SURFACE VEHICLE RECOMMENDED PRACTICE

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Low-Pressure Gasoline Fuel Injector

RATIONALE

This SAE Recommended Practice will permit the automotive industry to evaluate, characterize, and compare the fuel injector hardware for port fuel injection systems. The use of standardized testing and evaluation procedures for fuel injectors is important to the worldwide automotive community. Standardized test procedures provide both injector manufacturers and end-users with a uniform testing procedure for each of the key injector performance parameters, instead of a specialized test protocol for each of many customers and applications. The use of these procedures for test configurations, testing methods, data reduction, and reporting that are contained in this SAE Recommended Practice will significantly enhance the ability of one test laboratory to accurately repeat and verify the results of another.

FOREWORD

Port fuel injectors continue to be utilized in the majority of automotive gasoline engine applications, and thus remain a critical component of automotive gasoline fuel systems. The low-pressure port fuel injector (PFI) was the choice for fuel metering in gasoline systems since it began displacing carburetors in the early 1980s. Although the high-pressure, direct injector is now beginning to replace the low-pressure port fuel injector in an increasing number of applications, there will be a continuing need for updated recommended practice documents, such as SAE J1832, that detail the recommended testing procedures and the characterization of PFI injectors.

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1. SCOPE

This SAE Recommended Practice promotes uniformity in the evaluation tests and performance measurements that are conducted on fuel injectors used in low-pressure gasoline engine applications. The scope of this document is limited to electronically actuated fuel injection devices that are utilized in automotive gasoline port fuel injection systems where the fuel supply pressure is normally less than 1000 kPa. Detailed test procedures are provided for determining numerous PFI injector parameters, including, but not limited to, flow curves, leakage, electromechanical performance, fluid compatibility and corrosion susceptibility, durability, the effects of vibration and torsional deflection, thermal cycling effects, and noise. The standardized measurement procedures in this document are all bench tests. Characterization of the fuel spray from a low-pressure gasoline port fuel injector is quite important; however, these spray characterization tests are not addressed in this document, but are covered in a companion publication: SAE J2715.

Tests and references to types of low-pressure gasoline injectors that are no longer commonly used in modern production are not included in the main body of this document. Superseded systems such as throttle body injection (TBI), central port injection (CPI), pressure-drop ratio (PDR), bottom-feed injectors, and eight-ring patternation are examples of this older technology. Those fuel system components and diagnostic tests were extensively utilized in prior decades, but find little application in the industry today. The historical detailed measurement procedures that applied to the tests on these types of injectors have been removed from the main sections of the updated SAE J1832; however, the associated overall descriptions of these hardware items that were in previous versions of SAE J1832 have been retained in the appendix for archival purposes.

1.1 Purpose

The purpose of this SAE Recommended Practice is to provide the original equipment manufacturers and the end users within the automotive industry with a neutral, unbiased test for each defined PFI injector performance parameter. This should reduce the overall time and overhead required to develop a proven fuel system for a gasoline PFI engine, as it permits injector manufacturers and engine developers to conduct one set of injector tests per SAE J1832 as opposed to a separate set of test procedures for each customer and application. The specific, stated purposes of the SAE J1832 document are:

- To standardize the use of nomenclature specifically related to the testing of low-pressure gasoline port fuel injectors.
- To define the parameters and key metrics that are associated with the measurement of the performance characteristics of low-pressure gasoline port fuel injectors.
- To establish test procedures and recommend test equipment to measure the key metrics in order to characterize the performance and assure field reliability over the life of the component.
- To establish the recommended data reduction procedures for the measurement and characterization of port fuel injector performance.
- To establish the criteria for reporting the specific data that must be documented in order to provide the ability to interpret and reproduce the test results.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of each applicable document shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J313	Diesel Fuels
SAE J814	Coolants for Internal Combustion Engines
SAE J2713	Direct Injection Gasoline Fuel Injector Characterization
SAE J2715	Gasoline Fuel Injector Spray Measurement and Characterization

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM B117, ver. 19	Standard Practice for Operating Salt Spray (Fog) Apparatus
ASTM D56, ver. 05	Standard Test Method for Flash Point by Tag Closed Cup Ester
ASTM D86, ver. 12	Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure
ASTM D323, ver. 08	Test Method for Vapor Pressure of Petroleum Products (Reid Method) - Superseded by ASTM D5191
ASTM D445, ver. 12	Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
ASTM D471, ver. 12a	Standard Test Method for Rubber Property - Effect of Liquids
ASTM D893, ver. 12	Standard Test Method for Insolubles in Used Lubricating Oils
ASTM D1266, ver.13	Standard Test Method for Sulfur in Petroleum Products (Lamp Method) - Superseded by ASTM D5453
ASTM D1298, ver. 12b	Standard Practice for Density, Relative Density or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
ASTM D1319, ver. 13	Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption
ASTM D1744, ver. 13	Standard Test Method for Determination of Water in Liquid Petroleum products by Karl Fischer Reagent - Superseded by ASTM D6304
ASTM D2699, ver. 13b	Standard Test Method for Research Octane Number of Spark-Ignition Engine Fuel
ASTM D3231, ver. 13	Standard Test Method for Phosphorus in Gasoline
ASTM D3237, ver. 12	Standard Test Method for Lead in Gasoline by Atomic Absorption Spectrometry

ASTM D4806, ver. 13a Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as an Automotive Fuel

ATSM D4814, ver. 13b Standard Specification for Automotive Spark-Ignition Engine Fuel

ASTM D5191, ver. 07 Standard Test Method for Vapor Pressure of Petroleum Products - Mini Method (ASTM D5191 is the suggested replacement for ASTM D323)

ASTM D5453, ver. 12 Standard Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence (ASTM D5453 is the suggested replacement for ASTM D1266)

ASTM D5598, ver. 01 Standard Test Method for Evaluating Unleaded Automotive Spark-Ignition Engine Fuel for Electronic Port Fuel Injector Fouling Deposit Formation

ASTM D6304, ver. 07 Standard Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration (ASTM D6304 is the suggested replacement for ASTM D1744)

2.1.3 ISO Publications

Copies of these documents are available online at http://webstore.ansi.org/.

ISO 3744:2010-10-01 Acoustics - Determination of Sound Power Levels and Sound Energy Levels of Noise Sources Using Sound Pressure - Engineering Methods for an Essentially Free Field Over a Reflecting Plane

ISO 3745:2012/Amd1:2017 Acoustics - Determination of Sound Power Levels and Sound Energy Levels of Noise Sources Using Sound Pressure - Precision Methods for Anechoic Rooms and Hemi-Anechoic Rooms

ISO 16750:2012-3 Road Vehicles - Environmental Conditions and Testing for Electrical and Electronic Equipment - Part 3: Mechanical Loads

2.1.4 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

40 CFR 86.113 Controls of Emissions from New and in-use Highway Vehicles and Engines Fuel Specifications

40 CFR 600.109 Fuel Economy of Motor Vehicles EPA Driving Cycles

49 CFR 571.116 Federal Motor Vehicle Safety Standards Motor Vehicle Brake Fluids

2.1.5 U.S. Government Publications

Copies of these documents are available online at https://quicksearch.dla.mil.

MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests

3. BASIC CHARACTERISTICS, DEFINITIONS, AND ABBREVIATIONS

3.1 Definitions Related to Fuel Injection

3.1.1 FUEL INJECTION (FI)

A general term referring to any type of fuel injection system. Fuel delivery may occur mechanically, or may be electronically actuated and controlled. The quantity of fuel delivered in modern gasoline injection systems is scheduled by an electronic engine control unit (ECU). The electronic signal to the injector is based upon information received from several sensors that monitor the operating conditions of the engine.

3.1.2 PORT FUEL INJECTION (PFI)

A fuel delivery system in which the injector is located in the intake manifold, or in the intake port in a location that is normally close to the intake valve. The fuel spray is injected into the intake port upstream of the intake valve, and is normally directed at the back of the intake valve. The fuel being injected is commonly gasoline, but in some applications it may be ethanol, methanol, or natural gas. A multi-point fuel injection system will have at least one injector for each intake runner.

3.1.3 SEQUENTIAL FUEL INJECTION

A fuel delivery strategy in which each injector is individually energized and timed relative to its corresponding cylinder event. Fuel is injected into the intake runner of each cylinder once per two crankshaft revolutions in a four-stroke engine, and once per crankshaft revolution in a two-cycle engine.

3.1.4 GASOLINE DIRECT INJECTION (GDI)

A fuel delivery system in which the gasoline injector is located in the engine cylinder head, and in which the fuel spray is injected directly into the engine combustion chamber.

3.1.5 FUEL INJECTOR

A general term for an electromagnetic or mechanical device that is used to meter and deliver pressurized fuel to any type of combustion engine.

3.1.6 SINGLE SPRAY PFI INJECTOR

A PFI fuel injector that develops one distinct spray plume.

3.1.7 DUAL SPRAY PFI INJECTOR

A PFI fuel injector that is designed to provide two distinct spray plumes during the injection event; this is usually intended for an engine having two intake valves per cylinder, with one plume intended for each intake valve.

3.1.8 VACUUM AIR-ASSISTED FUEL INJECTION

A fuel injection system in which auxiliary air is drawn into the delivered fuel by means of the pressure differential caused by the intake manifold vacuum. This air is mixed with the metered fuel to aid in the atomization and vaporization of the fuel. See also pressurized air-assisted fuel injection.

3.1.9 PRESSURIZED AIR-ASSISTED FUEL INJECTION

A fuel injection system in which pressurized auxiliary air is mixed with the metered fuel to aid in the vaporization and transport of the fuel. See also vacuum air-assisted fuel injection.

3.2 Additional Definitions (in Alphabetical Order)

3.2.1 CLOSING TIME (CT)

The time required for the injector needle (the moving element in the fuel injector which cycles to both allow and prevent flow from the valve seat) to first attain its fully closed position after the termination of the driver circuit pulse input. The units are in milliseconds (ms).

3.2.2 CLOSING TIME INSTABILITY (CTI)

A measure of the variation in injector closing time (CT) and, along with the OTI, is an indirect indicator of the pulse-to-pulse repeatability of mass fuel delivery. It is defined as the maximum measued CT minus the minimum measured CT for a specified number of injection events. The units are in milliseconds (ms).

3.2.3 COIL RESISTANCE (R)

The measured resistance of the coil winding of the injector. Knowing the value of this resistance permits the injector user to determine the current requirement for a given system voltage. Presently, injector solenoid designs consist of either high- or low-resistance coils. The units are in ohms (Ω).

3.2.4 DYNAMIC MASS FLOW (Q_d)

The general fuel mass delivered per injection pulse when the injector is operated at any specified IPW and P and under any specified operating temperature and downstream manifold pressure. The units of Q_d are in milligrams per pulse (mg/pulse).

3.2.5 DYNAMIC MASS FLOW CALCULATED (Q_{dc})

The fuel mass delivery per injection pulse that is calculated for a specified injection pulse width (IPW) using the slope (m) and the X or Y offsets that determine the linear flow curve for that injector. X and Y are the absolute values of the distances of the linear-curve intercepts from the origin. The linear relationship for the calculated dynamic flow is shown in Equation 1 for the normal case of the linear curve passing below the origin. The slope (m) and the X and Y intercepts are determined from a regression analysis of the flow measurements. For the relatively rare case where the linear curve passes above the origin, the minus signs in Equation 1 should be changed to plus signs. The units are in milligrams per pulse (mg/pulse).

$$Q_{dc} = (m * IPW) - Y = m * (IPW - X) \quad \text{(Eq. 1)}$$

where:

Y = the absolute value of the intercept of the regressed linear flow curve on the flow axis

X = the absolute value of the intercept of the regressed linear flow curve on the IPW axis

m = the slope of the regressed linear flow curve

3.2.6 DYNAMIC MASS FLOW AT STANDARD CONDITIONS (Q_{std})

The fuel mass delivered per injection pulse, Q_{std}, that is delivered by the injector when operated at the specified limits for the standard environmental operating conditions as stated in Section 5. The units of Q_{std} are in milligrams per pulse (mg/pulse).

3.2.7 DYNAMIC MASS FLOW SHIFT PERCENTAGE (Q_{fs})

This parameter is useful for quantifying the effects of environmental conditions such as temperature and pressure on the metering characteristics of the injector. Q_d is the fuel mass delivery under general, non-standard environmental operating conditions, and will generally differ from that delivered under standard environmental operating conditions, Q_{std}. The dynamic mass flow shift percentage, Q_{fs}, is the term that quantifies this measured shift in fuel delivery per pulse as a percentage change from that delivered when functioning at standard operating conditions, Q_{std}. Equation 2 should be used to compute the Q_{fs} value. The units are in percentage (%).

$$\text{Dynamic flow shift percentage} = Q_{fs} = 100 * (Q_d - Q_{std})/Q_{std} \quad \text{(Eq. 2)}$$

3.2.8 DYNAMIC MINIMUM OPERATING VOLTAGE (DMOV)

A measure of the capability of the fuel injection system to operate under low voltage conditions. The driver circuit has a significant effect on the injector response characteristics; therefore, the driver circuit for that particular injection system must be used in that test. DMOV is the voltage at which the flow rate decreases to 50% of the fuel flow rate that is delivered at 14.0 V. The units are in volts (V).

3.2.9 DYNAMIC SET-POINT PULSE WIDTH

The particular injection pulse width (IPW) for which a specified fuel delivery is set during the manufacture of the injector. This dynamic set point pulse width is specified as 2.50 ms for the PFI performance tests in this document. This injection pulse width establishes Q_{sp}, as well as the dynamic performance and offset characteristics of the injector. The units are in milliseconds (ms).

3.2.10 DYNAMIC SET-POINT MASS FLOW (Q_{sp})

The measured fuel delivered per injection event pulse that is delivered by the injector when energized at the dynamic set point pulse width. This set-point flow is utilized for numerous inspection and quality control tests during and following manufacture of the injector. This flow is measured in units of milligrams per injection, which is commonly stated within the industry as milligrams per pulse (mg/pulse).

3.2.11 DYNAMIC SET-POINT FLOW SHIFT

For a particular injector, the set-point fuel mass delivery per injection event pulse may be adversely affected by any number of the tests within this document, such as corrosion, physical, or durability tests. One important measure of the effects of any one of those tests is to measure the change (shift) in the set-point flow delivery that occurs due to the test. This change in set-point flow (in percent) is obtained by measuring the set-point flow both before and after the particular test, then computing the percentage shift. This may be computed from Equation 3. The full descriptive term for this parameter should really be the dynamic set-point mass flow shift percentage, but it is called the dynamic set-point flow shift for short. The units are in percentage (%).

$$\text{Dynamic set-point flow shift (\%)} = 100 * \{Q_{sp}\text{ (end of test)} - Q_{sp}\text{ (start of test)}\}/Q_{sp}\text{ (start of test)} \quad \text{(Eq. 3)}$$

3.2.12 EXTERNAL LEAKAGE

Fuel Leakage from any source other than that the from the contact surface between the seat and the needle at the injector tip is considered external leakage.

3.2.13 FLOW-OFFSET (Y)

The displacement of the calculated linear regression flow curve from the origin along the ordinate y-axis, which is the Q_d axis. This value has a purely graphical purpose, as in some instances the related flow rate at Y could have a negative sign. The units are in milligrams per pulse (mg/pulse).

3.2.14 INDUCTANCE (L)

The inductance of an electromagnetic solenoid is a function of the number of turns in the solenoid coil and the permeance of the magnetic circuit. Inductance is an indirect measure of the material properties and geometry of the flux path. Its value is, therefore, meaningful as a production control parameter. The units are in millihenries (mH).

3.2.15 INSULATION RESISTANCE (IR)

The resistance of the insulation around the injector solenoid coil. The test for this resistance is designed to check for a potential failure of the insulation between the coil assembly and the case of the injector. It is usually performed on completed injectors to ensure that the coil insulation has not been damaged during the assembly process, or during any of the physical tests, and that the terminal to case clearance has been adequately maintained. The units are in ohms (Ω).

3.2.16 LINEAR FLOW RANGE (LFR)

A dimensionless injector performance parameter that is computed by dividing the maximum linearized flow point, LF_{max}, by the minimum linearized flow point, LF_{min}, as is shown in Equation 4. The values of LF_{max} and LF_{min} are determined at their respective pulse widths where the measured fuel mass flow deliveries deviate ±5.0% from the linearized flow curve.

$$LFR = LF_{max}/LF_{min} \quad \text{(Eq. 4)}$$

3.2.17 LINEARITY DEVIATION (LD)

Ideally, the mass fuel flow delivery from an injector would be linear, which is to say that the fuel mass flow delivery is directly proportional to the injection pulse width over the full flow range of injector operation. In reality, there are always some deviations. A deviation from linearity at a particular value of IPW is defined as the percentage difference between the actual measured fuel mass flow delivery, Q_d, and the corresponding calculated fuel mass flow delivery, Q_{dc}. This linear deviation may be computed for any value of IPW using Equation 5. The units are in percentage (%).

$$LD\ (\%) = 100 * \{Q_d - Q_{dc}\}/Q_{dc} \quad \text{(Eq. 5)}$$

3.2.18 MAXIMUM OVERLOAD VOLTAGE

The voltage utilized in the maximum voltage overload test. The injector should be capable of maintaining calibration after a maximum overload voltage of 24.0 VDC is applied to the injector terminals (if a saturated driver is employed) or to the driver terminals (if a peak-and-hold driver is employed). The overload voltage is to be applied for a period of 60 seconds. This test is intended to simulate an extreme jump-start condition. The units are in volts (V).

3.2.19 NORMAL FUEL PRESSURE (P_{NORM})

The fuel pressure supplied to the injector in a returnless injection system that is used to calibrate and establish the flow characteristics of the injector. This fuel pressure is defined by the application, and is the intended, normal operating pressure of that injector (example: 345 kPa). It is to be specified in SI units (kilopascals [kPa]) and measured at the inlet to the injector. In the event that there is no particular application pressure provided for the injector being tested, then 400 kPa should be used for P_{NORM} for the tests within this document. It should be noted that for an injector that is intended to be used in a return-type injection system, which has a pressure regulator that is normally biased to manifold pressure (either vacuum or a positive pressure from forced induction), this normal pressure will be the total differential pressure across the injector from the fuel inlet to the volume into which the fuel spray enters.

