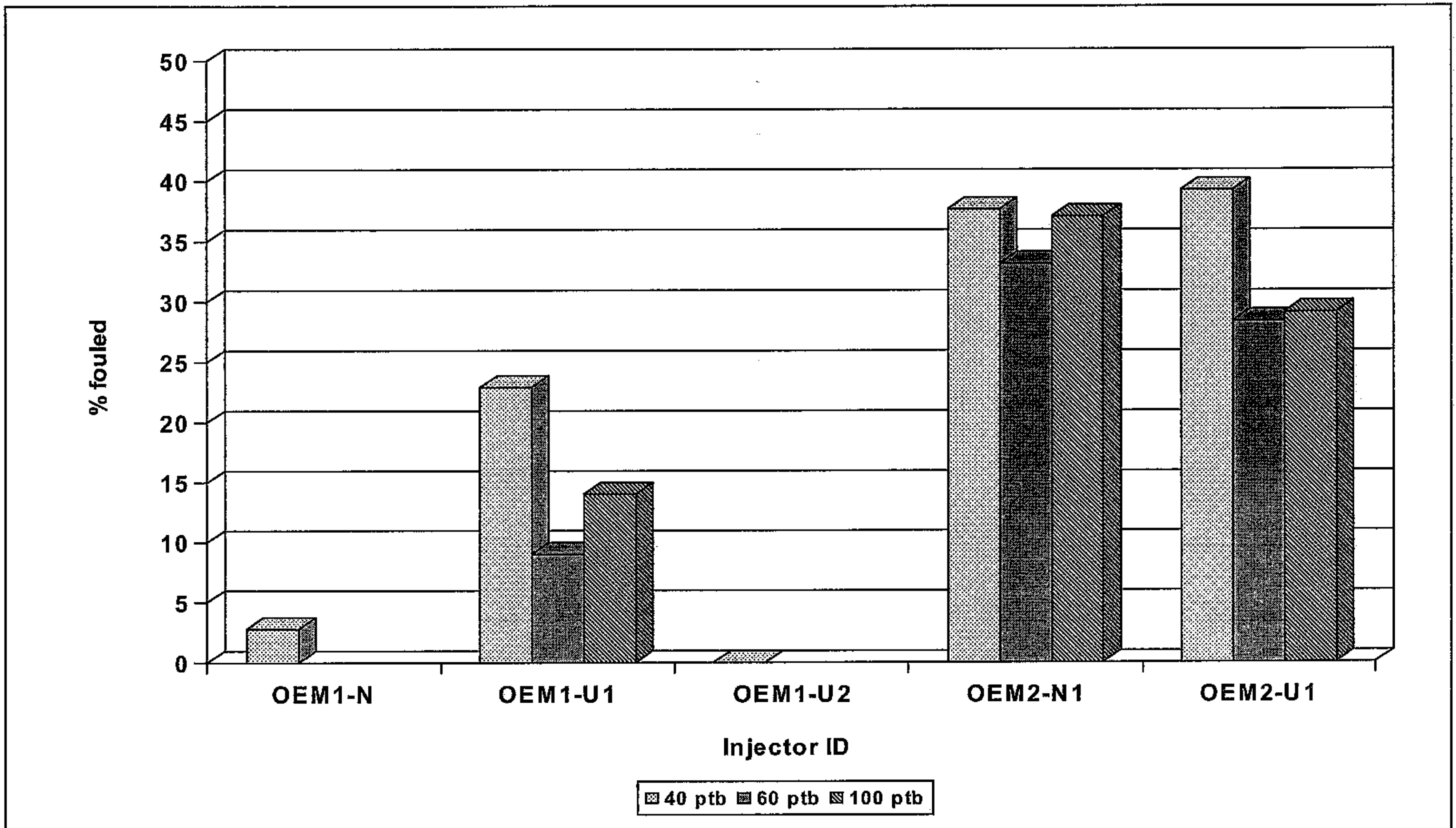
Fouling results less than zero are shown as zero.

Figure 8a: Average Fouling Results for Additive B and OEM Injectors After 44 Cycles



Fouling results less than zero are shown as zero.

Figure 8b: Average Fouling Results for Additive B and OEM Injectors After 88 Cycles



Fouling results less than zero are shown as zero.

