

**CRC Report No. AVFL-28**  
**Phase II**

**GASOLINE DIRECT INJECTION (GDI)  
ENGINE WEAR TEST DEVELOPMENT**

**Final Report**

**October 2019**



**COORDINATING RESEARCH COUNCIL, INC.**  
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**San Antonio, Texas**  
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**GASOLINE DIRECT INJECTION (GDI) ENGINE  
WEAR TEST DEVELOPMENT**

**Final Report**

**CRC Project No. AVFL-28**  
**SwRI Project No. 08.22469, Phase II Revision 1**

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As per the contract, this report is presented as a scientific paper ready for Journal submission. This will give an excellent project overview. Additional supporting data and project specifics are given in the appendices.

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## **ACRONYM LIST**

ACEA - Association des Constructeurs Europeens d'Automobiles (French)  
- European Automobile Manufacturers' Association (English)

API - American Petroleum Institute

ASTM - American Society of Testing Materials

ILSAC - International Lubricants Standardization and Approval Committee

SAE - Society of Automotive Engineers

SLA - Surface Layer Activation



## **1.0 ABSTRACT**

Almost all engine lubrication wear tests based on ILSAC and ACEA specifications were developed for engines and operating conditions representative of port fuel injection (PFI) engine technology. The automotive industry is trending away from the PFI engine towards gasoline direct injection (GDI) technology with approximately 40 percent of passenger cars sold in 2014 having GDI engines, many of which are turbo-charged. These turbo-charged GDI engines often produce more severe operating conditions than PFI engines due to their higher operating temperatures, cylinder pressures, and specific torques. In addition, most turbo GDI engines are downsized, therefore operating at higher loads for a greater portion of their operating cycle. Some vehicles use alternative combustion cycles or stop-start technology which further subjects the engine and lubricants to higher levels of stress compared to conventional PFI engines.

In an effort to guide the development of engine lubrication wear tests in the next ILSAC and ACEA categories, the top and second rings, liner, rod bearings, crankshaft bearings, balance shaft bearings, turbo shaft, turbo thrust washer and turbo thrust plate of a modern turbo charged GDI engine, a Ford 2.0L Ecoboost engine, were irradiated. The irradiation of these engine components resulted in the formation of isotopes, depending on the component material. However, there are not sufficiently different materials in an engine to undertake the testing of all these components at the same time, therefore, two separate engine tests had to be undertaken. Phase I of this work was reported in October 2017 and this report covers Phase II. In both, Phase I and Phase II, a series of in-field operating conditions were selected and the engine operated at these conditions using both a SAE 5W-30 oil and a SAE 0W-16 oil with the same additive package. Using the SwRI® Radioactive Tracer Technology (RATT®) the level of radioactive particles in the oil, present due to wear of the irradiated engine components, can be detected and the strength of the signal for each isotope can be correlated with the mass of wear material in the oil. All engine run-in and testing was completed using lube certified EEE fuel to ensure repeatability between Phases.

The first attempt at running the engine for Phase II resulted in an engine failure caused by loss of the balance shaft bearings. Following this a second engine was sourced and run without having the balance shaft bearings removed, irradiated and reinstalled.

Results for Phase II showed wear in all the engine components irradiated and tested in the engine. These were top ring face and sides, crankshaft main bearings and the turbo shaft, thrust washer and thrust plate. Cold start showed significantly higher wear than any other test sequence. There was no clear difference in component wear between steady state and transient test cycles. Roughly, only two thirds of the operating conditions resulted in higher wear in the measured engine components using SAE 0W-16 oil over SAE 5W-30 oil.

## **2.0 INTRODUCTION**

Tests designed by ASTM for inclusion in the current API/ILSAC oil specifications dictate modern oil formulations. Many of the oils available to consumers only meet the minimum standard of quality specified. Additionally, these tests serve as a readily available, standardized, and well administrated method to test engine lubricant performance in situations other than API/ILSAC certification. These tests often provide a test-bed for research in this area or formulating lubricants

to exceed the current requirements. The current low-temperature valve-train wear test procedure (Sequence IVA, ASTM D6891), as part of the ILSAC GF-5 oil specification, requires the use of a naturally-aspirated, a port fuel injected, a 3 valve per 4-cylinder, a low-compression 2.4L Nissan engine first in service in 1988. Significant advances in mechanical engine design, combustion strategies, materials, and coatings have been made since 1988 resulting in lubricants for modern engines operating in conditions which this dated test cannot emulate.

The replacement tests developed for ILSAC GF6 require the use of a naturally aspirated, port fuel injected engine using a 4 valve per 4-cylinder 1.5L Toyota Engine. While this is certainly an improvement over the previous version of the test with respect to modern engine architecture, it does not provide a method of testing lubricants in the unique environment encountered in gasoline direct injected turbocharged engines. GDI engines are found in a significant portion of new passenger cars being sold today, and are expected to continue to expand across model lines as consumer demand for higher power and regulatory demand for lower emissions and higher fuel economy continues. GDI engines produce significantly higher abrasive soot content in the oil and higher levels of sump fuel dilution, along with unique pre-ignition phenomenon, higher pressures, power densities, and lubricant temperatures, all of which present new challenges for oil formulations.

In any engine, there are numerous components that could exhibit wear, and different engine conditions result in different wear rates of these components in various ways. In addition, the wear of each engine component is influenced by mechanical design, metallurgy, surface finish, coatings, and/or lubrication strategies. The Sequence IVA, IVB and Sequence X are currently the only approved tests specifically designed for gasoline engine wear. These tests measure valve-train wear (IVA and IVB) and chain wear (X). With modern engine design to production schedules of 5-6 years, it is clear that modern GDI engine tests need to be developed for additional engine component wear testing over and above the Sequence IVB and X wear tests.

In an effort to guide the development of engine lubrication wear tests in the next API/ILSAC and ACEA categories, CRC funded a program in two phases to investigate wear of engine components in a modern turbo charged GDI engine, a Ford 2.0L Ecoboost engine. In Phase I of this work, the rings, the liner, and the rod bearings were irradiated and the engine was assembled on a test stand. The irradiation of these engine components results in different isotopes being formed, depending on the material from which the components are manufactured. Using the SwRI® Radioactive Tracer Technology (RATT®), the level of radioactive particles in the oil present due to wear of the irradiated engine components, can be detected, and the strength of the signal for each isotope can be correlated with the mass of wear material in the oil. A test matrix was developed to operate the engine through a series of in-field operating conditions expected to create wear of the engine components. The aim of the project was to discover which engine conditions created wear in which engine components, thereby guiding future wear test development. The engine was operated at these conditions using both the recommended lubricant grade for the engine – SAE 5W-30 and a low viscosity lubricant - SAE 0W-16 to investigate effects of reduced viscosity. The same additive package was used in both oils to ensure observed differences were an artifact of viscosity grade only. Phase I of this work was reported in October 2017. In Phase II of this work, reported here, the same method, engine, oils and test sequences were used to investigate wear in the crankshaft bearings, balance shaft bearings and the Turbo shaft, turbo thrust washer and turbo

thrust plate. The top ring was also irradiated as in Phase I in order to have a common component between the two Phases and allow correlation between wear results.

During the Phase II the first engine experienced a failure and the work had to be repeated using a second engine and a second set of irradiated parts. For clarity, this report separates these discussions, referring to Engine 1 and Engine 2 where Engine 1 failed and Engine 2 was successful. Failure results are presented for Engine 1 and Wear results are presented for Engine 2.

### **3.0 SCOPE OF WORK**

#### **3.1 Test Engine and Test Cell**

The engine selected for this work was the Ford 2.0L EcoBoost engine used in the 2012 Ford Explorer. This engine was selected for a number of reasons, including being representative of current and future engine technology (downsizing, turbo, high BMEP), being early in its product life cycle, and guaranteed support from the manufacturer. The engine was installed in a test cell with engine control and absorbing dynamometer. The cell was chosen for its location away from high foot traffic and because it had space for the radiation detector and peripheral equipment. This engine is the same as currently used for the Low Speed Pre-Ignition (LSPI) test developed for the ILSAC GF6 oil specification, therefore, the project team had a high level of familiarity with the engine and its control systems. This engine, like many turbo charged down-sized engines, has a tendency for LSPI. In order to reduce the chance of engine damage, aftermarket pistons were chosen as they have more material below the oil control ring and therefore less prone to damage from LSPI events. Both OEM and aftermarket pistons are shown in Figure 1 for comparison.



**Figure 1. Comparison of OEM piston (left) and aftermarket piston (right)**

In Phase I, a slave engine was used to develop the test cycles to be run and LSPI events were avoided by working closely with Ford in order to program the ECU appropriately. All target

operating points of interest were achieved with knock-avoidance. Operating temperatures were maintained below critical levels, in part achieved through the use of a cooling fan directed at the turbo.

## 3.2 Test Fuels and Lubricants

### 3.2.1 Test Fuels

Lube Certification EEE fuel from Haltermann was used for all engine run-in and testing. This fuel was chosen so as to increase repeatability as this fuel is certified for industry engine testing. In addition, the aim of this project was to identify wear in engine components under different engine conditions to aid future test development, as such using the test fuel was a logical approach.

### 3.2.2 Test Lubricants

Testing was conducted using two oils containing the same additive package - a SAE 5W-30 and a SAE 0W-16. The oils were low LSPI dexos1™ Gen2 oils. The SAE 5W-30 was selected as this is the manufacturer-recommended lubricant for the Ford 2.0L Ecoboost engine. The SAE 0W-16 was selected as this represents the current lubricant trend of reducing viscosity. Using the same additive package for both oils ensured that difference in wear rates were attributable to the change in viscosity only. Viscometrics for the lubricant blends are given in Table 1.

**Table 1. Test lubricant viscometrics**

Lubricant	Temperature (°C)	ASTM D7042		
		Dynamic (cP)	Kinematic (cSt)	Density (kg/m <sup>3</sup> )
SAE 5W-30	40	57.264	69.706	0.822
	100	9.631	12.346	0.780
SAE 0W-16	40	28.462	34.859	0.817
	100	5.477	7.066	0.775

## 3.3 Engine Run-in

Prior to running the engines through the designed test matrix of operating conditions, the engines were run-in using the SAE 5W-30 oil for 76 hours following a Ford recommended 8-hour break-in procedure. The break-ins consisted of several low to moderate load steady state conditions in increments between 1,500 rpm and 5,000 rpm. The 8-hour break-in procedure was repeated until the engines were run-in for 76 hours in order to replicate that done in Phase I of the work. In Phase I no oil filter was fitted during the break-in or the engine testing phase of this project. This was to ensure all wear particles collected in the lubricating oil was available to pass through the radiation detector. A small change was made in Phase II in that an oil filter was fitted for the first 8 hours of engine run-in in order to collect any initial large particles generated. The oil filter was removed after the first 8 hours and was not used for the remainder of the run-in or engine testing.

## 3.4 Engine Testing

Following the run-in, the engine oil was drained and the engine flushed before being re-filled with SAE 5W-30 oil. Fresh oil was used at the start of each day in order to maintain repeatability across the test matrix and ensure the effect of oil aging was negated from the results. Initially three baseline steady state conditions were run – low load at low, medium and high speed. The medium speed baseline steady state condition was run every time the SAE 5W-30 oil was run in the engine, as a baseline point of reference.

Testing conditions were developed to subject the engine and oil to severe conditions and/or to subject the engine to anticipated high wear events. They were chosen to be representative of the anticipated most severe wear conditions for the engine when operated in the field. Engine temperature and torque set points are shown in Table 2, with engine operating conditions shown in Table 3. The turbo was replaced half way through the testing as a preventative measure against failure, just as in Phase I.

Each of the operating conditions were tested using both the SAE 5W-30 and the SAE 0W-16 oils. After each set of conditions were run using SAE 5W-30 oil, the engine was drained, flushed with SAE 0W-16 and then filled with SAE 0W-16 oil before the same engine conditions were repeated. Once completed, the next set of conditions were run using SAE 5W-30 after flushing with SAE 5W-30 oil. This allowed direct comparison at the same stage of overall engine wear. The only exception to this was that the cold start condition was run every morning when the engine had been idle overnight. In addition, after the initial baseline steady state conditions were run on the first day, the “Baseline Steady State Mid Speed” was repeated each time the SAE 5W-30 oil was in the engine. This was used as a baseline point of reference. In total, 113.5 hours of engine testing were performed in this program, 16 hours using Engine 1 and 97.5 hours using Engine 2.

**Table 2. Engine temperature and torque set points**

Temperature (°C) Set Points						Engine Torque (N-m) Set Points		
Test Point	Very Cold	Cold	Warm	Hot	Very Hot	Engine Speed (rpm)	Low Load	High Load
Oil Gallery Temp	25	60	70	95	120	Low - 2000	50	280
Coolant Temp	35	57	70	90	100	Medium - 3500	50	330
Charge Air Temp	15	67	30	35	40	High - 5000	50	315

**Table 3. Engine operating conditions**

Operation Condition	Description
Baseline: Steady State, Low Speed	Hold engine at low speed and low load for extended period at warm engine temperatures.
Baseline: Steady State, Moderate Speed	Hold engine at moderate speed and low load for extended period at warm engine temperatures.
Baseline: Steady State, High Speed	Hold engine at high speed and low load for extended period at warm engine temperatures.
Cold Start	Once an engine has cooled and settled overnight, start engine and immediately accelerate to max torque for 30 seconds, ramp to low speed/moderate load for one minute, repeat three times.
Turbo Transient	Start at low speed/low load and ramp to medium speed/high load at hot engine temperatures, repeat for extended time.
Transient Load: Low Speed, Low-High Load	Ramp torque from low to high at low speed and warm engine temperatures
Transient Load: High Speed, Low-High Load	Ramp torque from low to high at high speed and warm engine temperatures
Transient Load: High Speed, High-Low Load	Ramp torque from high to low at high speed and warm engine temperatures
Transient Speed: Low Load, Low-High Speed	Ramp engine speed from low to high at low engine torque and warm engine temperatures
Transient Speed: High Load, Low-High Speed	Ramp engine speed from low to high at high engine torque and warm engine temperatures
Transient Speed: High Load, Low to High Speed, 115°C Oil	Ramp engine speed from low to high at high engine torque and hot engine temperatures
Trailer Tow	Start at low speed/max load, decrease load incrementally below max load, increase speed at just below max load curve to high speed/high load, increase load incrementally above max load (causing engine lugging), allow engine to slow to low speed/high load, reduce load to just under max load (to prevent engine stall), repeat for extended time. Hot engine temperatures.
Trailer Tow, 115°C Oil	Start at low speed/max load, decrease load incrementally below max load, increase speed at just below max load curve to high speed/high load, increase load incrementally above max load (causing engine lugging), allow engine to slow to low speed/high load, reduce load to just under max load (to prevent engine stall), repeat for extended time. Oil temperatures elevated 5-10°C above standard trailer tow cycle. Air intake temperature also elevated 20°C.
Boundary Lubrication	Start at max load and moderate engine speed. Hold WOT while slowly ramping engine speed to idle. Warm engine temperatures.
Stop-Start, 4hr Hot Temp	Hot start, immediate hard acceleration at high load to moderate speed for 20 sec, drop to low load/ moderate speed for 10 sec, stop engine, hot soak 1 min, repeat for extended period of time.
Stop-Start	Hot start, immediate hard acceleration at high load to moderate speed for 20 sec, drop to low load/ moderate speed for 10 sec, stop engine, hot soak 1 min, repeat for extended period of time. Hot engine temperatures.
Stop-Start, Very Cold	Hot start, immediate hard acceleration at high load to moderate speed for 20 sec, drop to low load/ moderate speed for 10 sec, stop engine, hot soak 1 min, repeat for extended period of time. Very cold engine temperatures.
Wide Open Throttle (WOT) Transient Cold	Ramp engine speed from low to high speed at high engine torque and cold engine temperatures
WOT: Steady State, 2500rpm	Hold engine at low speed and high load for extended period at warm engine temperatures.
WOT: Steady State, 3500rpm	Hold engine at high speed and high load for extended period at warm engine temperatures. Normal boost.
WOT: Steady State, 5000rpm	Hold engine at high speed and high load for extended period at cold engine temperatures. Normal boost.
WOT: 3500rpm Max. Boost	Hold engine at high speed and high load for extended period at cold engine temperatures. Maximum boost.
WOT: 5000rpm Max. Boost	Hold engine at high speed and high load for extended period at cold engine temperatures. Maximum boost.

#### 4.0 METALLURGICAL ANALYSIS

In this Phase II, the turbo, the crankshaft, and the balance shaft bearings were the focus for the wear study. The top rings were also irradiated and wear measured for them in order to correlate the testing in Phase I and Phase II of the project. Detailed metallurgical information for these components are listed in Table 4, obtained using Energy-Dispersive X-ray Spectroscopy (EDS) on a Scanning Electron Microscope (SEM).

**Table 4. Elemental analysis of wear components**

Component	Percent Mass Concentration by Element %										
	Zn	Al	Si	V	Ni	Cr	Mn	Fe	Cu	Sn	Mo
Top ring running surface		0.57	0.42			98.35		0.66			
Top ring base material			2.17			0.61	0.65	96.57			
Turbo Shaft		0.36	0.82		0.18	1.01	0.71	96.45			0.47
Turbo thrust washer	0.24	0.53	0.40			0.13	1.16	96.47	0.52		0.56
Turbo thrust plate	35.24		0.30						64.46		
Balance shaft bearing running face		81.62	9.92	0.2			0.12	1.23	0.72	6.04	0.16
Balance shaft bearing base material		0.42	0.30				0.22	99.07			
Main bearing running surface		89.35	5.00	0.22			0.21	0.26	0.73	4.23	
Main bearing base material		0.37	0.25				0.27	99.10			

## 4.1 Top Ring

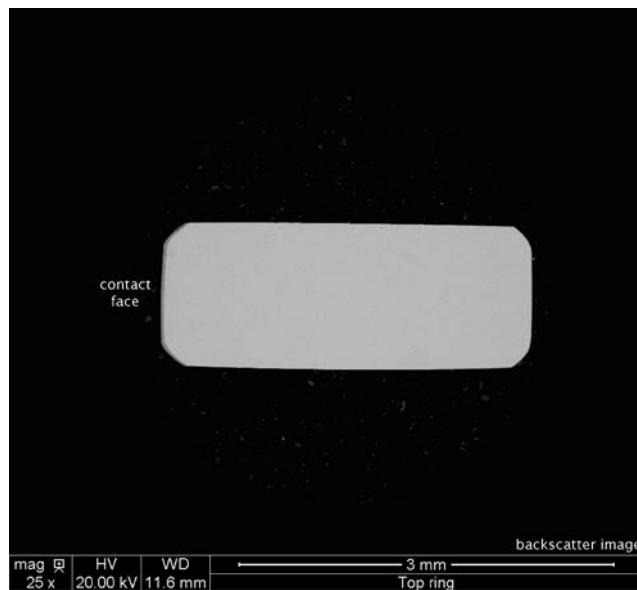


Figure 2. Top ring cross section



Figure 3. Top ring contact face

The top piston ring shown in Figure 2 is a rectangular cross section with rounded corners and a slight barrel on the contact face. The ring bulk material is iron and the contact face of the ring comprises a chromium based coating that extends from the top, across the face, to the bottom, as shown in Figure 3. Figure 3 also shows pockets of black material within the coating on the top ring face. These pockets are elemental molybdenum and are largely concentrated where the peripheral coating connects with the parent ring substrate. The molybdenum is likely present to improve durability and/or flexibility of the adhesion between the hard chromium coating and the base iron material. Full elemental analysis is given in Table 4.

## 4.2 Main Bearings

There are 5 main bearings which support the crankshaft. The center bearing is also the thrust bearing. The upper bearing halves contain the oiling holes and center oil channel, while the lower halves are continuous. The bearings consist of a steel backing with an aluminum-tin matrix on the running face.

## 4.3 Balance Shaft Bearings

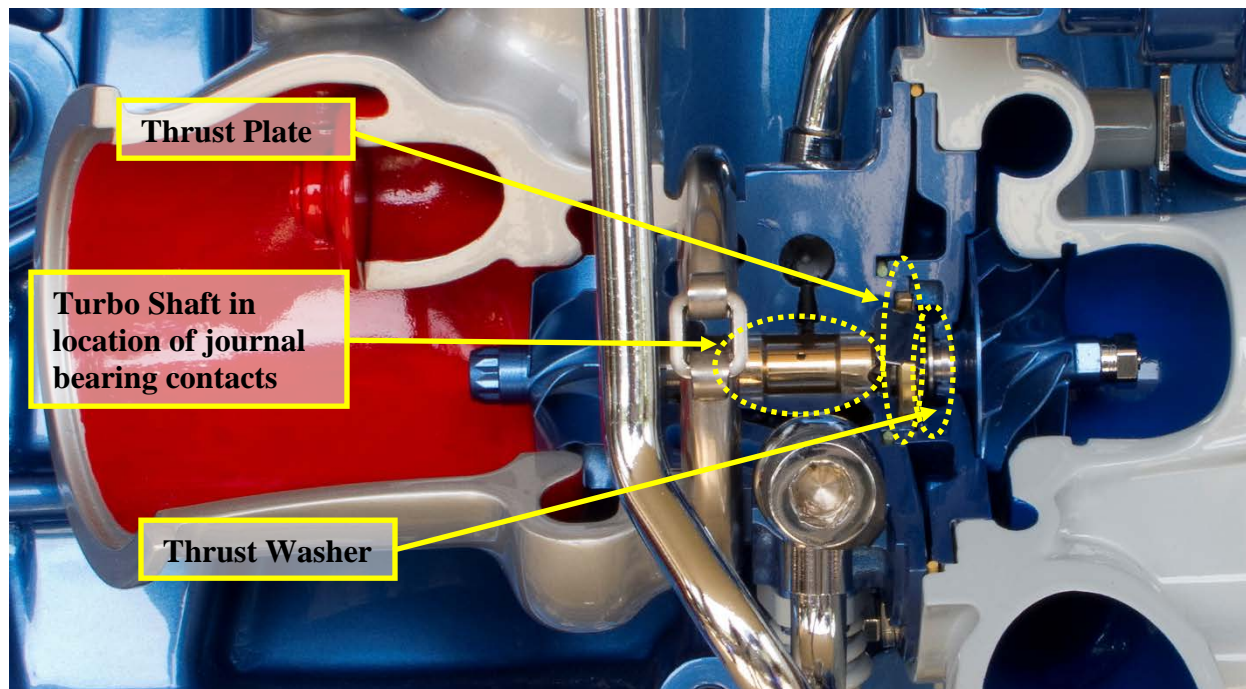
There are 2 balance shaft bearings for each of the 2 balance shafts. The bearings are approximately 1 inch in diameter and  $\frac{3}{4}$  of an inch wide. The bearings are made of an aluminum-tin matrix with no backing material. There is an oil hole and an oil channel in each bearing half.

## 4.4 Turbo Parts

There were 3 turbocharger components of interest for this phase. The thrust washer, thrust plate, and turbo shaft. The thrust washer rides against the back of the compressor wheel and is of a steel composition. The thrust plate is immediately behind the thrust washer and is made entirely of



bronze. The turbo shaft is permanently affixed to the turbine wheel and is also made of steel, although with a higher chrome content than the thrust washer. The location of each of these components is shown in a cutaway view in Figure 4.



**Figure 4. Cross section of turbo showing location of parts that were activated**

## 5.0 ENGINE 1 COMPONENT ACTIVATION

There was substantial overlap in the component metallurgy, as shown in Table 4. This influenced the decision on how to activate the components in order to obtain distinct isotopes for detection of wear particles in the oil. Some components were bulk activated and others were surface layer activated (SLA) using different activation beams, as summarized in Table 5 and discussed below.

**Table 5. Summary of test part, activation technique and resulting isotopes**

Part	Activation Technique	Parent Isotope	Active Isotope
Top Ring Face	Bulk neutron bombardment	Cr	Cr-51
Top Ring Side	Bulk neutron bombardment	Fe	Fe-59
Balance Shaft Bearings	Bulk neutron bombardment	Sn	Sn-113
Main Bearings	Proton SLA	Sn	Sb-124
Turbo Shaft	Deuteron SLA	Fe	Co-57
Turbo Thrust Plate	Bulk neutron bombardment	Zn	Zn-65
Turbo Thrust Washer	Proton SLA	Fe	Co-56

## **5.1 Bulk Activated Components**

### **5.1.1 Top rings**

The top rings for each cylinder were bulk activated, yielding two isotopes, Cr-51 for the ring face coating and Fe-59 for the ring sides, being the base material of the ring. The rings were activated for 60 hours to yield a wear rate resolution of 20  $\mu\text{g/hr}$ .

### **5.1.2 Balance Shaft Bearings**

In the same canister, the balance shaft bearings were arranged within the inside diameter of the top rings. These were therefore activated over the same 60hour period. The 60hour activation of the balance shaft bearing material netted 25.32 $\mu\text{Ci}$  of total activity from 220mg of Tin material. Radioactive isotope production from a parent Tin material is less efficient than ferrous metals. The total activity yield from a bulk activation or (SLA) when using Tin will be an order of magnitude less than chromium or iron undergoing the same activation process. The balance shaft bearing activation only yields a high confidence wear measurement when the wear rate exceeds approximately 200 $\mu\text{g/hr}$ . The measurement technique has sensitivity below this threshold, so for bearing surfaces of tin composition the expense of activation can be justified for causal response of the system.

### **5.1.3 Turbo Thrust Plate**

A second small canister was manufactured for the activation of a single turbo thrust plate. The thrust plate mass and composition made packaging the thrust plate with other bulk components difficult. The thrust plate would have generated hundreds of mCi of activity if subjected to the same 60hr activation that the rings and balance shaft bearings underwent. The beneficial by-product of using a smaller activation canister for the thrust bearing was that the small canister could fit into an activation tube much closer to the center of the reactor. Subjected to a higher neutron flux the turbo thrust washer needed only a 25 hour activation to reach 11.59mCi of total activity. The specific activity created for the turbo thrust washer projected to measure < 10 $\mu\text{g/hr}$  with 0.05% or less standard error.

Details of these bulk activations are shown in Table 6.

