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Port Fuel Injection (PFI) Intake Valve Deposit (IVD) Test Development

CRC Project No. CM-136-18-1

Final Report

January 2025

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FINAL REPORT

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Acknowledgements

This report represents results and conclusions from an effort from the Coordinating Research Council, Inc. (CRC) Performance Committee, Gasoline Deposit Group Intake Valve Deposit (IVD) Test Program members. Various workstreams were involved including Project Execution, Data Analysis, Test Fuel, Engine Testing, Additives, and EPA & CARB. A detailed listing of the workstreams including members is found in Annex A1.

The project was conducted by the CRC with the goal of developing a new engine-based test method suitable to replace the existing ASTM D5500 test method for demonstrating the effectiveness of gasoline detergent additives. Intertek Automotive Research based in San Antonio, TX was the contract laboratory that performed the testing.

Program: Port Fuel Injection (PFI) Intake Valve Deposit (IVD) Test Development

Objective

The objective of this program was to develop a new engine-based test method suitable to replace the existing ASTM D5500 test method for demonstrating effectiveness of gasoline detergent additives. The program entailed researching and developing test fuel specifications, test parameters, operating conditions, engine hardware requirements, and recommendations for pass / fail criteria. The goal was to provide an ASTM test methodology for IVD measurement and be acceptable to the EPA and potentially CARB for use in their Lowest Additive Concentration (LAC) certification test programs.

Background

Current test methods used to demonstrate effectiveness of gasoline detergent additives to reduce Intake Valve Deposits (IVD) in Port Fuel Injection (PFI) engines include:

• ASTM D5500 – This test uses a 1985 model BMW car operated on a prescribed test cycle performed on a test track or public road. This test method is used by the U.S. Environmental Protection Agency (EPA) and California Air Resources Board (CARB) to certify gasoline detergent additives.

• ASTM D6201 – This test uses a 1994 model Ford inline 4-cylinder engine from a Ford Ranger truck operated on prescribed test cycle on an engine dynamometer.

These test vehicles, engines and associated test fuels have become increasingly outdated, difficult to obtain replacement parts, and not representative of modern vehicle/engine/fuel technology. It is desirable to replace these outdated tests with modern test engines and fuels.

This work was a continuation of the American Chemistry Council Fuel Additives Task Group (FATG) IVD Test Consortium's development of the GM LE9 Ecotec 2.4L engine test

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1. Technical Approach - Summary

1.1 Engine Testing Summary

The engine testing portion of the technical program consisted of an initial scoping test phase using the ASTM D6201 test procedure followed by three program prove-out phases using the GM LE9 engine configuration summarized as follows:

- Pre-program Scoping Phase - Primary objective: establish ASTM D6201 response relative to the selected program test fuels and Phases I-III primary additive (i.e., described as Detergent 1)
- Phase I – Prove-Out Test Cycle. Primary objective: establish and prove out a test cycle that optimizes IVD.
- Phase II – Prove-Out Test Fuel. Primary objective: understand today's market fuel and impact on IVD formation.
- Phase III – Prove-Out Detergent. Primary objective: verify mainstream detergent with acceptable response.

Phases one through three utilized a General Motors 2.4L four-cylinder (LE9 configuration) engine in a dynamometer-based engine test stand.

1.2 Fuels and Additives Selection Summary

1.2.1 Fuel Selection

The EPA lowest additive concentration (LAC) certification test specifies a 65th percentile test fuel that also produces a minimum level of deposits in the ASTM D5500 test without additive. The 65th percentile test fuel is defined as representing the severity of market fuels for deposit forming tendencies based on market fuels in the 1990's. If a fuel met the specifications of the 65th percentile fuel, then it would be more severe than two-thirds of the fuels in the marketplace at the time. The parameters for deposit forming tendencies of the 65th percentile test fuel are well defined in literature and are relevant for today's fuels. These are: Aromatics, Olefins, Sulfur, and heavier end components. Heavier end components are represented by a minimum temperature for 90% distillation (10% heaviest liquid faction) or T90. While the parameters for deposit forming tendencies remain the same, the market fuels have changed dramatically in the past two decades. The 65th percentile test fuel for the ASTM D5500 test is no longer found in the marketplace today. In addition, early testing by the ACC FATG in the GM LE9 showed that an EPA 65th test fuel proved too severe for use in additive keep clean demonstrations. Following the ACC FATG guidance, the CRC IVD Test program selected a fuel meeting Top Tier™ test fuel requirements for Phase I. We were successful in demonstrating the ability to form deposits using this as the base fuel in the GM LE9 and prevent deposit formation with the use of a deposit control additive.

Our approach to developing a test fuel specification for the GM LE9 test started with evaluating the fuel parameters for deposit forming tendencies in market fuels. With permission from the ABCG consortium, we obtained fuel survey data for 16,000 retail samples from all 5 PADD between 2017-2020. We statistically evaluated for trends and to bracket known deposit forming fuel parameters averages by percentile. This survey data, along with Top Tier™ and CARB Phase 3 specifications formed the basis for the first draft test fuel recommendations. (Reference figures from the fuel survey shown below via Figures 1 through 4)

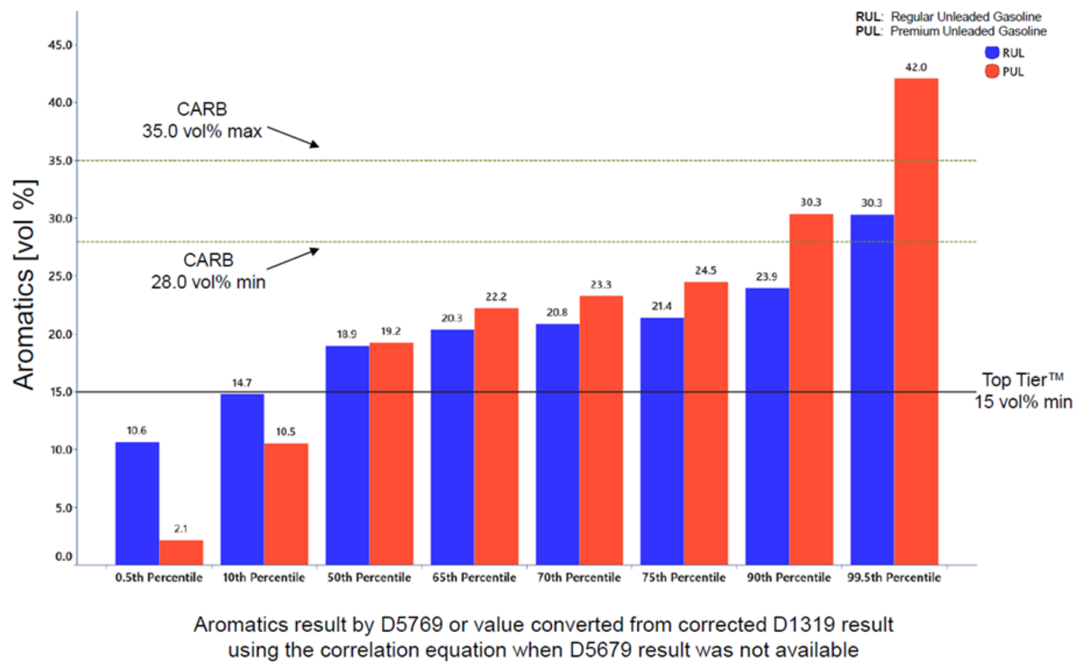

Figure 1 - Aromatics, ASTM D5769

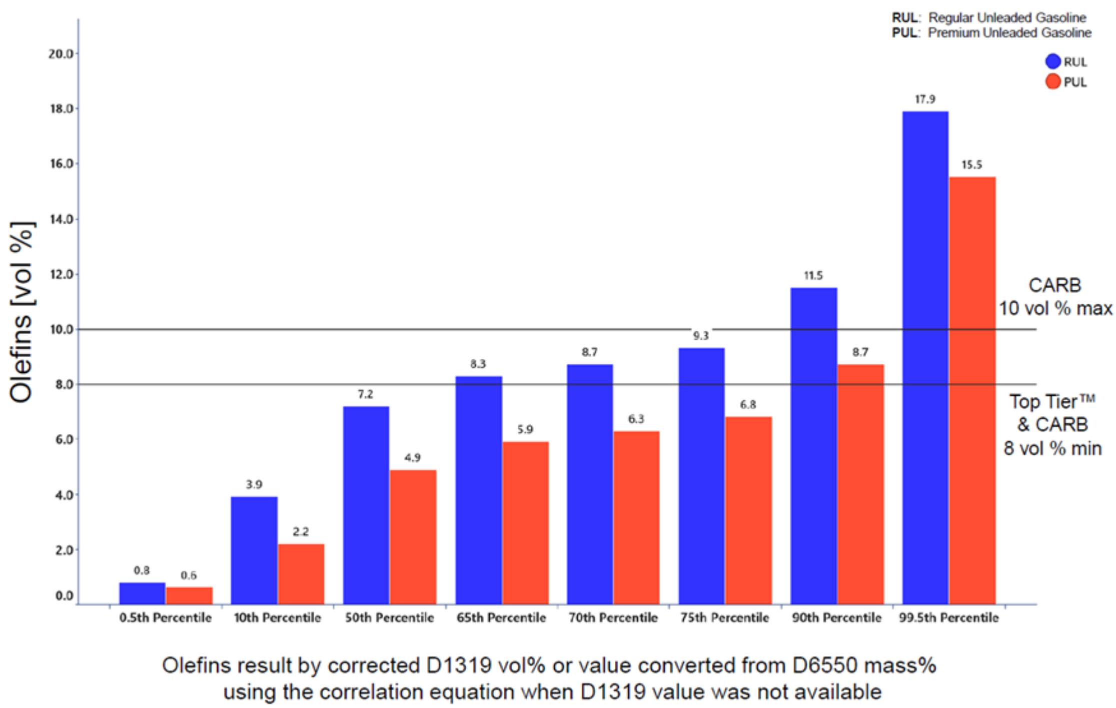

Figure 2 - Olefins, ASTM D1319

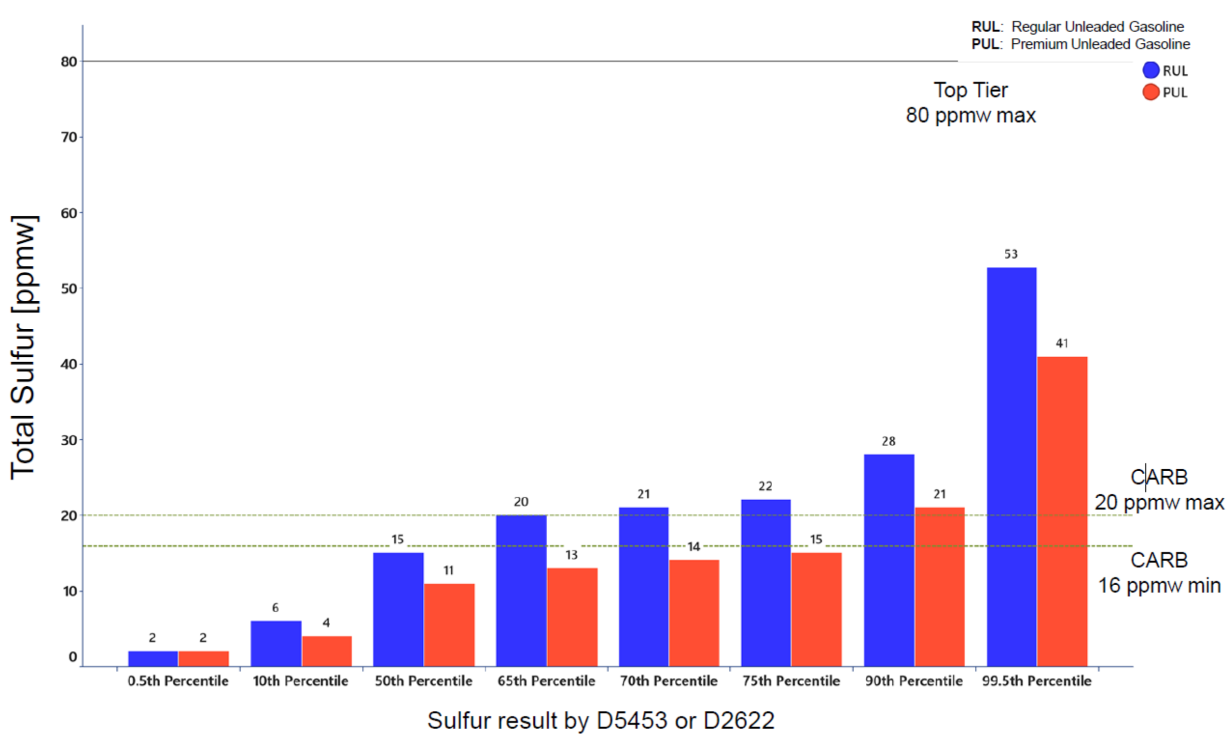

Figure 3 - Sulfur, ASTM D5453 & D2622

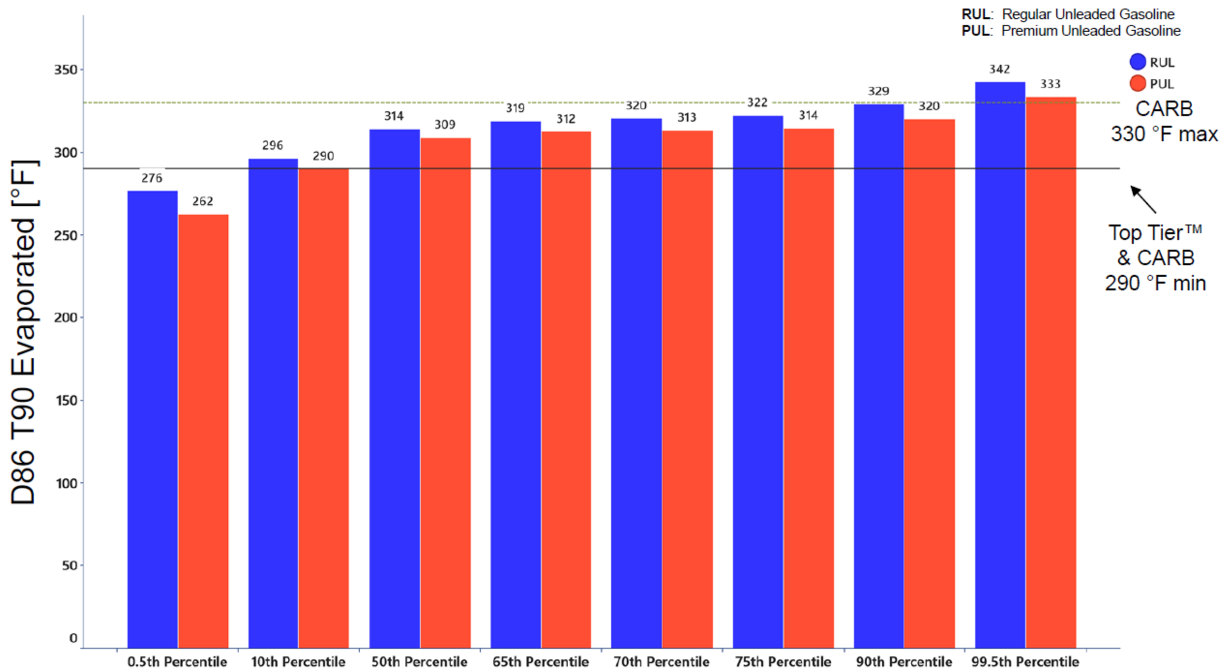

Figure 4 - Distillation Temperature at 90% Evaporation, ASTM D86

EPA 65th% fuel specification limits (Table 1) were not highlighted on the previous figures for the following reasons:

- Title 40 CFR Part 1090(a)(1) specifies four fuel properties of certification fuel prior to the addition of ethanol
- ABCG fuel samples included in this analysis contained variable levels of ethanol, ranging 8.0-10.5vol%, and the equivalent limits of the key properties were dependent on the actual ethanol content of each sample

None of the ABCG survey fuel samples from 2017-2020 met all EPA certification test fuel requirements due to the much lower sulfur limits set for today's finished retail gasoline.