Figure 9a: Average Fouling Results for Additive C and OEM Injectors After 44 Cycles

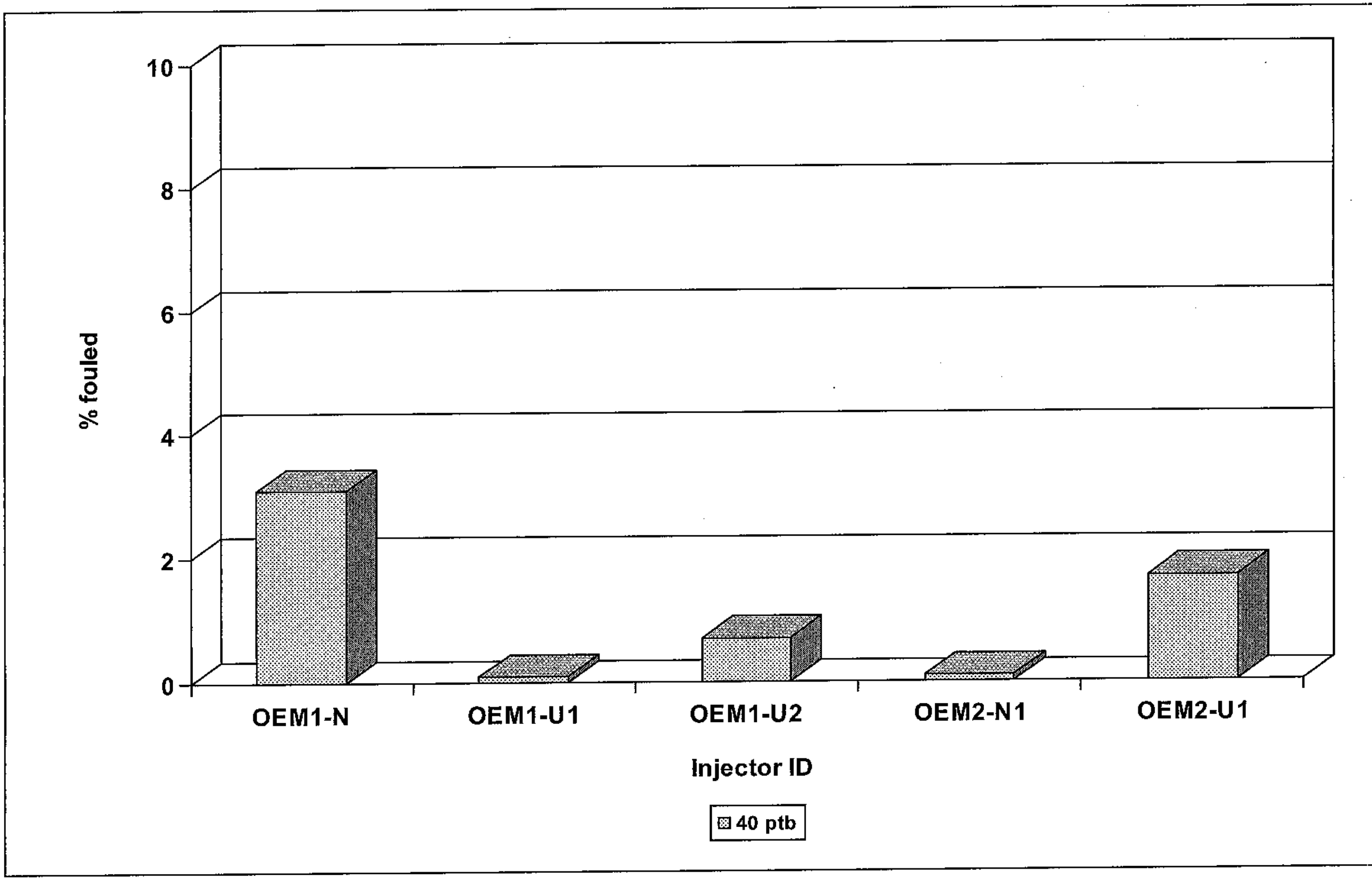
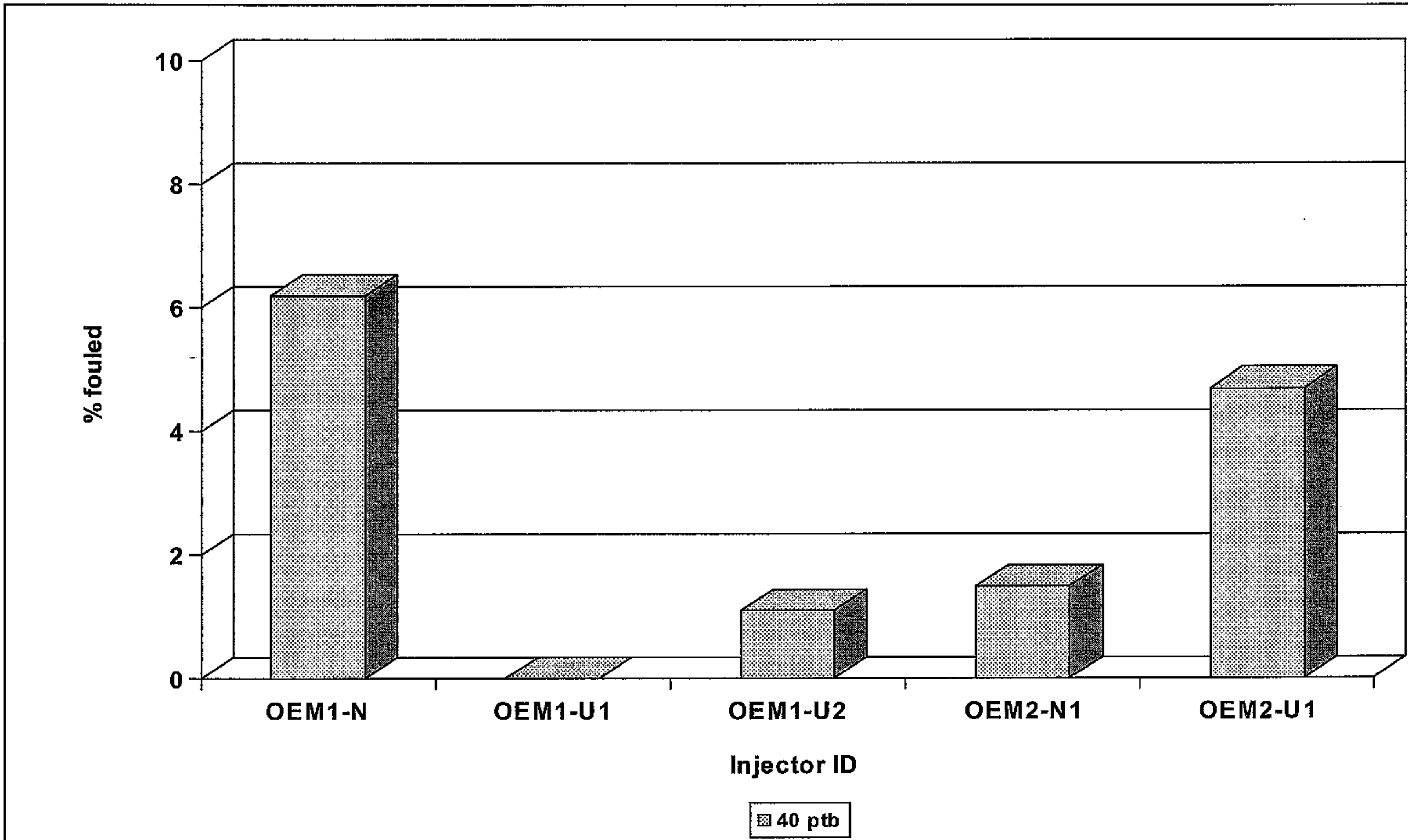
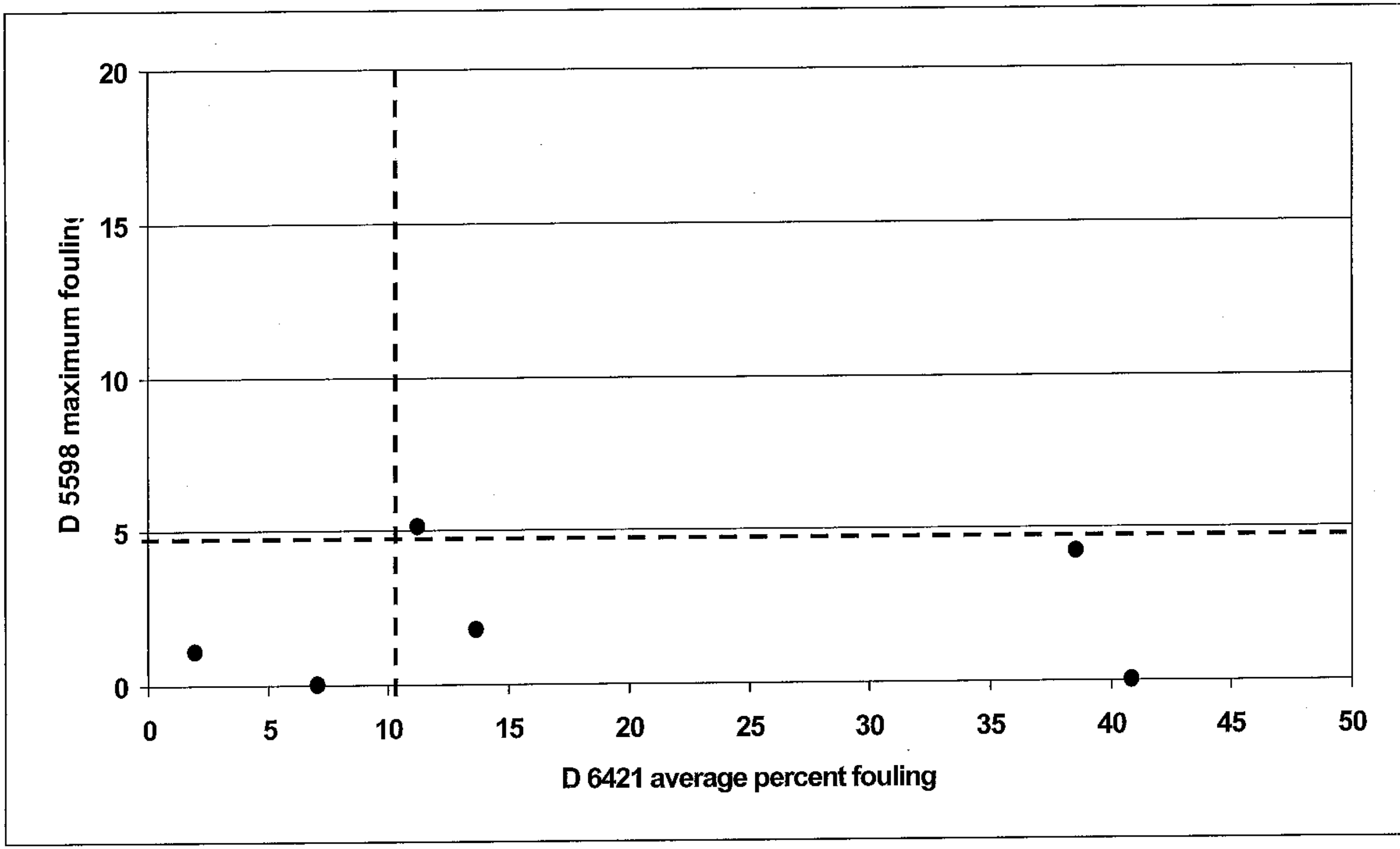


