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FreedomCAR & Vehicle Technologies Program

Diesel Engine Idling Test

TECHNICAL REPORT

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February 2006

Idaho National Laboratory
Operated by Battelle Energy Alliance

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ABSTRACT

In support of the U.S. Department of Energy (DOE), FreedomCAR and Vehicle Technologies Program's goal to minimize diesel engine idling and reduce the annual consumption of millions of gallons of diesel fuel during heavy vehicle idling periods, the Idaho National Laboratory (INL) conducted tests to characterize diesel engine wear rates during extended engine idling periods as part of its support of DOE's Advanced Vehicle Testing Activity. INL idled two of its fleet buses (equipped with Detroit Diesel Series 50 engines) for 1,000 hours each. Engine wear metals were characterized from weekly oil analysis samples and destructive filter analyses. Engine oil full-flow and bypass filter cartridges were removed at four stages of the testing and sent to an oil analysis laboratory for destructive analysis to ascertain the metals captured in the filters and to establish wear-rate trends. Weekly oil samples were also sent to two independent oil analysis laboratories. Concurrent with the filter analysis, a comprehensive array of other laboratory tests ascertained the condition of the oil, wear particle types, and ferrous particles. Extensive ferrogram testing physically showed the concentration of iron particles and associated debris in the oil. The tests results did not show dramatic results during the extended idling periods, but did show wear trends. New West Technologies, LLC, a DOE support company, supplied technical support and data analysis throughout the idling test.

CONTENTS

FIGURES

TABLES

ACKNOWLEDGEMENTS

The Idaho National Laboratory Fleet Operations group provided the fuel and staff personnel for this testing. The primary fleet personnel included Brett Hobbs, fleet operations manager; John Kay, fleet bus operations leader; Aaron Taylor, service mechanic; Jim Neff, maintenance scheduling; and Tony Rushin, shipping. Others include the four bus lot schedulers and the many drivers who started the buses in the early morning, logged oil use and fuel consumption data, and shut down the buses in the evening or early morning. Mike Beateag of National Tribology Services Inc. of Minden, Nevada and his staff provided the extensive oil and destructive filter analysis. Jerry Gibbs, New West Technologies, LLC, provided technical support and data analysis throughout the idling test.

Diesel Engine Idling Test

1. INTRODUCTION

The 900-square-mile Idaho National Laboratory (INL) site and 81,672-square-foot INL Fleet Operations service and maintenance facility, which services over 1,000 vehicles and items of equipment, constitute a natural test bed for research and testing of vehicles, devices, and equipment. Since October 2002, INL has conducted an evaluation of oil bypass filter technology on 17 heavy- and light-duty vehicles for the U.S. Department of Energy's (DOE's) FreedomCAR and Vehicle Technologies Program (see http://avt.inel.gov/obp for reports and data germane to this test). Other ongoing activities include use of alternate fuels by light vehicles and fleet buses.

The engine idling testing continues work performed by INL for the DOE FreedomCAR and Vehicle Technologies Program in support of the DOE's goal to minimize diesel-powered heavy vehicle idling in the United States and reduce the associated annual consumption of over 850 million gallons of diesel fuel during periods of engine idling for heating, cooling, and auxiliary power generation. In addition to the economic advantage of minimizing fuel use by avoiding or eliminating engine idling, engine life should be extended and oil change intervals lengthened if idling periods are shortened or eliminated. However, while this is widely believed, there are few independent public testing results that document this. The INL idling project was designed to characterize the volumes and trend of engine wear metals and the degradation of oil quality during 2,000 hours of engine idling (1,000 hours each on two bus engines). The two participating INL fleet buses, 73432 and 73433, are both equipped with Detroit Diesel Series 50 engines, were both part of the INL oil bypass filter evaluation project, and both have over two years of documented oil analysis (used as the base case for comparisons). During the INL idling test, weekly reports of engine oil analysis were obtained, and the engine-wear metals were further characterized by destructive analysis of both bypass and full-flow oil filters to measure the engine-wear metal particles actually captured by the two filters.

2. THE EXPERIMENT

The test comprised five tasks: generate a test plan (Section 2.1), prepare for the test (Section 2.2), conduct the test (Section 2.3), and report the results (Section 3) and conclusions (Section 4).

2.1 Test Plan

The idling test plan was patterned after the *Oil Bypass Filter Technology Evaluation Test Plan* (http://avt.inl.gov/pdf/oilbypass/oilbypass_testplan.pdf). The idling test procedures were generated from discussions with the Oil Bypass Filter Technology Evaluation team and other contacts, including:

- INL Fleet Operations personnel: bus drivers, dispatchers, mechanics, and fleet management
- Advanced Vehicle Testing personnel: principal investigator and test engineer
- National Tribology Services, Inc: test laboratory manager and two corporate tribologists (oil scientists)
- puraDYN Filter Technologies Inc: filter engineer
- New West Technologies, LLC personnel: heavy vehicle consultant.

The scope of the test plan is defined and limited by several factors:

- Availability of the Oil Bypass Filter Technology Evaluation buses
- Funding for the test
- Interface with Fleet Operations
- Idling time requirements
- Conditioning the oil
- Oil analysis laboratories
- Methodologies to measure wear metal
- Oil quality tests
- Destructive filter analysis.

2.1.1 Test Buses

Availability of buses was a limiting factor. Initially, motor coaches or buses with the six-cylinder series-60 Detroit Diesel engine were the primary choice, but since these buses had the larger 55-passenger capacity and could not be taken out of service (no larger-capacity replacement buses were available), the available and smaller four-cylinder 44-passenger, series-50 Detroit Diesel engine buses, were used.

Three buses with series-50 Detroit Diesel engines were part of the Oil Bypass Filter Technology evaluation with puraDYN filter systems, but only two buses could be taken out of service for two months. Bus 73432 had 84,000 miles without an oil change, and bus 73433 had 92,000 miles without an oil change, and both buses had ample oil analysis history for comparative analysis with the idling test data. Details of the test buses are shown in Table 1.

Table 1. Details of the test buses.

Bus Number	Engine	Cylinders	Cubic Inches	Horsepower	Oil Capacity (quarts)	Oil: Shell Rotella-T
73432	Series 50	4	518	315	28	15W-40
73433	Series 50	4	518	315	28	15W-40

2.1.2 Test Funding

The available funding limited the depth and breath of the test. The test was designed primarily as a qualitative evaluation of the idling test parameters.

2.1.3 Fleet Operations

The test plan detailed the interactions with fleet operations contacts and their involvement in the test. They provided much good input and review of the test plan.

Another major contributor was the Fleet Operations safety and health staff. Work performed at the INL Fleet Operations facility, Building CFA-696, is always conducted with a focus on safety to the worker. All project planning requires integration of work authorization documents, hazard analysis, standard practices, and test planning/readiness in the review processes. The philosophies of the Integrated Safety Management System and Voluntary Protection Program are both integrated into all work performed at INL.

Safety professionals at CFA-696 reviewed the test plan and found no unique safety concerns with the idling test beyond the normal hazards relating to servicing the oil and oil filters on heavy vehicles. No hazardous processes were added to the scope of work for the service mechanics beyond that of the ongoing oil bypass filter technology evaluation.

The one potential hazard with servicing the bypass filter is the temperature of the filter housing. The evaporation chamber (inside of the filter housing where fuel and water are evaporated) is heated, causing the outside surface of the filter housing to be about 200ºF. The housing is labeled at the factory ("HOT"). In addition, INL posted a sign that states the filter housing is hot. Given the training and warning signs, the mechanics avoided this hazard as they do other hot engine parts, such as exhaust manifolds, which is also a factor in the ongoing oil bypass filter technology evaluation. Even though no new hazards were introduced to the mechanic, the test engineer did go over the project with the mechanic and review his duties germane to the idling test.

2.1.4 Idling Time

The literature suggests that a wide range of annual idling times occurs for individual over-the-road trucks: 350 to 2000 hours per year are commonly reported. One thousand hours of idling time were selected for this test because the number fit into this range, it was about the time limit the buses could be taken out of service, and funding was limited. To correlate the number of hours idling to the normal INL 12,000-mile oil service intervals, the following were assumed:

- The normal engine idling speed of each bus is about 700 rpm; the highway rpm is normally about 1,400 rpm (depending on the speed limit)
- Two hundred hours normal bus operation (12,000 mile service interval ÷ 60 mph) is equivalent to each 12,000-miles-in-service interval
- 200 hours (normal operations) × 1,400 rpm × 60 minutes = 16.8 million revolutions per 12,000-miles-service interval
- 700 rpm (idling) × 60 minutes = 42,000 rph (revolutions per hour when idling)
- 16.8 million revolutions ÷ 42,000 rph = 400 hours idling, which is about equivalent to 12,000 over-the-road miles (the service interval and bypass filter change time).

The one-thousand hours idling is about equivalent to two and one half 12,000-miles-in-service intervals.

2.1.5 Conditioning the Oil

Many team members suggested that the oil should be conditioned before starting the idling. To condition the oil means to use it for a period. The test buses were operated in their normal routes for 5,000 miles before starting the test. The oil used for this test is Shell, Rotella-T, 15W-40, the same oil used for the Oil Bypass Filter Evaluation.

2.1.6 Oil Analysis Laboratories

During the Oil Bypass Filter Technology Evaluation Test, two oil analysis laboratories were used to document the condition of the oil. This dual testing was also performed on each of the weekly idling test samplings: one sample was sent to Staveley Services Fluids Analysis (formerly CTC Analytical Services) of Phoenix, Arizona, and one was sent to National Tribology Services (NTS) of Minden, Nevada for analysis. For the destructive filter tests, only NTS was used. The suite of tests performed by both oil analysis laboratories is shown in Appendix A. Table 2 shows the tests performed by the test laboratories.

Table 2. The various tests performed by the test laboratories

Oil Analysis Samples	Spectroscopy Analysis, w/oil Contaminants and Quality	Rotrode Filter Spectroscopy Analysis	Heptane Pentane Insoluble Analysis	X-ray Florescence Alloy Analysis	Analytical Ferrography and Photographs
Baseline Historical Tests					
CTC Laboratory	x				
NTS Laboratory	x	x			
Weekly Tests					
CTC Laboratory	x				
NTS Laboratory	x	x			
Destructive Filter Tests (NTS)					
Used oil	x	x	x		X
Full-flow filter oil[a]	x[b]	x	[b]	Only on the filter medium segment before sonification	X
Bypass filter oil[a]	x[b]	x	[b]	Only on the filter medium segment before sonification	X
Full-flow residual oil	x	x	x		X
Bypass residual oil	x	x	x		X

a. No particle counts were performed on oil from the sonicated filters—too many filter particles.

b. Some oil quality tests, e.g., viscosity, were not done because this was not the engine oil.

2.1.7 Wear Metal Quantification

The test hypothesis was that wear metal quantification could be obtained or measured from oil analysis reports and destructive filter analysis. A multitude of testing and analysis procedures were researched to obtain an optimum measure and detection of all sizes of wear metals particles in used engine oils.

The typical oil analysis report uses spectroscopy analysis or atomic emission spectroscopy (AES) to identify wear metals in parts per million (ppm), but AES analysis is blind to sizes of particles larger than 10 microns. Rotrode filter spectroscopy (another spectroscopy method) was added to the test regimen to quantify the 10- to 50-micron metal particles.

Ferrography is another method to capture all oil-borne iron particles and to aid researchers to identify the wear particle types. Wear particle types define the source of the particle: rubbing wear, severe wear, cutting wear, etc. Ferrography, with the aid of a strong permanent magnet, traps all ferrous materials on a glass slide in lines matching the spacing of the magnetic lines of flux. Other oil debris, both paramagnetic and nonmagnetic particles, are also often trapped by the magnetism and the surface attraction along the lines of iron particles. This phenomenon is shown elsewhere in this report. The trapped debris is then examined with a microscope and photographed for subsequent review, analysis, and characterization.

Additional analysis tests were selected to complete the range of tests to bracket wear metal and particle quantification. One of these tests is x-ray florescence, used to characterize the filter medium surface for metals. It does not quantify particle size, but identifies the metal speciation trapped in filter medium. Another test used is particle counting. Particle counting methods quantify the particles by binning the particles into six size groups: >4, >6, >14, >21, >38, and >70 microns.

2.1.8 Oil Quality Tests

Oil quality was determined by various methods. The standard oil analysis test measures several oil quality variables: viscosity, soot, fuel/water/glycol contamination, and total base number (TBN). Another analysis added to this test measured the oxidation and nitration levels in the oil. Oxidation and nitration levels are a direct measure of oil quality and have an inverse relationship to TBN—as oxidation and/or nitration increase, TBN values decrease. The last method is heptane/pentane insoluble analysis, which measures the insoluble particles in suspension.

2.1.9 Destructive Filter Analysis

Traditionally, engine wear metals are monitored by regular oil analysis sampling, which does not consider the particles the oil filters pick up. An innovation of the idling project was to determine the wear metal volumes by destructive analysis of the full-flow and bypass filters. Both test buses were equipped with two standard spin-on full-flow oil filters and one aftermarket PFT-40 puraDYN bypass filter system. NTS tribologists, consulted during the early development phases of test plan, identified how wear metals could be extracted from the filters and quantified. In developing the optimum data for the test, we determined that destructive examination of a full-flow and bypass filter at four intervals during the test would give us enough data to determine engine-wear-metal trends. The four intervals were (1) after the 5,000 mile oil conditioning, (2) after 400 hours of idling, (3) after 800 hours of idling, and (4) after 1000 hours of idling.

2.1.10 Writing the Test Plan

The test plan was patterned after the *Oil Bypass Filter Technology Evaluation Test Plan* (http://avt.inl.gov/pdf/oilbypass/oilbypass_testplan.pdf). Text details were generated from discussions with the various members of the oil bypass filter technology evaluation team and other contacts.

2.2 Test Preparation

The first validation point for test readiness occurred when the test plan was signed by all parties. At that time, the test engineer and the project principal investigator reviewed the maturity of the test to ascertain readiness to begin the test. They generated the following list of tasks to be accomplished before the idling test could begin:

- Define all tasks, performers, and deliverables
- Order supplies and services for the test
- Complete at least one 12,000-mile service event to acquire filters for the destructive filter test
- Conduct destructive filter analysis tests on each bus for baseline data
- Purchase, install, and demonstrate an updated version of ProDriver (Detroit Diesel onboard data log system)
- Develop test tracking logs
- Conduct training
- Service the buses.

2.2.1 Tasks, Performers, and Deliverables

To ensure all supplies, services, and parts for the test were acquired, the project tasks, the performers, and deliverables were defined. Table 3 lists the physical items and needs of the test.

Table 3. General tasks, performers, and deliverables.

Task	Performer	Deliverable	Needs
Perform baseline destructive filter analysis on the filters at the end of the 12,000-mile service interval.	INL and NTS Laboratories	Baseline destructive filter analysis of filters at the end of the 12,000-mile service interval for each bus	• Four 5-gal buckets in which to ship filters to NTS. • List of analysis tests for NTS to perform. • Opportunity for NTS to practice and to refine their procedures for the destructive analysis tests. • Filters for both buses at the end of the 12,000-mile service interval
Update the online ProDriver data logger.	Bus fleet bus operations manager, mechanic, and/or test engineer	Electronic data from the on-board data logger	• Disks of data • Hard copies of data
Clean or flush bus engines before 5,000-mile oil conditioning phase.	Service mechanic	Engine cleaned with fresh oil.	• Eighteen gallons of oil • Two bypass filters • Four full-flow filters
Change oil in test buses to start 5,000-mile oil conditioning phase.	Service mechanic	Fresh oil for test	• Eighteen gallons of oil • Two bypass filters • Four full-flow filters

Task	Performer	Deliverable	Needs
Drive buses for 5,000 miles.	Bus drivers	5,000 miles on buses	• Condition oil (get it dirty) for 5,000 miles • Oil analysis kits, 2 NTS at 3,000 miles • Oil analysis reports at 3,000 miles
Service buses (filters) after 5,000 miles.	Service mechanic	First set of filters	• Oil analysis kits, 2 NTS • Oil analysis reports at 5,000 miles • Four buckets to ship filters to NTS. • Destructive filter test results, both buses
Train the team.	Test engineer and fleet bus operations manager	Trained drivers, dispatchers, and service mechanic	• Log books for both buses • Drivers to know how to complete the idling test log book • Dispatchers to keep the buses idling on regular and back shifts • Mechanics to retrieve filters and samples
Run idling test.	Bus drivers and dispatchers	Start idling phase of the test	• Twenty gallons of oil for cargo bays • Idling for 1,000 hours • Drivers log start/stop time and oil and fuel consumption daily
Capture weekly oil analysis samples.	Test engineer	Weekly oil analysis reports	• Forty oil analysis kits, 20 NTS and 20 CTC • Twenty oil analysis reports from NTS • Twenty oil analysis reports from CTC • Twenty sample bottles for weekly archive sample for each bus
Perform weekly carbon blowout.	Driver	Drive bus on shuttle run to the site once a week (110-mile round trip)	• Run buses weekly for 110 highway miles to blow out carbon build up in the engine. • Log time, miles, and fuel used on the run.
Perform bus service.	Service mechanic	Filter for destructive tests and oil analysis samples	• Twelve gallons of oil • Filter servicing after 400 hours of idling • Filter servicing after 800 hours of idling • Filter servicing after 1000 hours of idling • Six bypass filters • Twelve full-flow filters • Six NTS oil analysis kits • Six NTS oil analysis reports • Twelve 5-gallon buckets in which to ship filters to NTS • Six destructive filter test results, three for each bus
Compile the test data.	Test engineer and project PI	Data for reports	• Data for report • Write final report • Issue final report • Present data at conference
Assist test data analysis.	Consultant	Data reduction	• Data for report • Review of final report

2.2.2 Supplies and Services

The idling test leveraged several key elements from the Oil Bypass Filter Evaluation project: filter systems already installed on the buses, replacement filters already purchased, buses with an oil analysis history, maintenance facility, and test personnel (engineers/managers/mechanics/drivers/dispatchers) already available. However, additional items and services were needed to be purchased for the test:

- Sixty-eight additional gallons of oil, 15W-40 Shell, Rotella-T
- Fifty additional oil analysis kits
- Twenty additional archive sample bottles
- Twenty 5-gallon buckets in which to ship oil filters
- Ten additional destructive filter analysis reports
- One update to the ProDriver online data logger software.

2.2.3 Destructive Filter Analysis Tests

The NTS tribologists and laboratory managers with whom we consulted during the early phases of the test plan development explained their basic destructive filter analysis processes. The destructive filter testing entails three aspects:

- Filter preparation
- Debris analysis
- Oil quality analysis.

The INL idling test engineer and principal investigator worked with NTS staff to establish a suite of processes and tests to augment the NTS processes to adequately capture the engine wear metals and determine the engine oil quality from the oil analysis samples and filters acquired from the idling test. The final suite of tests included:

- Filter medium/canister separation
- Filter medium ultrasonic cleaning
- Spectroscopy analysis
- Rotrode filter spectroscopy analysis
- Analytical ferrography and photographs
- X-ray florescence alloy analysis
- Heptane/pentane insoluble analysis
- Particle count.

2.2.4 Baseline Destructive Analysis Tests

To establish a baseline, a full-flow filter and bypass filter from both test buses were removed at the end of the regular 12,000-mile service interval before beginning the idling test and were sent to NTS for destructive analysis. The analysis results established a comparative baseline for the subsequent idling test destructive analyses. A secondary benefit of this initial destructive analysis was that it allowed NTS personnel to refine their filter testing protocol and give their technicians a chance to practice on some actual filters before the idling phase began. This practice was important because the examination is very intrusive and nonrepeatable, with only a single opportunity to capture the data from the filters.

