

Limitations and Recommended Practice In the Use of Compression and Leak-Down Tests to Monitor Gradual Engine Degradation

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Oak Ridge National Laboratory

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ABSTRACT

Compression and leak-down tests are frequently used to identify and diagnose failed engine power cylinders. It is also often desirable in research and testing programs to use these tests to monitor incremental changes in cylinder leakage. This paper investigates whether these tests are adequate in their present form to monitor incremental changes in cylinder leakage. Results are presented from two vehicle fleets at two test sites. Compression and leak-down tests were conducted on these fleets periodically during a mileage accumulation study. The results were used to establish the variability inherent in the compression and leak-down test processes. Comparisons between the results at the initial mileage test for the study vehicles with those at the final mileage test are shown to be largely within the uncertainty established for repeat assessments. The relative overlap in the magnitude of leakage changes and measurement uncertainty shows that the leak-down and compression tests are not useful in their present forms for monitoring incremental changes in engine leakage. Recommendations for reducing the variability of the leak-down test, perhaps making it useful for future studies, are presented.

INTRODUCTION

It is often desirable in research programs (for example fuel or lubricant research programs) and other circumstances to periodically monitor engines for changes in cylinder leakage that may be a result of wear or damage to the valves, valve seats, cylinder bore, or piston rings. The objective of monitoring leakage changes is to identify situations that result in abnormally high wear or damage to the sealing components or to detect such circumstances prior to the onset of a catastrophic failure of the power cylinder. Two tests are frequently used to characterize the relative health of the

sealing components in the power cylinders. These are the compression and the leak-down (sometimes referred to as differential compression) tests.

Compression tests measure the maximum pressure attained in each cylinder while exercising the engine using the starter motor. In order to accomplish this measurement, the spark plugs are removed and a pressure gauge connected using a length of hose to each spark plug port in turn. The connection to the spark plug port utilizes a check valve so that the pressure in the hose and gauge will increase as the hose is filled with compressed air by repeated compression strokes. To prevent an explosion hazard, it is important that the engine's fueling and ignition systems be disabled during this process, often accomplished by removing the fuse(s) to interrupt power to the engine control unit (ECU) and/or fuel injectors. This test is most repeatable when conducted on a fully-warmed engine and through use of a battery charger during the test to prevent differences in cranking speed due to battery voltage droop during cranking. Removing all of the spark plugs and holding open the throttle prior to making measurements on any given cylinder also aids in maintaining a steady cranking speed during the tests and allows the cylinder to fill without any loss due to a closed throttle.

A leak-down test characterizes the amount of leakage from a cylinder by filling the cylinder with compressed air from an external source. This measurement is accomplished by connecting a leak-down tool to the spark plug port of each cylinder in turn. The leak-down tool is connected to the spark plug port using a short length of hose, just as with the compression test, but in this case the connection does not include a check valve. The leak-down tool itself is comprised of a pressure regulator, an orifice of standard dimensions, and one or two pressure gauges, as shown schematically in [Figure 1](#). The regulator is adjusted to provide a known air pressure at

the inlet of the orifice, and the downstream side of the orifice is connected to the engine power cylinder. The gauges are positioned on either side of the orifice to measure differential pressure across the orifice as compressed air flow is discharged through the engine power cylinder. The engine power cylinder is moved by hand to firing top dead-center as this location results in closure of both the intake and exhaust valves, providing a sealed power cylinder. At this point, the differential pressure across the orifice is noted and expressed as a percentage. For example, a 9 PSIG (62.0 kPa) pressure drop using a pressure upstream of the orifice of 90 PSIG (620 kPa) would be termed a 10% leak-down. The repeatability of this test is also improved when it is performed on a fully-warmed engine. In contrast to the relatively simple and generally very similar tools used for the compression test, there are a variety of designs of leak-down tools and a similar variety of test procedures provided by the tool manufacturers. [1,2,3,4]

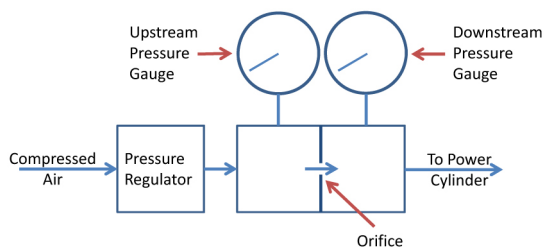


Figure 1. Schematic of a leak-down tool.