Figure 9b: Average Fouling Results for Additive C and OEM Injectors After 88 Cycles



Fouling results less than zero are shown as zero.

Figure 10: Comparison of ASTM D 6421 and D 5598 Injector Fouling Results



APPENDIX A

MEMBERSHIP OF THE CRC DEPOSIT GROUP

PORT FUEL INJECTOR PANEL

MEMBERSHIP OF THE CRC DEPOSIT GROUP PFI PANEL

Name	Affiliation
N. L. Avery, Deposit Group chairman	ExxonMobil
A. Buczynsky, PFI Panel co-chairman	General Motors
J. Jetter, PFI Panel co-chairman	Honda R&D Americas
M. Ahmadi	Chevron Oronite
J. Galante-Fox	Delphi
L. M. Gibbs	Chevron Products Company
J. T. Joseph	BP Oil
A. Kulinowski	Afton Chemical
R. Peyla	Chevron Oronite
J. Russo	Shell Global Solutions

APPENDIX B

CRC PORT FUEL INJECTOR PANEL PROGRAM

CRC PORT FUEL INJECTOR PANEL PROGRAM

Title: 2003 CRC PORT FUEL INJECTOR FOULING SURVEY

Project: CM-136-03

Objective: Determine the extent of fuel injector fouling in one region of the US and the adequacy of current deposit control additive dosages to prevent injector fouling.

Deliverables: (1) An assessment of port fuel injector fouling tendency of commercial gasoline samples collected in one region of the US. (2) A correlation between injector fouling tendency and fuel properties. (3) A comparison of the fouling tendency of standard test injectors to current OEM injectors. (4) An assessment of the adequacy of a Lowest Additive Concentration (LAC) of a deposit control additive in preventing fouling in current OEM injectors.