**Table 6. Total activity for bulk activation parts**

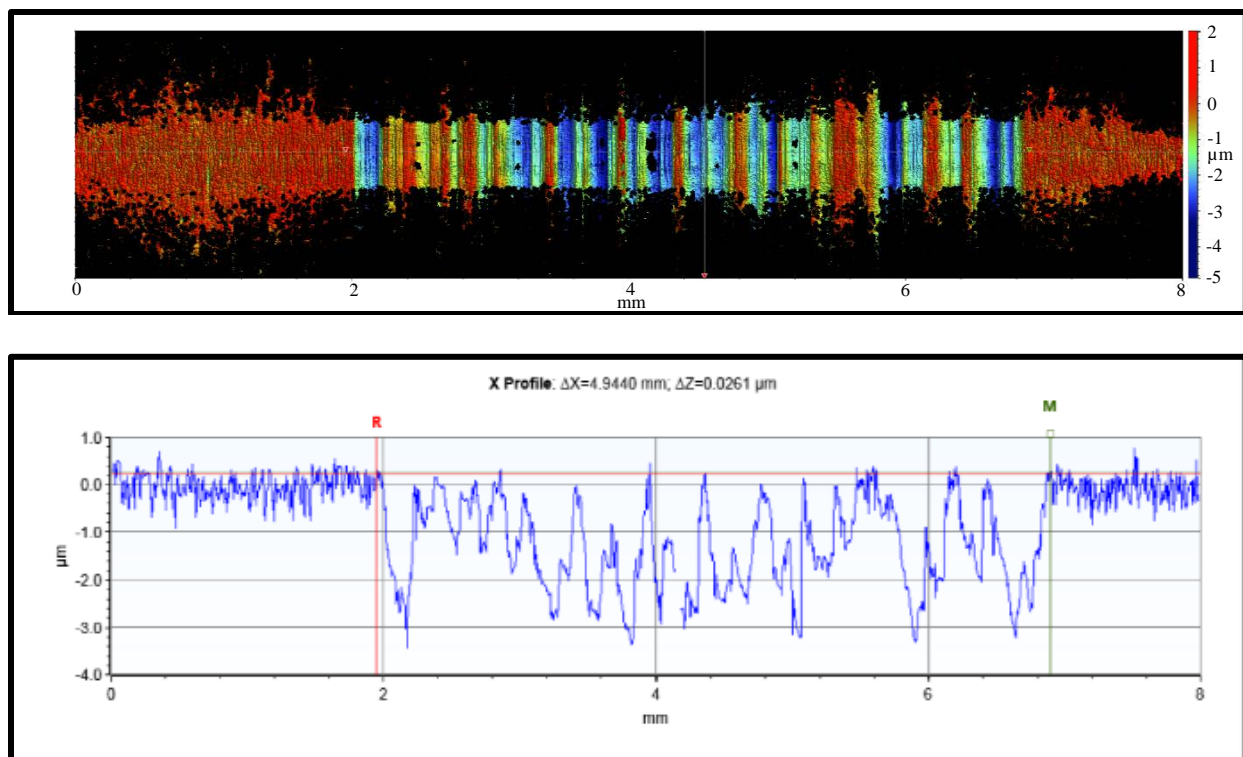
<b>Bulk Activation Products</b>							
<b>Component</b>	<b>Mass (g)</b>	<b>Original Nuclide</b>	<b>Mass (g)</b>	<b>Process</b>	<b>Product Nuclide</b>	<b>Activity</b>	<b>Half Life</b>
Top ring side	143.6	Fe-54	8.048	(n,G)->	Fe-55	54.15 mCi	2.7 years
		Fe-58	0.4471	(n,G)->	Fe-59	31.80 mCi	44.53 days
Top ring face	0.74	Cr-50	0.03092	(n,G)->	Cr-51	46.48 mCi	27.7 days
Balance Shaft Bearings	62.11	Sn-112	0.220	(n,G)->	Sn-113	25.32 $\mu$ Ci	64.9 days
Reactor neutron flux = 6.811e12 per cm <sup>2</sup> s							
Irradiation time = 60hrs			Delay for short life decays = 7 days				
Turbo Thrust Plate	8.1	Zn-64	2.1	(n,G)->	Zn-65	11.59	243.9 days
Reactor neutron flux = 8.432e12 per cm <sup>2</sup> s							
Irradiation time = 25hrs			Delay for short life decays = 7 days				

## 5.2 Surface Layer Activated Parts

Surface Layer Activation (SLA) is desirable when several components consist of the same metallurgy and unique isotopes are required for independent part tracking. SLA can also be helpful in limiting the total activity of the tested assembly. Unsafe dosage fields can result from excessive bulk activation of test parts. SLA is a targeted process and therefore results in an activated area on the surface of the test part rather than the test part becoming homogeneously activated. The targeted nature of the process creates much higher specific activity (isotopes per unit mass) than a comparable bulk activation. This can be extremely beneficial when looking at low wear interfaces. In this project the turbo shaft and turbo thrust washer underwent an SLA process to generate unique isotopes from both parts. This was necessary as the top rings, turbo shaft, and thrust washer were all ferrous components. Details of these SLA activations are shown in Table 7.

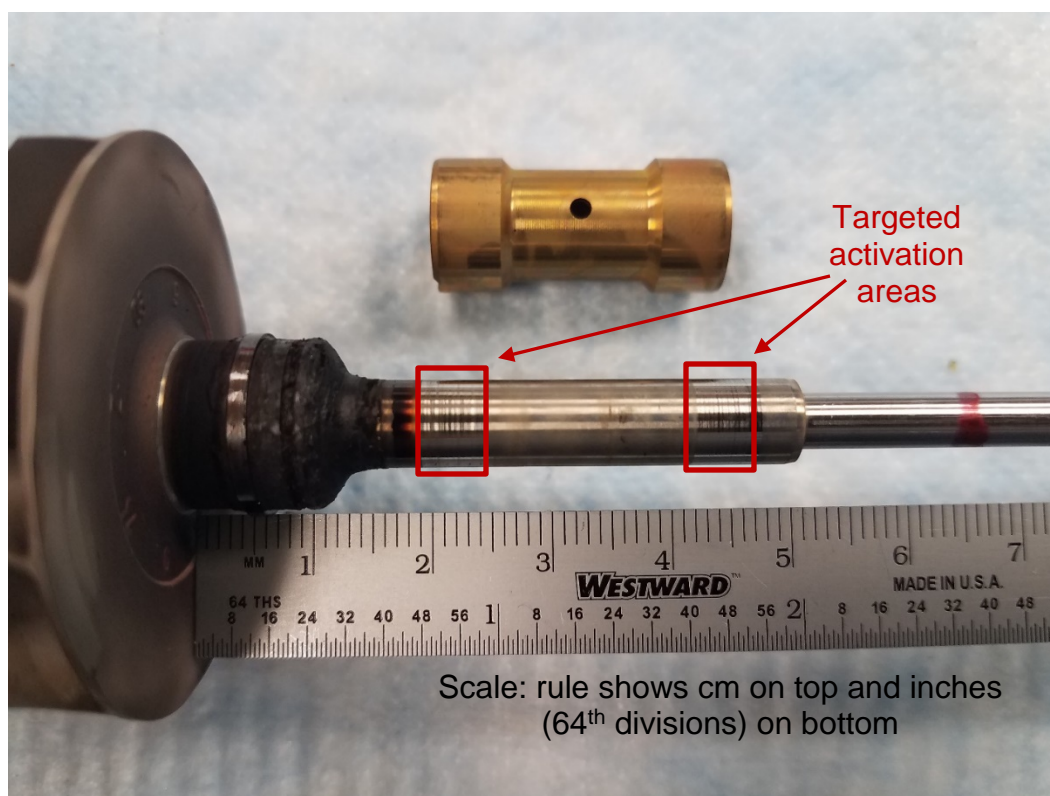
### 5.2.1 Turbo Shaft

The turbo shaft from a used engine was inspected at the onset of Phase II to plan and place the shaft activation. White light interferometer measurements were taken. The resultant imagery of the shaft measurements highlighted wear areas around the journal bearing interface. The compressor and turbine sides of the shaft were worn from the previous testing with the turbine side of the shaft exhibiting more wear than the compressor side. The shaft wear from the used turbo shaft is depicted in Figure 5. The top image is the 3D white light visualization of the shaft. The material height or wear depth is determined by color as defined in the scale on the right of the image. Immediately below is the x-axis profile of the shaft along the center line of the shaft (left to right). This shows wear from 2mm to 7mm along the shaft with wear as deep as 3.5 $\mu$ m in places.



**Figure 5. Image of turbo shaft highlighting area that was activated**

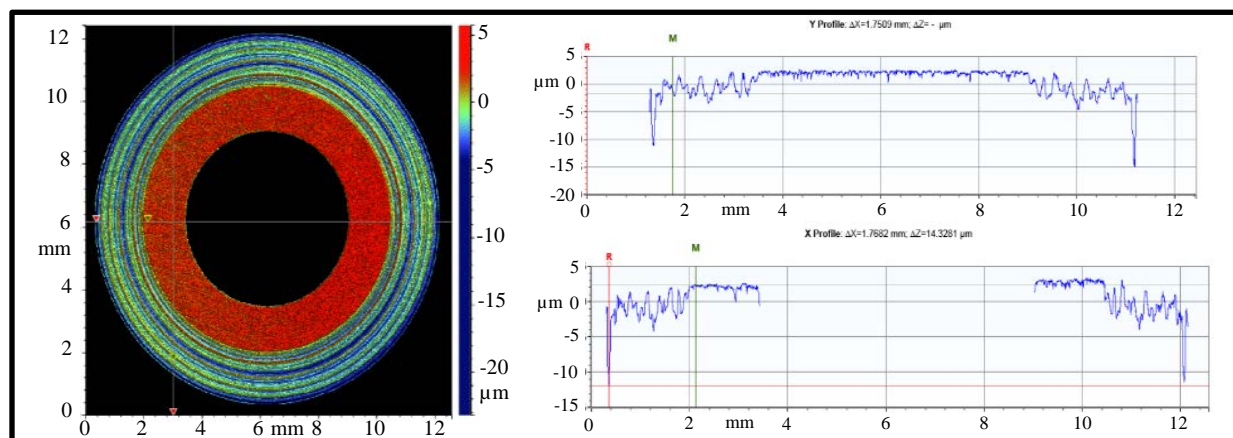
Both areas of the turbo shaft (turbine and compressor sides) were included in the targeted SLA. Two circumferential activation bands of 8mm width were created to capture the shaft and journal bearing wear interaction. A total of 104 $\mu$ Ci of activity was created at the narrow bands of target area on the turbo shafts. The designed minimum wear rate to produce a 0.05% standard error on the turbo shaft surfaces was 3-4nm/hr. Figure 6 further depicts the targeted activation areas.



**Figure 6. Turbo shaft wear areas shown with journal bearing and scale**

### 5.2.2 Turbo thrust washer

A used turbocharger thrust washer was also used to plan the thrust washer activation. Figure 6 depicts the circular grooving on the used turbo thrust washer. This grooving was present on both sides of the thrust washer. Figure 7 shows one side of the thrust washer. Wear can be seen roughly  $5\text{ }\mu\text{m}$  deep around the outer  $\sim 1.5\text{ mm}$  of the washer. The size of the turbo thrust washer allowed for cost effective activation over its entire surface on both faces of the thrust washer. The turbo thrust washer was activated to produce  $200\mu\text{Ci}$  of Co-56 isotope. The specific activity of the thrust washer allows for high confidence measurements at  $1\text{ nm/hr}$  wear rates.



**Figure 7. Thrust washer wear pattern from used turbocharger**



### 5.2.3 Main bearings

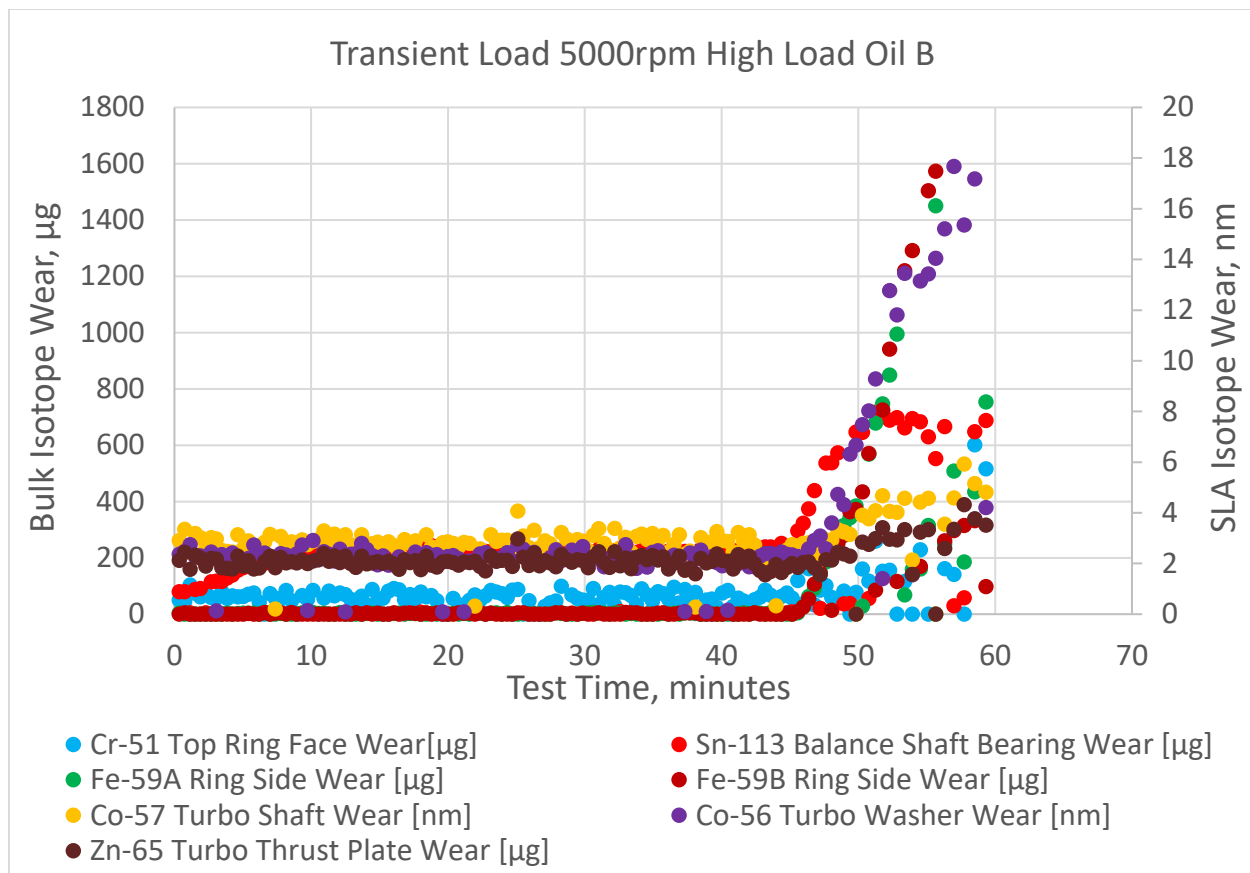
The main bearings had very similar metallurgy to the balance shaft bearings. To create unique radiolabels for each of the bearing locations, the main bearings were chosen to be surface activated. Tin does not have great production rates when generating radioactive isotopes, so a narrow column across the width of the lower main bearing halves was selected to generate 5 $\mu$ Ci of total activity on the five lower bearing halves. The full width of the activation column was 10mm placed at the 6 o'clock position of the bearing halves. The clocking of the activation column was 180° away from the main bearing oil feed. The limited ability to generate significant activity on the main bearings results in reduced measurement confidence at low wear rates. The benefit of the activation is measured in the ability to identify conditional sensitivity of the main bearing wear.

**Table 7. Surface layer activated (SLA) parts**

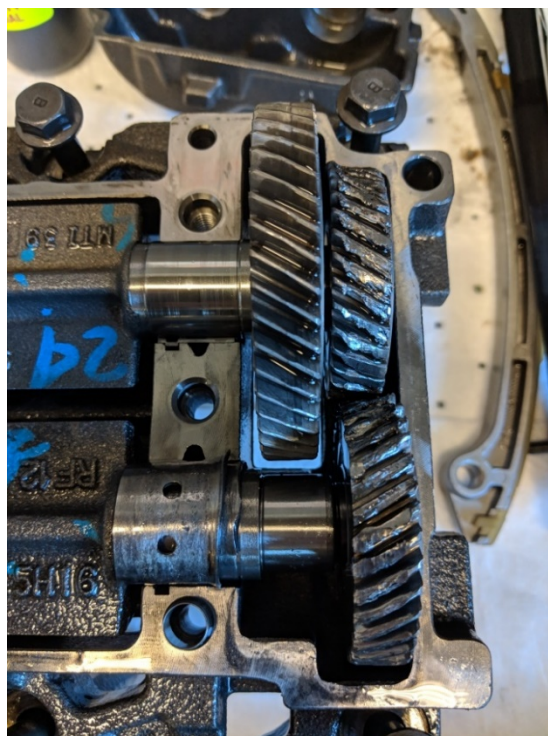
Surface Layer Activated Products							
Component	Activation Area	Depth of Activity	Original Nuclide	Process	Product Nuclide	Activity	Half Life
Turbo Shaft	(2) 8mm bands	40 $\mu$ m	Fe	(d,n)	Co-57	104 $\mu$ Ci	272 days
Turbo Thrust Washer	Full surface / both sides	60 $\mu$ m	Fe	(p,n)	Co-56	200 $\mu$ Ci	77.2 days
Main Bearings (lower halves)	10mm band @ 6 o'clock	40 $\mu$ m	Sn	(p,n)	Sn-113	5 $\mu$ Ci	60.2 days

## 6.0 ENGINE 1 FAILURE

While running the 'transient load high speed' test sequence using the low viscosity lubricant, the engine suffered a catastrophic failure, resulting in the end of the testing. This was early in the test sequence after only 16 hours of testing. Analysis of the isotopes in the oil in Figure 8 shows that the initial component to fail was the balance shaft bearing moving from under 100 $\mu$ g of wear to over 200 $\mu$ g of wear within the first 10 minutes of the test sequence. At approximately 45 minutes into the test sequence, the balance shaft bearing wear accelerates significantly followed almost immediately by all the other measured radioactive engine parts. Note that in this graph, a direct comparison in wear between the bulk (in  $\mu$ g) and the surface layer (in nm) activated parts cannot be made; the aim of this data processing was to confirm which engine component failed first. Figure 9 shows the failed bearings.



**Figure 8. Analysis of isotopes from engine wear particles**



**Figure 9. Image of damage to balance shaft gears and bearings**

It was concluded that this failure was due to the balance shafts being a non-serviceable part. As the shell bearings had been removed from the assembled part, sent for irradiation, and then reassembled they had already been crushed on initial assembly. This likely resulted in them not seating correctly on the assembly prior to install in the engine.

## **7.0 ENGINE 2 COMPONENT ACTIVATION**

Engine components were activated in the same way for Engine 2 as described in section 5.0 above for Engine 1 with exception of two small changes. Tables 8 and 9 summarizes Engine 2 component activations.

### **7.1 Balance Shaft Bearings**

Due to the failure of the balance shaft bearings, these were not activated and the module was not disassembled prior to installation in the second engine.

### **7.2 Main Bearings**

As the balance shaft bearings were no longer being measured and therefore not being bulk activated, a number of the main bearings could be bulk activated instead of SLA. This made activation of the main bearings cheaper, but only some of the bearing could be activated due to keeping the total level of engine activation safe for operation. The half shells chosen for activation were the #1 upper half, #2 upper half, and #5 lower half. These activations are summarized in Table 8.

**Table 8. Summary of test part, activation technique and resulting isotopes**

<b>Part</b>	<b>Activation Technique</b>	<b>Parent Isotope</b>	<b>Active Isotope</b>
Top Ring Face	Bulk neutron bombardment	Cr	Cr-51
Top Ring Side	Bulk neutron bombardment	Fe	Fe-59
Main Bearings	Bulk neutron bombardment	Sn	Sn-113
Turbo Shaft	Deuteron SLA	Fe	Co-57
Turbo Thrust Plate	Bulk neutron bombardment	Zn	Zn-65
Turbo Thrust Washer	Proton SLA	Fe	Co-56

All components came back with the same activations as did Engine 1 with the exception of the main bearings, which were bulk activated. This activation level is shown in Table 9.



**Table 9. Total activity for bulk activated main bearings**

<b>Bulk Activation Products</b>							
<b>Component</b>	<b>Mass (g)</b>	<b>Original Nuclide</b>	<b>Mass (g)</b>	<b>Process</b>	<b>Product Nuclide</b>	<b>Activity</b>	<b>Half Life</b>
Main Bearings	18.1	Sn-112	0.169	(n,G)->	Sn-113	2.070 $\mu$ Ci	115 days
Reactor neutron flux = 6.811e12 per cm <sup>2</sup> s							
Irradiation time = 60hrs			Delay for short life decays = 7 days				

## 8.0 ENGINE 2 RESULTS AND DISCUSSION

Wear values for each irradiated engine part were compiled for all of the test conditions, comparing the SAE 5W-30 and SAE 0W-16 lubricants. Figures 10-14 depict the wear trend for the top ring face, top ring side, turbo spindle, turbo thrust plate, turbo thrust washer and crankshaft bearings for both lubricants over the full test matrix. For clarity, only those results giving measurable wear values with consideration to the measurement technique have been included in the graphs and these values are noted on the graph titles. Table 10 shows a matrix of irradiated engine component vs. engine test sequence giving a concise overview of noticeable wear. Wear values included in Figures 10-15 are shown as gray cells.

‘Cold Start’ was run 10 times on each oil in order to obtain sufficient data points for analysis. This was because cold start could only be run for 210 seconds before the engine began to warm up.

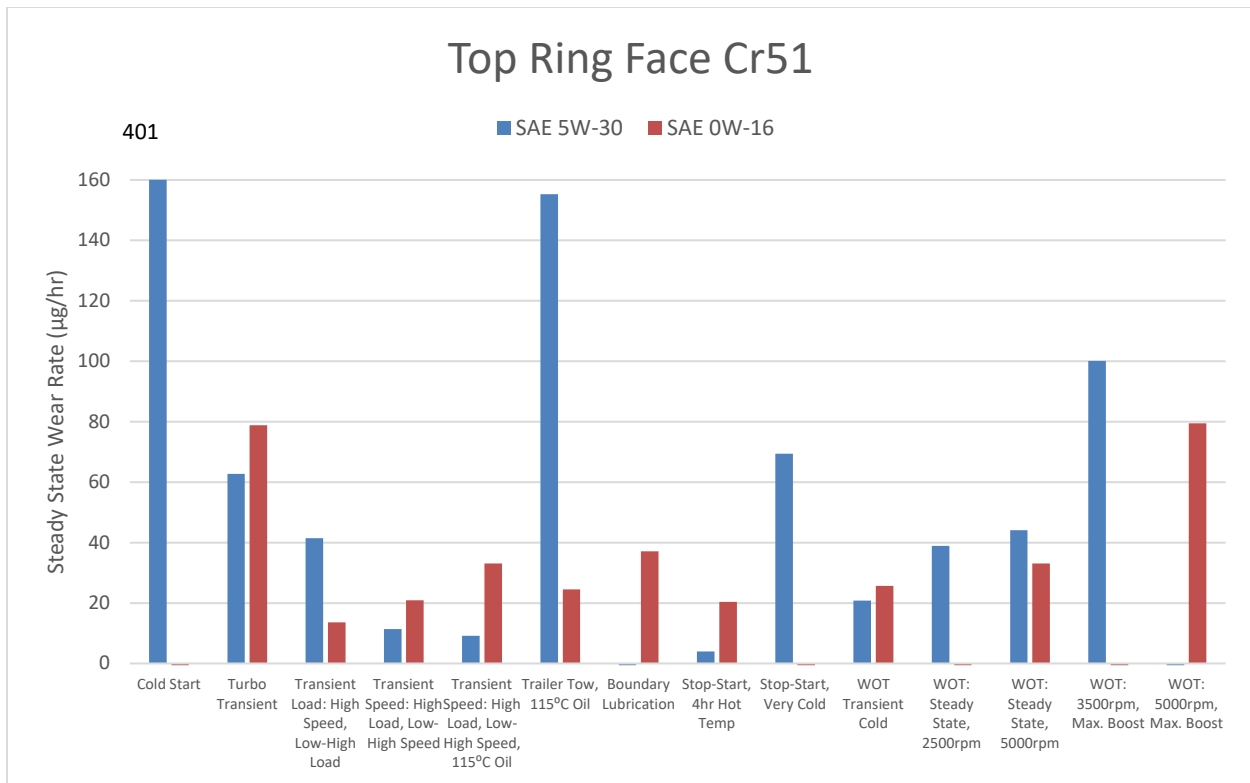
‘Stop-Start’ was a sever ramp up to 3500rpm and therefore only run 4 times during the test sequence. In order to obtain sufficient data points for analysis, this was repeated once for each oil, giving a total of 8 data points for each oil.

The same logic was also applied to two of the transient cycles (‘Transient Load, High Speed, Low-High Load’ and ‘Transient Speed, High Load, Low-High Speed’). This was not done for all the cycles in order to save engine test time for other sequences and because the repeatability of the data obtained for those repeated cycles gave confidence in the results of those not repeated.

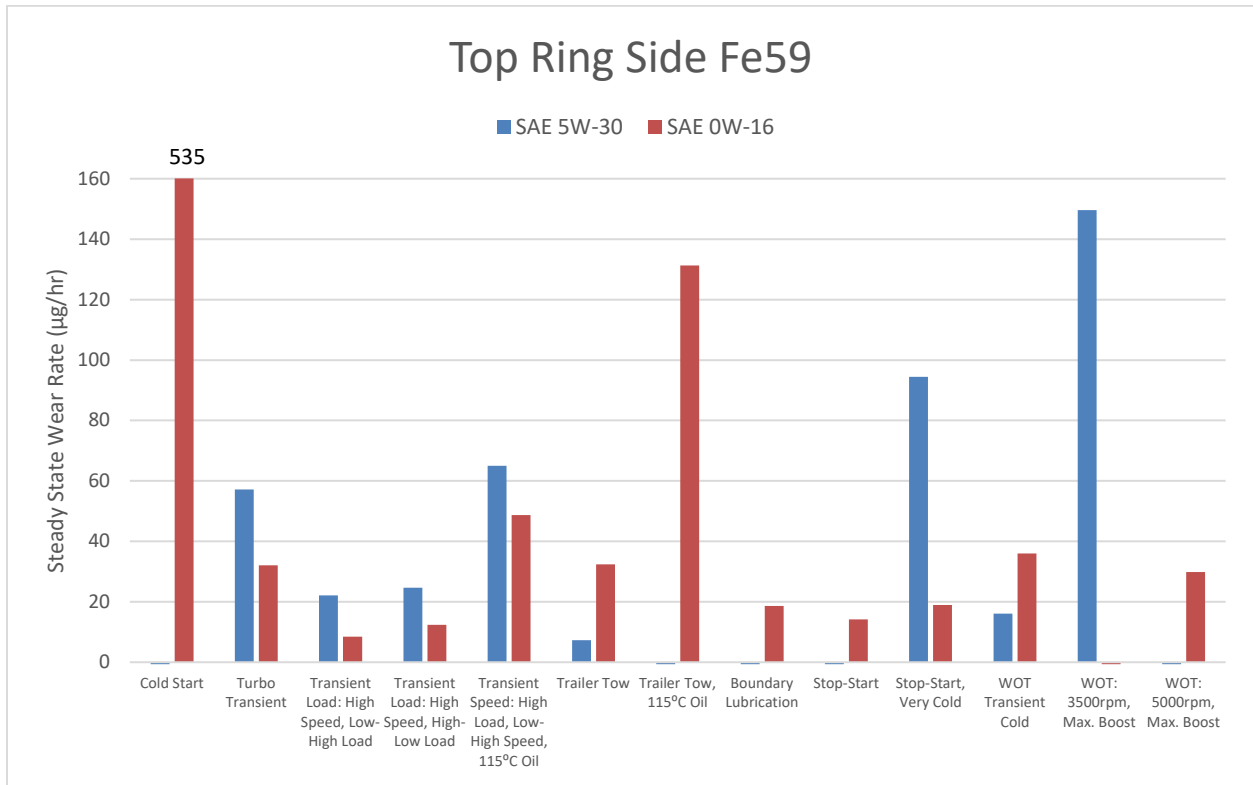
Baseline steady state conditions, as noted in lines 1-3 of Table 2, were run prior to the start of the test matrix. The moderate speed steady state condition was run each time the engine was filled with SAE 5W-30 oil. This was used to monitor the wear rates to ensure no significant change occurred throughout the test program. Steady state wear was achieved throughout the testing.