Table 1 - Summary of EPA 65th % Certification Fuel Property

EPA 65th % Certification Fuel Property	Base Fuel Limit (min)	*Approx. E10 Limit (min)*
Aromatics [vol %]	31.1	*28.0*
Olefins [vol%]	11.4	*10.3*
Sulfur [ppmw]	340	*306*
D86 T90 [°F]	339	*<339*

From these recommendations, three potential fuels were outlined for consideration by the team (see Table 2).

Table 2 - Summary of Test Fuel Options for Phase I

	Fuel Supplier 1	Fuel Supplier 2 - Mild*	Fuel Supplier 2 - Severe*	Top Tier™ Certification Fuel Requirements
Olefins [vol%] ASTM D1319	9.4	11.6	10.9	≥ 8
Aromatics [vol%] ASTM D1319	28.7	32.7	33.5	≥ 15
Sulfur [ppmw] ASTM D5453	19.3	12.44	51.57	≤ 80
T90 [F] ASTM D86	312	347.8	356	≥ 290
Ethanol [vol%] ASTM D4815	9.5	9.1	9.2	9.0-11.0
IVD Demonstration [mg/valve]	~900	588	1190	>500

The Fuels Workstream made the decision to move forward with the mild fuel from Fuel Supplier 2 and the Severe fuel from Fuel Supplier 1 in order to allow maximum variability between the fuels in Phase I, while also ensuring the test wasn't developed in a way that would make it difficult to source test fuel from more than one source. Both test fuels demonstrated deposits in base fuel test runs and the ability to keep clean with a deposit control additive in the additized test runs.

The objective of Phase II was to understand today's market fuel variability and impact on intake valve deposit formation. Based on the CRC's scope of work for Phase II, a minimum of four base fuels with different severity and one detergent at two treat rates (1x, 2.5x LAC) were identified.

Fuel analysis of the test fuels from Phase I indicated that both fuels were in the upper ranges of severity for the fuel deposit forming parameters, based on the 2017 – 2020 market survey data. Fuel A measured at 72nd percentile and Fuel B measured at 95th percentile. The test fuels from Phase I were suitable for representing severe fuels in our Phase II testing. It was determined that the two additional test fuels for Phase II should be lower severity, and a target between 50th and 60th percentile was set. Test Fuels 3 and 4 have severities of 54th percentile and 58th percentile respectively.

Table 3 - Analytical Analysis Summary of Fuels A, B, 3, and 4

	Fuel A		Fuel B		Fuel 3		Fuel 4	
	Measured	CoA	Measured	CoA	Measured	CoA	Measured	CoA
Olefins [vol%] ASTM D6729	10.2		11.5		9.2		8.8	
Olefins [vol%] ASTM D6550		8.1		13.2*		7.1		6.7*
Aromatics [vol%] ASTM D6729	26.5		30.4		18.8		19.5	
Aromatics [vol%] ASTM D5580		29.6		37.5*		19.1		18.9*
Sulfur [ppmw] ASTM D5453		19.3		30		13.1		12.7
T90 [F] ASTM D86		312		349		315		313
Ethanol [vol%] ASTM D6729	9.4		8.9		8.6		8.8	
Ethanol [vol%] ASTM D4815		9.5		9.3		9.1		9.2
Average Percentile	72	75	95	96	54	50	58	48

Data from the certificate of analyses for the four base fuels are included in Annex A2

Results from Phase II testing demonstrated that all the test fuels performed well in base fuel and additized fuel testing. While fuel selection has a large influence on deposit forming tendencies, we found that the fuels with severity greater than 50th percentile adequately formed deposits at the engine test parameters established in Phase I. In addition, Fuel 3 demonstrated slightly better response to additive dosages and was selected as the test fuel for Phase III deposit control additive testing.

The CRC Fuels workstream revisited the market survey data in light of the Phase II testing. They made a comparison of Top Tier^{TM}, CARB Phase 3 and the test fuels used in the CRC program and have made the recommendations for test fuel specification ranges shown in Table 4.

Table 4 - Analysis of Market Fuel Survey Data

	Top Tier Specification[1,2]	CARB Phase 3	2017 - 2019 Fuel Survey 65th		70th		75 th		90th		99.5		Ranges Fuel Survey 65th - 99.5	Ranges Fuel Survey 65th - 99.5	CRC Test Fuel Recommendations
			Reg	Prem	Reg	Prem	Reg	Prem	Reg	Prem	Reg	Prem	Regular	Premium	
Aromatic (vol %)			20.5	22.1	21	23.2	21.6	24.4	24.1	30.5	30.2	41.9			
Min	**15**	**28**											**20.5**	**22.1**	25
Max		**35**											**30.2**	**41.9**	35
Olefins (vol%			8.6	6.1	9	6.5	9.6	6.9	11.7	8.9	17.9	16.4			
Min	**8** [3]	**8** [5]											**8.6**	6.1	8
Max		**10** [5]											**18**	**16.4**	18
Sulfur (ppmw)			21	14	22	15	24	17	29	22	54	42			
Min		**16** [6]											**21**	**14**	
Max	**80** [4]	**20**											**54**	**42**	80
Ethanol (vol%)			10.01	10.05	10.06	10.09	10.1	10.13	10.27	10.3	10.49	10.49			
Min	**8**	**8**											**10.01**	**10.05**	9
Max	**10**	**10**											**10.49**	**10.49**	10.5
Distillation (T90F)			319	312	321	313	322	314	329	319	342	333			
Min(°F)	**290**	**290**											**319**	**312**	290
Max(°F)		**330**											**342**	**333**	374

1.2.2 Fuel Additive Selection

Fuel additives for the CRC IVD test program were provided through the ACC FATG fuel additive sampling process, which allowed for blind selection of market general deposit control additives (DCA) at their prescribed "lowest additive concentration" (LAC) treat rate. The additives and their respective treat rates were known only to the ACC FATG director and Intertek's test coordinator. The fuel additives were EPA certified using the ASTM D5500 test on the BMW 318i vehicle. The goal of having multiple fuel additive types and treat rates to verify the test engine's ability to discriminate IVD performance with and without DCA and relative scale of the IVD by varying DCA treat rates.

2. Pre-program Phase: ASTM D6201 Testing

Prior to Phase I, four ASTM D6201 tests were conducted to establish the response of Fuel A, B, and Detergent 1 to the ASTM D6201 protocol. A summary of the matrix is shown in Table 5 and Figure 5.

Table 5 - Phase I Test Matrix Summary

TEST NUMBER	TEST FUEL	Avg. IVD wts. mg/valve
IVD9-288	Fuel A	894.4
IVD9-292	Fuel B	905.7
IVD9-294A	Fuel A + Detergent 1 @ 2.5xLAC	120.5
IVD9-295	Fuel B + Detergent 1 @ 2.5xLAC	150.9

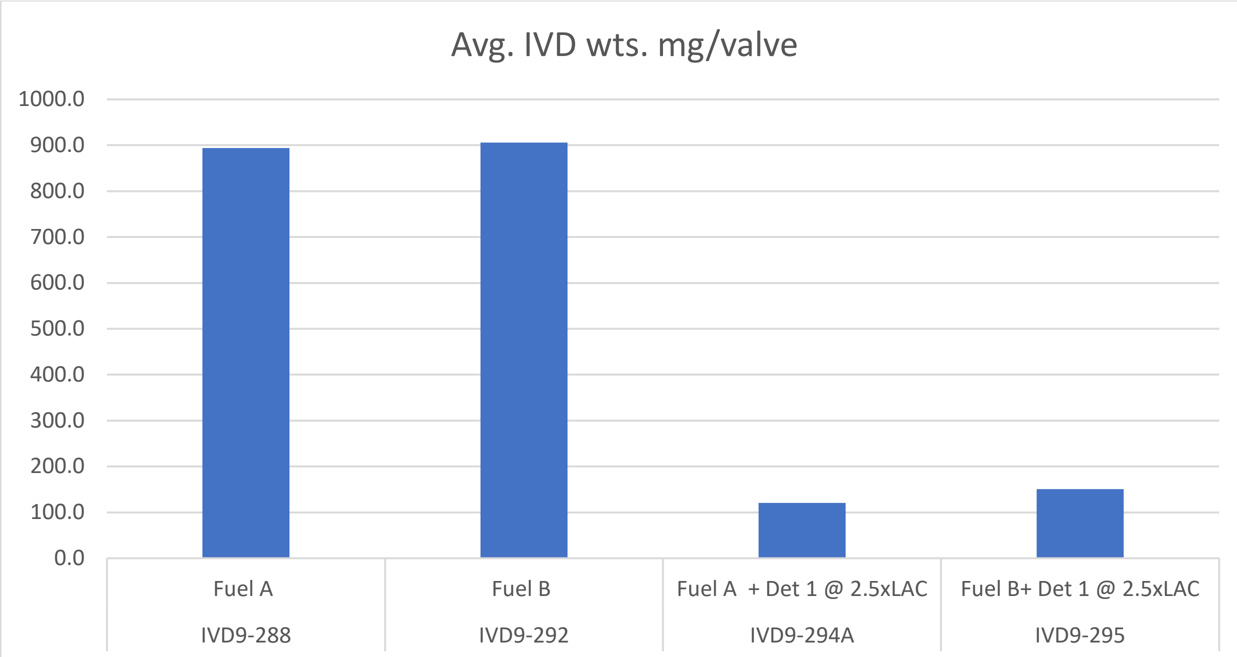

Figure 5 - ASTM D6201 Test Fuel Comparison

As shown in Figure 5, significant intake valve deposits of approximately 900 mg/valve were produced from the unadditized test fuels in the ASTM D6201 tests IVD9-288 and IVD9-292. The addition of 2.5 x LAC of Detergent 1 to both test fuels resulted in significant improvement in the keep clean performance of the additized fuels with 120.5 and 150.9 mg/valve for Fuel A and Fuel B, respectively. This approximately 85% reduction in intake valve deposit was consistent with the expected performance of Detergent 1 at the 2.5 x LAC treat rate and demonstrates that the test fuels were responsive to the detergent additive.

3. Technical Approach – Phase I Detail

The objective of Phase I was to establish and prove out a test cycle. Based on previous experimental test data from General Motors, Toyota, and others, the optimal temperature for intake valve deposits is 450°F (232°C) [Annex A6, 1]. Engine speed and load are independent variables and intake valve temperature is dependent upon engine speed and load [Annex A6, 2]. Moreover, based on initial ASTM D6201 test development and input from Ford, thermal cycling of the intake valves is desired. General Motors provided LE9 engine intake valve temperature mapping data (Annex A3) that was used as the basis for optimizing the test cycle.

Eight tests were conducted in Phase I. The first five tests were conducted to optimize the test cycle for maximum deposit formation using Fuel A and the remaining three tests were conducted to verify the similar deposit formation with Fuel A and confirm that deposits generated by the optimized cycle can be controlled by Detergent 1.

A two-stage cycle was utilized, cycling between a low load stage 1 and high load stage 2. Stage 1 speed and load setpoints remained constant (2000 RPM / 29.2 kPa) for all tests which provided the intake valve temperature cool off period (thermal unloading). Stage 2 speed and load setpoints were specified to provide the thermal loading on the intake valves. One engine block and one cylinder head were used for all of the tests conducted in Phase I.

The time period for Stage 1 was 4 minutes and 8 minutes for Stage 2. The ramps between the stages were 30 seconds. The speed/load setpoints of Stage 2 varied for the first five tests to achieve the maximum deposit formation and remained consistent for the final three tests to verify the condition can still generate sufficient deposits with Fuel B and the generated deposits are responsive to Detergent 1.

A summary of the Phase I test operational targets are shown in Table 6

Table 6 - Phase I Operational Target Summary

STAGE	1	2
OIL GALLERY TEMP (DEG C)	101	101
COOLANT TEMP ENGINE OUT (DEG C)	90	90
INLET AIR PRESSURE (kPa)	0.05	0.05
EXHAUST BACK PRESSURE (kPa)	102	105
INLET AIR TEMPERATURE (DEG C)	32	32
COOLANT FLOW (L/M)	Record	Test Specific
FUEL TEMPERATURE (DEG C)	28	28
INLET AIR HUMIDITY (G/KG)	11.4	11.4

A summary of the eight-test matrix including the Stage 1 and 2 speed and load (controlled by intake manifold absolute pressure) targets are shown in Table 7

Table 7 - Phase I Test Summary

TEST NUMBER	TEST FUEL	TEST LENGTH	STAGE 1		STAGE 2		Avg. IVD WEIGHTS
		(Hours)	SPEED (rpm)	MAP (kPa)	SPEED (rpm)	MAP (kPa)	(mg/Valve)
GMIVD91-001A	Fuel A	100	2000	29.2	2800	43.5	74.2
GMIVD91-002	Fuel A	100	2000	29.2	2800	51.6	67.7
GMIVD91-003	Fuel A	100	2000	29.2	2800	66.5	101.1
GMIVD91-004	Fuel A	100	2000	29.2	2400	66.5	125.0
GMIVD91-005	Fuel A	100	2000	29.2	2000	80.0	375.3
GMIVD91-006	Fuel B	100	2000	29.2	2000	80.0	361.4
GMIVD91-007	Fuel A + Detergent 1 @ 2.5xLAC	100	2000	29.2	2000	80.0	20.5
GMIVD91-008	Fuel B + Detergent 1 @ 2.5xLAC	100	2000	29.2	2000	80.0	69.0

The first 5 runs (Tests GMIVD91-001A through GMIVD91-005) with different Stage 2 conditions are plotted on the LE9 intake valve temperature contour plot (Figure 6). It was designed to verify the impact of engine loading (Runs 1-2-3, GMIVD91-001A through GMIVD91-003) and engine speed (Runs 3-4-5, GMIVD91-003 through GMIVD91-005). The increased loading between Runs 1 to 3 likely led to higher intake valve temperatures, possibly approaching the previously mentioned optimal intake valve temperature, resulting in an increase in deposits shown in Figure 7. However, the 101 mg/valve deposits were still below the expectation. Decreasing the engine speed and increasing the loading (Run 5), significantly increased the amount of deposit to an average of 375 mg/valve or 750 mg/cylinder, which is comparable to deposit levels in other standard IVD tests. The lower engine speed during Stage 2 should have provided more time for deposit formation under the high load/high temperature condition. Run 5 changed to a relatively higher loading than Runs 3 and 4 to achieve higher intake valve temperature at 2000 rpm as indicated by IVD temperature contour (Figure 6). As Run 5 had produced the target level of intake valve deposits, no further optimization was conducted considering time and budget constraints.