Test Program Plan

Test Apparatus: ASTM D 6421, the PFI bench test, will be used to determine the fouling tendency of gasoline samples. This test is a quick and inexpensive means to measure fouling tendency. The bench test has been correlated with the vehicle injector-fouling test, ASTM D 5598, and has been shown to be a good predictor of PFI fouling (SAE 1999-01-1548).

Fuels: Florida was chosen as the region to collect commercial gasoline samples. Several OEMs have determined Florida to be an area of very high injector fouling problems. The state has a unique distribution system in that its gasoline is almost exclusively supplied by marine transport. In addition the two Florida coasts receive gasoline from different sources: the Gulf Coast (Tampa) is supplied by US Gulf Coast refineries, whereas the southern Atlantic Coast (Miami) is supplied primarily by offshore refineries in the Caribbean, South America, or across the Atlantic Ocean.

Commercial gasoline will be obtained from, 8-10 of the main marketers in both Tampa and Miami, FL. Ten gallons of unleaded regular gasoline will be collected from each service station. Research on the supply system will be done in advance to ensure the fuel samples are sourced from as many different terminals as possible.

Fuel Testing: The following gasoline analysis will be done at Southwest Research Institute:
Distillation by ASTM D 86
Unwashed and solvent washed gum content by ASTM D 381
Induction period by ASTM D 525
Total sulfur by ASTM D 2622
Peroxide number by ASTM D 3703
Manganese by ASTM D 3831
Diolefins by maleic anhydride test method
Copper by UOP-144

Detailed hydrocarbon analysis of the gasoline samples will be done by Chevron Products Company.

Test Plan: The injector-fouling tendency of each commercial gasoline will be measured using ASTM D 6421 at Southwest Research Institute. Injectors recommended by General Motors and Honda will be substituted into the PFI bench rig, and their fouling tendency will be measured using a known fouling fuel without deposit control additive such as Port Fuel Injector Fouling Fuel or another fuel selected by SWRI. If fouling is observed, the GM and Honda injectors will be tested using the same fuel now containing a LAC dosage of a deposit control additive. Additive supplier or fuel marketers will supply LAC additives as blind samples along with treat rates. SWRI will pick one at random to use in testing.

Timing: Commercial fuels will be collected in July/August 2003. Testing will start shortly thereafter.

Program Costs (Plan)

Fuel Sampling	\$3,000 (20 10-gallon samples @ \$150/sample)
Fuel Analysis	\$7,340 (20 samples at \$367/sample)
PFI Test:	\$9,100 (20 fuels + 6 injector/additive tests @ \$350/test)
TOTAL:	\$19,440

Andrew Buczynsky and Jeff Jetter, Co-Chairmen
CRC PFI Panel
April 2003

CRC PORT FUEL INJECTOR PANEL PROGRAM

Title: 2003 CRC PORT FUEL INJECTOR FOULING SURVEY

Project: CM-136-03

Objective: Determine the extent of fuel injector fouling in one region of the US and the adequacy of current deposit control additive dosages to prevent injector fouling.

Deliverables: (1) An assessment of port fuel injector fouling tendency of commercial gasoline samples collected in one region of the US. (2) A correlation between injector fouling tendency and fuel properties. (3) A comparison of the fouling tendency of standard test injectors to current OEM injectors. (4) An assessment of the adequacy of a Lowest Additive Concentration (LAC) of a deposit control additive in preventing fouling in current OEM injectors.

Results from Phase 1

Twenty commercial fuels have been collected in Miami and Tampa, FL. They were analyzed for composition, oxidation stability, and additive content and tested for fouling tendency using the bench rig at SWRI. A number demonstrated higher-than-expected fouling characteristics (6 of 20 fuels showed >10% fouling). No correlation was found between injector fouling and any fuel properties, including additive content. Based on unwashed gum content, fouling fuels appeared to include those with lower additive dosages as well as those with premium dosages. Replicate PFI bench tests on five samples resulted in a large increase in fouling for three samples. The reason for the increase in fouling is not known; however, the time lag between replicate tests was about 2 months, indicating fuel stability may have been a factor.

Budget: $19,440
Spent: $18,910

<u>Proposal for Phase 2</u>

Objective: Compare the fouling tendency of current OEM injectors to standard Chrysler test injectors using the PFI bench test. Assess the adequacy of current commercial deposit control additive concentrations to prevent fouling in standard Chrysler test injectors. Compare performance in the bench rig to performance in the Chrysler PFI vehicle test.

