CRC Report No. DP-04-22-1B

Internal Diesel Injector Deposit (IDID) Test Rig Precision – Solve Decay of Deposit Level with Time

Final Report

June 2026

COORDINATING RESEARCH COUNCIL, INC.
1 CONCOURSE PARKWAY • SUITE 800 • ATLANTA, GA 30328

The Coordinating Research Council, Inc. (CRC) is a non-profit corporation supported by the petroleum and automotive equipment industries with participation from other industries, companies, and governmental bodies on research programs of mutual interest. CRC operates through committees made up of technical experts from industry and government who voluntarily participate. The five main areas of research within CRC are: air pollution (atmospheric and engineering studies); aviation fuels, lubricants, and equipment performance; heavy-duty vehicle fuels, lubricants, and equipment performance (e.g., diesel trucks); light-duty vehicle fuels, lubricants, and equipment performance (e.g., passenger cars); and sustainable mobility (e.g., decarbonization). CRC's function is to provide the mechanism for joint research conducted by industries that will help in determining the optimum combination of products. CRC's work is limited to research that is mutually beneficial to the industries involved. The final results of the research conducted by, or under the auspices of, CRC are available to the public.

LEGAL NOTICE

This report was prepared by SwRI as an account of work sponsored by the Coordinating Research Council (CRC). Neither the CRC, members of the CRC, SwRI, nor any person acting on their behalf: (1) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report, or (2) assumes any liabilities with respect to use of, inability to use, or damages resulting from the use or inability to use, any information, apparatus, method, or process disclosed in this report. In formulating and approving reports, the appropriate committee of the Coordinating Research Council, Inc. has not investigated or considered patents which may apply to the subject matter. Prospective users of the report are responsible for protecting themselves against liability for infringement of patents.

Internal Diesel Injector Deposit (IDID) Test Rig Precision – Solve Decay of Deposit Level with Time

CRC Project No. DP-04-22-1B

FINAL REPORT

Prepared for:

Coordinating Research Council, Inc.
1 Concourse Parkway, Suite 800
Atlanta, GA 30328

Prepared by:

G. Hansen

Southwest Research Institute® (SwRI®)
San Antonio, TX

June 2026

Reviewed by:

Kevin Shannon

Kevin Shannon, Manager
Fuels & Lubricants Technology Department

Approved by:

Scott Hutzler

Scott A. Hutzler, Director
Fuels & Lubricants Technology Department

EXECUTIVE SUMMARY

This report documents the findings and developments from the Coordinating Research Council (CRC) Project No. DP-04-22-1B, focusing on improving the precision and repeatability of the Internal Diesel Injector Deposit (IDID) Test Rig. Southwest Research Institute® (SwRI®) conducted this project under the sponsorship of the CRC to address issues related to deposit growth and its evolution over time.

The primary goal of this project was to refine and enhance the capability of the IDID test rig to generate consistent, quantitative results for evaluating deposit formation on diesel injectors using both sodium-doped and undoped fuels. Throughout the program, significant modifications were made to the IDID rig to improve its operational accuracy including mechanical adjustments, instrumentation and controls, and procedural updates. These changes addressed the major sources of variability as seen in previous testing programs.

A matrix of tests was conducted under varying conditions to evaluate the impact of fuel dopants, injector duty cycles, and other operational parameters on deposit formation. The tests were divided into distinct phases, given that the modifications to the rig created differences in the testing protocol and results over time. Tests #11–17 were unique compared to earlier experiments due to the cumulative adjustments and improvements.

The rig successfully produced distinguishable deposit layer variations using different fuel formulations, including thick hydrocarbon deposits with sodium-doped fuel. Deposit growth rates varied significantly under different conditions, emphasizing the need for further refinement in methodologies. As deposit thickness increased, interpreting optical data became more complex due to changes in composition and layer characteristics. SwRI collaborated with specialists to develop advanced models to analyze this data, though proprietary constraints limited inclusion of model details.

Key Findings:

- Small changes in test rig hardware preparation can have a significant impact on results
- Robust and thick deposits can be achieved on the pintle
- Deposit chemistry is dependent on temperature
- VASE analysis of film thickness is model (chemistry) dependent
- At optimal conditions, dopant has a significant impact on deposit formation

Key Recommendations:

- Determine a test temperature and dopant level which maximizes the measurable difference between doped and un-doped fuel
- Perform a repeatability study at optimal conditions

TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

CLyy-xxxx	SwRI Chemistry Lab Sample ID (yy = year, xxxx = sample number)
CRC	Coordinating Research Council
DDSA	Dodecenyl Succinic Acid
ETR	Ellipsometric Tube Rating
IDID	Internal Diesel Injector Deposit
JFTOT	Jet Fuel Thermal Oxidation Test
MSE	Mean Squared Error
SwRI	Southwest Research Institute
VASE®	Variable Angle Spectroscopic Ellipsometer

1.0 INTRODUCTION AND OBJECTIVE

High pressure common rail diesel fuel injection systems have experienced internal diesel injector deposits leading to injector sticking and loss of engine performance. Test methods are needed to evaluate the effects of fuels and additives on deposit formation in fuel injection systems. Phase 1 of this project evaluated the effect of fuels doped with additives on deposit formation in two injector test rigs. Some good results were found, but at least one major problem was encountered: there was a systematic decay of deposit thickness with time. Phase 1B was intended to perform additional testing to solve this problem before consideration of proceeding to the Phase 2 study.

Previous CRC studies of Internal Diesel Injector Deposits (IDID) were performed using various methods, additives, and doping rates with measurement of deposit thicknesses ranging from 2 to over 500 microns.

The initial objective of this project was to perform scoping tests to identify test procedures and conditions suitable to produce repeatable deposits in the fuel injector deposit test rig. Suitable results should feature time-stable deposit thickness, not systematic decay of deposit thickness with time as observed in Phase 1.

Initial rig testing should be performed identically as in Phase 1 with the following differences:

- All testing was performed using one test rig instead of two rigs as in Phase 1.
- Test run time of 7 hours was used in Phase 1. In Phase 1B, test run times of 7, 14 and 21 hours were evaluated for initial runs before deciding on preferred duration for subsequent testing. All test variables were determined by consultation between the CRC project panel and SwRI personnel.
- A fresh batch of fuel was prepared before each run from original additive solutions, not from a pre-mixed concentrated “master” solution as was done in Phase 1.

Disclaimer: It is not the purpose of this series of CRC studies to assert or point out strengths or weaknesses of particular additives or their suitability for any application. The additives used in these studies were chosen for their known effect of producing surface deposits when combined with sodium contamination. Therefore, these additives were chosen to study the ability to produce and characterize IDID in a repeatable manner to develop test methods to produce and measure IDID. The CRC rig test conditions are intentionally harsh, with elevated levels of additives and contaminants to accelerate deposit formation. However, these conditions do not accurately reflect real-world driving conditions or typical additive concentrations, (normal field concentrations are usually orders of magnitude smaller) and presence of contaminants (sodium contamination is not expected in normal field application).

2.0 SUMMARY OF CHANGES MADE TO IDID RIG #1

These changes are categorized as mechanical (rig hardware), operational (controls, instrumentation), and procedural (chemicals & blending).

With the goal of improving precision of the IDID test rig, a systematic approach was taken for evaluation of every major component. This process continued through the first 12 tests of this 17-test project, and resulted in what is essentially a fully rebuilt test rig. Some major issues with operability, maintenance, and correlation of instrument data were observed in both the previous testing program and early tests in this program.

2.1 Mechanical

The largest mechanical change to the rig was a redesign of the heater body/fuel capture cup. The first iteration had some manufacturing errors that resulted in sealing problems and retained fuel volume in the capture cup. This version corrected those issues with a more robust design, and a smaller volume for the capture cup. The heater body was also redesigned to bring the injector mounting bolts significantly toward the injector. This allowed the new injector bracket to apply a greater force on the copper washer between the injector body and the bottom of the hole in the heater body. The redesigned assembly can be seen in figure 1.

This higher force on the sealing washer also allowed observation of the degree of sealing on both sides of the washer face. The high temperatures and presence of fuel caused oxidation and deposits on the copper washer where sealing pressure was low. A custom lapping tool was manufactured to ensure the bottom of the hole was flat, and the copper washers used in testing were sanded flat to within 0.0005" end-to-end thickness tolerance. On an engine, this is typically not an issue as the mounting bolts are immediately adjacent to the injector and can apply a much larger force on the injector bracket, but in this rig, design priority was given to the heater elements for optimal thermal conditions. A picture of the washer can be found in figure 2.

The fuel filter was also removed from the system to prevent unwanted reactions between the filter element and the fuel additives. To provide a similar level of fuel cleanliness, several drums of diesel fuel were filtered to a determined particle count result and then set aside for this project.

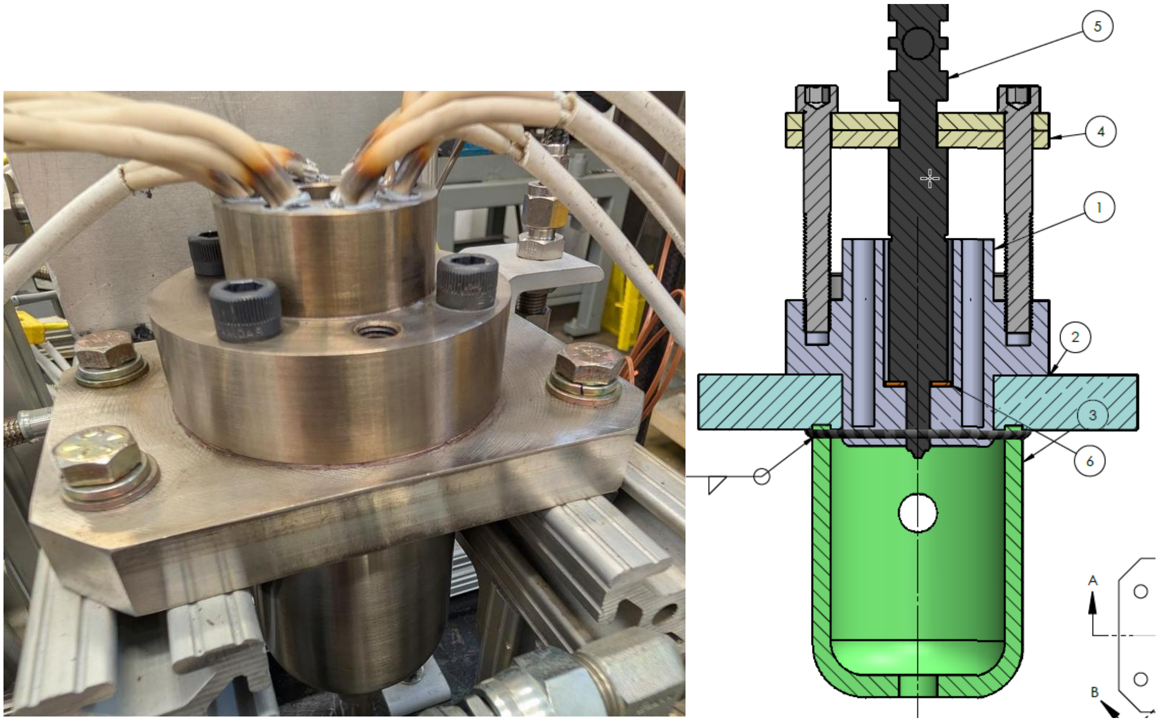


Figure 1: New Heater Body & Fuel Capture Cup Assembly

Figure 2: Sanded Copper Sealing Washer

2.2 Instrumentation and Controls

The largest change in instrumentation was replacing the mass balance system with a positive displacement volume flowmeter for determining injected fuel. The mass balance system had issues that could not be overcome. The maximum capacity of the balance was 30 kg, and the published accuracy was 0.2 grams. A measurement signal was sent every 10 seconds, and at a nominal flow of 5 g/min, this signal should have been around 0.8 grams. However, temperature variations and turbulent flow inside the vessel on the mass balance produced signals between 0 and 2.5 grams (a coefficient of variation, COV, as high as 300%).

