

Exhaust Valve & Valve Seat Insert – Development for an Industrial LPG Application

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ABSTRACT

Automotive engines are regularly utilized in the material handling market where LPG is often the primary fuel used. When compared to gasoline, the use of gaseous fuels (LPG and CNG) as well as alcohol based fuels, often result in significant increases in valve seat insert (VSI) and valve face wear. This phenomenon is widely recognized and the engine manufacturer is tasked to identify and incorporate appropriate valvetrain material and design features that can meet the ever increasing life expectations of the end-user. Alternate materials are often developed based on laboratory testing – testing that may not represent real world usage. The ultimate goal of the product engineer is to utilize accelerated lab test procedures that can be correlated to field life and field failure mechanisms, and then select appropriate materials/design features that meet the targeted life requirements.

INTRODUCTION

LPG is the fuel of choice in the material handling market. It is recognized that the use of LPG can reduce regulated exhaust emissions when compared to gasoline engines, and the ease of fuel handling and storage in the off-road industrial market has further increased the popularity of this fuel compared with more traditional on-road fuels.

However, when using gaseous fuels, increased wear rates on valve seats and/or valve faces can result in

premature engine failure. To address this issue, alternative material or design strategies are employed. Laboratory testing is often utilized to quantify wear rates with the desire to correlate this rate to in-field life expectancy.

This paper describes an automotive engine that was upgraded to operate on LPG for a material handling product. Despite extensive pre-production dynamometer and in-vehicle testing, production field experience uncovered a valve recession failure mode on the exhaust valve/VSI.

A new dynamometer test schedule was developed to demonstrate the failure mode in an accelerated time period. Statistical analysis (B_{10} @ 90% confidence) of the field data was used to correlate the dynamometer results to the field data.

To resolve the field issues and increase valvetrain life, alternate exhaust valve and valve seat insert (VSI) materials have been evaluated using this new dynamometer schedule. Results show the final material combination selected has the ability to increase valvetrain life by a factor of more than tenfold. Field tests currently underway are expected to confirm the dynamometer accelerated test results.

PRODUCT HISTORY / BACKGROUND

A new material handling product was introduced to the market in early 2005. Although the California (1) and

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Federal (2) "Useful Life" for this product is required to be no less than 5,000 hours / 7 years (whichever occurs first), the program direction was to target a B₁₀ life of no less than 10,000 hours. The primary issue to be addressed to achieve this life expectancy was the wear of valve and VSI when using LPG fuel.

ENGINE DESCRIPTION – An automotive 2.4L engine was selected to meet the performance and packaging requirements of the product. Key engine specifications are shown in Table 1.

Engine Type	In-Line 4 cylinder
Bore x Stroke (mm)	87.5 X 100.0
Displacement (cc)	2405
Block / Head Mat'l	Cast iron / Aluminum
Valvetrain	2V / SOHC
Fuel Type	LPG
Fuel System	Sequential Vapor PFI
Rated Power (kW)	49.0 @ 2700 rpm

Table 1 Engine Specifications

It was recognized that this engine had limited field experience with LPG in mobile equipment, thus vehicle "Mule" testing was conducted to identify any performance/durability issues for the engine in the new application. Past experience has shown that VSI and valve face materials used for gasoline fuels are typically not durable when used with LPG, consequently valve and VSI design and material upgrades were immediately pursued.

PRELIMINARY MULE LEARNINGS – The original "Mule" vehicle testing identified specific issues to be addressed prior to production, including significant exhaust VSI/valve wear with the automotive grade components. This wear affected engine operation after approximately 1,500 test hours. Exhaust recession levels of approximately 1mm were observed in the worst cylinder. Intake recession was minimal with even wear patterns.

VALVETRAIN UPGRADES – Figure 1 shows the "End Pivot (Type 2) Valvetrain" used for this application.

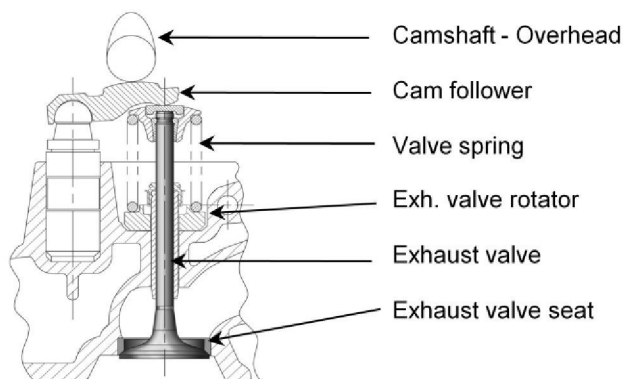


Figure 1 Valvetrain Configuration

Upgrades to the automotive valvetrain components were incorporated to provide an LPG capable engine (denoted as an Industrial engine). The revisions made to the intake and exhaust components are summarized in Tables 2 and 3. For the exhaust side, it was desired to significantly increase the hardness of both the valve face and VSI to compatible levels. The VSI Cu infiltration was utilized to improve thermal conductivity, while also acting as a solid lubricant to reduce adhesion and improve machinability. The reduced-load valve spring was selected to lower seat loads and reduce abrasive wear.