3.2.20 OPENING TIME (OT)

A measure of the time required for the injector needle to first attain the fully-open position after initiation of the driver circuit pulse input. The units are in milliseconds (ms).

3.2.21 OPENING TIME INSTABILITY (OTI)

A measure of the variation in injector opening time (OT) which, along with the CTI value, is an indirect measure of the pulse-to-pulse variability in fuel mass flow delivery. It is defined as the maximum observed OT minus the minimum observed OT over a specified series of injection events. The units are in milliseconds (ms).

3.2.22 OPERATING VOLTAGE RANGE

The range of voltage for which the injector will continue to operate. Under certain circumstances, such as cold engine cranking, normal operating voltage may not be available. The minimum opening voltage of the injector is especially critical for high-resistance injectors, as the coil current is directly proportional to the available voltage. Low-resistance injectors are not as sensitive to lower battery voltage due to the current limiting driver circuit characteristics. The units are in volts (V).

3.2.23 PERIOD (P)

The time elapsed between the beginning of one injection to the beginning of the next injection. This is the reciprocal of the frequency of injection. The units are in milliseconds per pulse (ms/pulse).

3.2.24 PRESSURE DROP RATIO (PDR)

The dimensionless ratio of the fuel pressure drop across the metering orifice of an injector compared to the fuel pressure drop across the valve seat.

3.2.25 INJECTION PULSE WIDTH (IPW)

The increment of time that the injectors are commanded to deliver fuel for a single injection event. The units are in milliseconds (ms).

3.2.26 SHOT-TO-SHOT (STS) VARIABILITY

A measure of the variation in the mass of fuel delivered from one injection event to another. It is a variable that has an influence on the emissions from an engine. If sufficient measured values of STS mass delivery have been obtained, then the STS variability may be computed using Equation 6. It should be noted that the computed variability may be affected by the number of measurements that are made. The units are in percentage (%).

$$\text{STS variability in } \% = 100 * \{Q_d(\text{max}) - Q_d(\text{min})\}/Q_d(\text{ave}) \qquad \text{(Eq. 6)}$$

3.2.27 SLOPE (m)

This slope value represents the change in Q_d per unit of IPW that is computed using a linear regression of measured flow data over the operating range of the injector. See 5.6 for details on the computation of the slope and offsets. The units are in milligrams per millisecond (mg/ms).

3.2.28 STATIC FLOW RATE (Q_s)

The mass flow rate of fuel delivered by an injector when energized to remain in the fully opened position. It is the maximum mass flow rate of the injector for the level of fuel pressure that is being employed. For higher fuel pressures, the static flow rate will increase; therefore a value for the static flow rate should always be associated with a particular fuel pressure. The units are in grams per second (g/s).

3.2.29 STATIC DROP-OUT CURRENT (I/S-OFF)

The minimum current required to hold the injector open after it has been energized. It is used to determine the holding current calibration of the peak-hold driver. The units are in amperes (A).

3.2.30 STATIC MINIMUM OPERATING VOLTAGE (SMOV)

The voltage measured at the injector electrical connector at which the injector opens as determined by an accelerometer or other sensing device capable of detecting the commencement of fluid flow. The units are in volts (V).

3.2.31 STATIC PULL-IN CURRENT (I/S-ON)

The minimum current required to actuate the injector from the closed to the open position. It can be used to calculate the SMOV if multiplied by the value of R. The value of the static pull-in current can provide information for diagnosing functional problems and designing injector driver circuits. The units are in amperes (A).

3.2.32 TIME-OFFSET (X)

The displacement of the calculated linear regression flow curve from the origin along the ordinate x-axis, which is the pulse-width axis. The units are in milliseconds (ms).

3.2.33 WORKING FLOW (WF_{min} and WF_{max})

The minimum and maximum flows of a population of similar injectors of the same make and model that can be utilized in calibration while still not exceeding a prescribed limit of flow standard deviation. The units of each are in milligrams per pulse (mg/pulse).

3.2.34 WORKING FLOW RANGE (WFR)

A dimensionless performance parameter that numerically quantifies the usable flow range of any subset of a population of similar injectors of the same make and model. In this usable flow range, any injector from the total population of all such injectors will deliver a fuel mass flow that is statistically within a specified percentage of 3.0 standard deviations of the mean flow value of all of the injectors. That specified percentage is 5.0% for a PFI injector. The specification of 3.0 standard deviations sets a 99.7% statistical confidence level that the delivered flow of any subset of the injectors will be within 5.0% of the mean flow of the entire population. The WFR is determined from flow testing at least 24 sample injectors and dividing the resultant maximum working flow point, WF_{max}, by the minimum working flow point, WF_{min}. This is shown in Equation 7.

$$\mathrm{WFR} = \{\mathrm{WF_{max}}/\mathrm{WF_{min}}\} \quad \text{(Eq. 7)}$$

3.2.35 FID LEAKAGE RATE (q_{LEAK})

The measured fuel leakage from the tip of a PFI injector as determined from a test utilizing a flame ionization detector. The units are in cubic millimeters per minute (mm^3/min).

3.2.36 PERCENTAGE DEVIATION FROM FLOW LINEARITY (LD)

At any injection pulse width, the percentage deviation of the actual measured fuel flow rate from that calculated from a linear flow curve. It is computed by dividing the difference in the two flow rates by the calculated flow rate, times 100.

3.3 Abbreviations

These are additional abbreviations that are within the text of this document that are not listed in the definitions subsection.

A amperes (for current)

A/F air-fuel ratio

CCW counter-clockwise

cP centipoise

cSt centistokes

CW clockwise

E85 gasoline blend containing 85% ethanol

ECU engine control unit

EPA Environmental Protection Agency

GDI gasoline direct injection

H hours

kPa a general pressure level in kilopascals

kPaa an absolute pressure value in kilopascals

kPag a gauge pressure value in kilopascals

M15 gasoline blend containing 15% methanol

mg milligram

mH millihenry (for inductance)

mm millimeter

MPFI multi-port fuel injection

ms millisecond

NL normal liters

Ω ohms (for resistance)

OEM original equipment manufacturer

T1 the time at which the injector needle lifts from the seat

T2 the initial time at which the injector needle is fully open

T3 the time at which the injector needle begins to close

T4 the initial time at which the injector needle is fully closed

P period

PFI port fuel injection

ppm parts per million

rms root mean square

s seconds

UBHC unburned hydrocarbons

V volts

3.4 PFI Injector Operating Principles

3.4.1 Introduction to PFI Injector Operating Principles

A port fuel injector delivers a specific amount of fuel to the engine by means of an electromechanical solenoid. Fuel systems which introduce fuel directly into the individual cylinder air intake runner are commonly referred to as multi-port fuel injection (MPFI) or, alternatively, as port fuel injection (PFI). The amount of fuel that is delivered during each actuation is controlled by the length of time the injector is open, and upon the differential fuel pressure across the injector. A more detailed description of the injector flow path and basic operation may be found in the Appendix of this document. The amount of time the injector is open is typically determined by an engine control module that senses the engine speed, engine load, air mass flow quantity, and the ambient (barometric) and intake manifold pressures, and then computes the injection pulse width (IPW) that is required.

3.4.2 Injector Fuel Flow Path

Fuel enters a typical top-feed PFI injector at the top, as is illustrated in Figure 1. Metered fuel exits through the bottom. The amount of fuel that exits on each actuation of the solenoid is controlled by the duration of the electrical logic pulse that is transferred to the injector solenoid by the driver. A fuel filter is typically designed as an integral part of the injector at the fuel inlet. Its main purpose is to serve as a final filter to prevent fuel line and fuel rail contaminants from entering the injector, however, it also provides contamination protection during testing and servicing of the fuel system. This filter is not normally designed to be serviceable, because a separate in-line filter in the fuel line from the tank normally functions as the primary fuel system filtration device.

From the inlet filter section, the fuel moves to the fuel-metering portion of the injector. The metering of fuel is accomplished by a needle and seat in conjunction with a metering orifice. With the coil energized, magnetic force pulls the needle away from the seat allowing fuel to pass through the needle/seat and out through the metering orifice. The static flow rate of the injector is the fuel flow rate that results when the injector is tested at full lift. The magnitude of the static flow will depend on the exit orifice size, the injector lift or stroke, the fuel pressure, and the hydraulic losses in the injector fuel flow path. By design, the metering orifice usually presents the largest pressure drop; however, most designs also rely on a pressure drop across the valve and seat. The configuration of a typical valve and seat are also depicted in Figure 1. As the stroke, or lift, of the needle is varied, the static flow is changed and can be used as a means for the manufacturer to obtain the specified static flow rate. For hot fuel handling concerns, the metering orifice is also usually the largest pressure drop in the hydraulic circuit. A spring is incorporated to return the needle to the closed position when the coil is de-energized. This ensures that the injector is normally closed and fuel can only flow when the coil has been energized. The spring also effects the time required for the needle to open and close, which changes the injector dynamic characteristics. Many designs, therefore, provide the manufacturer with the ability to adjust the spring load to obtain the dynamic set point flow.

Most designs use highly finished metal-to-metal surfaces to provide a leak tight seal and minimize flow shift due to life cycling. Metal also helps minimize the changes in stroke that could occur due to thermal expansion when operated at extreme environmental temperatures. Ball-and-seat and mating cones have been successfully employed as injector sealing surfaces.

In the energized condition, fuel passes from the valve section to a downstream spray-generating geometry. This area of the injector uses the energy of the fuel pressure to generate a specific spray pattern and provide a level of fuel atomization. Older injectors used in throttle body injection systems typically used wide, hollow-cone spray patterns targeted to the throttle bore perimeter. Port fuel injectors typically target the fuel toward the rear face of the intake valve, as this has been shown experimentally to be very advantageous for power, emissions, and cold drivability. This results from the minimization of the amount of port wall wetting that occurs. Due to the fact that there are many port and valve geometries, a wide variety of spray patterns and generating techniques exist.

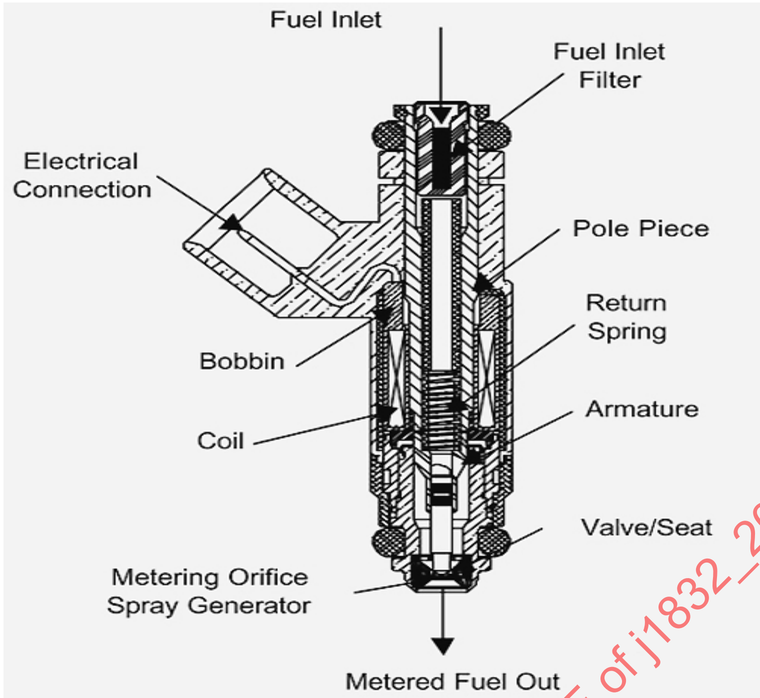


Figure 1 - Schematic cross section of a typical top-feed PFI injector

A number of typical PFI fuel spray patterns are illustrated in Figure 2. The patterns are many, and include a single, coaxial stream a single, off-axis stream; dual angled streams; and multiple streams. An example of a dualangled stream pattern is one that targets the rear surfaces of the two inlet valves of a four-valve engine. These various patterns may be generated by means of single-hole orifices, multiple-hole orifices and jet-deflection design techniques.

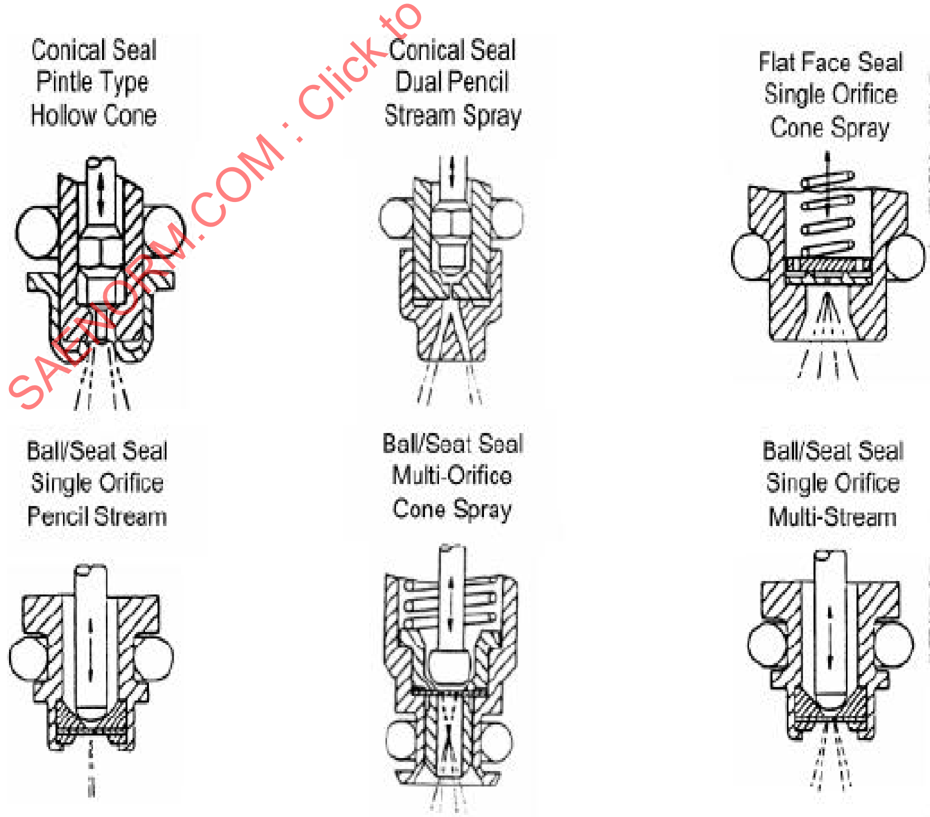


Figure 2 - Examples of PFI injector tip designs with various spray patterns

3.4.3 Magnetic Circuit of a PFI Injector

The solenoid assembly of an electromagnetic fuel injector supplies the force to actuate the fuel-metering valve. One typical example of this is illustrated in Figure 3. Two commonly used solenoid designs are the plunger-style armature, which is commonly designated as the needle in some designs, and the flat-face, disk armature. The major components of the solenoid assembly include the coil assembly, solenoid body, pole piece, armature (needle), and the return spring.

The function of the coil assembly is to generate a magnetic field when energized. The coil consists of a specified number of turns of insulated wire wound around a bobbin. The material and size of the wire is chosen to provide a given number of turns to develop the magnetic force while achieving the required electrical resistance for the injector driver circuit. The total electrical resistance of an injector is essentially equal to that of the coil assembly, which is a function of the resistivity of the wire, diameter of the wire, length of the wire, and the termination of the wire to an electrical connector. Inductance, on the other hand, is a function of the number of turns in the coil, materials used for the body, armature (needle), and pole piece, geometric construction, air gaps, etc. Inductance, therefore, must be measured on the completed assembly while the injector is not energized. The magnetic field produced by the coil generates flux, which travels in a closed loop around the coil assembly. It is the function of the components in the magnetic path to carry the flux efficiently. The solenoid body is the segment of the circuit that carries flux from the pole piece to the armature. The armature is the moving element of the solenoid, which controls the flow of fuel by opening and closing a needle-shaped element. The pole piece is the stationary element that attracts the armature when the coil is energized. The predetermined clearance between the pole piece and the armature is called the working air gap. It is through this air gap that the force of attraction is generated. The working air gap consists of both a fixed and a variable air gap, the latter of which is dependent on the position or stroke of the armature. The fixed air gap prevents contact between the armature and pole piece to minimize the effect of residual magnetism. Since contact between these two parts would result in longer closing times, a spacer or a coating made from nonmagnetic material such as chrome is normally employed to ensure that a fixed clearance is maintained when the valve is fully opened. The magnetic force of attraction is most important in the working air gap; consequently, the magnetic properties of the materials used and the geometry of the parts are critical to the performance of the design. The remaining parts of the magnetic circuit have a lesser effect on the total reluctance and response of the solenoid.

The major difference between the plunger solenoid design and the flat-face disk design is the path of the flux into the armature from the solenoid body. In the plunger design, radial and working air gaps are used. The radial gap is necessary to permit the armature to move axially relative to the nonmoving components of the solenoid assembly. The working air gap accommodates the motion of the armature assembly. In the flat face disk design, an additional working air gap is required with no radial air gap between the armature and solenoid body.