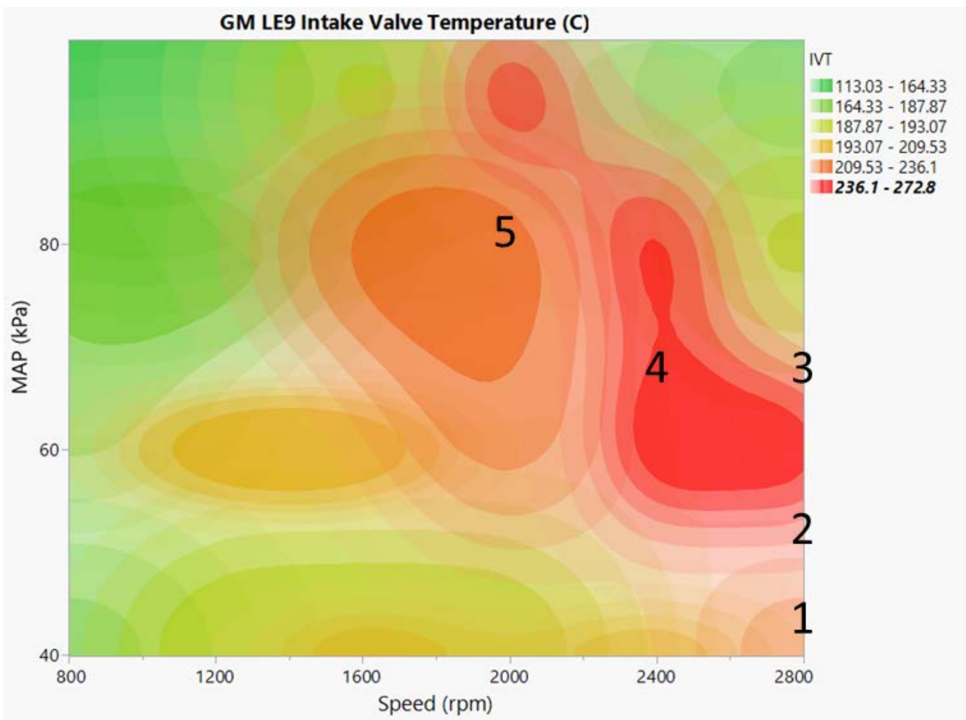

Figure 6 - GM LE9 Intake Valve Temperature Contour Plot

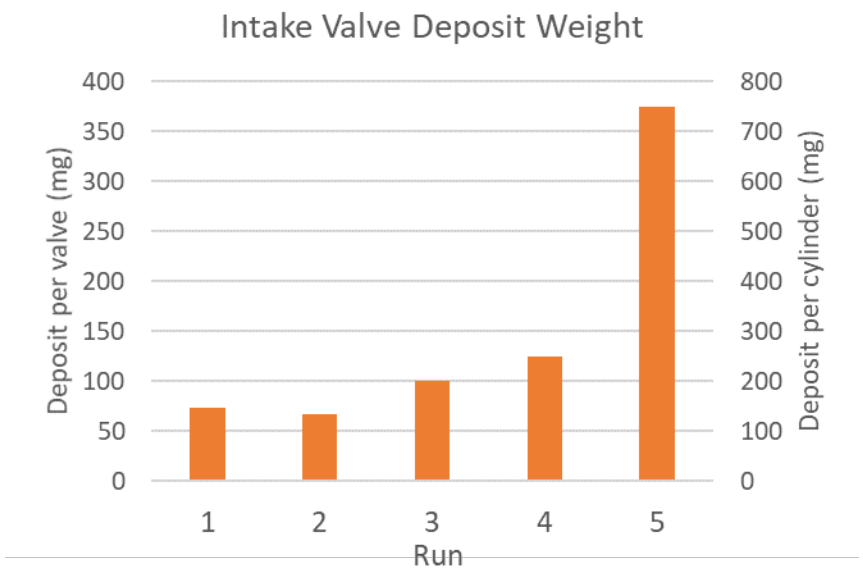

Figure 7 - Intake Valve Deposit Weight from Different Test Runs

Runs 6 to 8 (GMIVD91-006 through GMIVD91-008) were carried out to further verify that Test Fuel B and the addition of detergent to both fuels also responded to the conditions of Run 5. The comparison of the Fuel A and B and their response to Additive 1 in the GM LE9 and the Ford 2.3 are provided in Figure 8. It can be seen that per cylinder based IVD weight was on a par with the Ford 2.3L test results for both Fuel A and Fuel B. Also, the weight should be close to deposit weight in BMW testing based on SAE paper 981365 [Annex A6, 3]. It was estimated that 100 mg/valve in the BMW test should be equivalent to approximately 135 mg/valve in the Ford 2.3L test. The deposit morphology from the two engines is very similar as seen in Annex A5. Furthermore, Detergent 1 had very similar and good keep clean performance in both engines for both fuels. This comparison study confirmed that the engine conditions established by Phase I can generate sufficient amounts of deposits and that deposits are responsive to detergent.

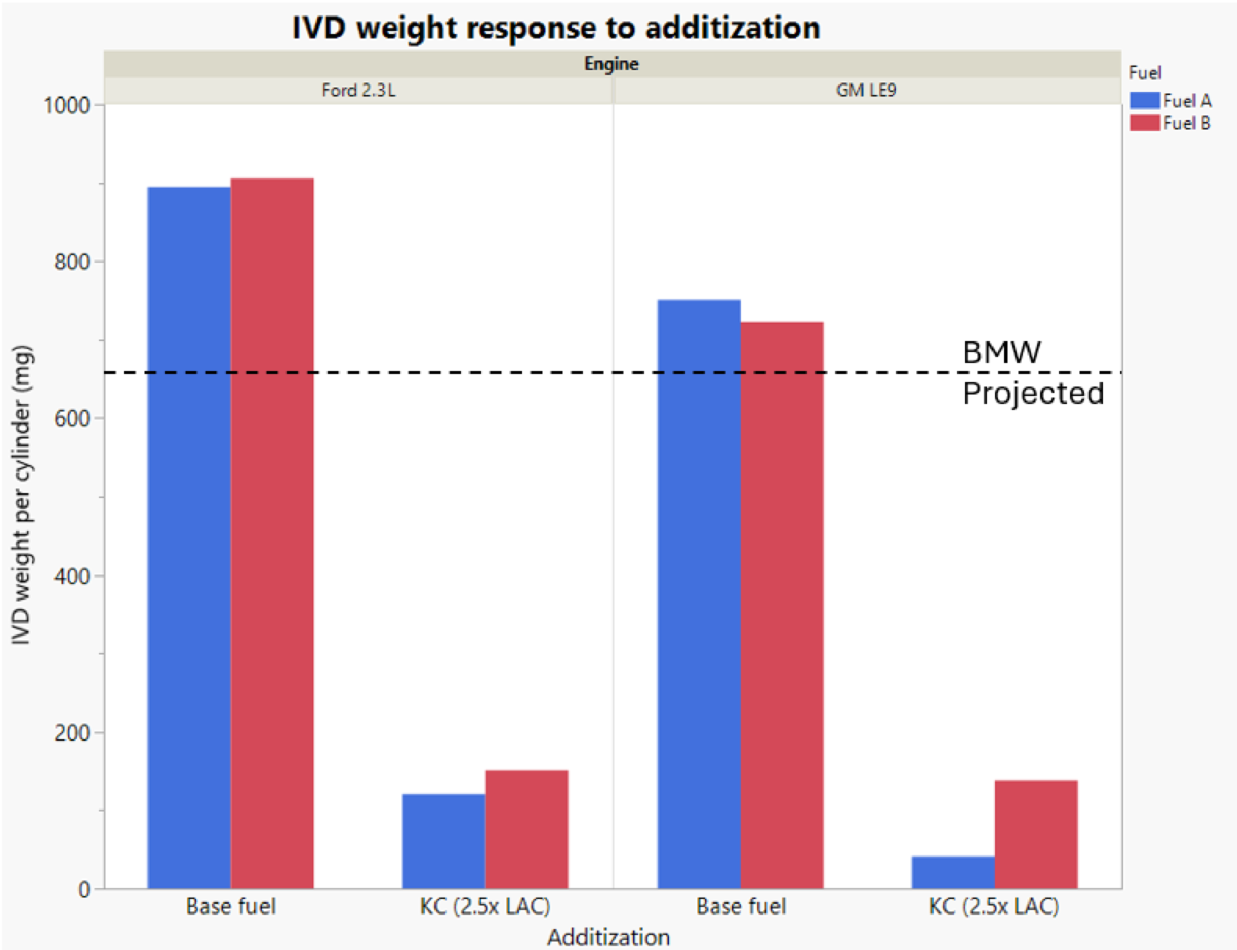

Figure 8 - IVD Keep Clean Test Results in Ford 2.3L and LE9

4. Technical Approach – Phase II Detail

The objective of Phase II was to understand today's market fuel change and impact on intake valve deposit formation. Four base fuels (Fuels 3 and 4 intended to be of lower severity) and one detergent (Detergent 1) at two treat rates (1xLAC and 2.5x LAC) were used identified as follows:

- Fuel A – Fuel Supplier #1
- Fuel B – Fuel Supplier #2
- Fuel 3 – Fuel Supplier #1
- Fuel 4 – Fuel Supplier #2

The test cycle used throughout Phase II was the same test cycle used for Tests GMGDI91-005 through GMGDI91-008 in Phase I. The test operational targets are summarized in Table 8

Table 8 - Phase II Operational Targets

STAGE	1	2
OIL GALLERY TEMP (DEG C)	101	101
COOLANT TEMP ENGINE OUT (DEG C)	90	90
INLET AIR PRESSURE (kPa)	0.05	0.05
EXHAUST BACK PRESSURE (kPa)	102	105
INLET AIR TEMPERATURE (DEG C)	32	32
COOLANT FLOW (L/M)	45	45
FUEL TEMPERATURE (DEG C)	28	28
INLET AIR HUMIDITY (G/KG)	11.4	11.4

Thirteen tests were conducted during Phase II. The test length for the first eleven tests were 100 hours and the test length for the final two tests were 50 hours. The test length was reduced to 50 hours to investigate the impact of IVD weight and flaking versus test time. Flaking, deposit which comes off the valve surface in sections, was observed on a number of intake valves. This phenomenon will affect the end of test deposit level and may bias the results low. The addition of Detergent 1 appeared to significantly decrease the amount of flaking that was observed.

To conform to engine build specifications, two different engine blocks and four different cylinder heads were used during Phase II. The engine blocks and cylinder heads were different than those used in Phase I. See Annex A4 for details.

A summary of the thirteen-test matrix including the Stage 1 and 2 speed and load (controlled by intake manifold absolute pressure) targets are shown in Table 9.

Table 9 - Phase II Test Summary

TEST NUMBER	TEST FUEL	TEST LENGTH	STAGE 1		STAGE 2		Avg. IVD WEIGHTS
		(Hours)	SPEED (rpm)	MAP (kPa)	SPEED (rpm)	MAP (kPa)	(mg/Valve)
GMIVD91-009	Fuel B	100	2000	29.2	2800	80.0	203.8
GMIVD91-010	Fuel B + Detergent 1 @ 2.5xLAC	100	2000	29.2	2800	80.0	115.3
GMIVD91-011	Fuel B + Detergent 1 @ LAC	100	2000	29.2	2800	80.0	242.2
GMIVD91-012	Fuel A	100	2000	29.2	2400	80.0	325.1
GMIVD91-013	Fuel A + Detergent 1 @ 2.5xLAC	100	2000	29.2	2000	80.0	44.0
GMIVD91-014	Fuel A + Detergent 1 @ LAC	100	2000	29.2	2000	80.0	320.2
GMIVD91-015	Fuel 3	100	2000	29.2	2000	80.0	373.8
GMIVD91-016	Fuel 3	100	2000	29.2	2000	80.0	270.5
GMIVD91-017	Fuel 3 + Detergent 1 @ 2.5 x LAC	100	2000	29.2	2000	80.0	78.7
GMIVD91-018	Fuel 4	100	2000	29.2	2000	80.0	273.7
GMIVD91-019	Fuel 4 + Detergent 1 @ LAC	100	2000	29.2	2000	80.0	310.9
GMIVD91-020 @ 50 Hours	Fuel 3	50	2000	29.2	2000	80.0	229.4
GMIVD91-021 @ 50 Hours	Fuel 3 + Detergent 1 @ LAC	50	2000	29.2	2000	80.0	268.4

NOTE: Test 016, Cylinder 4 IVD affected by mechancial issue with Cylinder 4/High Oil Consumption

Operationally, all tests performed consistently and as expected except for GMIVD91-016 which had a mechanical issue in cylinder number four which caused the test to experience unusually high oil consumption leading to unreliable cylinder four IVD results.

The intake valve deposit results for the Phase II fuel severity/formulation response testing are shown in Figure 9.

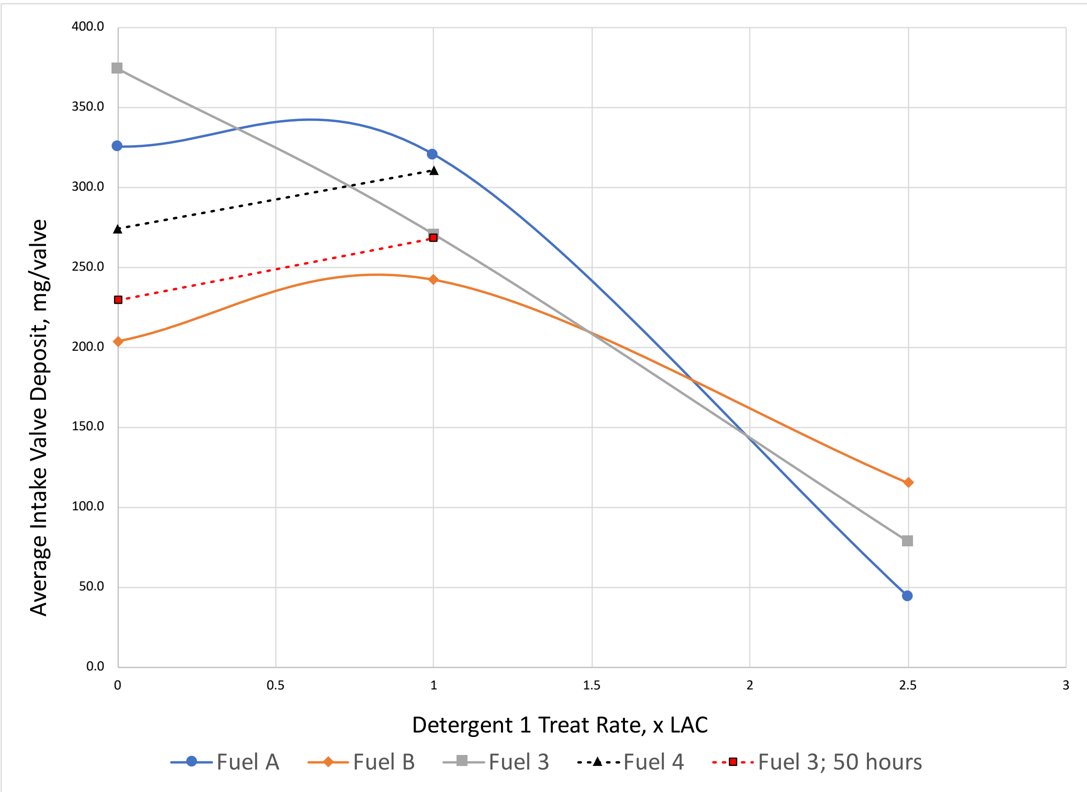

Figure 9 - Fuel Severity/Formulation Response Testing Results

In the unadditized state, all four test fuels had intake valve deposit levels in the 200-375 mg/valve range. One explanation for the large range of average deposit levels may be due to deposit flaking off the intake valve tulip. Figure 10 shows images of the front and rear valves of cylinder 3 from the test utilizing Fuel B (GMIVD91-009; 204 mg/valve). As can be seen, significant deposit flaking or delamination is observed which results in spots of bare metal being exposed. It is not known whether this flaking was a continuous process or whether it occurred toward the end of the test cycle, but some level of flaking occurred with all four test fuels. This results in high variability and may lead to an under reported total intake valve deposit level for the unadditized fuels.

Figure 10 - Intake Valve Photos from GMIVD91-009 (Unadditized Fuel B)

The range of intake valve deposit test results with 1 x LAC of Detergent 1 are much narrower than that observed for the unadditized fuels spanning from 240-320 mg/valve. In addition, several of the 1 x LAC tests show deposit levels higher than the unadditized result which may indicate a "hump effect". The hump effect occurs when a low dosage of additive causes an increase in the deposit level of a fuel. This effect is known to the industry and is a result of the fuel, additive, test engine and test cycle. However, since the unadditized fuel results showed significant flaking, the "hump effect" could be an incorrect interpretation caused by the under-reporting of the deposit level formed during the testing of unadditized fuels. Figure 11 shows cylinder 3 intake valves for the test utilizing Fuel B + 1 x LAC of Detergent 1 (GMIVD91-011; 240 mg/valve). These images show that the addition of Detergent 1 appears to eliminate the flaking phenomenon resulting in intake valve deposits that are much more uniform and relatively homogeneous.