The new flowmeter was installed on the gravity-drain from the fuel capture cup. This presented new challenges to overcome. A significant volume of fuel vapor exists in the capture cup. A custom inline heat exchanger was made to condense most of the vapors and recombine the droplets into a fluid stream. The remaining uncondensed vapor is allowed to flow into a chilled recovery column, which then recombines the output prior to the flowmeter. To convert the measured fuel volume into mass, a thermocouple measured fuel temperature at the flow meter. The test fuel was measured for density versus temperature via ASTM D4052 and those results are in a lookup table in the data analysis program. The COV for the new flowmeter is consistently less than 60%.

It was decided to add fuel temperature control at the pump inlet to increase the thermal stress and (potentially) the pintle deposit amount. This system required additional control valves and heat exchangers. A schematic can be seen in figure 3. Fuel temperature into the pump can now be easily varied between ambient and 60 °C.

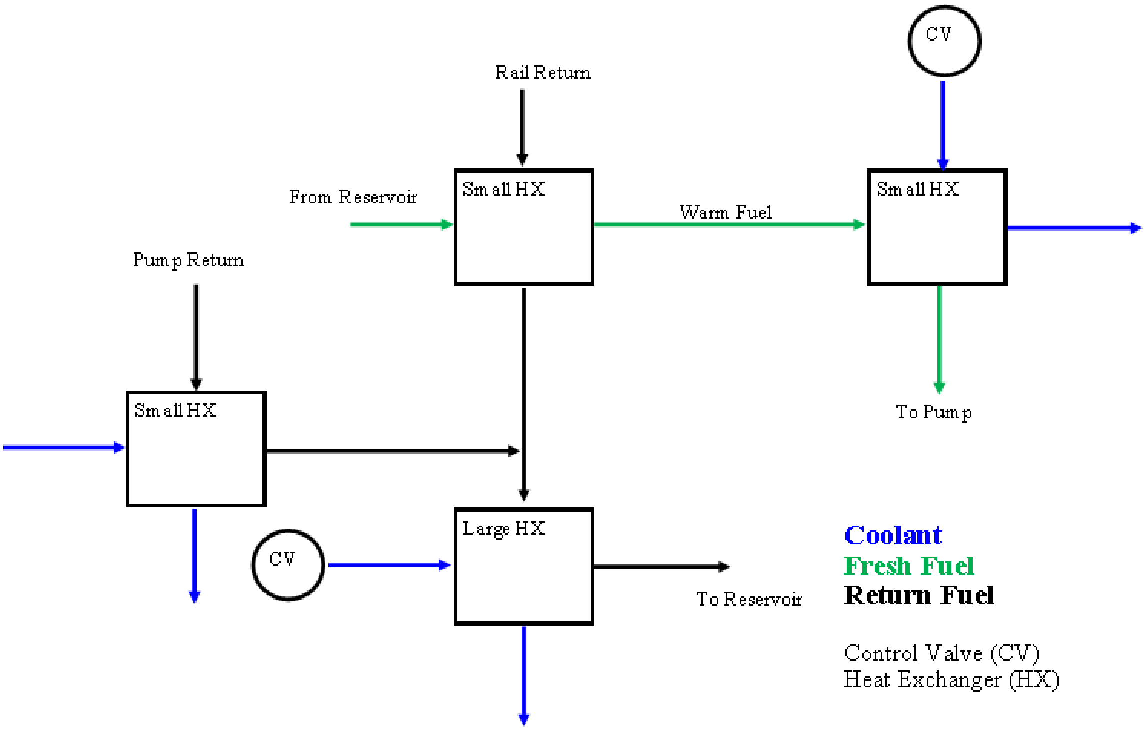


Figure 3: Pump Inlet Fuel Temperature Control Schematic

The injector utilizes a single shot duty cycle driver to control the fuel flow. Previous testing programs prompted an operator to adjust this value manually on a fixed evaluation period using a series of estimates for what the new value might be. This led to both under and overshooting the flow target of 5 g/min and contributed significantly to imprecision in the overall test. An automated injector driver control based on a long-term moving average of fuel flow was implemented. This control was based on many tests worth of data and resulted in nominally consistent fuel flow for the 7-hour test.

In conjunction with the copper sealing washer, the thermocouples on the injector were also modified to solve a temperature control issue. It was observed during the first 12 tests of this program that there was almost no correlation between the heater body temperature and the injector temperature. This indicated that heat transfer to the nozzle was inconsistent and there was a potential problem with the thermocouples. On close investigation, it was discovered that the surface mount thermocouples were incapable of measuring higher than 218 °C and when the heater body exceeded 240 °C, the insulation on the thermocouples melted.

The 218 °C limit corresponded to the melting point of the solder used to join the twisted thermocouple wires. This was remedied by removing the factory tips, dry twisting the wires, and then spot welding them together. The melting insulation issue caused junction creep and grounding issues. This was remedied by untwisting the insulated portion for 6 inches and installing a layer of Kapton tape between the thermocouple wires and the injector body. A reference image of the injector can be found in figure 4, and a picture of the final surface mount thermocouple solution is shown in figure 5.

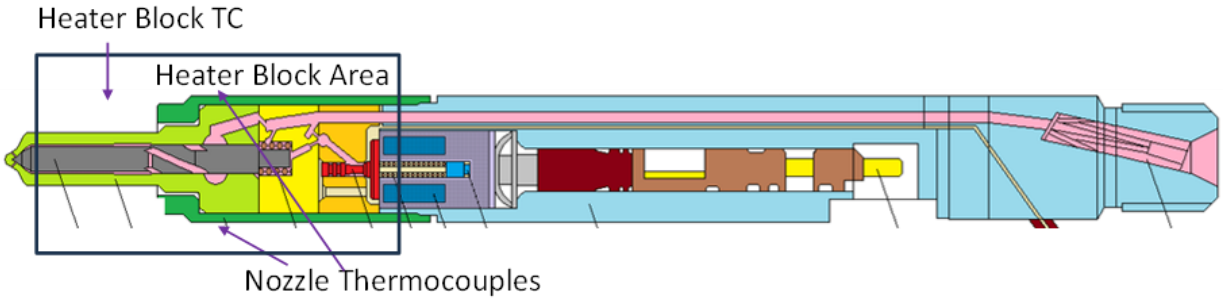


Figure 4: Cutaway Reference for Thermocouple Placement

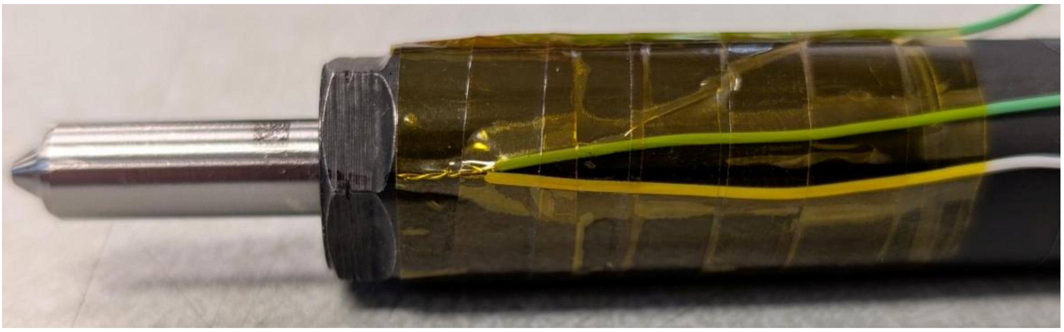


Figure 5: Installed Thermocouples Near Injector Tip

2.3 Procedural

As previously mentioned, there is a new preparation step for the base fuel in this program. The fuel is clay treated and then filtered until a predetermined particle count (less than 100) is achieved via ASTM D8166. The fuel blending procedures have also been updated so that each test fuel is made from pure reagents and not premix blends. For instance, the sodium naphthenate is measured out and dissolved into 1 L of the test fuel on a stir plate for 30 minutes. It is then mixed into an additional 7 L of test fuel to make the final volume of 8 L.

The previous method of flushing the rig used a fixed amount as measured by the mass balance. This flushing procedure was averaged over several tests and found to be almost 2 minutes in length. The new flowmeter only measures injected fuel and is not involved with the rig flush step, where the injector is not firing, and all return flows are directed away from the supply tank to a disposal canister. The new flushing procedure is simply to run the rig in flush configuration for a total of 2 minutes at fixed pump speed and fixed rail pressure. This flushing ensures any residual fuel in the system and lines is replaced by the new test fuel prior to start of injection.

3.0 TEST CONDITIONS

3.1 Fuel and Additives

The fuel used for this program is EPA 2007 Certified ULSD. It is a new batch as of April 08, 2025. The COA can be found in Appendix A.

The additives used in this program were Dodecenyl Succinic Acid (DDSA), and Sodium Naphthenate. The concentration of sodium refers to the elemental amount of sodium, not the molecular amount of sodium naphthenate.

3.2 Condition Matrix

Table 1. Test Conditions

Run#	Na (mg/kg)	Pump T (°C)	Nozzle T (°C)	Time (hr)
1	2	30	200	7
2	2	30	200	14
3	2	30	200	21
4	3	45	210	7
5	4	30	200	7
6	2	45	200	7
7	2	60	200	7
8	2	30	210	7
9	2	45	220	7
10	4	60	220	7
11	2	30	200	7
12	2	60	220	7
13	4	45	210	7
14	4	30	200	7
15	4	60	220	7
16	2	60	190	7
17	2	45	180	7

The test conditions are seen in Table 1. The first three tests attempted to determine a response of deposit versus test time. The purpose of tests 4 through 17 was to reliably increase deposit formation and see what trends existed in relation to temperatures. Many of these points were repeated as rig changes and improvements were made.

All tests are operated at an injected fuel flow setpoint of 5.0 grams per minute and a rail pressure of 1800 bar.

4.0 INJECTOR DEPOSIT EVALUATIONS

VASE® Ellipsometry: VASE® is a registered trademark of the J.A. Woollam Co. (Woollam), Lincoln, NE. Dr. Woollam is the acknowledged industry leader in understanding the use of spectroscopic ellipsometry. As the contractor that performed prior CRC projects, a VASE® instrument is available at SwRI for evaluating injector needle deposit thicknesses.

Further refinements in analysis were made during this program, which included a substantial increase in the number of data points collected along the pintle shaft, and an increase in the number of radial segments analyzed. This was done to provide a 3-dimensional map of the pintle surface, similar to how the JFTOT® ETR provides results.

As the deposits grew thicker towards the end of the program, additional consultation with J.A. Woollam Co. was required. The shapes of the optical data change significantly with both composition and thickness. They were able to provide SwRI with additional models to fit the data and provided guidance on when to use each model type. A final analysis of each data set is provided in this report, but due to intellectual property concerns, the model details will not be included.

5.0 IDID RIG CHANGE LOG

Much of the detailed test data is not relevant to the results as changes to the test rig, instrumentation, and controls occurred throughout this program. Tests 11 through 17 were effectively different tests than tests 1 through 10 and any prior IDID tests performed for CRC. A short timeline summary of changes is provided.

Prior to test 1:

- Fuel leaks were minimized by welding several parts of the collector cup which were on threaded connections
- A check valve was added to the nitrogen supply line
- Fuel filter was removed from system
- New fuel blending procedures

Prior to test 2:

- VASE fidelity increased – total number of data points

Prior to test 4:

- Operational controls for automated injector duty cycle adjustments implemented

Prior to test 5:

- Flow meter was added

Prior to test 7:

- Custom fuel cooler added to injected flow drain

Prior to test 10:

- Vapor condensing column added to injected flow drain

Prior to test 11:

- Mass balance removed from system – full transition to flowmeter control
- New heater & capture cup assembly
- New fuel tank
- New fuel temperature control system (pump inlet)
- Injector thermocouple situation resolved
- Thermocouple added to flowmeter for volume to mass conversion
- Heat transfer issues resolved with sanding/lapping of injector washer sealing surfaces

6.0 DEPOSIT THICKNESS MEASUREMENT AND MATRIX TEST INJECTOR DEPOSIT RESULTS

The VASE® is a non-destructive technique that uses polarized light to measure films/deposits at a specified angle of incidence. As the polarized light interacts with the film, the light may undergo a measurable change in polarization dependent on the properties of the film. The changes are captured in the form of two variables, ψ (amplitude component) and Δ (phase change), which are each a function of wavelength. A data model is then generated to fit the experimental data to calculate the film thickness. Some of the variables utilized in the modeling are refractive index, UV contribution, and IR contribution. The typical output from a model consisted of the deposit thickness and a measure of the modeling error in the form of a mean squared error (MSE).