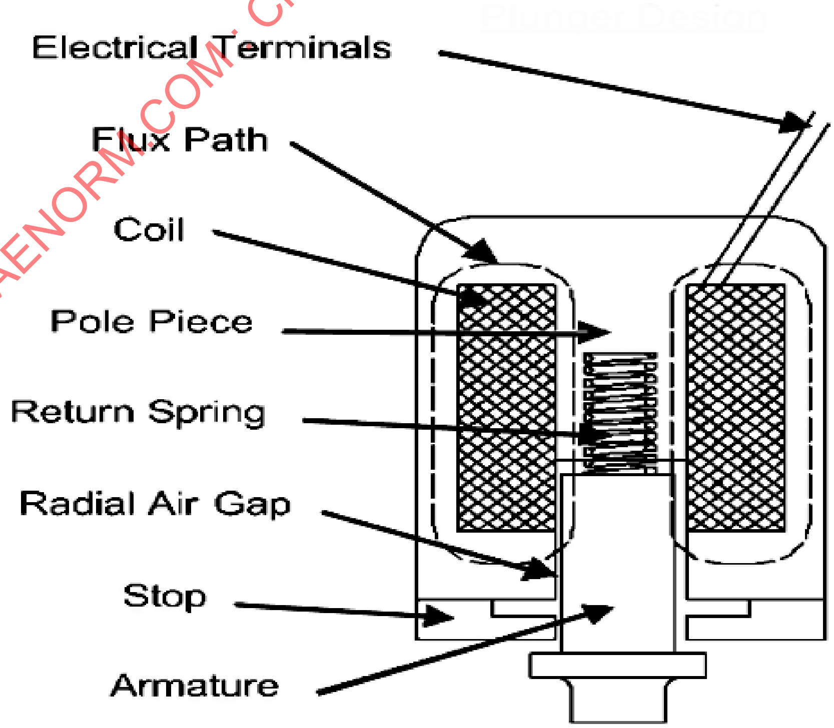


Figure 3 - Schematic diagram of the coil magnetic circuit

3.4.4 PFI Injector Drivers

An injector driver is an electronic circuit that receives and converts an electrical logic pulse into a specific driving voltage waveform that controls the opening, hold and closing phases of the injection event. These voltage waveforms are delivered for a precise time duration at a given repetition rate. The saturated driver and the peak-and-hold driver are currently the most commonly used by the automotive industry, with the saturated driver now becoming predominant for PFI injectors.

3.4.4.1 Injector Driver - Saturated

This type of driver is also commonly referred to as a saturated-switch driver. This is an injector driver in which a power transistor turns fully on for the entire duration of the injection pulse width. A typical current trace for this common driver type is illustrated in Figure 4. This type of driver is commonly used with injectors having high-resistance coils (typically 8 to 16 Ω) or with injectors having low-resistance coils in combination with a ballast resistor.

- Advantages: Heat is primarily dissipated through the injector or ballast resistor and not at the driver circuit. The circuitry is simplified compared to the peak-hold driver.

- Disadvantages: The inherently slower dynamic response of this system decreases the injector usable flow range. The dynamic flow of an injector used with this type of circuit is more duty-cycle sensitive due to heat dissipation considerations. This driver's inductive suppression element, which may be a resistance-capacitance circuit or a zener diode, significantly affects the injector Q_d rates due to variations in the circuit's current decay rate. This decay results in a change of the injector closing time. The dynamic flow rate delivered by this type of driver is typically more sensitive to fluctuations in battery voltage and operating temperature than with a peak-and-hold driver.

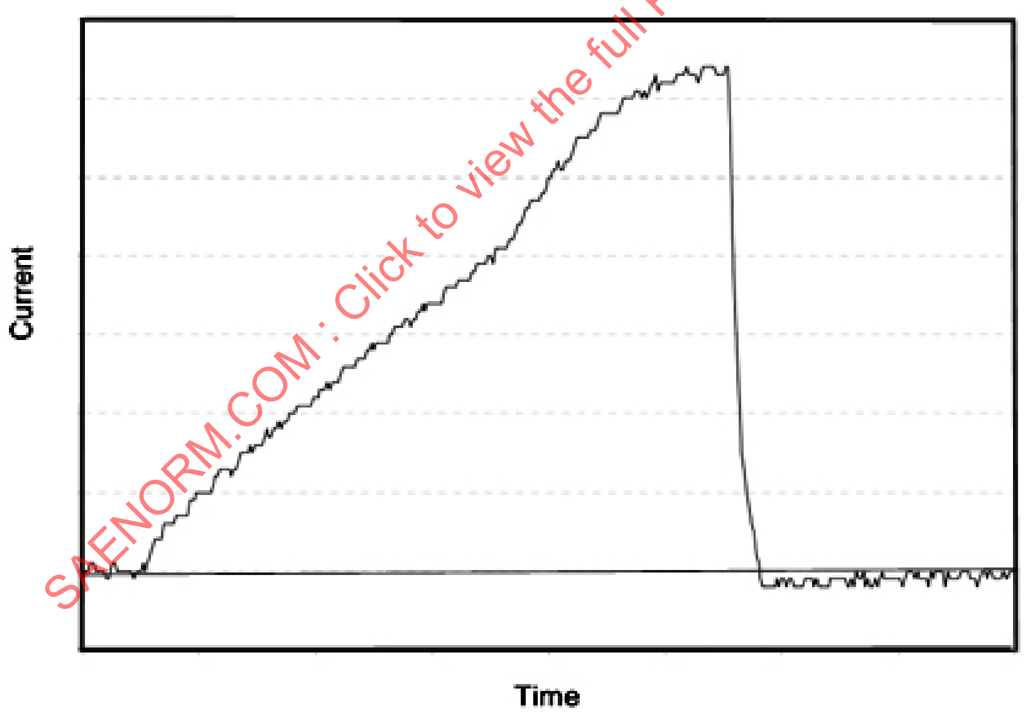


Figure 4 - Typical injector current trace for a saturated driver

3.4.4.2 Injector Driver - Peak-and-Hold

The peak-and-hold driver is a type of driver that uses two, or sometimes more, levels of current to operate the injector. Variations in this type of driver include intermediate hold, final hold, peak, and dwell designs. This type of driver circuit applies battery voltage to the injector until a predetermined current level is reached. The current is then reduced and held at a lower level for the duration of the IPW. This type of driver is normally used with injectors having low-resistance coils (typically around 2 Ω). A typical current trace for this common driver type is illustrated in Figure 5. The accuracy of both the driver peak current level and the hold current level is normally held to a tolerance of ±5.0%. In order to minimize OT instability, it is advisable to match the injector and driver characteristics such that the switch from peak-current to hold-current does not occur until after the injector is fully open.

- Advantages: The high peak current minimizes OT response and the low hold current minimizes the closing-time response. This method of control results in an increased linear range of injector operation.
- Disadvantages: Heat is primarily dissipated at the driver. The circuitry is more complex than that of the saturated driver.

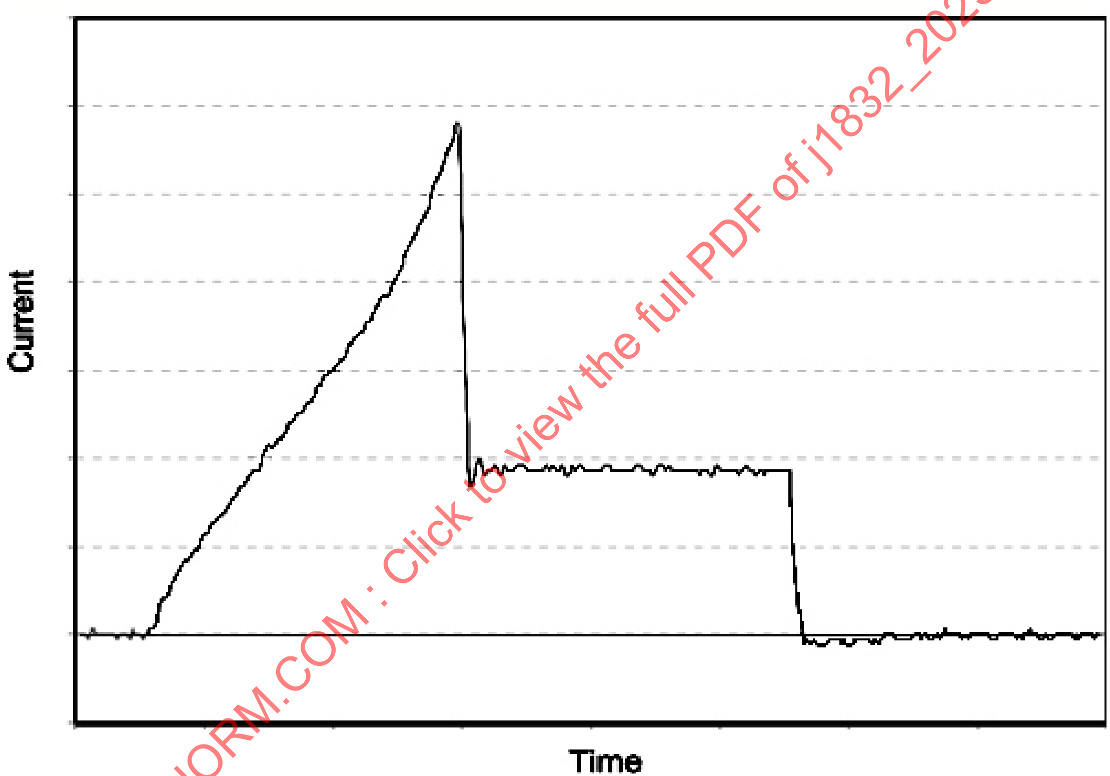


Figure 5 - Typical injector current trace for a peak-and-hold driver

4. STANDARD TEST CONDITIONS

Unless otherwise specified, the following test conditions are to be utilized:

4.1 Ambient Pressure and Temperature

The testing is to be performed at an ambient pressure of 100 kPa ± 5 kPa abs and a temperature of 21 °C ± 2.0 °C.

4.2 Test Fluid

Normal heptane (n-heptane) at a fuel pressure of P_{NORM} is specified as the standard test fluid and pressure for the measurement of injector performance characteristics. This is specified in order to promote test standardization, and to allow a more accurate comparison of the performance characteristics of samples of injectors. An inspection of the data reporting sheets within this document will show that many PFI performance tests result in an SAE J1832 performance parameter if n-heptane at P_{NORM} has been used along with the other specified standard conditions. Any other test fluid may optionally be used, such as mineral spirits or solvent, and any other fluid pressure other than P_{NORM} may optionally be used. This is permissible as long as it is clearly indicated on the data reporting sheet. However, it should be noted that such deviations preclude referring to the final performance parameter that is obtained as the SAE J1832 parameter. There are some exceptions to this, such as for those tests listed under corrosion and fluid compatibility measurements or thermal shock tests at very elevated temperature. In these cases, and in any special tests that are designated, the measurement tests are to be performed with the designated test fluids, which may not be n-heptane. The use of any test fluid that differs from that designated in the test procedure must be clearly indicated on the proper data reporting sheet and the text of the particular test procedure must be read carefully to determine if the use of a test fluid is or is not to be considered as a test deviation.

Automotive port fuel injectors are designed to spray gasoline, and most engine development and vehicle testing of fuel systems involves verification testing with that fuel. Gasoline, however, is a mixture of many components of varying volatility, and exhibits a change in physical properties with partial evaporation. Therefore, a pure hydrocarbon liquid of somewhat less volatility having well-documented physical properties and a viscosity and density near that of pump gasoline has a number of advantages as a test fluid. It is certainly recognized that no single test fluid is ideal, and can perfectly duplicate the performance of injectors operating on multi-component hydrocarbon fuels that are found in the field. N-heptane was selected as the best compromise on the basis having worldwide availability, as well as the stability of physical properties if reused. In addition, the fluid properties are not only well specified, but are very similar to that of gasoline. This is illustrated in Table 1, whereas a comparison of the properties of n-heptane with those of mineral spirits and indolene clear is provided in Table 5. Tests that are more application-related or conducted for quality control, durability, and corrosion compatibility may be performed with fluids specified by the test procedure or optionally specified by the user. N-heptane is one of the two common pure hydrocarbons used to define the octane number scale, and is stocked in all petroleum refinery control and analytical laboratories worldwide to known levels of purity and consistency. The fuel spray parameters that result from n-heptane are known to be very similar to that obtained from pump gasolines, and yields excellent reproducibility of spray form, penetration and flow rates. However, as indicated in Table 1, n-heptane is not gasoline and is known to flow in most common injector designs at about a 3 to 4% lower rate than does the U.S. EPA emission test gasoline, 40 CFR 86.113. For some less-typical injector designs, other values of this flow difference may be exhibited.

Table 1 - Comparison of N-heptane to the EPA emission test gasoline

	Viscosity (20 °C) centipoise	Specific Gravity (20 °C)	Static Flow (g/s)	Dynamic Flow (mg/pulse)
40 CFR 86.113	0.468	0.75	1.993	3.63
n-heptane	0.438	0.68	1.918	3.52
% difference	-6.41	-9.33	-3.75	-3.03

The most significant advantage of n-heptane over gasoline is reusability. It is a pure hydrocarbon compound and not a complex mixture of many hydrocarbon compounds, as is the case with gasoline. Therefore, repeated flow testing that results in partial evaporation of the test fluid does not change the physical properties of the remaining fluid. With gasoline, the lighter and more volatile components are preferentially lost, thus changing many of the physical properties. One of the few exceptions to this is the reuse of the test fluid for fuel spray testing in a humid environment, in which case the entrainment of moisture from the air could contaminate the n-heptane. Otherwise, the fluid properties of n-heptane will remain quite stable during repeated testing.

Pump gasolines, the EPA emission test fluid, and n-heptane are all light, volatile liquids and have flash points well below normal room temperature. The vapor from any of these liquids, therefore, poses a fire hazard that must be continuously monitored and controlled in the laboratory areas.

As opposed to laboratory test benches, factory-floor environments seldom permit the routine use of flammable liquids in temperatures above their flash points. The manufacture of fuel injectors generally involves a flow measurement of the completed (or partially completed) injector; therefore, a test liquid of less volatility than gasoline is usually chosen for this purpose, so that the flash point of the liquid is higher than the factory working area temperature. One such liquid is a typical medium petroleum distillate usually called "mineral spirits" in the USA, which has a flash point over 43 °C. The use of such a liquid requires a laboratory-to-factory floor calibration step in which a flow rate on the test fluid corresponding to the desired gasoline flow rate must be established for each individual injector design and test condition. The use of n-heptane for the testing in this document avoids this difficult step.

4.3 Fluid Temperature

The temperature of the test fluid should be measured at the injector inlet, and, unless stated otherwise, should normally be stabilized before any testing to 21 °C ± 2.0 °C.

4.4 Injector Temperature

The body temperature of the test injector should be stabilized at an ambient temperature of 21 °C ± 2.0 °C prior to any pre-conditioning procedure that may be required prior to some tests. If pre-conditioning is not specified, the injector body temperature should be stabilized at 21 °C ± 2.0 °C prior to the test.

4.5 Fuel Pressure

The fuel pressure at the injector inlet should be P_{NORM}. It is to be maintained within ±0.5% of this value throughout the test. If there is no specified application pressure associated with the injector that is being tested, then 400 kPa should be used for P_{NORM}. The actual fuel pressure that is used for a test should always be recorded on the data reporting sheet in the units of kilopascals (kPa).

4.6 Period (P)

The injection period should be 10.0 ms if a value is not specifically designated in a test procedure, then 10.0 ms should be used and recorded on the data reporting sheet.

4.7 Injection Pulse Width (IPW)

The IPW shall be determined by the type of test being conducted. Many values of IPW are specified for the various tests within this document; therefore, careful attention must be given to setting the IPW to the required test value. For example, the specified IPW for determining the set-point dynamic flow rate is 2.5 ms. In general; the IPW is to be maintained within ±0.005 ms.

4.8 Injector Driver

The type of injector driver is to be determined by the specified application, and is to be of instrument grade quality. It should be noted that the saturated-switch type is commonly specified for most PFI applications today. The voltage supplied to the driver shall be 14.0 VDC ± 0.05 VDC unless otherwise specified by the application. The specified driver type and operating voltage are to be recorded on the appropriate data reporting sheet. A detailed description of the two most common driver types is provided in 3.4.4.

4.9 Polarity

The polarity of the injector coil connectors is to be the same as specified in the application, and is to be maintained constant throughout all testing.

4.10 Test Apparatus

The type of test fixture utilized will vary with the particular injector parameter being measured, and will be specified in each test description.

4.11 Instruments

All instruments utilized shall be operated and stabilized.

4.12 Injector Position

The axis of the injector shall be mounted vertically with the spray tip down unless otherwise designated in the particular test procedure. The only test in this document for which this is not the case is the injector drip test.

4.13 Injector Pre-Conditioning

Total pre-conditioning consists of two separate procedures: flushing and purging. The injector and the test apparatus should be flushed and purged with test fluid (n-heptane in most tests) prior to any testing to remove all air, vapors, residue, and shipping fluids. The procedure and test conditions for flushing and purging are provided in Table 2. For both procedures the injector should be operated at an injector pulse width of 5.0 ms and a period of 10.0 ms. Flushing requires at least 6000 pulses, whereas purging requires at least 2000. The test fluid used for the flush is to be discarded, and is not to be used in any subsequent test. Flushing is to be performed only once for any given injector, unless there is a fluid change or a long period of storage (for example, exceeding a week). Purging may be required at the start of many tests following the installation of an injector in its test fixture.

Table 2 - Pre-conditioning procedure (flushing and purging)

Procedure	Purpose	Test Conditions	Discard Fluid?
Flushing	Clear the injector of any shipping fluids and contaminants	IPW = 5.0 ms Period = 10.0 ms No. of pulses = 6000 (minimum) (Minimum test time = 60 seconds)	Yes
Purging	Clear the injector of air bubbles and vapor	IPW = 5.0 ms Period = 10.0 ms No. of pulses = 2000 (Total test time = 20 seconds)	Optional

4.14 Flow Measurement Parameters and Options

The fluid flow rate may be measured by either volume or mass flow with the latter being the preferred method. If measured in volume per time, the data should be converted using the fluid density, and should then be reported in mass flow units. Either grams per second of fluid or milligrams per pulse may be reported, or both. All additional pertinent information to the flow test shall also be recorded (number of pulses, fuel mass, etc.). Prior to the initiation of the flow measurement test procedure, the injector should be pre-conditioned once as noted in Table 2.

4.15 Summary of Standard Test Conditions

The summary of standard test conditions is provided in Table 3 for each of the port fuel injection test procedures. Any deviations from the recommended standard test conditions described in Table 3 must be recorded and clearly noted as a deviation on the applicable data reporting sheet.