The leak-down test is not generally a perfect replacement for the compression test and vice-versa. Furthermore, the results from both tests can be influenced by factors other than the health of the power cylinder being measured. For example, the compression pressure is dependent upon the speed of rotation of the engine during the test. Hence, a weak battery on a test vehicle can cause abnormally low compression pressures because the starter spins less rapidly under this condition. The thermal condition of the power cylinder can skew the results of either test because of slight temperature-induced changes to the geometry of the various sealing surfaces in the system. Furthermore, results from both methods can be influenced by the personnel performing the test and the tools and procedures being used. Hence, these measurements are only relative indicators of the health of the power cylinders. Generally, the compression results are compared across a given vehicle to judge power cylinder health. This process is accomplished by comparing the compression values of each cylinder to one another and noting any results that are significantly different from the results on other cylinders. Hence, the compression test, used in a relative sense, can be used to locate cylinders suspected to have undesirable leakage. Leak-down testing is often used as a diagnostic to determine the source of a leak in a faulty cylinder (intake valves, exhaust valves, or piston rings). The leak-down test is also often used in a relative sense as many

factors can influence the results of this procedure. For example, large displacement engines can have higher leak-down rates than smaller engines even in the absence of an abnormal condition. [5] As evidenced by the continuing use of these procedures to diagnose failed power cylinders over several decades, they can be quite effective in reporting a pass or fail result when used in a repeatable manner. This paper will examine whether or not compression and leak-down tests are adequate in their present form to monitor incremental changes in cylinder leakage in otherwise healthy power cylinders.

APPROACH

During a recent study conducted under the auspices of the United States Department of Energy, two groups of test vehicles (each at a different test site) were subjected to periodic compression and leak-down tests during the course of a vehicle full-useful-life research program. [6] The tests were conducted at the beginning, middle, and end of a mileage accumulation program that used the Environmental Protection Agency (EPA) standard road cycle. [7] This cycle is intended for mileage accumulation associated with aging of emissions control components, and is not an engine durability cycle. Nonetheless, compression and leak down measurements were carried out in parallel with periodic emissions tests in an effort to assess engine wear that might be associated with the test fuels that were the subject of the program. The vehicles included a mix of both new and used vehicles, and hence the exact mileage accumulations varied. However, the minimum accumulated mileage between the beginning and middle (and the middle and end) of mileage accumulation was at least 25,000 miles (40,225 km). Three or four matched vehicles of each model were tested, thus the data for this study was gathered from 68 individual vehicles. Actual mileage accumulation was the same for all of the vehicles of each model. At test site “A” the vehicles were subjected to a single compression and leak-down test at each interval. Two additional tests were conducted at the end of mileage accumulation so that triplicate results were available to establish the measurement variability at this site. Test site “B” conducted the tests at similar mileage increments, but conducted triplicate tests at each mileage increment. Each site used its preferred tool and procedure for the both the compression and the leak-down tests. In both cases a battery charger was specified to be used during the compression tests and the vehicles were fully-warmed prior to each test. (In the case of triplicate tests, the vehicle was re-warmed in between tests.) Additionally, a small number of tests were conducted at Oak Ridge National Laboratory (ORNL) to provide information about differences among several popular leak-down tools.

Test site “A” used a leak-down tool that featured two gauges. The gauge upstream of the orifice was calibrated to read pressure in PSIG, with demarcations for every 2 PSIG (13.8



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kPa). The gauge downstream of the orifice on this tool was a pressure gauge that was set up to read % leakage, with demarcations for every 5%. A photograph of a Star Products model CLT-2PB Cylinder Leakage Tester is shown in [Figure 2](#) as an example of the configuration of the tool in use at site “A”.



Figure 2. Photograph of a Star Products Model CLT-2PB Cylinder Leakage Tester.

Site “A” used a procedure that specified that the tool be connected and used as follows:

1. Rotate the crankshaft until the piston of the cylinder being tested is at top-dead-center on the compression stroke.
2. Be sure regulator knob is turned to “off” position prior to connecting input hose.
3. Connect the air input to the tool and adjust the pressure until the downstream gauge reads 0% leakage.
4. Connect the output hose from the tool to the cylinder.
5. Read and record the percentage of leakage.