MSE is the difference between the optical model used, and the optical data Psi (Ψ) and Delta (Δ). Some optical data can be easily fit using a 3rd order curve or a B-spline. Some data, especially with thick, or semi-opaque layers, needs very advanced models. If the optical data presents as having many peaks and valleys and a wide range of amplitudes, the MSE is unlikely to be small regardless of how quickly the model converges to a solution. The engineering units for MSE are degrees, which does not correlate with the deposit thickness in nanometers.

One important factor discovered in this program was the length of time between disassembly of the injector and measurement of the pintle. There needs to be a minimum of 12 hours between these events to allow the surface deposit to fully dry. The VASE® is incapable of providing consistent results (scan to scan) from wet films that are outgassing. After disassembly, the pintles are rinsed in isooctane and placed in a clean glass 5 mL container with the lid not fully tightened. After a 12-hour rest period, the pintle can be measured accurately and the lid can be sealed for storage after measurement.

6.1 Numerical Results

Table 2. VASE® Results Tests 1 through 10

	Avg. Deposit (nm)	StDev	Max Deposit Depth (nm)	Average MSE
Run1	20.8	7.6	65.6	2.2
Run2	25.5	5.8	45.6	2.5
Run3	26.9	7	67.2	2
Run4	57.6	31.8	133.2	5.6
Run5	37.5	6.3	58.3	2.4
Run6	38.2	6.7	64.1	2.2
Run7	36.7	4.6	48.1	2.3
Run8	211.1	62.5	463.1	51.4
Run9	110.8	45.4	285.3	37.8
Run10	42.9	10.4	77.5	2.5

Table 3. VASE® Results Tests 11 through 17

	Avg. Deposit (nm)	StDev	Max Deposit Depth (nm)	Average MSE
Run11	462.8	70.1	735.0	47.1
Run12	1493.0	1110.9	8606.7	65.6
Run13	1482.2	709.6	5267.0	44.4
Run14	537.8	247.4	1782.7	63.5
Run15	1368.2	542.7	3773.1	64.6
Run16	835.5	378.3	2770.9	49.2
Run17	n/a			

6.2 Data Analysis

In the VASE® images, the slice# refers to a radial position and is indexed to a randomly chosen pintle flute, as seen at the far right of Figure 23. The position indicates approximate distance from the pintle flutes – the measurements start near the flutes and move towards the tip. Deposit depth is determined by model interpretation of optical data. Please note, color scales and depth axis are unique for each image.