Table 3 - Summary of standard test conditions for PFI injector testing

Type of Testing	Testing Categories in SAE J1832								
	Flow Testing	**Leakage Testing**	**Electromech Testing**	**Physical Testing**	**Noise Testing**	**Durability Testing**	**Thermal Testing**	**Corrosion Testing**	**Drip Testing**
Test Fluid	n-heptane (if fluid is used)					Multiple fluids	As specified	As specified	n-heptane
Ambient Temperature (°C)	21 ± 2					21 ± 2	As specified	As specified	21 ± 2
Ambient Pressure (kPa abs)	100 ± 5								100 ± 5
Fluid Temperature (°C)	21 ± 2 (if fluid is used)					As specified	As specified	As specified	21 ± 2
Initial Injector Temperature (°C)	21 ± 2					As specified	As specified	As specified	21 ± 2
Fluid Pressure (kPa gauge)	P_{NORM}, as specified by the application, to within ±0.5%							N/A	P_{NORM}, as specified by application, to within ±0.5%
Injection Period (ms)	10				100	5	As specified	N/A	50 ± 0.01
Injection Pulse Width (ms)	Various	N/A	N/A	N/A	4	2.5	As specified	N/A	5 ± 0.01
Flow Rate Units	To be reported in mass flow units (g/s or mg/pulse)								N/A
Injector Axis Orientation	Vertical unless specified by application; report orientation if not vertical				Vertical	Vertical unless specified by application; report orientation if not vertical			45 degrees ± 1 degree

Table 4 contains a tabulation of the key physical property specifications for 40 CFR 86.113, and Table 5 provides a comparison of the physical properties of three very common test fluids; 40 CFR 86.113, n-heptane, and mineral spirits.

Table 4 - Key physical property specifications for 40 CFR 86.113

Property	40 CFR 86.113 (Clear) Indolene[(1)], EEE[(2)]
Research octane number (ASTM D2699)	93
Sensitivity	7.5
Lead (organic) (ASTM D3237)	0.050 g/gal 0.013 g/L
Sulfur, weight (ASTM D5453)	0.10% max
Phosphorus (ASTM D3231)	0.005 g/gal 0.0013 g/L
Reid vapor pressure (ASTM D5191)	8.7 to 9.2 psi 60.0 to 63.4 kPa
Hydrocarbon composition (ASTM D1319) Olefins Aromatics Saturates	 10% by volume max 35% by volume max Remainder

(1) Trademark of BP.
(2) Trademark of specified fuels.

Table 5 - Physical property specifications for common test fluids

Property	Test Fluids		
Name of Fluid	Normal heptane (CP grade)	40 CFR 86.113 (clear) Indolene[1], EEE[2]	Mineral spirits
Purpose of Fluid	Primary reference fuel grade pure; hydrocarbon liquid in gasoline; boiling range, for injector; flow tests in engineering and development	Engineering and emission test; gasoline for injector tests that require a full-boiling gasoline	Middle distillate for production floor quality control tests
Specific Gravity at 15.6 °C (60 °F) (ASTM D1298)	0.681 to 0.685	0.734 to 0.744	0.775 to 0.790
Kinematic Viscosity at 20 °C (68 °F) (ASTM D445)	0.60 to 0.64 cSt	0.59 to 0.65 cSt	1.195 to 1.205 cSt
Absolute Viscosity at 20 °C (68 °F) (ASTM D445)	0.418 to 438 cP	0.418 to 0.468 cP	0.94 to 0.96 cP
Flash Point (typical) (ASTM D56)	-1 °C (30 °F)	-40 °C (-40 °F)	43.3 °C (110 °F)
Distillation (ASTM D86) Initial	97.7 °C (208 °F)	24 to 35 °C (75 to 95 °F)	150 °C min (300 °F)
Distillation (ASTM D86) 10% evaporated	-	49 to 57 °C (120 to 135 °F)	-
Distillation (ASTM D86) 50% evaporated	98.4 °C (209 °F)	93 to 110 °C (200 to 230 °F)	-
Distillation (ASTM D86) 90% evaporated	-	149 to 163 °C (300 to 325 °F)	-
Distillation (ASTM D86) End Point	99.4 °C (211 °F)	213 °C max (415 °F)	210 °C max (410 °F)
Pentane Insolubles (ASTM D893) % by weight	0.001 max	0.001 max	0.01 max
Water Content (ASTM D6304) % by weight	0.001 max	0.001 max	0.10 max

(1) Trademark of BP.
(2) Trademark of specified fuels.

5. ELECTROMECHANICAL AND FLOW PARAMETERS

5.1 Overview of Electromechanical and Flow Parameters

This section contains numerous test procedures that will serve to characterize the non-spray performance of a port fuel injector. The subsections of this section contain test procedures for determining the electrical properties, opening and closing times, tip leakage, and fuel flow characteristics of any particular PFI injector. Taken as a whole, the values obtained for these parameters contribute significantly to defining the operating envelope and performance of the injector. It should be noted that the determination of the spray quality delivered by the injector requires a separate set of tests that are fully defined in a separate document, SAE J2715. The majority of the tests in this chapter are independent, and may be conducted with or without conducting the other tests.

5.2 Injector Electrical Parameter Measurements

5.2.1 Coil Resistance (R)

5.2.1.1 Overview of Coil Resistance

The measurement of the coil resistance permits the injector user to determine the electrical current requirement for a given system voltage. Presently, injector solenoid designs consist of either high-resistance or low-resistance coils. The high-resistance design is typically 8 to 16 Ω and used with a saturated circuit driver. The driver turns the battery voltage on and off, allowing the current through the coil to be controlled by the coil resistance. The low-resistance design is typically 1 to 4 Ω and uses a current limiting driver. This system allows a peak current for rapid opening response followed by a lower current level, called the hold current, for the remainder of the command pulse.

5.2.1.2 Procedure for Coil Resistance Measurement Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. The recommended measurement procedure is to utilize an ohmmeter in a four-wire bridge arrangement. A two-wire bridge measurement is acceptable if the measuring leads are zeroed. The ohmmeter measurement should be made with the injector at a uniform temperature of 21 °C ± 2.0 °C. Caution should be taken to not physically touch the injector just before taking measurement, as it may alter the injector coil temperature and affect the resistance readings.

d. Conduct the measurement of the coil resistance. The unit of measurement is to be ohms (Ω), with a measured accuracy of ±0.01 Ω.

e. Repeat the test for the remaining injectors in the set.

5.2.1.3 Data Reduction and Analysis for Coil Resistance Measurement Test

None required.

5.2.1.4 Data Reporting for Coil Resistance Measurement Test

Report the measured coil resistance in ohms (Ω) on the data reporting sheet. If there are any test deviations, such as the use of a two-wire bridge, this should be noted on the sheet.

5.2.2 Solenoid Inductance (L)

5.2.2.1 Overview of Solenoid Inductance

The inductance of an electromagnetic solenoid is a function of the number of turns in the solenoid coil and the permeance of the magnetic circuit. Inductance is an indirect measure of the material properties and geometry of the flux path. Its value is therefore meaningful as a production control parameter. Inductance, together with resistance, provides the time constant when the voltage is known and therefore can be used in predicting the initial current rise profile.

5.2.2.2 Procedure for Solenoid Inductance Measurement Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. The recommended method of measurement of solenoid inductance is with the injector in the non-energized, closed position using a Wheatstone Bridge or equivalent, connected in a four-wire series mode. The standard test frequency shall be 1.0 kHz + 0.5%, with a potential of 1.0 Vrms.

d. Conduct the inductance measurement using the Wheatstone Bridge. The unit of measurement is the millihenry (mH), with a resolution of ±0.01 mH.

e. Repeat the test for the remaining injectors in the set.

5.2.2.3 Data Reduction and Analysis for Solenoid Inductance Measurement Test

None required.

5.2.2.4 Data Reporting for Solenoid Inductance Measurement Test

Report the measured solenoid inductance in mH on the data reporting sheet.

5.2.3 Insulation Resistance (IR)

5.2.3.1 Overview of Insulation Resistance

This test is designed to check for a potential failure of the insulation between the coil assembly and the case of the injector. It is usually performed on completed injectors to ensure that the coil insulation has not been damaged during the assembly process and that the terminal to case clearance has been adequately maintained. IR is also measured after any mechanical integrity testing to ensure that the insulating abilities of the injector coil assembly have not been degraded.

In most existing applications, a voltage is applied to one of the injector terminals and the unit is energized by completing the ground circuit. In a situation where the IR breaks down, the injector could become continuously energized and flood the engine. On systems that energize the unit by providing the positive voltage through the driver, breakdown can cause the injector to misfire or not fire at all depending on where the coil assembly is shorted.

5.2.3.2 Procedure for Insulation Resistance Measurement Test

a. A minimum set of five new injectors from serial production is to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. Connect a standard megohmmeter tester, set to 1000 VDC, between the injector case and a coil terminal post.

d. After 2 seconds, measure the resistance. The typical minimum resistance normally exceeds 300000 Ω, with some applications requiring a minimum of 500000 Ω.

e. Repeat the test for the remaining injectors in the set.

5.2.3.3 Data Reduction and Analysis for Insulation Resistance Measurement Test

None required.

5.2.3.4 Data Reporting for Insulation Resistance Measurement Test

Report the measured insulation resistance in ohms (Ω) on the data reporting sheet.

5.2.4 Static Minimum Operating Voltage (SMOV)

5.2.4.1 Overview of the Static Minimum Operating Voltage

Under certain circumstances, such as cold engine cranking, normal operating voltage is not available. The minimum opening voltage of the injector is especially critical for high-resistance injectors as the coil current is directly proportional to the available voltage. Low-resistance injectors are not as sensitive to lower battery voltage due to the current limiting driver circuit characteristics. The SMOV is the minimum voltage, measured at the injector electrical connector, at which the injector opens as determined by an accelerometer or other sensing device capable of detecting the opening event.

5.2.4.2 Procedure for Static Minimum Operating Voltage (SMOV) Test

a. A minimum set of five new injectors from serial production is to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet. All of the injectors are to be pre-conditioned according to Table 2.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. Mount the injector in the test fixture and connect a variable DC power supply to the injector connector terminals. Before applying any voltage, allow sufficient time for the injector body to cool down to the standard test temperature after the pre-conditioning operation.

d. The recommended method of measurement is to increase the level of the voltage to the injector solenoid in a staircase waveform with an increment of 100 mV and a duration of 10 ms until the injector opens. The injector opening event may be detected by means of an accelerometer signal or an alternative sensing device.

e. Note the voltage level at which the injector first opens. This is the SMOV value.

f. Repeat the test for the remaining injectors in the set.

5.2.4.3 Data Reduction and Analysis for Static Minimum Operating Voltage Test

None required.

5.2.4.4 Data Reporting for Static Minimum Operating Voltage Test

Record the measured static minimum operating voltage on the data reporting sheet.

5.2.5 Dynamic Minimum Operating Voltage (DMOV)

5.2.5.1 Overview of the Dynamic Minimum Operating Voltage

This parameter is a measure of the fuel injection system response to low voltage conditions. The driver circuit has a significant effect on the injector response characteristics; therefore, the driver circuit as used in the vehicle must be used.

5.2.5.2 Procedure for Dynamic Minimum Operating Voltage Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet. All of the injectors are to be pre-conditioned according to Table 2.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. Mount the injector in the test fixture and attach the output of a driver circuit from the vehicle application of the injector. Connect a logic pulse generator with variable DC voltage to the input of the driver.

d. Using a logic pulse width to the driver of 10 ms, and a pulse period of 20 ms, increase the supply voltage to the driver in steps of 0.10 V starting at the SMOV. 1200 injection pulses (24 seconds) are to be supplied at each voltage step.

e. Measure the applied supply voltage and the injector dynamic flow rate, Q_d, at each voltage step point.

f. The DMOV is defined as that voltage at which the delivered dynamic flow rate equals 50% of the flow rate that is delivered at 14.0 V. See Figure 6.

g. Repeat the test for the remaining injectors in the set.

5.2.5.3 Data Reduction and Analysis for Dynamic Minimum Operating Voltage Test

Determine the DMOV value from the data on dynamic flow rate versus voltage.

5.2.5.4 Data Reporting for Dynamic Minimum Operating Voltage Test

Record the measured dynamic minimum operating voltage (DMOV) on the data reporting sheet.

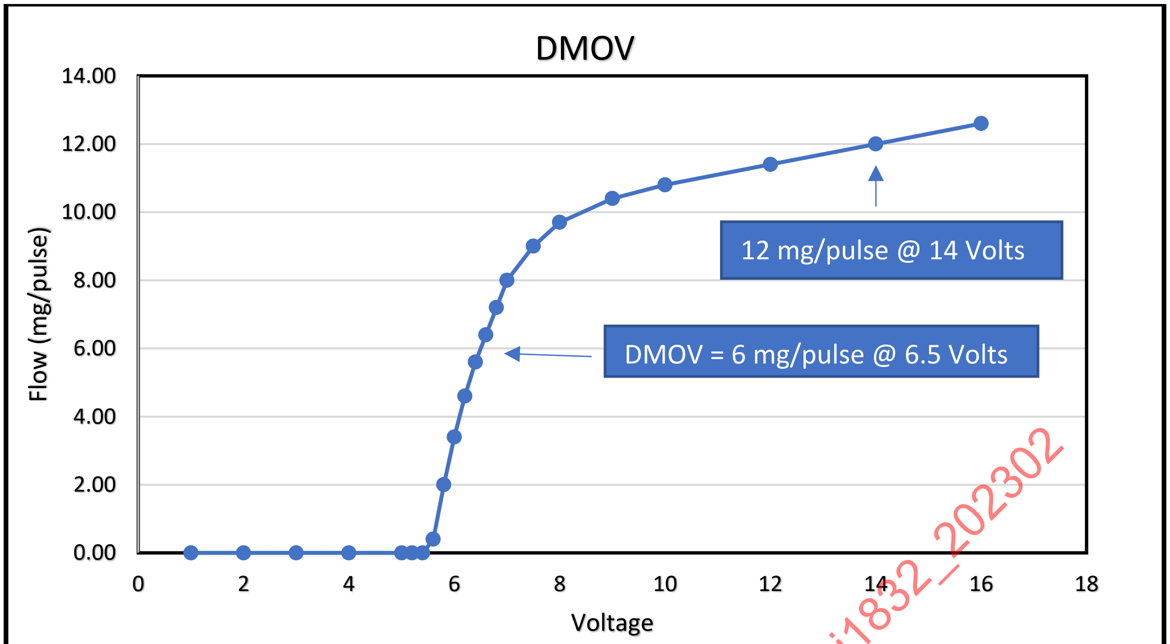


Figure 6 - Dynamic minimum operating voltage (DMOV)

5.2.6 Maximum Overload Voltage (MOV) Tolerance

5.2.6.1 Overview of the Maximum Overload Voltage Tolerance

The injector must maintain calibration after a maximum overload voltage (MOV) test. In this test, a maximum of 24.0 V is applied to the driver in the case of a peak-and-hold driver and directly to the injector terminals in the case of a saturated switch driver. The voltage is applied for a period of 60 seconds while the injector is operating at Q_{sp}. This test is intended to simulate an extreme jump-start condition using a 24 V battery.

5.2.6.2 Procedure for Maximum Overload Voltage Tolerance Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet. All of the injectors are to be pre-conditioned according to Table 2.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. Measure the parameters of Q_s, Q_{sp}, R, IR, and tip leakage for the injector prior to the application of any overload voltage.

d. Mount the injector in a suitable test fixture that contains the proper driver. The injector and driver are to be tested as an assembly with the injector operating at Q_{sp} and a system fuel pressure of P_{NORM}.

e. A 24 V test voltage is to be applied for 60 s to the driver input if the injector uses a peak-and-hold driver, and directly to the injector terminals in the case of a saturated switch driver. Following the application of the voltage, the injector is to be retested for any resulting change in the parameters of Q_s, Q_{sp}, R, IR, and tip leakage.

f. Repeat the test for the remaining injectors in the set.

5.2.6.3 Data Reduction and Analysis for the Maximum Overload Voltage Tolerance

Compute the percentage change in the values of Q_s and Q_{sp} from the pre-test value to the post-test value.

5.2.6.4 Data Reporting for the Maximum Overload Voltage Tolerance Test

Record the measured pre-test and post-test values of Q_s, Q_{sp}, R, IR, and tip leakage along with the computed percentage changes in Q_s and Q_{sp} on the data reporting sheet.

5.2.7 Voltage Sensitivity

5.2.7.1 Overview of Voltage Sensitivity

As the fuel flow is a function of battery voltage with most injectors, particularly high-resistance injectors, this operating map is normally a very useful piece of data. For example, having this data map may permit voltage compensation curves or maps to be generated for use in fuel system control or calibration programs.

5.2.7.2 Procedure for the Voltage Sensitivity Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet. All of the injectors are to be pre-conditioned according to Table 2.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. Mount the injector in the test fixture and attach the output of a driver circuit from the vehicle application of the injector. Connect a logic pulse generator with variable DC voltage to the input of the driver.

d. Using the driver circuit from the vehicle application, set the supply voltage to the driver to 5.0 V. For a period (IPW) of 10.0 ms and the following series of injection pulse widths: 1.4, 1.6, 1.8, 2.0, 2.2, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 7.5, 8.0, 8.5, 9.0, 9.5, and 10.0 ms, measure the delivered dynamic flow, Q_d at each IPW.

e. Repeat step (d) incrementally for the additional DC voltage levels of 6.0, 7.0, 8.0, 10.0, 12.0, 14.0, and 16.0 V. Any additional special voltages that correspond to the vehicle application requirements may also be added.