**Table 10. Matrix of wear of irradiated engine part vs. engine test sequence**

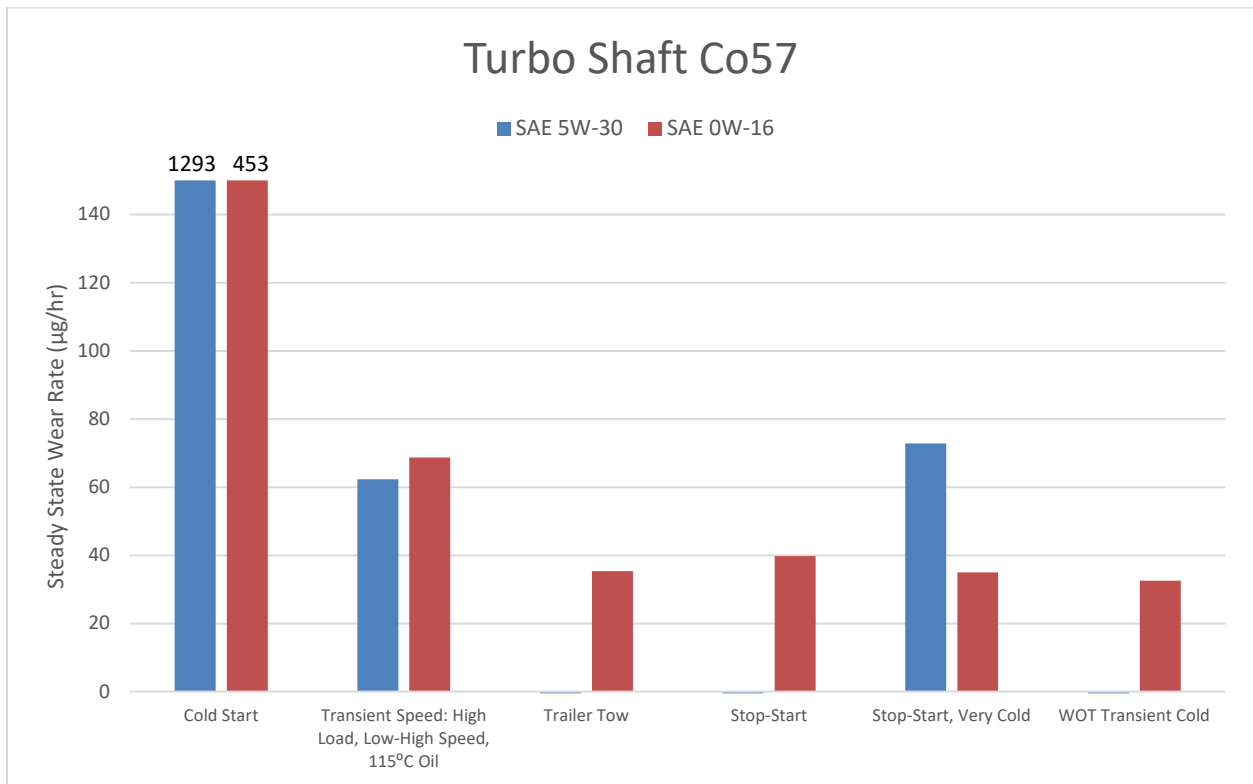
Description	Top Ring Face	Top Ring Side	Turbo Shaft	Turbo Thrust Plate	Turbo Thrust Washer	Main Bearing
Cold Start						
Turbo Transient						
Transient Load: Low Speed, Low-High Load						
Transient Load: High Speed, Low-High Load						
Transient Load: High Speed, High-Low Load						
Transient Speed: Low Load, Low-High Speed						
Transient Speed: High Load, Low-High Speed						
Transient Speed: High Load, Low-High Speed, 115°C Oil						
Trailer Tow						
Trailer Tow, 115°C Oil						
Boundary Lubrication						
Stop-Start, 4hr Hot Temp						
Stop-Start						
Stop-Start, Very Cold						
Wide Open Throttle (WOT) Transient Cold						
WOT: Steady State, 2500rpm						
WOT: Steady State, 3500rpm						
WOT: Steady State, 5000rpm						
WOT: 3500rpm, Max. Boost						
WOT: 5000rpm, Max. Boost						



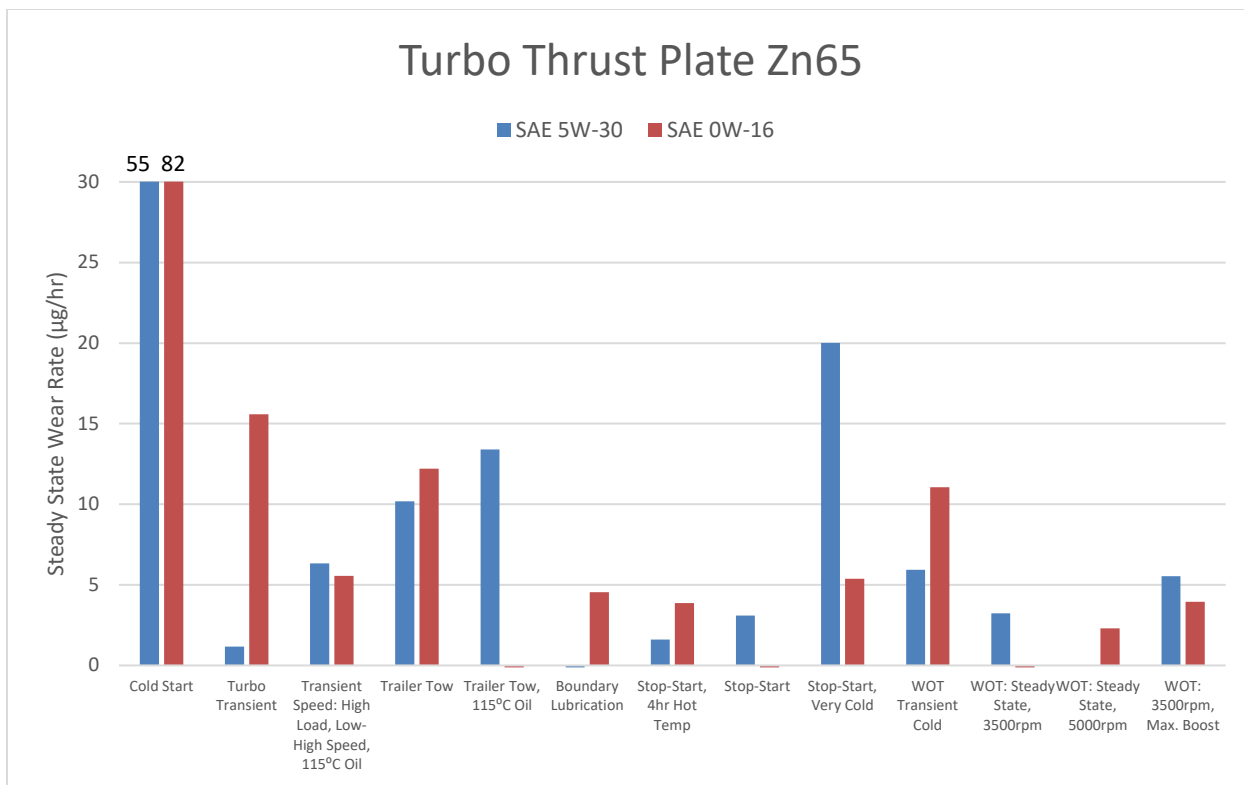
**Figure 10. Top ring face wear for test cycles showing greater than 20µg/hr on either oil.**



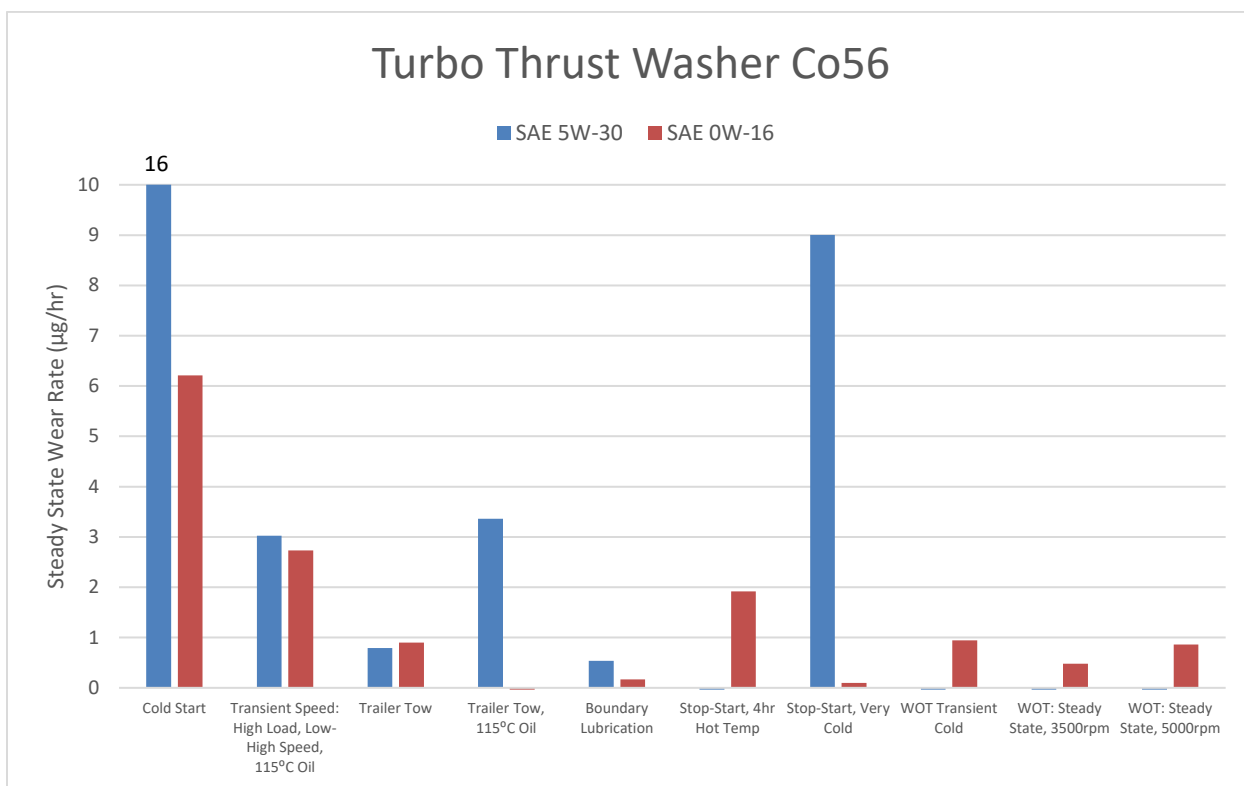
**Figure 11. Top ring side (Fe59) wear for test cycles showing greater than 8µg/hr on either oil.**



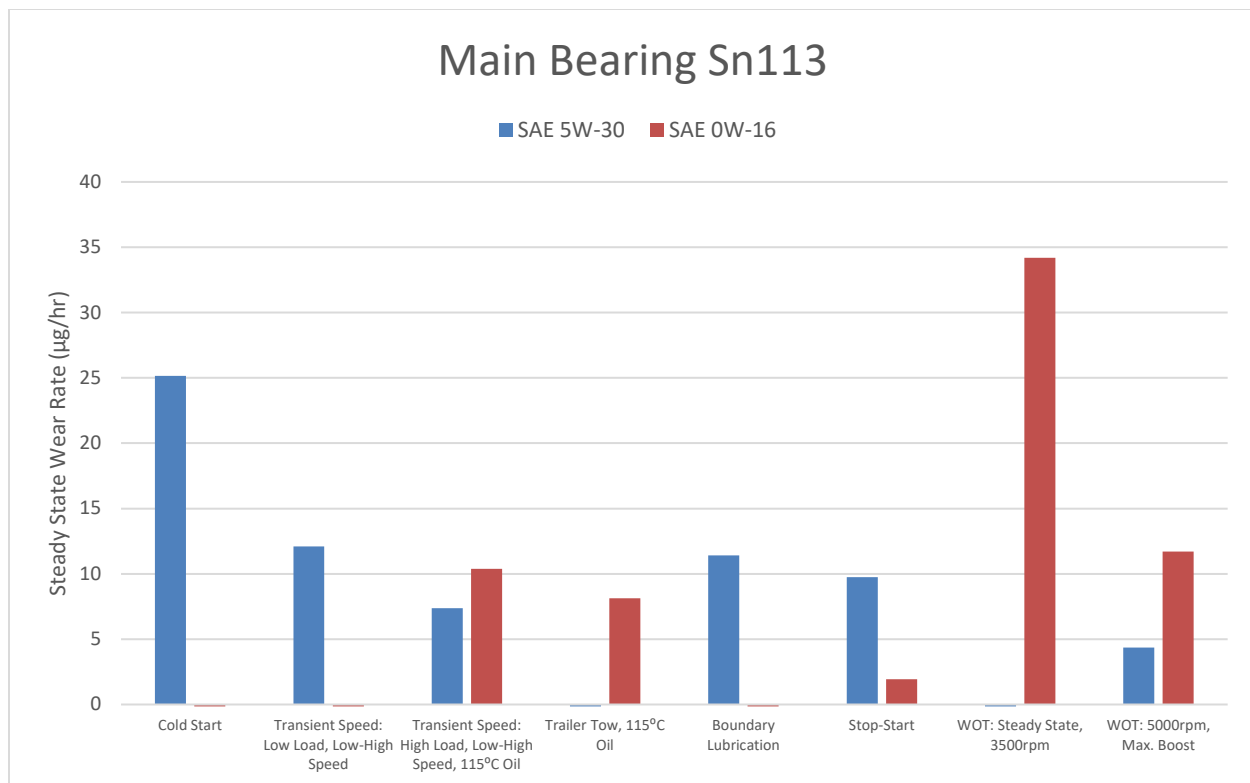
**Figure 12. Turbo shaft wear for test cycles showing greater than 18µg/hr on either oil.**



**Figure 13. Turbo thrust plate wear for test cycles showing greater than 0.3µg/hr on either oil.**



**Figure 14. Turbo thrust washer wear for test cycles showing greater than 0.3µg/hr on either oil**



**Figure 15. Main bearing (Sn113) wear for test cycles showing greater than 8µg/hr on either oil.**

Table 10 shows that all but one engine operating cycles exhibited appreciable wear on at least one of the irradiated engine components. The only engine test cycle that showed no appreciable wear was Transient Load: Low Speed, Low-High Load. Only one operating condition showed wear across all irradiated engine parts; Cold start.

Although it may be expected that the SAE 0W-16 lubricant would give higher wear across all operating conditions and engine components tested, this did not prove to be the case, with a significant number of engine operating cycles giving higher component wear for the SAE 5W-30 oil. Of particular note is the wear of the main bearings where four of the reported eight test sequences gave higher wear for the SAE 5W-30 oil, three of these showed no measurable wear when run using SAE 0W-16 oil. SAE 0W-16 displayed higher wear over SAE 5W-30 in roughly two thirds of the presented data.

The test sequence that systematically displayed the highest wear in all the engine components was Cold Start. The three components with significantly higher wear responses for Cold Start were the turbo shaft, top ring face and top ring side. It is interesting to note that for top ring face SAE 5W-30 showed the high wear with SAE 0W-16 showing negligible wear whereas for top ring side this was the opposite, with SAE 5W-30 showing negligible wear and SAE 0W-16 showing high wear. It is also of interest that the turbo shaft showed higher wear than the main bearings with SAE 0W-16 oil.

Other general observations are that the top rings and turbo thrust plate showed higher wear during more of the engine test cycles than the turbo shaft, turbo thrust washer or main bearings. The turbo

shaft showed no significant wear during steady state wide open throttle testing or transient testing with the exception of high temperature transient. The turbo thrust plate and washer in general showed no significant wear during the transient cycles but did in the steady state cycles. The main bearing did not display any correlation between transient and steady state testing.

## **9.0 CONCLUSIONS**

A project was undertaken to investigate the wear of top rings, turbo shaft, turbo thrust washer, turbo thrust plate and main bearings in a Ford 2.0L Ecoboost engine using Radioactive Tracer Technology® to track real time wear of the components individually. The results clearly show the operating cycles that created significant wear in the irradiated engine components.

A significant amount of data was produced for the five irradiated engine components across the engine operating test matrix. The main findings are:

- All irradiated engine components displayed wear during this Phase II of engine testing
- Top ring face and side, and turbo thrust plate displayed wear during the most number of engine cycles of the components tested.
- The turbo shaft displayed wear during the least number of engine cycles of the components tested.
- Comparing the wear rates using SAE 5W-30 and SAE 0W-16 oils, lower viscosity lubricant resulted in higher wear across roughly two thirds of the engine operating conditions
- In general, transient engine operating conditions created similar wear to steady state conditions
- The cold start cycles operated at the beginning of every day of testing showed the highest wear rates of any of the engine test cycles

# **APPENDIX A**

## **Engine Specifications**

Item	Specification
<b>Engine</b>	
Displacement	2.0L (122 Cubic Inch Displacement (CID))
No. cylinders	4
Bore/stroke	87.5 mm (3.4449 in) - 83.1 mm (3.2717 in)
Fire order	1-3-4-2
Oil pressure (hot @ 2,000 rpm)	200 kPa (29.01 psi) - 268 kPa (38.87 psi)
Compression ratio	9.3:1
Spark plug	NGK T4025R
Spark plug gap	0.8 mm (0.0315 in)
Engine weight (without accessory drive components)	141 kg (311 lb)
<b>Cylinder Block</b>	
Cylinder bore diameter	87.5 mm (3.4449 in) - 87.53 mm (3.4461 in)
Cylinder bore maximum out-of-round	0.008 mm (0.0003 in)
Main bearing bore diameter	57.018 mm (2.245 in) - 57.040 mm (2.246 in)
Head gasket surface flatness	0.1 mm (0.0039 in) - 0.05 mm (0.002 in)/200 mm (7.874 in) x 200 mm (7.874 in)
<b>Piston and Connecting Rod</b>	
Piston diameter (grade 1)	87.465 mm (3.4435 in) - 87.475 mm (3.4439 in)
Piston diameter (grade 2)	87.4725 mm (3.4438 in) - 87.4875 mm (3.4444 in)
Piston diameter (grade 3)	87.485 mm (3.4443 in) - 87.495 mm (3.4447 in)
Piston-to-cylinder bore clearance	0.0225 mm (0.0009 in) - 0.0475 mm (0.0019 in)
Piston ring groove width - compression (top)	1.23 mm (0.0484 in) - 1.25 mm (0.0492 in)
Piston ring groove width - compression (bottom)	1.23 mm (0.0484 in) - 1.25 mm (0.0492 in)
Piston ring groove width - oil ring	2.03 mm (0.0799 in) - 2.05 mm (0.0807 in)
Piston skirt coating thickness	0.009 mm (0.0004 in) - 0.019 mm (0.0007 in)
Piston pin diameter	22.497 mm (0.8857 in) - 22.5 mm (0.8858 in)
Piston pin length	55.7 mm (2.1929 in) - 56 mm (2.2047 in)
Piston-to-pin clearance	0.0035 mm (0.0001 in) - 0.045 mm (0.0018 in)
Piston pin-to-connecting rod clearance	0.003 mm (0.0001 in) - 0.018 mm (0.0007 in)
Piston ring width — compression (top)	1.2 mm (0.05 in)



Item	Specification
Piston ring width — compression (bottom)	1.2 mm (0.05 in)
Piston ring width — oil	2 mm (0.08 in)
Piston ring gap (in bore) — compression (top)	0.17 mm (0.0067 in) - 0.27 mm (0.0106 in)
Piston ring gap (in bore) — compression (bottom)	0.45 mm (0.0177 in) - 0.65 mm (0.0256 in)
Piston ring gap (in bore) — oil	0.15 mm (0.0059 in) - 0.45 mm (0.0177 in)
Connecting rod bearing-to-crankshaft clearance	0.027 mm (0.0011 in) - 0.052 mm (0.002 in)
Connecting rod bearing thickness	1.495 mm (0.0589 in) - 1.519 mm (0.0598 in)
Connecting rod crankshaft bore diameter	55.025 mm (2.1663 in) - 55.045 mm (2.1671 in)
Connecting rod pin bore diameter	22.510 mm (0.8862 in) - 22.516 mm (0.8865 in)
Connecting rod length (center -to-center)	155.869 mm (6.1366 in)
Connecting rod side clearance (assembled to crank)	2.59 mm (0.1020 in) - 3.69 mm (0.1453 in)
Axial clearance	0.014 mm (0.0006 in) - 0.36 mm (0.0142 in)
<b>Crankshaft</b>	
Main bearing journal diameter	51.978 mm (2.0464 in) - 52.002 mm (2.0473 in)
Balance shaft	No details available
Main bearing clearance	0.016 mm (0.0006 in) - 0.046 mm (0.0018 in)
Connecting rod journal diameter	51.980 mm (2.0465 in) - 52 mm (2.0472 in)
End play	0.22 mm (0.0087 in) - 0.45 mm (0.0177 in)
<b>Cylinder Head</b>	
Cylinder head gasket surface flatness	0.08 mm (0.0031 in) maxim overall, a maximum of 0.05 mm (0.0020 in) within 150 mm (5.9055 in) and a maximum of 0.025 mm (0.0010 in) within 25 mm (0.9843 in)
Maximum valve lift @ 0 lash — exhaust	6.9 mm (0.2717 in)
Maximum valve lift @ 0 lash — intake	7.9 mm (0.3110 in)
Valve guide diameter	5.509 mm (0.2169 in) - 5.539 mm (0.2181 in)
Valve seat width - intake/exhaust	1.40 mm (0.0551 in) - 1.50 mm (0.0591 in)
Valve seat angle	45°
Valve seat runout	0.075 mm (0.003 in)
Valve lash adjuster bore diameter	31 mm (1.2205 in) - 31.03 mm (1.2217 in)
Cam bore diameter	25.015 mm (0.9848 in) - 25.04 mm (0.9858 in)

Item	Specification
<b>Valve</b>	
Valve head diameter - intake	32.5 mm (1.2795 in)
Valve head diameter - exhaust	28 mm (1.1024 in)
Valve stem diameter - intake	5.5 mm (0.2165 in)
Valve stem diameter - exhaust	5.5 mm (0.2165 in)
Valve stem-to-guide clearance - intake	0.03 mm (0.0012 in) - 0.07 mm (0.0028 in)
Valve stem-to-guide clearance - exhaust	0.03 mm (0.0012 in) - 0.07 mm (0.0028 in)
Valve face runout	0.05 mm (0.002 in)
Valve face angle	45.25° - 45.75°
<b>Valve Spring — Compression Pressure</b>	
Intake and exhaust (installed)	17 kg (37.478 lb)
Intake (valve open) 9.2 mm (0.3622 in) of lift	39 kg (85.979 lb)
Exhaust (valve open) 9.2mm (0.3622 in) of lift	42 kg (92.593 lb)
Free length	47.91 mm (1.8862 in)
Assembled height	37.9 mm (1.4921 in)
<b>Valve Tappet</b>	
Diameter	30.98 mm (1.2197 in) - 30.964 mm (1.2191 in)
Tappet-to-valve clearance — intake	0.19mm (0.0075 in) - 0.31 mm (0.0122 in)
Tappet-to-valve clearance — exhaust	0.30 mm (0.0118 in) - 0.42 mm (0.0165 in)
Tappet-to-bore clearance	0.02 mm (0.0008 in) - 0.06 mm (0.0024 in)
<b>Camshaft</b>	
Lobe lift — intake	-
Lobe lift — exhaust	-
Runout	0.03 mm (0.0012 in)
Thrust clearance	0.115 mm (0.0045 in) - 0.145 mm (0.0057 in)
Journal diameter	24.96 mm (0.9827 in) - 24.98 mm (0.9835 in)
Journal-to-bore clearance	0.035 mm (0.0014 in) - 0.08 mm (0.0031 in)

## **APPENDIX B**

### **Test Cycles**

Controlled Parameters	Unit
Engine Speed	rpm
Engine Load	Nm
Coolant Out Temp	deg C
Oil Gallery Temp	deg C
Air Charge Temp	deg C
Coolant Pressure	kPaG

Monitored Parameters	Unit
Inlet Air Temp	deg C
Inlet Air Press	kPaG
Exhaust Back Press	kPaA
Humidity	g/kg
Coolant Flow	L/m
Lambda	unitless
Barometric Pressure	kPaA
Oil Gallery Pressure	kPaG
Oil Head Pressure	kPaG
Oil Out Temp	deg C
Exhaust Temp	deg C
Crank Case Pressure	kPaG
Fuel Pressure	kPaG
Power	kW
Pre-Intercooler Air Pressure	kPaA
Ambient Temperature	degC
Coolant In Temperature	degC
Boost Pressure	kPaA
Fuel Temp	deg C
Fuel Flow	kg/hr
Manifold Absolute Pressure (MAP)	kPaA

<b>PCM CAN Bus Parameters</b>	<b>Unit</b>
Ignition Timing Advance for #1Cylinder	deg
Absolute Throttle Position	%
Engine Coolant Temperature	deg C
Intake Air Temperature	deg C
Equivalence Ratio (Lambda)	unitless
Absolute Load Value	%
Intake Manifold Absolute Pressure	kPa
Fuel Rail Pressure	kPa
Accelerator Pedal Position	%
Boost Absolute Pressure - Raw Value	kPa
Turbocharger Wastegate Duty Cycle	%
Actual Intake (A) Camshaft Position	deg
Actual Exhaust (B) Camshaft Position	deg
Intake (A) Camshaft Position Actuator Duty Cycle	%
Exhaust (B) Camshaft Position Actuator Duty Cycle	%
Charge Air Cooler Temperature	deg C