2.2.5 Test Tracking Logs

Both manual and electronic tracking logs were used. The daily manual log was kept by the bus drivers, who tracked oil use, fuel use, temperature/oil pressure, hours idled, and weekly shuttle run details. The log was kept in a three-ring binder, with instructions, replacement pages, and a copy of the test plan. In addition, plastic signs were made and put on the doors of the buses to explain to curious INL staff why the buses were idling. The buses were idled in a secured bus lot in the city of Idaho Falls, Idaho. The lot is a fenced staging area for about 50 buses, which are used each day. A dispatcher is on site from 6:00 p.m. on Sunday until 11:00 a.m. on Friday. From 1:00 p.m. Friday until Sunday evening, a dispatcher is on site only periodically to support the back-shift and weekend bus service. The dispatchers were indispensable to ensuring the buses were started and turned off; bus fuelers would log oil/fuel use during the day. Appendix B shows a copy of a log sheet.

The ProDriver system is an electronic data log system from Detroit Diesel that records a multitude of functions specific to fleet operations, many of which were beyond the needs of this test, but the germane data were collected. To ensure the electronic data were captured, they were downloaded weekly and stored for later data analysis.

2.2.6 Conduct of Training

Training of personnel for the idling test was one-on-one with each player by either the test engineer or bus fleet manager. The training focused on the drivers, the bus lot dispatchers, service mechanic, and test engineers. The dispatchers were trained to ensure the drivers started and stopped the buses daily. The starting drivers were trained to record in the manual log the:

- Date
- Mileage
- Coolant level check
- Oil level check
- Oil added to engine
- Time when idling started.

The fueling and shuttle drivers were trained to record in the manual log the:

- Fuel/oil added, gallons
- Mid-day oil and temperature check
- Shuttle run start time
- Mileage before and after shuttle run
- Fuel used during the shuttle run.

The shut-off drivers were trained to record in the manual log the:

- End of day oil and temperature check
- Time when each bus was shut down.

The service mechanic was trained to:

- Save the bypass filter and one full-flow filter for shipment
- Not damage the filter (not to puncture the canister wall or to drain the oil from the filters)
- Capture oil analysis samples during the filter servicing.

The test engineers were trained by fleet operations personnel to take the weekly oil analysis samples and to download the electronic data from the onboard ProDriver system.

2.2.7 Bus Servicing

The oil on both buses was changed on 2/22/05. Since the oil in both buses had not been changed for over two years, it was prudent to flush the engines to clean out any debris in the "nooks and crannies" of the engine. Flushing consisted of running the buses for several days with new oil, and then changing the flushing oil before starting the idling test. Both buses were again serviced on 3/10/05 with new oil and filters to start the idling test.

2.3 Conduct of the Test

The test consisted of the following elements:

- Five-thousand-mile oil conditioning
- One thousand hours of idling
- Weekly data gathering
- Filter replacements
- Destructive filter analyses
- Oil analysis test regimen
- Analysis results.

2.3.1 Five-thousand-Mile Oil Conditioning

The test began on 3/10/05, when the two test buses started accumulating road miles to condition the oil before starting the idling. The buses traveled on their regularly scheduled routes. Bus 73433 had the longer route and 5,000 total miles a few days sooner than bus 73432. At about the mid-point of the 5,000-mile interval, an oil analysis sample was taken. This was the first of many used-oil analysis samples taken directly from each bus engine. During this period, the INL mileage tracking system broke down without the idling project staff's knowledge, and by the time it was back online bus 73432 had 6,597 miles and bus 73433 had 6,859 miles on the oil.

2.3.2 One-thousand Hour Idling

After the 5,000-mile filter servicing (actually 6,597 and 6,859 miles respectively), each bus was driven to a secure bus lot in Idaho Falls. Bus 73433 began idling on 4/27/05, bus 72432 on 5/5/05. The bus dispatchers were again instructed on what was required, and they arranged for the buses to be started every morning and turned off every evening by the bus drivers. Since there were four rotating bus dispatchers, the training was repeated four times. Most INL workers who ride buses work a four-day 10-hour schedule. During this Monday through Thursday four-day schedule, the buses would idle about 20 hours per day. There is reduced bus service to the INL work areas on the three off days, for back-shift crews and other support workers. On these off days, the drivers would have different start and stop times, and the buses would idle about 14 hours each day. This idling schedule was followed fairly consistently for the whole test, the exception being a small hiccup when drivers went on vacation and the replacement drivers were not informed of the idling test duties. The total idling time for bus 73432 was 1,056 hours, ending on 7/5/05. The total idling time for bus 73433 was 1,029 hours, ending on 6/28/05. Both buses went somewhat over the 1,000 hours because the idling was not stopped exactly at the 400-, 800-, and 1,000-hour periods, as no one was there to turn them off.

2.3.3 Weekly Data Gathering

As the idling progressed, test engineers periodically stopped by during the week to monitor and retrieve the records kept in the log books by the drivers, and to periodically check the engine temperature and oil pressure. Every Monday, one engineer would take oil samples directly from both engines for analysis. Three samples were taken: one was sent to CTC Laboratory (owned by Stavely Services and Fluids Analysis), one was sent to NTS oil analysis laboratory, and one was archived in case a sample was lost in the mail. Once (5/23/05 for bus 73433), the Monday sampling coincided with filter servicing. These weekly samples provided data for trending of oil quality and wear metals in the engine oils during the test. Also, on Mondays the other test engineer would download the data from the on-board data logger onto both a portable PC and CD for future data analysis.

2.3.4 Filter Replacement

There were four filter replacement events during the idling test: at 5,000 miles, and at 400, 800, and 1000 hours of idling. When each bus reached each of these milestones, the test engineer would schedule the bus to be driven to CFA-696, the INL Fleet Operations Maintenance Shop at Central Facilities Area, for filter replacement. When at the maintenance shop, both full-flow filters (the two commercial spin-on cartridge filters) and the bypass filter cartridge were replaced. Of the filters removed, only one of the two full-flow filters and the one bypass filter from each bus were set aside for laboratory testing. As a full-flow filter for testing was separated from the engine (see Figure 1), it was placed into a heavy-duty plastic bag (see Figure 2) and set right-side up into a 5-gallon plastic bucket (see Figure 3). Later, in the shipping area of CFA-696, each bus's pair of filters was prepared for shipment. To prevent damage and leakage from a filter, the plastic bag was securely tapped shut, the filter-in-a-bag was tightly packed into the bucket with bubble wrap, and the lid was securely hammered shut. The bucket lids were then sealed and shipped to NTS at Minden for destructive filter analysis.

Figure 1. Full-flow filter separated from the engine.

Figure 2. Test engineer with a bypass filter in a plastic bag.

Figure 3. Test engineer placing a filter in a bucket.

2.3.5 Destructive Filter Analysis

When the laboratory technicians received a filter shipment at the NTS facility, they immediately attached a unique sample and batch number onto the buckets and logged these numbers into their computer. Then, extracting the filters from the buckets, they transferred the sample and batch number onto the actual filter cartridges. These numbers tracked each sample throughout the analysis and reporting process, which included:

- Separating the metal filter jacket from the filter medium
- Dissecting a one-pound section from each filter
- Shaking the filter medium samples by ultrasonic processing
- Analyzing the processed oil
- Issuing oil analysis reports.

The tops of the metal jackets or canisters were removed during filter separation. A common kitchen can opener was deployed on the bypass filter canister, whereas a special pipe cutter was used for the full-flow filters. Figure 4 shows this top removal activity.

Figure 4. Removing the tops of the bypass filter (left) and full-flow filter (right).

Care was taken to keep outside debris from contaminating the filter medium. After the tops were removed from each filter, the filters were placed in separate plastic tubs lined with blotter paper. The filter medium was lifted out and dissected (Figure 5) to obtain representative samples of the filters—about one pound of medium. To capture the optimum cross section of filter medium, dissected sections were cut through the whole length of the filter to get a representative cross section of wear metals and debris. Figure 6 shows the basic dissection sketch for the filters. The oil-soaked full-flow filter medium weighs about 1.4 lb, whereas the oil-soaked bypass filter medium weighs about 9.6 lb.

Figure 5. Filter medium being dissected.

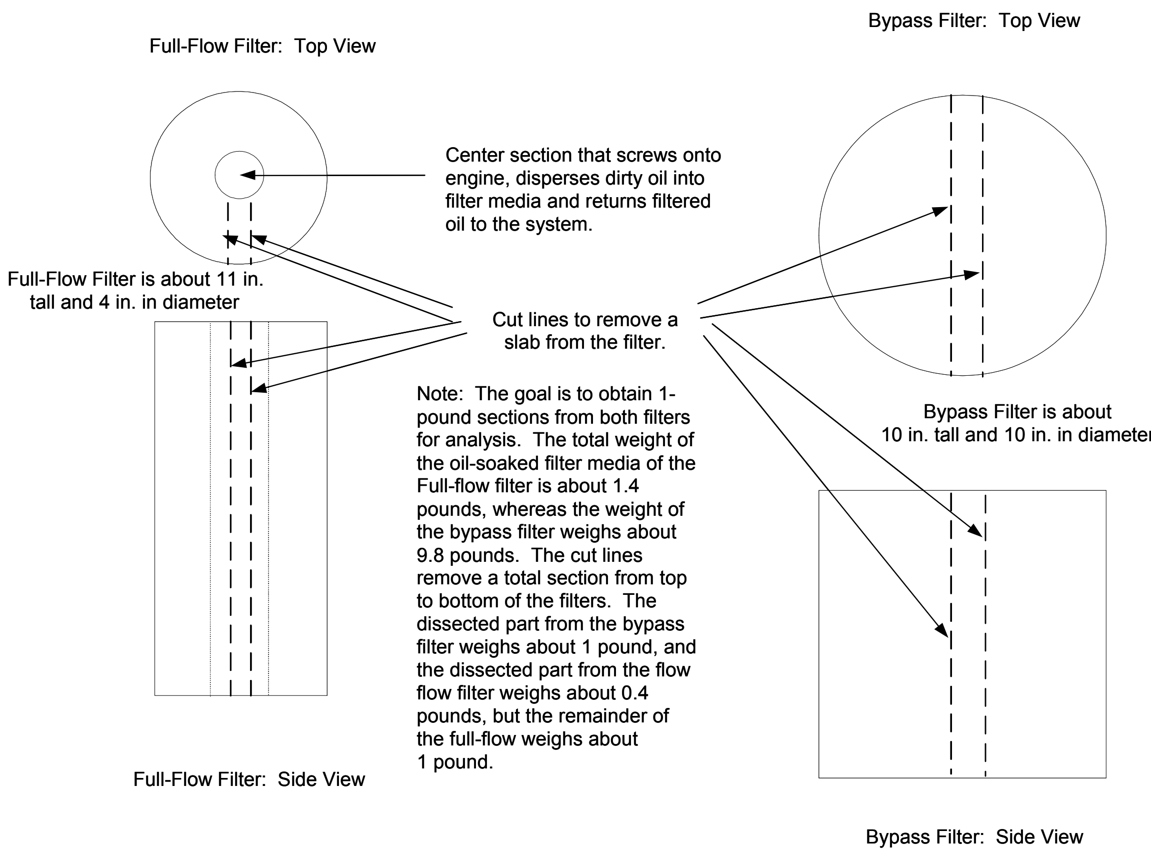


Figure 6. Diagram of filter sectioning.

To understand the differences in densities of the filters, remember that a full-flow filter takes the full-flow volume of the oil pump (about 35 gallons per minute) and concurrently filters or removes contaminates down to the 40- to 60-micron particle size. The engine oil pump pumps oil to both lubricate and cool the engine. If the filter were denser to filter smaller-size particles, the filter would restrict the oil flow. On the other hand, the bypass filter system bypasses a small flow of oil (about eight gallons per hour) from the engine oil system, into the larger and denser bypass filter to remove down to 1-micron particles.

The dissected, one-pound samples pieces were then placed into separate sample jars containing one liter of Chevron 100R neutral base oil and sonicated (Figure 7) in a Branson Model 3500 ultrasonic cleaning bath machine for 8 hours (per ASTM G131-96). This ultrasonic shaking separates the trapped particles from the filter medium and captures them in the neutral base oil.

The main purpose for the destructive filter testing is to measure or quantify only the wear particles captured by the filters. Since the neutral base oil is the carrier oil for the wear particles, some oil quality and additive values are off-normal, e.g., viscosity, calcium and TBN, because the oil being tested is not the engine oil.

Figure 7. Ultrasonic cleaning unit.

When the destructive filter analysis initially began with the first set of baseline filters, it was limited to three samples: one directly from the engine, and the other two generated as a result of the ultrasonic shaking of the two filters. When the first filters were sent to NTS, the laboratory technicians noted that when the filter medium was lifted from the filter canister shells, there was more than 100 ml of residual oil in the bypass filter shell. NTS knew the research nature of this project, so they retained these oils and included these residual oil samples in the test regimen for analysis. The filters were thereafter shipped without the oil being drained, and subsequent tests were conducted on both the residual full-flow filter oil and the residual bypass filter oil. Residual oil is the oil drained from the filter medium and trapped in the filter canister. Several days elapsed from the time the filters were placed into the buckets until the filter medium was extracted from the filter shell, to allow oil to drain from the filter medium. These oil samples are somewhat nontraditional.

2.3.6 Oil Analysis Test Regimen

The oil analysis test regimen is shown in Table 4. The goal or scope of these tests is to conduct both an analysis of the debris in the oil and to assess the oil quality throughout the length of the idling test.

2.3.6.1 Atomic Emission Spectroscopy Analysis

Spectroscopy analysis is the mainstay of all oil analysis testing. The basic oil analysis report is widely used to show the condition of an engine and its oil. The basic oil analysis report shows essentially three things: engine wear metals (iron, copper, etc.), additive/contaminate conditions (silicon, calcium, etc.), and the condition of oil quality (fuel dilution, viscosity, etc.). The engine wear metals and the additive/contaminates are both detected and quantified by spectroscopic analysis. The cost of an oil analysis report depends on the analysis package or number of tests performed. A minimum oil analysis report costs in the range of ten to twenty dollars. Additional tests cost more, e.g., for oxidation and nitration values. The diversity of oil analysis packages fulfill the various and esoteric needs of the end users. Appendix C shows a typical oil analysis report. Spectroscopy analysis results are part of the report. This report form, of which over 100 were issued during the idling test, is the mule for carrying the results of testing and analysis.

Table 4. Number of wear metal quantification and oil quality analysis tests.

Oil Samples	Spectroscopy Analysis[a]	Rotrode Filter Spectroscopy Analysis	Heptane/Pentane Insoluble Analysis	X-ray Florescence Alloy Analysis[b]	Analytical Ferrography and Photographs	Particle Count	Oxidation and Nitration Analysis
Baseline Tests[c]							
Used oil	6	6	6		6	6	6
Full-flow filter oil	6	6		6	6	6	6
Bypass filter oil	6	6	6	6	6	6	6
Full-flow residual oil[d]	5	5	5		5	5	5
Bypass residual oil	6	6	6		6	6	6
Weekly Tests							
CTC laboratory	20						20
NTS laboratory	20	20				20	20
Destructive Filter Tests							
Used oil	8	8	8		7[e]	8	8
Full-flow filter oil	8	8		8	8		8
Bypass filter oil	8	8		8	8		8
Full-flow residual oil	8	8	8		8	8	8
Bypass residual oil	8	8	8		8	8	8

1. Spectroscopy analysis. This analysis includes wear metal, additives, and contamination characterization. Other data are included on the oil analysis report, i.e., viscosity, total base number, and oxidation and nitration numbers.
2. X-ray florescence alloy analysis. This analysis is taken on a piece of filter medium that is not sonicated.
3. Baseline Tests. Three baseline tests were conducted: one for bus 73432, two for bus 73433.
4. The full-flow residual oil was not captured in the first baseline test.
5. Used Oil. The used oil analysis at the 400-hour interval for bus 73433 was taken, but the ferrograms were inadvertently not conducted.

Some tests measure particle size directly, but other tests measure particle size indirectly. Figure 8 shows an indirect measuring method (adapted from the NTS Website). Although, spectrometric analysis is the mainstay of oil analysis reports, Figure 8 graphically shows that spectrometric analysis essentially works only on particles of less than ten microns; spectrometric analysis is blind to larger particles.

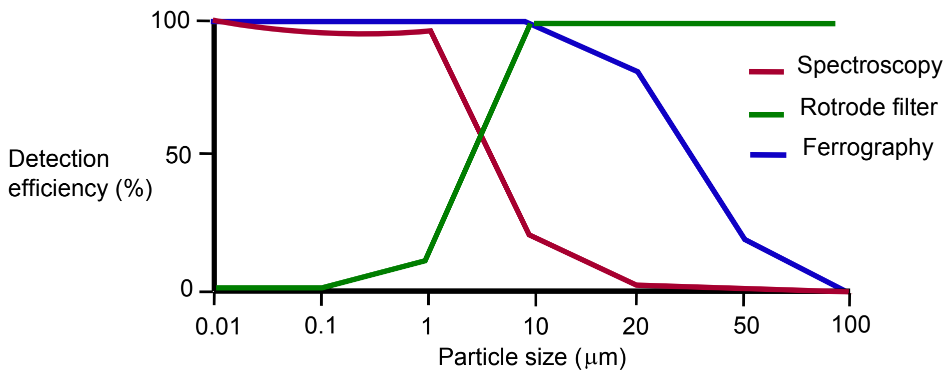


Figure 8. NTS detection efficiency versus particle size.

The spectroscopy or spectrochemical analysis of wear metals, contaminates, and additives for the idling test included the following metals at the parts per million (ppm) level:

Iron
Chromium
Lead
Copper
Tin
Nickel
Silver
Silicon
Boron
Sodium
Aluminum
Magnesium
Calcium
Barium
Phosphorous
Zinc
Molybdenum
Titanium
Vanadium
Potassium

2.3.7 Rotrode Filter Spectroscopy

The rotrode filter spectroscopy (RFS) process forces oil through a porous disk or filter to capture the larger particles. The metal particles (iron, copper, etc.) are washed with a solvent and are then identified with a rotating disc electrode spectrometer. This process quantifies the course metals in the oil samples, and is another indirect method of sizing particles in oil. Figure 8 shows that RFS detects particles of 10 to 50 microns. These larger particles can be the first indicator of abnormal wear.

2.3.8 Analytical Ferrography

Analytical ferrography is a process wherein a small volume of oil is poured across a glass slide setting on a strong permanent magnet. The strongly attracted iron particles are initially captured in the entry region of the slide where the oil is first poured onto the slide. The particles align with magnetic lines of flux as they traverse the slide. This is why ferrograms have striations or bands of particles and are not completely coated with iron particles. A ferrogram is a microphotograph of the ferrous materials trapped on a glass slide with the aid of a magnet. Both the small and large iron particles congregate together and stack up as lines on the glass. The nonmagnetic or paramagnetic items—silicon, aluminum, lead, etc.—will randomly stick along the lines of iron as they flow over the glass. After the particles are captured, the slide is then carefully washed with a solvent to remove the oil but not to wash off the particles. The slide is photographed with a bichromatic microscope configured with both reflected and transmitted light sources illuminating from both above and below the stage. Figures 9 and 10 are sketches of the ferrography process.