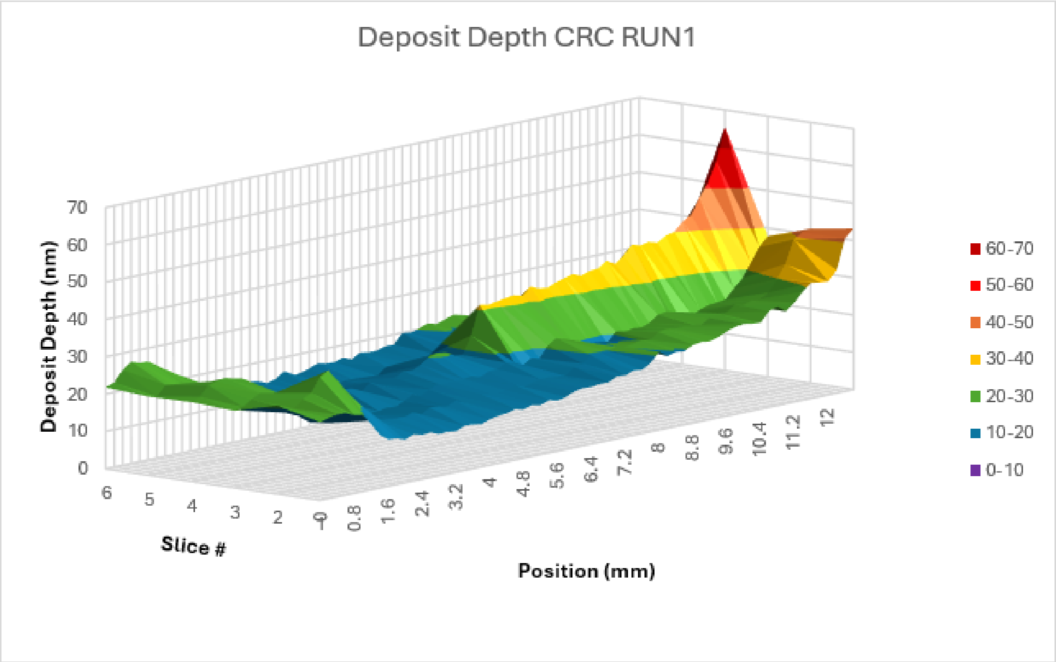


Figure 6. Run 1 Deposit Depth

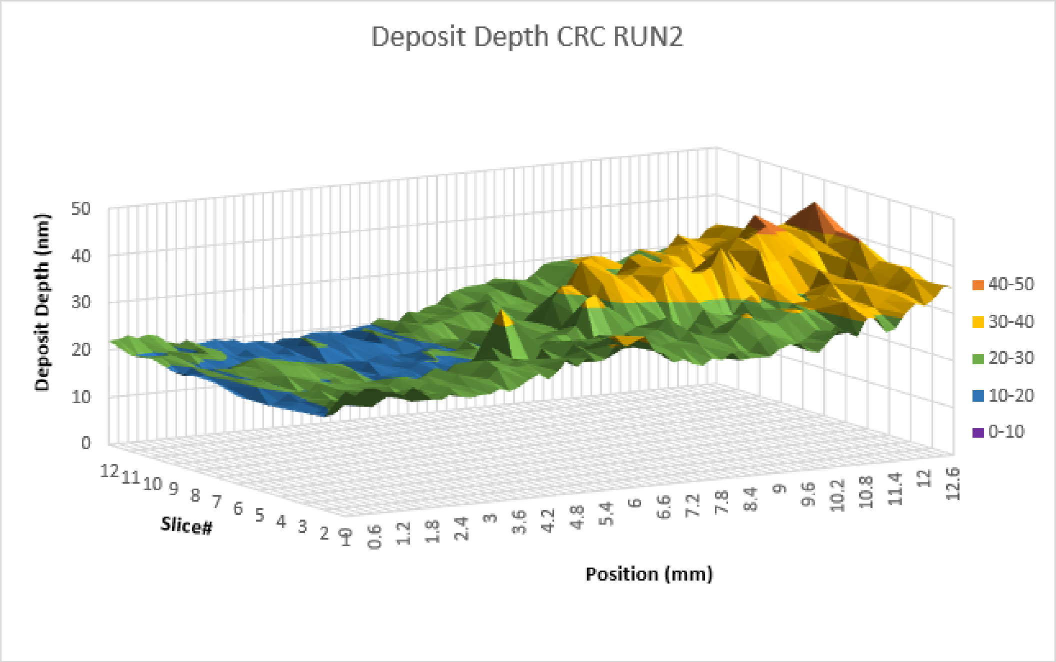


Figure 7. Run 2 Deposit Depth

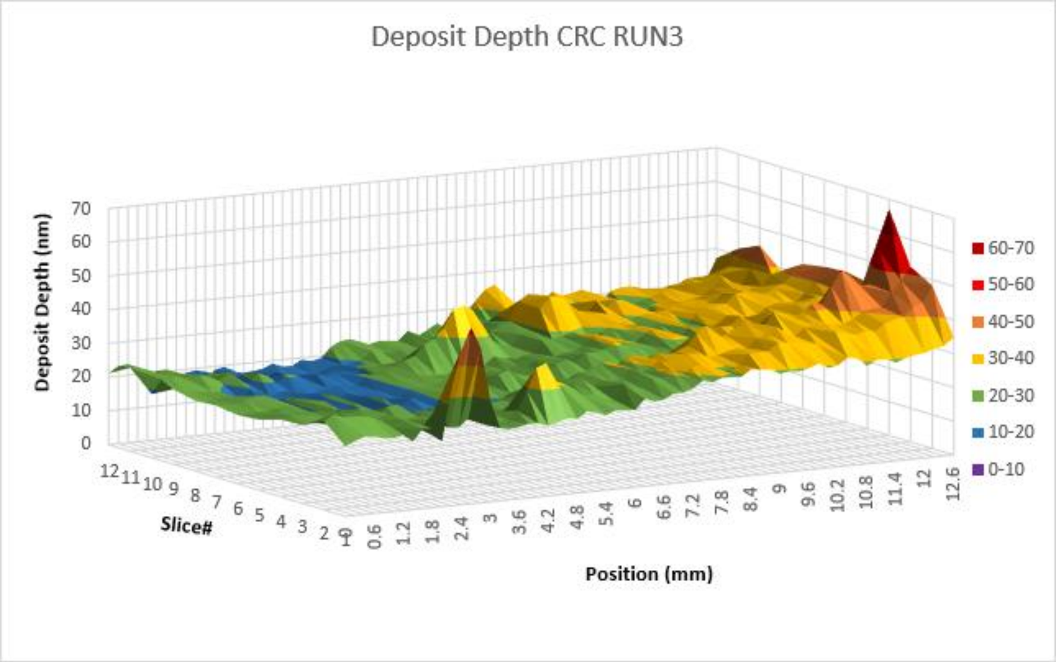


Figure 8. Run 3 Deposit Depth

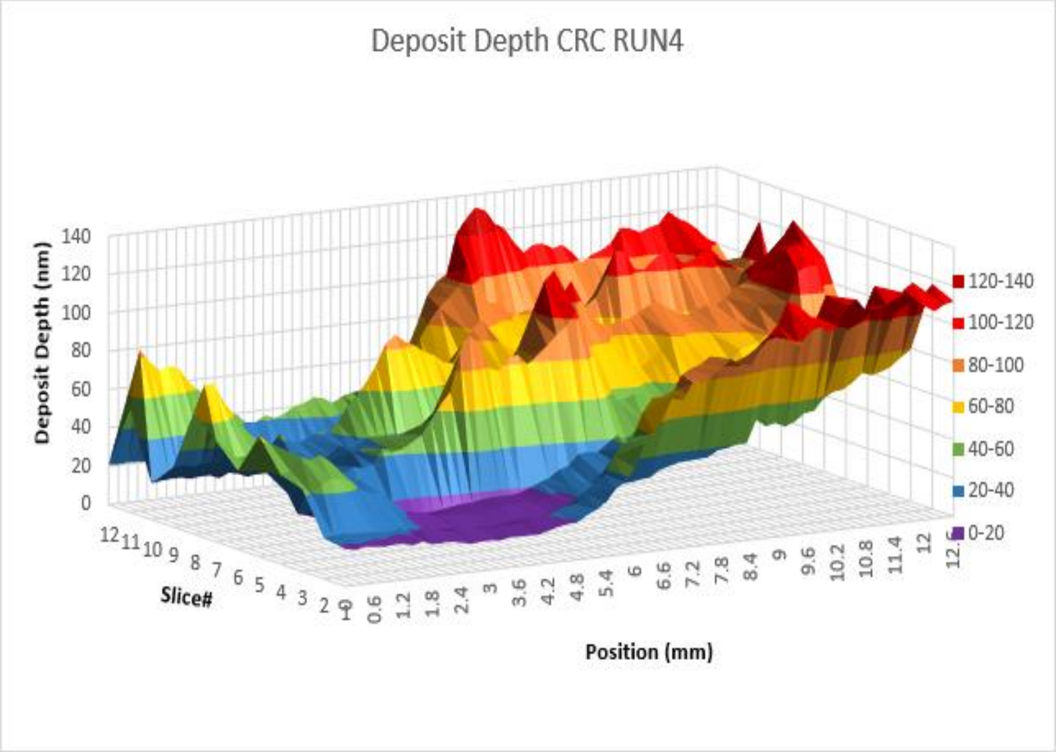


Figure 9. Run 4 Deposit Depth

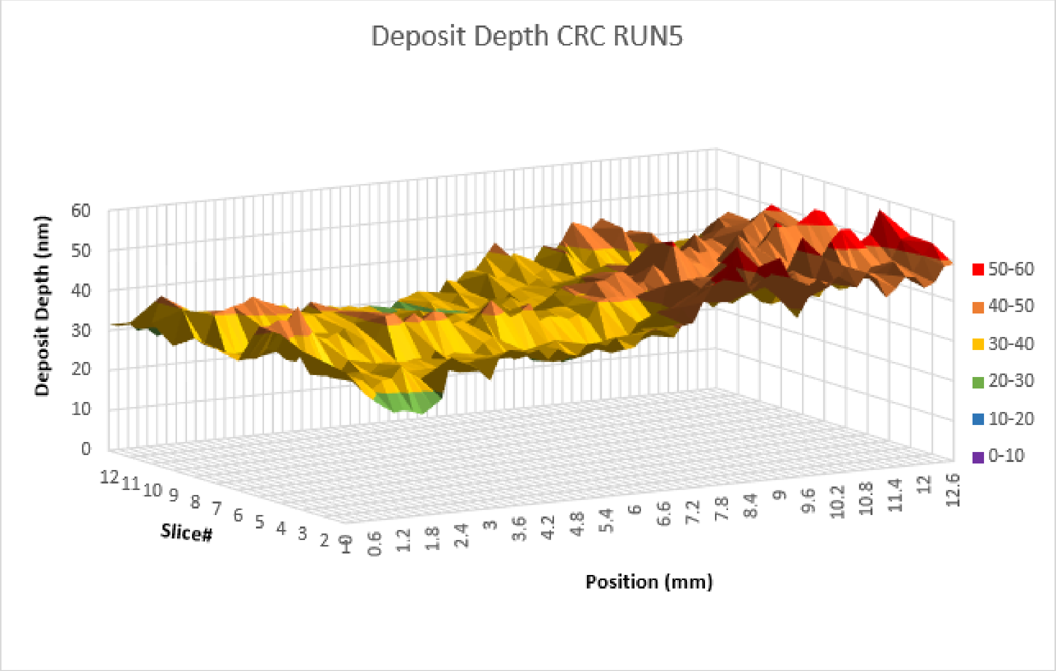


Figure 10. Run 5 Deposit Depth

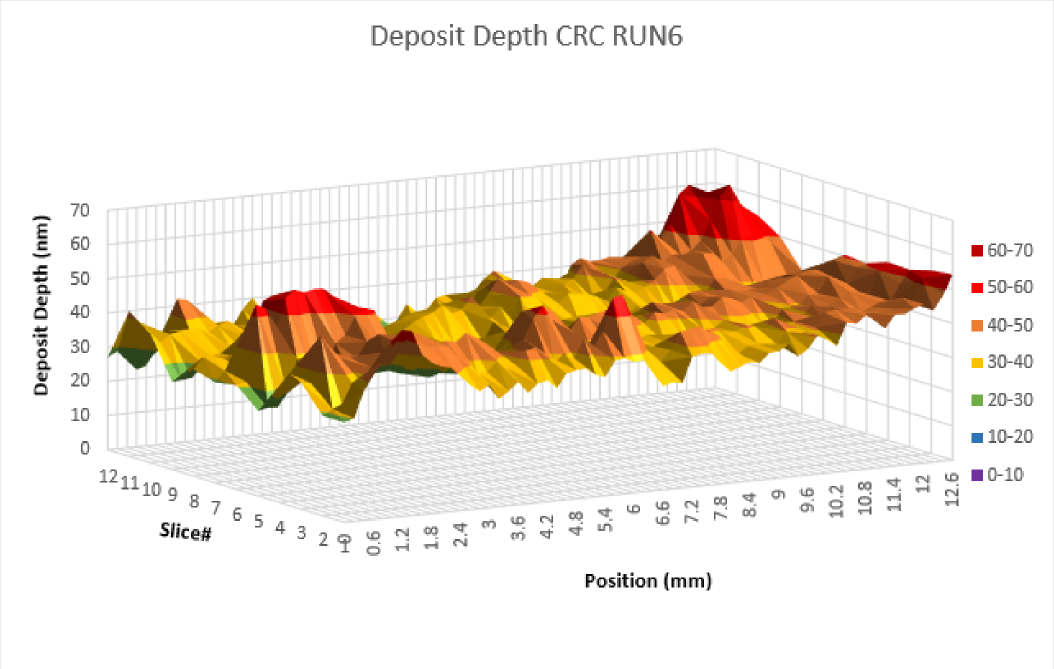


Figure 11. Run 6 Deposit Depth

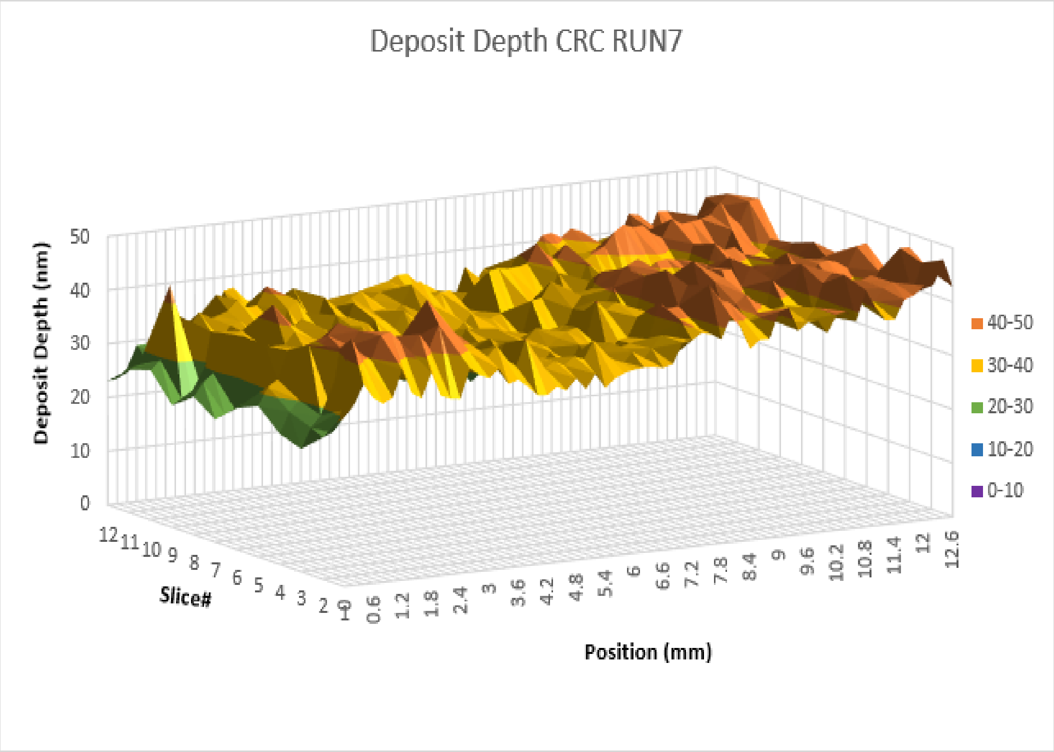


Figure 12. Run 7 Deposit Depth

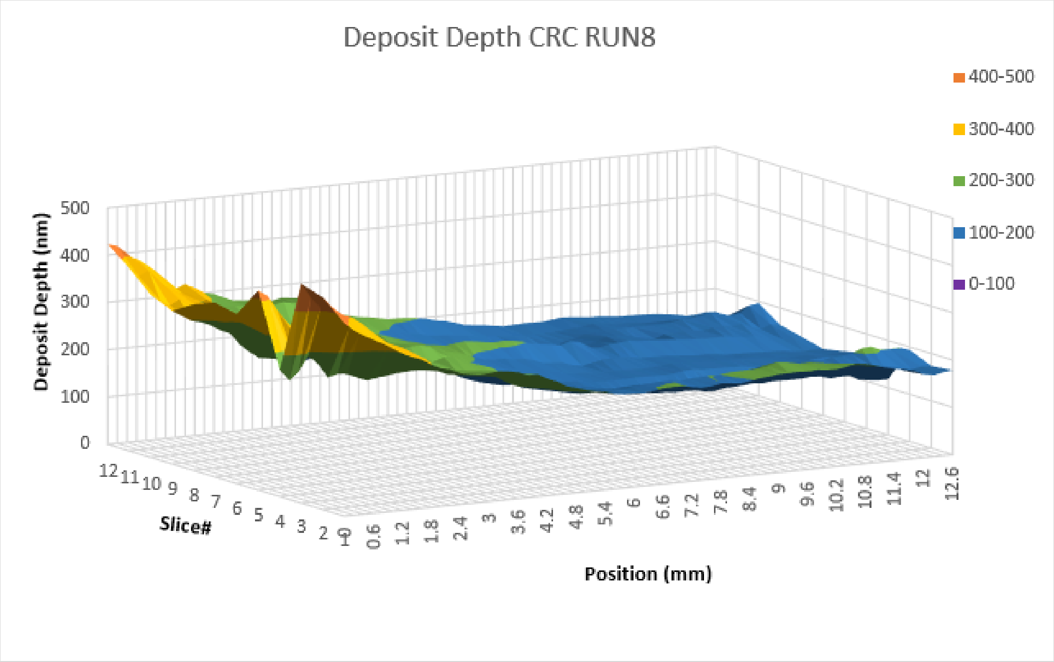


Figure 13. Run 8 Deposit Depth

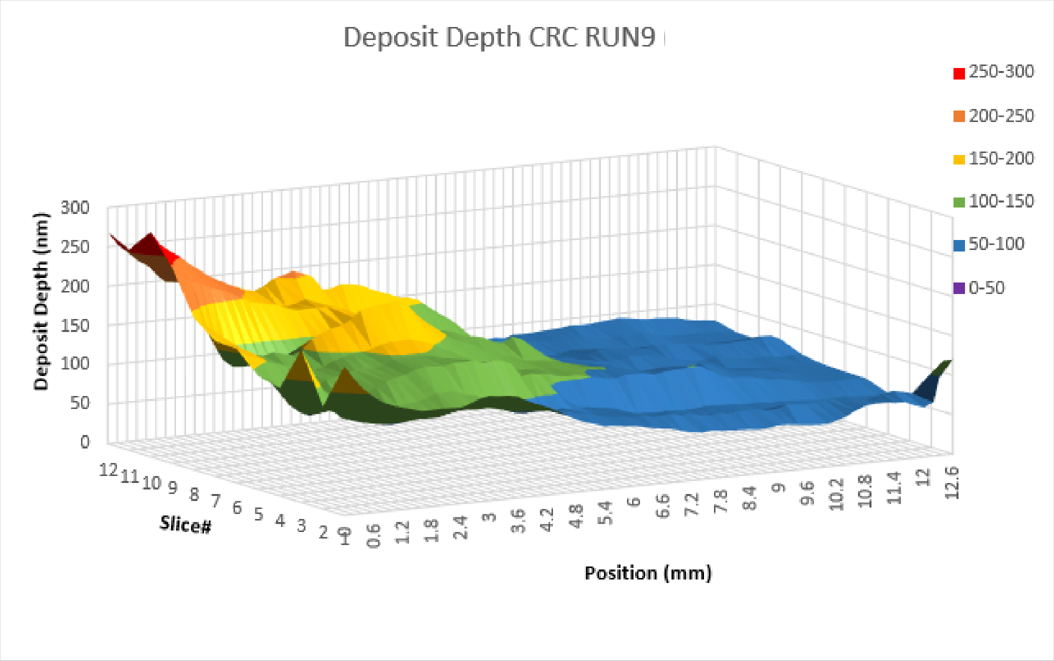


Figure 14. Run 9 Deposit Depth

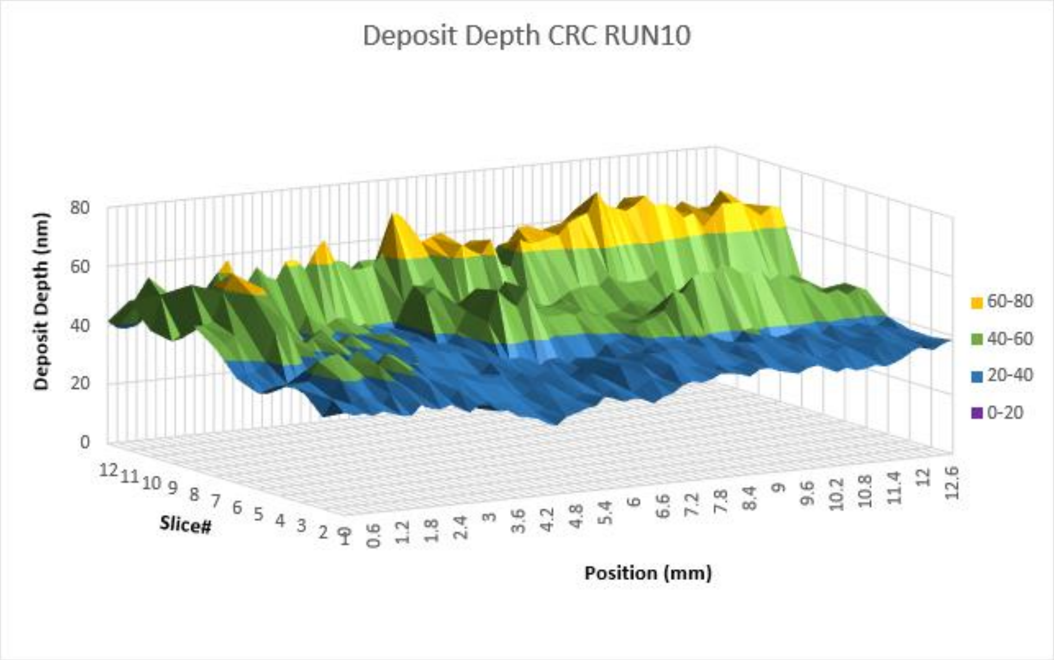


Figure 15. Run 10 Deposit Depth

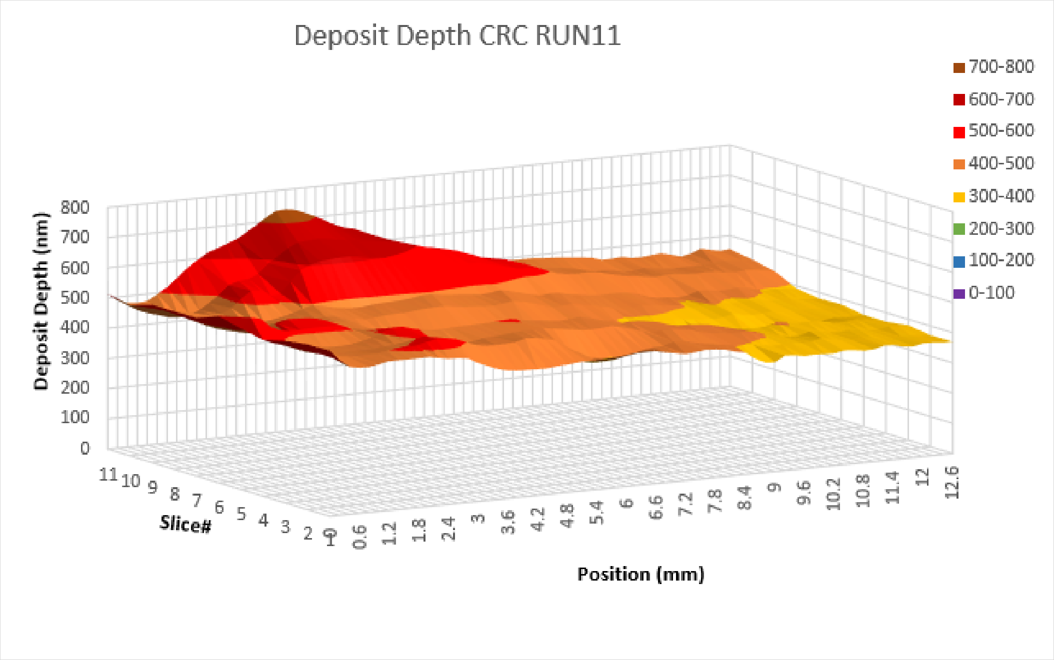


Figure 16. Run 11 Deposit Depth

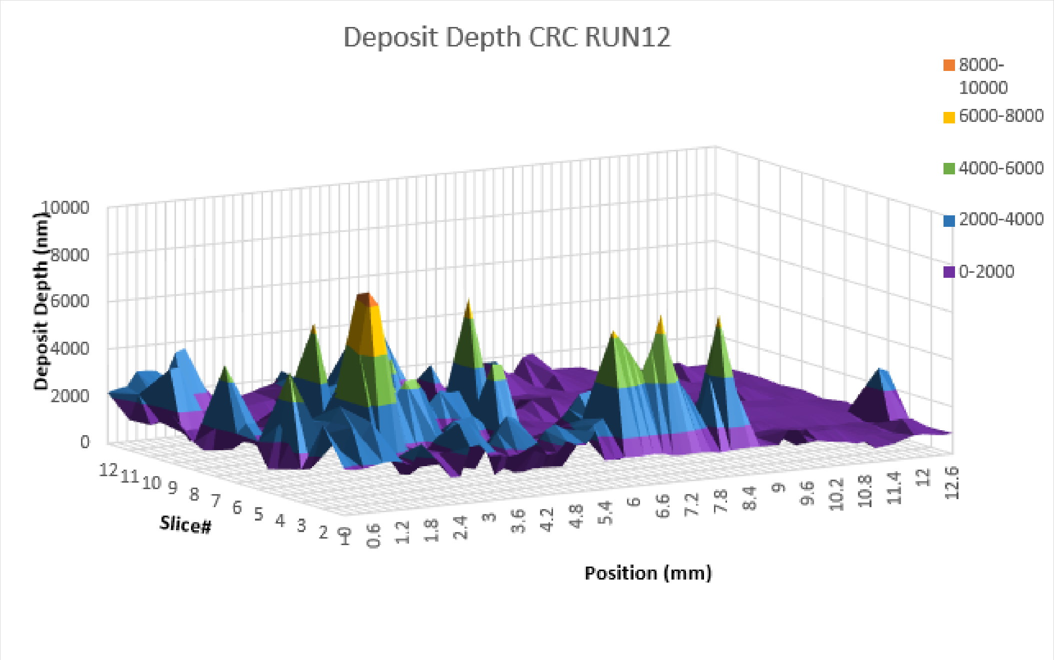


Figure 17. Run 12 Deposit Depth

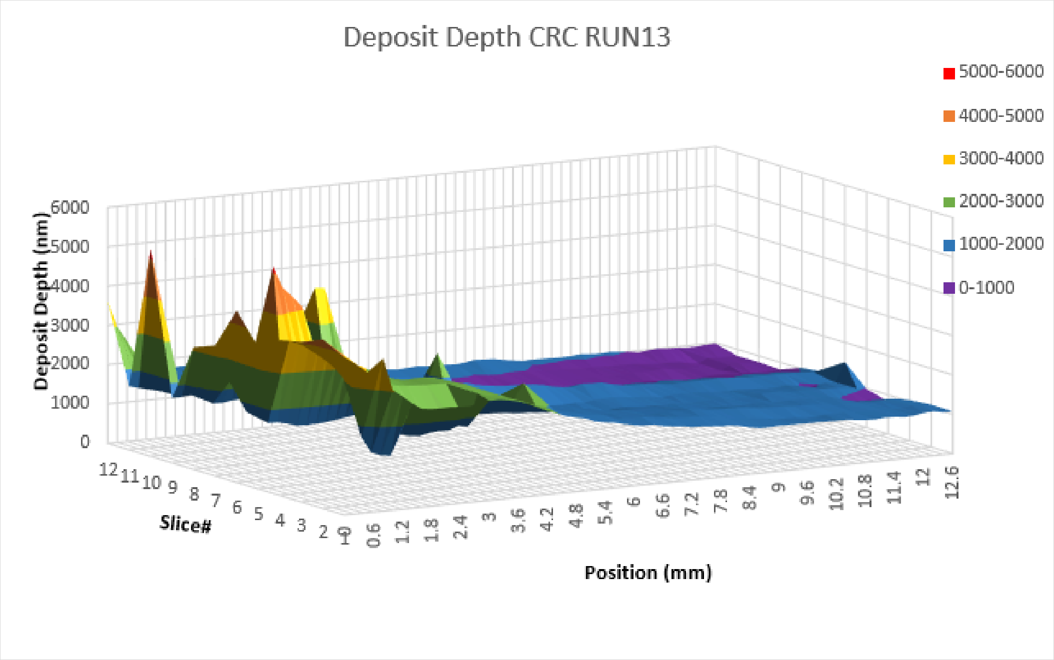


Figure 18. Run 13 Deposit Depth

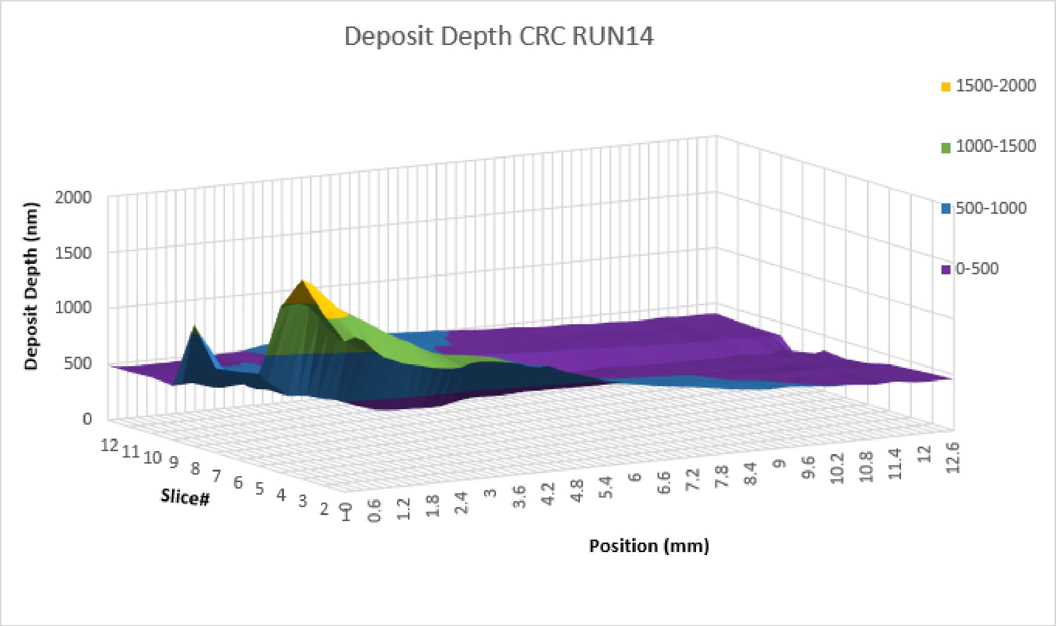


Figure 19. Run 14 Deposit Depth

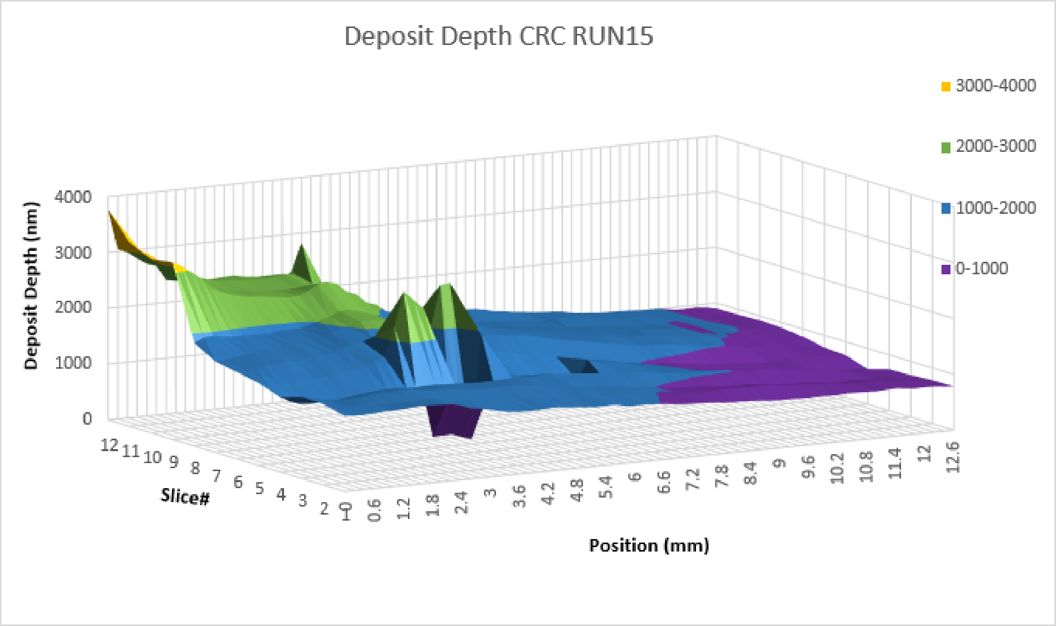