Figure 11 - Intake Valve Photos from GMIVD91-011 (Fuel B + 1 x LAC Detergent 1)

Significant improvement in intake deposit level is observed for Fuels A, B, and 3 when the level of Detergent 1 is increased to 2.5 x LAC. As shown in Figure 12, deposit levels for the higher treat rate of Detergent 1 are below 115 mg/valve and as low as 44 mg/valve. Images of cylinder 3 intake valves from the test utilizing Fuel B + 2.5 x LAC Detergent 1 are shown in Figure 12 (GMIVD91-010; 115 mg/valve) and show a significantly lower coverage of deposit than observed in Figure 11 with 1 x LAC Detergent 1.

Figure 12 - Intake Valve Photos from GMLIVD91-010 (Fuel B + 2.5 x LAC Detergent 1)

To minimize the deposit flaking which was occurring during the 100-hour test, it was decided to reduce the run time to 50 hours. Fuel 3 was tested unadditized and with 1 x LAC while limiting the test duration to 50 hours as shown in Figure 13. Unadditized Fuel 3 produced about 230 mg/valve which was approximately 39% less deposits than the same fuel tested for 100 hours. In contrast, the 1 x LAC result at 50 hours was nearly identical to the deposit level at 100 hours. While the reduction in test duration from 100 to 50 hours has helped with deposit flaking, it hasn't eliminated it. Cylinder 3 (rear valve) from the test using unadditized Fuel 3 still shows signs of flaking as shown in Figure 13.

Figure 13 - Intake Valve Photos from GMLIVD91-010 (Unadditized Fuel 3 @ 50 hours)

Phase II results indicate that the test fuels show an additive response with increasing treat rate of Detergent 1 and that higher levels of additive (2.5 x LAC) provide for a significant reduction in intake valve deposit levels. In addition, significant flaking of deposits was observed in testing of the unadditized test fuels. Reduction of the test duration from 100 hours to 50 hours did not appear to significantly alter the results, especially for test conducted at 1 x LAC of Detergent 1 and may reduce the level of intake valve deposit flaking.

5. Technical Approach – Phase III Detail

The objective of Phase III was to verify that mainstream detergents provided acceptable deposit control response. One base fuel with three different market general detergent packages at three treat rates (1xLAC, 1.5xLAC, 2.5xLAC) were used and identified as follows:

- Fuel 3 – Fuel Supplier #1
- Detergent 1
- Detergent 2
- Detergent 3

The market general additive packages were provided in blind fashion to the CRC by the FATG for the additive response testing with their respective LAC treat rates. The additive samples were coded by Intertek so that the identities were not even known to the FATG submitters. The LAC treat rate was then used to generate an additive response curve for each additive package in Fuel 3.

The test cycle and operational targets used throughout Phase III were the same as used during Phase II. Nine tests were conducted. The test length for each test was 50 hours as demonstrated in Phase II that 50 hour tests can reduce flaking tendency versus the 100 hour tests.

To conform to engine build specifications, one engine block and two different cylinder heads were used during Phase II. The engine block and cylinder heads were different than those used in Phases I and II. See Annex A4 for details.

A summary of the nine-test matrix including the Stage 1 and 2 speed and load (controlled by intake manifold absolute pressure) targets are shown in Table 10.

Table 10 - Phase III Test Summary

TEST NUMBER	TEST FUEL	TEST LENGTH	STAGE 1		STAGE 2		Avg. IVD WEIGHTS
		(Hours)	SPEED (rpm)	MAP (kPa)	SPEED (rpm)	MAP (kPa)	(mg/Valve)
GMIVD91-022	Fuel 3	50	2000	29.2	2800	80.0	226.0
GMIVD91-023	Fuel 3 + Detergent 2 @ LAC	50	2000	29.2	2800	80.0	276.4
GMIVD91-024	Fuel 3 + Detergent 3 @ LAC	50	2000	29.2	2800	80.0	130.8
GMIVD91-025	Fuel 3 + Detergent 2 @ 1.5 x LAC	50	2000	29.2	2400	80.0	279.5
GMGDI91-026	Fuel 3 + Detergent 1 @ 1.5 x LAC	50	2000	29.2	2000	80.0	219.6
GMGDI91-027	Fuel 3 + Detergent 2 @ 1.5 x LAC	50	2000	29.2	2000	80.0	262.4
GMGDI91-028	Fuel 3 + Detergent 3 @ 1.5 x LAC	50	2000	29.2	2000	80.0	4.6
GMGDI91-029	Fuel 3 + Detergent 2 @ 2.5 x LAC	50	2000	29.2	2000	80.0	106.3
GMGDI91-030	Fuel 3 + Detergent 1 @ 2.5 x LAC	50	2000	29.2	2000	80.0	41.1
NOTE: Test 025, barometric sensor false reading caused ignition timing, cam timing & fuel flow to shift off typical values							

Test GMIVD91-025 was considered invalid due to the engine's barometric sensor giving a false reading which caused ignition timing, camshaft timing, and fuel flow to shift from historical values.

The intake valve deposit results for the Phase III additive response testing are shown in Figure 14. Detergents 1 and 2 were tested at 1, 1.5 and 2.5 x LAC while Detergent 3 was only tested at 1 and 1.5 x LAC. Several observations can be made from the results of Phase III testing. First, the "hump effect" is observed for Detergents 1 and 2 at their registered EPA LAC treat rates. The hump effect occurs when a low dosage of additive causes an increase in the deposit level of a fuel. This effect is known to the industry and is a result of the fuel, additive, test engine and test cycle.

Figure 14 shows that the deposit level increases from approximately 228 mg/valve for unadditized Fuel 3 to approximately 270 mg/valve for the 1 x LAC treated Fuel 3 using Detergents 1 and 2. These detergent additives are still within the hump effect even at 1.5 x LAC with Detergent 1 decreasing to about 220 mg/valve and Detergent 2 to 260 mg/valve.

Additional ASTM D6201 testing was conducted to determine if a similar effect would be seen in the Ford 2.3L engine. Fuel 3 had not been evaluated on the ASTM D6201 engine so a Phase IIIB program was run to evaluate intake valve deposit performance of this fuel unadditized and additized with 1 x LAC of Detergent 1. The results of this additional testing in comparison to the LE9 results are shown in Figure 15. Unadditized Fuel 3 shows 979 mg/valve while addition of 1 x LAC of Detergent 1 to Fuel 3 leads to an increase in deposits to 1,143 mg/valve (hump effect) in the D6201 test. The Fuel 3 performance with different detergent treat rates in the LE9 engine is also shown in Figure 15 with similar hump effect despite the absolute deposit weight difference between the two engines. At the same time, both engines showed good detergent response at 2.5X LAC, even though the 2.5x LAC in Ford 2.3 were results of Fuel A, not Fuel 3.

The LE9 engine operating with the conditions developed in Phases 1 and 2 can show IVD Keep Clean discrimination at higher treat rates. Detergents 1 and 2 provide significant IVD keep clean protection at a treat rate of 2.5 x LAC with deposits levels of 41 and 106 mg/valve, respectively. In addition, at all three treat rates tested, Detergents 1 and 2 show a similar performance trend. In sharp contrast, Detergent 3 provides significantly different deposit performance at the EPA LAC treat rate. The difference in performance for Detergent 3 results from the fact that this additive package utilized an alternative test method (§1090.1395 (a) Top Tier™ -Based Test Method) for certification of its EPA LAC treat rate. This leads to a significantly higher treat rate than is typically determined via the ASTM D5500 test method (§1090.1395 (c) EPA BMW method). As a result, the 1 x LAC performance of Detergent 3 cannot be directly compared to the 1 x LAC performance of Detergents 1 and 2. However, the IVD keep clean performance of Detergent 3 is consistent with the performance of Detergents 1 and 2 at 2.5 times their respective LAC treat rates.

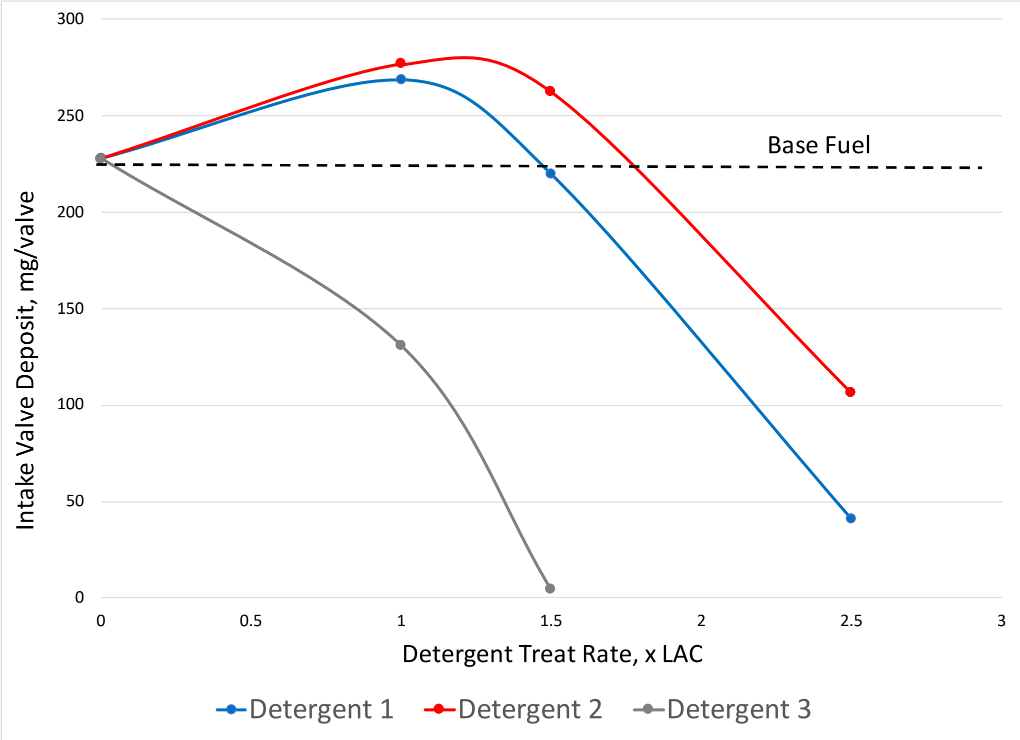

Figure 14 - Additive Response Testing Results

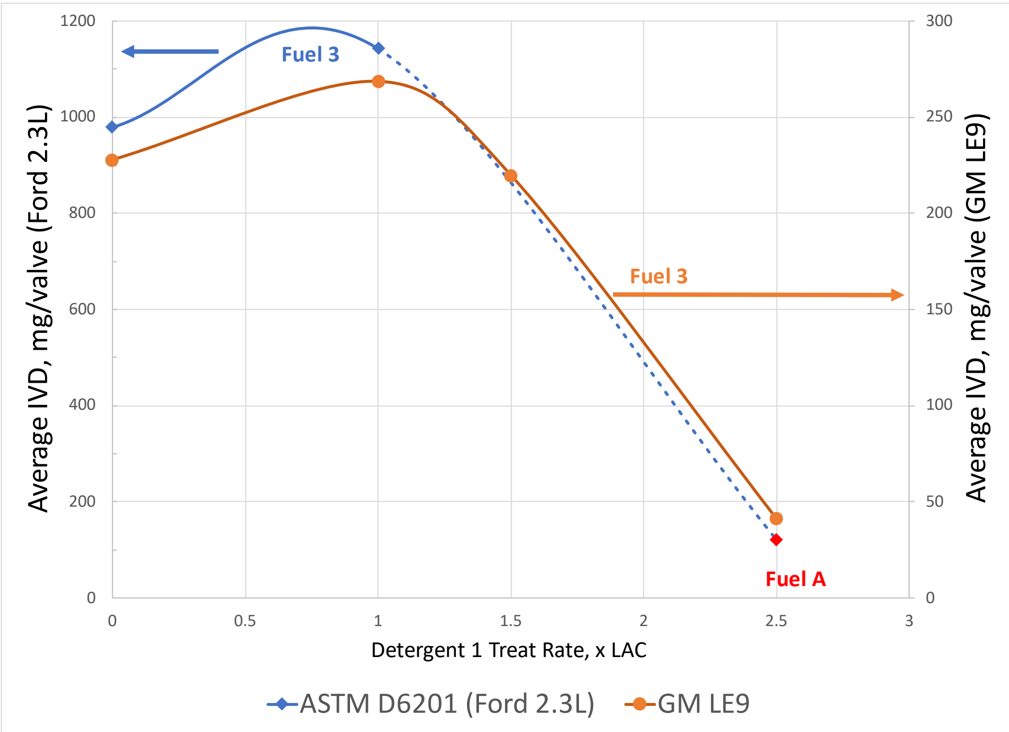

Figure 15 - Detergent 1 Response in Ford 2.3L and LE9

6. Data Detailed Summary – Initial Scoping Test Phase (ASTM D6201) and Phases I, II, & III

A detailed data summary of the intake valve deposit, piston top deposit, cylinder head deposit, induction system merit ratings, injector flow rates, fuel consumption, and oil consumption for all tests are shown in Annex A4.

7. Test Engine Detail – Injector Spray, Cylinder Head Configuration, & Intake Valve and Valve Spring Rotation Study

The following provides test engine detail that was gathered during the test program.

7.1 Fuel Injector Configuration and Spray

The test engine's cylinder head comprises of four valves per cylinder with dual intake ports. The fuel injectors utilize a dual spray pattern to inject fuel into the two ports. Pictures of the fuel injector and spray pattern are shown in Figure 16.

Fuel Injector – Side View | Fuel Injector – Tip | Dual Spray Pattern

Figure 16 - LE9 Fuel Injector & Spray Pattern Detail

7.2 Cylinder Head Configuration – Fuel Injector Ports, Intake Manifold Runner Ports, and Intake Valves

Figure 17 provides configuration detail relative to the fuel injector ports and the cylinder head's intake manifold runner ports and intake valves.