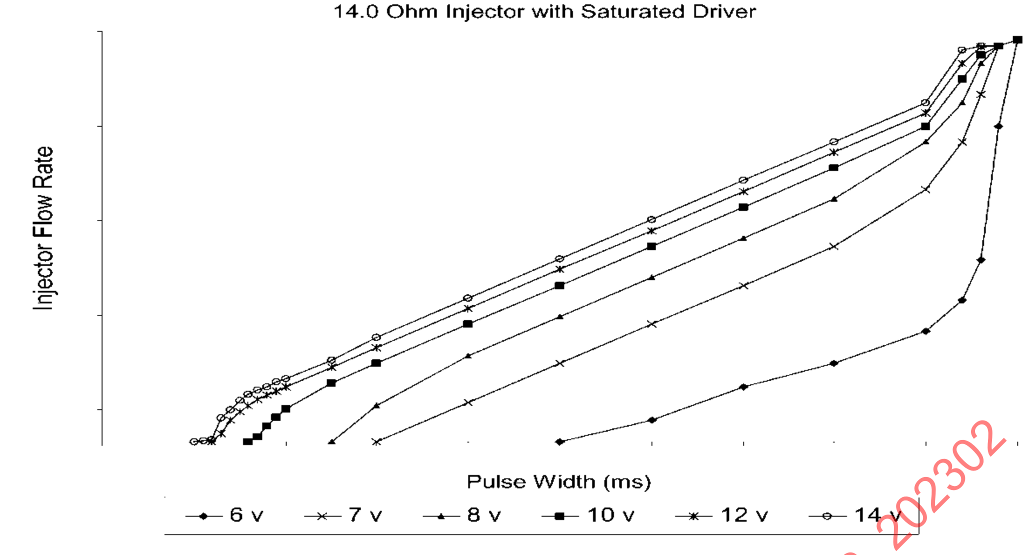
f. Repeat the test for the remaining injectors in the set.

5.2.7.3 Data Reduction and Analysis for the Voltage Sensitivity Test

Plot the measured curves of dynamic fuel flow rate, Q_d, versus the injection pulse width for each of the eight test voltages. Typical injector voltage sensitivity performance maps for both a saturated driver and a peak-and-hold driver are illustrated in Figure 7.

5.2.7.4 Data Reporting for the Voltage Sensitivity Test

Attach the family of curves of voltage sensitivity to the data reporting sheet.



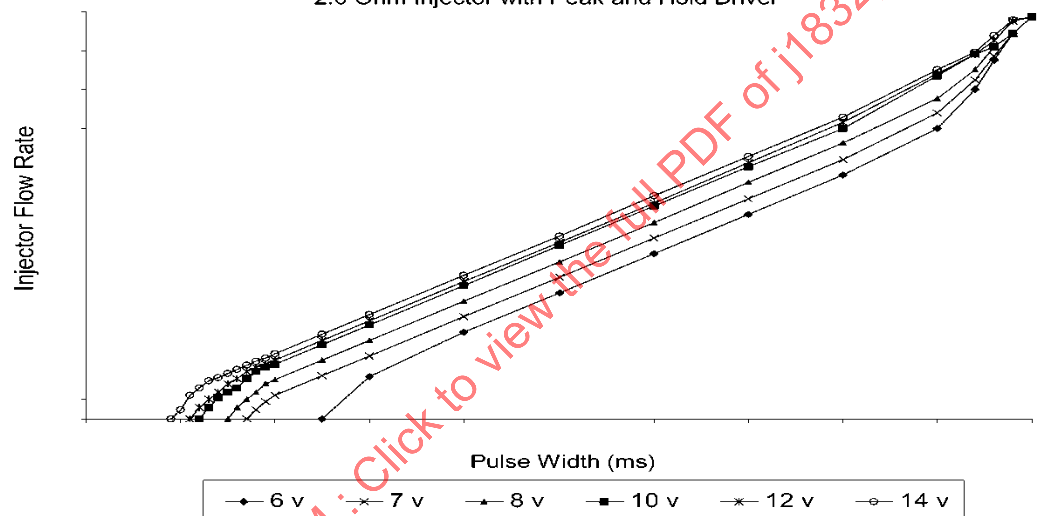


Figure 7 - Typical measured curves of voltage sensitivity

5.2.8 Static Pull-In Current (I/S-ON)

5.2.8.1 Overview of the Static Pull-in Current

I/S-ON is the minimum current required to actuate the injector from the closed to the open position. It can be used to calculate the SMOV if multiplied by the R and can be useful information in diagnosing functional problems and designing of injector driver circuits.

5.2.8.2 Procedure for the Static Pull-in Current Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet. All of the injectors are to be pre-conditioned according to Table 2.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. Mount the injector in the test fixture. The injector is to be mounted vertically with the nozzle pointing downward and with the system application pressure, P_{NORM}, applied to the fuel inlet. Connect a variable DC power supply to the injector connector terminals. A precision ammeter should be installed to control and measure the level of current supplied to the injector solenoid.

d. The recommended method of measurement is to increase the level of current to the injector solenoid in a staircase waveform with a step height of 1.0 mA and a duration of 10 ms until the injector opens. The injector-opening event may be detected by means of an accelerometer signal or an alternative sensing device. The test should be started at a current level that is approximately 90% of the anticipated I/S-ON current in order to avoid overheating the injector solenoid.

e. Note the value of the solenoid current (in amperes) at which the injector first opens. This is the static pull-in current, I/S-ON.

f. Repeat the test for the remaining injectors in the set.

5.2.8.3 Data Reduction and Analysis for the Static Pull-in Current Test

None required.

5.2.8.4 Data Reporting for the Static Pull-in Current Test

Record the measured value of the static pull-in current, I/S-ON, on the data reporting sheet. The units are to be in amperes (A).

5.2.9 Static Drop-out Current (I/S-OFF)

5.2.9.1 Overview of the Static Drop-out Current

I/S-OFF is the minimum current required to hold the injector open after it has been energized. It is used to determine the holding current calibration of a peak-and-hold driver.

5.2.9.2 Procedure for the Static Drop-out Current Test

a. A minimum set of five new injectors from serial production are to be tested. If the injectors are from pre-production, this should be stated in the comments section of the data reporting sheet. All of the injectors are to be pre-conditioned according to Table 2.

b. Establish the standard test conditions listed on the data reporting sheet in this section.

c. It is recommended that the static drop-out current be measured immediately following the measurement of the static pull-in current.

d. Mount the injector in the test fixture. The injector is to be mounted vertically with the nozzle pointing downward and with the system application pressure, P_{NORM}, applied to the fuel inlet. Connect a variable DC power supply to the injector connector terminals. A precision ammeter should be installed to control and measure the level of current supplied to the injector solenoid.

e. The recommended method of measurement is to apply sufficient current to the injector solenoid to assure that the injector is in the open position, and then to decrease the current in a staircase waveform with a step height of 1.0 mA and a duration of 10 ms until the injector closes. The injector closing event may be detected by means of an accelerometer signal or an alternative sensing device. The test should be started at a current level that is no more than approximately 10% higher than the anticipated I/S-OFF current in order to avoid overheating the injector solenoid.

f. Note the value of the solenoid current in milliamperes at which the injector closes. This is the static drop-out current, I/S-OFF. It should be noted that I/S-OFF value is always lower than the I/S-ON value. This is mainly due to the solenoid air gap being smaller by the distance of the stroke, which will yield higher magnetic forces for any given current level.

g. Repeat the test for the remaining injectors in the set.

5.2.9.3 Data Reduction and Analysis for the Static Drop-out Current Test

None required.

5.2.9.4 Data Reporting for the Static Drop-out Current Test

Record the measured value of the static drop-out current, I/S-OFF, on the data reporting sheet. The units are to be in amperes (A).

5.2.10 Control Module Power Dissipation

There are three key areas of concern when driving a solenoid with a control module output. The first is the power dissipation in the driver and snubbing devices (one device may perform both functions) and the effect on the internal temperature of the system. Snubbing is the dissipation of energy stored in an inductive device when the output driver is switched off. This energy is also referred to as the inductive kickback or alternatively as the inductive flyback. The second area of concern is the cumulative energy the snubbing device absorbs each time the driver is turned off. The third area of concern is the total power dissipation of the control module.

There are two components to the power dissipated by the output driver during operation. First, there is the power dissipated during the “on” time as the solenoid current flows through the output transistor. This power is the I^2R loss due to the saturation voltage of the driver. The second contributor is the power dissipated during the inductive flyback as the solenoid is turned off and the energy stored in the magnetic field is removed.

The typical control module contains a clamping feature that “avalanches,” or breaks down, at output voltages normally between 32 to 120 V during the snubbing interval, depending on the type of driver used. This clamping action continues until the current through the solenoid reaches zero. Avalanche or breakover is the characteristic of a semiconductor device that causes it to become conductive at and above a specified voltage. This specified voltage level is known as the clamp or zener voltage.

These power dissipation measurements will not be detailed in this document, and it is recommended that such measurements be coordinated and conducted in conjunction with the supplier of the control module to ensure the reliability of the system operation.

5.3 Injector Opening Time (OT) and Closing Time (CT)

5.3.1 Overview of Injector Opening Time and Closing Time

The opening time (OT) of an injector is a measure of the time required for the injector needle to first attain its fully opened position after initiation of the injector logic pulse. The closing time (CT) is the time required for the injector needle to first attain its fully closed position after the termination of the injector logic pulse. A schematic representation of the needle movement and injector logic pulse is provided in Figure 8. The needle movement normally exhibits a trajectory with time that is characterized by the specific points T1, which is the start of needle movement from the seat, T2, which is the time when the needle reaches its maximum lift, T3, which is the time when the needle begins to move from the maximum lift and T4, which is the time when the needle first reaches its contact position on the seat. The two parameters of OT and CT provide a relative indication of the combined mechanical and magnetic response time. The total time to open and close the injector orifice also is also a major contributing factor in the usable flow range of the injector.

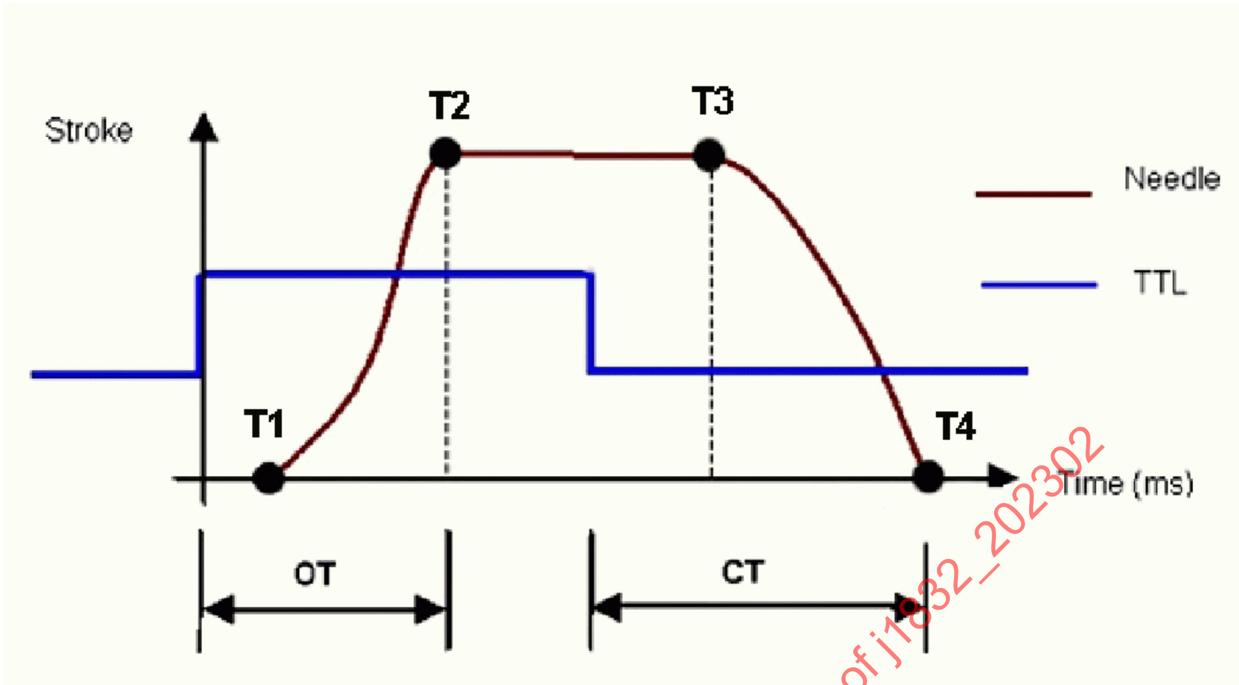


Figure 8 - Representation of needle movement relative to the logic pulse

5.3.2 Test Equipment for Opening-Time and Closing-Time Tests

The test equipment recommended for the measurement of the OT and CT intervals is a precision accelerometer mounted within 2.5 cm of the injector body, as well as a precision storage oscilloscope that is capable of accurately measuring time intervals and overlaying multiple traces. The accelerometer may be mounted on either the injector body or on the fixture as illustrated in Figure 9.

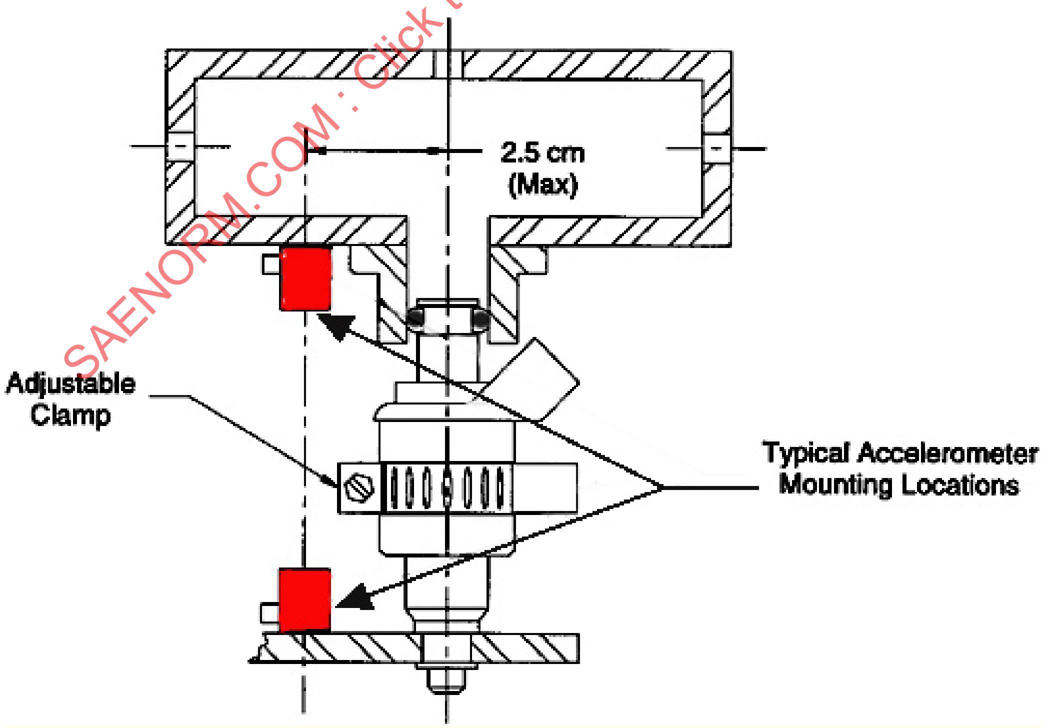


Figure 9 - Accelerometer mounting locations for OT and CT tests

5.3.3 Procedure for Opening-Time and Closing-Time Tests

a. A minimum set of five new injectors from serial production are to be tested. All of the injectors are to be pre-conditioned according to Table 2.

b. Mount the test injector on the test fixture that contains a fast-response accelerometer (10 kHz or higher). See Figure 9.

c. Utilizing n-heptane at a fuel pressure of P_{NORM}, set the injection pulse width (IPW) to 5.0 ms and the period (P) to 50 ms. If other than n-heptane test fuel is used, the actual fuel type should be noted on the data reporting sheet as a test deviation.

d. The resolution of the storage oscilloscope should be adjusted such that variations as small as of 10 ms can be discerned. Energize the injector and verify on the oscilloscope that each injection has two distinct acceleration events as depicted in either Figures 10A or 10B. A typical trace that occurs when using a peak-hold driver with an injector coil of low resistance is shown in Figure 10A, whereas Figure 10B illustrates a representative trace that is obtained when using a saturated driver and an injector coil having high resistance.

e. The traces for OT and CT should be recorded for six consecutive injection events. Record the accelerometer trace, the trace of the current through the injector coil, the voltage applied to the connector terminals, and the logic pulse. A digital timer can also be used to directly measure the elapsed time of the opening events during the test by triggering it to begin counting at the initiation of the logic pulse.

f. Repeat the test for the remaining injectors in the set.