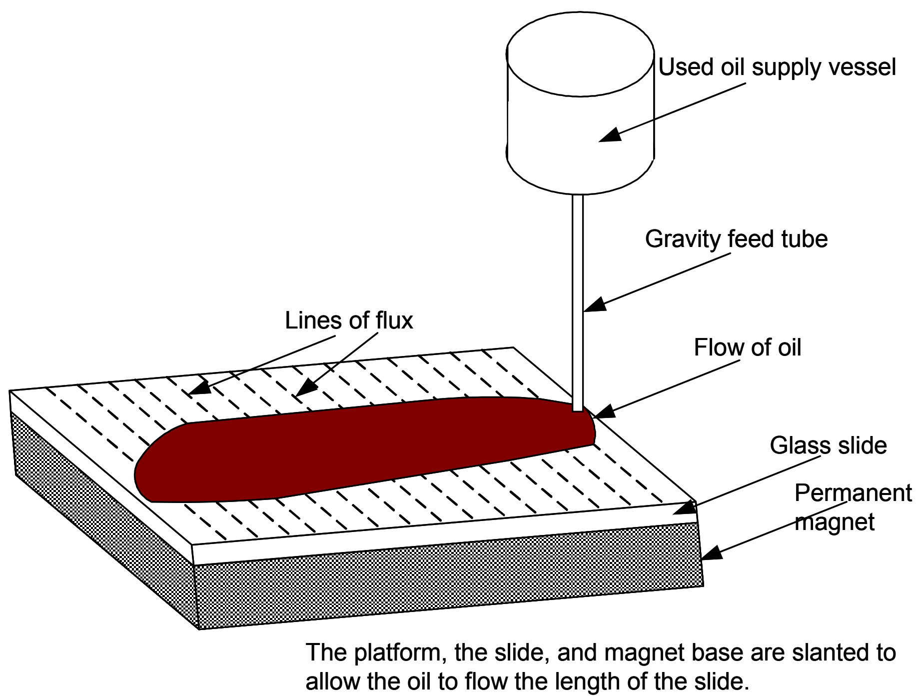


Figure 9. Elements of a ferrogram.

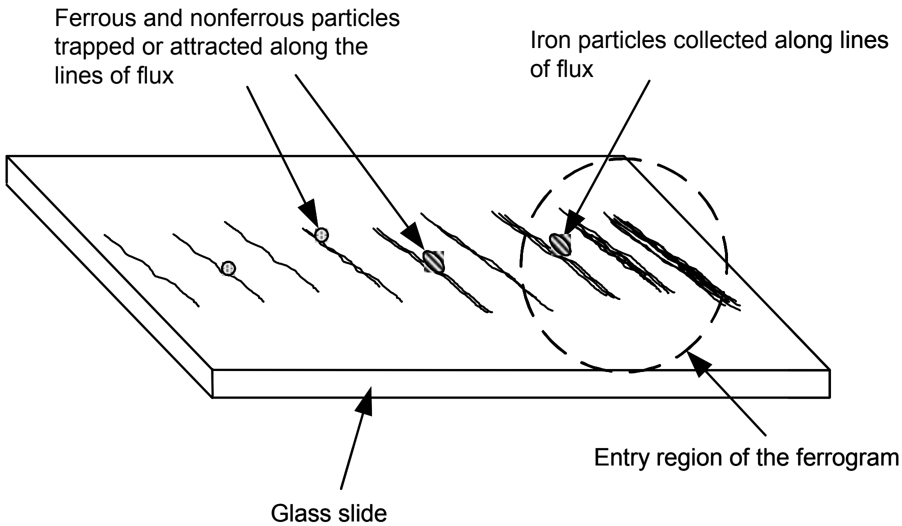


Figure 10. Detail of particles on the clean glass slide.

Since iron is the predominant engine wear metal present in these engines, ferrogram photographs were an excellent tool to compare engine wear between the service intervals of the idling test. Five sets of ferrograms are available for graphical comparison for Bus 73432 and six for Bus 73433. Ferrograms, actual photographs at various magnifications, were taken on all of the oil samples related to the destructive filter analysis effort.

Another aspect of the analytical ferrography is characterization of wear particle types. During the microscopic analysis of the ferrogram, the tribologist tracks or quantifies the wear particle types noticed on the ferrogram in the following population ratings:

- 0 = None
- 2 = Trace
- 5 = Moderate
- 9 = Heavy.

These wear particle types include rubbing wear, severe wear, cutting wear, fatigue particles, laminar particles, spheres, dark metallo-oxide, red oxide, nonferrous metals, nonmetallic inorganics, organics, friction polymers, fibers.

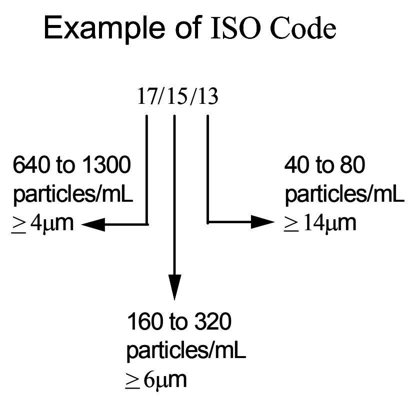
2.3.9 Particle Count

The particle count process is another process selected to characterize wear particles generated during the idling test. Particle count bins the particles in oils into six groups by size: >4, >6, >14, >21, >38, and >70 microns. Particle-count analysis does not identify metals; it bins the particulates into ranges of size or scale numbers per 100-ml volume of oil.

The particle count process also includes a secondary breakdown of the particle binning to ISO 4406 (International Standards Organization), a cleanliness code. ISO 4406 has a three-part cleanliness code based on the number and range of particles in a 1-ml volume of oil. The code is represented as $R_4/R_6/R_{14}$. R_4 represents the number of particles greater than or equal to 4 microns (μm); R_6 represents the number of particles greater than or equal to 6 µm; and R_{14} represents the number of particles greater than or equal to 14 µm. The ISO code allows the end user to scale or rank used oil to a standard of cleanliness (Table 5).

Table 5. ISO 4406 (International Standards Organization) fluid cleanliness codes. Source: http://www.bently.com/articles/4Q01orbit/4Q01whitefield.asp.)

Number of Particles per 1 Milliliter of Fluid					
ISO Code	Minimum	Maximum	ISO Code	Minimum	Maximum
1	0.01	0.02	15	160	320
2	0.02	0.04	16	320	640
3	0.04	0.08	17	640	1300
4	0.08	0.16	18	1300	2500
5	0.16	0.32	19	2500	5000
6	0.32	0.64	20	5000	10000
7	0.64	1.3	21	10000	20000
8	1.3	2.5	22	20000	40000
9	2.5	5.0	23	40000	80000
10	5.0	10.0	24	80000	160000
11	10.0	20.0	25	160000	320000
12	20.0	40.0	26	320000	640000
13	40.0	80.0	27	640000	1300000
14	80.0	160.0	28	1300000	2500000



2.3.10 Oil Quality Test

Part of the oil analysis report includes the following physical properties data. These items are a measure of oil contamination and oil quality.

- Fuel (vol%)
- Viscosity (at 100ºC)
- Water (vol%)
- Soot (wt%)
- Glycol (vol%).

Additional oil quality tests were performed for the idling test, which included:

- Calculating the total base number (TBN) (≥3.0 milligrams (mg) of potassium hydroxide (KOH)/ milliliter (ml) of oil, or mgKOH/mL)
- Determining the oxidation and nitration numbers [≤30 absolute per cubic centimeter (Abs/cm)]
- Conducting heptane/pentane insoluble analysis.

The TBN is generally accepted as an indicator of the ability of the oil to neutralize harmful acidic byproducts of engine combustion. The oil used for this test had an average TBN value of 10 mgKOH/ml when new. TBN values typically degrade over time with use. The condemnation value or limit of 3.0 mgKOH/ml was used for this test.

Oxidation and nitration analysis is conducted using a form of absorption spectroscopy or Fourier transform infrared spectroscopy (FT-IR). When used oil is analyzed with FT-IR, specific classes of oxidization- or nitration-based compounds in the used oil absorb specific infrared wavelengths, allowing detection and quantification. Oxidation and nitration are chemical processes of aging in the oil driven by engine events (high temperature), catalysts (water, air, wear metals), and such other contaminants as fuels and process chemicals. As oxidation and nitration values increase, other oil quality elements (TBN, viscosity) tend to degrade and to reduce lubricant life. New oil has oxidation and nitration values of 0.0 absolute (Abs). For this test, the oxidation and nitration condemnation values were 30.0 Abs. These values reflect both oil quality and the presence of oil contaminates. Oxidation and nitration levels increase with an oil's service life and reflect the degradation of the oil. In most instances, as oxidation products accumulate they cause the oil to be more acidic. If the acid levels become severe, the lubricant will corrode the equipment's critical surfaces.

The heptane/pentane insoluble analysis measures the quantity of insolubles suspended in the used oil. These fine particles (typically less than 0.02 μm) are suspended in the oil and are believed to be harmless to the lubrication value of the oil. A drop in the insoluble level suggests that the particles have agglomerated, forming sludge or engine deposits. By tracking the insoluble levels, an important measure of lubricant quality is obtained. The maximum level of insolubles should not exceed 5%, since these are typically byproducts of combustion, soot, or degradation contaminants.

The standard test to determine insoluble content in lubricating oil is ASTM D893. A representative sample of used lubricating oil is mixed with pentane and centrifuged. The precipitate is rinsed with pentane, dried, and weighed to obtain the pentane insolubles from the following calculation:

$$\text{Insolubles, \%} = 10(B - A)$$

where

A = Mass of clean, dried, centrifuge tube in grams (g)

B = Mass of dried insolubles and centrifuge tube (g).

Engine deposits are formed as the result of lubricating oil being used under normal engine operating conditions. Engine deposits are insoluble in oil and can agglomerate to such a size that they will drop out of suspension. Insoluble material may be sourced from polymerization of unburned fuel, fuel carbon and highly carbonized materials from degradation of fuel, oil, and additives. Other sources may be external contamination of the oil, engine wear, and engine corrosion debris.

To maintain proper engine performance, deposit formation must be kept to a minimum. The most effective means is to maintain small particles of the insoluble material, to typically less than 0.02 microns, thus keeping the particles harmlessly suspended in the lubricant. A lubricant with superior additives to keep insolubles in suspension will maintain engine performance and cleanliness. The additives disperse the insoluble materials throughout the oil and prevent precipitation of the particles as sludge by forming films around the individual particles.

The purpose for performing the insoluble test (along with other lubricant analysis tests) is to determine the useful life of a lubricant. The quantity of insolubles that a lubricant may carry depends on the detergency/dispersancy level of the lubricant, which may be several percentage points for a highly formulated lubricant. Continuous monitoring of the insoluble content will reveal a decrease in the insoluble level, indicating the deposits are not being kept in suspension (an indication of additive depletion) and formation of sludge in the engine and oil-ways.

3. RESULTS AND DISCUSSIONS

This section presents the following data:

- Climate during the test period
- Supportive idling test data
  - Weekly gathered data
  - On-board computer data
- Historical oil analysis data
- Baseline destructive filter data
- Weekly oil analysis data
- Destructive filter data at 5,000 miles and at 400-, 800-, and 1,000 hours
- Disposition of the wear metal data
- Disposition of the oil quality data.

3.1 Climate

The test plan for the idling test required that climatic data be recorded. The weather was mild during the idling phase of the test (between 4/27/05 and 7/5/05). Table 6 shows the temperature ranges.

Table 6. Temperature ranges.

Time Period	High Temperature (Average, ºF)	Low Temperature (Average, ºF)
Last week of April	61	34
May	67	39
June	77	46
First week of July	84	50

3.2 Supportive Data

Supportive idling test data came from the daily logs and the on-board data logger. Appendix D presents the complete record of the daily manual logs. Appendix E presents the complete on-board logger data. Table 7 compares three data points between the data obtained from the daily logs and the on-board data logger.

Table 7. Manual and ProDriver data.

	Bus 73432		Bus 73433	
	Manual Log	ProDriver	Manual Log	ProDriver
Total idling hours	1056	981	1029	1004
Total miles driven	1207	1268	1112	1358
Total fuel used (gal)	998	1108	997	1175

Appendix D lists all manual data, idling times, shuttle runs, fuel consumption, and engine oil use for both buses from the Daily Log. Engine oil use was 8.5 gallons for bus 73432, 15 gallons for bus 73433. Also, about eight gallons of oil was used for each for the filter servicing to replace the oil lost when the filters were changed out

3.3 Oil Analysis Data

The historical oil analysis data for the two test buses were derived from oil analysis reports received during the Oil Bypass Filter Technology Evaluation and from six oil analysis reports issued before the Oil Bypass Evaluation. The data also include analyses performed on the new Shell Rotella-T 15W-40 oil used for the evaluation. Note that three different oil analysis test laboratories were used during the Oil Bypass Filter Evaluation. The initial two laboratories were CTC and ANA Laboratories, but ANA was replaced with NTS, which was able to perform tests not available at ANA.

Table 8 shows the start and stop times of the Oil Bypass Filter Technology Evaluation and the Idling Test. Appendix F presents the history of filter changeouts for buses 73432 and 73433. This history shows that bus 73432 traveled over 84,000 miles without a change of oil, and during these 24 months the bus had eight filter changes. Bus 73433 traveled over 92,000 miles without a change of oil, and had nine filter changes. With each filter change, two oil analysis samples were taken. These 17 filter changing events generated 34 oil analysis reports, which recorded the historical data. Appendix G presents the historical data from all three laboratories. Reports on the virgin oil are also included, along with other data.

Table 8. Start and stop times of Oil Bypass Filter Technology Evaluation and the Idling Test.

	73432		73433	
	Oil Bypass Filter Technology Evaluation	Idling Test	Oil Bypass Filter Technology Evaluation	Idling Test
Start of test	2/11/03	3/10/05	12/4/02	3/10/05
End of test	3/10/05	7/5/05	3/10/05	6/28/05
Months of testing	24	4	27	3.5

3.4 Baseline Destructive Filter Data

There were three baseline destructive filter analyses. The one for bus 73432 was recorded on 12/12/04; the two for bus 73433 were recorded on 9/22/04 and 1/24/05. The wear metal baseline data were obtained from these three destructive filter analyses. Appendix H shows the data sheets for the three analyses. Essentially, bus 73432 had one service event; bus 73433 had two 12,000-mile service events before the idling began.

3.5 Weekly Tests

During the idling time on each Monday (except on July 4), four oil analysis samples were taken (two from each bus). Two samples were sent to CTC and two to NTS. In addition, an archive sample for each bus was kept in the event of loss in shipping. Appendix I presents all of the oil analysis data of the weekly tests, which include:

- Wear metals: fine and course
- Metal contaminates
- Additives
- Oil quality
- Particle count.

The charts and graphs showing the results of these weekly samples may also include one or two samples taken during the 5000-mile portion of the test.

3.5.1 Wear Metals

The wear metals are divided into both fine and course particles. The fine wear metals are quantified in parts per million using spectroscopy analysis. Fine wear metals from both test laboratories are shown in the following charts, Figures 11 and 12. Metals not plotted were not detected.

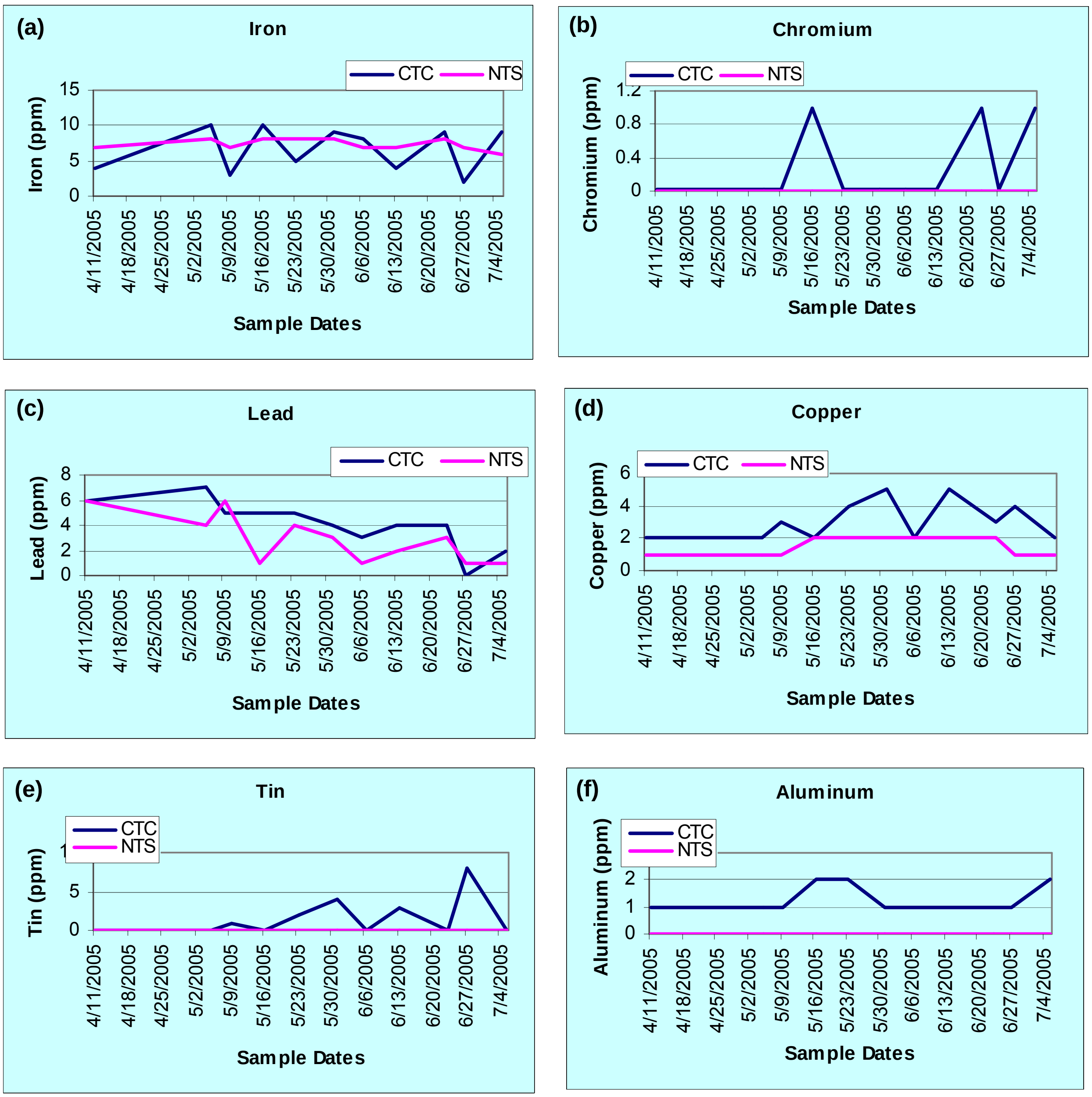
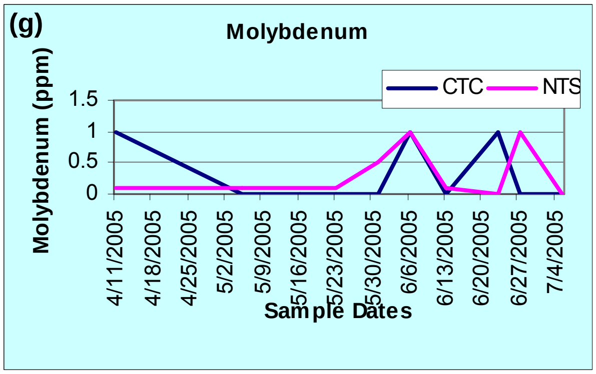


Figure 11. Bus 73432 fine wear metals.



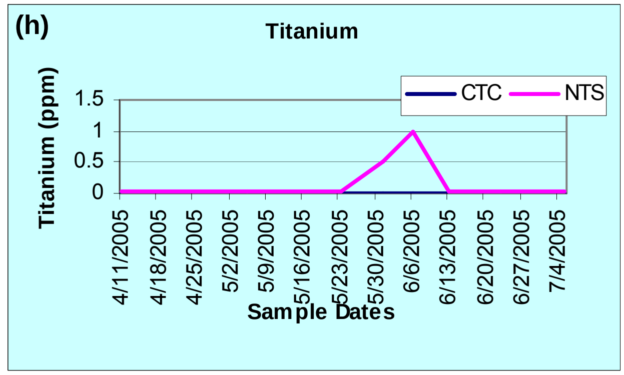


Figure 11 (continued). Bus 73432 fine wear metals.