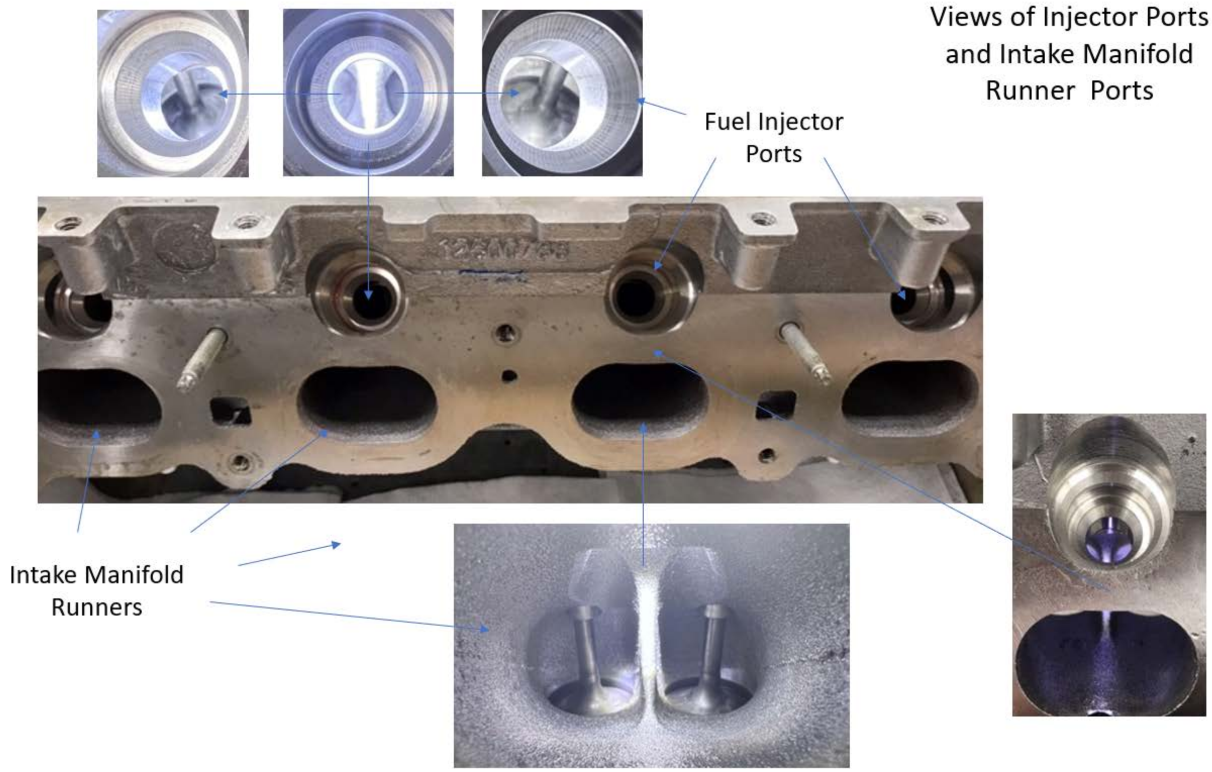

Figure 17 - LE9 Cylinder Head Detail

7.3 Intake Valve Assembly and Valve Rotation

A study was conducted during the test program to get an indication as to whether the intake valves were rotating during the test. To accomplish this, the intake valves and valve springs were indexed with a yellow paint marker prior to the start of test and inspected for rotation at the end of test. Movement of the paint mark would infer valve/spring rotation. In addition, the wear pattern on the tip of the valve was inspected. A linear wear pattern would infer that the valves were not rotating whereas the starburst wear pattern would indicate that the valves were rotating. Based on these two observations, it was found that rotation was minimal for any of the valves. Figures 18 through 20 provide detail of indexed intake valves and valve springs as well as a typical linear wear pattern on the tip of an intake valve.

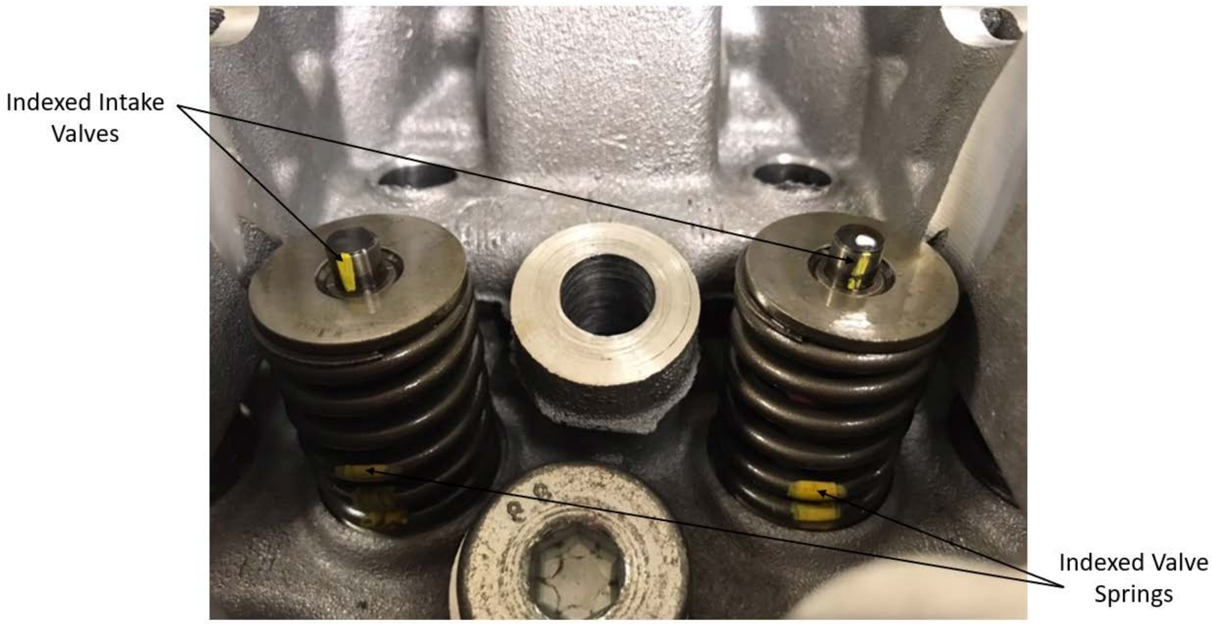

Figure 18 - Indexed Intake Valves and Valve Springs

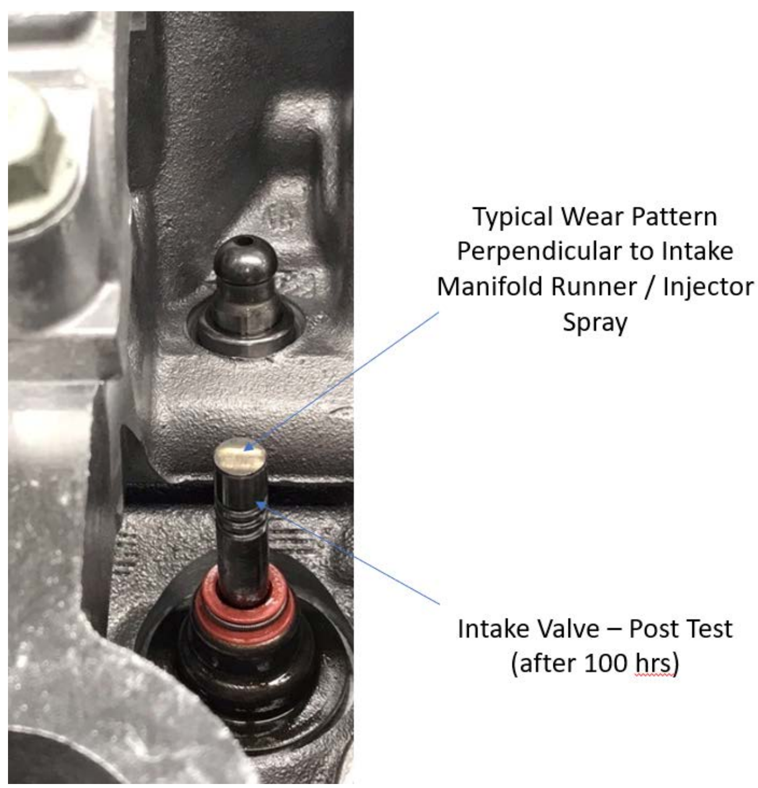

Figure 19 - Intake Valve Wear Pattern

Figure 20 - Wear Pattern on Intake Valve Tip

8. Operational Parameter Summary – Phases II & III

Table 11 summarizes the operational parameters that were utilized during Phases II and III.

Table 11 - Summary of Phase II & III Operational Parameters

CONTROL PARAMETERS	STAGE	1	2
	STAGE LENGTH (MIN)	4	8
	RAMP TIME BETWEEN STAGES (MIN)	0.5	0.5
		TARGET	
	ENGINE SPEED (R/MIN)	2000	2000
	MANIFOLD ABSOLUTE PRESSURE (kPaA)	29.2	80.0
	OIL GALLERY TEMP (DEG C)	101	101
	COOLANT TEMP ENGINE OUT (DEG C)	90	90
	INLET AIR TEMPERATURE (DEG C)	32	32
	FUEL TEMPERATURE (DEG C)	28	28
	INLET AIR PRESSURE (kPa)	0.05	0.05
	EXHAUST BACK PRESSURE (kPa)	102	105
	COOLANT FLOW (L/M)	45	45
	INLET AIR HUMIDITY (G/KG)	11.4	11.4

MONITORING PARAMETERS	AIR FUEL RATIO	RECORD
	FUEL FLOW (KG/HR)	RECORD
	OIL SUMP TEMPERATURE (DEG C)	RECORD
	COOLANT IN TEMPERATURE (DEG C)	RECORD
	EXHAUST TEMPERATURE, CYL 1 (DEG C)	RECORD
	EXHAUST TEMPERATURE, CYL 2 (DEG C)	RECORD
	EXHAUST TEMPERATURE, CYL 3 (DEG C)	RECORD
	EXHAUST TEMPERATURE, CYL 4 (DEG C)	RECORD
	INTAKE MANIFOLD TEMPERATURE (DEG C)	RECORD
	COOLANT IN PRESSURE, kPa	RECORD
	COOLANT OUT PRESSURE, kPa	RECORD
	OIL GALLERY PRESSURE (kPa)	RECORD

9. Observations and Discussion of Test Program Results

The goal of the CRC PFI IVD Test Development program was to define engine operating conditions which demonstrate the ability of a base fuel to generate IVD, and when additized with a deposit control additive generate reduced levels of deposits. We have defined operating conditions that can be used for IVD testing across a wide specification of base fuels. The test responds to varying levels of deposit control additives (DCA), across the variety of DCA chemistries available in the market today. The objectives of the first three phases of the program have been met.

Given the level of expertise in engine testing, fuels and fuel additives on our team, we would like to share observations that we made relative to the performance of the test. This includes what we have learned about base fuel, additives at their lowest additive concentration (LAC) and at 2½ times LAC relative to intake valve performance for EPA testing. The team acknowledged early on that direct comparison with the ASTM D5500 would be cost, time and equipment prohibitive. That said, we wanted to include some information relative to LAC performance in a discussion of the test results.

While the GM LE9 test is capable of generating differentiated IVD results based on additive treat rates, we were still limited by the number of tests available and the milligram of deposits per valve average results (one result per test). Is there a different approach to quantifying deposits that could be used?

The answer is yes. For each base fuel and additized test, Intertek's trained IVD raters used the CRC IVD Rating Scale to visually assign an IVD rating to every valve. Each valve in the test program was weighed for deposits and evaluated by a trained rater. The rating the scale is an industry excepted method for standardizing the level of an intake valve's cleanliness. A rating between 1 and 6 is severely deposited and would visibly restrict the flow of air and fuel to the engine. A rating between 7 and 8 is a visually dirty valve that could result in engine performance or emissions demerits. A rating of 9.0 is a visually clean valve and above 9.5 excellent or like new performance. Subject matter experts from ExxonMobil, Afton Chemical and Top Tier™ provided an evaluation and comparison of the IVD Ratings for valves in this program to those resulting from other tests using the Ford 2.3L and the GM LE9.

From the CRC IVD test development program, we used the Phase III testing on Fuel 3 to show groupings of dirty and clean valves based on IVD ratings. The dirty valves are from base fuel tests and tests that generated increased deposits due to the hump effect for DCA's observed in this test. The clean valves are from additized fuel tests where pronounced keep clean results were observed. The analysis of the grouping of IVD ratings vs IVD weight is provided in Figure 21.

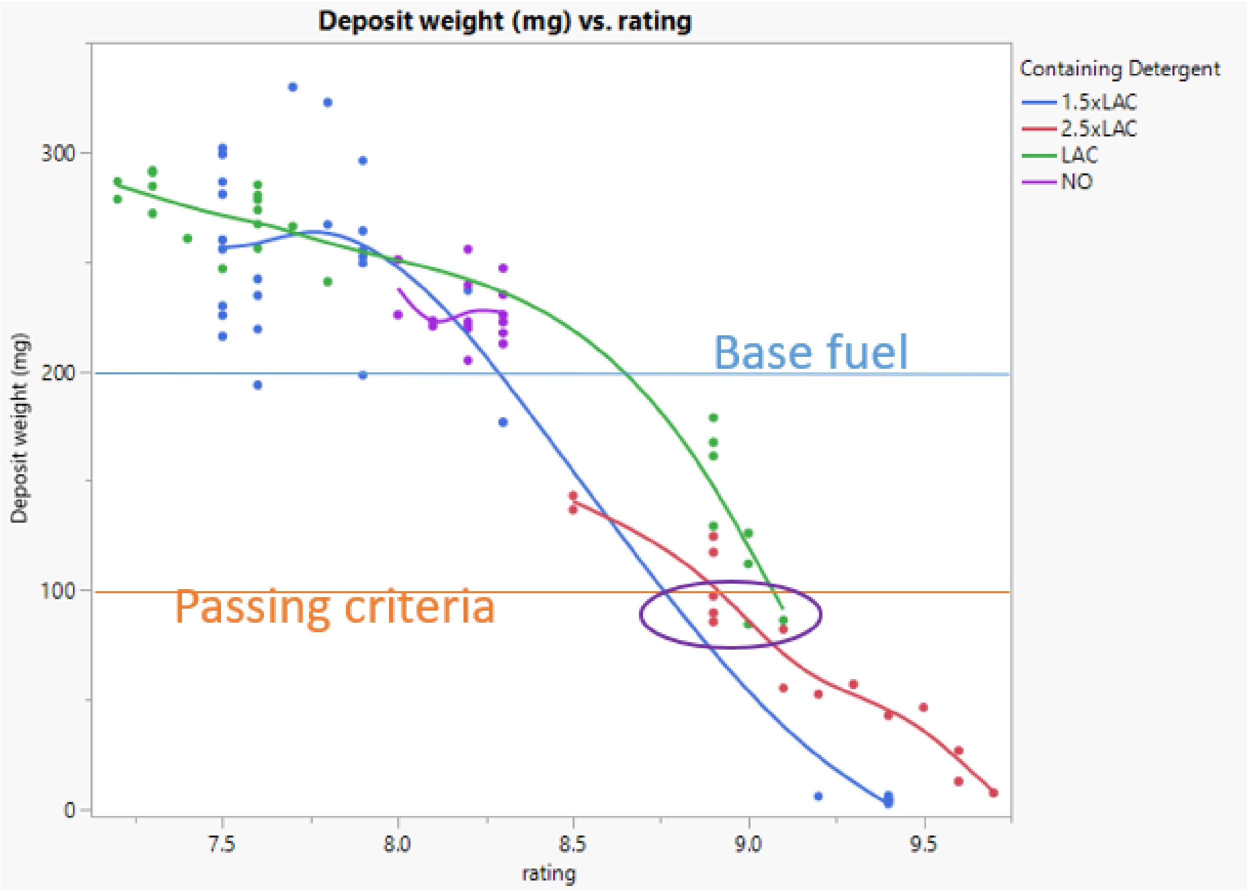

Figure 21 - Comparison of IVD Weight and CRC IVD Ratings Across 50-hr Run Time Testing on Fuel 3

The analysis showed that dirty valves in our test program had an IVD rating below 8.3. This could be used to set a minimum deposit level for the base fuel above 200 mg/valve average. Clean valves were observed to have an IVD rating higher than 8.8, which could be used to set a passing criterion for LAC treat rates at 100 mg/valve average. Examples of valves from our test program with less than 100 mg/valve are shown in Figure 22.