## **APPENDIX C**

### **Test Matrix and Engine Operating Conditions**

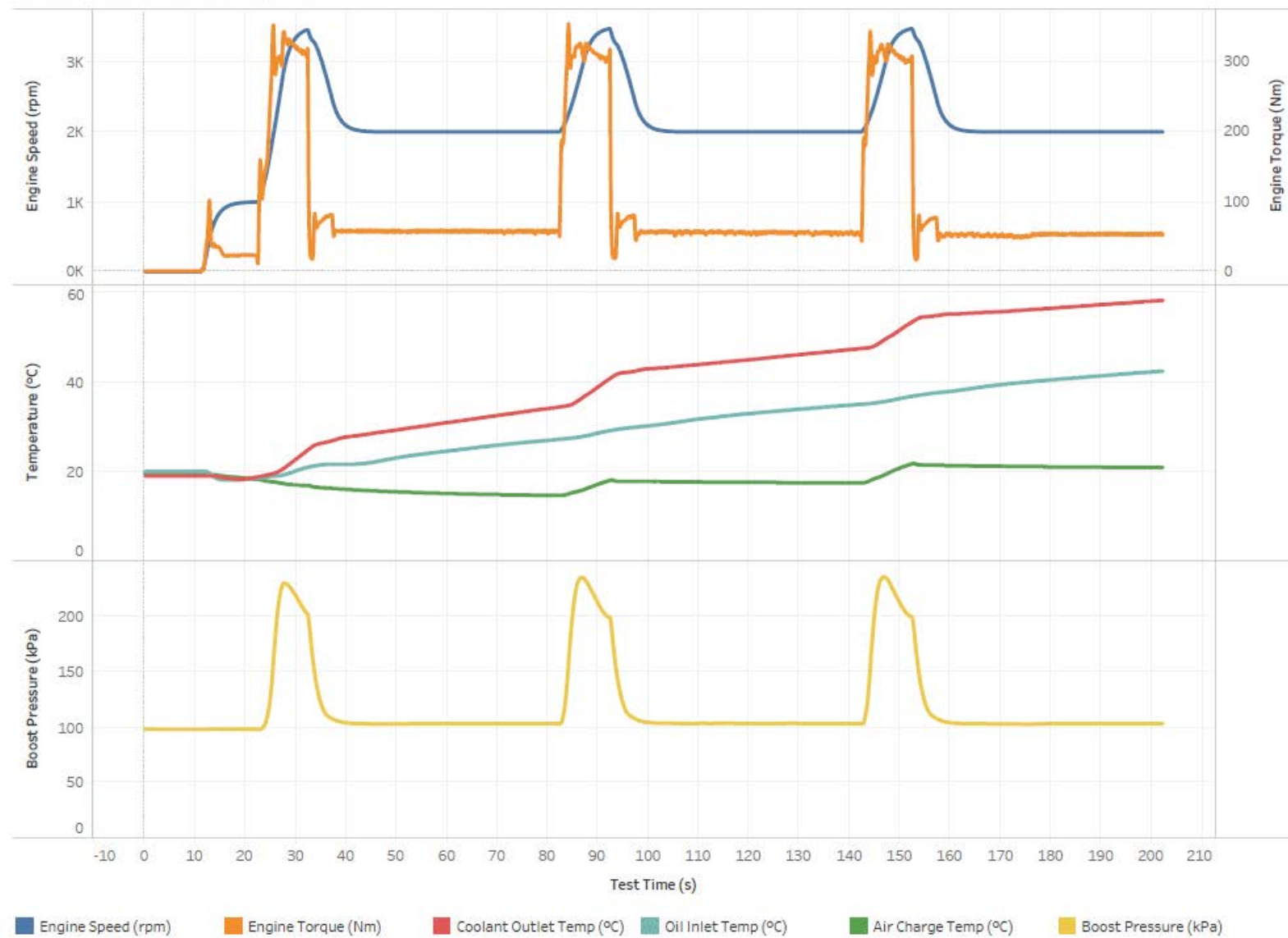
Test Condition	Oil
Note A = SAE 5W-30, B = SAE 0W-16.	
Cold Start	A
Baseline Steady State Low Speed	A
Baseline Steady State Mid Speed	A
Baseline Steady State High Speed	A
Stop-Start	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Stop-Start	B
Transient Load, Low Speed, Low to High Load	B
<i>Oil Change to Oil A</i>	
Cold Start	A
Transient Load, Low Speed, Low to High Load	A
Transient Load, High Speed, Low to High Load	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Transient Load, High Speed, Low to High Load	B
Transient Load, High Speed, High to Low Load	B
<i>Oil Change to Oil A</i>	
Cold Start	A
Transient Load, High Speed, High to Low Load	A
Transient Speed, Low Load, Low to High Speed	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Transient Speed, Low Load, Low to High Speed	B
Transient Speed, High Load, Low to High Speed	B
<i>Oil Change to Oil A</i>	
Cold Start	A
Transient Speed, High Load, Low to High Speed	A
Baseline Steady State Mid Speed	A
Cold Start	A
Stop-Start	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Stop-Start	B
Transient Load, High Speed, Low to High Load	B
<i>Oil Change to Oil A</i>	
Cold Start	A
Transient Load, High Speed, Low to High Load	A
Transient Speed, High Load, Low to High Speed	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Transient Speed, High Load, Low to High Speed	B

Test Condition	Oil
<b><u>Turbocharger Replacement</u></b>	
Cold Start	A
WOT Transient	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
WOT Transient	B
Cold Start	B
Trailer Tow	B
<i>Oil Change to Oil A</i>	
Cold Start	A
Trailer Tow	A
Turbo Transient	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Turbo Transient	B
WOT: steady-state, low speed	B
<i>Oil Change to Oil A</i>	
Cold Start	A
WOT: steady-state, low speed	A
Cold Start	A
WOT: steady state, moderate speed	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
WOT: steady state, moderate speed	B
Cold Start	B
WOT: steady state, high speed	B
<i>Oil Change to Oil A</i>	
WOT: steady state, high speed	A
Cold Start	A
Boundary Lubrication	A
Baseline Steady State Mid Speed	A
<i>Oil Change to Oil B</i>	
Cold Start	B
Boundary Lubrication	B

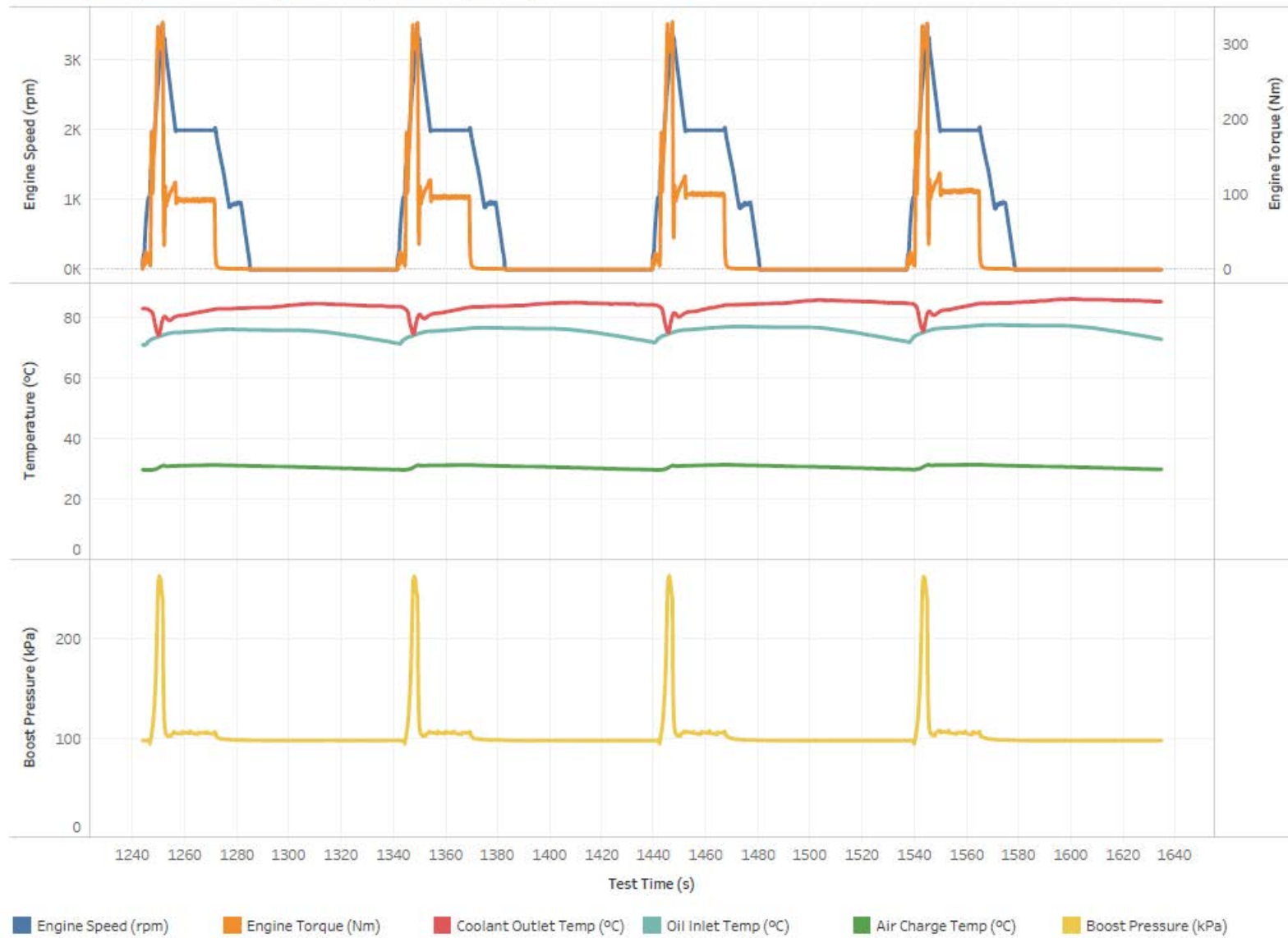


<b>Test Description</b>	<b>Oil</b>
Hot Temp Stop-Start 4hr	Oil B
<i>Oil Change to Oil A</i>	
Hot Temp Stop-Start 4hr	Oil A
Trans Speed High Load (115C Oil Temp)	Oil A
Baseline Steady State Mid Speed	Oil A
<i>Oil Change to Oil B</i>	
Trans Speed High Load (115C Oil Temp)	Oil B
WOT 3500	Oil B
<i>Oil Change to Oil A</i>	
WOT 3500	Oil A
Trailer Tow (115C oil Temp)	Oil A
Baseline Steady State Mid Speed	Oil A
<i>Oil Change to Oil B</i>	
Trailer Tow (115C oil Temp)	Oil B
Stop-Start Very Cold	Oil B
<i>Oil Change to Oil A</i>	
Stop-Start Very Cold	Oil A
WOT 5000 Cold	Oil A
Baseline Steady State Mid Speed	Oil A
<i>Oil Change to Oil B</i>	
WOT 5000 Cold	Oil B

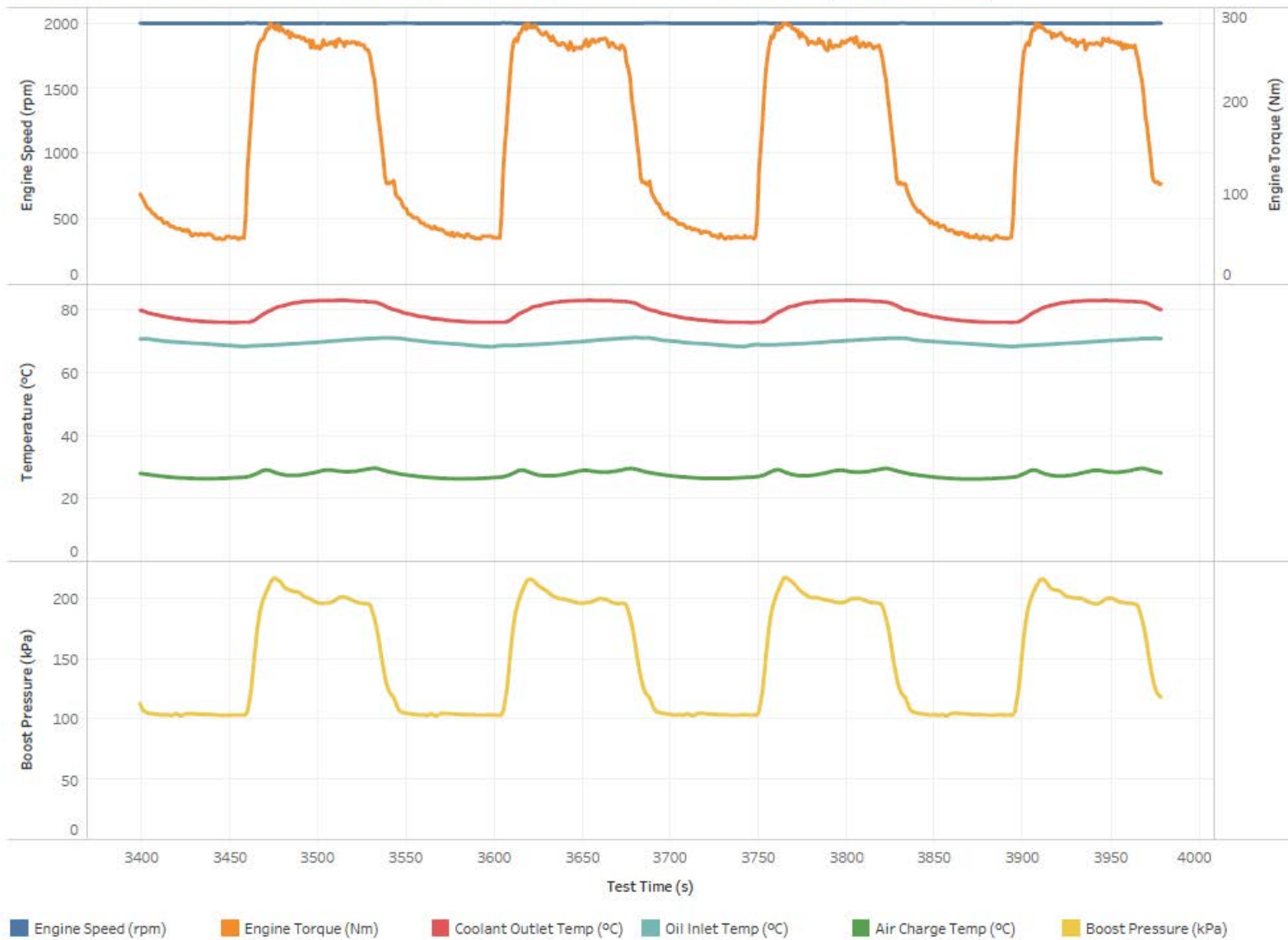
## Cold Start Test Sequence



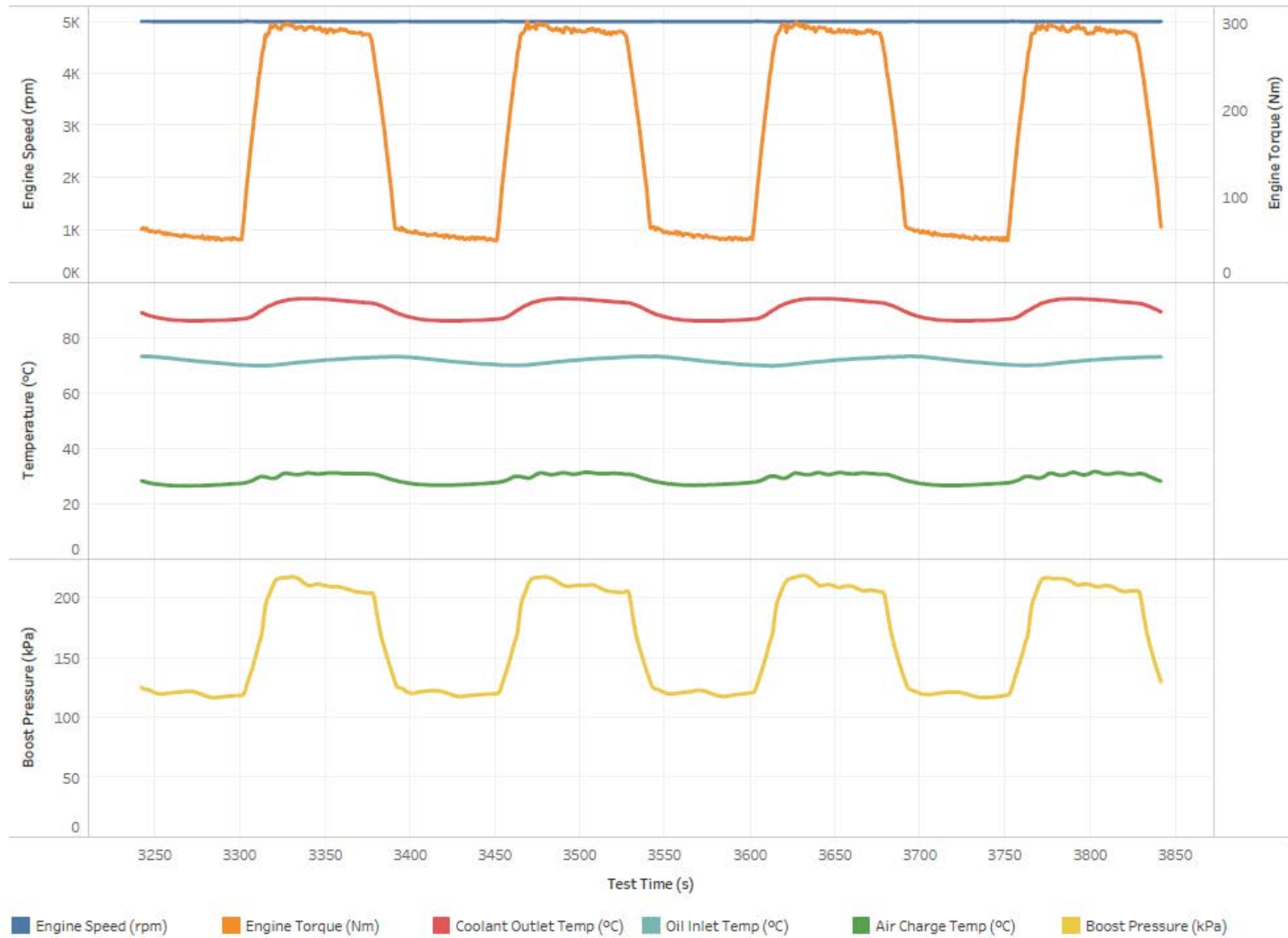
## Start/Stop Test Sequence (Four Cycles)



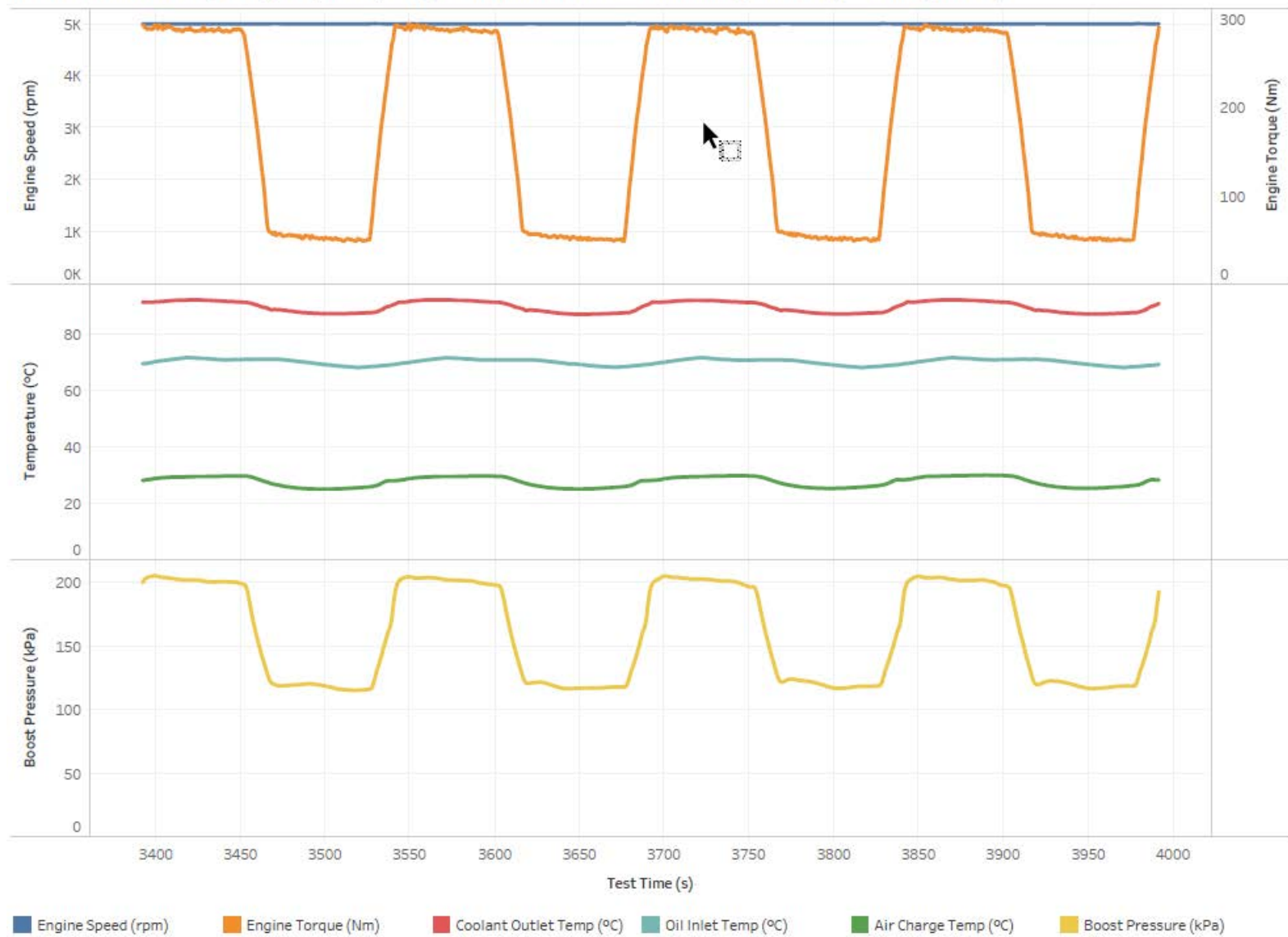
Transient Load, Low Speed, Low to High Load Test Sequence (Four Cycles)



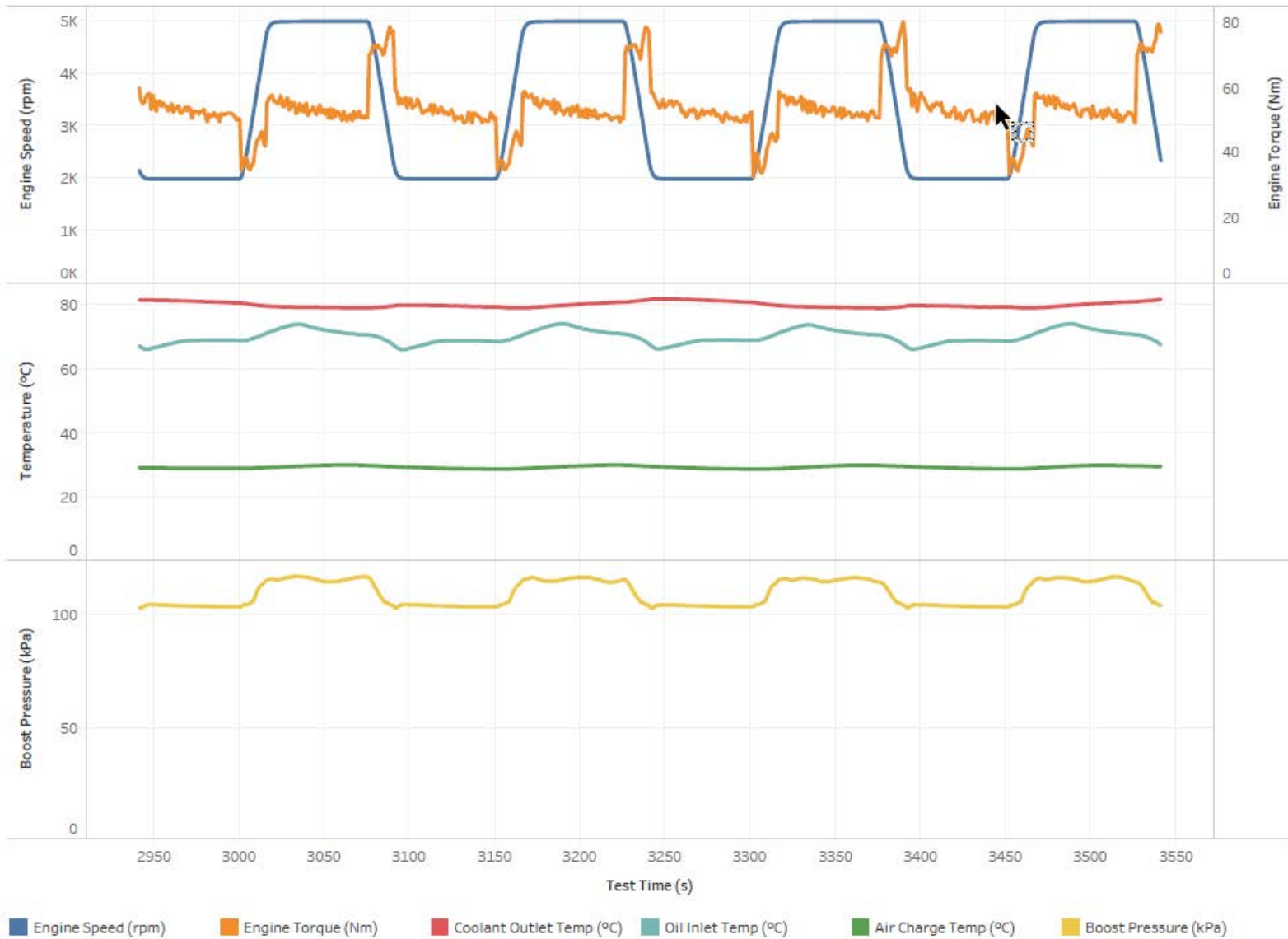
## Transient Load, High Speed, Low to High Load Test Sequence (Four Cycles)



Transient Load, High Speed, High to Low Load Test Sequence (Four Cycles)

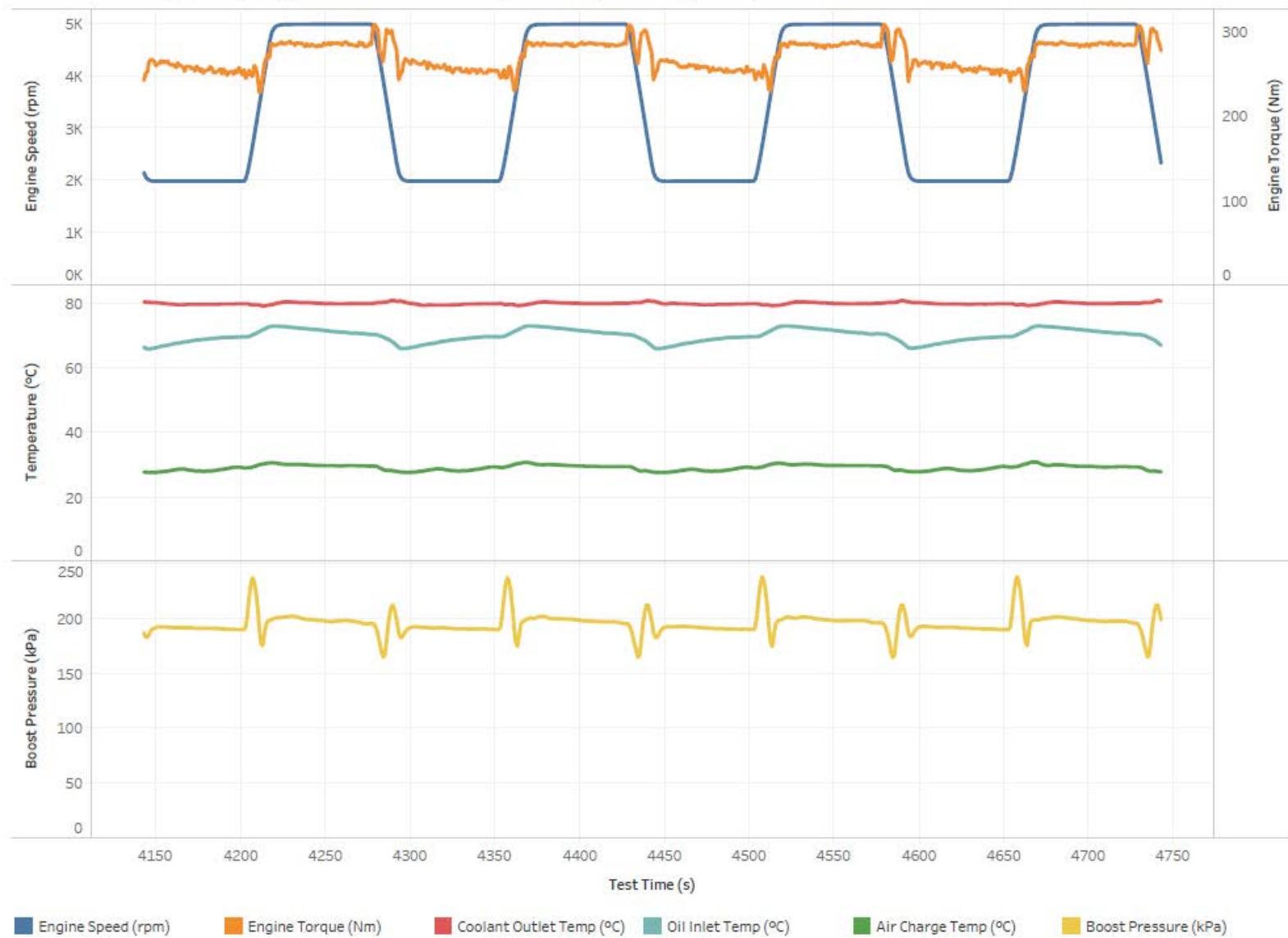


Transient Speed, Low Load Test Sequence (Four Cycles)