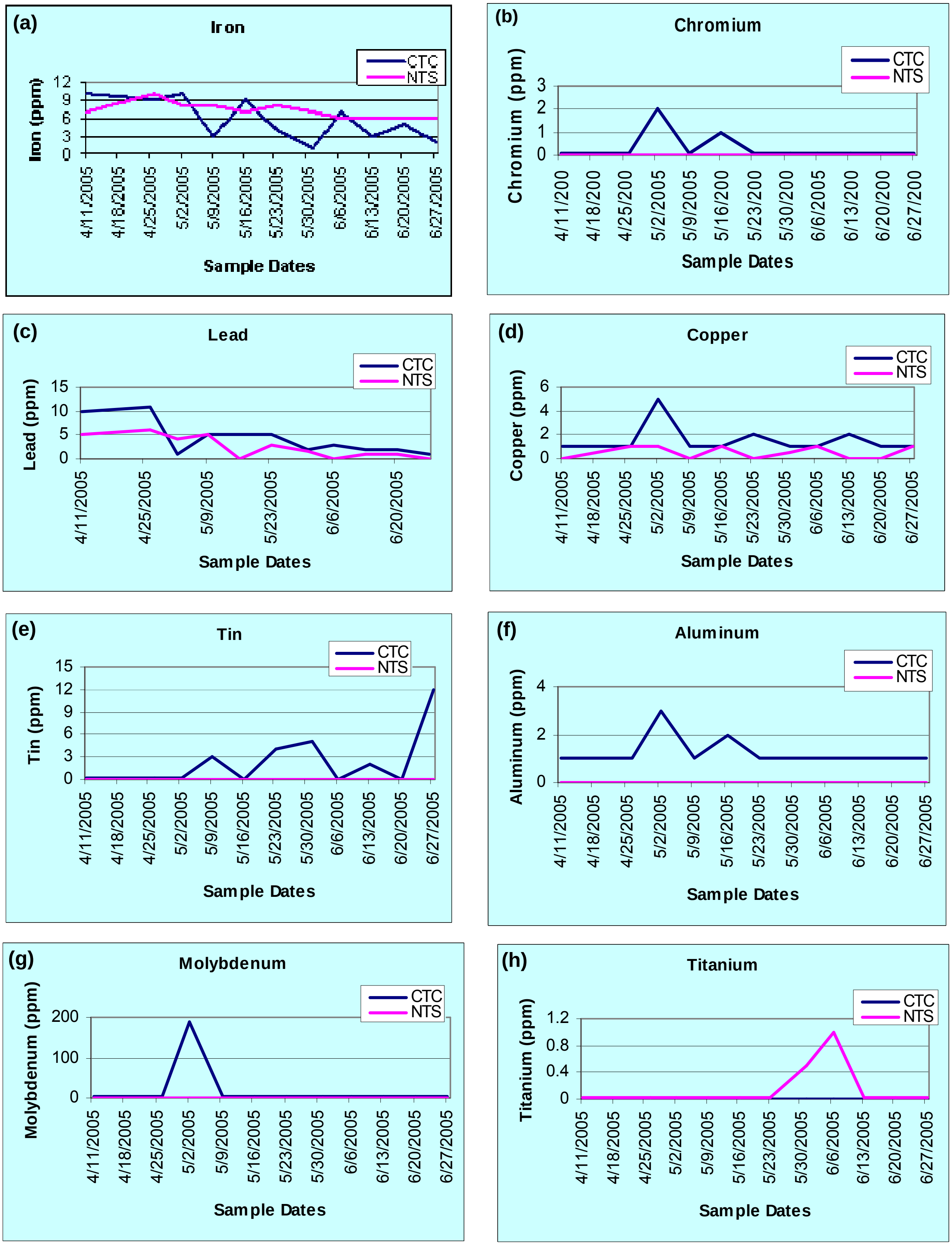


Figure 12. Fine wear metals recorded for Bus 73433.

Course (10- to 50-micron) metal particles were characterized by rotrode filter spectroscopy (RFS) analysis. These results are shown in Tables 9 and 10. (N/G = not given. The sample was apparently lost).

Table 9. Course wear metal for Bus 73432.

Test week	5000 miles	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
Iron	0	1	1	0	1	0	0	N/G	0	0
Chromium	0	0	0	1	0	0	1	N/G	0	0
Lead	0	0	0	0	0	0	0	N/G	0	0
Copper	0	1	0	0	0	0	0	N/G	0	0
Tin	0	1	0	2	1	0	0	N/G	1	0
Aluminum	0	9	0	0	0	0	0	N/G	1	0
Nickel	0	0	0	0	0	0	0	N/G	0	0
Silver	0	0	0	0	0	0	0	N/G	0	0
Molybdenum	0	0	0	0	0	0	0	N/G	0	0
Titanium	0	0	0	0	0	0	0	N/G	0	0

Table 10. Course wear metal for bus 73433.

Test Week	5000 miles	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Iron	1	1	1	0	1	0	0	1	0	0	0
Chromium	0	0	0	0	0	0	0	1	0	0	1
Lead	0	0	0	0	0	0	0	0	0	0	0
Copper	0	1	0	0	0	0	0	0	0	0	0
Tin	1	0	1	0	0	0	0	0	0	0	1
Aluminum	0	0	0	4	1	0	0	0	0	0	1
Nickel	0	0	0	0	0	0	0	0	1	0	0
Silver	0	0	0	0	0	0	0	0	0	0	0
Molybdenum	0	0	0	0	0	0	0	0	1	0	0
Titanium	0	0	0	0	0	0	0	0	0	0	0

3.5.2 Metal Contaminates

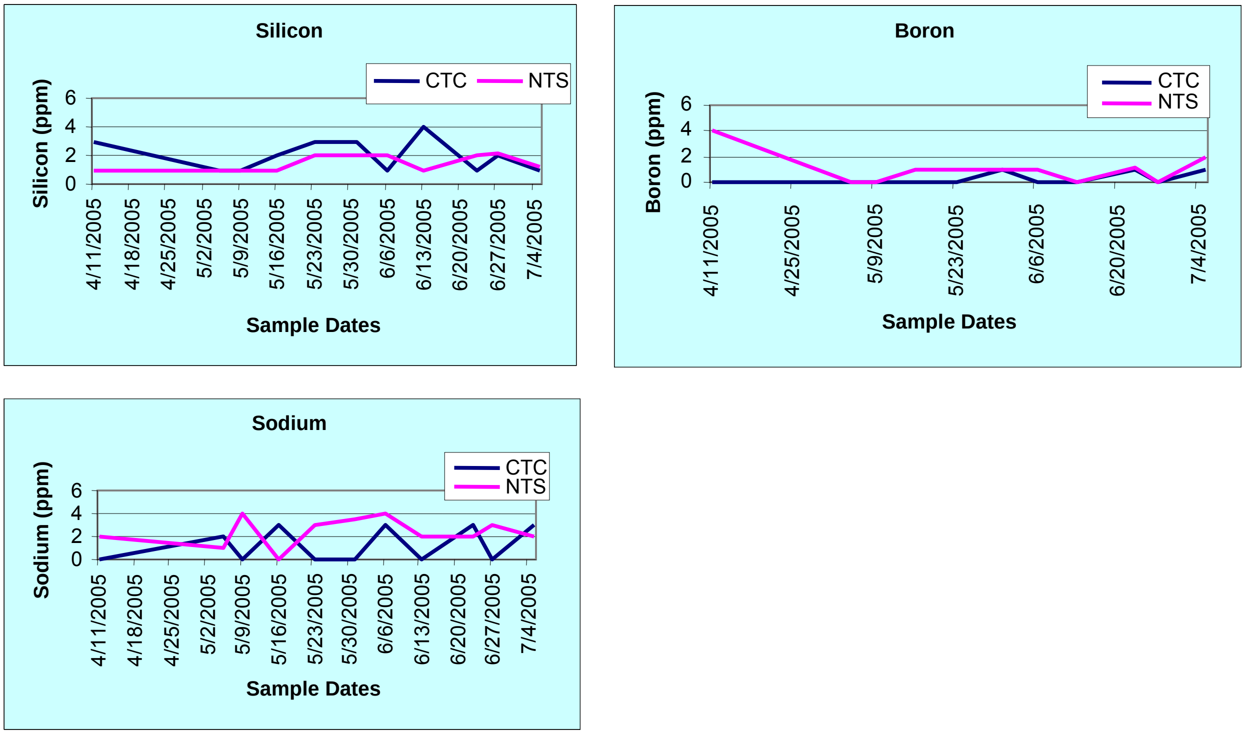


Figure 13. Metal contaminates recorded for Bus 73432.

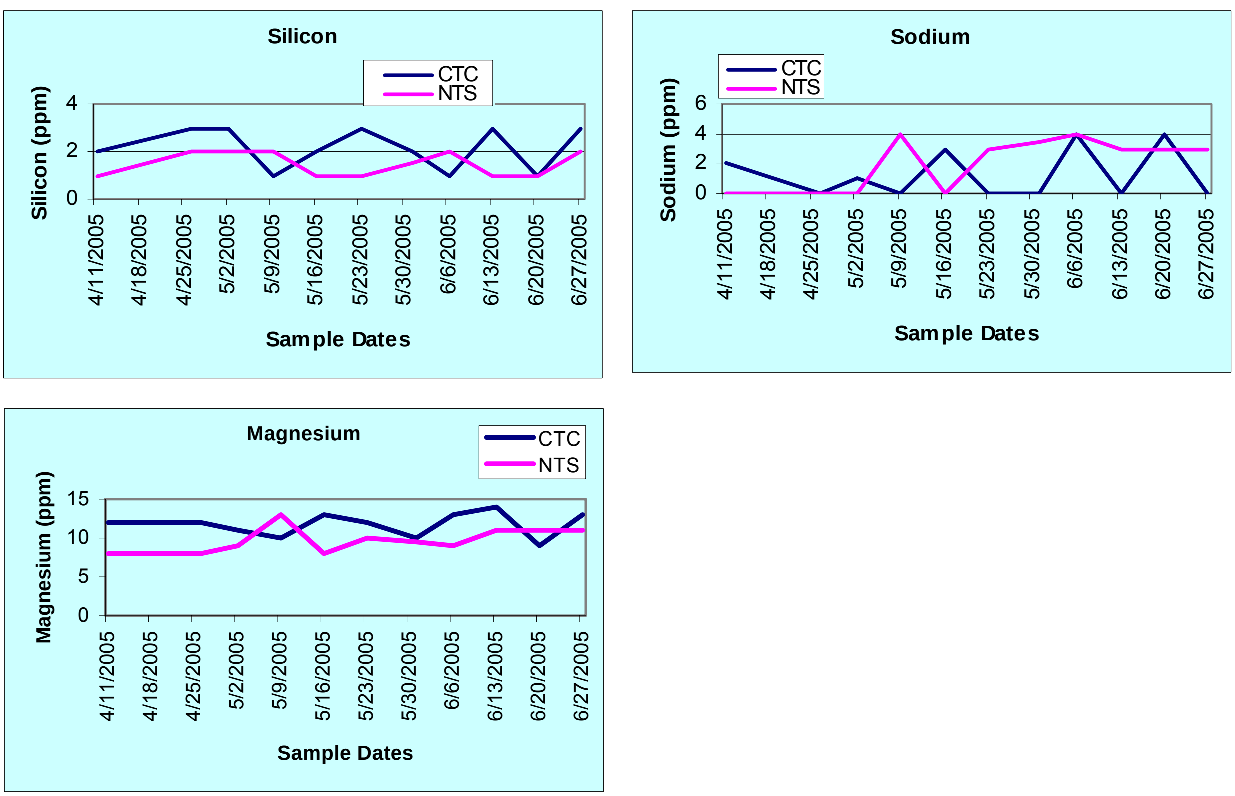


Figure 14. Metal contaminates recorded for Bus 73433.

3.5.3 Additives

The calcium, phosphorous, and zinc additives are plotted together in Figure 15 for bus 73432 and in Figure 16 for bus 73433.

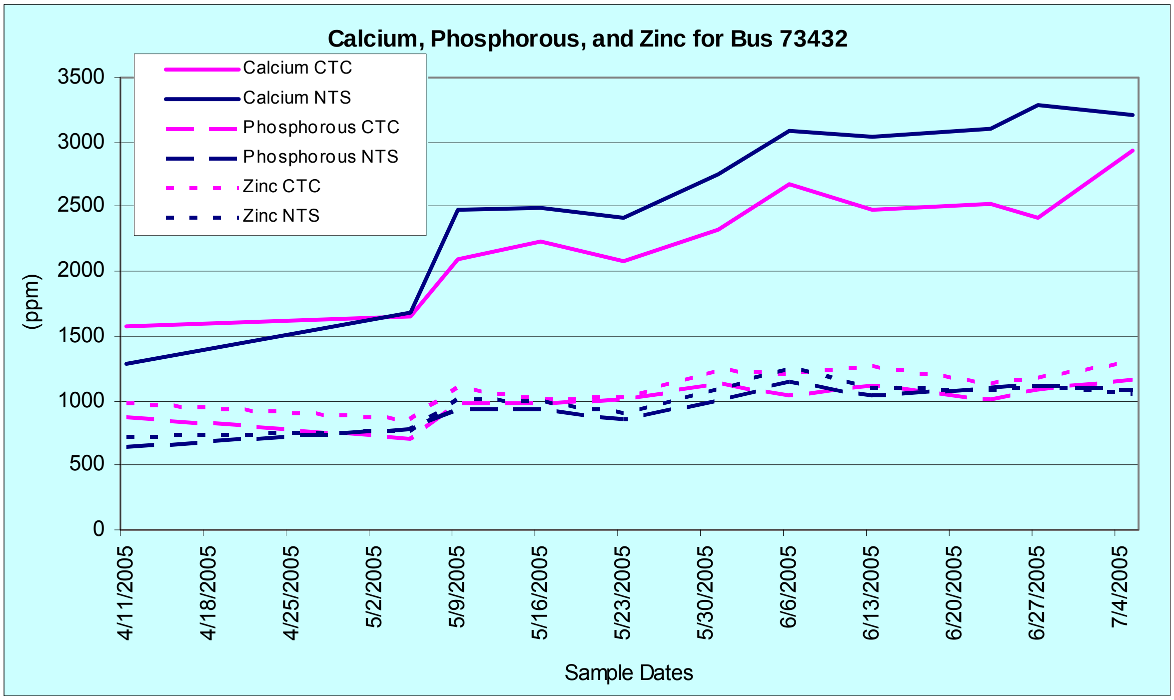


Figure 15. Bus 73432 calcium, phosphorous, and zinc additives.

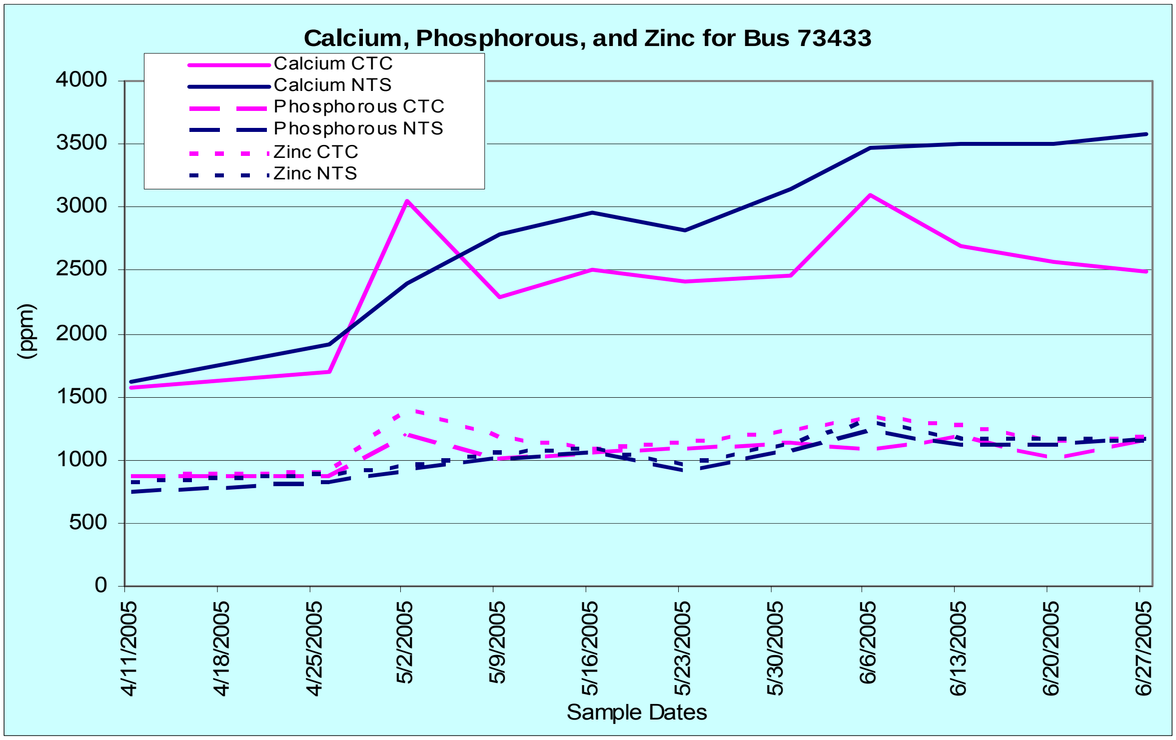


Figure 16. Buss 73433 calcium, phosphorous, and zinc additives.

3.5.4 Oil Quality

Appendix I shows all of the oil quality values together. For this report, oil quality is partitioned into the following bins:

- Viscosity value
- Oxidation/nitration numbers
- Total base number (TBN)
- Water and glycol contamination
- Fuel dilution
- Soot.

3.5.4.1 Viscosity

The viscosity values from NTS are shown in Figure 17.

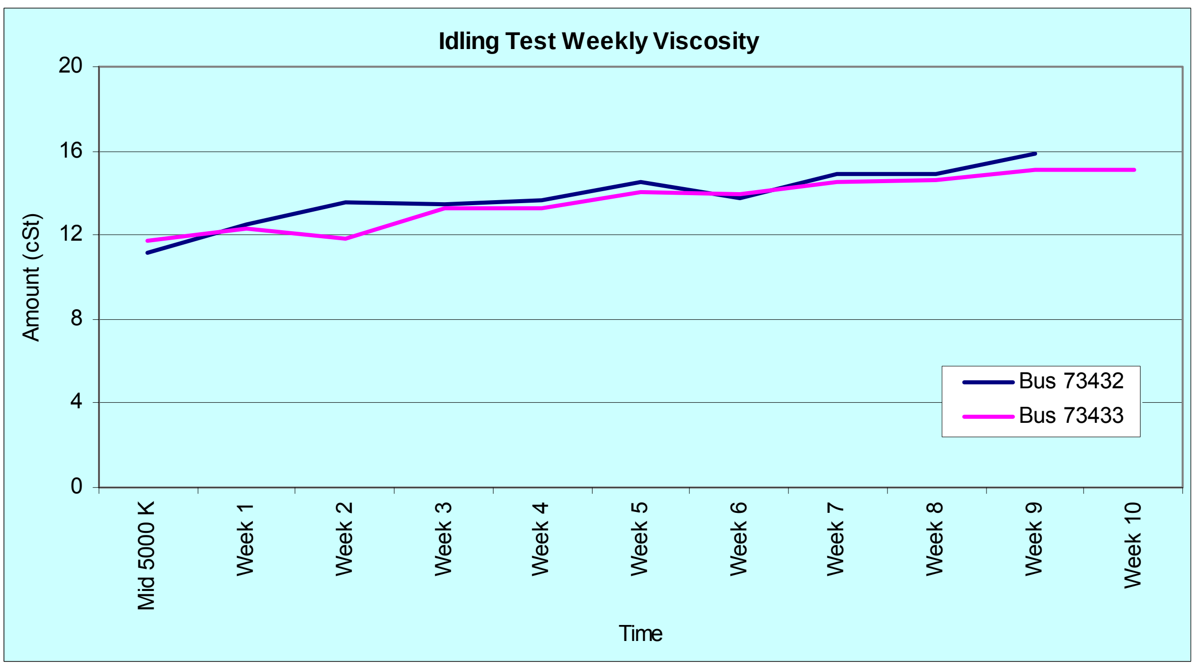


Figure 17. Weekly viscosity results from NTS for both buses.