	Automotive (gasoline)	Industrial (LPG capable)
Intake valve material (3)	Sil 1	Sil 1
Intake Valve Seat Insert	PM "A" (Powder Metal A)	PM "B"
Intake VSI Features	Fe base / 0.8% C 3% Ni 3% Pb 0.9% Mo 0.6% S Density:>7.3g/cm ³ HB: 280-320	Fe base / 0.8% C 10% Co 2.5% Mo 1.5% Ni 1% Pb Density:>7.4g/cm ³ HRC: 34-37
Spring Load (Valve Closed)	300 N	240 N
Rotator	No	No

Table 2 Intake Valve/VSI Specifications

	Automotive (gasoline)	Industrial (LPG capable)
Exhaust valve material (3)	21-2N	21-2N
Exhaust Valve Face	No	Stellite F (HRC: 35-45)
Exhaust Valve Seat Insert	PM "B"	PM "C"
Exhaust VSI Features	Fe base 10% Co 2.5% Mo 1.5% Ni 1% Pb Density:>7.4g/cm ³ HRC: 34-37	Fe base 20% Cu 4.5% W 4% Mo 3% Cr 1.7% V Density:>7.8g/cm ³ HRC: 38-46
Spring Load (Valve Closed)	300 N	240 N
Rotator	Yes	Yes

Table 3 Exhaust Valve/VSI Specifications

Use of Rotators – The use of valve rotators has been controversial due to various compromises. Lewis/Dwyer-Joyce (4) have shown that the primary contributor to VSI wear is the closing velocity of the camshaft profile and their modeling predicts that 98% of the wear for a sintered insert is due to the valve/seat impact. Seating velocities for both intake and exhaust

valves for this automotive engine are less than 300 mm/s over the entire operating speed range – a level below that evaluated by Lewis/Dwyer-Joyce (and presumably deemed acceptable). This same study recommends the use of valve rotators to maintain an even and uniform wear, as well as to provide the ability to remove foreign debris. Based on the engine manufacturing/assembly flexibility, the “Mule” results and previous field experience, the design team agreed to continue using the rotators on the exhaust side.

DESIGN VALIDATION TESTING - A durability schedule was developed with the intent to represent field usage and estimate “in-field” life. Recognizing precedence had been set in both CARB and EPA defining LSI (Large Spark Ignition) durability schedules (1, 2, 5), a test cycle was formed using the ISO-8178 C2 schedule and the emission weighting percentages. Figure 2 shows this “Modified C2” Test Cycle to be used for dynamometer based testing.

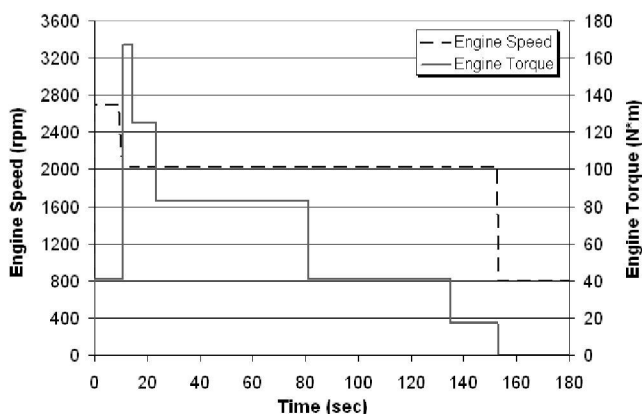


Figure 2 “Modified C2” Test Cycle

Valve recession was initially believed to be strongly influenced by the usage duty cycle (calculated as “Average Power per Unit Time”). Figure 3 shows the severity of this Modified C2 test schedule as compared to numerous customer duty cycles and manufacturer durability schedules.