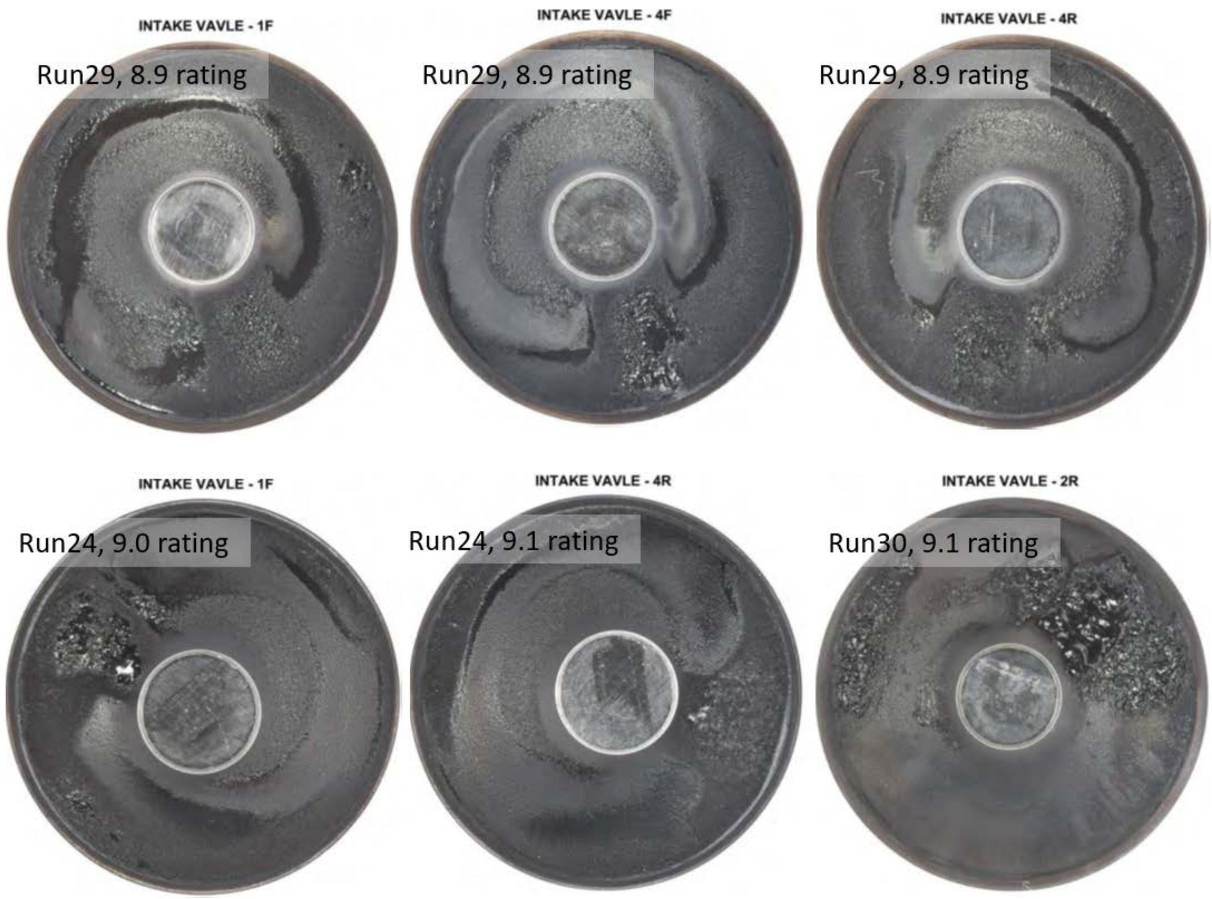

Figure 22 - Examples of Test Intake Valves with IVD less than 100 mg

Independent data from Top Tier™ and Afton using CRC IVD ratings from Ford 2.3l and GM LE9 testing showed similar results. In general, ratings below 8.0 were considered dirty valves and ratings of 8.5 – 9.0 and higher were considered clean valves.

ANNEX A1

PFI IVD TEST DEVELOPMENT PROJECT WORKSTREAM ROSTER

	Project Execution	Data Analysis	Test Fuel	Engine Testing	Additives	EPA & CARB
Bruce Alexander	x	x	x	Lead	x	x
Elena Chapman	x					
John Cruz	Lead					Lead
Garry Gunter	x	Lead				
Kim Johnson	x		Lead	x		x
Russ Lewis	x	x	x	x	x	x
Jo Martinez	x	Lead		x		
Rebecca Monroe	x					
Beth Raney-Pablo	x					
Matt Sheehan	Lead	x	x	x	Lead	Lead
Ruth Smocha	x		Lead			
Chris Tenant	x					
Jan Tucker	x					
Marie Valentine	x					
Yi Xu	x	x	x	Lead	x	x

Additive Companies						
Alex Kulinowski			x		x	x
Stuart Bartley			x		x	
Mike Neisen				x		
Sheril Reston					x	
George Szappanos				x		
Colleen Stevens					x	x
Specialty Fuels						
Bob Patzelt			x			
Indresh Mathur			x			
Jonathan VanScoyoc			x			

ANNEX A2

TEST PROGRAM BASE (UNADDITIZED) FUELS CERTIFICATE OF ANALYSIS DATA

Fuel Properties	Method	Units	Fuel Code			
			Fuel A	Fuel B	Fuel 3	Fuel 4
Specific Gravity	ASTM D4052	kg/L	0.7541	0.7623	0.7392	0.7382
API Gravity	ASTM D4052	°API	56.1	54.1	59.9	60.0
Vapor Pressure	ASTM D5191	psi	7.02	9.65	7.20	9.43
RON	ASTM D2699	Rating	92.3	100.6	92.6	94.2
MON	ASTM D2700	Rating	82.4	87.8	81.8	86.0
AKI	D2699/D2700	Calculation	87.4	94.2	87.2	90.1
Hydrogen	ASTM D5291	wt%	13.3	13.0	14.1	14.1
Hyrogen (CORRECTED)	Calculation	wt%	12.8	12.6	13.6	13.6
Carbon	ASTM D5291	wt%	86.7	83.6	85.9	82.5
Carbon (CORRECTED)	Calculation	wt%	83.8	80.8	83.0	79.7
Oxygen	ASTM D4815	wt%	3.39	3.35	3.41	3.45
Net Heat of Combustion	ASTM D240	BTU/lb	18,426	17,795	18,625	18,001
Existent Gums (Unwashed)	ASTM D381	mg/100 ml	1.0	6.0	<0.5	2.5
Existent Gums (Washed)	ASTM D381	mg/100 ml	<0.5	2.0	<0.5	<0.5
Oxidation Stability	ASTM D525	min	980	> 1000	980	> 1000
Copper Corrosion (3 hr @ 50 °C)	ASTM D130	Rating	1A	1A	1B	1A
Sulfur	ASTM D5453	ppm	19.3	30	13.1	12.7
Lead	ICP/OES	g/gal	<0.0009	ND	<0.0009	ND
Phosphorus	ICP/OES	g/gal	<0.001	ND	<0.001	ND
Distallation						
IBP	ASTM D86	°F	103	96	104	94.8
5%	ASTM D86	°F	128	124	131	121.1
10%	ASTM D86	°F	136	131	139	130.2
20%	ASTM D86	°F	145	141	148	141
30%	ASTM D86	°F	152	150	156	148.9
40%	ASTM D86	°F	162	166	195	161.2
50%	ASTM D86	°F	208	214	217	206.7
60%	ASTM D86	°F	222	232	229	222.5
70%	ASTM D86	°F	232	247	239	244.6
80%	ASTM D86	°F	253	276	262	267.6
90%	ASTM D86	°F	312	349	315	313.2
95%	ASTM D86	°F	361	364	353	335.6
FBP	ASTM D86	°F	406	400	388	377.0
Recovery	ASTM D86	vol%	97.1	98.4	97.2	97.9
Loss	ASTM D86	vol%	1.8	1.1	1.7	1.0
Residue	ASTM D86	vol%	1.1	0.5	1.1	1.1
Aromatics, vol%	ASTM D1319	vol%	31.6	37.5	19.1	18.9
Aromatics (CORRECTED), vol%	Calculation	vol%	28.6	34.0	17.4	17.2
Olefins, vol%	ASTM D1319	vol%	10.4	13.2	7.1	6.7
Olefins (CORRECTED), vol%	Calculation	vol%	9.4	12.0	6.5	6.1
Saturates, vol%	ASTM D1319	vol%	58.0	49.3	73.8	74.4
Saturates (CORRECTED), vol%	Calculation	vol%	52.5	44.7	67.1	67.6
Ethanol, vol%	ASTM D1319	vol%	9.5	9.3	9.1	9.2

ANNEX A3

GENERAL MOTORS LE9 INTAKE VALVE TEMPERATURE MAPPING

LE9 Intake Valve Temperature Mapping

- **Steady state temperature mapping, coolant (85 - 95C), ambient temp. (70 -80 F)**
- **Yellow cell is our current standard 2-hour cycle test point**
- **Tan cell is a higher speed test point shown on a previous slide.**
- **Red border shows max IVT for a given engine load (generally decreases with fuel enrichment)**

TC: 1a				
Eng_Speed	P_Map (kPa)			
	40	60	80	95
800	149.1	176.5	177.0	159.8
1200	193.3	210.7	182.4	131.3
1600	198.9	209.8	205.1	193.2
2000	194.1	212.4	230.6	244.3
2400	207.0	256.6	244.9	183.4
2800	224.7	258.6	184.5	160.0

TC: 3a				
Eng_Speed	P_Map (kPa)			
	40	60	80	95
800	146.4	160.6	147.7	159.1
1200	179.7	201.8	155.0	94.9
1600	182.7	194.3	212.1	179.3
2000	176.5	198.1	226.4	201.2
2400	196.3	255.7	233.7	148.5
2800	219.0	270.0	155.3	115.9

TC: 4b				
Eng_Speed	P_Map (kPa)			
	40	60	80	95
800	150.7	172.6	168.3	147.9
1200	193.4	212.2	176.1	112.9
1600	197.6	214.9	211.4	196.1
2000	193.0	218.4	243.7	262.8
2400	209.5	260.1	242.3	178.0
2800	226.1	289.8	231.0	149.1

Dataset Provided by General Motors

Valve Temp (Deg C)

TC: 1a

Engine Speed RPM	MAP (kPa) 40	60	80	95
800	149.1	176.5	177.0	159.8
1200	193.3	210.7	182.4	131.3
1600	198.9	209.8	205.1	193.2
2000	194.1	212.4	230.6	244.3
2400	207.0	256.6	244.9	183.4
2800	224.7	258.6	184.5	160.0

TC: 3a

Engine Speed RPM	MAP (kPa) 40	60	80	95
800	146.4	160.6	147.7	159.1
1200	179.7	201.8	155.0	94.9
1600	182.7	194.3	212.1	179.3
2000	176.5	198.1	226.4	201.2
2400	196.3	255.7	233.7	148.5
2800	219.0	270.0	155.3	115.9

TC: 4b

Engine Speed RPM	MAP (kPa) 40	60	80	95
800	150.7	172.6	168.3	147.9
1200	193.4	212.2	176.1	112.9
1600	197.6	214.9	211.4	196.1
2000	193.0	218.4	243.7	262.8
2400	209.5	260.1	242.3	178.0
2800	226.1	289.8	231.0	149.1

Avg of TC 1a, 3a, 4b

Engine Speed RPM	MAP (kPa) 40	60	80	95
800	148.7	169.9	164.3	155.6
1200	188.8	208.2	171.2	113.0
1600	193.1	206.3	209.5	189.5
2000	187.9	209.6	233.6	236.1
2400	204.3	257.5	240.3	170.0
2800	223.3	272.8	190.3	141.7

Proposed Speed / MAP Points Based on GM Dataset

* Points in red are interpolated

232 deg C Valve Temperature Speed / MAP points.

Engine Speed RPM	MAP (kPa) 40	43.5	47.1	50.4	60	80	95
800	148.7				169.9	164.3	155.6
1200	188.8				208.2	171.2	113.0
1600	193.1				206.3	209.5	189.5
2000	187.9				209.6	233.6	236.1
2200	196.1				233.6		
2400	204.3			232.0	257.5	240.3	170.0
2600	213.8		232.0		265.2		
2800	223.3	232.0			272.8	190.3	141.7

SUMMARY - 232 deg C Valve Temperature Speed / MAP points.

SPEED (RPM)	MAP (kPa)
2000	80
2200	60
2400	50.4
2600	47.1
2800	43.5

232 deg C +/- 20 deg C Speed / MAP points

Engine Speed RPM	MAP (kPa) 40	42.3	50.4	57.9	60
2400	204.3	212.0	232.0	252.0	257.5
	40	39.3	47.1	54.9	60
2600	213.8	212.0	232.0	252.0	265.2
	40	35.4	43.5	51.6	60
2800	223.3	212.0	232.0	252.0	272.8

ANNEX A4

DETAILED DATA SUMMARY INCLUDING INITIAL SCOPING TEST PHASE (ASTM D6201) AND PHASES I, II, & III

INTAKE VALVE DEPOSIT, PISTON TOP DEPOSIT, CYLINDER HEAD DEPOSIT, INDUCTION SYSTEM MERIT RATINGS, INJECTOR FLOW RATES, FUEL CONSUMPTION, AND OIL CONSUMPTION

COORDINATING RESEARCH COUNCIL
INTAKE VALVE DEPOSIT TEST DEVELOPMENT PROGRAM
DATA SUMMARY - INTAKE VALVE DEPOSIT WEIGHTS
Performed at INTERTEK

ASTM D6201 TEST SUMMARY

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	IVD WEIGHTS (mg) Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average
IVD9-288	Fuel A	7/23/2021	7/27/2021	20180420	34	854.2	987.5	896.6	839.2	**894.4**
IVD9-292	Fuel B	8/27/2021	8/31/2021	20180420	34	954.9	908.6	684.2	1074.9	**905.7**
IVD9-294A	Fuel A + Detergent 1 @ 2.5xLAC	10/7/2021	10/11/2021	20180420	34	41.4	29.5	364.6	46.5	**120.5**
IVD9-295	Fuel B + Detergent 1 @ 2.5xLAC	10/15/2021	10/19/2021	20180420	34	216.4	40.4	267.1	79.6	**150.9**

GMIVD LE9 TEST SUMMARY - PHASE I

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	IVD WEIGHTS (mg) 1F	1R	2F	2R	3F	3R	4F	4R	Average
GMIVD91-001A	Fuel A	8/11/2021	8/15/2021	LE9152330222	JR22UU008U	100	2800	43.5	57.3	64.5	48.6	80.7	89.1	71.6	87.7	94.0	**74.2**
GMIVD91-002	Fuel A	8/18/2021	8/22/2021	LE9152330222	JR22UU008U	100	2800	51.6	49.8	52.9	50.7	83.4	104.9	62.1	67.2	70.2	**67.7**
GMIVD91-003	Fuel A	8/25/2021	8/29/2021	LE9152330222	JR22UU008U	100	2800	66.5	112.5	79.4	71.0	174.0	85.5	121.3	63.4	101.4	**101.1**
GMIVD91-004	Fuel A	9/1/2021	9/5/2021	LE9152330222	JR22UU008U	100	2400	66.5	128.0	94.1	129.4	95.7	135.8	126.0	154.0	136.7	**125.0**
GMIVD91-005	Fuel A	9/9/2021	9/13/2021	LE9152330222	JR22UU008U	100	2000	80.0	390.3	335.6	363.7	366.2	356.7	388.7	390.2	410.7	**375.3**
GMIVD91-006	Fuel B	9/16/2021	9/20/2021	LE9152330222	JR22UU008U	100	2000	80.0	395.8	391.3	330.2	341.5	347.8	361.9	368.6	354.0	**361.4**
GMIVD91-007	Fuel A + Detergent 1 @ 2.5xLAC	10/1/2021	10/5/2021	LE9152330222	JR22UU008U	100	2000	80.0	10.2	35.6	31.1	12.1	51.2	9.9	7.3	6.9	**20.5**
GMIVD91-008	Fuel B + Detergent 1 @ 2.5xLAC	10/8/2021	10/12/2021	LE9152330222	JR22UU008U	100	2000	80.0	18.6	33.6	138.7	144.6	62.1	69.5	58.0	26.6	**69.0**