3.5.4.2 Oxidation/Nitration Numbers

The oxidation/nitration numbers did not vary widely. They are listed in Appendix I.

3.5.4.3 TBN

The TBN values are shown in Figure 18.

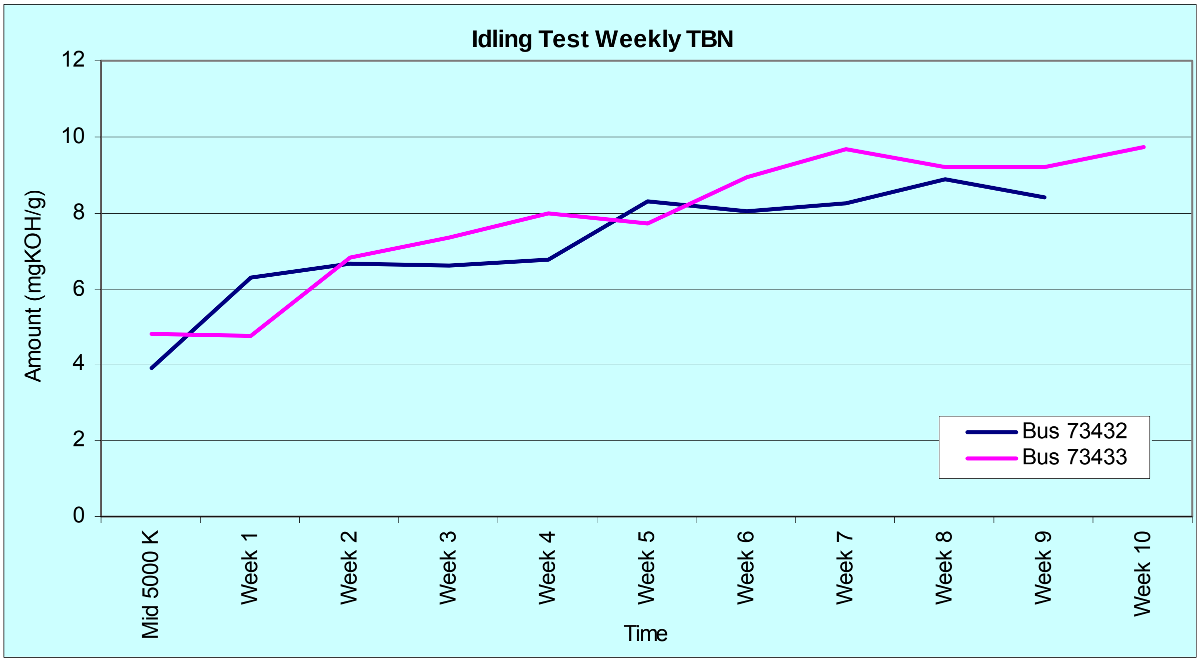


Figure 18. Weekly TBN results from NTS for both buses.

3.5.4.4 Water and Glycol Contamination

There was no water or glycol contamination noted in the weekly oil analysis results.

3.5.4.5 Fuel Dilution

The viscosity values are shown in Table 11.

Table 11. Idling tests fuel dilution.

NTS data for Bus 73432										
Sample Type	Mid 5000 mi	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly
Date	4/11/05	5/9/05	5/16/05	5/23/05	5/31/05	6/6/05	6/13/05	6/20/05	6/27/05	7/5/05
Fuel dilution	3.81	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00

NTS data for Bus 73433											
Sample Type	Mid 5000 mi	Start	Weekly	Weekly	Weekly	Used Oil	Weekly	Weekly	Weekly	Weekly	Weekly
Date	4/11/05	4/26/05	5/2/05	5/9/05	5/17/05	5/23/05	5/30/05	6/6/05	6/13/05	6/20/05	6/27/05
Fuel dilution	2.79	2.11	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	<2.00	N/G	<2.00

There was some fuel dilution noted starting with the middle oil analysis test during the 5,000 miles oil break-in period. The source of the contamination was never ascertained, and both buses had contamination. This contamination coincided with a significant drop in TBN, viscosity, calcium, potassium, and zinc of both buses. Subsequent oil analysis reports from the Oil Bypass Filter Technology Evaluation also show that when there is diesel fuel contamination, these other values drop. The viscosity values were actually lower than typically allowed during the Oil Bypass Filter Technology Evaluation, but since the bypass filters have heating elements that vaporize fuel and fine filters that catch contaminates, it was decided to continue the test. The TBN, viscosity, calcium, potassium, and zinc values all increased during the test, and the data show this direct correlation. This improvement could result from adding make-up oil to replace the weekly loses and from the filter changes, and also from the affects of the bypass filter system on the oil.

3.5.4.6 Soot

Appendix I presents the soot values, which were low.

3.5.5 Particle Count

The particle counting process, based on a one-milliliter volume of oil, bins the particles into the three ISO sizes: >4, >6, and >14 microns. The count from the weekly tests is shown in Figures 19 and 20. The oil had significantly more particles during the initial weeks, then dramatically dropped to lower values over the last several weeks.

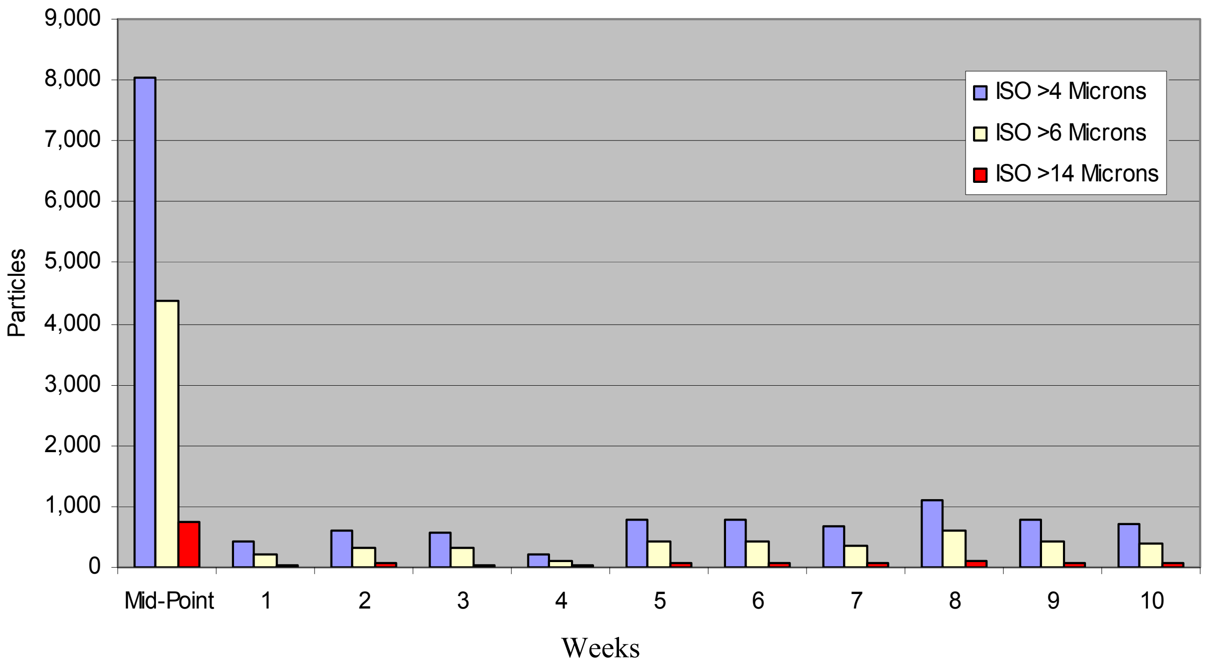


Figure 19. Particle sizes of the used oil for bus 73432.

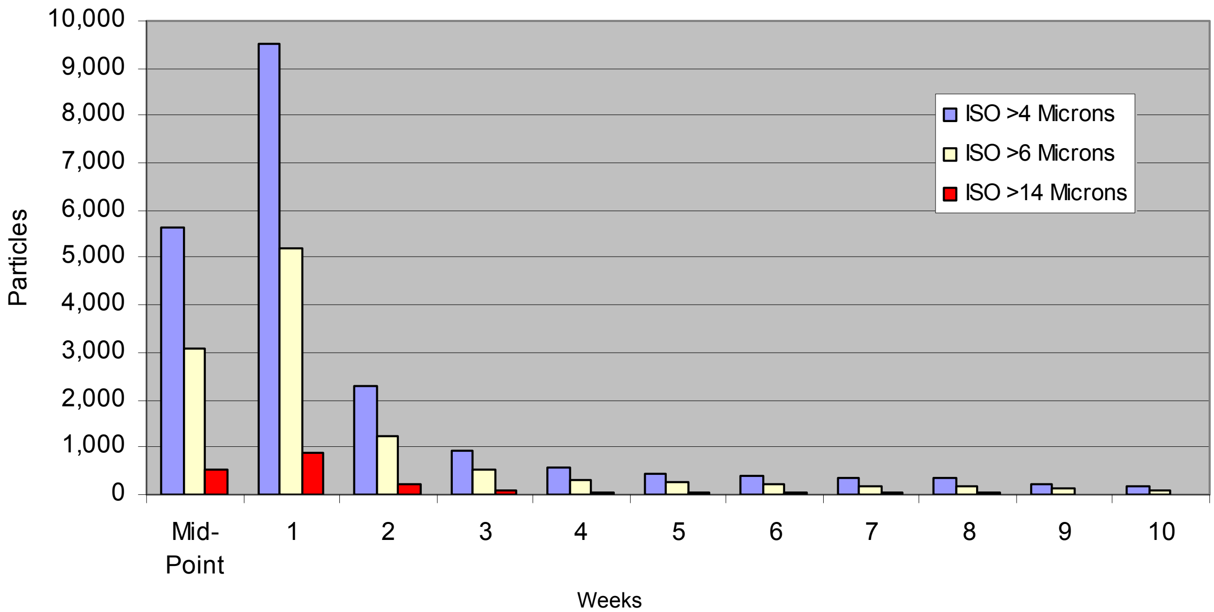


Figure 20. Particle sizes of the used oil for bus 73433.

3.6 Destructive Filter Tests

The destructive filter tests occurred for each bus at four intervals: 5,000 miles and 400, 800, and 1,000 hours. In addition, there are five oil analysis reports generated with each interval for the following oils: used engine oil, bypass filter residual oil, full-flow filter residual oil, bypass filter oil (sonicated neutral oil), and full-flow filter oil (sonicated neutral oil). Note that NTS conducted all of the destructive filter tests and oil analyses. Appendix J presents on eight pages the total oil analysis test results for both buses for all four intervals. The destructive tests have the same specific data breakdown as the weekly tests:

- Fine wear metals
- Contaminates
- Additives
- Course wear metals
- Oil quality: viscosity, TBN, fluids contamination, oxidation/nitration numbers
- Particle count.

The following tests were also conducted:

- Ferrograms
- Wear particle types
- X-ray florescence alloy analysis
- Heptane/pentane insoluble analysis.

A couple of caveats or exceptions need to be mentioned. Particle count analysis for the bypass and full-flow filter oils were not applicable during testing because vast numbers of filter particles became disassociated from the medium while it was ultrasonically cleaned. Oil quality values (viscosity and TBN values) for the sonicated oil are not applicable because the neutral base oil was used, not the engine oil, in the ultrasonic cleaning process. And the x-ray florescence alloy analysis was used only on the filter medium before cleaning.

3.6.1 Fine Wear Metals

Appendix J presents all of the fine wear-metal data for the five oils. Since the trends are similar for all five oils, Figure 21 shows only the fine wear metals detected in the used-oil sample.

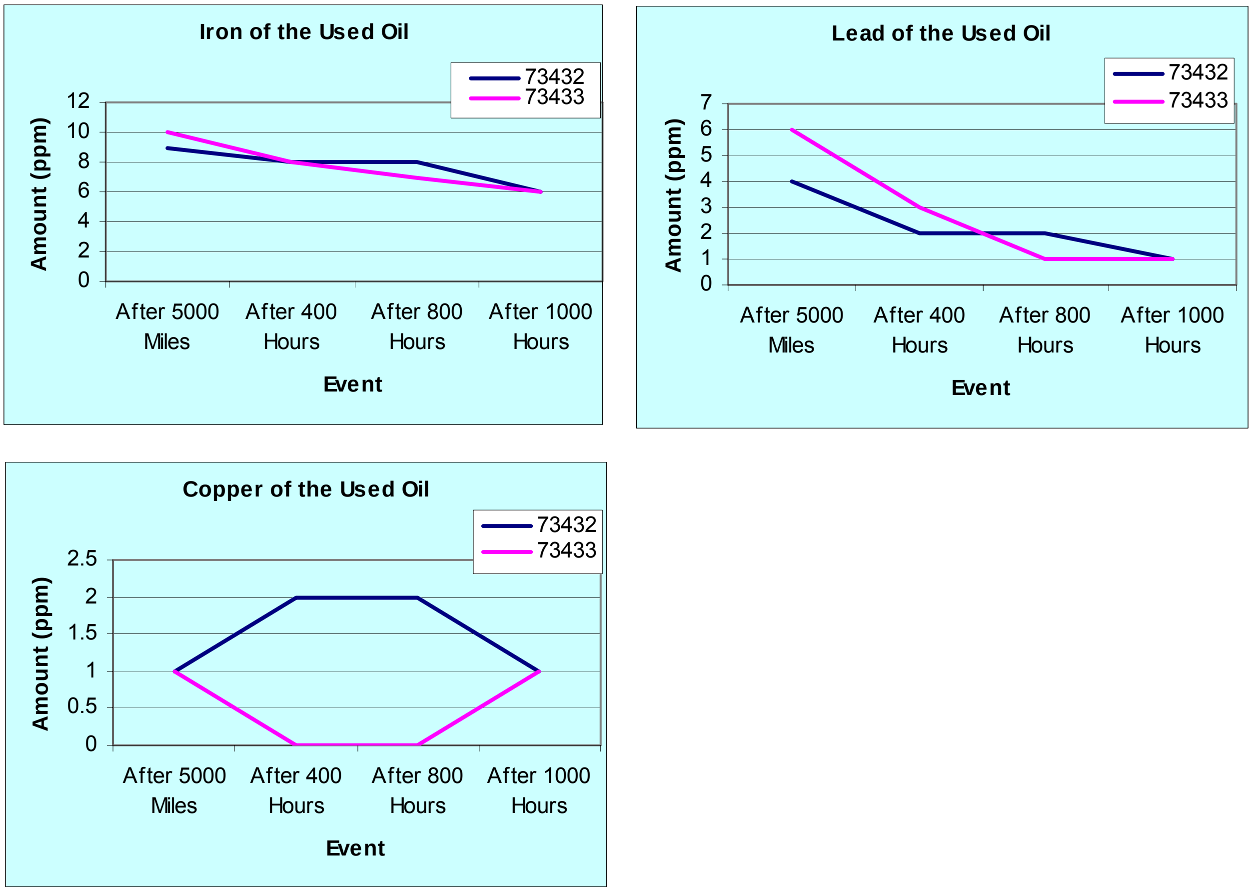


Figure 21. Wear metals in the used oils for both test buses.

Another way to look at wear metals is to derive the wear-rate ratio: the ratio of the metal accumulated per 1,000 miles driven. For example, if the iron values were 35 ppm, and the miles driven were 25,000, the equation would be 35/25, or a wear rate ratio of 1.4. The miles driven were the actual miles driven during the conditioning phase of the test; and each 400 hours of idling time were equivalent to 12,000 miles. The wear rate ratios were derived from the used oil taken at the time the filters were removed and the bypass and full-flow filter oils (oil from the ultrasonic cleaning). The only significant wear metals were iron, lead, and copper. Tables 12, 13, and 14 show that the wear rates, almost across the board, decreased over time.

Table 12. Wear rate ratio of used oil samples taken at filter changing.

Point at Which Sample Was Taken	Mileage on Oil at Sampling	Particles per Million (ppm)	Wear Rate Ratio (ppm/1,000 miles)
Iron: Sample from Bus 73432			
5000 miles	6597	9	1.36
400 hours	18,597	8	0.43
800 hours	30,597	7	0.23
1000 hours	35,597	2	0.05
Lead: Sample from Bus 73432			
5000 miles	6597	4	0.61
400 hours	18,597	2	0.11
800 hours	30,597	2	0.07
1000 hours	35,597	0	0.00
Copper: Sample from Bus 73432			
5000 miles	6597	1	0.15
400 hours	18,597	2	0.11
800 hours	30,597	2	0.07
1000 hours	35,597	0	0.00
Iron: Sample from Bus 73433			
5000 miles	6839	10	1.46
400 hours	18,839	8	0.42
800 hours	30,839	7	0.23
1000 hours	36,839	6	0.16
Lead: Sample from Bus 73433			
5000 miles	6839	6	0.88
400 hours	18,839	3	0.16
800 hours	30, 839	1	0.03
1000 hours	36, 839	0	0.00
Copper: Sample from Bus 73433			
5000 miles	6839	1	0.15
400 hours	18, 839	0	0.00
800 hours	30, 839	0	0.00
1000 hours	36, 839	1	0.03

Table 13. Wear rate ratio of bypass filter oil after ultrasonic cleaning.

Point at Which Sample Was Taken	Mileage on Oil at Sampling	Particles per Million (ppm)	Filter Value	Adjusted ppm	Wear Rate Ratio (ppm/1,000 miles)
Iron: Sample from Bus 73432					
5000 miles	6597	9	9.6	86.4	1.36
400 hours	18,597	2	9.6	19.2	1.0
800 hours	30,597	2	9.6	19.2	0.6
1000 hours	35,597	2	9.6	19.2	0.5
Lead: Sample from Bus 73432					
5000 miles	6597	4	9.6	38.4	5.8
400 hours	18,597	0	9.6	0	0.0
800 hours	30,597	0	9.6	0	0.0
1000 hours	35,597	1	9.6	9.6	0.3
Copper: Sample from Bus 73432					
5000 miles	6597	1	9.6	9.6	1.5
400 hours	18,597	0	9.6	0	0.0
800 hours	30,597	0	9.6	0	0.0
1000 hours	35,597	1	9.6	9.6	0.3
Iron: Sample from Bus 73433					
5000 miles	6839	4	9.6	38.4	5.6
400 hours	18,839	2	9.6	19.2	1.0
800 hours	30,839	2	9.6	19.2	0.6
1000 hours	36,839	2	9.6	19.2	0.5
Lead: Sample from Bus 73433					
5000 miles	6839	0	9.6	0	0.0
400 hours	18,839	1	9.6	9.6	0.5
800 hours	30, 839	0	9.6	0	0.0
1000 hours	36, 839	0	9.6	0	0.0
Copper: Sample from Bus 73433					
5000 miles	6839	0	9.6	0	0.0
400 hours	18, 839	0	9.6	0	0.0
800 hours	30, 839	0	9.6	0	0.0
1000 hours	36, 839	0	9.6	0	0.0

Table 14. Wear rate ratio of full-flow filter oil after ultrasonic cleaning.