Figure 20. Run 15 Deposit Depth

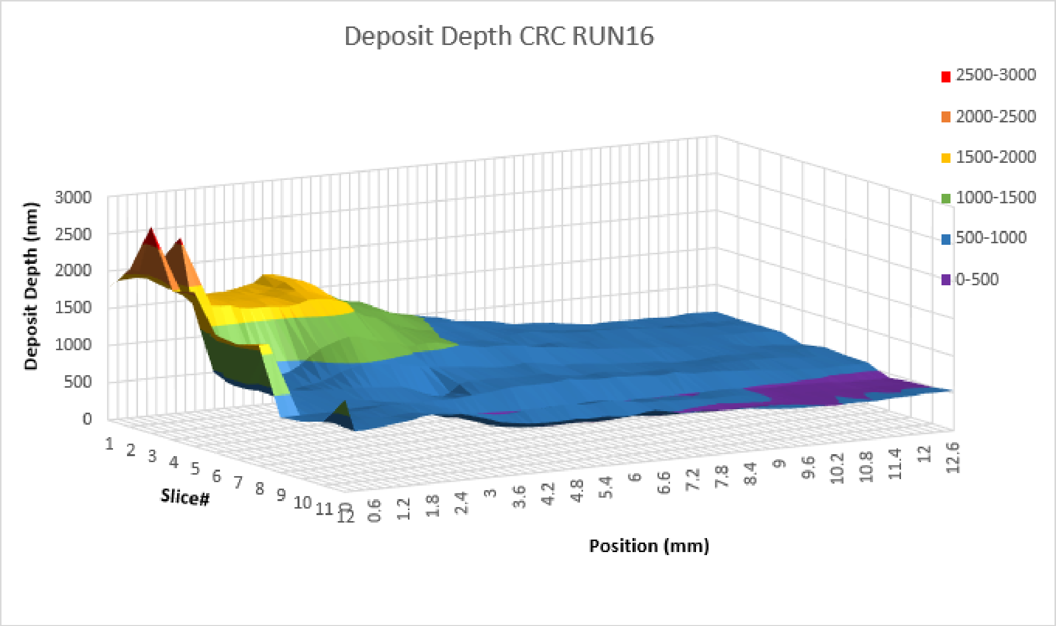


Figure 21. Run 16 Deposit Depth

Interpretation of Results

Starting with run 11 and the fully rebuilt test rig, the average deposit increased significantly. As stated earlier, there were also large changes in deposit composition. Both changes brought issues with the VASE® measurement and modelling process. Figure 22 shows an SEM image of the pintle from run 12. Dark spots can be observed at center (small) and far right (large) of the image.

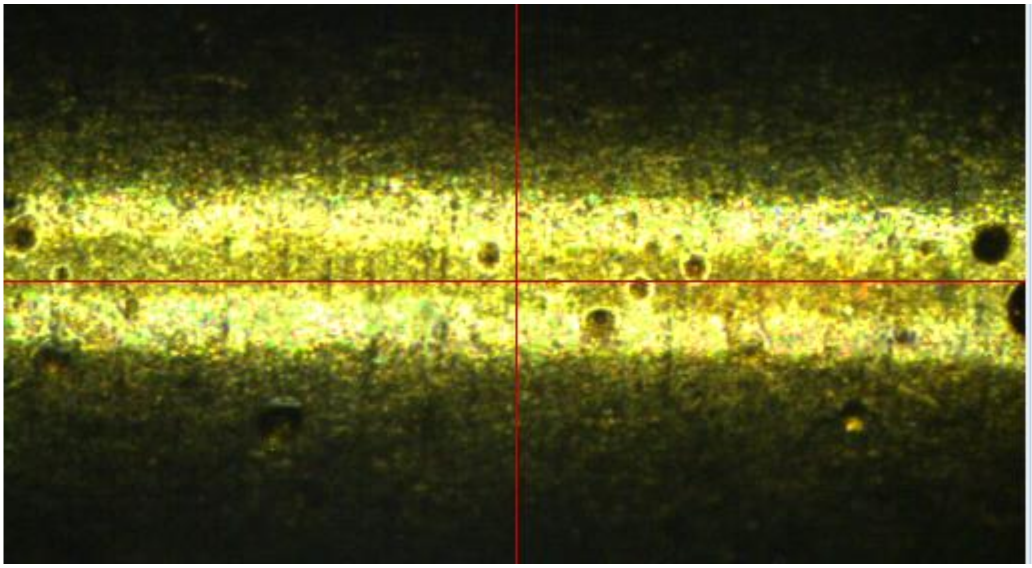


Figure 22. Run 12 SEM Scan

Elemental analysis showed these dark spots consisted mainly of sodium oxide, carbon, and some silicon. Exact composition was dependent on location and size of the dark spot. Where the image shows a consistent yellow reflection, an expected hydrocarbon of nominal thickness 1-2 microns was seen in the SEM results. The presence of the dark spots may explain the sporadic peaks seen in the VASE® analysis of the same pintle (Figure 17).