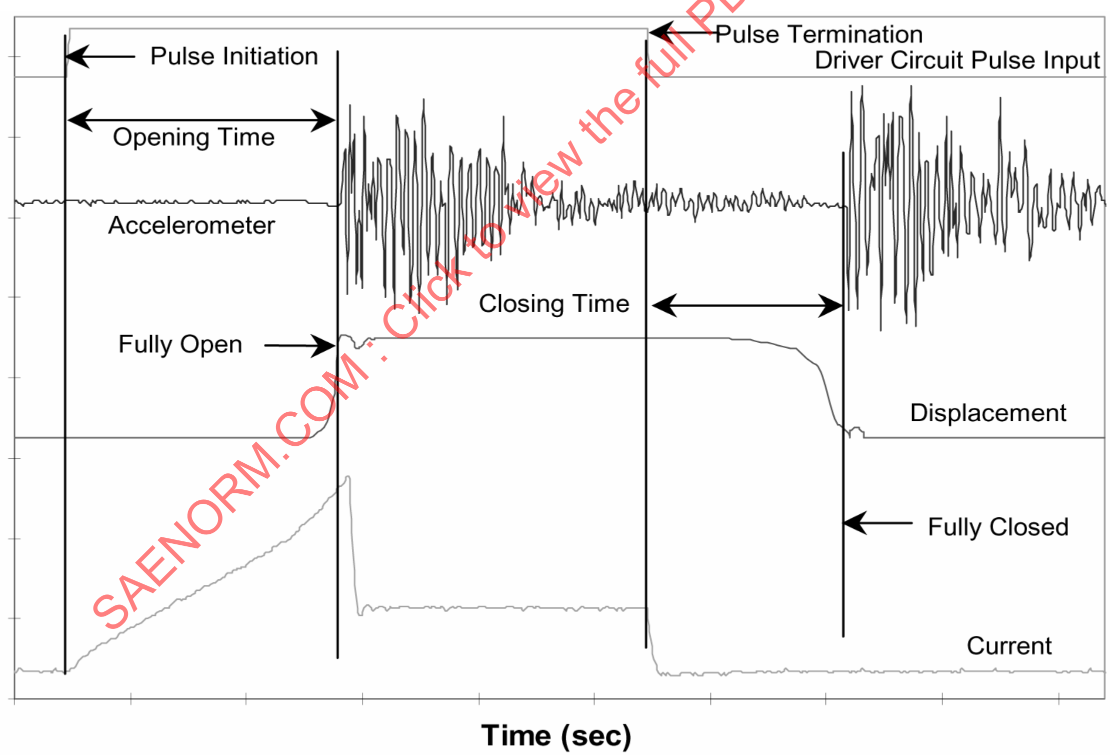


Figure 10A - Typical opening and closing events with peak and hold driver

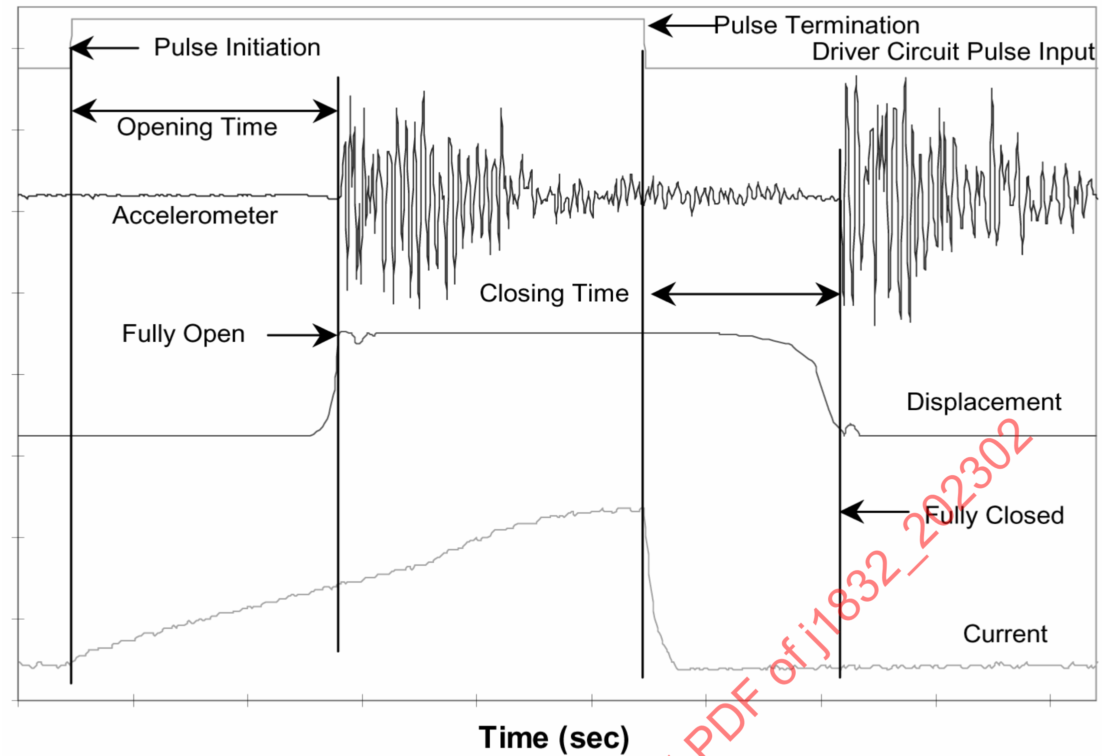


Figure 10B - Typical opening and closing events with saturated driver

5.3.4 Data Reduction and Analysis for Opening-Time and Closing-Time Tests

a. Determine the opening time (OT) of each of the six individual injection events by measuring the time interval between the start of the injector logic pulse (LPW) and the first rise on the first set of the accelerometer signal traces.

b. Determine the closing time (CT) of each of the six individual injection events by measuring the time interval between the end of the injector logic pulse (LPW) and the first movement on the second set of the accelerometer signal traces.

c. Calculate the average and standard deviation of the OT for the set of all six injection events.

d. Calculate the average and standard deviation of the CT for the set of all six injection events.

5.3.5 Data Reporting for Opening-Time and Closing-Time Tests

Record the calculated averages and standard deviations for OT and CT on the data reporting sheet for electromechanical properties. The units are to be in milliseconds (ms).

5.3.6 Alternative Test Methods for Opening Time and Closing Time

Recent alternative measurement technologies might be used to determine the flow rate shape relative to the electrical input signals to the injector. These alternatives include the use of an injection rate meter or a suitable commercial single-shot flow measurement device. If an alternate method is utilized this should be noted on the data reporting sheet. It is important that response time and accuracy of the flow measurements allow a precise determination of the variation in the needle movement as a function of the time from the start of the injection logic pulse.

5.4 Opening-Time Instability (OTI) and Closing-Time Instability (CTI)

5.4.1 Overview of Opening-Time Instability and Closing-Time Instability

The opening time instability (OTI) and the closing time instability (CTI) are measures of variations that occur in the injector OT and CT, and they are direct indicators of possible injection-to-injection variability in the amount of fuel mass delivered during consecutive injection events. This is also commonly referred to in the literature as pulse-to-pulse variability or shot-to-shot (STS) variability. The magnitude of the STS is currently commonly measured on specialized equipment that is specifically designed to measure this parameter. If no specialized equipment for injection-to-injection variability of mass fuel delivery is available, the following test for instabilities may provide some limited information on the tendency of the injector to exhibit such variability.

5.4.2 Procedures for the Opening-Time Instability and Closing-Time Instability Tests

a. A minimum set of five new injectors from serial production are to be tested. All of the injectors are to be pre-conditioned according to Table 2.

b. Mount the test injector on the test fixture that contains a fast-response accelerometer (10 kHz or higher). See Figure 9 for the positioning of the accelerometers.

c. Utilizing n-heptane at a fuel pressure of P_{NORM}, set the injection pulse width (IPW) to 5.0 ms and the period (P) to 50 ms. If other than n-heptane test fuel is used, the actual fuel type should be noted on the data reporting sheet as a test deviation.

d. The resolution of the storage oscilloscope should be adjusted such that variations as small as of 10 ms can be discerned. Energize the injector and verify on the oscilloscope that each injection has two distinct acceleration events as depicted in either Figures 10A or 10B. A typical trace that occurs when using a peak-hold driver with an injector coil of low resistance is shown in Figure 10A, whereas Figure 10B illustrates a representative trace that is obtained when using a saturated driver and an injector coil having high resistance.

e. The accelerometer traces for OT and CT should be recorded and superimposed for a minimum of 200 consecutive pulses. Also record traces for the current through the injector coil, the voltage applied to the connector terminals and the logic pulse. A digital timer can also be used to directly measure the elapsed time of the opening events for the 200 pulses by triggering it to begin counting at the initiation of the injector logic pulse.

f. Repeat the test for the remaining injectors in the set.

5.4.3 Data Reduction and Analysis for the Opening and Closing-Time Instability Tests

The 200 traces of the injector closing event should be superimposed, and the earliest and latest closing times of the 200 noted. This is the observed range of closing times, with the units being microseconds (µs). A representative plot of the overlay of numerous consecutive closing events for a typical PFI injector is illustrated in Figure 11. The observed range of injector opening times (latest minus earliest) should also then be determined in a similar manner.

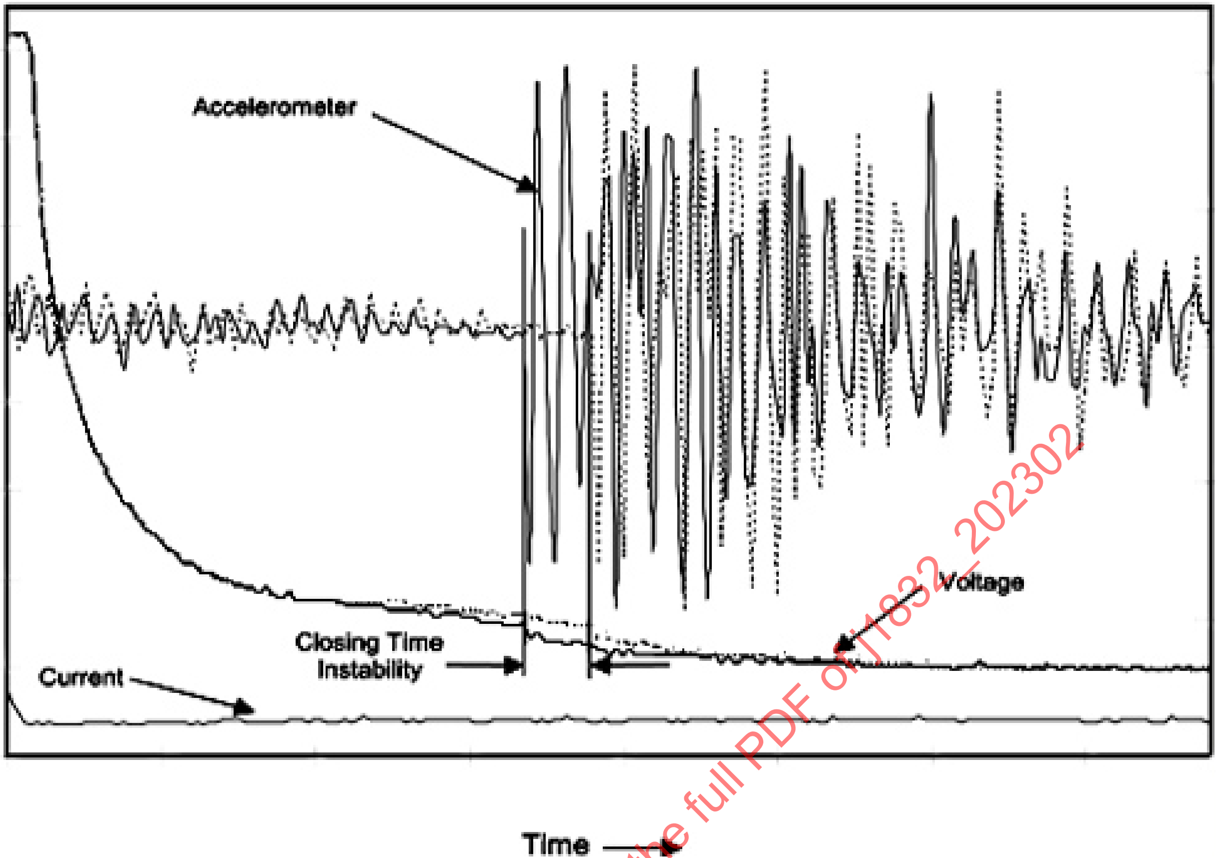


Figure 11 - Illustration of the closing-time instabilities of a PFI injector

5.4.4 Data Reporting for the Opening-Time Instability and Closing-Time Instability Tests

Record the observed limiting ranges of injector opening time and closing time on the data reporting sheet. These values should be reported in microseconds.

Table 6 - SAE data reporting sheet for PFI electromechanical characteristics

SAE Data Reporting Sheet for PFI Electromechanical Characteristics

Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			

Part 2: Information on Injector	
Injector manufacturer	
Injector description Static flow rate (at pressure) Inward/outward single/dual Type Bent/coaxial Multi-hole Normal pressure (P_{NORM})	
Injector part number	
Injector serial number	
Additional information	

Part 3: Test Conditions	**Specific Test Conditions**	**Standard PFI Test Conditions**
Test fluid		n-heptane
Ambient temperature (°C)		21 ± 2
Ambient pressure (kPaa)		100 ± 5
Fluid temperature (°C)		21 ± 2
Test fuel pressure (kPa)		P_{NORM} ± 0.5%
Test pressure tolerance		±0.5%
Injector temperature (°C)		21 ± 2
Injection pulse width (ms)		Dependent upon specific test; 5.0 ± 0.005 for OT and CT 10.0 ± 0.005 for DMOV
Injection period (ms)		Dependent upon specific test; 50.0 ± 0.2% for OT and CT tests 10.0 ± 0.2% for Voltage Sensitivity

Part 4: Description and Comments on Test Instruments or Test Deviations	
Clarifying information and comments: also any deviations or instabilities present	

Part 5: Test Results for Electromechanical Characteristics		
Opening time as obtained from the recorded time trace (ms); this is the SAE J1832 opening time if there are no test deviations		
Closing time as obtained from the recorded time trace (ms); this is the SAE J1832 closing time if there are no test deviations		
Coil resistance as obtained from the bridge (Ω)		
Insulation resistance from the ohmmeter (Ω)		
Solenoid inductance as obtained from the Wheatstone Bridge (millihenries)		
Static minimum operating voltage (SMOV); this is the SAE J1832 SMOV if there are no test deviations		
Dynamic minimum operating voltage (DMOV); this is the SAE J1832 DMOV if there are no test deviations		
Maximum overload voltage (MOV) - Application of 24 V: Change in Q_s (percent)		
Change in Q_{sp} (percent)		
Insulation resistance (IR) (Ω)	Pre-Test	Post-Test
Coil resistance (R) (Ω)	Pre-Test	Post-Test
Tip leakage (mm^3/minute)	Pre-Test	Post-Test
Voltage sensitivity curve plotted and attached? Circle YES or NO	YES	NO
Static pull-in current I/S-ON (amperes)		
Static drop-out current I/S-OFF (amperes)		
Opening time instability (microseconds)		
Closing time instability (microseconds)		

5.5 Injector Tip Leakage Measurement

5.5.1 Overview of Injector Tip Leakage and Measurement Methods

The injector seat generally has metal-to-metal sealing surfaces for durability reasons. A sealed interface is required between the mating surfaces of the injector valve seat components to maintain fuel pressure, to prevent the accumulation of unmetered fuel in the intake manifold and to reduce deposit formation at the injector tip. The seat leakage rate will vary with fuel pressure, injector temperature and heat-soak duration, and may result in an imprecise A/F ratio, injector deposits, and elevated levels of UBHC.

A reduction in fuel pressure during extended periods of engine shutdown under hot ambient conditions may cause excessive fuel vaporization and an incorrect amount of fuel being delivered during the subsequent engine start. The increased time required to achieve the normal rail pressure, combined with vapor entrained in the fuel, can result in increased cranking time, rough idles, stalls, or even a failure to start. Fuel leakage into the intake manifold will generally result in a richer than normal A/F ratio during an engine start. Engine emissions may be adversely affected under these conditions. Even small amounts of fuel leakage through the injector tip may significantly increase deposit formation at the metering orifice of the injector. These deposits can partially plug the orifice thereby reducing the amount of fuel delivered, potentially affecting both vehicle emissions and drivability.

Two types of leakage are generally considered for automotive fuel injectors: external and seat or tip leakage. Seat leakage is defined as the unmetered fuel that escapes the injector through the valve-to-seat interface, which is normally located at the injector tip. All leaks not originating from the seat are defined as external leakage. With the advent of improved welding practices and optimal injector design, specific testing for external leakage is not provided in this document.

There have been a number of testing methods employed over the years to make PFI injector tip leakage measurements. These include the gaseous test methods such as the bubble-rise, pressure-decay, and helium techniques, as well as the hydraulic testing methods. The bubble-rise and pressure-decay methods both use dry nitrogen as the test medium, whereas the hydraulic testing methods utilize liquid fuel under pressure. Because injectors commonly contain some fluid that can mask gaseous leakage, drying processes tend to be highly influential on the leakage results with these gaseous methods. The difficulty of ensuring dry sealing surfaces increases the uncertainty of the measurements and is therefore not recommended in this document.

Hydraulic test measurements eliminate the need for a drying procedure and provide a more direct correlation to fuel leakage. Two such methods are described below: the bellows method and the flame ionization detector (FID) method. It is recommended that the hydraulic-bellows method be utilized for tip leakage rates above 1.0 mm^3/min. The FID hydraulic method is a superior technique that utilizes a FID to measure the small amount of fuel that is leaked through the injector tip. This method is capable of reliably measuring very small leakage rates and is the test procedure recommended in this document for leak rates that are less than 1.0 mm^3/min.

5.5.2 Hydraulic Tip Leakage Measurement Method Using a Calibrated Bellows

5.5.2.1 Overview of the Calibrated Bellows Tip Leakage Measurement

The calibrated bellows measurement method is recommended for determining the tip leakage of a PFI injector when the expected maximum leakage rate is above 1.0 mm^3/min. The general measurement concept is as follows: the injector is fitted with a precision calibrated bellows at the tip where the fuel exits. The injector is filled with a hydrocarbon test fluid and is pressurized using air or nitrogen. This pressure is applied for 30 seconds, allowing the leaked fuel to enter the bellows and expand it. The pressure is removed and the net change in the bellows position is noted.

5.5.2.2 Procedure for the Hydraulic Tip Leakage Measurement Test

a. A minimum set of five new injectors of the same make and model from serial production are to be tested. Pre-condition each of these injectors according to Table 2.

b. Set the test conditions to comply with those recommended on the data reporting sheet.

c. Clamp the injector into the fixture with the injector body vertical and the tip down. The fixture should contain a pre-calibrated bellows with an indicator of volume change in cubic millimeters.

d. See Figure 12 for the hydraulic bellows test fixture details. Also see Table 7 for the standard test conditions to be utilized for the hydraulic calibrated bellows test.

e. Open the test fluid inlet valve and introduce the test fluid. Ensure that no air or other gases are present within the injector. The fluid temperature should be 21 °C ± 2 °C.

f. Close the test fluid valve.

g. Measure the starting or reference position of the calibrated bellows.

h. Open the air (or nitrogen) flow valve to pressurize the fluid to P_{NORM} ± 0.5%.

i. Leave the air (or nitrogen) flow valve open for 30 seconds.

j. Close the air (or nitrogen) flow valve.

k. Measure the final (new) bellows position.

l. Repeat the test for the remaining injectors in the set.