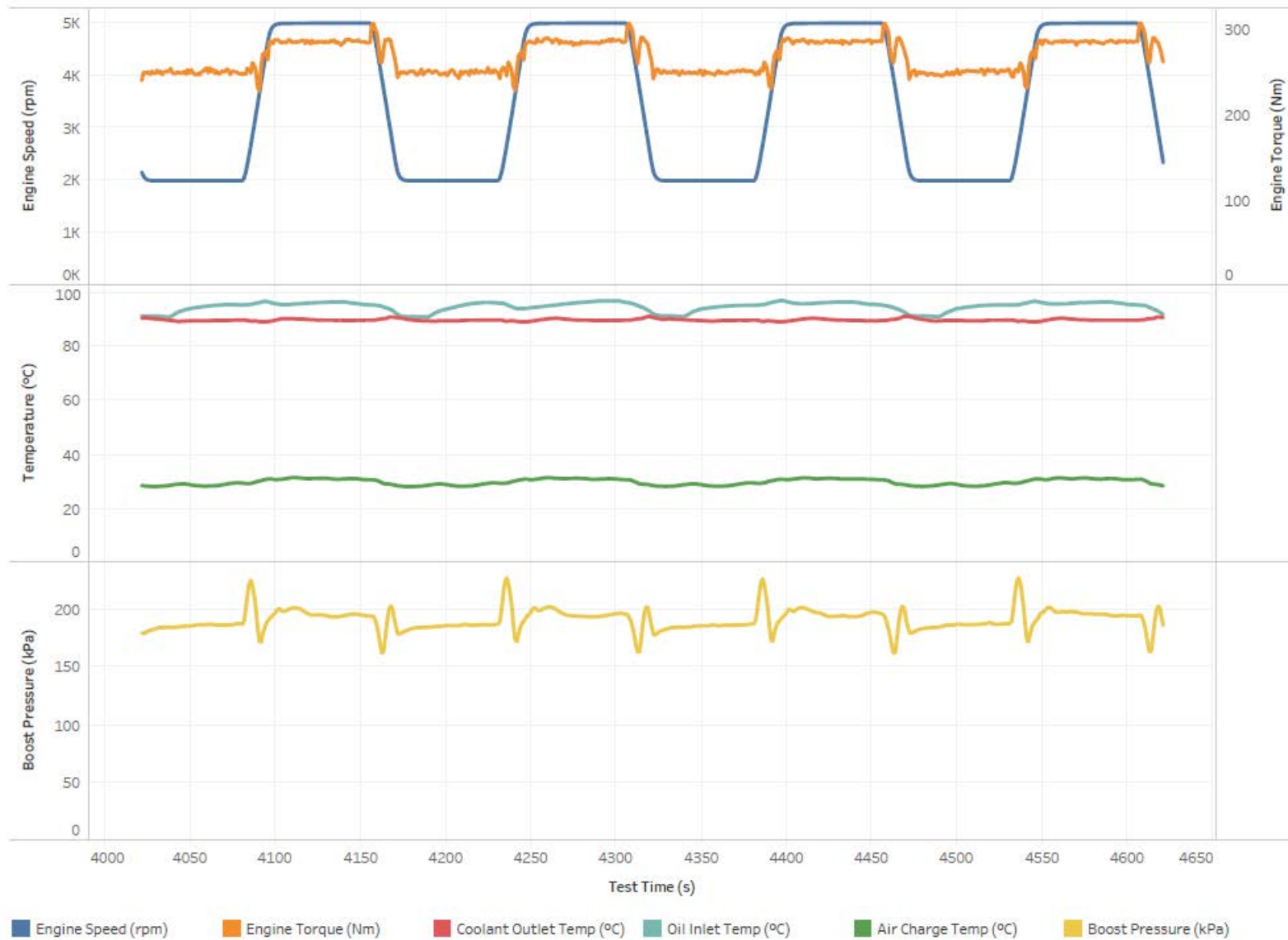


Transient Speed, High Load Test Sequence (Four Cycles)

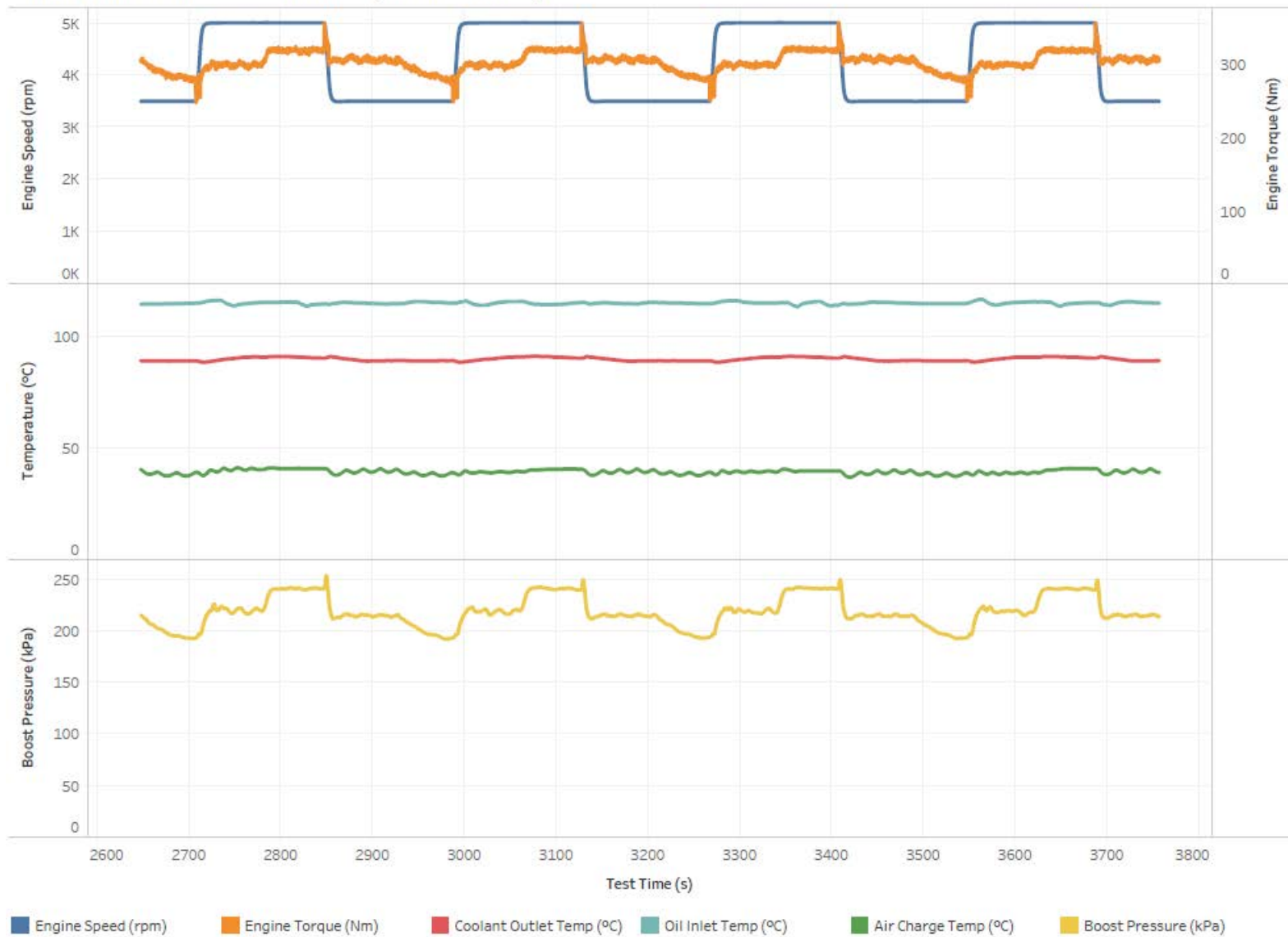




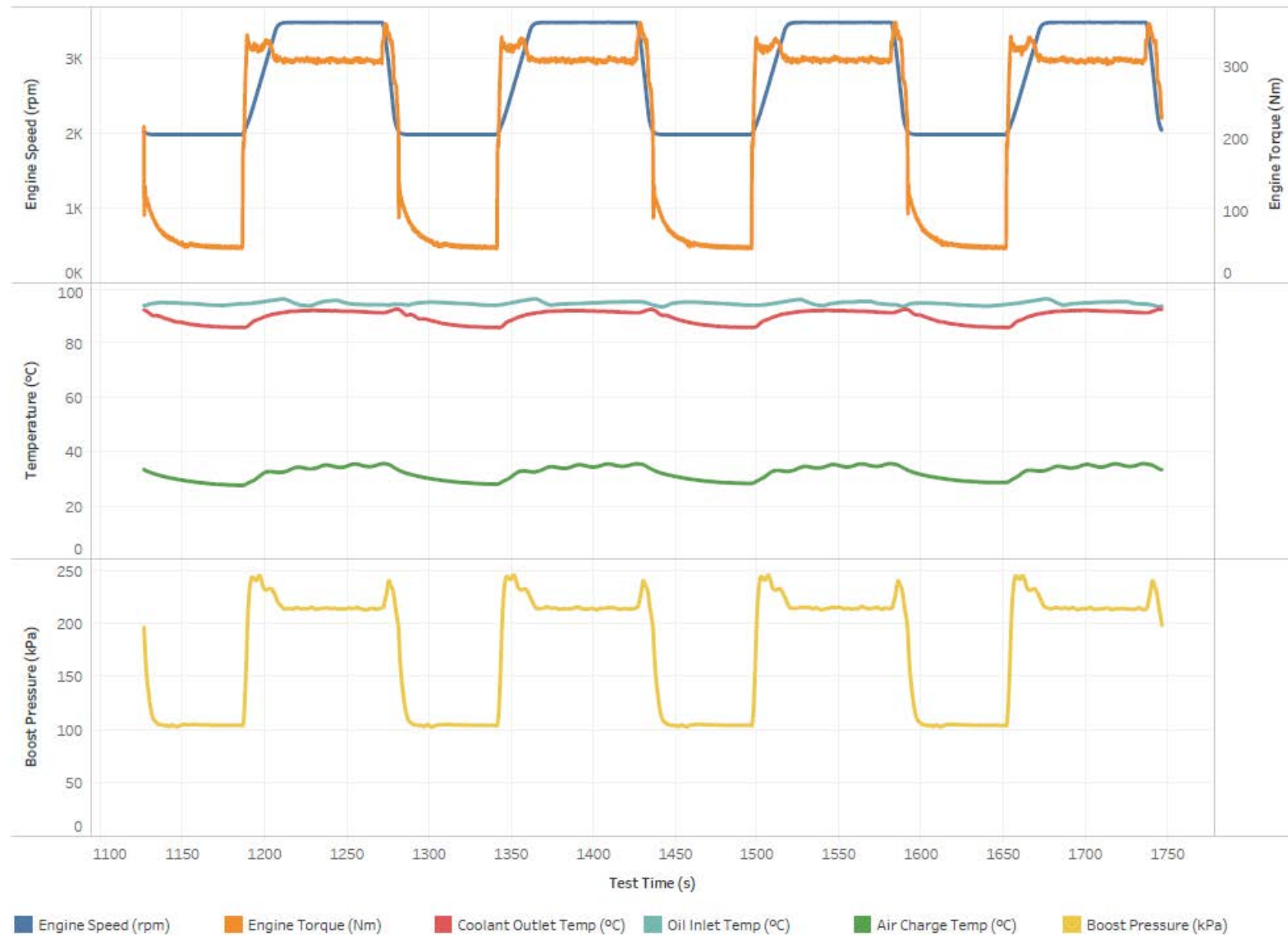
## WOT Transient Test Sequence (Four Cycles)



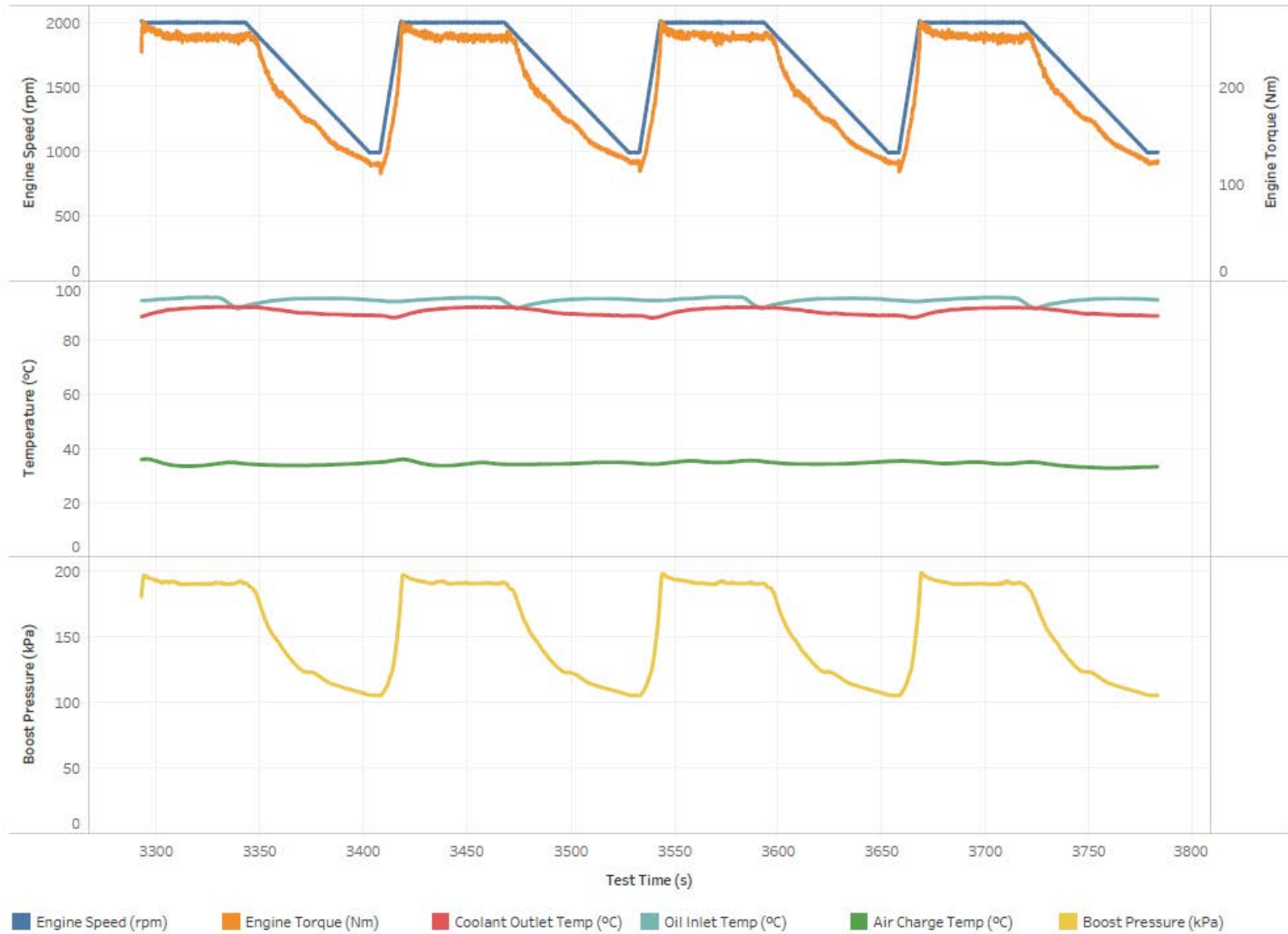
## Trailer Tow Test Sequence (Four Cycles)



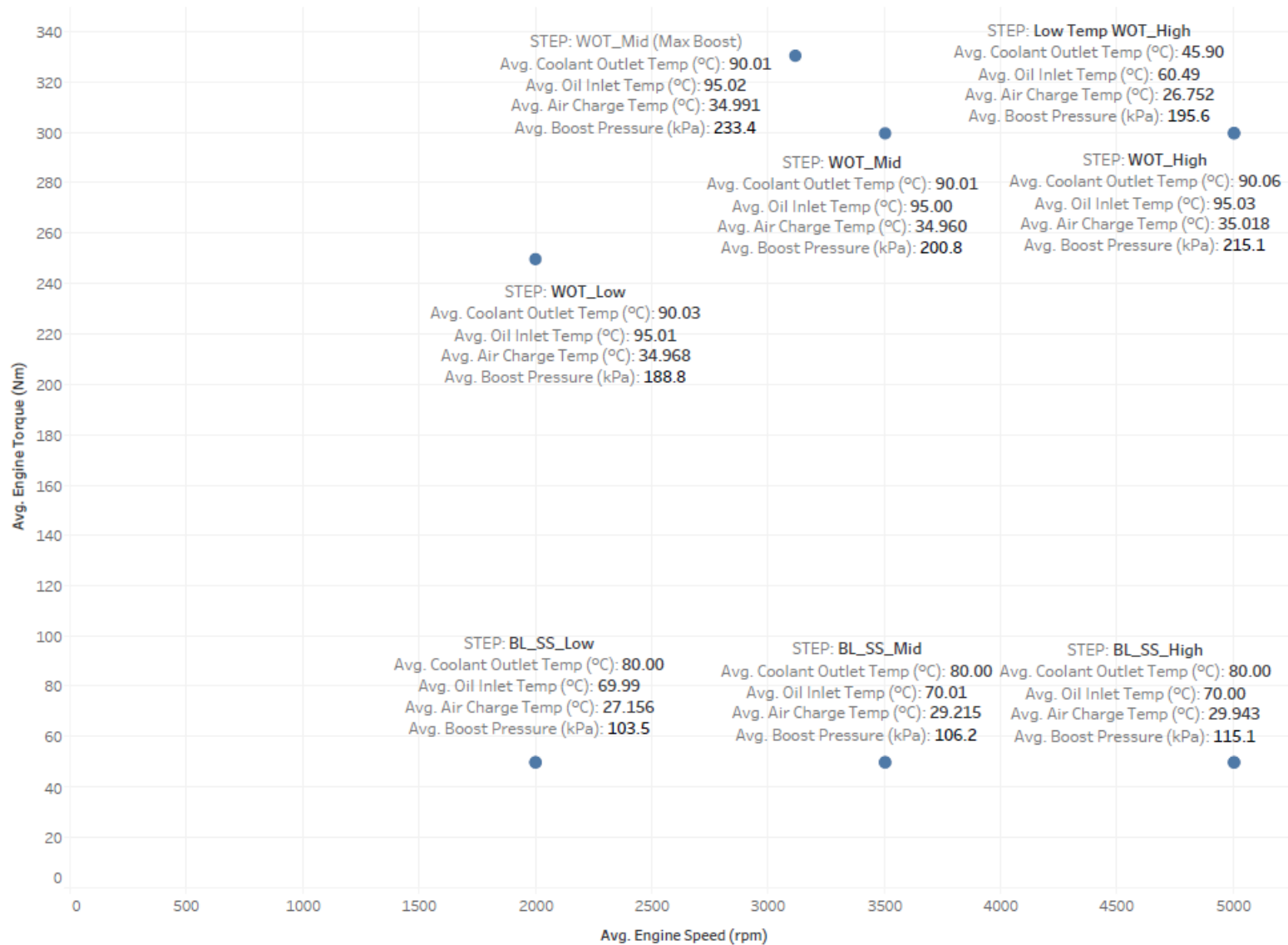
## Turbo Transient Test Sequence (Four Cycles)



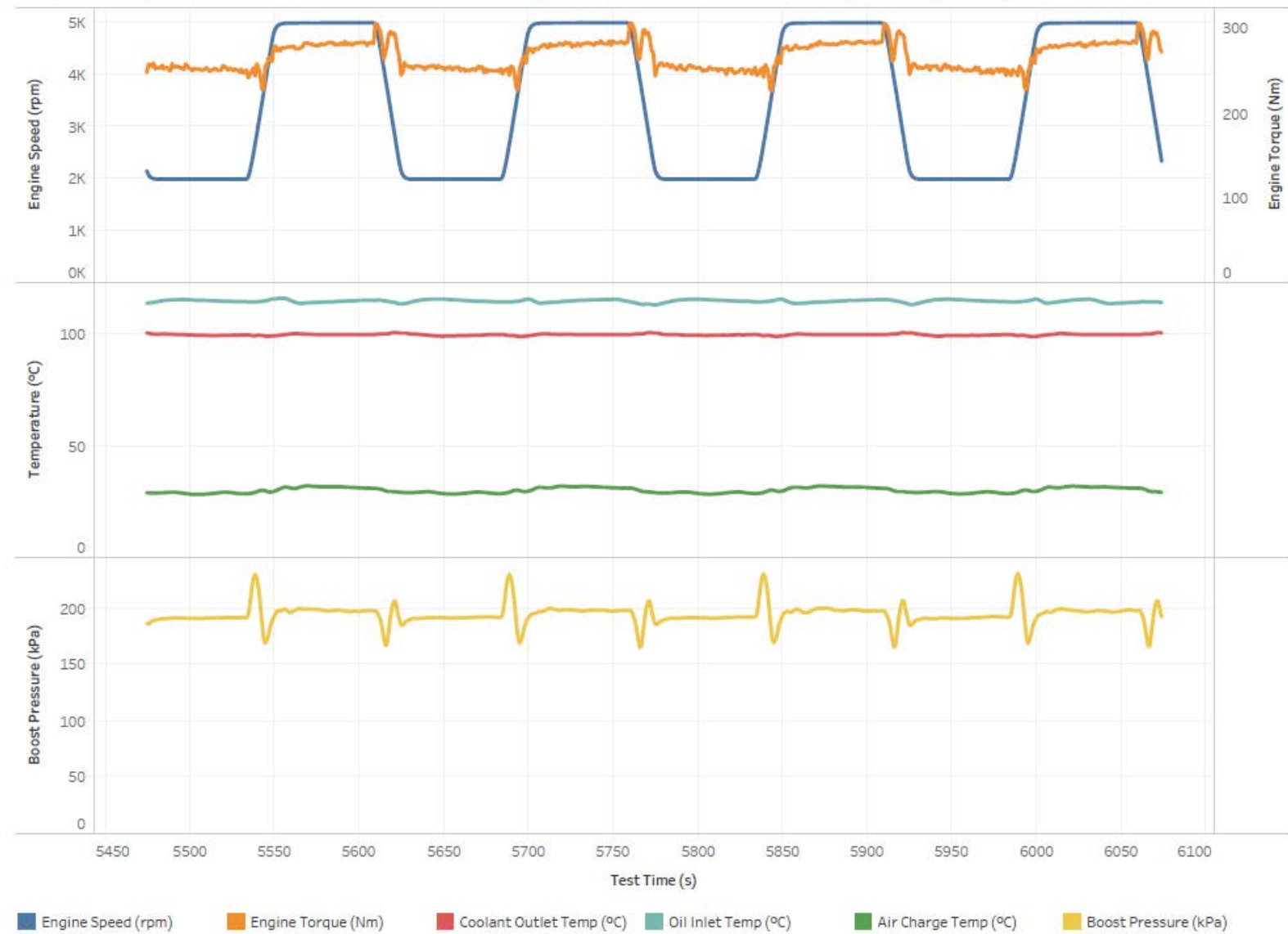
## Boundary Lubrication Test Sequence (Four Cycles)