The Run 17 pintle could not be scanned using the VASE®. This was due to the catastrophic level of sodium oxide deposited on the pintle as seen in Figure 23. The VASE® requires a transparent film in order to function properly.

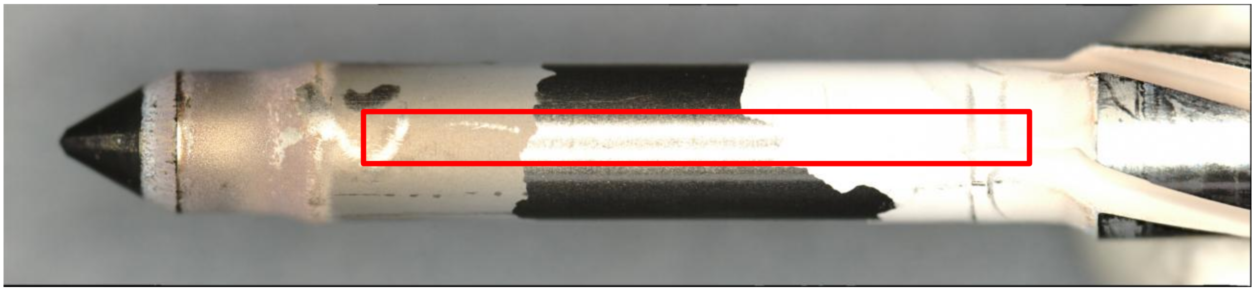


Figure 23. Run 17 Deposit Image

The pintle for Run 17 was imaged on a Keyence 3D microscope and the virtual profilometer trace seen in Figure 24 corresponds to the area indicated in Figure 23, and is similar in position and length to a single VASE® slice. As can be seen, maximum deposit depth was in excess of 20 microns. The nominal hydrocarbon deposit depth is difficult to quantify on the microscope but is likely less than 5 microns.

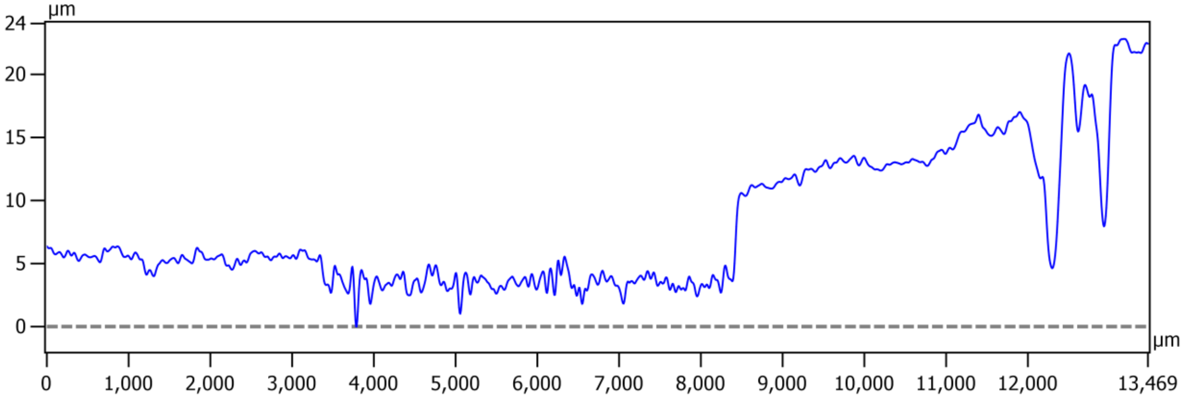


Figure 24. Run 17 Deposit Depth

The following data is from tests 11 through 16. A minor correlation can be observed in Figure 25 between deposit thickness and fuel pump inlet temperature.

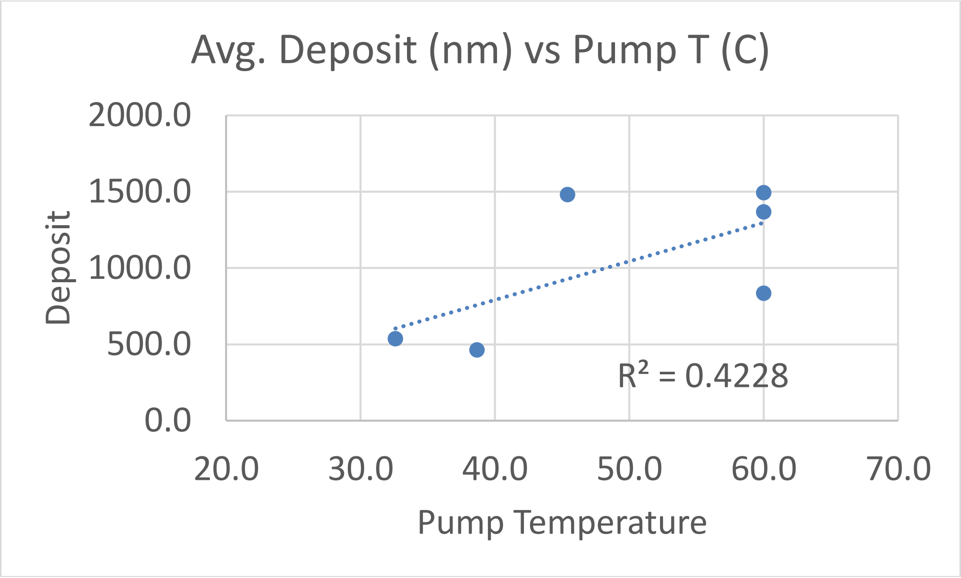


Figure 25. Deposit Depth vs Pump Inlet Temperature

A moderate correlation can be observed in Figure 26 between deposit thickness and nozzle surface temperature.