GMIVD LE9 TEST SUMMARY - PHASE II

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	IVD WEIGHTS (mg) 1F	1R	2F	2R	3F	3R	4F	4R	Average
GMIVD91-009	Fuel B	12/9/2021	12/13/2021	94520451	JR22U80165	100	2000	80.0	198.1	128.7	217.9	220.6	231.2	194.9	267.1	171.8	**203.8**
GMIVD91-010	Fuel B + Detergent 1 @ 2.5xLAC	12/17/2021	12/22/2021	94520451	JR22U80165	100	2000	80.0	99.8	112.6	129.2	90.9	104.2	145.0	75.9	164.6	**115.3**
GMIVD91-011	Fuel B + Detergent 1 @ LAC	12/30/2021	1/3/2022	94520451	JR22U80165	100	2000	80.0	272.2	257.2	235.9	239.9	254.4	224.8	264.0	189.3	**242.2**
GMIVD91-012	Fuel A	1/21/2022	1/25/2022	94520451	JR22U80196	100	2000	80.0	392.5	377.6	220.2	252.2	304.6	297.2	343.2	413.6	**325.1**
GMIVD91-013	Fuel A + Detergent 1 @ 2.5xLAC	1/28/2022	2/1/2022	94520451	JR22U80196	100	2000	80.0	11.1	23.5	77.2	45.1	49.2	50.2	20.5	75.1	**44.0**
GMIVD91-014	Fuel A + Detergent 1 @ LAC	2/4/2022	2/8/2022	94520451	JR22U80196	100	2000	80.0	304.5	344.0	298.2	289.6	333.2	285.5	335.1	371.3	**320.2**
GMIVD91-015	Fuel 3	2/11/2022	2/15/2022	94520451	JR22760231	100	2000	80.0	395.8	333.4	326.0	329.1	414.9	356.1	454.2	380.5	**373.8**
GMIVD91-016	Fuel 3	2/18/2022	2/22/2022	94520451	JR22760231	100	2000	80.0	218.6	314.9	331.8	282.8	371.1	311.9	286.7	45.8	**270.5**
GMIVD91-017	Fuel 3 + Detergent 1 @ 2.5 x LAC	3/5/2022	3/9/2022	94521309	JR22U80215	100	2000	80.0	66.9	30.9	211.1	217.0	19.5	61.1	8.3	14.6	**78.7**
GMIVD91-018	Fuel 4	3/11/2022	3/16/2022	94521309	JR22U80215	100	2000	80.0	303.5	267.4	278.0	245.5	279.1	281.6	293.2	241.4	**273.7**
GMIVD91-019	Fuel 4 + Detergent 1 @ LAC	3/18/2022	3/21/2022	94521309	JR22U80215	100	2000	80.0	340.7	361.9	290.3	288.4	283.0	330.3	295.4	296.9	**310.9**
GMIVD91-020 @ 50 Hours	Fuel 3	4/22/2022	4/25/2022	94521309	JR22U80215	50	2000	80.0	255.6	219.4	222.5	225.7	235.0	212.6	247.0	217.5	**229.4**
GMIVD91-021 @ 50 Hours	Fuel 3 + Detergent 1 @ LAC	4/29/2022	5/1/2022	94521309	JR22U80215	50	2000	80.0	278.3	256.1	285.1	266.1	273.6	267.1	280.3	240.9	**268.4**

NOTE: Test 016, Cylinder 4 IVD affected by mechancial issue with Cylinder 4/High Oil Consumption

GMIVD LE9 TEST SUMMARY - PHASE III

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	IVD WEIGHTS (mg) 1F	1R	2F	2R	3F	3R	4F	4R	Average
GMIVD91-022	Fuel 3	7/29/2022	8/2/2022	94522369	JR22220275	50	2000	80.0	250.9	204.9	225.7	221.0	239.4	223.0	222.7	220.7	**226.0**
GMIVD91-023	Fuel 3 + Detergent 2 @ LAC	8/5/2022	8/8/2022	94522369	JR22220275	50	2000	80.0	290.8	286.6	291.5	260.6	272.0	278.5	284.4	246.8	**276.4**
GMIVD91-024	Fuel 3 + Detergent 3 @ LAC	8/12/2022	8/14/2022	94522369	JR22220275	50	2000	80.0	84.5	161.3	129.3	178.8	112.1	167.5	126.1	86.4	**130.8**
GMIVD91-025	Fuel 3 + Detergent 2 @ 1.5 x LAC	8/19/2022	8/22/2022	94522369	JR22220275	50	2000	80.0	266.9	329.7	264.0	249.3	322.6	255.2	296.1	252.3	**279.5**
GMGDI91-026	Fuel 3 + Detergent 1 @ 1.5 x LAC	8/26/2022	8/28/2022	94522369	JR22220275	50	2000	80.0	219.2	215.9	229.8	198.2	286.4	193.7	236.9	176.7	**219.6**
GMGDI91-027	Fuel 3 + Detergent 2 @ 1.5 x LAC	9/9/2022	9/12/2022	94522369	JR22270231	50	2000	80.0	299.0	255.7	260.0	234.5	280.8	225.5	301.7	242.1	**262.4**
GMGDI91-028	Fuel 3 + Detergent 3 @ 1.5 x LAC	9/16/2022	9/18/2022	94522369	JR22270231	50	2000	80.0	6.4	3.8	4.9	4.5	6.0	4.3	4.1	2.7	**4.6**
GMGDI91-029	Fuel 3 + Detergent 2 @ 2.5 x LAC	9/23/2022	9/25/2022	94522369	JR22270231	50	2000	80.0	97.5	117.4	136.8	143.3	124.7	55.4	89.7	85.7	**106.3**
GMGDI91-030	Fuel 3 + Detergent 1 @ 2.5 x LAC	9/30/2022	10/2/2022	94522369	JR22270231	50	2000	80.0	26.9	57.2	46.6	82.3	52.6	12.8	42.9	7.6	**41.1**

NOTE: Test 022, borescope inspection at 25 hours. Photos were taken of the intake valves.

NOTE: Test 025, barometric sensor false reading caused ignition timing, cam timing & fuel flow to shift off typical values

COORDINATING RESEARCH COUNCIL
INTAKE VALVE DEPOSIT TEST DEVELOPMENT PROGRAM
DATA SUMMARY - INTAKE VALVE DEPOSIT WEIGHTS
Performed at INTERTEK

ASTM D6201 TEST SUMMARY

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	PTD WEIGHTS (mg)					CHD WEIGHTS (mg)				
						Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average
IVD9-288	Fuel A	7/23/2021	7/27/2021	20180420	34	375.9	585.2	372.0	500.0	**458.3**	638.1	969.6	676.2	762.1	**761.5**
IVD9-292	Fuel B	8/27/2021	8/31/2021	20180420	34	603.5	595.4	385.8	603.4	**547.0**	874.8	947.5	813.2	921.2	**889.2**
IVD9-294A	Fuel A + Detergent 1 @ 2.5xLAC	10/7/2021	10/11/2021	20180420	34	559.8	744.6	603.3	601.7	**627.4**	751.2	902.1	818.0	778.1	**812.4**
IVD9-295	Fuel B + Detergent 1 @ 2.5xLAC	10/15/2021	10/19/2021	20180420	34	639.0	622.9	711.0	1125.1	**774.5**	926.6	989.4	1022.7	1218.7	**1039.4**

GMIVD LE9 TEST SUMMARY - PHASE I

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	PTD WEIGHTS (mg)					CHD WEIGHTS (mg)				
									Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average
GMIVD91-001A	Fuel A	8/11/2021	8/15/2021	LE9152330222	JR22UU008U	100	2800	43.5	208.6	261.5	353.6	209.5	**258.3**	240.6	210.8	246.6	301.7	**249.9**
GMIVD91-002	Fuel A	8/18/2021	8/22/2021	LE9152330222	JR22UU008U	100	2800	51.6	181.0	244.1	255.0	164.9	**211.3**	131.1	241.6	143.8	154.2	**167.7**
GMIVD91-003	Fuel A	8/25/2021	8/29/2021	LE9152330222	JR22UU008U	100	2800	66.5	111.3	92.3	47.8	55.5	**76.7**	37.2	76.2	45.0	42.1	**50.1**
GMIVD91-004	Fuel A	9/1/2021	9/5/2021	LE9152330222	JR22UU008U	100	2400	66.5	276.4	184.1	147.7	175.4	**195.9**	85.1	66.7	62.8	48.0	**65.7**
GMIVD91-005	Fuel A	9/9/2021	9/13/2021	LE9152330222	JR22UU008U	100	2000	80.0	419.8	271.7	131.0	102.7	**231.3**	95.7	54.7	67.1	49.3	**66.7**
GMIVD91-006	Fuel B	9/16/2021	9/20/2021	LE9152330222	JR22UU008U	100	2000	80.0	381.4	228.3	139.9	111.3	**215.2**	109.4	61.9	39.6	34.6	**61.4**
GMIVD91-007	Fuel A + Detergent 1 @ 2.5xLAC	10/1/2021	10/5/2021	LE9152330222	JR22UU008U	100	2000	80.0	671.1	387.2	289.9	247.2	**398.9**	222.0	123.8	63.9	70.9	**120.2**
GMIVD91-008	Fuel B + Detergent 1 @ 2.5xLAC	10/8/2021	10/12/2021	LE9152330222	JR22UU008U	100	2000	80.0	937.0	526.2	356.3	343.0	**540.6**	545.7	185.4	90.6	79.0	**225.2**

GMIVD LE9 TEST SUMMARY - PHASE II

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	PTD WEIGHTS (mg)					CHD WEIGHTS (mg)				
									Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average
GMIVD91-009	Fuel B	12/9/2021	12/13/2021	94520451	JR22U80165	100	2000	80.0	242.2	105.6	137.5	217.9	**175.8**	71.6	54.8	72.4	93.9	**73.2**
GMIVD91-010	Fuel B + Detergent 1 @ 2.5xLAC	12/17/2021	12/22/2021	94520451	JR22U80165	100	2000	80.0	198.8	287.3	363.9	190.4	**260.1**	55.3	77.9	61.7	53.1	**62.0**
GMIVD91-011	Fuel B + Detergent 1 @ LAC	12/30/2021	1/3/2022	94520451	JR22U80165	100	2000	80.0	195.2	299.2	332.1	227.7	**263.6**	70.0	85.2	131.0	91.6	**94.5**
GMIVD91-012	Fuel A	1/21/2022	1/25/2022	94520451	JR22U80196	100	2000	80.0	153.1	330.9	440.2	163.4	**271.9**	34.7	54.5	80.5	33.5	**50.8**
GMIVD91-013	Fuel A + Detergent 1 @ 2.5xLAC	1/28/2022	2/1/2022	94520451	JR22U80196	100	2000	80.0	290.8	336.6	497.9	333.0	**364.6**	61.7	54.2	93.9	59.3	**67.3**
GMIVD91-014	Fuel A + Detergent 1 @ LAC	2/4/2022	2/8/2022	94520451	JR22U80196	100	2000	80.0	166.0	412.0	404.5	199.1	**295.4**	96.5	92.2	96.2	69.7	**88.7**
GMIVD91-015	Fuel 3	2/11/2022	2/15/2022	94520451	JR22760231	100	2000	80.0	144.9	315.1	560.2	192.5	**303.2**	38.4	97.0	117.0	41.9	**73.6**
GMIVD91-016	Fuel 3	2/18/2022	2/22/2022	94520451	JR22760231	100	2000	80.0	517.3	646.8	861.9	2576.3	**1150.6**	92.0	151.9	162.3	812.2	**304.6**
GMIVD91-017	Fuel 3 + Detergent 1 @ 2.5 x LAC	3/5/2022	3/9/2022	94521309	JR22U80215	100	2000	80.0	386.2	304.7	294.4	296.8	**320.5**	52.3	20.3	31.9	35.0	**34.9**
GMIVD91-018	Fuel 4	3/11/2022	3/16/2022	94521309	JR22U80215	100	2000	80.0	129.9	195.8	170.7	130.1	**156.6**	10.0	11.3	18.8	6.1	**11.6**
GMIVD91-019	Fuel 4 + Detergent 1 @ LAC	3/18/2022	3/21/2022	94521309	JR22U80215	100	2000	80.0	486.9	248.0	263.2	596.2	**398.6**	57.9	29.4	62.0	60.8	**52.5**
GMIVD91-020 @ 50 Hours	Fuel 3	4/22/2022	4/25/2022	94521309	JR22U80215	50	2000	80.0	449.3	275.9	279.1	515.7	**380.0**	48.5	35.5	40.5	57.2	**45.4**
GMIVD91-021 @ 50 Hours	Fuel 3 + Detergent 1 @ LAC	4/29/2022	5/1/2022	94521309	JR22U80215	50	2000	80.0	440.4	434.1	324.2	477.5	**419.1**	54.9	70.3	81.2	80.4	**71.7**

NOTE: Test 016, Cylinder 4 IVD affected by mechancial issue with Cylinder 4/High Oil Consumption

GMIVD LE9 TEST SUMMARY - PHASE III

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	PTD WEIGHTS (mg)					CHD WEIGHTS (mg)				
									Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average	Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average
GMIVD91-022	Fuel 3	7/29/2022	8/2/2022	94522369	JR22220275	50	2000	80.0	102.1	94.0	71.7	79.3	**86.8**	28.3	20.7	17.8	26.5	**23.3**
GMIVD91-023	Fuel 3 + Detergent 2 @ LAC	8/5/2022	8/8/2022	94522369	JR22220275	50	2000	80.0	152.0	215.7	128.3	140.6	**159.2**	51.2	42.0	24.4	28.7	**36.6**
GMIVD91-024	Fuel 3 + Detergent 3 @ LAC	8/12/2022	8/14/2022	94522369	JR22220275	50	2000	80.0	244.2	192.9	160.9	207.9	**201.5**	57.0	54.1	56.0	45.8	**53.2**
GMIVD91-025	Fuel 3 + Detergent 2 @ 1.5 x LAC	8/19/2022	8/22/2022	94522369	JR22220275	50	2000	80.0	187.8	192.9	142.2	124.3	**161.8**	53.2	68.6	45.9	57.9	**56.4**
GMGDI91-026	Fuel 3 + Detergent 1 @ 1.5 x LAC	8/26/2022	8/28/2022	94522369	JR22220275	50	2000	80.0	149.1	129.6	172.8	212.4	**166.0**	76.8	61.6	64.5	73.6	**69.1**
GMGDI91-027	Fuel 3 + Detergent 2 @ 1.5 x LAC	9/9/2022	9/12/2022	94522369	JR22270231	50	2000	80.0	347.4	214.2	303.3	165.1	**257.5**	106.4	53.8	59.3	46.5	**66.5**
GMGDI91-028	Fuel 3 + Detergent 3 @ 1.5 x LAC	9/16/2022	9/18/2022	94522369	JR22270231	50	2000	80.0	338.7	325.4	365.9	176.3	**301.6**	93.5	75.2	101.8	85.7	**89.1**
GMGDI91-029	Fuel 3 + Detergent 2 @ 2.5 x LAC	9/23/2022	9/25/2022	94522369	JR22270231	50	2000	80.0	232.6	245.1	237.7	148.3	**215.9**	77.1	74.3	134.0	74.3	**89.9**
GMGDI91-030	Fuel 3 + Detergent 1 @ 2.5 x LAC	9/30/2022	10/2/2022	94522369	JR22270231	50	2000	80.0	308.3	236.9	275.2	163.0	**245.9**	56.3	48.5	85.2	65.8	**64.0**

NOTE: Test 022, borescope inspection at 25 hours. Photos were taken of the intake valves.
NOTE: Test 025, barometric sensor false reading caused ignition timing, cam timing & fuel flow to shift off typical values

COORDINATING RESEARCH COUNCIL
INTAKE VALVE DEPOSIT TEST DEVELOPMENT PROGRAM
DATA SUMMARY - INTAKE VALVE DEPOSIT WEIGHTS
Performed at INTERTEK

ASTM D6201 TEST SUMMARY

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	MERIT RATINGS (Average of all Four Cylinders) Int Val Tulip	Int Port	Int Head Rnr	Piston Top	Cyl Head
IVD9-288	Fuel A	7/23/2021	7/27/2021	20180420	34	6.65	8.98	9.36	7.05	7.09
IVD9-292	Fuel B	8/27/2021	8/31/2021	20180420	34	7.52	9.26	9.67	7.52	7.07
IVD9-294A	Fuel A + Detergent 1 @ 2.5xLAC	10/7/2021	10/11/2021	20180420	34	9.25	9.59	9.43	7.10	7.08
IVD9-295	Fuel B + Detergent 1 @ 2.5xLAC	10/15/2021	10/19/2021	20180420	34	8.95	8.07	9.45	7.88	7.41