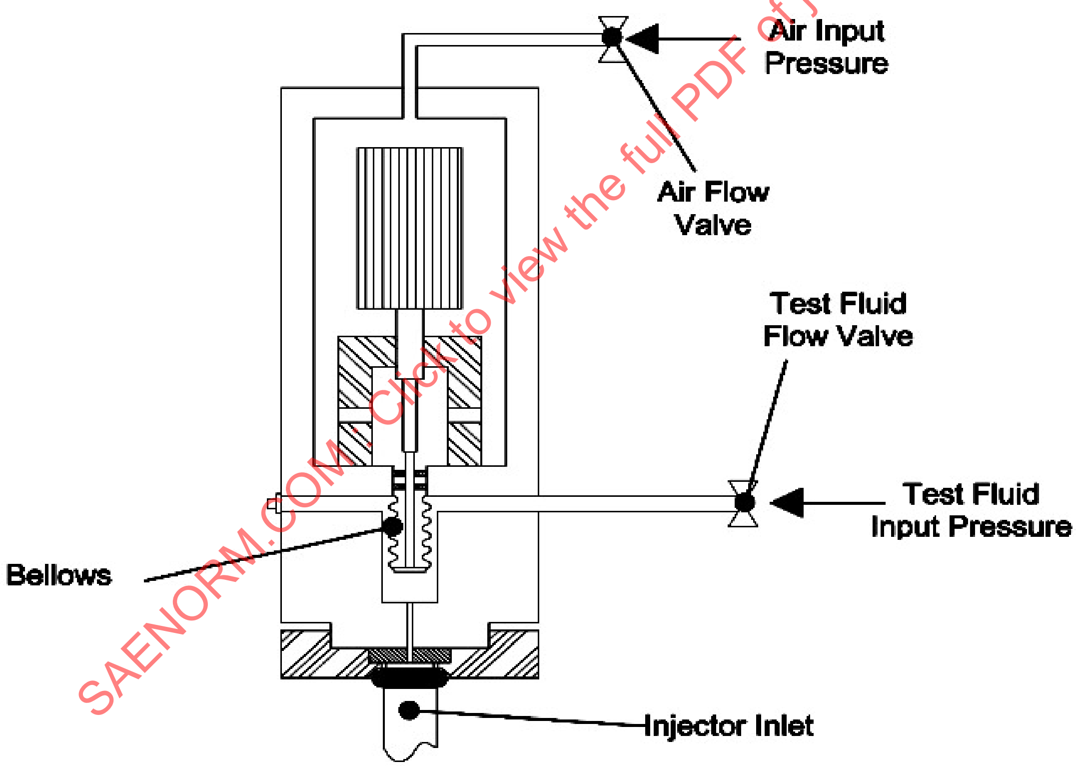


Figure 12 - Hydraulic leak test configuration using calibrated bellows

Table 7 - Standard test conditions for FID and bellows leakage tests

Test Parameter	Standard Value
Test fluid	n-heptane
Ambient pressure (kPaa)	95 to 102
Ambient temperature (°C)	21 ± 2
Fluid temperature (°C)	21 ± 2
Injector temperature (°C)	21 ± 2
Fluid pressure (kPa)	P_{NORM} ± 0.5%
Injector axis orientation	Vertical

5.5.2.3 Data Reduction and Analysis for the Hydraulic Bellows Test

From the final position of the bellows, calculate the volume of fuel in cubic millimeters that has exited the injector. Then calculate the observed tip leakage rate in cubic millimeters per minute by dividing by 0.5 minute.

5.5.2.4 Data Reporting for the Hydraulic Bellows Test

If there are no known test deviations, record the calculated leak rate in mm^3/min on the bottom-right of the data reporting sheet. This will be the SAE J1832 hydraulic tip leakage rate. If known test deviations exist, record the observed leak rate on the bottom-left of the sheet. The observed leak rate with deviations will be the measured leak rate, but it will not be the SAE J1832 calibrated bellows tip leakage rate.

5.5.3 Tip Leakage Measurement using the Flame Ionization Detector (FID) Method

5.5.3.1 Overview of the FID Tip Leakage Measurement Method

The recommended test technique for determining the tip leakage of a PFI injector when the leakage rate is below 1.0 mm^3/min is the FID method. A general measurement concept is as follows: the injector is mounted in a special test fixture and filled with a hydrocarbon test fluid. It is then pressurized using air or nitrogen gas. A known flow rate of nitrogen gas is then passed over the injector tip. The flow path around the injector tip is designed such that all leaking fuel is evaporated into the nitrogen stream. The hydrocarbon (HC) concentration of the flow stream is then measured with a FID analyzer that is downstream of the tip. The analyzer is calibrated prior to the test with a calibration gas (propane) spanning the appropriate measurement range. The sampling stream flow rate is maintained constant during the measurement. The FID measures the parts per million of hydrocarbons in the nitrogen stream, and this value is converted into the equivalent cubic millimeters per minute of fuel leakage. The requirements of the FID analyser used for the FID tip leakage test are:

- Analyzer type: Commercial FID analyzer.
- Repeatability: Within ±1% of the instrument full scale.
- Response time: Within 1.5 seconds.
- Zero drift: Within ±1% of the instrument full scale per 8 hours.
- Calibration drift: Within ±1% of the instrument full scale per 8 hours.
- Linearity: Within ±1% of the instrument full scale.

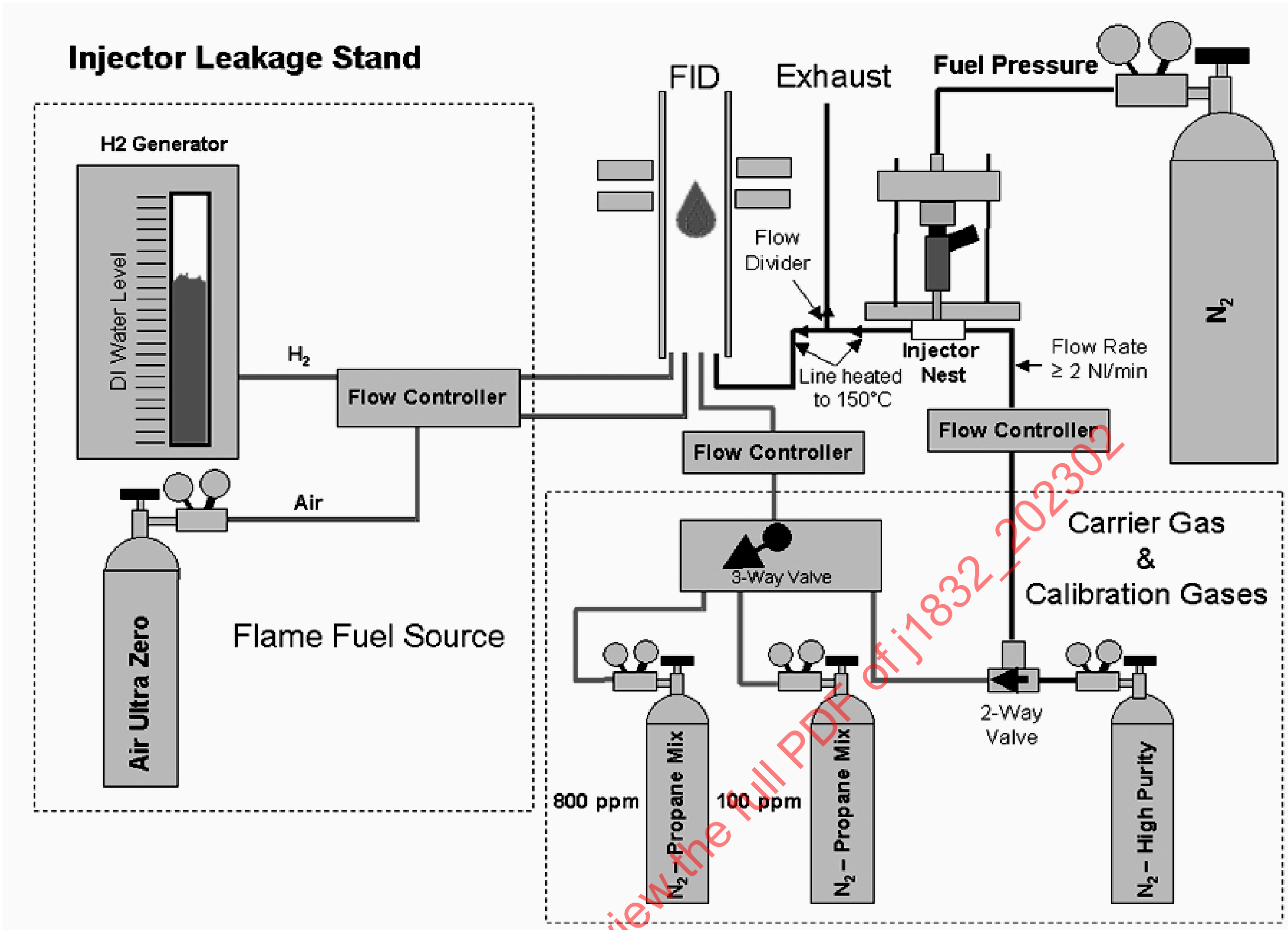


Figure 13 - Schematic diagram of FID fixture for tip leakage test

5.5.3.2 Procedure for the FID Tip Leakage Test

a. FID calibration: First, conduct a three-point calibration of the FID instrument. See Figure 13 for the schematic of the FID test stand. Note that the sample line from the injector to the FID must be heated to 150 °C. The flow lines within the FID must be heated as well. A minimum of 2 normal liters per minute (NL/min) of carrier gas (nitrogen) flow rate past the injector is required. It is recommended that for PFI tip leakage measurements, the FID analyzer should be calibrated with propane using the following three calibration gas ranges: 0 ppm, 1 to 300 ppm, and 300 to 2400 ppm. The propane concentrations within the test bottles should be 1/3 of the maximum value being calibrated. Those concentrations are noted in the steps that follow.

b. Calibration Step 1: Calibrate using 0 ppm (use pure nitrogen).

c. Calibration Step 2: Calibrate for the 1 to 300 ppm range using the calibration gas bottle containing 100 ppm propane in nitrogen.

d. Calibration Step 3: Calibrate for the 300 to 2400 ppm range using the calibration gas bottle containing 800 ppm propane in nitrogen.

e. A calibrated capillary tube may also be used to generate a specified, known leakage rate. This capillary, if used, is designated as the leak master.

f. Injector preparation: A minimum set of five new injectors of the same make and model from serial production are to be tested. Pre-condition each of these injectors according to Table 2. Discard the purged fluid that exits the injector, but leave the injector filled with test fluid.

g. Set the test conditions to comply with those recommended on the data reporting sheet. Note any deviations in the comments section of the data reporting sheet.

h. When removing the injector from the pre-conditioning and filling station, it is important that any fuel that is present on the external surfaces of the injector body or tip be completely removed using a stream of compressed air. This must be done prior to the installation into the FID measurement fixture. Any fuel left on the body or tip will lead to higher readings from the FID and may also saturate the FID and extinguish the flame. Conduct the test according to the list of standard test conditions that are listed in Table 3.

i. The injector is then mounted in an FID nest fixture, as depicted in Figure 14. In this fixture, pressurized nitrogen is applied to the injector fuel inlet as the designated test pressure to initiate the process of tip leakage. Install the injector in the FID nest fixture as illustrated and obtain a verification of zero leakage. The nest is designed to have the nitrogen gas flow around the tip of the injector such that all leaking fuel evaporates and is carried to the analyser in a vapor form. The tip of the injector protrudes into the nitrogen flow stream to aid in the evaporation of liquid fuel.

j. With the injector installed on the stand and filled with n-heptane as the test fluid, allow the nitrogen scavenging gas to flow. The injector solenoid should be non-energized (closed) without application of fuel pressure. Allow the FID reading to stabilize. The FID reading should ideally be zero (less than 1 ppm). If the indicated leakage is not less than 1 ppm, do not proceed with the test and do not apply fuel pressure because of the possible risk of saturating the FID detector.

k. The three possible causes for a non-zero reading are: (1) The sealing O-ring is permeating fuel. Install a new sealing O-ring or bake the fuel off the surfaces by placing the O-ring into an oven for a short period. (2) The injector exhibits a gross leak. To verify the magnitude of the leak, test with the alternate method (calibrated bellows) to determine if the injector indeed exhibits a gross leak. (3) The injector was not completely dry of exterior fuel when being inserted into the FID stand. In this case, allow the HC concentration to drop over time as the external fuel evaporates, or remove the injector and dry the external surfaces with compressed air or nitrogen.

l. Once a reading of less than 1 ppm is verified with no fuel pressure applied, pressurize the injector to P_{NORM} using nitrogen gas or air. Pressurize from the fuel inlet side. The pressure rise must occur quickly, ideally within 100 ms from start to P_{NORM}.

m. Let the FID measurement stabilize such that the reading from the FID does not vary by more than ±5%. Typically, this should take less than a few minutes. If the reading from the FID does not stabilize within 5 minutes, check to ensure that the carrier gas flow rate across the injector tip is staying constant within ±0.1 NL/min.

n. If the carrier gas flow rate is steady, record 20 seconds of data whether the FID reading is stable (within ±5%) or not. Record at a data rate of one per second (1 Hz).

o. Repeat the test for the remaining injectors in the set.

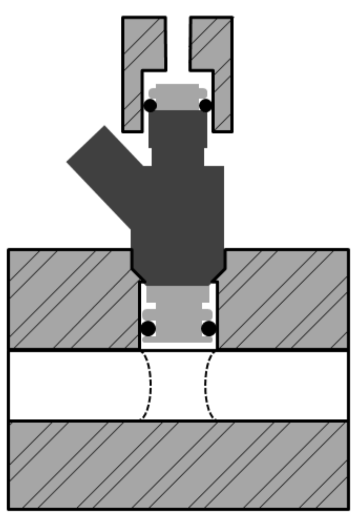


Figure 14 - Injector nest fixture for PFI FID tip leakage measurement

5.5.3.3 Data Reduction and Analysis for FID Tip Leakage

a. Determine the average of the 20 FID readings that were made at one per second.

b. Use the conversion Equation 8 to convert the readings to an equivalent volumetric flow rate of n-heptane. Using the FID ppm measurement, an equivalent n-heptane leak rate can be calculated

c. For HC analyzers that report in carbon parts per million, use Equation 8 to convert the carbon ppm reading to a volumetric flow rate of n-heptane representing the tip leakage flow. The resulting tip leakage flow rate, q_{LEAK}, is in mm^3/min of n-heptane.

$$q_{LEAK} = q_c * \frac{1000\ mL}{1\ L} * \frac{1\ mol}{22400\ mL} * \frac{x}{10^6}\ Carbon * \frac{3\ carbon}{1\ propane} * \frac{1\ nhept}{7\ carbon} * \frac{100.204\ g}{1\ mol} * \frac{1\ mL}{0.68376\ g} * \frac{1000\ \mu L}{1\ mL} \quad (Eq.\ 8)$$

where:

q_c = carrier gas flow rate in NL/min

c = concentration of carbon in ppm

q_{LEAK} = the leak rate in mm^3/min; note that this is the same as microliters per minute (1 mm^3 = 1 μL)

5.5.3.4 Data Reporting for Tip Leakage

Record the resultant leakage rate on the data reporting sheet. The units will be mm^3/min. If the readings were stable to within ±5%, and if there were no deviations in the other parameters on the data reporting sheet, record the result at the bottom right of the sheet. This will be the SAE J1832 FID tip leakage rate. If there were instabilities or any deviations in the standard test parameters, record the results at the bottom left and note any instabilities or deviations in the comments section. The observed leak rate with deviations will be the measured leak rate, but it will not be the SAE J1832 FID tip leakage rate.

Table 8 - SAE data reporting sheet for PFI fuel injector tip leakage measurements

SAE Data Reporting Sheet for PFI Fuel Injector Tip Leakage Measurements			
Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on Injector			
Injector manufacturer			
Injector description Static flow rate (at pressure) Inward/outward opening Normal pressure (P_{NORM})			
Injector part number			
Injector serial number			
Additional information			
Part 3: Test Conditions	**Specific Test Conditions**	**Standard Test Conditions**	
Test fluid		n-heptane	
Ambient temperature (°C)		21 ± 2	
Ambient pressure (kPaa)		95 to 102	
Fluid temperature (°C)		21 ± 2	
Fuel test pressure (kPa)		P_{NORM} ± 0.5%	
Test pressure tolerance		±0.5%	
Injector temperature (°C)		21 ± 2	
Data sampling rate		1 Hz	
Pressurization medium		Air or nitrogen	
Test method: check one	FID test (low leak)	Bellows test (high leak)	
Part 4: Specific Instrument Information and Test Parameters			
Additional info/comments, deviations, and instabilities			
Part 5: Test Results			
Recording of the average tip leakage rate		**For FID Test:** Average of the final 20 seconds of data **For Bellows Test:** Computed from a 30 second change in bellows position	
Calibrated Bellows: For non-stable data or for deviations in the standard test parameters, record the measured calibrated bellows leakage rate here in mm³/min: **FID Test:** For non-stable data or for deviations in the standard test parameters, record the measured FID leakage rate here in mm³/min:		**Calibrated Bellows:** There are no test deviations, therefore this is the SAE J1832 calibrated bellows tip leakage rate **FID Test:** There are no test deviations, therefore this is the SAE J1832 FID tip leakage rate	

5.6 Static and Dynamic Flow Tests

5.6.1 Overview of Static and Dynamic Flow Tests

The metered fuel flow delivered by the injector is the most important and influential of the performance parameters, thus the fuel flow calibrations are perhaps the most critical of all of the tests. Over the few decades since the introduction of port fuel injection, a significant number of fuel flow test parameters have been formulated, with specific test procedures developed to measure them. This includes such critical tests as those for the maximum flow capacity of an injector, the range of linearity of fuel delivery and the establishment of fuel-flow set points. This class of tests defines the fuel flow characteristics of an injector, and contributes significantly to defining the engine applications for which it may be suitable.

5.6.2 Overview of the Test Fluid Specified for Flow Testing

N-heptane is the preferred standard test fluid for the fuel flow tests in the SAE J1832 document. It is recognized that the use of n-heptane may not be possible with some flow test stands due to a number of factors, including a lack of design for explosion resistance or other fluid compatibility constraints. Some flow test stands are restricted to utilizing solvents or mineral spirits, and cannot be flowed with actual hydrocarbons as the test fluid. In spite of this, most of the industry now utilizes n-heptane as the flow test fluid of choice, and the majority of tests within SAE J1832 will specify this. In those cases where n-heptane cannot be utilized, another fluid may be used that is compatible with the local flow test equipment, and this can be specified as a test deviation on the data reporting sheet.