## Steady State Test Sequences Summary

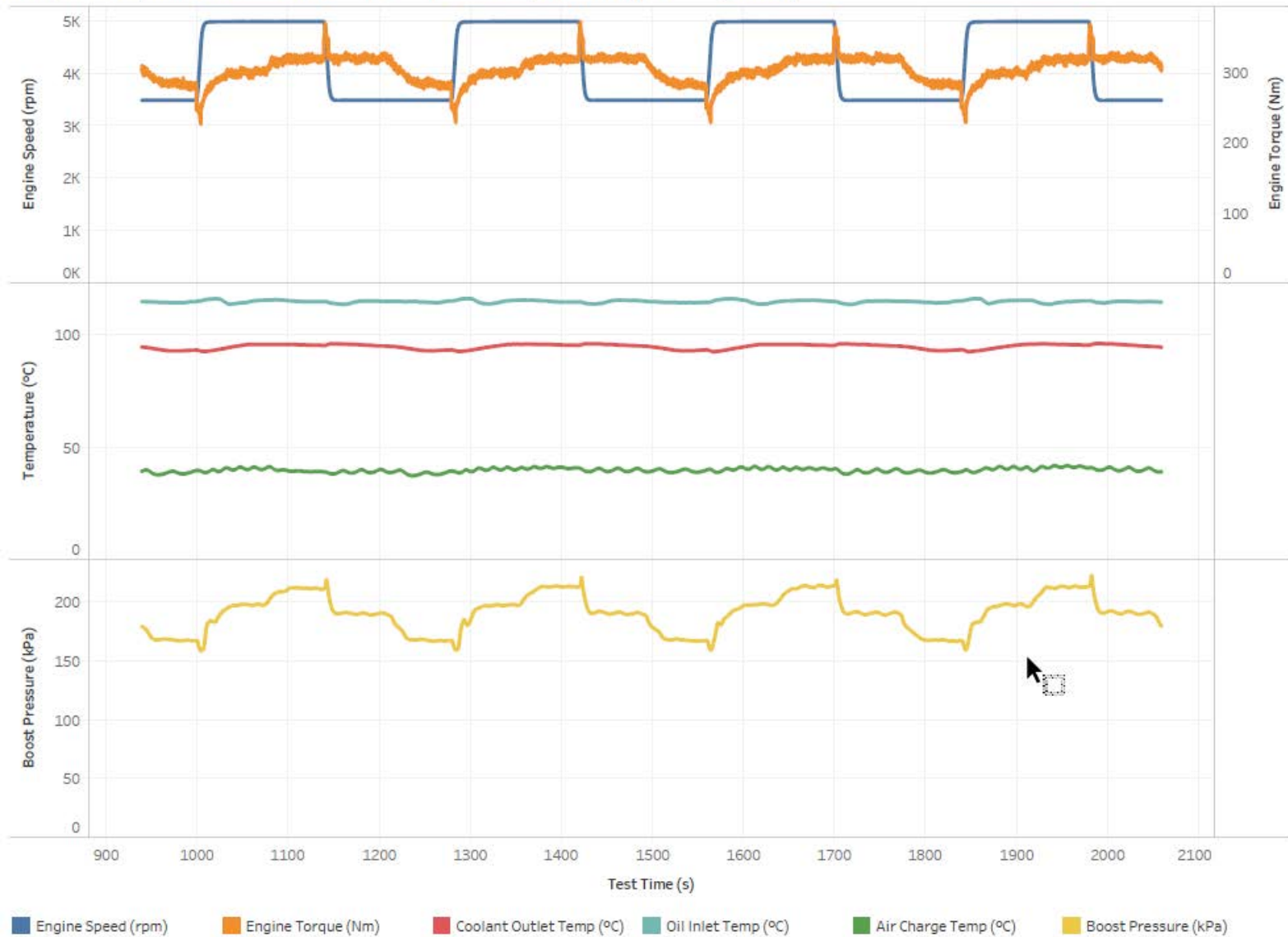


## High Temperature Transient Speed, High Load Test Sequence (Four Cycles)

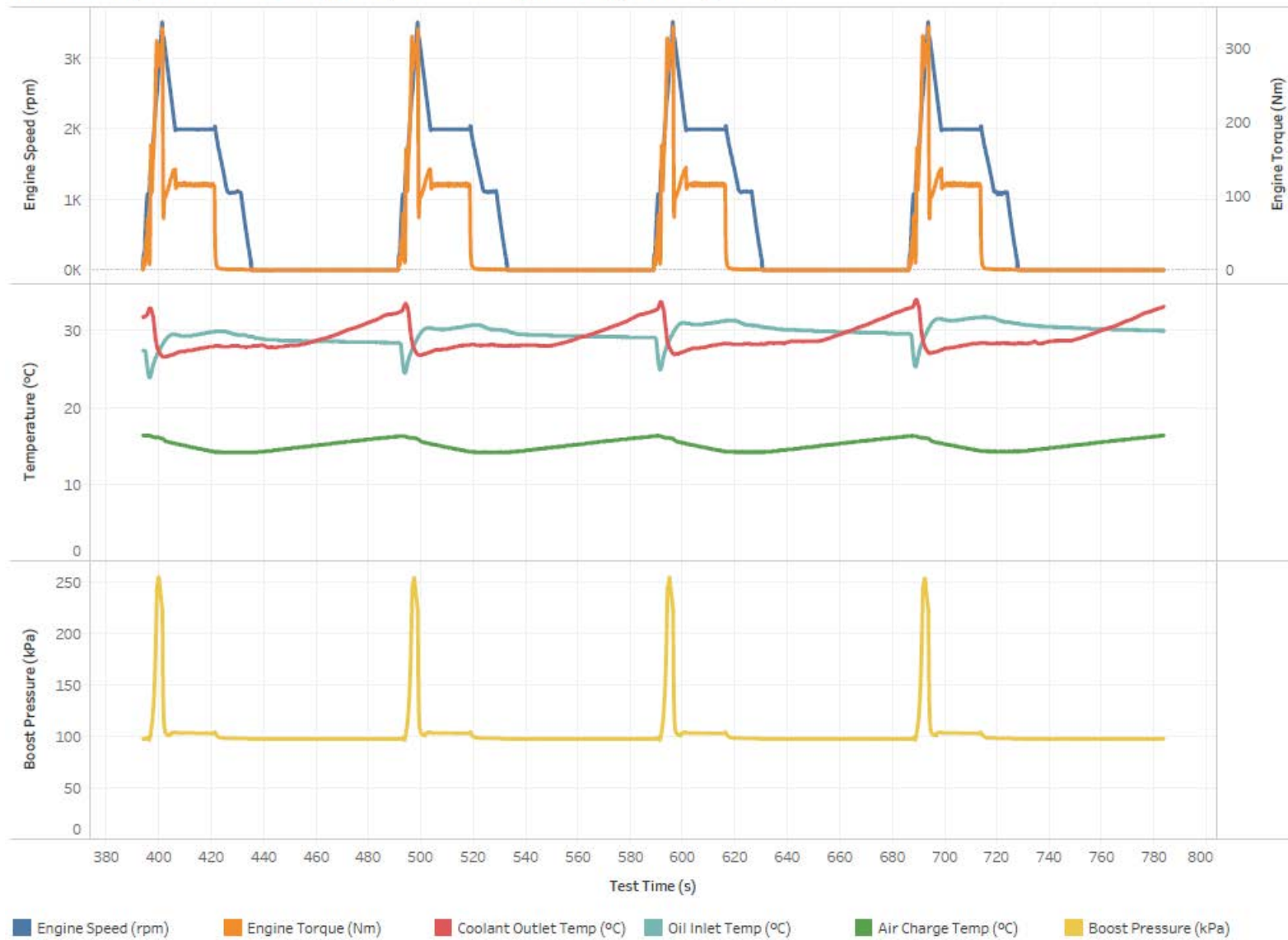




## High Temperature Trailer Tow Test Sequence (Four Cycles)



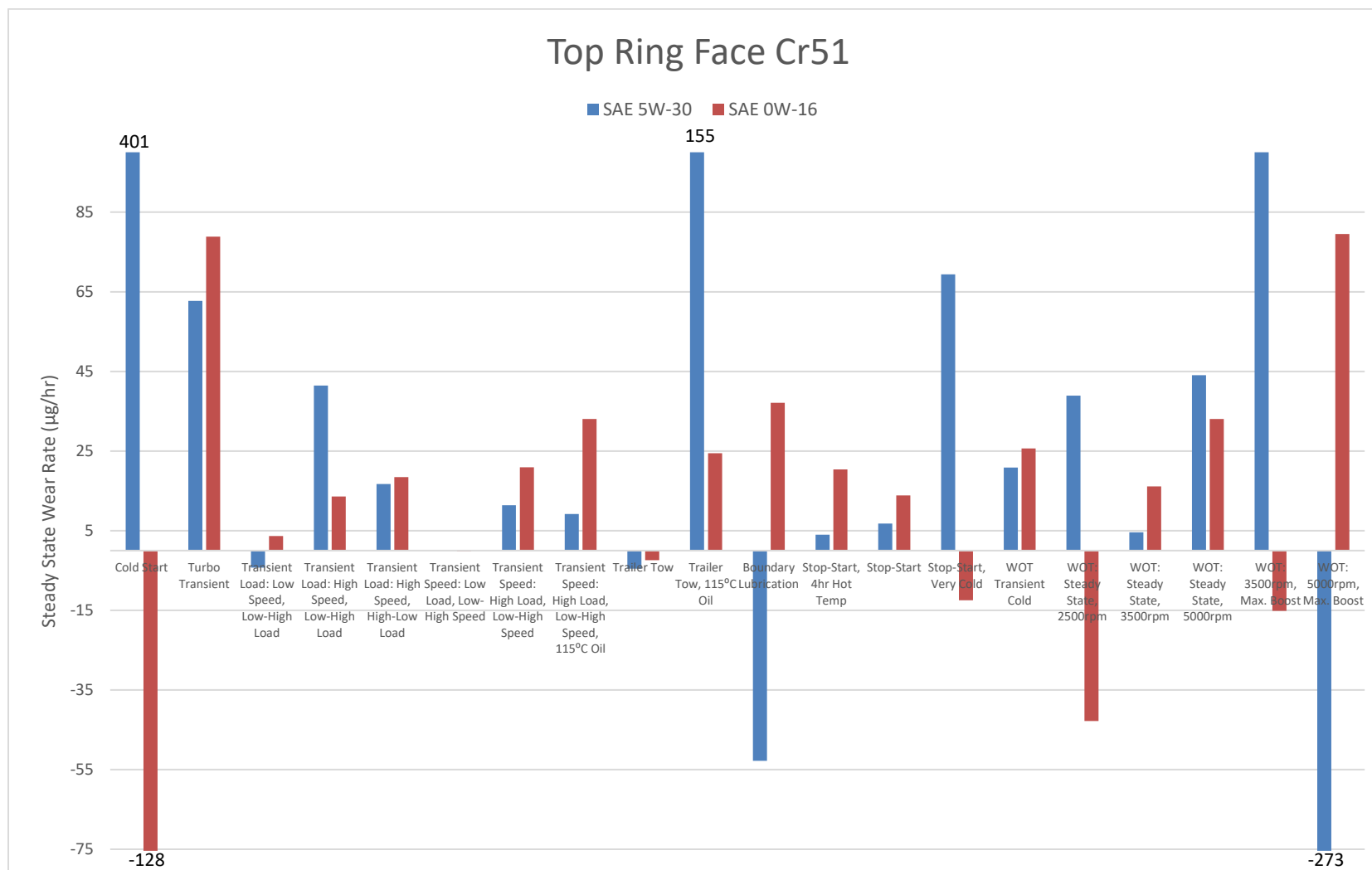
## Low Temperature Start/Stop Test Sequence (Four Cycles)



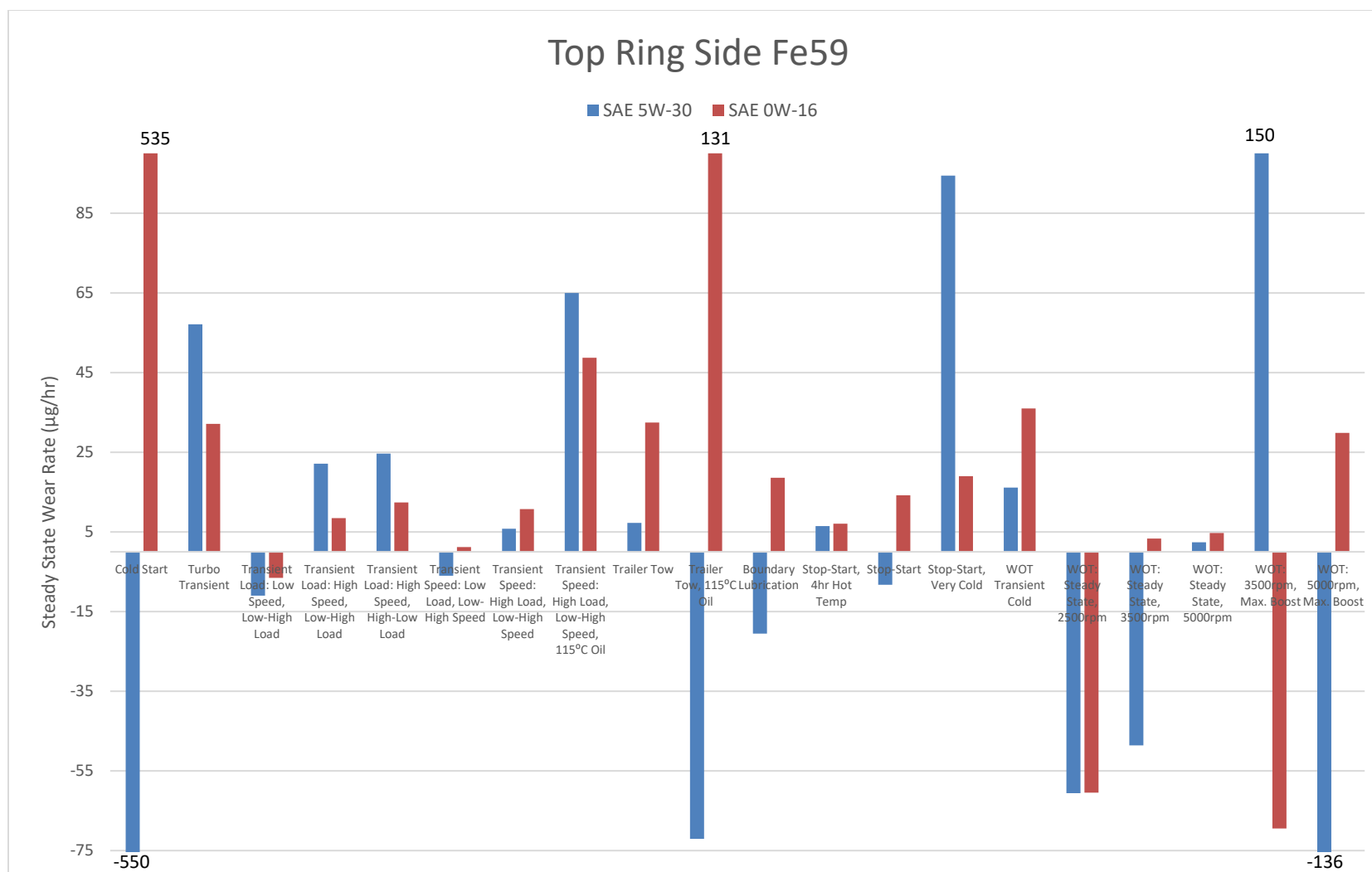


# **APPENDIX D**

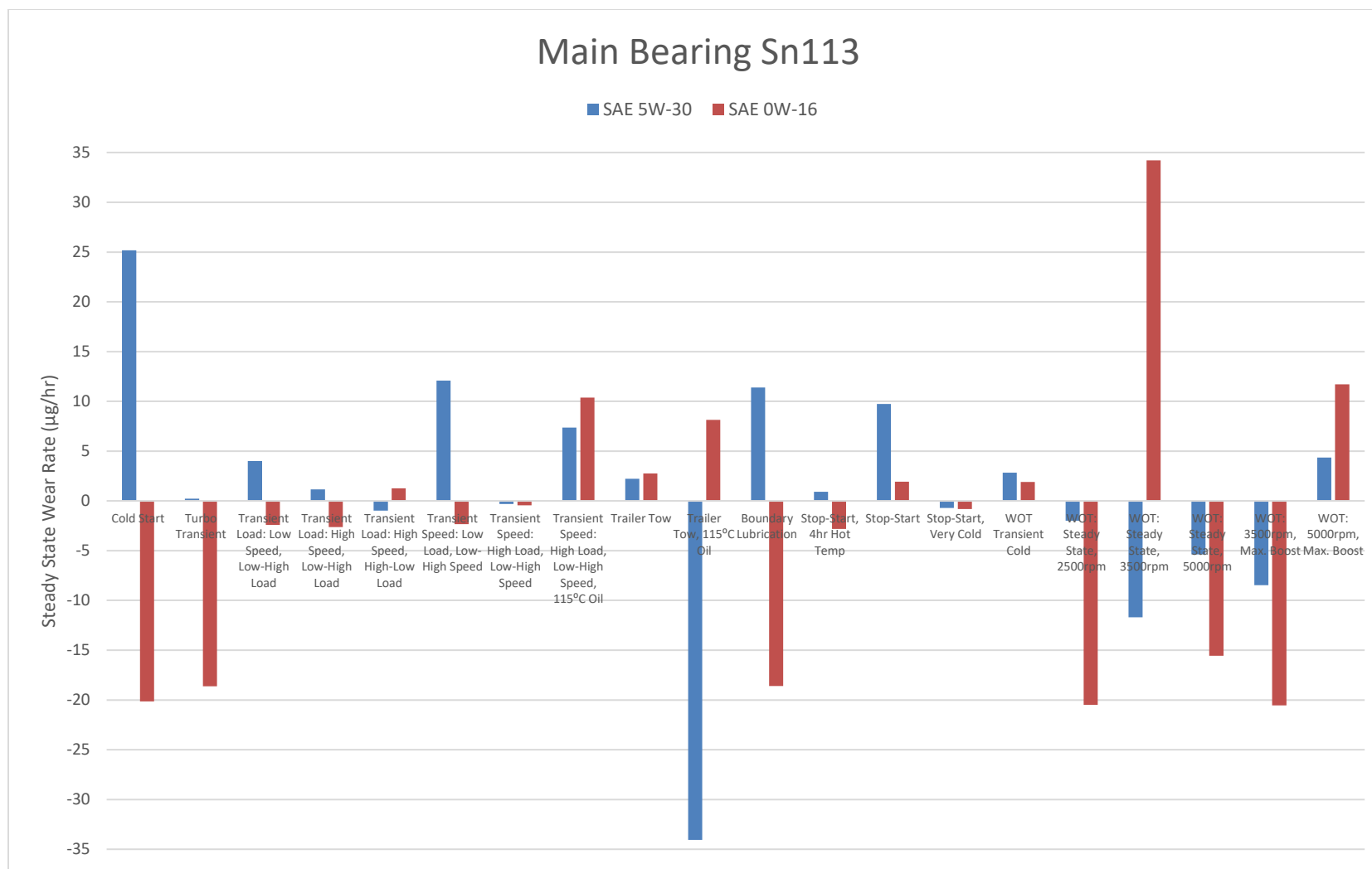
## **Engine Testing Results**



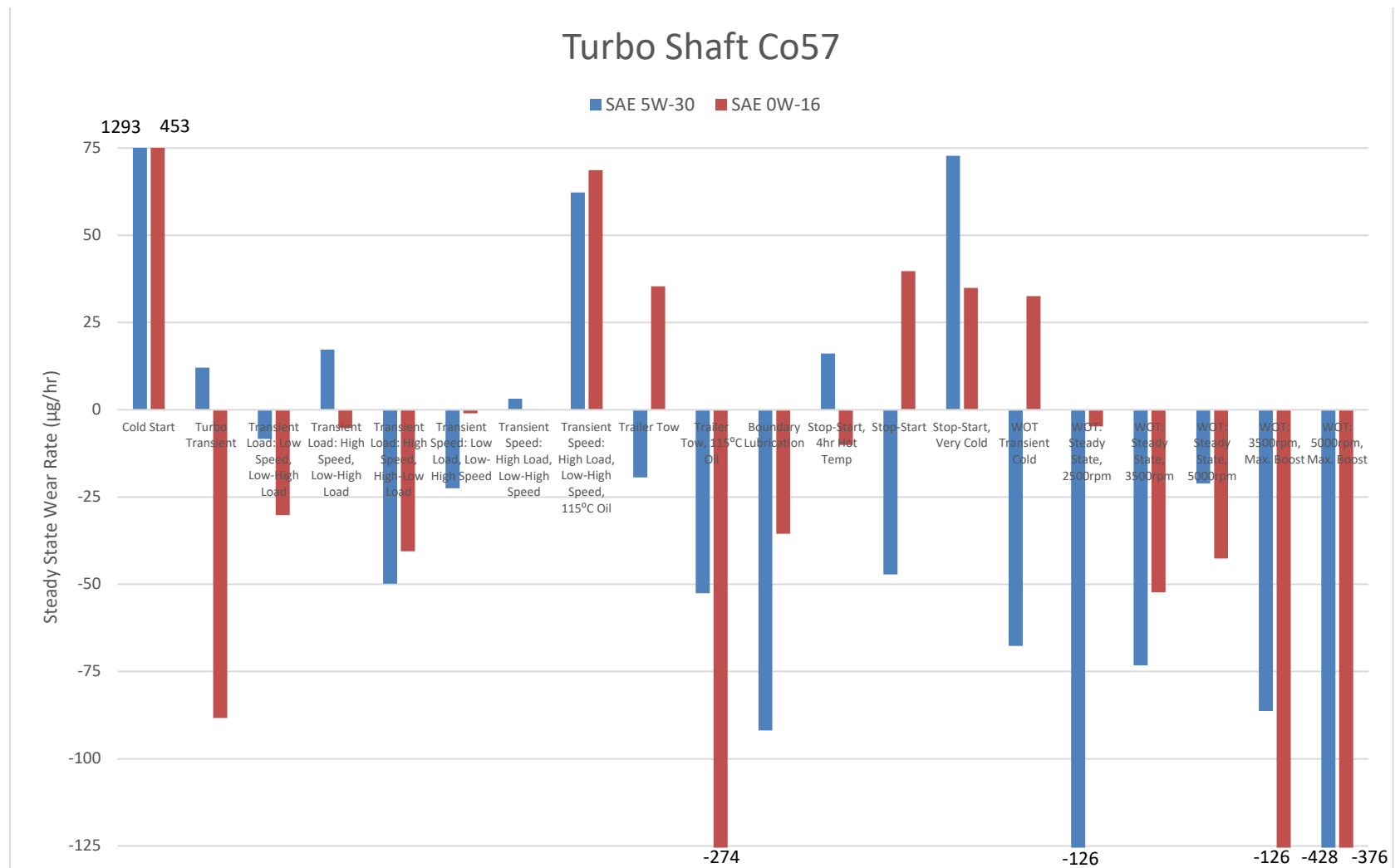
**Figure D1. Top Ring Face Wear for Complete Test Matrix in Chronological Testing Order**



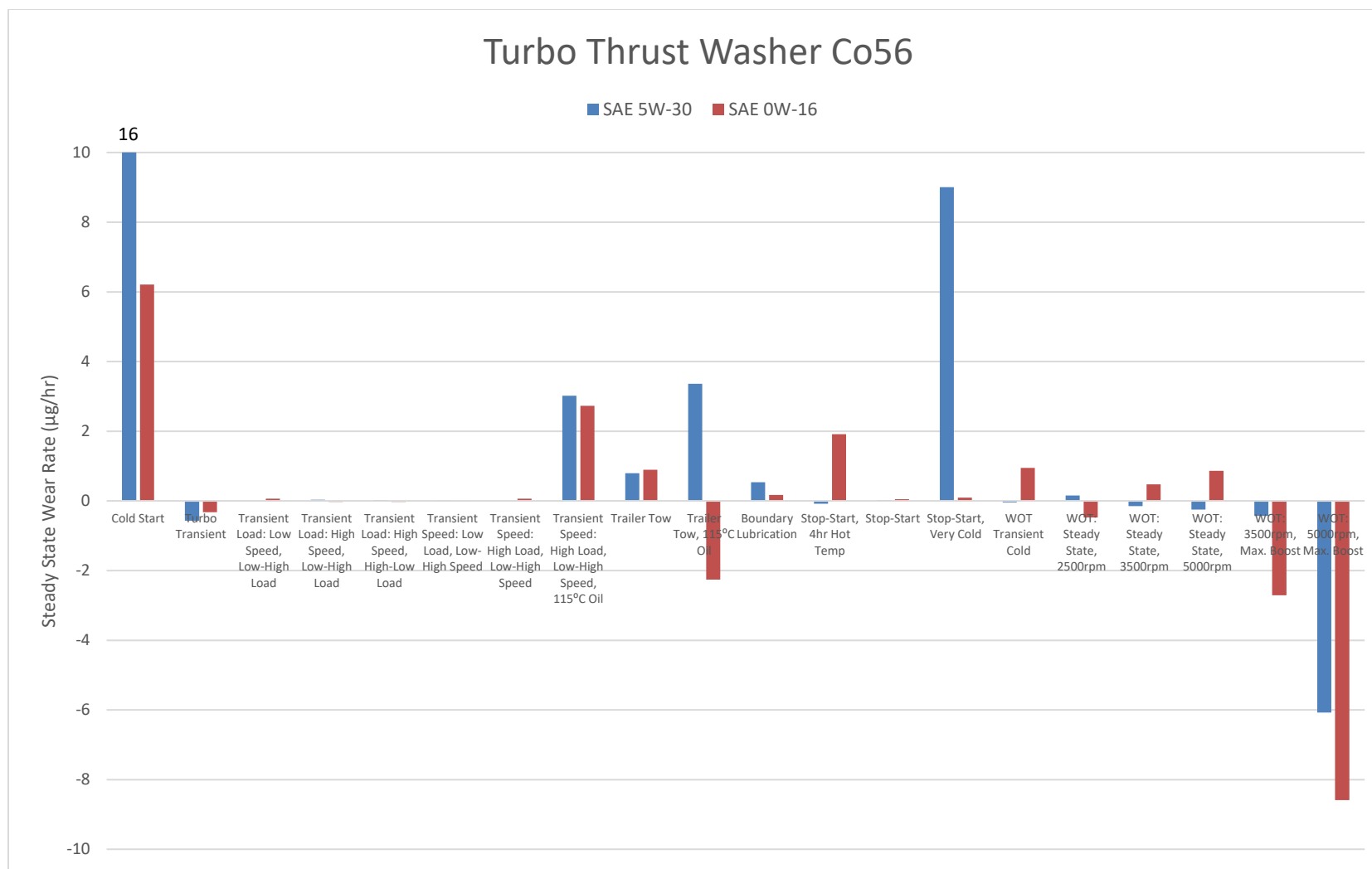
**Figure D2. Top Ring Side Wear Summary for Complete Test Matrix in Chronological Testing Order**



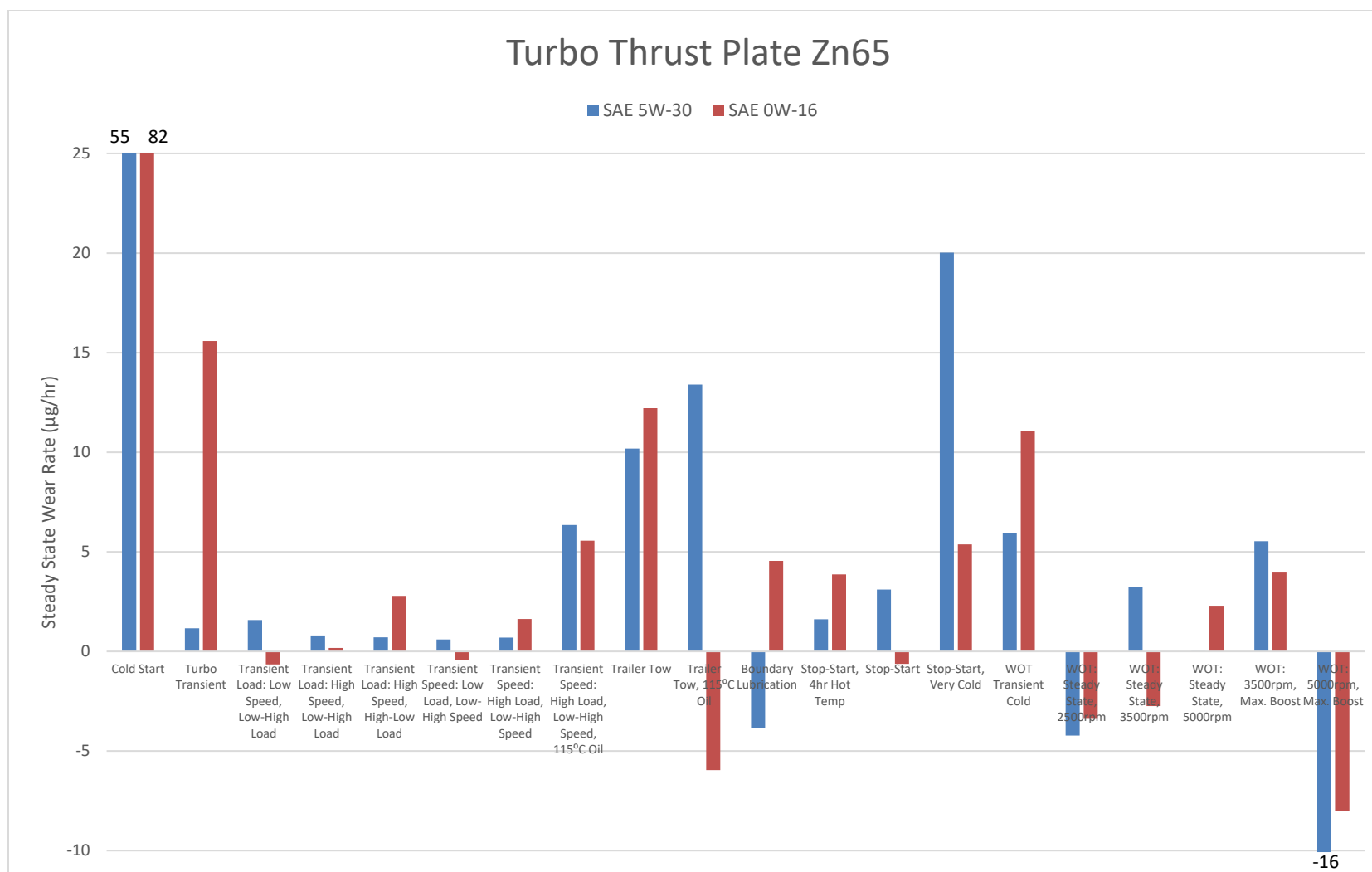
**Figure D3. Main Bearing Wear Summary for Complete Test Matrix in Chronological Testing Order**



**Figure D4. Turbo Shaft Wear Summary for Complete Test Matrix in Chronological Testing Order**



**Figure D5. Turbo Thrust Washer Wear Summary for Complete Test Matrix in Chronological Testing Order**



**Figure D6. Turbo Thrust Plate Wear Summary for Complete Test Matrix in Chronological Testing Order**

In a number of the tests, negative wear rates were recorded. This is not an unusual occurrence when using RATT<sup>®</sup> to measure real time wear of components. It is usual for this to occur in test conditions where the radioactive wear particles are lost at a faster rate than they are created. In almost all these circumstances it is reasonable to assume that the wear rates must be low, because if they are not, an increase in wear particles would be detected.