Point at Which Sample Was Taken	Mileage on Oil at Sampling	Particles per Million (ppm)	Filter Value	Adjusted ppm	Wear Rate Ratio (ppm/1,000 miles)
Iron: Sample from Bus 73432					
5000 miles	6597	2	1.4	2.8	0.42
400 hours	18,597	3	1.4	4.2	0.23
800 hours	30,597	1	1.4	1.4	0.05
1000 hours	36,597	2	1.4	2.8	0.08
Lead: Sample from Bus 73432					
5000 miles	6597	0	1.4	0	0.00
400 hours	18,597	1	1.4	1.4	0.08
800 hours	30,597	0	1.4	0	0.00
1000 hours	35,597	0	1.4	0	0.00
Copper: Sample from Bus 73432					
5000 miles	6597	0	1.4	0	0.00
400 hours	18,597	0	1.4	0	0.00
800 hours	30,597	0	1.4	0	0.00
1000 hours	36,597	0	1.4	0	0.00
Iron: Sample from Bus 73433					
5000 miles	6839	4	1.4	5.6	0.82
400 hours	18,839	2	1.4	2.8	0.15
800 hours	30,839	3	1.4	4.2	0.14
1000 hours	36,839	2	1.4	2.8	0.08
Lead: Sample from Bus 73433					
5000 miles	6839	0	1.4	0	0.00
400 hours	18,839	1	1.4	1.4	0.07
800 hours	30, 839	0	1.4	0	0.00
1000 hours	36, 839	0	1.4	0	0.00
Copper: Sample from Bus 73433					
5000 miles	6839	0	1.4	0	0.00
400 hours	18, 839	0	1.4	0	0.00
800 hours	30, 839	0	1.4	0	0.00
1000 hours	36, 839	0	1.4	0	0.00

3.6.2 Contaminates

All of the contaminate data for the five oils are minimal, as shown in Appendix J.

3.6.3 Additives

Figure 22 displays the additives (calcium, phosphorous, and zinc) for the used oil only. All five oils show a similar upward trend.

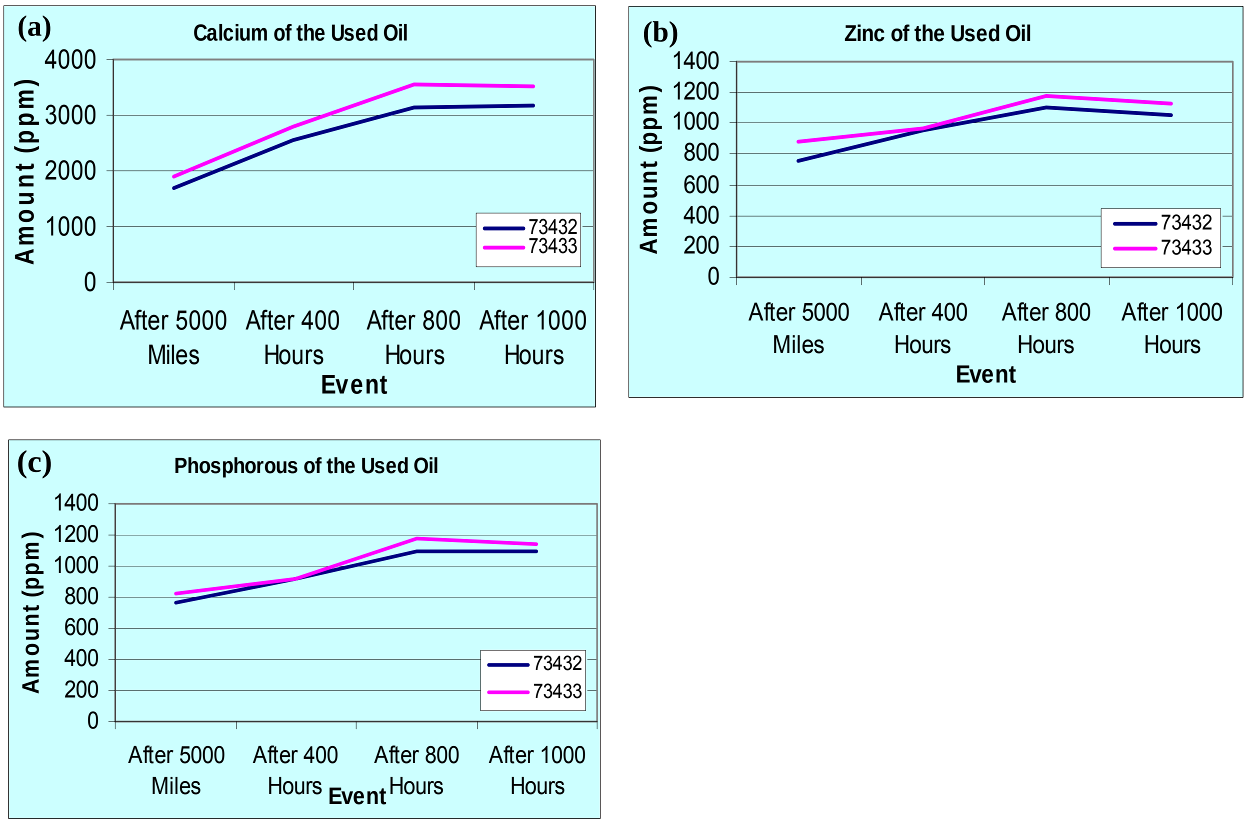


Figure 22. Used oil additive values.

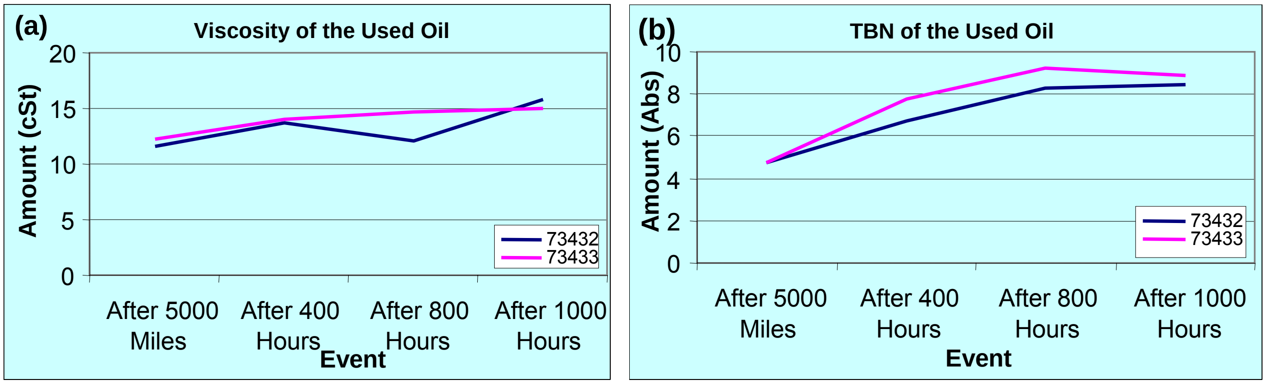
3.6.4 Course Wear Metals

Course wear metals obtained by the RFS process from NTS were not substantial, so the data were not graphed. To see the course wear metal data see Appendix J.

3.6.5 Oil Quality Values

Oil quality values include viscosity, TBN, fluids contamination, and oxidation/nitration values. The trend is similar for all of the five oils sampled; therefore, only the used-oil data are shown. The TBN and viscosity values for the used oil are shown in Figure 23.

There was no water or glycol contamination in the oil noted in the destructive filter oil analysis results. The destructive filter analysis results did reflect the same general amounts as the weekly tests on the fuel contamination. Those values can be found in Appendix J.



Figures 23. TBN and viscosity values for both buses.

The used oil oxidation/nitration values are shown in Figure 24.

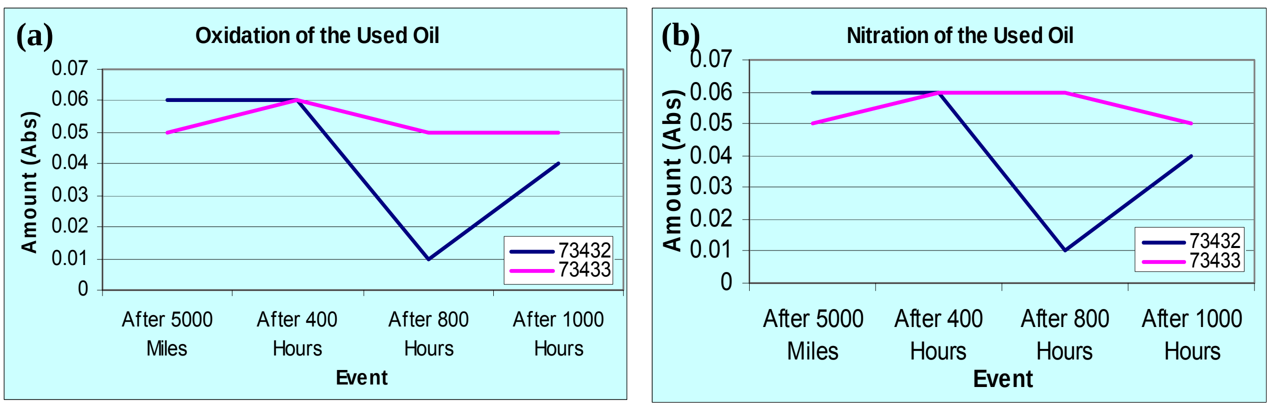


Figure 24. Oxidation/nitration values for the used oil in both buses.

3.6.6 Particle Count

Particle count data for used oil, bypass residual oil, and full-flow residual oil are show in Figures 25a–c. The particle count of the sonicated oil is biased because of the excessive number of particles from the filter debris.

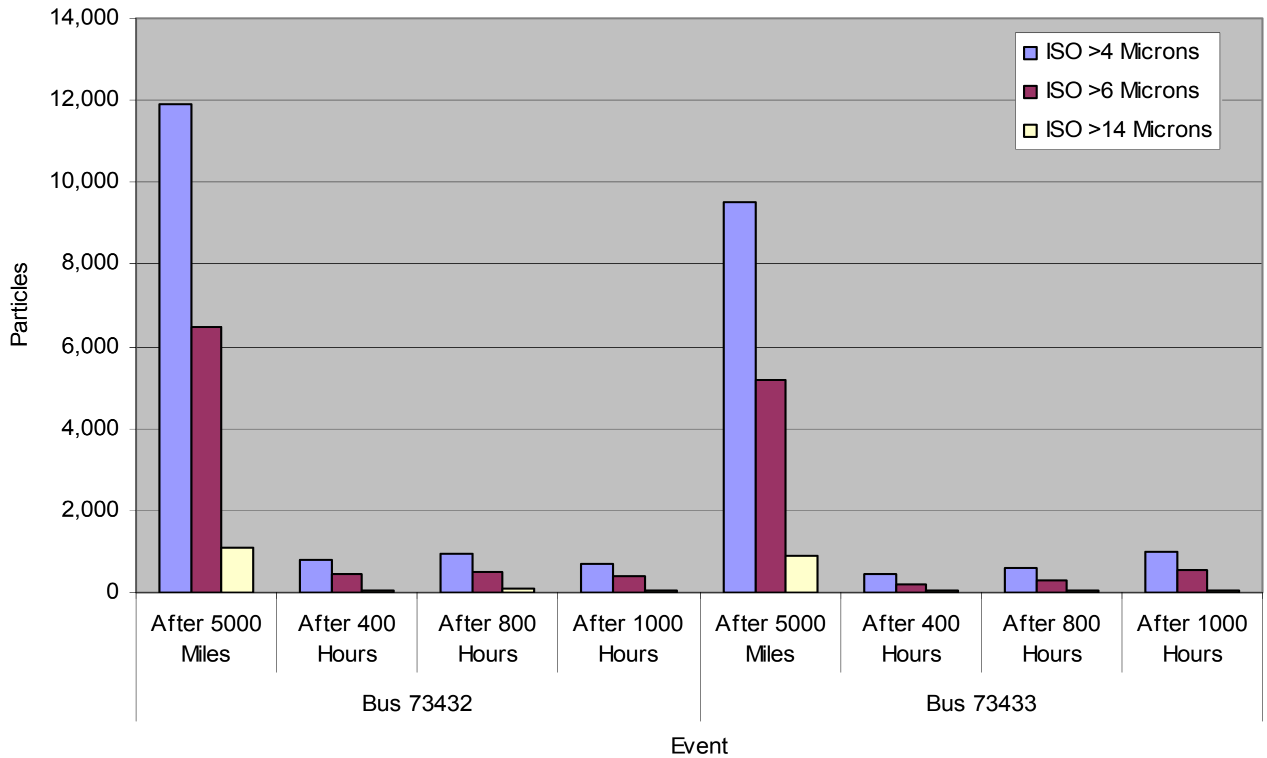


Figure 25a. Particle sizes of the used oil.

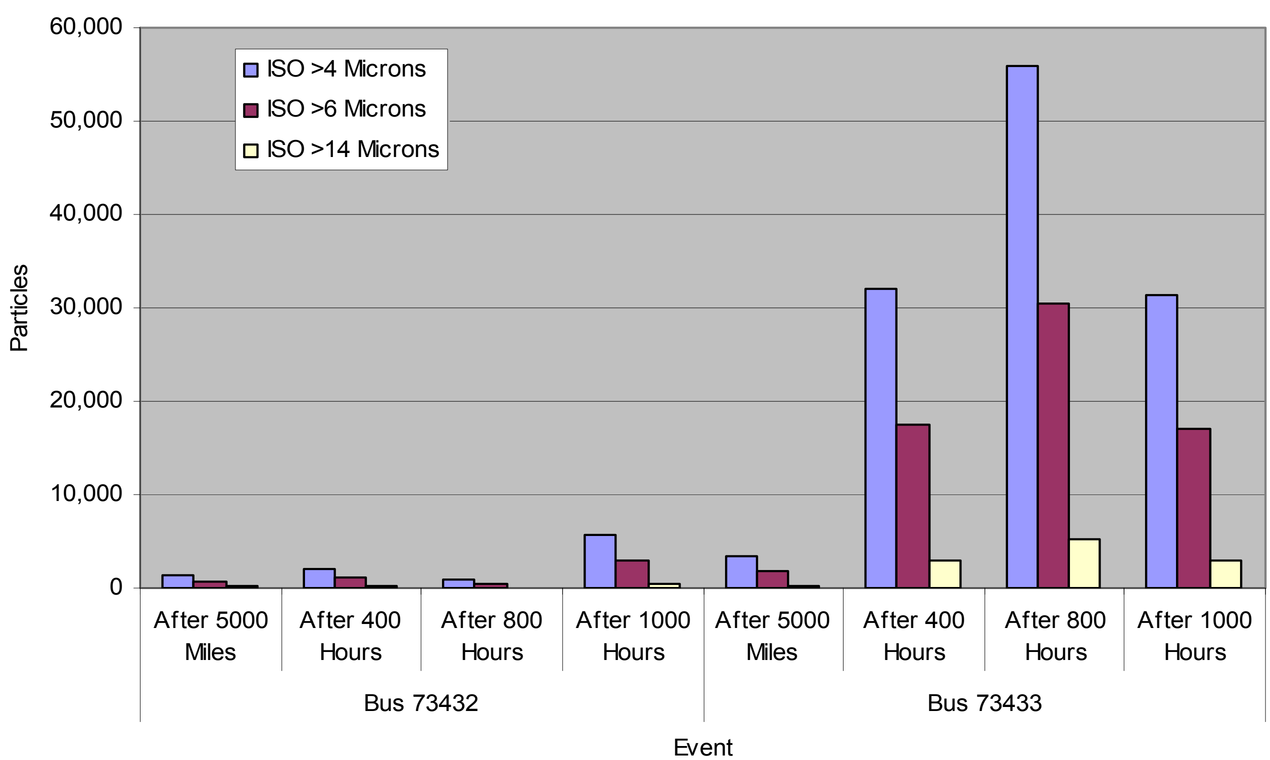
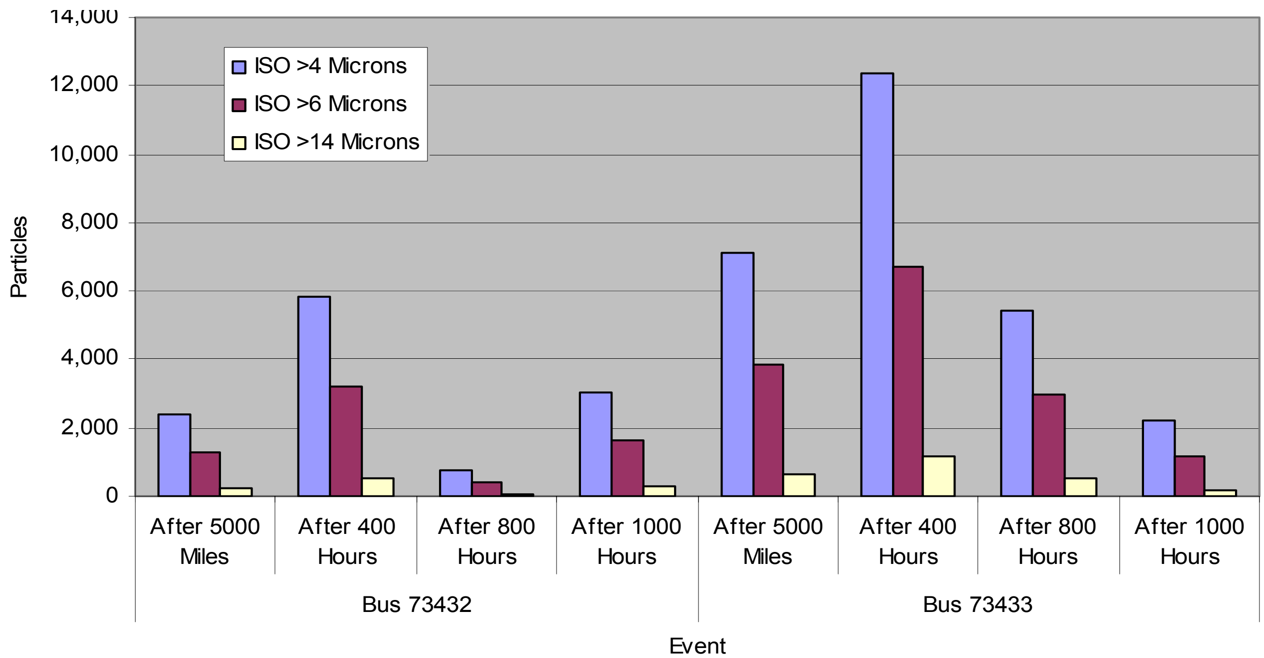


Figure 25b. Particle sizes of the full-flow residual oil.



Figures 25c. Particle counts for the bypass filter residual oil.

3.6.7 Ferrograms

Ferrograms were conducted on about 40 oil analysis samples, and photographs were taken at different magnifications—100X, 250X, 500X, 600X and 800X—on each sample, showing wear metals and general debris. Appendix K presents all of the ferrogram photographs. For the majority of ferrograms, the 100X photographs focused on the entry region of the glass slide to show a comparative analysis of the amount of particles in the oil samples, whereas the higher magnifications typically focused on a debris particle or interesting structure on the ferrogram. The entry region is where the oil is initially applied to the glass slide and therefore gets the highest population of particles. Note that the initial baseline ferrograms were conducted at the NTS Minden, Nevada laboratory, whereas for the rest of the test, the samples were processed at the NTS Peabody, Massachusetts laboratory. Some of the initial ferrograms did not have 100X photographs at the entry region, only at 250X.

The used oil samples from all of the samples typically showed a light amount of fine ferrous particulate, typical of normal rubbing wear. In a few cases, with other oils, there was a moderate amount of wear debris in many ferrograms. In the baseline ferrograms, there were a great number of fine (less than 10 microns) ferrous particulate. Figure 26 shows the differences between light, moderate, and heavy amounts of fine ferrous particulate. The baseline ferrogram shown in Figure 26c was conducted on oil that had been used for 77,000 miles.