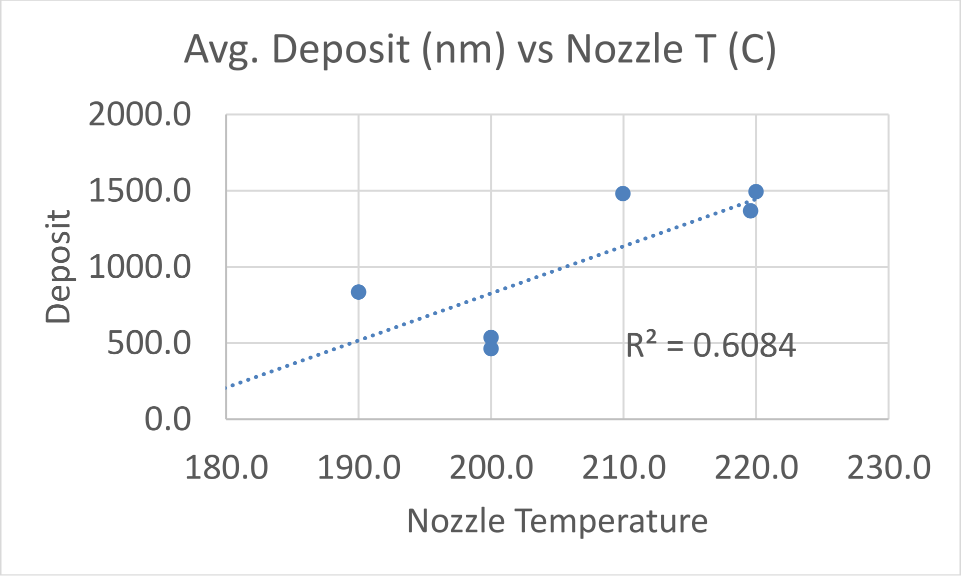


Figure 26. Deposit Depth vs Nozzle Surface Temperature

In Figure 27, there was no observed correlation between sodium concentration and deposit thickness. This may be a result of the temperature differences involved in the various runs, or if the overall sodium concentrations were too high and the deposit formation mechanisms were saturated with excess sodium.

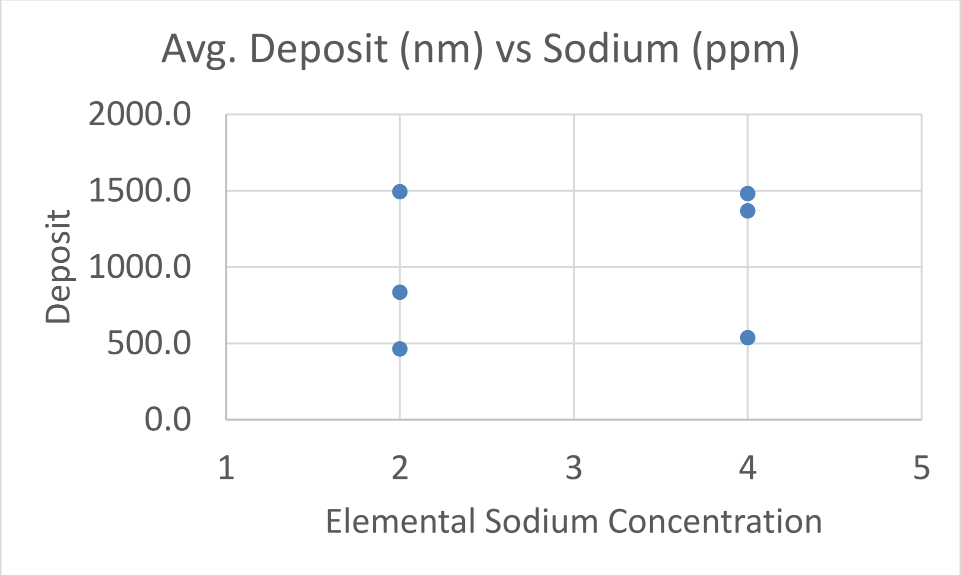


Figure 27. Deposit Depth vs Elemental Sodium Concentration

Figure 28 shows the correlation between nozzle surface temperature and internal heater block temperature. This indicates the heat transfer mechanism is stable between tests and not largely affected by other variables such as fuel temperature, fuel flow rate, mechanical setup, or test cell environment.

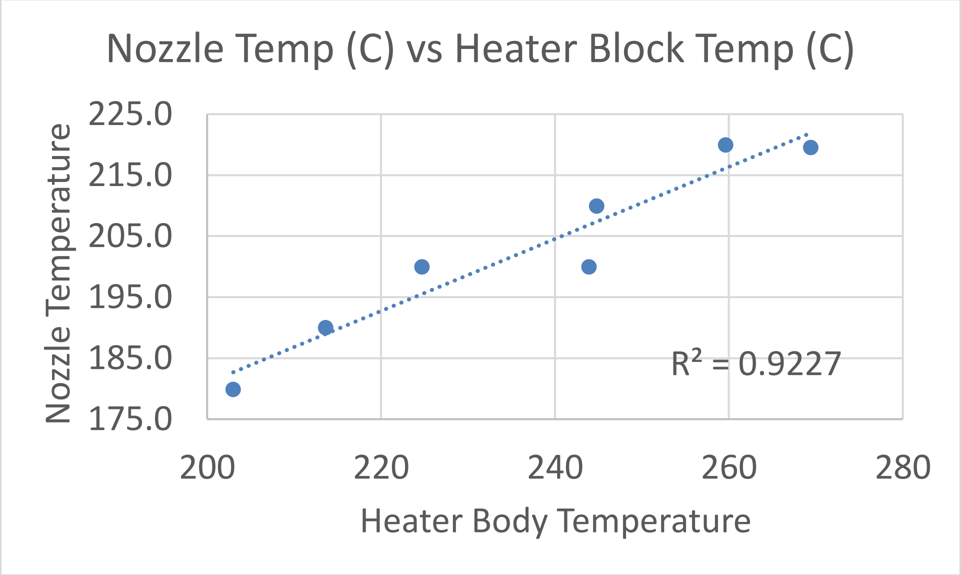


Figure 28. Temperature Correlation of Nozzle Surface to Heater Block

7.0 OPERATIONAL SUMMARIES

7.1 Test Matrix Operational Summaries

The last 7 tests showed good consistency in controlled variables. The fuel flow setpoint of 5.0 g/min averaged between 4.97 and 5.34 for each test. The nozzle temperature setpoints showed less than 0.5 °C average deviation for each test. The fuel inlet temperature was perfectly controlled at the 60 °C setpoint, showed a deviation of less than 0.5 °C at the 45-degree setpoint, and did have some drift issues at the 30-degree setpoint, which indicates loss of control.

In addition, some injectors experienced post-test sticking of the pintle during disassembly. These injectors tended to show more instantaneous variation in flow than those that did not have post-test stuck pintles. The root cause of the flow variation and pintle sticking may not be directly related as the spool valve and check valves were not evaluated for deposit. But it is assumed these phenomena are related.

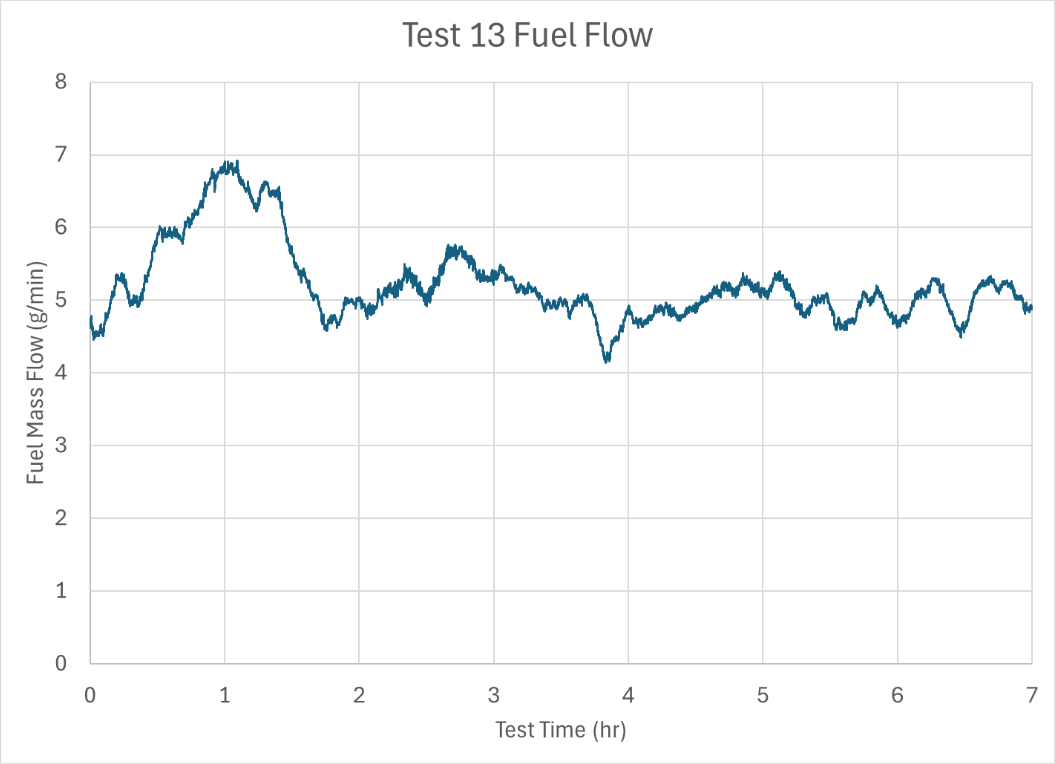


Figure 29. Plot of Fuel Flow vs Test Time for Run 13

Run 13 did not experience post-test pintle sticking and the fuel flow was relatively steady throughout the test. Well behaved tests – in terms of fuel flow rate – are characterized by minor deviations from the mean and potential long term injector controller corrections in a single direction (more output or less output, not both).

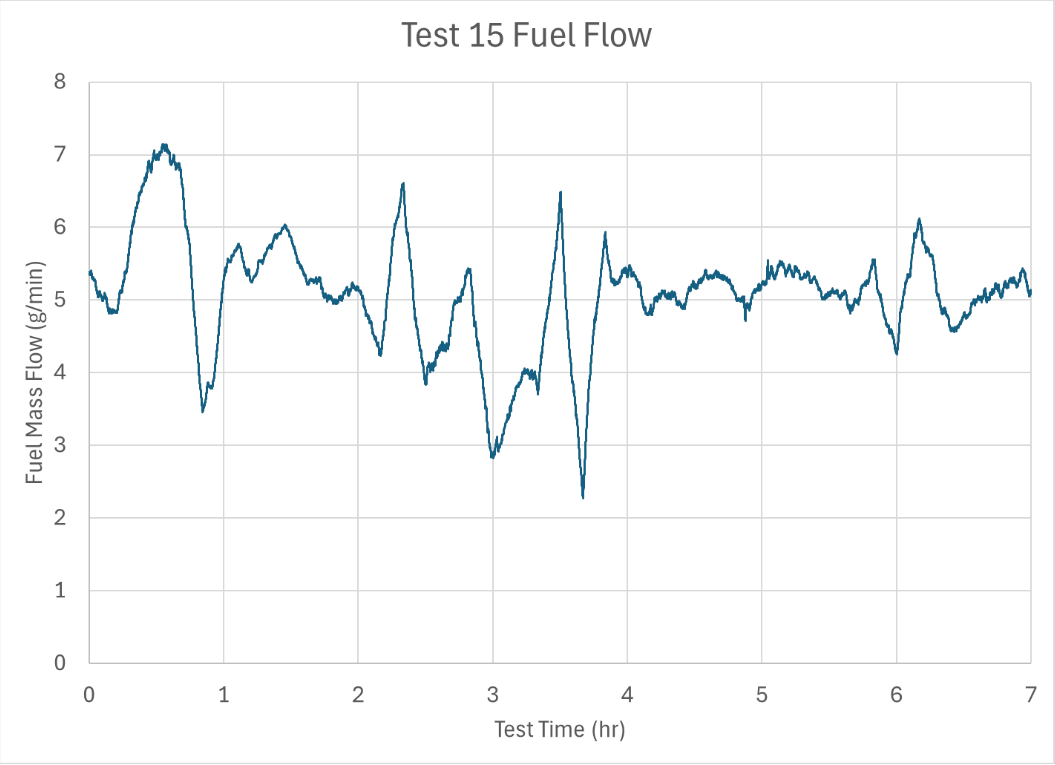


Figure 30. Plot of Fuel Flow vs Test Time for Run 15

Run 15 did experience post-test pintle sticking and showed dramatic swings in fuel flow during the test. At the end of the tests, during the cool-down period, as soon as the rail pressure was lowered from 1800 bar to 350 bar, the injector quit firing. Tests with sticky pintles at the disassembly stage are generally characterized during testing by these dramatic swings in fuel flow occurring frequently and large corrections in both directions by the injector controller.