# **APPENDIX E**

## **Elemental Mass Concentrations for Engine Parts**

	Percent Mass Concentration by Element, %																						
	Na	Mg	Al	Si	V	P	K	S	Ca	Ti	Cr	Mn	Fe	Co	Ni	Nb	Mo	W	Cu	Sn	Zn	Pb	
Wrist Pin Base metal			0.3	0.46							0.54	0.55	98.14										
Wrist Pin Surface Coating		1.47	1.13	3.2		1.5		2.86	1.92		4.68	3.04	78.81						0.27				
Piston Skirt Base metal		1.26	68.96	24.22								0.22	0.62		1.86				2.87				
Cylinder Liner Base metal			0.19	3.43		0.23					0.12	0.72	94.22		0.33		0.76						
Main Bearing Base metal			0.37	0.25								0.27	99.1										
Main Bearing Coating Layer			89.35	5	0.22							0.21	0.26						0.73	4.23			
Main Bearing Thrust Surface			0.29	0.23								0.29	99.18										
Wrist Pin Bushing Base metal			0.35	0.22								0.67	98.75										
Wrist Pin Bushing ID Layer			0.28	0.22															94.58	4.92			
Rod Bearing ID Layer			89.11	5.2	0.21														1.1	4.38			
Rod Bearing Base Material			0.62	0.66								0.34	98.37										
Top Ring Base metal				2.17							0.61	0.65	96.57										
Top Ring Contact Surface			0.57	0.42							98.35		0.66										
2nd Ring Base Metal				0.55							0.07	0.74	98.64										
Oil Ring Spacer			0.23	0.94	0.1						17.86	1.02	69.52		9.59		0.36		0.38				
Oil Ring Side Rails			0.26	0.63	0.05						18.06	0.24	78.99		0.2		1.57						
Turbine Wheel			9.43	0.19						1.04	12.51		0.61		67.47	3.18	4.69	0.88					
Turbocharger Compressor Wheel		0.62	81.03	16.72						0.12			0.21						1.3				
Turbine Shaft			0.36	0.82							1.01	0.71	96.45		0.18		0.47						
Turbo Journal Bearing			1.93	1.19								2.05	0.48						56.52		36.69	1.14	
Turbo Thrust Bearing				0.3															64.46		35.24		
Valve Bucket			0.32	0.3							0.77	0.95	97.66										
Valve Guide		0.48		1.02		0.69						0.17	93.59						4.05				
Valve Spring				2.43							0.59	0.63	96.34										
Valve Keeper				0.26							0.09	0.31	99.33										
Intake Valve Seat		0.44	0.49	0.78	0.07						2.1	0.55	83.79	8.29	1.31		2.08		0.09				
Intake Valve Stem			0.31	2.4	0.04						8.09	0.34	88.52		0.31								
Intake Valve Face				1.33							7.63	0.31	90.5		0.23								
Exhaust Valve Face					0.11						22.27	8.7	58.46		3.69	3.58		3.18					
Exhaust Valve Stem				3.99							8.72	0.43	86.63		0.23								
Exhaust Valve Seat			0.4	0.32								0.47	91.4				0.78		6.63				
Timing Chain Link			0.18	0.62							0.1	0.71	98.39										
Timing Chain Gear				0.54							1.09	0.82	97.55										
Timing Chain Pin			1.85	0.58							1.34	0.51	94.95		0.18		0.59						
Camshaft Bearing Base Metal			0.33	0.25								0.21	99.21										
Camshaft Bearing Babbitt			88.23	5.53	0.21								0.3						0.73	4.93			
Camshaft Lobe				1.92							0.12	0.69	96.92			0.34							
Oil Pump Gear			0.17	0.3							0.05	0.51	96.36				0.63		1.97				
Oil Pump Shaft			0.28	0.32								0.85	97.59				0.96						
Oil Pump Bearing		0.68	82.77	13.38								0.16	0.8						1.29		0.91		
Balance Shaft Bearing Base Metal			0.42	0.3								0.22	99.07										
Balance Shaft Bearing Babbitt			81.62	9.92	0.2							0.12	1.23				0.16		0.72	6.04			
Balance Shaft Gear			0.29	0.66							0.83	0.72	96.53		0.26		0.69						
Block		0.51	81.45	14.45						0.15		0.31	0.46						2.2		0.46		
Crankshaft (from Counterweight)			0.26	2.75								0.66	95.26						1.06				
Cylinder Head		0.72	82.3	12.97						0.18		0.36	0.58						2.49		0.41		
Mahle Piston Surface	2.78	0.53	54.87	28.5		9.36	0.16		1.63				0.31		0.95				1.18				
Mahle Piston Base Metal		1.56	75.55	21.39									0.2		0.63				0.68				

# **APPENDIX F**

## **Ford 8hr Run-in**

**Eight Hour Break-In.** Run as follows:

Stage No.	Time per Stage Hr:Min	Total Time Hr:Min	Engine Speed Setpoint rpm	BMEP Setpoint bar (psi)-lb/ft
1	0:12	0:12	Idle	Min. Load ^
2	0:18	0:30	Idle	Min. Load ^
3	0:30	1:00	1500	2.5-28.2 lb/ft
4	0:30	1:30	2000	4.5-52.8
5	0:30	2:00	2500	7.0-82.1
6	0:30	2:30	3000	8.5-99.7
Optional: Shut down engine to drain oil and remove oil filter. Replace drain plug with drain valve. Install new oil and new oil filter. If specified, install bottles in the pushover and pullover sides of the crankcase ventilation system.				
7	0:15	2:45	3000	Full Load *
8	3:00	5:45	3000	Full Load *
9	0:15	6:00	2000	4.5-52.8
10	0:15	6:15	3250	Full Load *
11	0:15	6:30	3500	Full Load *
12	0:15	6:45	3750	Full Load *
13	0:15	7:00	4000	Full Load *
14	0:15	7:15	4250 **	Full Load *
15	0:15	7:30	4500 **	Full Load *
16	0:15	7:45	4750 **	Full Load *
17	0:15	8:00	5000 **	Full Load *

^ "Min. Load" is defined as the greater value of either:  $47 \pm 7$  N-m ( $35 \pm 5$  ft-lbs) engine load or the load required to maintain zero crankcase pressure.

\* For boosted applications, "full load" points are set to zero boost, meaning intake manifold pressure equal to barometric pressure.

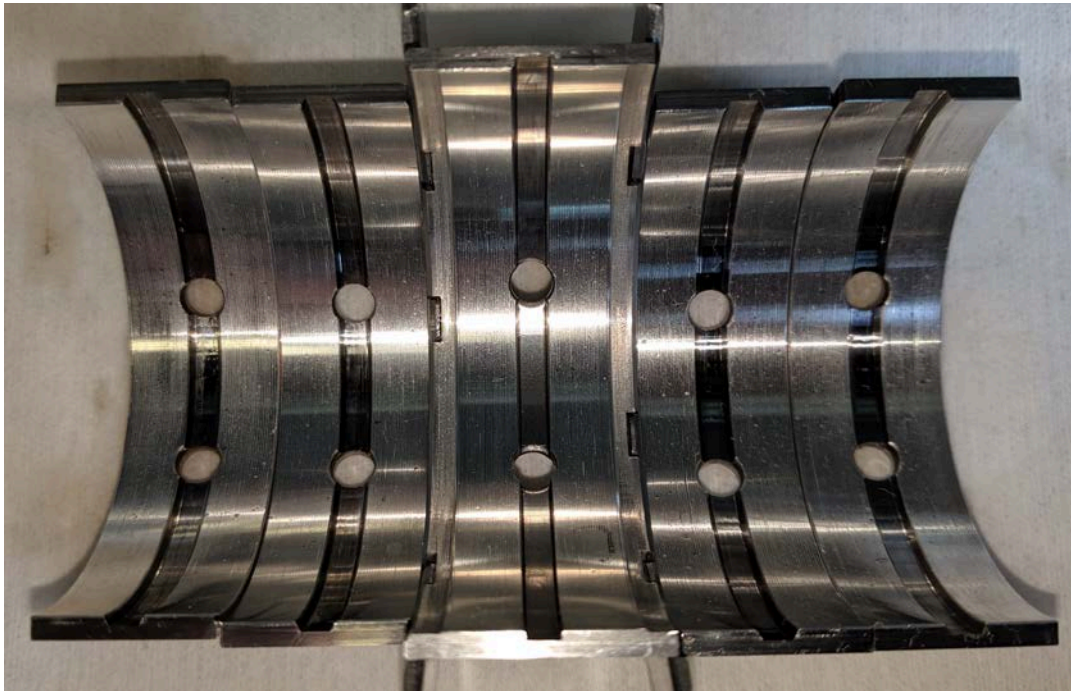
\*\* DO NOT EXCEED MAXIMUM RATED ENGINE SPEED DURING BREAK-IN.  
If this setpoint speed exceeds the maximum rated engine speed, run at maximum rated speed instead.

For this project, this 8hr run-in was repeated until 67hrs of run-in was achieved.

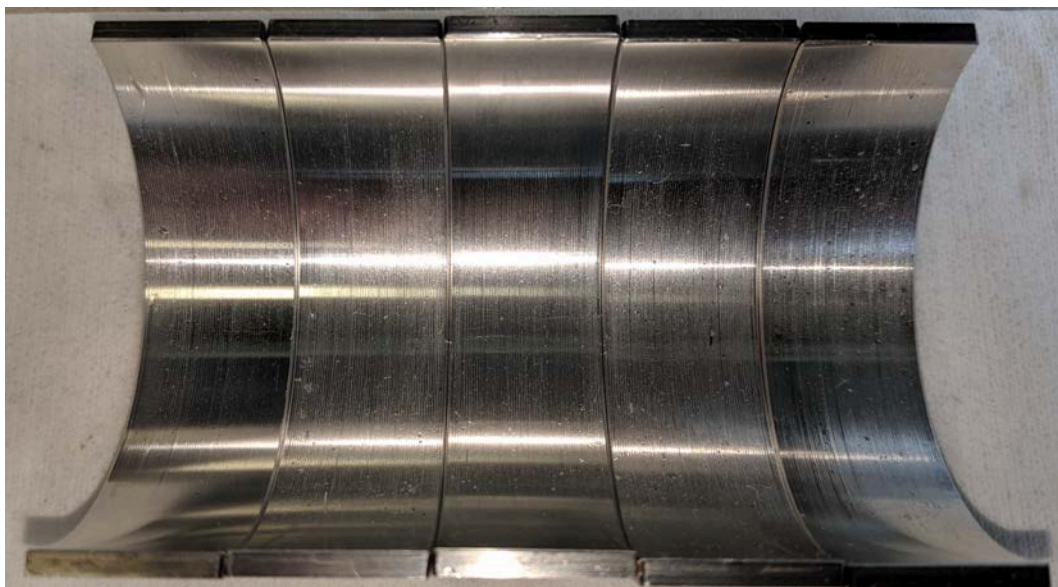
## **APPENDIX G**

### **End of Test Parts – Photographs and Discussions**

Figures G1-2 show the EOT main bearings. Since this testing program ran without an oil filter, higher than expected levels of embedded particles were present. Overall levels of normal bearing wear were low as corroborated by the radiation data.



**Figure G1. Main Bearings – Upper Halves**



**Figure G2. Main Bearings – Lower Halves**



Aside from some mild post-test corrosion the cylinder liners were free from excessive wear. Figures G3-6 show the thrust side.



**Figure G3. Cylinder 1 Thrust**



**Figure G4. Cylinder 2 Thrust**



**Figure G5. Cylinder 3 Thrust**



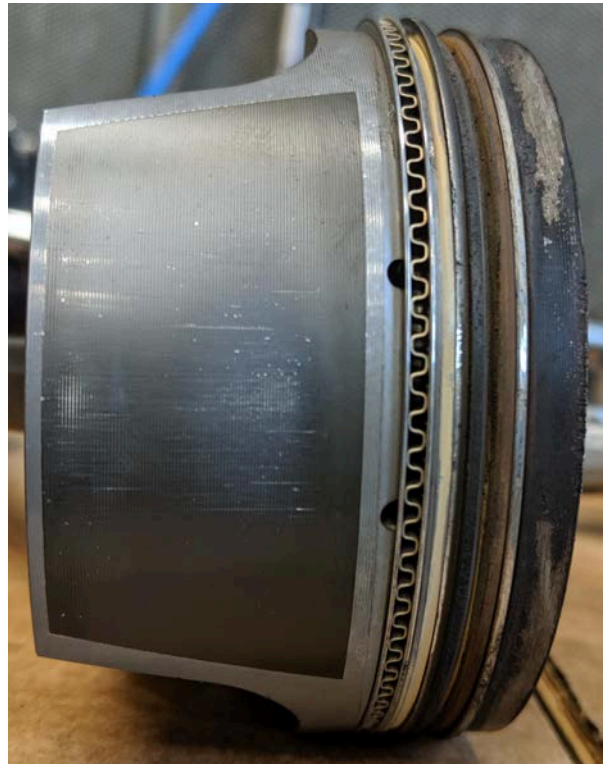
**Figure G6. Cylinder 4 Thrust**



Figures G7-10 show the pistons. Aside from some scratches on the skirt area, no unusual wear was observed. Post-test inspection of the ring pack showed all rings were free with minimal carbon buildup.



**Figure G7. Piston #1: Thrust (Left), Piston Anti-Thrust (Right).**

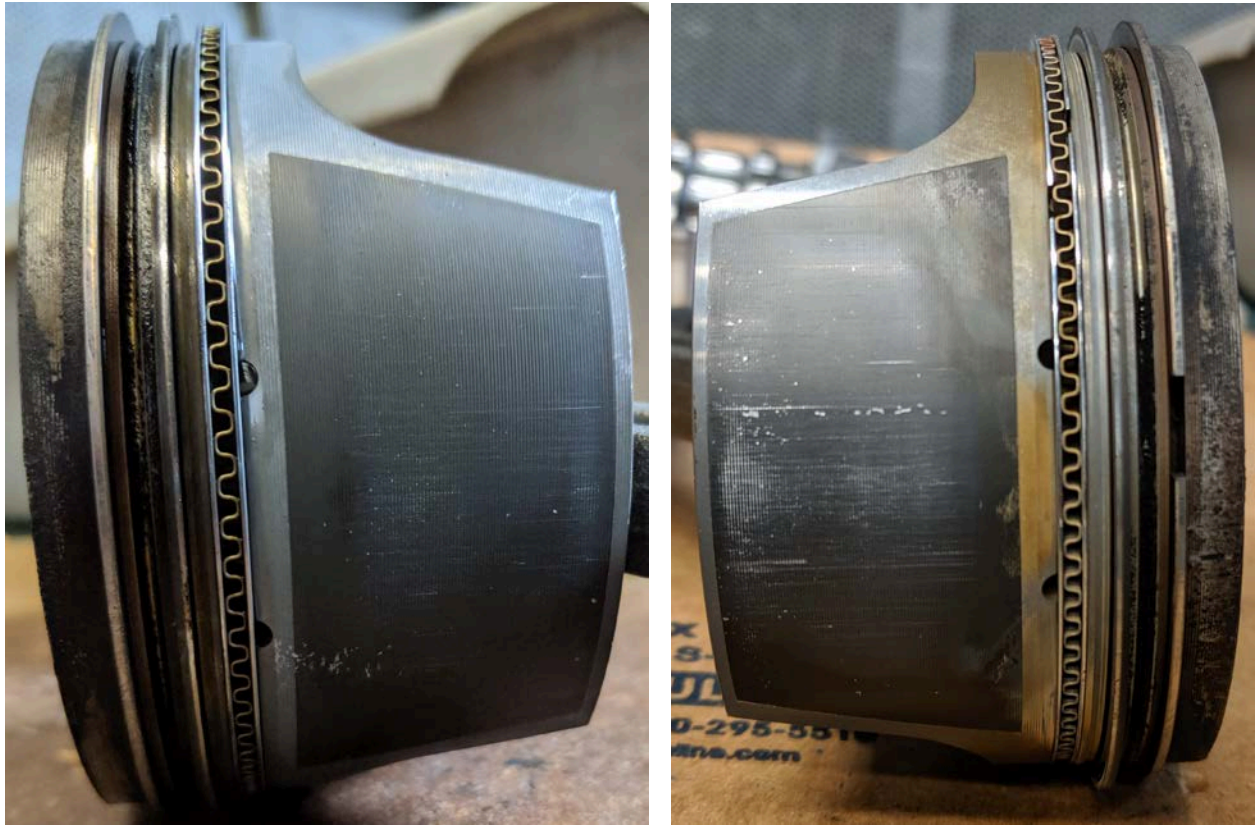


**Figure G8. Piston #2: Thrust (Left), Piston Anti-Thrust (Right).**



**Figure G9. Piston #3: Thrust (Left), Piston Anti-Thrust (Right).**





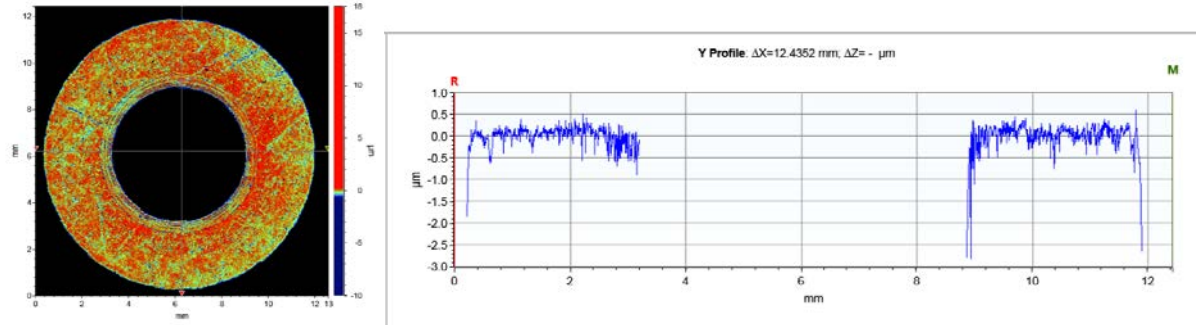
**Figure G10. Piston #4: Thrust (Left), Piston Anti-Thrust (Right).**

Figures G11-19 show the irradiated turbo components after testing. Wear areas were imaged for 3-D analysis for a better understanding of the amount of wear on each part.



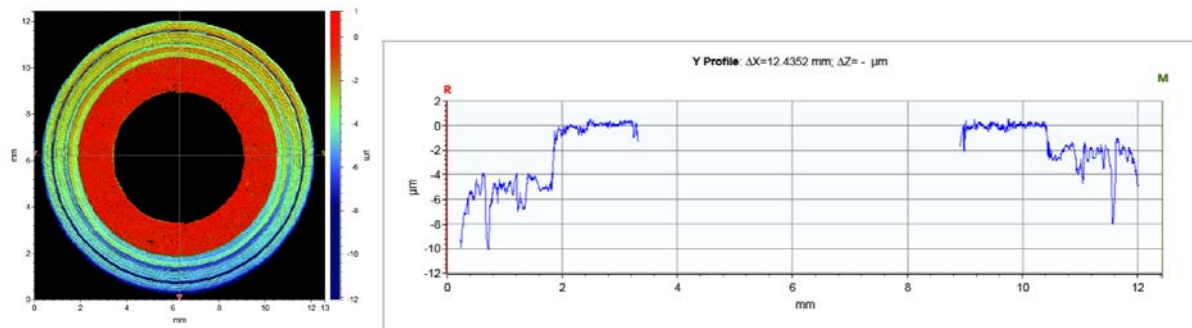
**Figure G11. Turbo Thrust Washer: Compressor Side (Left), Plate Side (Right).**

The turbo thrust washer compressor side showed less than 0.5 microns of wear.



**Figure G12. Turbo Thrust Washer: 3D Compressor Side**

The turbo thrust washer plate side showed about 10 microns of wear at the deepest groove.

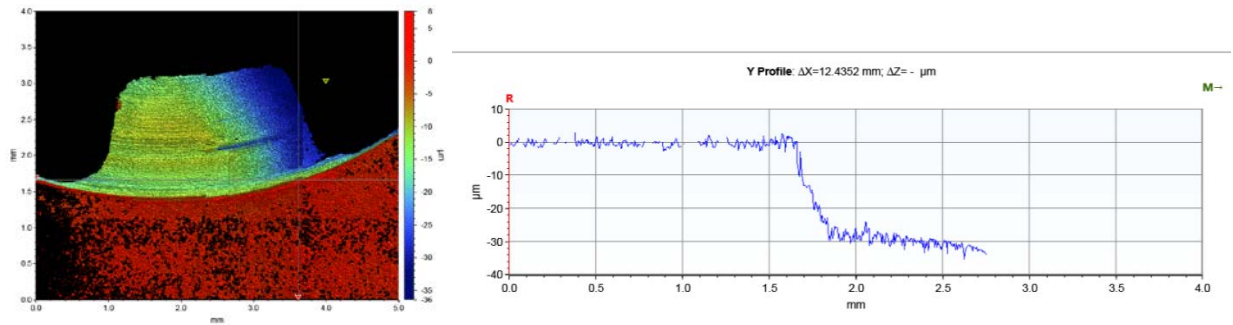


**Figure G13. Turbo Thrust Washer: 3D Plate Side**



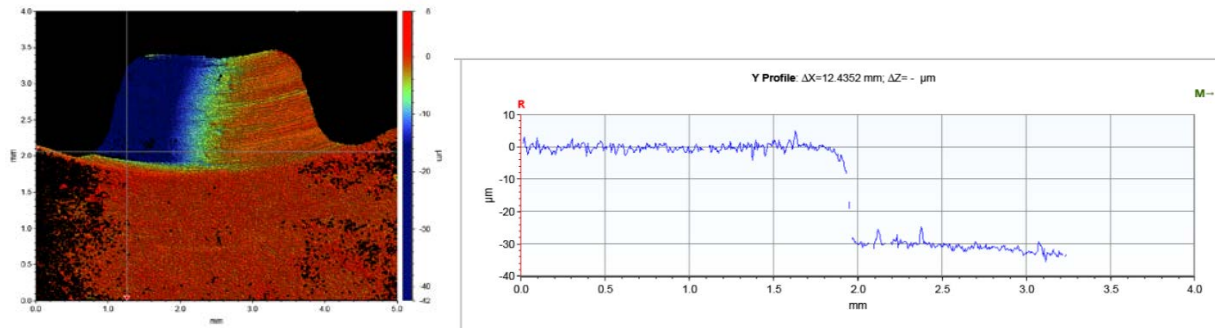
**Figure G14. Turbo Thrust Plate: Washer Side (Left), Journal Bearing Side (Right).**

The washer side of the turbo thrust plate had maximum wear on each tooth face of approximately 35 microns.



**Figure G15. Turbo Thrust Plate: 3D Washer Side**

The journal bearing side of the turbo thrust plate had maximum wear on each tooth face of approximately 35 microns.

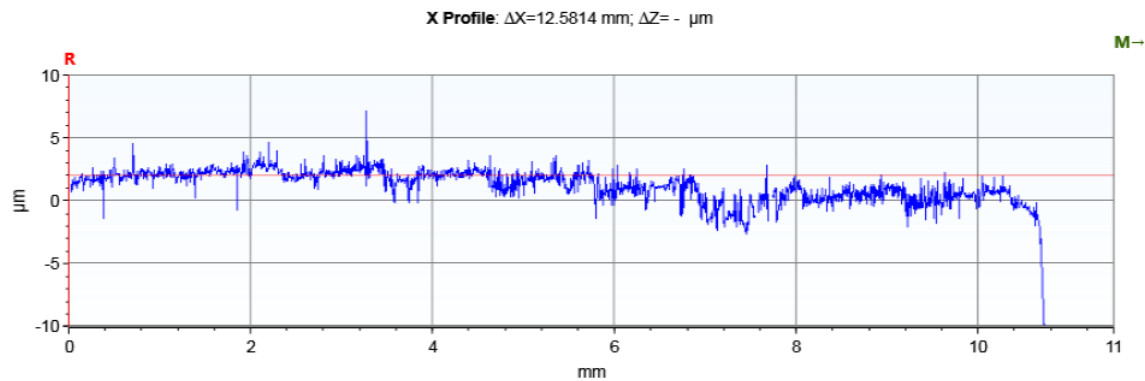


**Figure G16. Turbo Thrust Plate: 3D Journal Bearing Side**

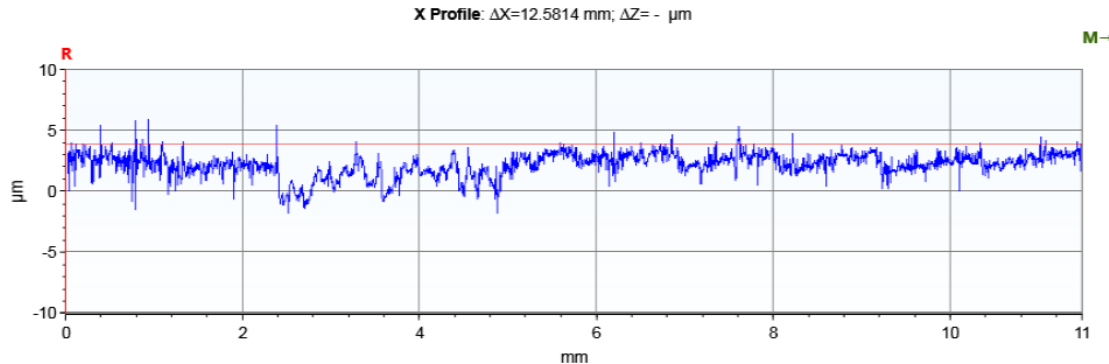


**Figure G17. Turbo Shaft – journal wear areas highlighted in yellow.**

3D profilometry on the turbo shaft wear areas showed only a few microns of wear on the deepest grooves. Overall the wear on the turbine side seemed higher than on the compressor side.