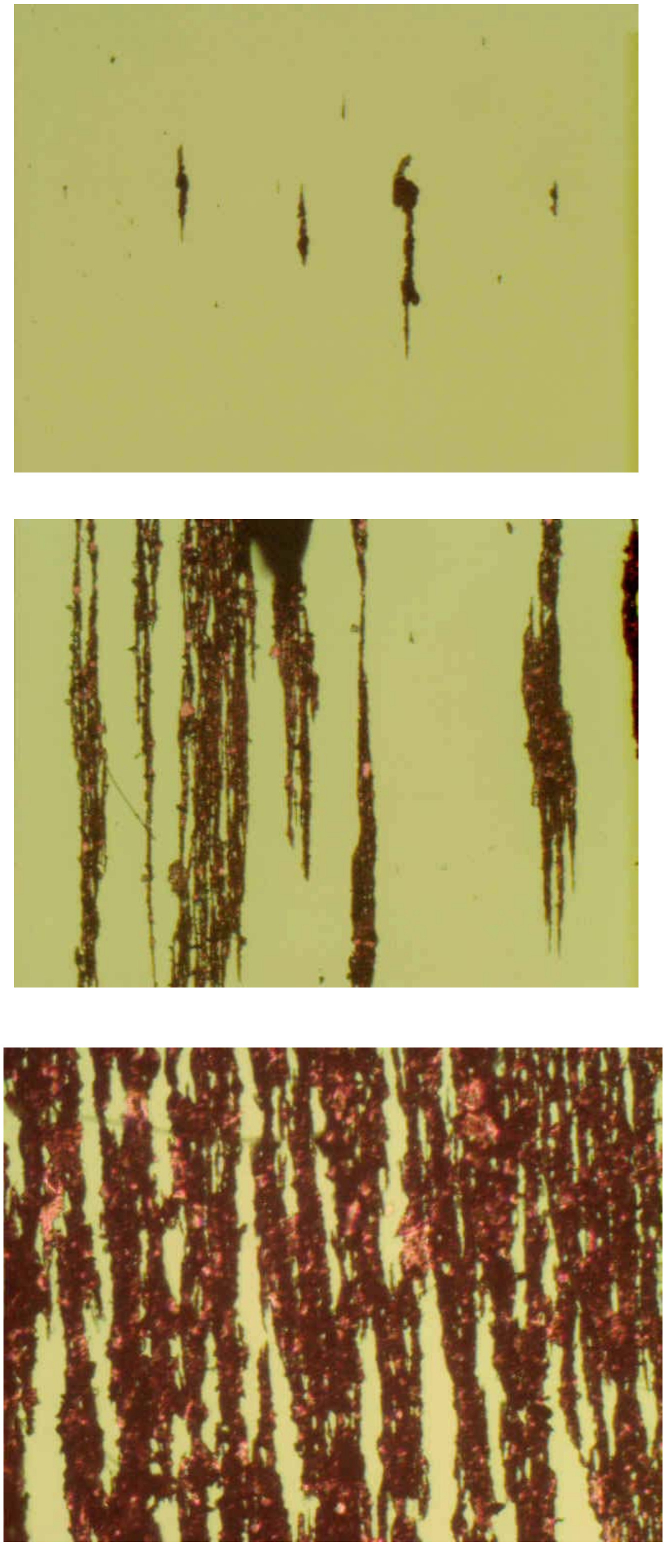
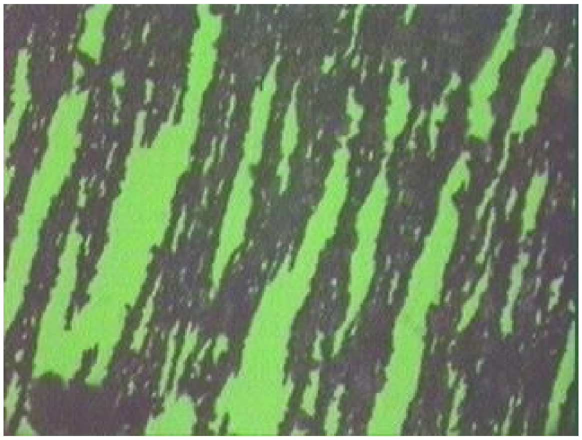
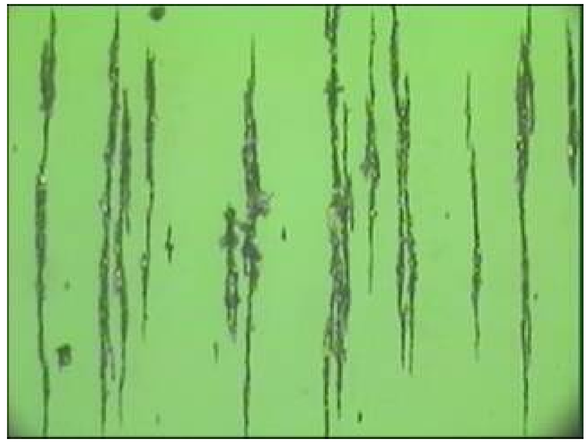


Figure 26. Example of light, moderate, and heavy amounts of fine (<10 microns) ferrous particulate.

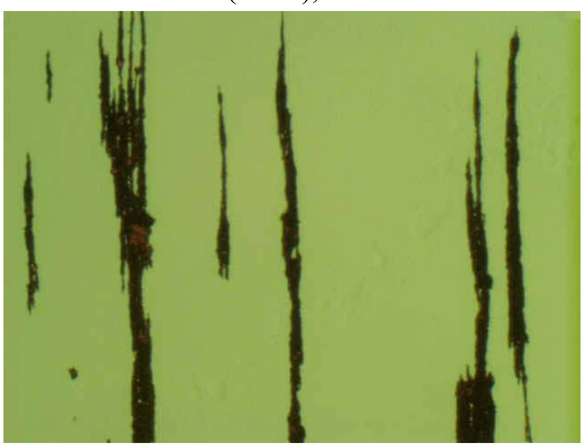
A comparison between 100X of used oil, bypass filter oil, and full-flow filter oil ferrograms is shown for the baseline interval (Figure 27), 5,000-mile interval (Figure 28), 800-hour interval (Figure 29), and 1,000-hour interval (Figure 30). The comparisons show the relative amounts that the filters catch and assists in ascertaining whether, and to what extent, idling is deleterious to diesel engines.



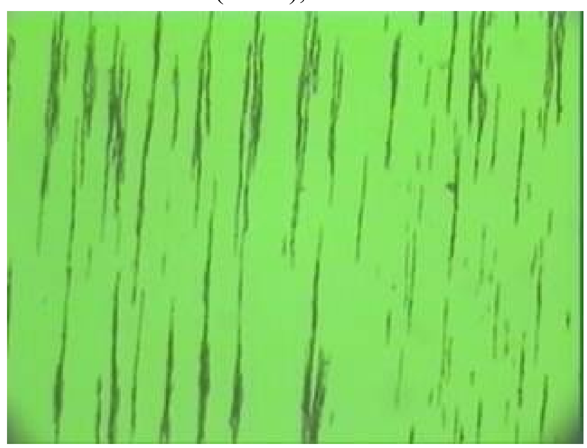
Used oil baseline (250X), bus 73432



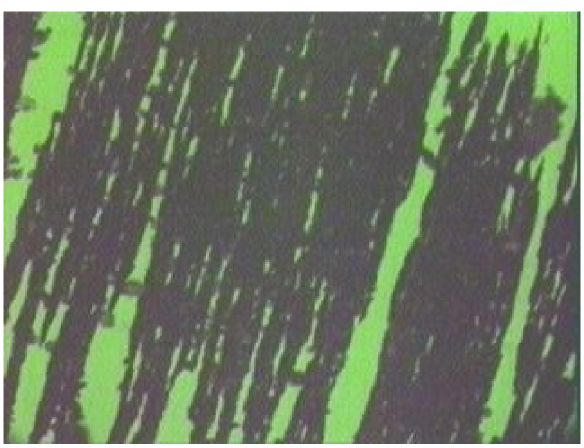
Used oil baseline (100X), bus 73433



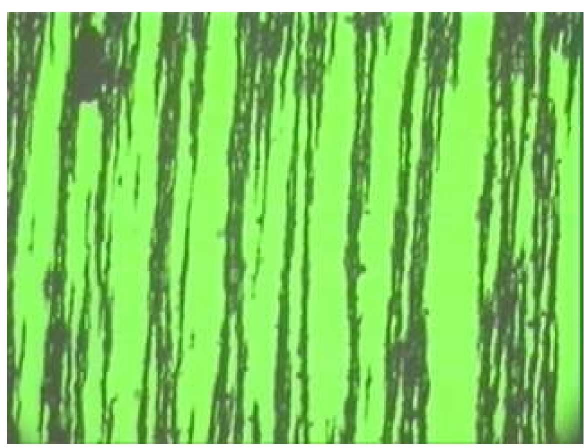
Bypass filter oil baseline (100X), bus 73432



Bypass filter oil baseline (100X), bus 73433

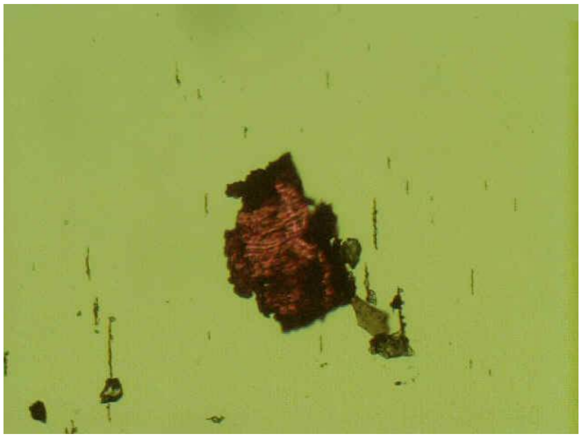


Full-flow filter oil baseline (250X), bus 73432

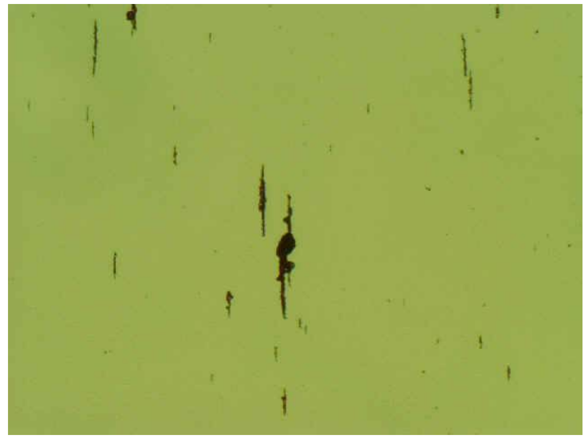


Full-flow filter oil baseline (100X), bus 73433

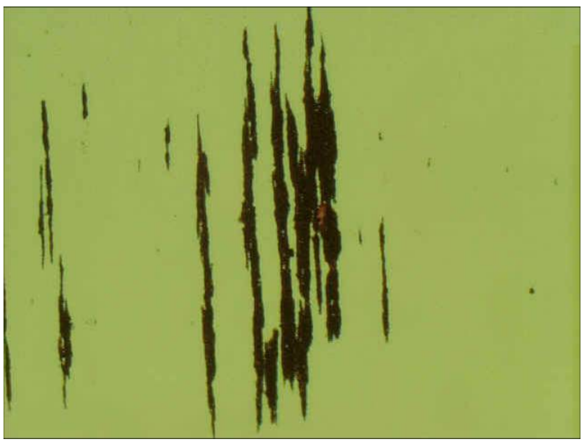
Figures 27. Comparison of baseline used, bypass filter, and full-flow filter oil ferrograms (100X and 250X; 250X photographs were used since 100X photographs were not taken).



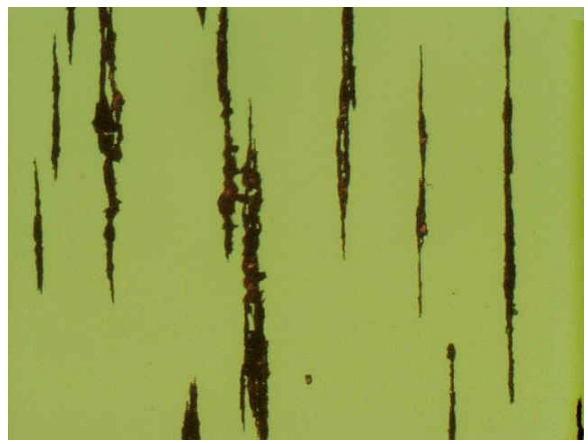
Used oil at 5,000 miles (100X), bus 73432



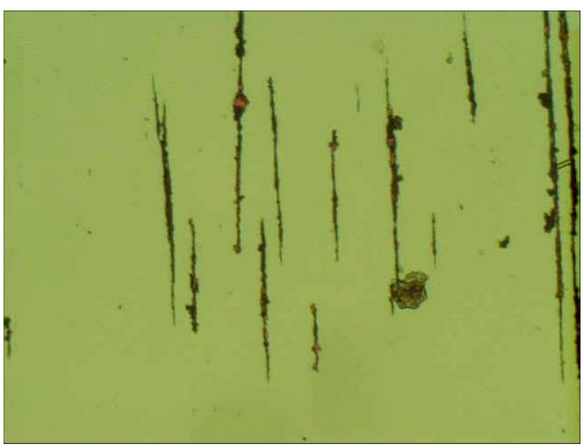
Used oil at 5,000 miles (100X), bus 73433



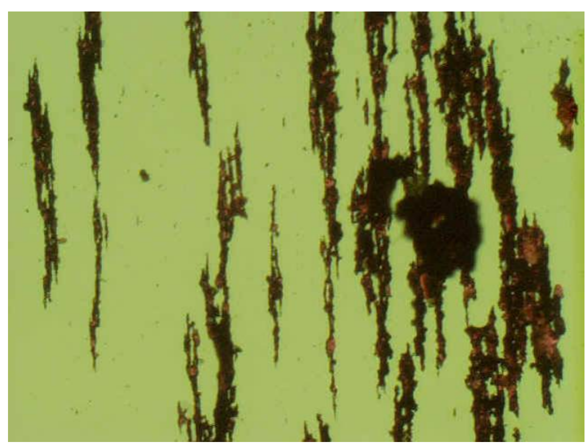
Bypass filter oil 5,000 miles (100X), bus 73432



Bypass filter oil 5,000 miles (100X), bus 73433

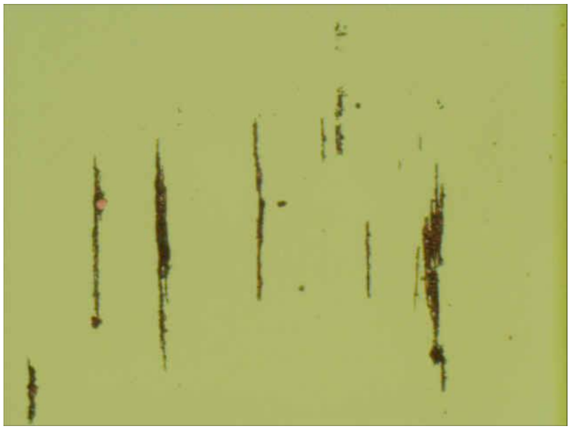


Full-flow filter oil 5,000 miles (100X), bus 73432

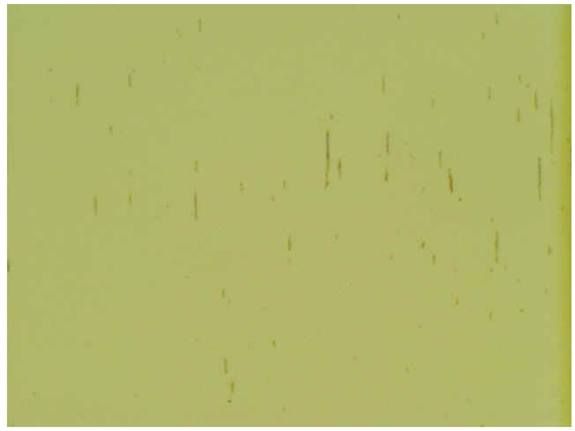


Full-flow filter oil 5,000 miles (100X), bus 73433

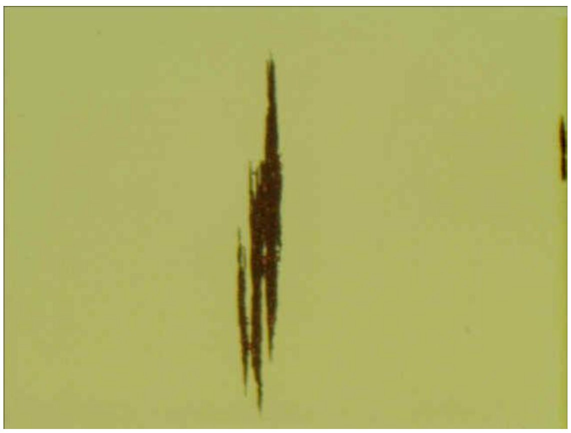
Figures 28. Comparison of used, bypass filter, and full-flow filter oil ferrograms (100X) at 5,000 miles.



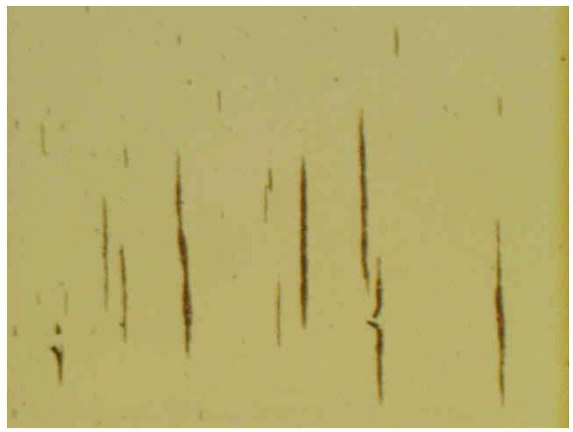
Used oil at 800 hours (100X), bus 73432



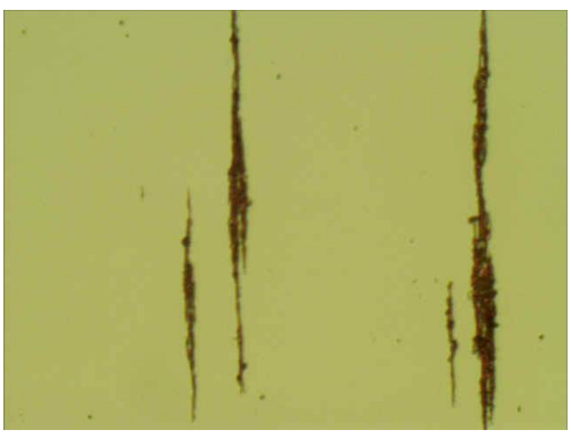
Used oil at 800 hours (100X), bus 73433



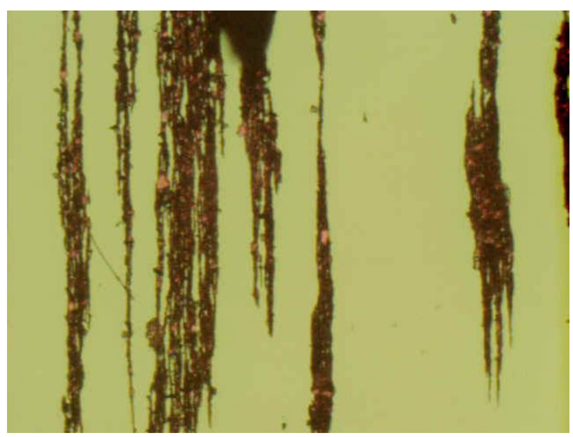
Bypass filter oil at 800 hours (100X), bus 73432



Bypass filter oil at 800 hours (100X), bus 73433

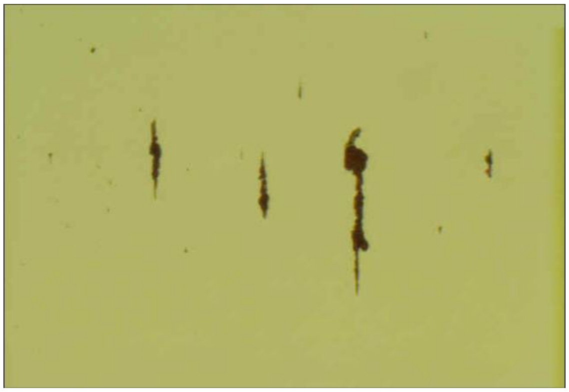


Full-flow filter oil at 800 hours (100X), bus 73432

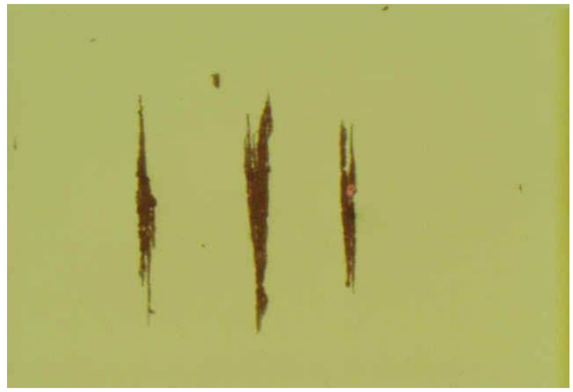


Full-flow filter oil at 800 hours (100X), bus 73433

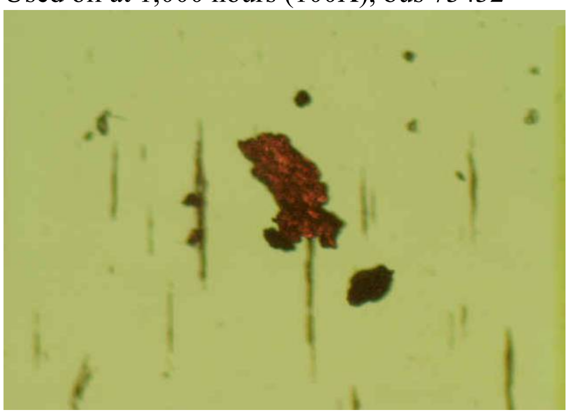
Figures 29. Comparison of used, bypass filter, and full-flow filter oil ferrograms (100X) at 800 hours.