8.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The original objective of this CRC project was to establish a single set of test conditions, including test fuel recipe, which produced a repeatable result. The secondary objective was to determine the root cause of test variability seen in previous testing. Due to the large amount of work performed toward the secondary objective, the primary objective was not achieved.

Initial testing based on test length showed little difference in deposit depth, but it did show huge problems with temperature control and fuel measurement/control. Incremental changes were made to the test rig and data acquisition and control system over the course of the first 10 tests, with some aspects showing improvement. The largest changes to the test rig occurred with the installation of a new heater body and capture cup prior to test #11.

Tests 11 through 17 showed a significant increase in level of deposit over all previous testing. There were some challenges in getting accurate measurements of these thick deposits, mainly due to compositional changes such as non-hydrocarbon nodules, increased opacity, or an excess of sodium-oxide.

Post program inspections of the test rig showed an excess of sodium oxide in the low pressure drain lines, but the high-pressure pump, fuel rail, and high-pressure lines only showed slight discoloration due to long term hot fuel exposure. This indicates that the flushing procedure is sufficient to prevent buildup of additives in the system.

The injector pintle is difficult to fully characterize while operating as it is affected by heat transfer, fluid flow, mechanical motion, and chemical reactions. Observations of the deposits have led to the author proposing Figure 31 as theory on what types of deposits are formed under which types of thermal conditions. This does not currently consider variables such as fuel quality or high flow conditions, as they were not a part of this test program. The temperature in the X-axis may be considered as the average temperature of the pintle and the surrounding fluid volume. The sodium formation mechanisms are not as critical to understand due to their opacity and inability to be measured accurately except by destructive techniques.

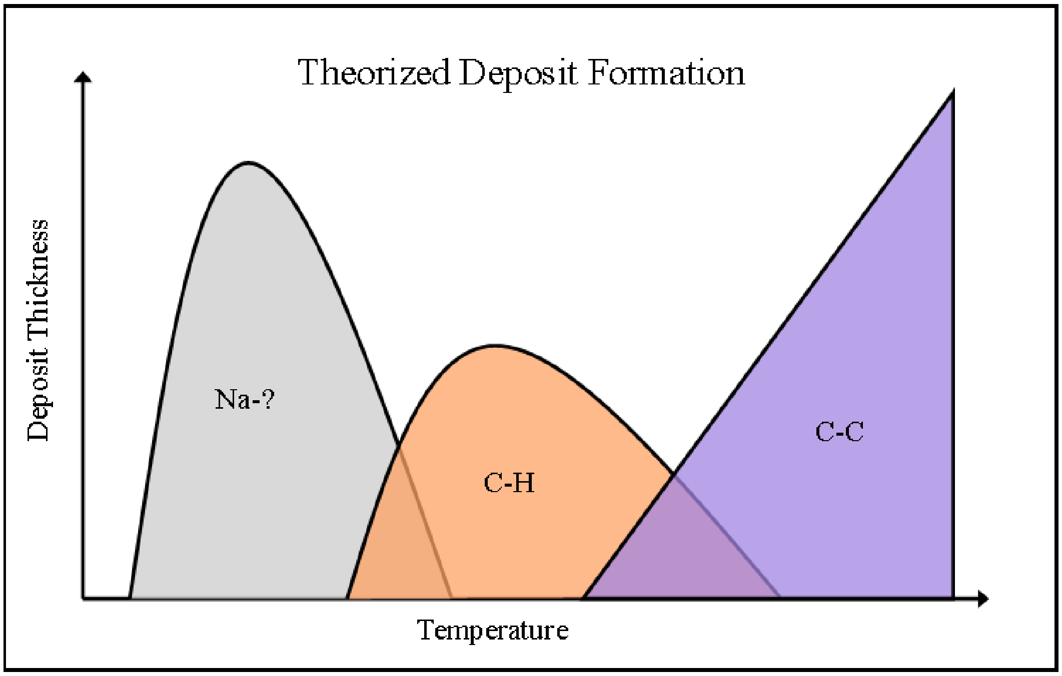
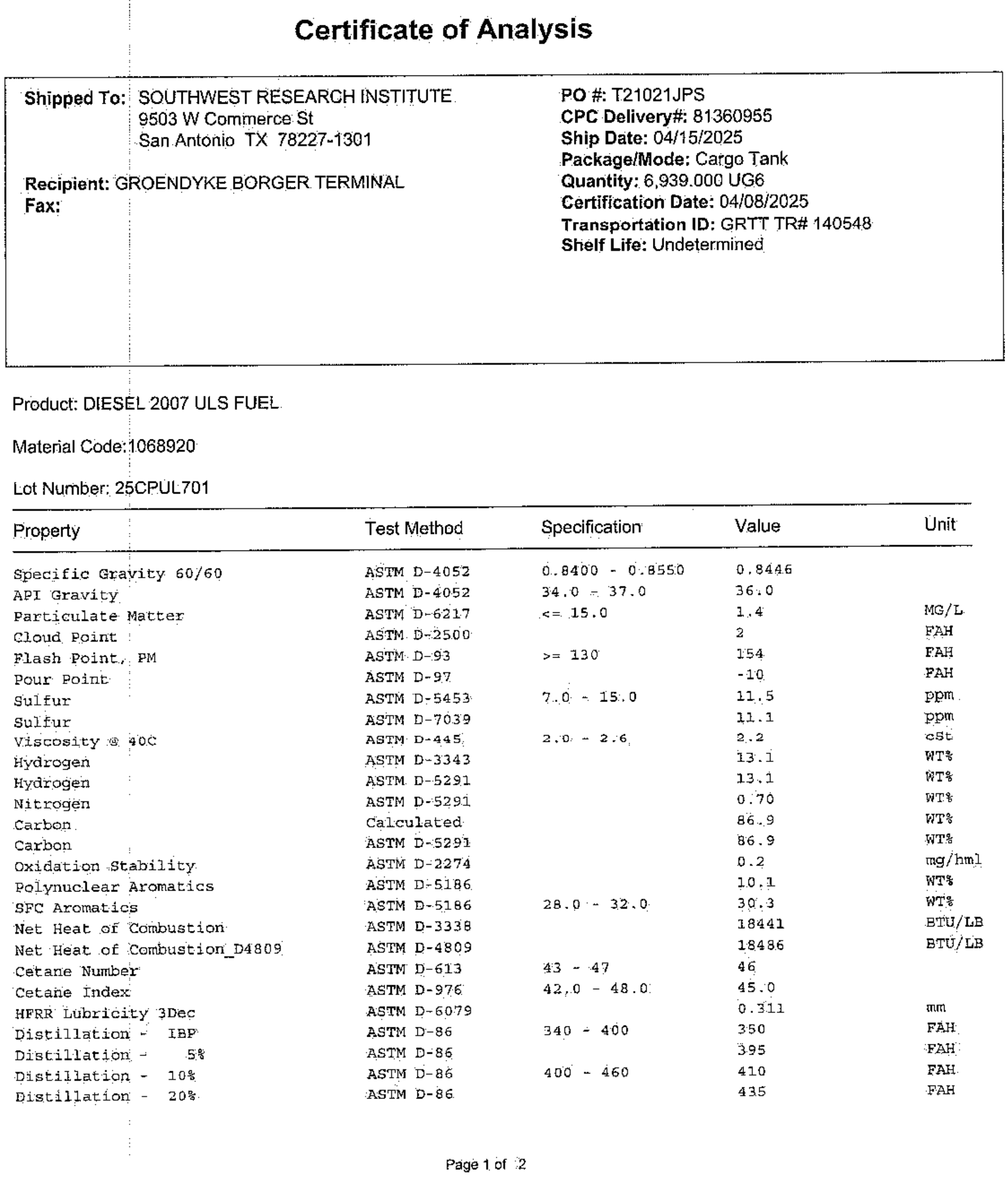


Figure 31. Theorized Deposit Formation on the IDID Pintle

It is accepted that sodium deposits have been seen in the field and are critical to avoid for the long-term health of the injector. However, it is assumed that for development of transparent thin films, there only need be a minimum quantity of sodium to act as a catalyst and not directly contribute to the film as sodium oxide. Going forward, SwRI intends to investigate the minimum concentration of sodium required to generate a film sufficient to measure, but not so thick as to cause pintle sticking issues as seen at the end of this testing program.

It is recommended that further testing be conducted to determine repeatability of the new IDID rig at conditions which produce thick hydrocarbon deposits when the fuel is doped with sodium, and thin hydrocarbon deposits with the same undoped base fuel.

APPENDIX A



Certificate of Analysis

Shipped To: SOUTHWEST RESEARCH INSTITUTE
9503 W Commerce St
San Antonio TX 78227-1301

Recipient: GROENDYKE BORGER TERMINAL
Fax:

PO #: T21021JPS
CPC Delivery#: 81360955
Ship Date: 04/15/2025
Package/Mode: Cargo Tank
Quantity: 6,939.000 UG6
Certification Date: 04/08/2025
Transportation ID: GRTT TR# 140548
Shelf Life: Undetermined

Product: DIESEL 2007 ULS FUEL

Material Code: 1068920

Lot Number: 25CPUL701

Property	Test Method	Specification	Value	Unit
Specific Gravity 60/60	ASTM D-4052	0.8400 - 0.8550	0.8446	
API Gravity	ASTM D-4052	34.0 - 37.0	36.0	
Particulate Matter	ASTM D-6217	<= 15.0	1.4	MG/L
Cloud Point	ASTM D-2500		2	FAH
Flash Point, PM	ASTM D-93	>= 130	154	FAH
Pour Point	ASTM D-97		-10	FAH
Sulfur	ASTM D-5453	7.0 - 15.0	11.5	ppm
Sulfur	ASTM D-7039		11.1	ppm
Viscosity @ 40C	ASTM D-445	2.0 - 2.6	2.2	cSt
Hydrogen	ASTM D-3343		13.1	WT%
Hydrogen	ASTM D-5291		13.1	WT%
Nitrogen	ASTM D-5291		0.70	WT%
Carbon	Calculated		86.9	WT%
Carbon	ASTM D-5291		86.9	WT%
Oxidation Stability	ASTM D-2274		0.2	mg/hml
Polynuclear Aromatics	ASTM D-5186		10.1	WT%
SFC Aromatics	ASTM D-5186	28.0 - 32.0	30.3	WT%
Net Heat of Combustion	ASTM D-3338		18441	BTU/LB
Net Heat of Combustion_D4809	ASTM D-4809		18486	BTU/LB
Cetane Number	ASTM D-613	43 - 47	46	
Cetane Index	ASTM D-976	42.0 - 48.0	45.0	
HFRR Lubricity 3Dec	ASTM D-6079		0.311	mm
Distillation - IBP	ASTM D-86	340 - 400	350	FAH
Distillation - 5%	ASTM D-86		395	FAH
Distillation - 10%	ASTM D-86	400 - 460	410	FAH
Distillation - 20%	ASTM D-86		435	FAH

Page 1 of 2

Certificate of Analysis

Product: DIESEL 2007 ULS FUEL

Material Code:1068920

Distillation - 30%	ASTM D-86		451	FAH
Distillation - 40%	ASTM D-86		467	FAH
Distillation - 50%	ASTM D-86	470 - 540	483	FAH
Distillation - 60%	ASTM D-86		499	FAH
Distillation - 70%	ASTM D-86		518	FAH
Distillation - 80%	ASTM D-86		543	FAH
Distillation - 90%	ASTM D-86	560 - 630	583	FAH
Distillation - 95%	ASTM D-86		617	FAH
Distillation - EP	ASTM D-86	610 - 690	653	FAH
Distillation - Loss	ASTM D-86		0.3	ml
Distillation - Residue	ASTM D-86		1.3	ml
Aromatics	ASTM D-1319		30.4	LV%
Olefins	ASTM D-1319		1.0	LV%
Saturates	ASTM D-1319		68.6	LV%
Cold Filter Plug Point	ASTM D-6371		-5	FAH
Biodiesel Content, wtpct	ASTM D-7371		0.0	WT%