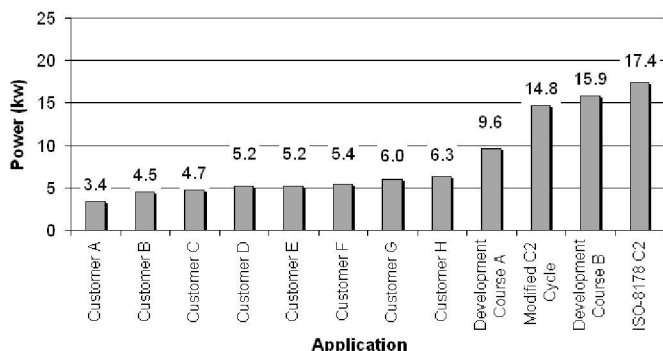


Figure 3 Duty Cycle Evaluation

None of the above schedules would be considered an accelerated schedule, rather a representation of the range of “normal field usage”. The “Modified C2”, although shifted more towards the aggressive end, was assigned an Acceleration Factor of one (AF=1), meaning 1 hour of dynamometer test would equate to 1 hour of severe field usage. It is noted that this AF was an assumption and was not correlated to any field data. With a 10,000+ hour design life target, a series of dynamometer durability tests were conducted to evaluate and extrapolate valve recession trends. Regular recession measurements were taken and compared to two recession limit parameters.

1. Design limit - valve recession was not to exceed 1.5mm due to loss of hydraulic lash control
2. Valve/VSI seal integrity limit - Valve recession not to exceed approximately 1.0mm based on “Mule” test result which suggested that this may be a limit for loss of valve/VSI seal integrity*.

*It is noted that subsequent field studies showed this empirical limit should not exceed 0.9 mm

Based on the test data trend lines obtained, testing was suspended after 3,500 hours as the data suggested a 10,000+ hour life would be achieved. Figures 4 and 5 show the intake and exhaust valve recession ranges with respect to the 0.9mm max recession limit at a 10,000 hr life. Note the recession limit line for an AF = 1 is shown.

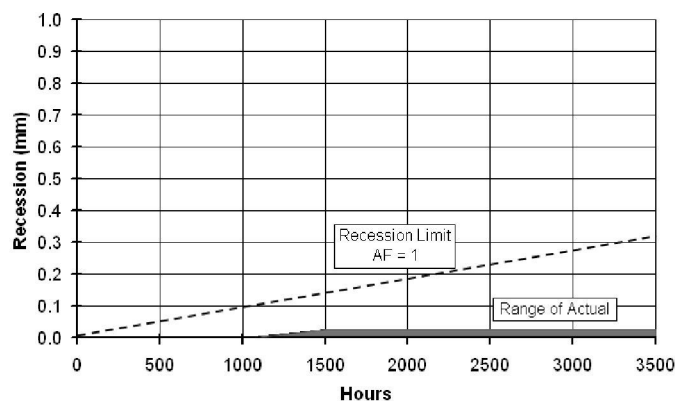


Figure 4 Intake Valve Recession

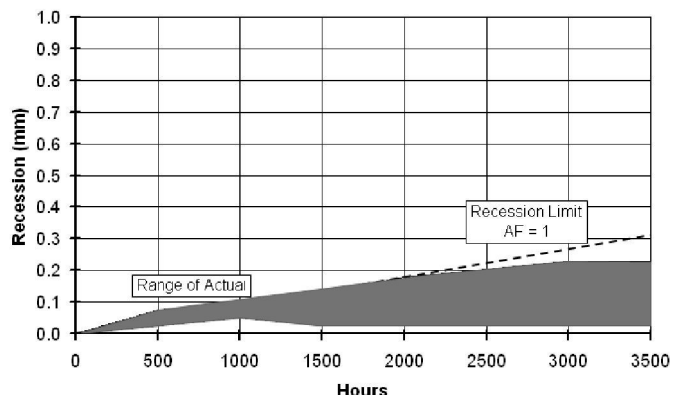


Figure 5 Exhaust Valve Recession

This data showed the intake valve/VSI recession were well below the threshold limits, while the exhaust trends were below the limit and “flattening” out. End of test hardware inspection showed the valves/VSI to be in good condition with minor evidence of “adhesive wear”. After 24,000+ successful program test hours (dynamometer and “in-truck”), production began in early 2005.

FIELD DATA / INVESTIGATION

Approximately 24 months after SOP, field complaints of “afterfire during cranking” and/or “rough idle/operation” began to surface. Engineering field investigations were conducted and subsequent analyses were completed.