GMIVD LE9 TEST SUMMARY - PHASE I

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	MERIT RATINGS (Average of all Four Cylinders) Int Val Tulip	Int Port	Int Head Rnr	Piston Top	Cyl Head
GMIVD91-001A	Fuel A	8/11/2021	8/15/2021	LE9152330222	JR22UU008U	100	2800	43.5	9.15	8.55	8.50	7.16	7.16
GMIVD91-002	Fuel A	8/18/2021	8/22/2021	LE9152330222	JR22UU008U	100	2800	51.6	8.85	8.82	8.50	7.02	7.54
GMIVD91-003	Fuel A	8/25/2021	8/29/2021	LE9152330222	JR22UU008U	100	2800	66.5	9.00	8.69	8.76	8.49	9.09
GMIVD91-004	Fuel A	9/1/2021	9/5/2021	LE9152330222	JR22UU008U	100	2400	66.5	8.65	8.50	8.72	7.68	8.74
GMIVD91-005	Fuel A	9/9/2021	9/13/2021	LE9152330222	JR22UU008U	100	2000	80.0	7.70	8.54	9.62	7.46	9.37
GMIVD91-006	Fuel B	9/16/2021	9/20/2021	LE9152330222	JR22UU008U	100	2000	80.0	7.78	8.50	9.89	7.67	9.00
GMIVD91-007	Fuel A + Detergent 1 @ 2.5xLAC	10/1/2021	10/5/2021	LE9152330222	JR22UU008U	100	2000	80.0	9.16	9.06	9.44	7.02	9.06
GMIVD91-008	Fuel B + Detergent 1 @ 2.5xLAC	10/8/2021	10/12/2021	LE9152330222	JR22UU008U	100	2000	80.0	9.10	8.93	9.80	7.29	8.83

GMIVD LE9 TEST SUMMARY - PHASE II

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	MERIT RATINGS (Average of all Four Cylinders) Int Val Tulip	Int Port	Int Head Rnr	Piston Top	Cyl Head
GMIVD91-009	Fuel B	12/9/2021	12/13/2021	94520451	JR22U80165	100	2000	80.0	8.21	8.05	9.80	8.16	8.93
GMIVD91-010	Fuel B + Detergent 1 @ 2.5xLAC	12/17/2021	12/22/2021	94520451	JR22U80165	100	2000	80.0	8.85	9.34	9.88	7.05	9.08
GMIVD91-011	Fuel B + Detergent 1 @ LAC	12/30/2021	1/3/2022	94520451	JR22U80165	100	2000	80.0	8.54	9.09	9.90	7.32	9.18
GMIVD91-012	Fuel A	1/21/2022	1/25/2022	94520451	JR22U80196	100	2000	80.0	7.36	5.97	9.43	7.84	9.06
GMIVD91-013	Fuel A + Detergent 1 @ 2.5xLAC	1/28/2022	2/1/2022	94520451	JR22U80196	100	2000	80.0	8.71	8.20	9.44	7.48	8.98
GMIVD91-014	Fuel A + Detergent 1 @ LAC	2/4/2022	2/8/2022	94520451	JR22U80196	100	2000	80.0	7.15	8.93	9.55	7.36	9.04
GMIVD91-015	Fuel 3	2/11/2022	2/15/2022	94520451	JR22760231	100	2000	80.0	7.21	8.03	9.69	7.21	9.09
GMIVD91-016	Fuel 3	2/18/2022	2/22/2022	94520451	JR22760231	100	2000	80.0	7.60	7.74	9.72	6.90	8.58
GMIVD91-017	Fuel 3 + Detergent 1 @ 2.5 x LAC	3/5/2022	3/9/2022	94521309	JR22U80215	100	2000	80.0	8.78	8.61	9.66	7.31	9.10
GMIVD91-018	Fuel 4	3/11/2022	3/16/2022	94521309	JR22U80215	100	2000	80.0	7.99	7.00	9.80	7.07	9.08
GMIVD91-019	Fuel 4 + Detergent 1 @ LAC	3/18/2022	3/21/2022	94521309	JR22U80215	100	2000	80.0	7.40	7.78	9.80	7.08	9.19
GMIVD91-020 @ 50 Hours	Fuel 3	4/22/2022	4/25/2022	94521309	JR22U80215	50	2000	80.0	8.28	7.50	9.90	7.39	9.22
GMIVD91-021 @ 50 Hours	Fuel 3 + Detergent 1 @ LAC	4/29/2022	5/1/2022	94521309	JR22U80215	50	2000	80.0	7.64	7.00	9.80	7.24	9.10

NOTE: Test 016, Cylinder 4 IVD affected by mechancial issue with Cylinder 4/High Oil Consumption

GMIVD LE9 TEST SUMMARY - PHASE III

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	MERIT RATINGS (Average of all Four Cylinders) Int Val Tulip	Int Port	Int Head Rnr	Piston Top	Cyl Head
GMIVD91-022	Fuel 3	7/29/2022	8/2/2022	94522369	JR22220275	50	2000	80.0	8.12	8.68	9.90	7.86	9.45
GMIVD91-023	Fuel 3 + Detergent 2 @ LAC	8/5/2022	8/8/2022	94522369	JR22220275	50	2000	80.0	7.31	9.47	9.89	7.95	9.42
GMIVD91-024	Fuel 3 + Detergent 3 @ LAC	8/12/2022	8/14/2022	94522369	JR22220275	50	2000	80.0	8.96	9.69	9.88	7.99	9.52
GMIVD91-025	Fuel 3 + Detergent 2 @ 1.5 x LAC	8/19/2022	8/22/2022	94522369	JR22220275	50	2000	80.0	7.85	9.58	9.88	7.44	9.39
GMGDI91-026	Fuel 3 + Detergent 1 @ 1.5 x LAC	8/26/2022	8/28/2022	94522369	JR22220275	50	2000	80.0	7.76	7.94	9.89	7.48	9.52
GMGDI91-027	Fuel 3 + Detergent 2 @ 1.5 x LAC	9/9/2022	9/12/2022	94522369	JR22270231	50	2000	80.0	7.52	9.40	9.90	7.44	9.18
GMGDI91-028	Fuel 3 + Detergent 3 @ 1.5 x LAC	9/16/2022	9/18/2022	94522369	JR22270231	50	2000	80.0	9.38	9.83	9.89	7.42	9.10
GMGDI91-029	Fuel 3 + Detergent 2 @ 2.5 x LAC	9/23/2022	9/25/2022	94522369	JR22270231	50	2000	80.0	8.82	9.78	9.90	7.34	9.10
GMGDI91-030	Fuel 3 + Detergent 1 @ 2.5 x LAC	9/30/2022	10/2/2022	94522369	JR22270231	50	2000	80.0	9.42	8.41	9.61	7.98	9.06

NOTE: Test 022, borescope inspection at 25 hours. Photos were taken of the intake valves.

NOTE: Test 025, barometric sensor false reading caused ignition timing, cam timing & fuel flow to shift off typical values

COORDINATING RESEARCH COUNCIL
INTAKE VALVE DEPOSIT TEST DEVELOPMENT PROGRAM
DATA SUMMARY - INTAKE VALVE DEPOSIT WEIGHTS
Performed at INTERTEK

ASTM D6201 TEST SUMMARY

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	SOT INJECTOR FLOW RATES (ml/min)					FUEL CONS (KG)	OIL CONS (g)
						Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average		
IVD9-288	Fuel A	7/23/2021	7/27/2021	20180420	34	125	124	125	124	125	566.3	454.9
IVD9-292	Fuel B	8/27/2021	8/31/2021	20180420	34	124	125	124	125	125	566.5	483.0
IVD9-294A	Fuel A + Detergent 1 @ 2.5xLAC	10/7/2021	10/11/2021	20180420	34	125	125	125	124	125	577.5	503.9
IVD9-295	Fuel B + Detergent 1 @ 2.5xLAC	10/15/2021	10/19/2021	20180420	34	124	124	124	126	125	580.5	483.4

GMIVD LE9 TEST SUMMARY - PHASE I

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	SOT INJECTOR FLOW RATES (ml/min)					FUEL CONS (KG)	OIL CONS (g)
									Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average		
GMIVD91-001A	Fuel A	8/11/2021	8/15/2021	LE9152330222	JR22UU008U	100	2800	43.5	190	190	190	190	190	376.2	-204.0
GMIVD91-002	Fuel A	8/18/2021	8/22/2021	LE9152330222	JR22UU008U	100	2800	51.6	190	190	190	190	190	443.9	-345.9
GMIVD91-003	Fuel A	8/25/2021	8/29/2021	LE9152330222	JR22UU008U	100	2800	66.5	188	188	190	189	189	599.9	-298.3
GMIVD91-004	Fuel A	9/1/2021	9/5/2021	LE9152330222	JR22UU008U	100	2400	66.5	189	190	190	190	190	522.0	-298.7
GMIVD91-005	Fuel A	9/9/2021	9/13/2021	LE9152330222	JR22UU008U	100	2000	80.0	190	190	190	190	190	549.0	-145.0
GMIVD91-006	Fuel B	9/16/2021	9/20/2021	LE9152330222	JR22UU008U	100	2000	80.0	190	190	190	190	190	549.1	-164.3
GMIVD91-007	Fuel A + Detergent 1 @ 2.5xLAC	10/1/2021	10/5/2021	LE9152330222	JR22UU008U	100	2000	80.0	190	190	190	190	190	536.1	-36.5
GMIVD91-008	Fuel B + Detergent 1 @ 2.5xLAC	10/8/2021	10/12/2021	LE9152330222	JR22UU008U	100	2000	80.0	189	190	190	189	190	532.8	-11.6

GMIVD LE9 TEST SUMMARY - PHASE II

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	SOT INJECTOR FLOW RATES (ml/min)					FUEL CONS (KG)	OIL CONS (g)
									Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average		
GMIVD91-009	Fuel B	12/9/2021	12/13/2021	94520451	JR22U80165	100	2000	80.0	190	189	190	190	190	552.4	-463.7
GMIVD91-010	Fuel B + Detergent 1 @ 2.5xLAC	12/17/2021	12/22/2021	94520451	JR22U80165	100	2000	80.0	189	190	190	190	190	543.7	-425.1
GMIVD91-011	Fuel B + Detergent 1 @ LAC	12/30/2021	1/3/2022	94520451	JR22U80165	100	2000	80.0	189	189	190	189	189	548.9	-200.8
GMIVD91-012	Fuel A	1/21/2022	1/25/2022	94520451	JR22U80196	100	2000	80.0	188	188	188	189	188	558.1	-252.0
GMIVD91-013	Fuel A + Detergent 1 @ 2.5xLAC	1/28/2022	2/1/2022	94520451	JR22U80196	100	2000	80.0	189	190	189	190	190	542.7	-221.9
GMIVD91-014	Fuel A + Detergent 1 @ LAC	2/4/2022	2/8/2022	94520451	JR22U80196	100	2000	80.0	190	189	190	189	190	551.2	-120.4
GMIVD91-015	Fuel 3	2/11/2022	2/15/2022	94520451	JR22760231	100	2000	80.0	190	189	189	189	189	544.0	-84.4
GMIVD91-016	Fuel 3	2/18/2022	2/22/2022	94520451	JR22760231	100	2000	80.0	189	189	189	189	189	537.5	1633.9
GMIVD91-017	Fuel 3 + Detergent 1 @ 2.5 x LAC	3/5/2022	3/9/2022	94521309	JR22U80215	100	2000	80.0	188	189	188	188	188	534.8	-249.9
GMIVD91-018	Fuel 4	3/11/2022	3/16/2022	94521309	JR22U80215	100	2000	80.0	189	189	188	190	189	546.5	-299.9
GMIVD91-019	Fuel 4 + Detergent 1 @ LAC	3/18/2022	3/21/2022	94521309	JR22U80215	100	2000	80.0	190	189	189	190	190	539.4	-196.1
GMIVD91-020 @ 50 Hours	Fuel 3	4/22/2022	4/25/2022	94521309	JR22U80215	50	2000	80.0	188	188	189	189	189	271.1	-326.6
GMIVD91-021 @ 50 Hours	Fuel 3 + Detergent 1 @ LAC	4/29/2022	5/1/2022	94521309	JR22U80215	50	2000	80.0	188	189	189	189	189	267.8	-173.3

NOTE: Test 016, Cylinder 4 IVD affected by mechancial issue with Cylinder 4/High Oil Consumption

GMIVD LE9 TEST SUMMARY - PHASE III

TEST NUMBER	TEST FUEL	SOT DATE	EOT DATE	ENG BLOCK NUMBER	CYL HEAD NUMBER	TEST LENGTH	STAGE 2 SPEED (rpm)	STAGE 2 MAP (kPa)	SOT INJECTOR FLOW RATES (ml/min)					FUEL CONS (KG)	OIL CONS (g)
									Cyl 1	Cyl 2	Cyl 3	Cyl 4	Average		
GMIVD91-022	Fuel 3	7/29/2022	8/2/2022	94522369	JR22220275	50	2000	80.0	190	189	190	190	190	269.2	-289.3
GMIVD91-023	Fuel 3 + Detergent 2 @ LAC	8/5/2022	8/8/2022	94522369	JR22220275	50	2000	80.0	191	190	192	191	191	269.2	-200.4
GMIVD91-024	Fuel 3 + Detergent 3 @ LAC	8/12/2022	8/14/2022	94522369	JR22220275	50	2000	80.0	189	191	190	190	190	266.7	-305.9
GMIVD91-025	Fuel 3 + Detergent 2 @ 1.5 x LAC	8/19/2022	8/22/2022	94522369	JR22220275	50	2000	80.0	190	189	190	189	190	236.2	-275.8
GMGDI91-026	Fuel 3 + Detergent 1 @ 1.5 x LAC	8/26/2022	8/28/2022	94522369	JR22220275	50	2000	80.0	190	190	190	189	190	267.5	-309.4
GMGDI91-027	Fuel 3 + Detergent 2 @ 1.5 x LAC	9/9/2022	9/12/2022	94522369	JR22270231	50	2000	80.0	190	190	190	190	190	268.1	-367.5
GMGDI91-028	Fuel 3 + Detergent 3 @ 1.5 x LAC	9/16/2022	9/18/2022	94522369	JR22270231	50	2000	80.0	190	190	190	190	190	262.5	-349.7
GMGDI91-029	Fuel 3 + Detergent 2 @ 2.5 x LAC	9/23/2022	9/25/2022	94522369	JR22270231	50	2000	80.0	190	190	190	190	190	263.8	-213.3
GMGDI91-030	Fuel 3 + Detergent 1 @ 2.5 x LAC	9/30/2022	10/2/2022	94522369	JR22270231	50	2000	80.0	189	190	190	190	190	263.5	-184.6

NOTE: Test 022, borescope inspection at 25 hours. Photos were taken of the intake valves.

NOTE: Test 025, barometric sensor false reading caused ignition timing, cam timing & fuel flow to shift off typical values

ANNEX A5

DEPOSIT MORPHOLOGY COMPARISONS BETWEEN FORD 2.3L IVD AND GM LE9 IVD

Ford 2.3L, Fuel A, Cylinder 1

GM LE9, Fuel A, Cylinder 2R

Ford 2.3L, Fuel A + 2.5xLAC, Cylinder 1

GM LE9, Fuel A + 2.5xLAC, Cylinder 2R

ANNEX A6

LIST OF REFERENCES

[1] Coordinating Research Council Report 606, pages 10 & 51

[2] Coordinating Research Council Report 606, pages 10 & 52

[3] SAE paper 981365