Test site “B” also used a leak-down tool with gauges both upstream and downstream of the orifice, but in this case the tool featured gauges that were both designed to read out in PSIG, with demarcations at each 1 PSIG (6.9 kPa). Site “B” used the following test procedure:

1. Rotate the crankshaft until the test cylinder is on top-dead-center on the compression stroke.
2. Connect test tool and air supply.
3. Adjust air pressure until the upstream gauge reads 100 PSIG (689 kPa).
4. Record reading on the downstream gauge.

A photograph of a Mac Tools model CLD210M Differential Cylinder Pressure Tester is shown in [Figure 3](#) as an example of the configuration of the tool in use at site “B”.

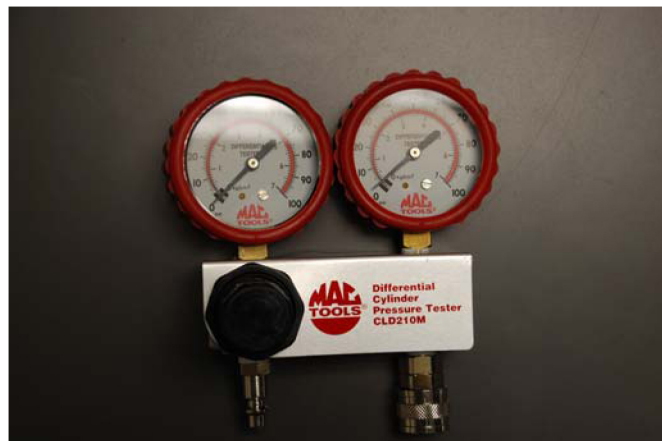


Figure 3. Mac Tools model CLD210M Differential Cylinder Pressure Tester.

The procedures for leak-down tests at both site “A” and site “B” are consistent with the procedures specified by the manufacturers of leak-down tools such as those in use at both sites. As mentioned previously, there is much less design and test procedure variability for compression test tools. The tools and procedures used at both test sites to conduct the compression tests were very similar. Both sites specified that all of the spark plugs should be removed prior to a test and that the throttle should be held fully open during the test.

RESULTS AND DISCUSSION

Leak-Down Measurement Uncertainty

Random uncertainty is often used synonymously with the term repeatability, and refers to how precise the measurement can be made. Repeatability is often used to describe the random uncertainty at a given test site, for example. Random measurement uncertainty was established for each test site by conducting triplicate measurements under conditions where the individual engine cylinders were not expected to change their leakage characteristics significantly between the three test procedures. At site “A”, this was accomplished by conducting triplicate tests after the completion of the mileage accumulation program, while at site “B”, triplicate tests were conducted at each test interval. In both cases, the triplicate tests involved re-warming the engine, re-positioning the cylinders at compression TDC, and re-installing the leak-down tool for each test. Hence, the process captures all of the expected sources of variability in this test procedure. The results from the triplicate tests were used to calculate a standard deviation for each average result, with one average result obtained for each cylinder tested. Since the cylinder was not expected to change its leakage characteristics due to

aging or damage between these tests, this standard deviation result can be used to assess random uncertainty associated with the tool and test procedure in use at a given site. Histograms of these standard deviation values were then constructed for each test site and are shown in [Figures 4 and 5](#). A total of 64 sets of triplicate tests were conducted at site “A” and 486 sets were conducted at site “B”. Three sets of results from site “B” exhibited more than 8% standard deviation as a result of abnormal engine leakage conditions. These results are not shown in [Figure 4](#), but are included in subsequent mathematical calculations.

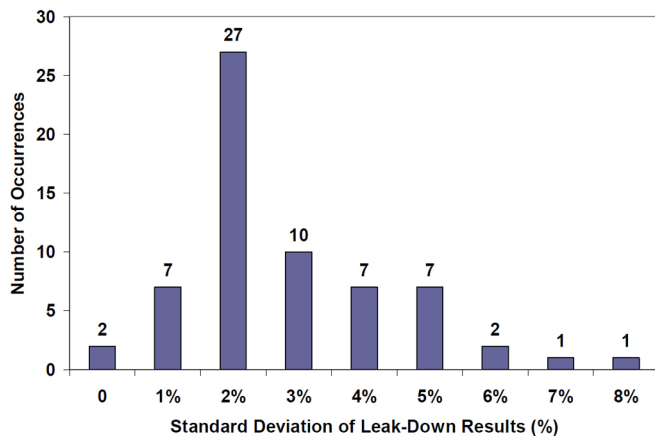


Figure 4. Histogram of the standard deviations from sets of triplicate leak-down tests at site “A”.