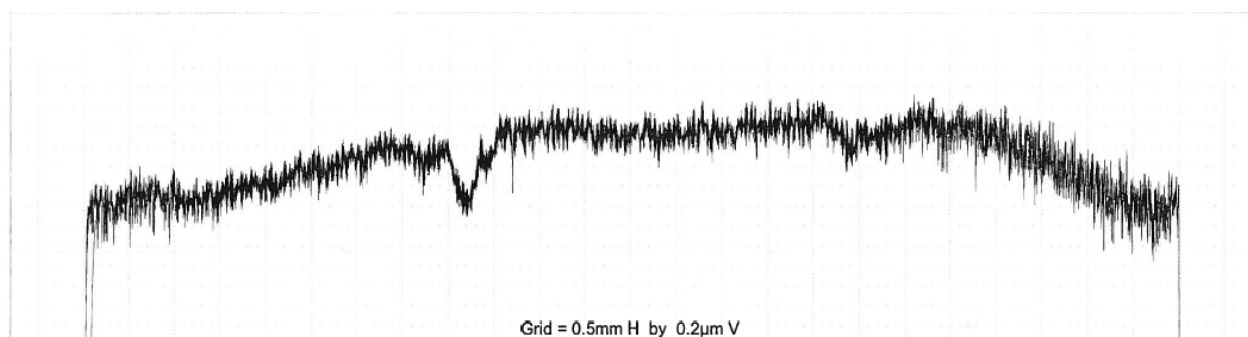


**Figure G18. Turbo Shaft Profile: Compressor Side**



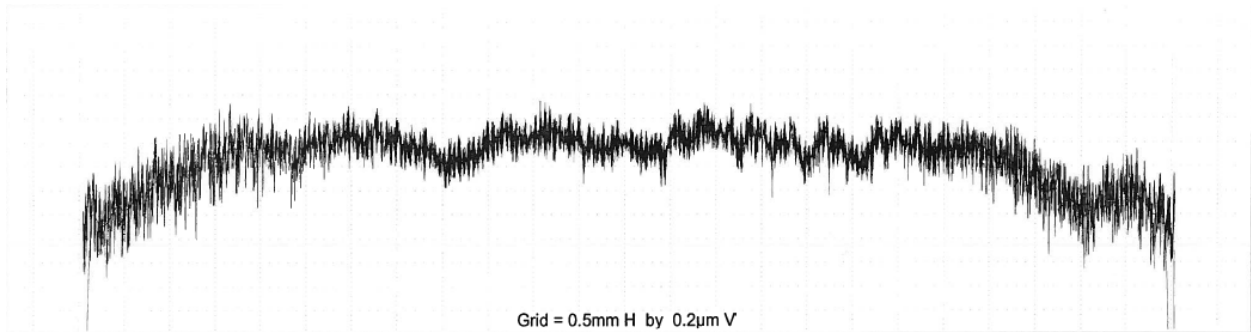
**Figure G19. Turbo Shaft Profile: Turbine Side**

During posttest inspections, it was observed that there was some wear on the camshaft journals and the tri-lobe for the fuel pump. Contact profilometry was used to characterize the amount of wear. The results can be seen in figures G20-38. Some cam journals showed near zero wear, but others, along with the fuel pump lobes, showed more than 7 microns of wear depth. Note the differing Y-axis scales on the images.

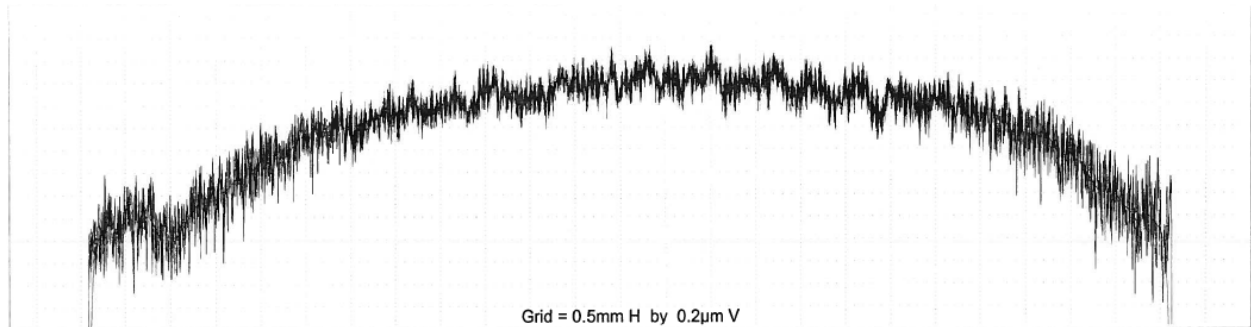


**Figure G20. Intake Camshaft Lobe #1**

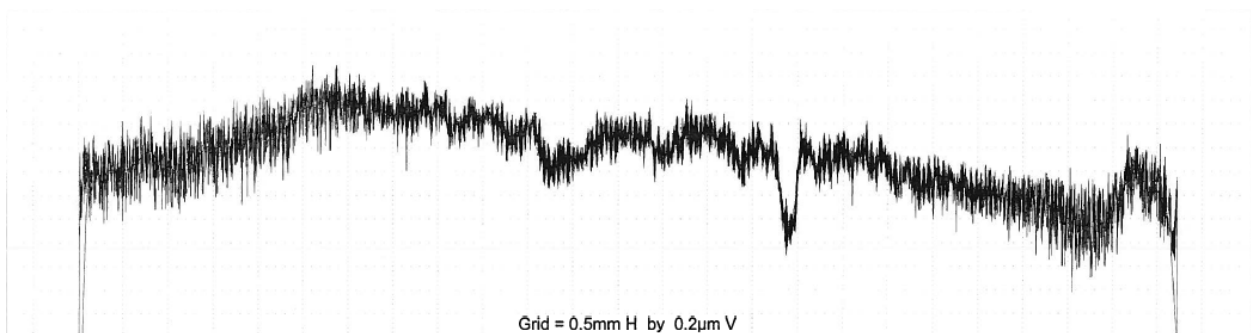




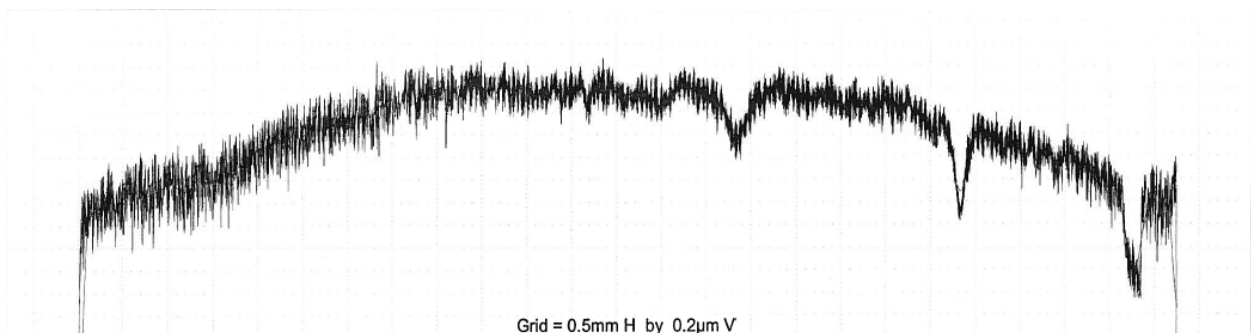
**Figure G21. Intake Camshaft Lobe #2**



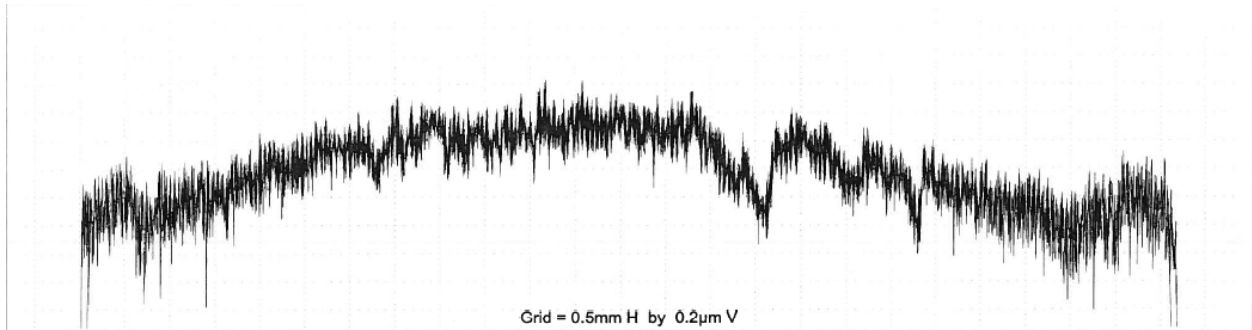
**Figure G22. Intake Camshaft Lobe #3**



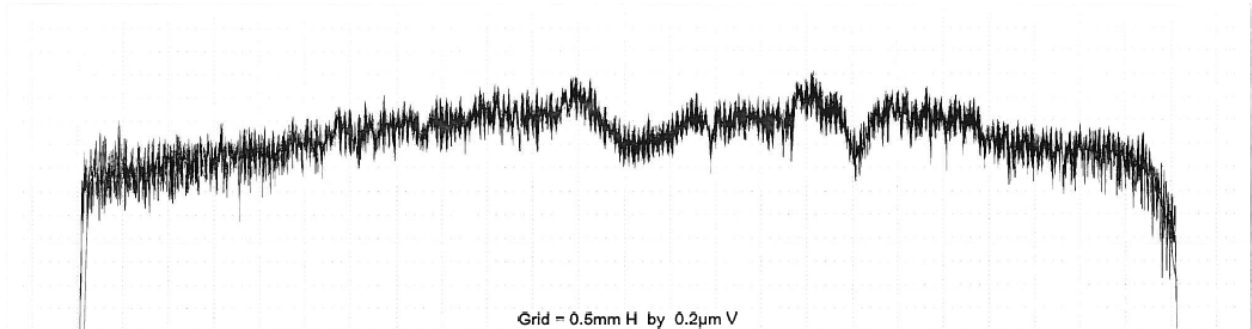
**Figure G23. Intake Camshaft Lobe #4**



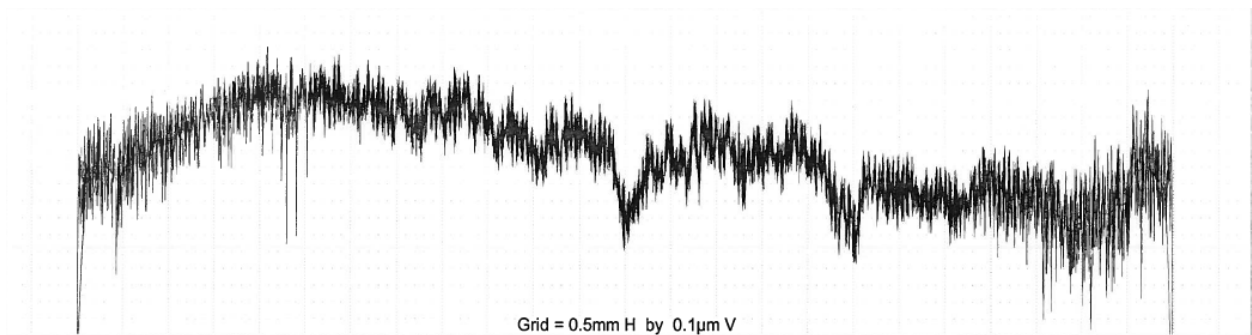
**Figure G24. Intake Camshaft Lobe #5**



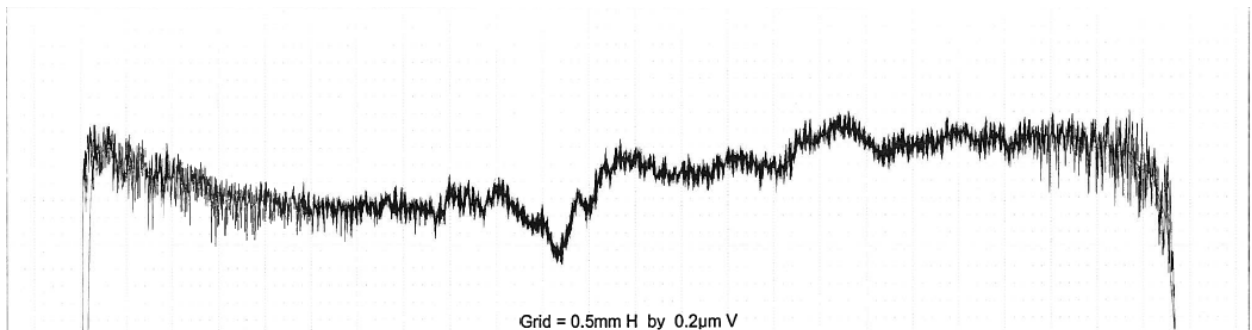
**Figure G25. Intake Camshaft Lobe #6**



**Figure G26. Intake Camshaft Lobe #7.**

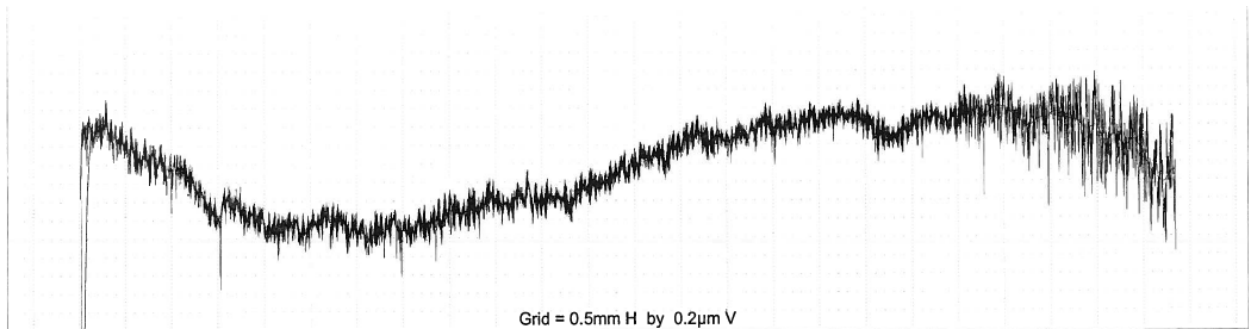


**Figure G27. Intake Camshaft Lobe #8.**

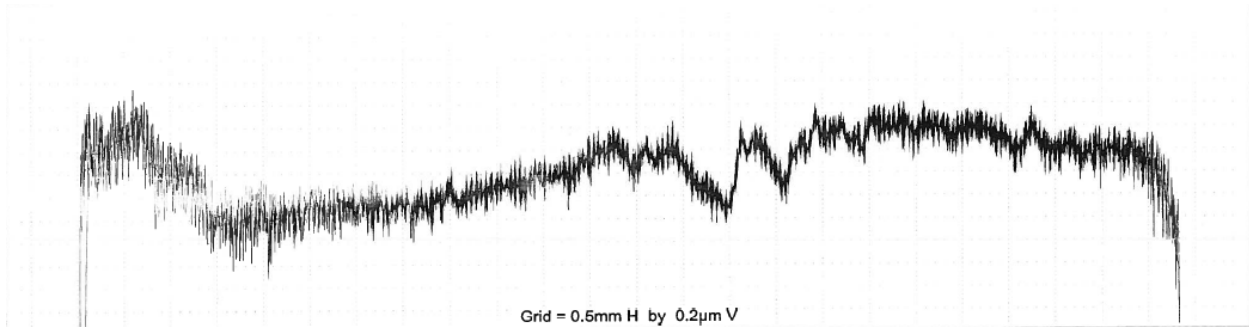


**Figure G28. Exhaust Camshaft Lobe #1**

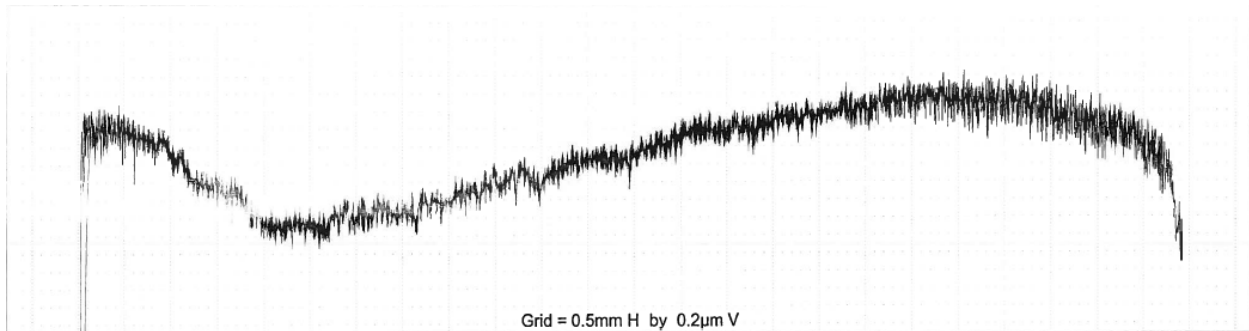




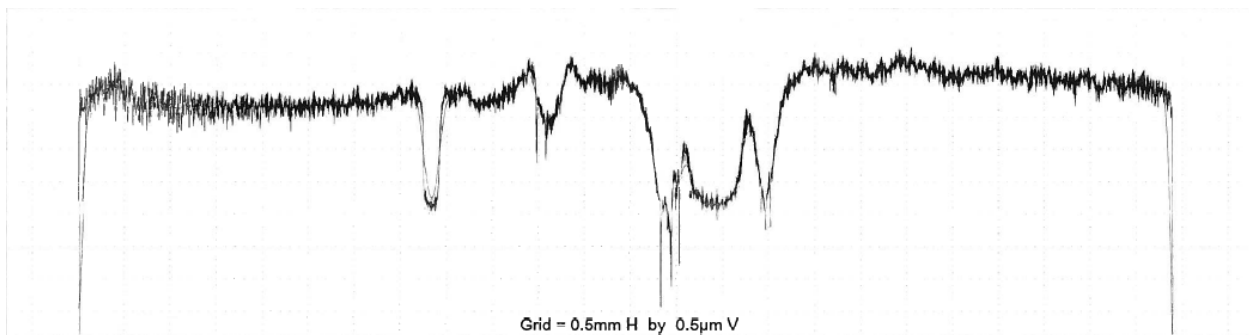
**Figure G29. Exhaust Camshaft Lobe #2**



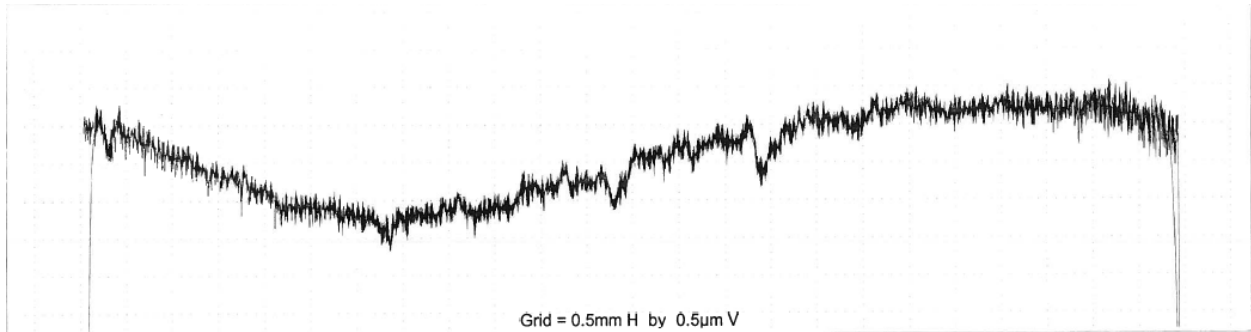
**Figure G30. Exhaust Camshaft Lobe #3**



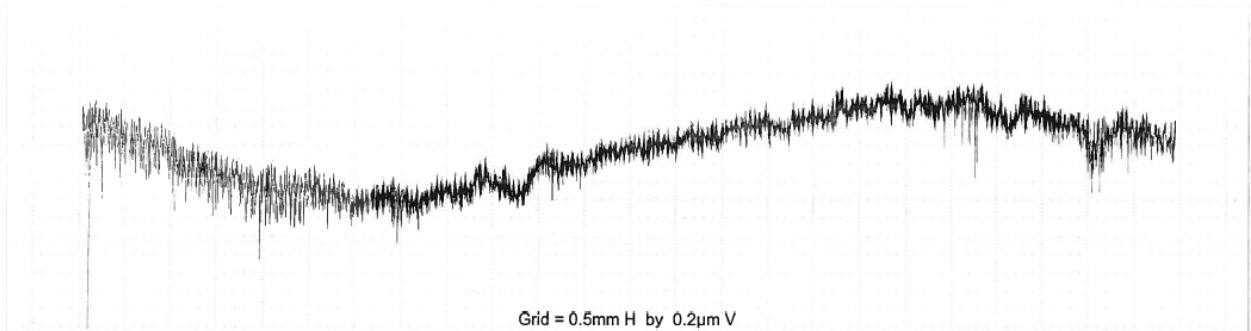
**Figure G31. Exhaust Camshaft Lobe #4**



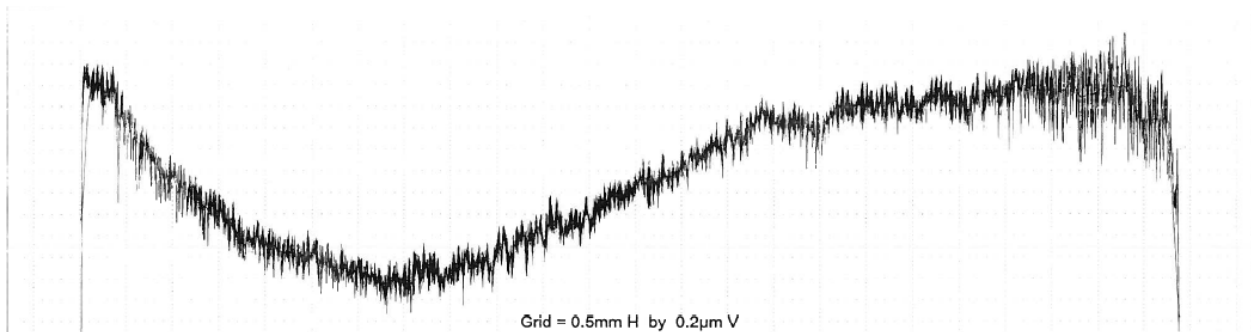
**Figure G32. Exhaust Camshaft Lobe #5**



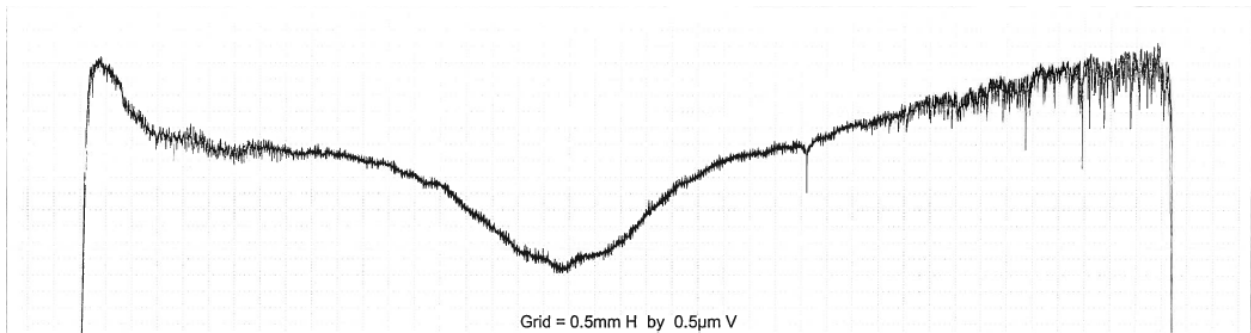
**Figure G33. Exhaust Camshaft Lobe #6**



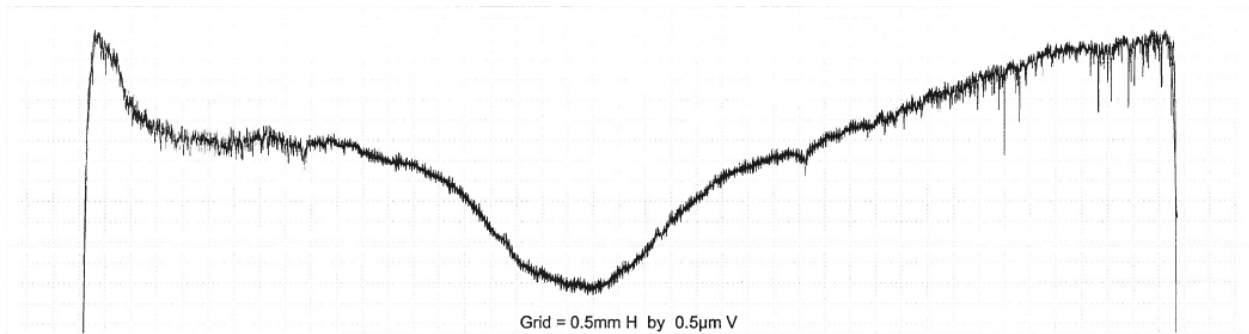
**Figure G34. Exhaust Camshaft Lobe #7**



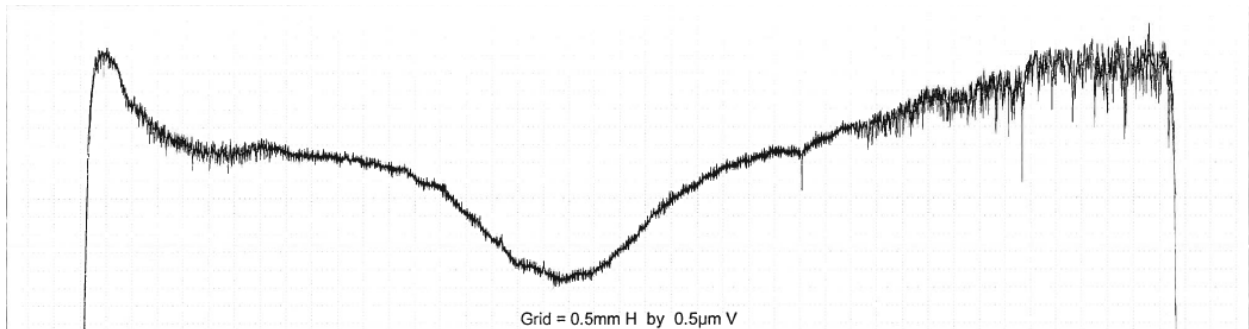
**Figure G35. Exhaust Camshaft Lobe #8**



**Figure G36. Exhaust Camshaft Fuel Pump Lobe #9, Nose A**



**Figure G37. Exhaust Camshaft Fuel Pump Lobe #9, Nose B**



**Figure G38. Exhaust Camshaft Fuel Pump Lobe #9, Nose C**

Figure G39 shows the exhaust valve #3 (or 2A depending on the numbering system). All of the valves looked similar and showed no measureable wear. The exhaust valve does have discoloration and surface deposits, but they are not severe.



**Figure G39. Exhaust Valve #3 Stem and Tulip**

Figure G40 shows the combustion chamber #4 on the head. This picture was taken after solvent cleaning to remove loose deposits. The exhaust ports are on top and the intake on the bottom. There is some mild corrosion of the seats inside the combustion chamber and some hard deposits on the seats in the port area. The sealing surfaces look normal with no measureable recession or wear. The other 3 combustion chambers of the head looks similar to this picture.



**Figure G40. Combustion Chamber / Head Area #4**