FIELD OBSERVATIONS - Field investigation found two issues were the predominant causes for the complaints:

1. Excessive exhaust VSI insert wear
2. Cracked exhaust valve – single or multiple radial cracks initiating from the valve head margin and propagating thru the valve face

Figures 6 and 7 show examples of these field observations.

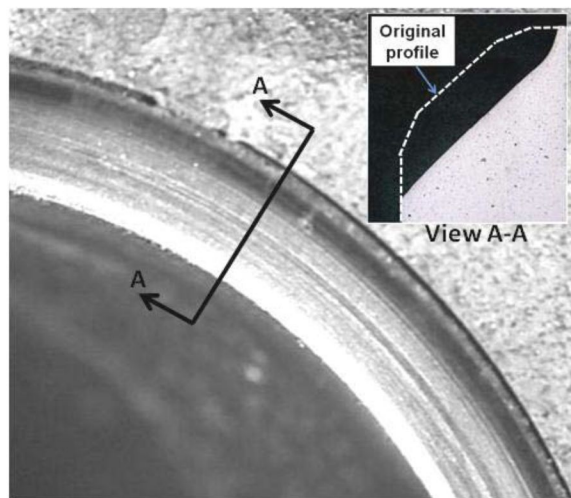


Figure 6 Excessive Exhaust VSI Wear

The exhaust valve face showed minimal wear effect, while the seat showed extreme wear. Circumferential grooves were easily evident in the seats (indicating the valve rotators were functioning) and resulted in even wear patterns. Field data comparing cylinder cranking compression values were compared to exhaust recession levels and it was determined that if valve recession exceeds 0.9mm then loss of valve sealing is expected.

It was noted that when the recession was excessive (1.0-1.5mm), cracked exhaust valves were also present.

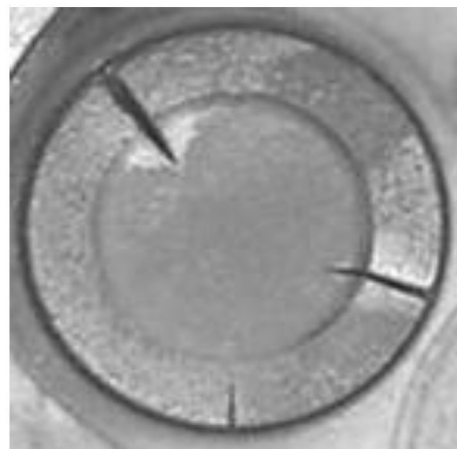


Figure 7 Exhaust Valve Cracking

A final note – field observations on the intake valves/VSIs showed minimal wear or recession.

WEIBULL ANALYSIS – To quantify the failure rates of product in the field, a Weibull analysis was conducted and is shown in Figure 8.

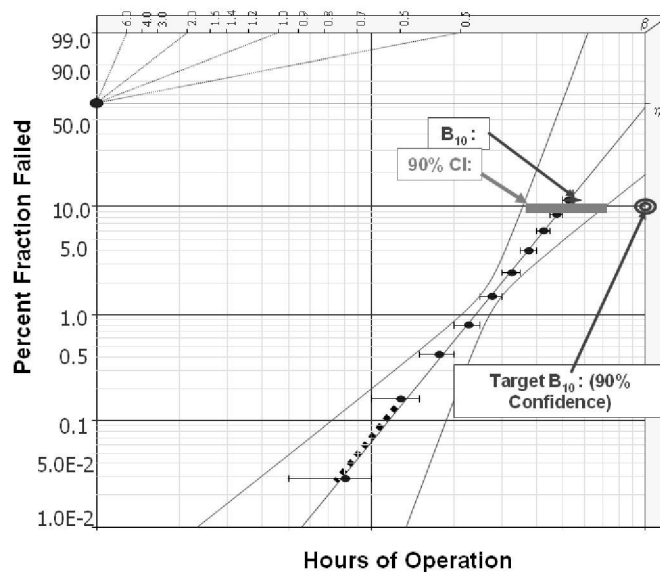


Figure 8 Weibull Analysis

Key values from the analysis

- B_{10} life = 5,046 hours (target > 10,000 hours)
- 90% Confidence Interval for B_{10} life = 3,850-7,100 hours
- Weibull slope $\lambda = 3$ (indicating a wide variation in the failure rate)

METALLURGICAL STUDIES – Various analyses were conducted on both the exhaust valves and VSIs. For all components evaluated, chemical composition, hardness and microstructures were to spec. Concentricity (TIR) of failed valves and VSIs were within allowable limits indicating no permanent distortion, thus run-out was not a likely source of leakage.