Deliverables: (1) A comparison of fouling in new and warranty-return injectors from GM and Honda to Chrysler test injectors. Testing in the PFI bench rig will be done using director plate (GM and Honda) and pintle style (Honda) injectors. Test fuel will be PIFF and several Florida fuels. Test other OEM injectors if available. (2) An assessment of detergent dosage impact on fouling in standard Chrysler test injectors using several commercial deposit control additives. Testing will be done initially with PIFF and then with one or more Florida fuels. (3) A comparison of fouling observed in the Chrysler PFI vehicle test to results obtained in the PFI bench rig.

Several fuels will be solicited from parties conducting testing at SWRI. The fuels will be analyzed for composition, oxidation stability, additive content by unwashed gum, and PFI fouling in the bench test.

Test plan: See Appendix I, II and III for specific details of the test plan.

Budget: $50,000

Andrew Buczynsky and Jeff Jetter, Co-Chairmen
CRC PFI Panel
January 2004

Appendix I

Objective: Compare the fouling tendency of current OEM injectors to standard Chrysler test injectors.

Test procedure: The procedure for testing warranty-return injectors is as follows:

1) If possible, obtain information (i.e., driving patterns, engine parameters, etc.) about the vehicles from which the injectors were obtained.
2) Clean all injectors using the procedure found in Annex A4.3 of ASTM D 6421.
3) View injector tips under microscope magnification and photograph them. The magnification should be high enough to show detail of the surface roughness.
4) Run all injectors in the PFI bench rig using PIFF.
5) Select four injectors of each style (i.e., GM director plate, Honda director plate, Honda pintle) with the highest fouling level and rerun them in the bench rig using one known Florida fouling fuel.
   i. Before running a Florida fuel in the bench rig, obtain a new baseline fouling value using standard Chrysler injectors. Also, determine the extent of fuel aging by measuring oxidation stability (D 525) and gum (D 381).

The procedure for testing new injectors is similar to the one above with the exception that injector cleaning will not be done.

1) View injector tips under microscope magnification and photograph them. The magnification should be high enough to show detail of the surface roughness.
2) Run all injectors in the PFI bench rig using PIFF.
3) Select four injectors of each style (i.e., GM director plate, Honda director plate, Honda pintle) with the highest fouling level and rerun them in the bench rig using one known Florida fouling fuel.
   i. Before running a Florida fuel in the bench rig, obtain a new baseline fouling value using standard Chrysler injectors. Also, determine the extent of fuel aging by measuring oxidation stability (D 525) and gum (D 381).
4) If injectors from other OEMs are available, test them in the same fashion as described in steps 1-3.

Budget: Injector photos: $50 x 60 = $3,000
PFI bench test with PIFF: $350 x 12 = $4,200
Fuel aging evaluation fuel analysis set: $272 x 2 = $544
Total: $7,744
Additional PFI tests: $350 per sample

Appendix II

Objective: Assess the adequacy of current commercial deposit control additive concentrations to prevent fouling in standard Chrysler test injectors.

Test procedure: Testing will be done using at least two commercial additives that represent different chemistries.

1) Run additive A at 40, 60, and 100 ptb (detergent active components) in PIFF in the PFI bench rig.
2) Run additive B at 40, 60, and 100 ptb (detergent active components) in PIFF in the PFI bench rig.
3) If fouling greater than 10% is observed at a particular concentration, run four selected GM and Honda injectors of each type (i.e., GM director plate, Honda director plate and pintle style) using the same fuel.
    i. Test other OEM injectors if available.

Budget: PFI bench test with standard injectors and PIFF: $350 x 6 = $2,100
Additional testing with OEM injectors: $350 per injector set

Appendix III

Objective: Compare performance in the bench rig to performance in the Chrysler PFI vehicle test.

Test procedure: SWRI will contact customers running the Chrysler PFI test and ask permission to obtain five gallons of additized fuel for testing in the PFI bench rig and for laboratory testing. Fuels that have both passed and failed the vehicle test will be solicited.

1) Run the fuel in the PFI bench rig.
2) Analyze the fuel for:
   i. Distillation by D 86
   ii. Sulfur
   iii. DHA
   iv. Oxidation stability by D 525
   v. Gum by D 381
   vi. Potential Gum by D 873, with 4 hour time

Budget: Fuel analysis: $877 per sample (assuming SWRI runs DHA)

PFI bench test: $350 per sample