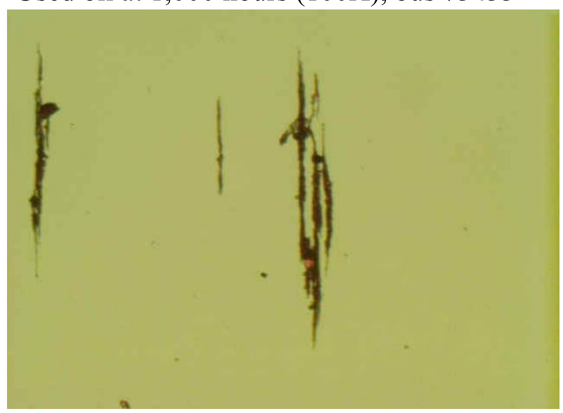
Used oil at 1,000 hours (100X), bus 73432



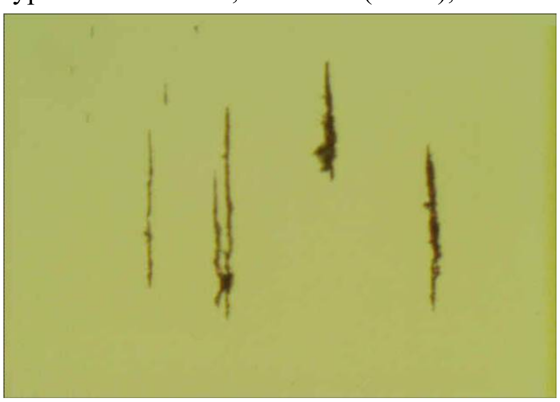
Used oil at 1,000 hours (100X), bus 73433



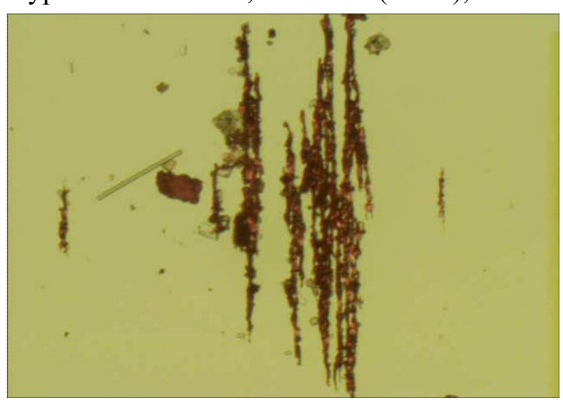
Bypass filter oil at 1,000 hours (100X), bus73432



Bypass filter oil at 1,000 hours (100X), bus 73433



Full-flow oil at 1,000 hours (100X), bus 73432



Full-flow oil at 1,000 hours (100X), bus 73433

Figures 30. Comparison of used, bypass filter, and full-flow filter oil ferrograms (100X), at 1000 hours.

3.6.8 Wear Particle Types

Another aspect of the analytical ferrography is characterization of the wear particle types. During microscopic analysis of the ferrogram, the tribologist (oil scientist) tracks or quantifies the wear particle types observed on the ferrogram in the following population ratings:

- 0 = None 2 = Trace 5 = Moderate 9 = Heavy.

These wear particle types include rubbing wear, severe wear, cutting wear, fatigue particles, laminar particles, spheres, dark metallo-oxide, red oxide, nonferrous metals, nonmetallic inorganics, and fibers. Not all of the particle types were detected in the ferrogram. Table 15 shows the population rating of the wear particle types of the used oil samples; the population of the bypass and full flow filter oil types, however, were normalized. Remember that the filter oil wear particle populations are based on a one-pound section of the filters, and to accurately represent the particle population, the number is adjusted or normalized. The normalized values are products of multiplying the population rating and ratio of the amount dissected from the filters.

Table 15. Normalized population values of wear particle types in used, bypass, and full-flow filter oils.

Wear Particle Types	Used Oil			Bypass Filter				Full-flow Filter			
	5,000	800	1000	5000	400	800	1000	5000	400	800	1000
Bus 73432											
Rubbing wear	4	4	4	154	86	86	86	45	70	25	45
Severe wear	9							3			
Cutting wear	1			10					11		
Fatigue particles	4	1		10				25	3	3	
Laminar particles	1	1				10			11	3	
Spheres	0										
Dark metallo-oxide	4	1		38	38	10	38	11	45	11	11
Red oxide	0	1							3		
Nonferrous metals	0										
Nonmetallic inorganics	36	4		86	38	10		11	70	3	
Fibers	1	25									
Totals	60	37		297	162	116	124	95	213	45	56
Bus 73433											
Rubbing wear	4	9	4	240	154	154	154	70	45	101	45
Severe wear											
Cutting wear	1			10			10	25	11	25	
Fatigue particles	4	1						11	3		
Laminar particles	1	1	1	38			38	25	11		
Spheres	1			10		10		3			
Dark metallo-oxide	4	4	1		38	10	38	25	25	45	11
Red oxide	1							3			
Nonferrous metals	1						10	3			
Nonmetallic inorganics	4	4	1	38	38	86	38	25	25	45	
Fibers	1	1	1								
Totals	22	20	8	336	230	260	288	190	120	216	56

The wear particle types for 400 hours were not conducted.

3.6.9 X-Ray Florescence Alloy Analysis

X-ray florescence is used to characterize the metal speciation trapped in the filter medium surface. Three metals were detected: iron, lead, and zinc. The amounts are shown in Figure 31. The iron and lead are wear metals, but zinc is an oil additive.

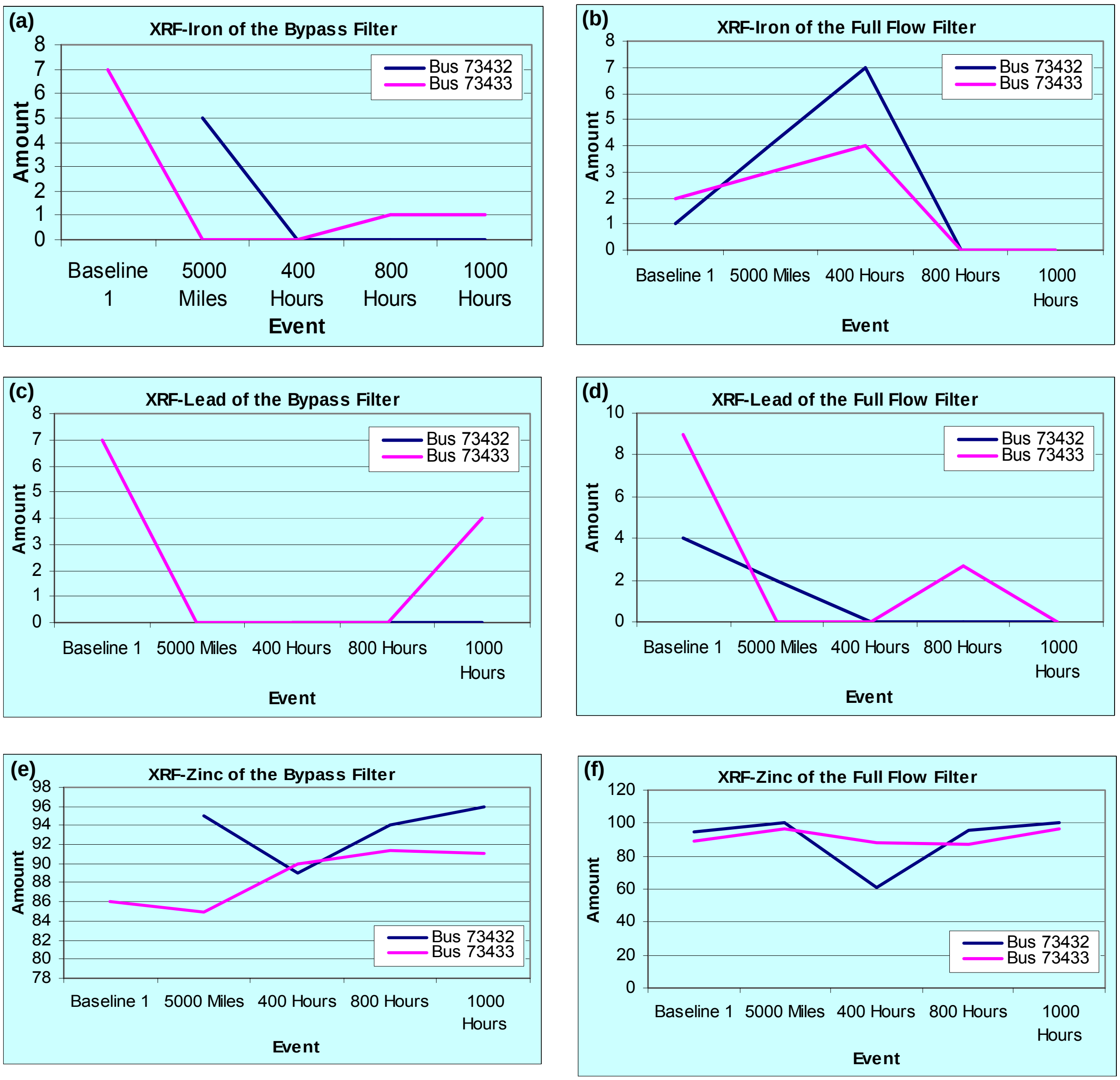
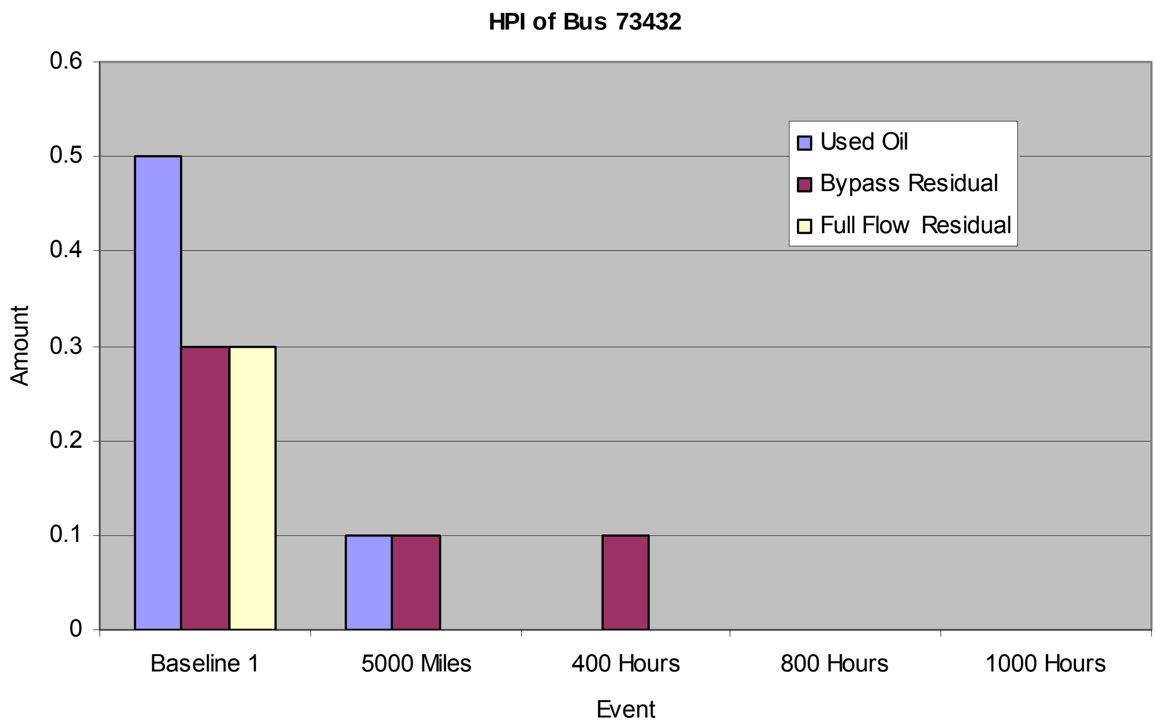
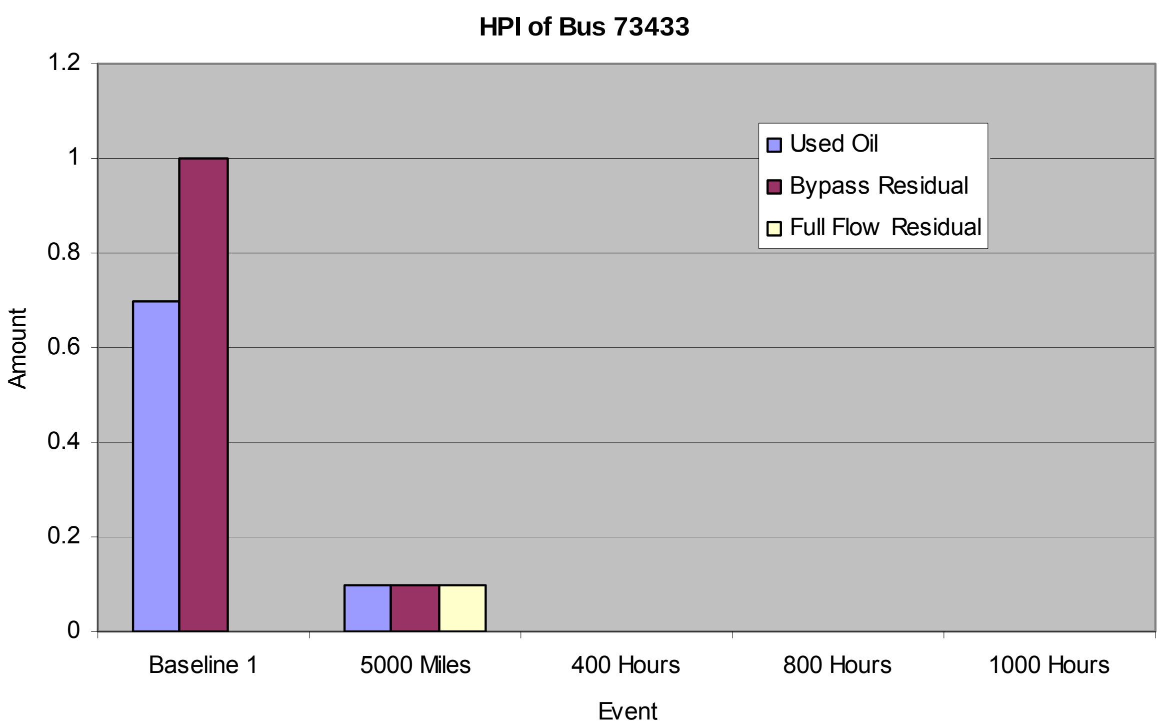


Figure 31. Metal speciation.

3.6.10 Heptane/Pentane Insoluble Analysis

The heptane/pentane insoluble analysis measures the quantity of insolubles suspended in the used oil. These tests showed a decreasing insoluble content—a positive trend—during the test. The results of these tests are shown in Figure 32.





Figures 32. Heptane/pentane insolubles for both test buses.

4. Notes on the Testing

The primary role of INL in this project was to ensure the buses were each safely idled for 1,000 hours and to collect oil samples and operation parameters, including idling times, engine speeds, and oil use. This has been accomplished. New West Technologies is analyzing the test results and their conclusions will be reported separately. However, several observations can be made about the idling project.

- The number of particles of all sizes generated during 1,000 hours of idling is less than after 5,000 miles of driving (Figure 25a)—a positive trend.
- The metals wear rate ratios of iron, lead, and copper were lower during idling (Table 12) than at 5,000 miles—a positive trend.
- Zinc, phosphorous, and calcium additive levels (Figures 22a and -c) and TBN values (Figure 23b) were all higher during idling than at 5,000 miles—a positive trend.
- Oxidation and nitration levels (Figures 24a and -b) were generally lower (improved) during idling than at 5,000 miles levels—a positive trend.
- Heptane and pentane insoluble levels (Figures 34a and -b) were lower during idling than at 5,000 miles—a positive trend.

As measured by the condition of the oils, the idling of the two bus engines appear to have been easier on the engines than during normal operations. Equating the 400 hours of idling to 12,000 miles of normal operations may not be accurate, based simply on engine revolutions, especially given that the 12,000 miles included what were likely to be heaver engine loads. Filter additives likely affected the results of the oil condition, but to what level is not known. Longer idling test hours may have provided better results, but funding did not make this possible.

When the buses were taken on their weekly road trips to blow out the carbon build-up, the bus drivers noted that the exhaust was “much more smoky” at the beginning of the runs. Also, an interesting anomaly occurred at the end of the testing. Both buses developed very rough downshifting from second to first gear. The INL bus mechanic explained this anomaly by saying the onboard computer has a learning mode, and it tries to mimic the drivers’ driving habits; also, the valves in the transmission tend to get sticky after lack of use. Both reasons are thought to have caused the very rough downshifting. After a couple of days of operation, the transmissions operated normally.

5. Appendices

Appendix A—Suit of Tests by the Idaho National Laboratory

Appendix B—Example of a Manual Log Sheet

Appendix C—Oil Analysis Report

Appendix D—Summary of Daily Logs

Appendix F—Filter Change-out History

Appendix G—Laboratory Engine Oil Reports

Appendix H—Destructive Filter Analyses

Appendix I—Examples of Weekly Oil Analysis Reports

Appendix J—Oil Analysis Reports from the Diesel Engine Idling Test

Appendix K—Ferrograms