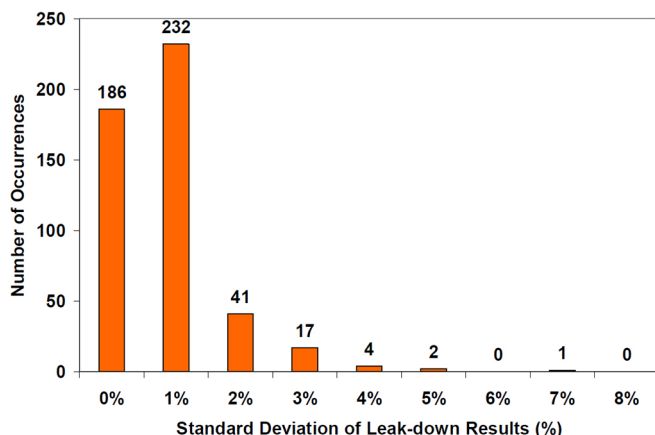


Figure 5. Histogram of the standard deviations from sets of triplicate leak-down tests at site “B”.

The results show that the tool and procedure in use at site “A” results in a relatively broad distribution of standard deviations, with some tests showing perfect repeatability, while an equal amount of tests show a standard deviation of 6%. The tool and procedure in use at site “B” are in general more repeatable, with many results showing perfect repeatability, and 86% of the tests showing less than a 1% standard deviation. The standard deviation results from each site were pooled and used to calculate a confidence interval

associated with the random uncertainty in the tests. At site “A”, the 95% confidence interval associated with the random uncertainty alone was $\pm 2.7\%$, while at site “B” it was $\pm 0.7\%$.

It is clear from these results that the procedure and tool in use at site “B” are much more repeatable than those in use at site “A”. In particular, the procedure in use at site “A” does not appear to provide a consistent pressure upstream of the orifice during tests. Thus, the pressure both upstream and downstream of the orifice is reduced when the engine power cylinder is connected because of the increase in air flow rate. In this case, any hysteresis present in the regulator may manifest itself as an inconsistent test condition, causing increased variability. If the pressure upstream of the orifice is adjusted to a fixed value while the engine power cylinder is connected, then all leakage results will be obtained from the same pressure upstream of the orifice regardless of the magnitude of the air flow rate. Since site “B” used a procedure that resulted in fixed pressure upstream of the orifice, the results from this site were much more repeatable.

Systematic uncertainty is often used synonymously with the term reproducibility, and is used to describe how well a measurement can be executed at different test sites. This definition is incomplete in that systematic uncertainty exists at every test site, but often the most important aspect of this concept is the systematic difference between test sites. Procedural as well as tool manufacturing and design variability between leak-down tools may impose differences in systematic uncertainty between the test sites. ORNL purchased several popular leak-down tool models in order to assess the impact that different tools and procedures could have at multiple test sites. The tools were first assessed with the use of a master orifice calibration tool. The master orifice was designed to represent the maximum acceptable leak rate when testing the leak-down on a Teledyne-Continental aircraft engine. This tool is used to establish the maximum acceptable cylinder pressure leakage limit for the test equipment and prevailing atmospheric conditions at the time of a leak-down test. [8] The tools were each operated at a series of pressures with the master orifice connected to the tool output hose, and the resulting leak-down fraction was noted. These data are shown in [Figure 6](#). The open symbols denote the result at the pressure specified by the tool manufacturer's operating instructions.

The results of this experiment showed that the tools were indeed sensitive to the upstream pressure, as expected. The maximum acceptable leak-down rate generally increases slightly as the orifice upstream pressure decreased. The difference in the result between 90 and 100 PSIG (620 and 689 kPa, respectively) upstream pressures was generally small in comparison to differences between tool models; hence, within limits, the upstream pressure in use under a given procedure is not as important as other factors in achieving repeatable results as long as the pressure is