5.6.3 Static Flow and Dynamic Set Point Flow Measurement

5.6.3.1 Overview of Static Flow and Dynamic Set Point Mass Flow

The static flow, Q_s, and the dynamic set point flow, Q_{sp}, are two important injector flow parameters that indicate the maximum flow capacity and the flow at a specified set-point pulse width. These two parameters are key factors in determining the suitability of a specific injector design to a particular engine application. The static flow is normally reported in grams per second, whereas the dynamic set point mass flow is reported in milligrams per injection, which is often shortened to milligrams per pulse.

5.6.3.2 Procedure for the Static Flow Measurement Test

This test procedure is for the characterization of an individual injector. If both the dynamic set point flow and the static flow are to be run concurrently, then the dynamic set point flow should preferentially be run first. This will reduce coil heating and its effect on coil resistance. It will also eliminate the need to perform two separate pre-conditioning cycled.

a. A minimum set of five new injectors of the same make and model from serial production are to be tested. Pre-condition each injector to be tested according to Table 2.

b. Use n-heptane at 21 °C as the test fluid, with a fuel pressure of P_{NORM}. If a test fluid other than n-heptane is utilized, or a fuel pressure other than P_{NORM} is used, this should be noted and later recorded on Page 1 of the data reporting sheet as a test deviation or deviations.

c. Energize the injector to a continuously open state. This will yield a continuous steady flow of the test fuel, without pulsations.

d. Measure the delivered fuel mass flow rate over a test period of 30 seconds.

e. Repeat step (d) twice more for a total of three times for the same injector and record the three static flow rates that were obtained. The later reduction of this data will yield the static flow rate, Q_s, of the injector.

f. Repeat steps (a) through (e) for the next injector if additional units of the same injector model are to be tested.

5.6.3.3 Data Reduction and Analysis for Static Flow Test

Average the three independent static flow rates that were measured for the test injector. Do this for each injector if more than one injector is tested. First average the three static flow rates for each tested injector to obtain the individual static flow rates. If more than one injector is tested, average all of the individual flow values (one per tested injector) to obtain the single, final static flow rate to be reported. The units of the reported Q_s are to be in grams per second.

5.6.3.4 Data Reporting for Static Flow Test

Record the serial number of the tested injector on Page 1 of the data reporting sheet. If more than one injector of the particular model is tested, the serial number of each tested injector shall be recorded on Page 1 of the data reporting sheet. Also, record the average static flow rate that was obtained from the three static flow rate measurements on Page 2 of the data reporting sheet. The units are to be in grams per second (g/s). If more than one injector of the particular injector model was tested, report the individual static flow values for each one in the indicated boxes at the top of Page 2 of the data reporting sheet. If n-heptane at P_{NORM} were both employed for the test, and there are no other test deviations, this will be the SAE J1832 static flow for that particular test injector and is to be entered in that box on Page 2 of the data reporting sheet. If more than one injector is tested, report the average of all of the individual static flow rate values (one per tested injector) that was computed in the data reduction and analysis subsection. If there are no test deviations, this will be the reported SAE J1832 static flow for those tested injectors and should be entered into that box on Page 2 of the data reporting sheet.

5.6.3.5 Procedure for Dynamic Set Point Mass Flow Measurement

This test procedure is for the characterization of an individual injector.

a. A minimum set of five new injectors of the same make and model from serial production are to be tested. Pre-condition each injector to be tested according to Table 2.

b. Use n-heptane at 21 °C as the test fluid with a fuel pressure of P_{NORM}. If a test fluid other than n-heptane is used, or if a different fuel pressure is used, this should be noted and later recorded on Page 1 of the data reporting sheet as a test deviation.

c. Operate the test injector using a 2.5 ms pulse width and a period (P) of 10.0 ms (100 Hz). Consult the injector manufacturer to determine if an alternative dynamic set point pulse width value should be used. The default SAE dynamic set point pulse width is 2.5 ms. The use of a set point pulse width other than 2.5 ms is not considered a test deviation if clearly noted in the specific test conditions section of the data reporting sheet.

d. Measure the delivered fuel mass flow rate over a test period of 20 seconds (2000 pulses).

e. Repeat step (d) twice more for a total of three times for the same injector and record the three dynamic set point flow delivery values that were obtained. The later reduction of this data will yield the dynamic set point flow rate, Q_{sp}, of the test injector.

f. Repeat steps (a) through (e) for the next injector if additional units of the same injector model are to be tested.

5.6.3.6 Data Reduction and Analysis for Dynamic Set Point Mass Flow Measurement

Convert the mass of fuel that was delivered for each of the three runs of 2000 injections into a mass of fuel delivered per injection event. This is achieved by dividing the total mass of fuel delivered in 20 seconds by 2000 injection events. With each injection event considered as a “pulse,” average the three independent values of milligrams per pulse for each tested injector. This average yields the individual value of the dynamic set point flow for the injector that was tested. Do this for each injector if more than one injector is tested. Also, if more than one injector is tested, average all of the individual set point flow values (one per tested injector) to obtain the single, final set point value to be reported.

5.6.3.7 Data Reporting for Dynamic Set Point Mass Flow Measurement

Record the serial number of the tested injector on Page 1 of the data reporting sheet. If more than one injector of the particular model is tested, the serial number of each tested injector shall be recorded on Page 1 of the data reporting sheet. Also, record the average set point flow rate, Q_{sp}, that was obtained from the three set point flow rate measurements on Page 2 of the data reporting sheet. The units are to be in milligrams per pulse (mg/pulse). If more than one injector of the particular injector model was tested, report the individual set point mass flow values for each one in the indicated boxes at the top of Page 2 of the data reporting sheet. If both n-heptane and P_{NORM} were employed for the test, and there are no other test deviations, this will be the SAE J1832 set point flow for that particular test injector and is to be entered in that box on Page 2 of the data reporting sheet. If more than one injector is tested, report the average of all of the individual set point flow rate values (one per tested injector) that was computed in the data reduction and analysis subsection. If there are no test deviations, this will be the reported SAE J1832 set point flow for those tested injectors and should be entered into that box on Page 2 of the data reporting sheet. If a set-point pulse width other than 2.5 ms (or period other than 10 ms) is used for the test, this is not to be considered a deviation if the actual pulse width utilized is clearly noted in the specific test conditions section of Page 1 of the data reporting sheet.

5.7 Operating Flow Range Tests

5.7.1 Overview of PFI Injector Operating Flow Ranges

Ideally, the flow from a particular injector should be linear and directly proportional to the pulse width over the full flow range of the injector. This is not the actual case, however, as significant deviations from linearity normally occur at both the high-flow and low-flow extremities of the PFI flow curve. Ideally, a vehicle calibration utilizing a linear flow curve that also has an extensive working flow range is desired. Typically, a commanded fuel quantity will be more precise and repeatable when operating within the linear portion of the flow curve. It should be noted that some newer engine control modules do have the ability to model non-linear flow curves, usually in the low-pulse-width regions. For these applications, the linearity of the flow curve is not quite as important, as long as the deviation from linearity is repeatable and can be described mathematically. It should be noted that in many applications it has been determined experimentally that the repeatability is also often degraded along with the linearity. Therefore, in engine calibration work it is important to understand the range of linearity of the injector flow curve, the variation of the flow in the linear region, the range and predictability of the non-linear flow, the variation within the non-linear flow region, and the variation that is inherent in a large population of similar production injectors. The knowledge of this information will permit the prediction of the fuel control error over the complete operating range of the injector.

The usable operating flow range of a PFI injector, or a population of PFI injectors, is normally represented by two main parameters, the linear flow range (LFR) and the working flow range (WFR). Both of these ranges represent a dimensionless ratio of a particular maximum operational flow rate in milligrams of fuel per injection divided by the corresponding minimum operational flow rate in the same units. The LFR is a performance parameter associated with a single injector, whereas the WFR is associated with a population of similar injectors of the same make and model. Thus, the WFR inherently includes the effects of part-to-part variations in fuel flow characteristics, whereas the LFR does not. The LFR defines a range of fuel delivery that is linear within the bandwidth of ±5.0%, whereas the WFR quantifies a fuel flow range within which any single injector or subset of injectors from the total population of similar injectors will deliver a metered flow that will be acceptably accurate. Regarding the LFR, a more precise terminology than “linear range” would be the “near-linear range,” as the linear regression line through the flow data does not necessarily pass through each of the individual flow points. The two key parameters of LFR and WFR, as well as the associated key parameter of WF_{min} are obtained by performing statistical operations on the flow test data that is obtained from the flow testing of either a single injector or a fairly large population of similar test injectors of the same make and model. Many of the testing procedures are identical for both LFR and WFR evaluation, although the details of data reduction differ somewhat.

5.7.2 Test Procedure for Measuring the Linear Flow Range

The test to determine the linear flow range of an injector is to be conducted using an injector of the model of interest. Additional injector units may be optionally tested.

a. A minimum set of five injectors of the same make and model from serial production are to be tested. The injector being tested is first to be pre-conditioned according to the procedures and test conditions in Table 2.

b. The injector for LFR determination is to be flow-tested in a flow measurement test stand according to the standard test conditions specified in Part 3 of the corresponding data reporting sheet. The flow rate of the standard test fluid is to be measured at a series of mid-range test points, all using an injection period (P) of 10.0 ms. These mid-range pulse width values are:

   Mid-range IPW values: 2.0, 2.2, 2.5, 3.0. 4.0, 5.0, 6.0. 7.0, 7.5, 8.0, 8.5, and 9.0 ms.

   In addition to these 12 mid-range test points, several high-flow and low-flow IPW values shall also be flow tested. These are fully described in the three subsequent steps.

c. To permit an accurate determination of the LFR following the testing, it is important to have enhanced pulse-width resolution in the areas of injector flow non-linearity, which normally occurs in the regions of very-low flow, but also occurs for some injector models at very-high flow. Therefore, it is required that the injector flow be measured in finer increments of IPW in both of these regions. At the high-flow end of the curve the flow should be measured for a range of IPW values that start at the 10.0 ms value of the period, minus 1.0 ms, and should extend to an IPW value that is equal to the 10.0 ms period. This fuel flow rate at this last high-flow point will be the static flow rate of the injector, Q_s. The specific IPW test points for each region are listed in steps (d) and (e), respectively. This adds ten flow test points for the high-flow region and as many as 14 to 15 for the low-flow region.

d. For the high-flow test points, measure the flow rate using a period (P) of 10.0 ms and IPW values comprised of closely spaced test points that are very near the static flow capability of the injector. As noted in step (c), the final test point at a Period of 10.0 ms will yield the static flow rate. The additional high-flow IPW values to be tested are:

   High-flow IPW values: 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7, 9.8, 9.9, and 10.0 ms.

e. The low-flow region of the flow curve is normally characterized by flow testing at range of IPW values starting just slightly higher than the injector opening time (OT) and extending to an IPW value of 1.9 ms. For the low-flow test points, start with an IPW value that is the measured injector opening time, rounded up to the next higher 0.10 ms. The procedure for measuring the OT is described in Subsection 5.3 of this document. Subsequent to measuring the initial low-flow test point, measure the flow using IPW increments that are obtained by adding 0.10 ms to the previous IPW. Repeat until an IPW of 1.9 ms is attained. For example, for a measured OT of 0.56 ms, the low-flow test points would be:

   Low-flow IPW values: 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8 and 1.9 ms.

f. Repeat steps (a) through (e) for the next injector if more than one similar injector of the same make and model is being tested for an LFR measurement.

5.7.3 Data Reduction and Analysis for the Linear Flow Range

As discussed in the overview subsection, the linear flow range (LFR) for a single injector is a key performance parameter that is used to compare the linear performance among injectors of different design or manufacture. The LFR is the ratio of the maximum operational flow rate within the linear range to the minimum operational flow rate within the linear range for a single injector. Within this range there is a linear relationship between the commanded pulse width and the delivered fuel flow. As discussed in the overview subsection, a more precise terminology than "linear range" would be the "near linear range." Within the limits of the LFR range, there is, in fact, a near-linear relationship between the pulse width and the resultant flow, as there is a 5% tolerance band on either side of the true linear curve. Thus it is more accurate to state that the delivered flow is linear to within a maximum ±5% deviation when operating within the linear flow range.

5.7.3.1 Regression Analysis

All of the flow data obtained is to be plotted as the measured dynamic flow rate, Q_d, versus the commanded injection pulse width (IPW). In order to quantify the deviation of the flow from linearity, a simple least-squares, linear regression analysis is to be performed on five specific mid-range flow points, which are at IPW values of 3.0, 4.0, 5.0, 6.0, and 7.0 ms. Q_d and IPW are, respectively, the dependent and independent variables for the regression analysis. This linear regression analysis will generate a best-fit linear line that passes among the five measured points. The linear regression line will normally pass below the origin of the plot for most PFI injectors, generating a slope for the line, as well as two offsets that are denoted as the “time-offset” and the “flow offset.” On the relatively unlikely event that the regression line passes above the origin, the time offset will be negative. As is illustrated in Figure 15, the determination of the values of the flow offset and the slope define the linear flow curve. Although the simple schematic drawing shows the resultant line passing through the five test points, in reality it will likely not pass through any of the five points exactly, as it is a “best-fit” line. Therefore, at each value of IPW there are actually two different flow rates; the first is the actual measured flow rate, Q_d, and the second is the flow rate computed at that same IPW by using the line that was generated by the regression analysis, Q_{dc}. The actual flow data will generally track the straight line of the linear flow curve quite well over the mid-flow portion of the data, but will begin to deviate at both the low-flow and high-flow ends of the flow curve. The deviation at the low-flow end will almost certainly exceed one of the imposed ±5.0% band limits as the pulse width becomes very small, and it will most likely be the -5% band line that is crossed. The deviation at the high-flow end may or may not exceed one of the imposed ±5.0% band limits, depending upon the particular injector design.

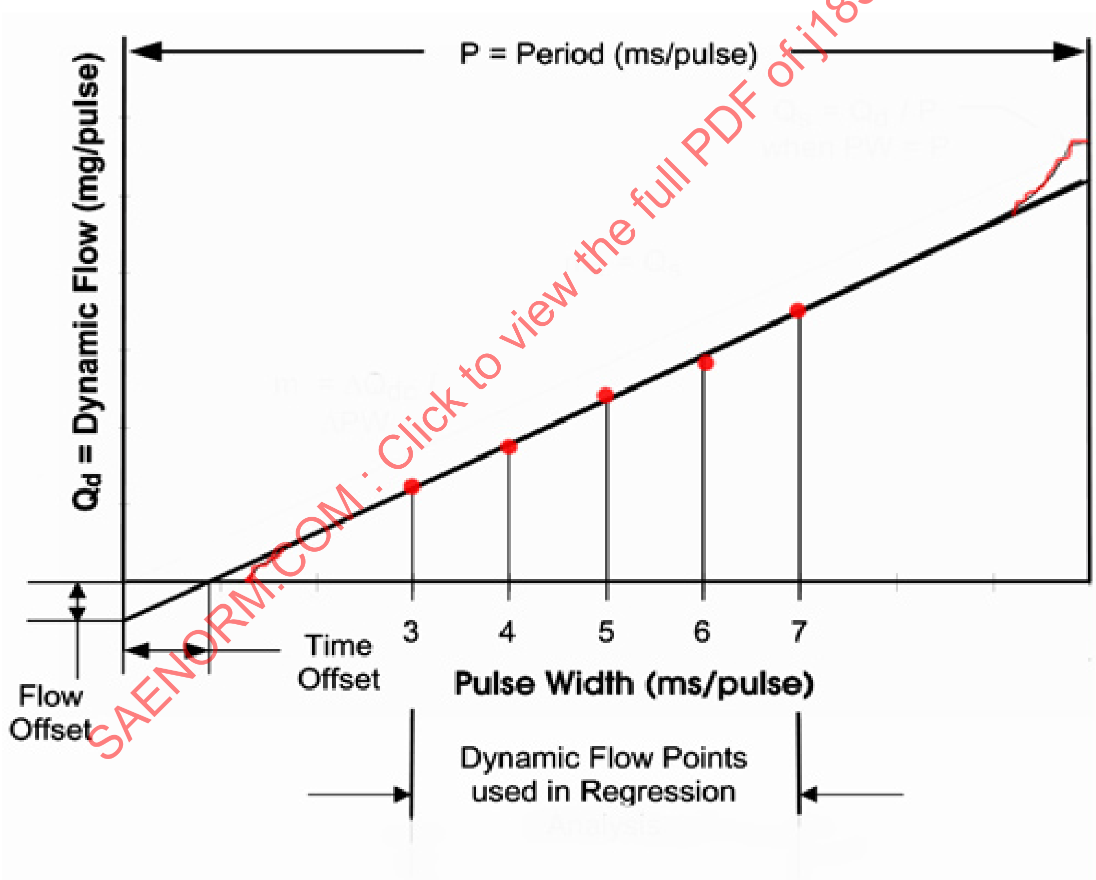


Figure 15 - Illustration of regression used to obtain the linear flow curve

The slope (m) of the resultant linear regression curve is the change in Q_{dc} per unit of pulse width based on the calculated linear regression flow curve (mg/ms). The time-offset of the linear curve is the displacement of the calculated linear regression flow curve from the origin along the abscissa, or pulse width axis. The flow-offset is the displacement of the calculated linear regression flow curve from the origin along the ordinate, or flow axis. Both offsets are clearly illustrated in Figure 15. The values of the slope, flow offset and time offset will be obtained from the regression analysis. It should be noted that the actual flow data are denoted by Q_d, whereas the flows computed from the linear regression line are designated as Q_{dc}. The resultant best-fit line for the linear flow rate may be expressed in terms of the flow offset as shown in Equation 9, or may alternatively be expressed in terms of the time offset as shown in Equation 10.

$$\text{Linear flow rate} = Q_{dc} = (\text{Slope} * \text{IPW}) - \text{Flow offset} \quad \text{(Eq. 9)}$$

$$\text{Linear flow rate} = Q_{dc} = \text{Slope} * (\text{IPW} - \text{Time offset}) \quad \text{(Eq. 10)}$$

5.7.3.2 Generation of Percentage Difference from Linearity

Once the slope and offsets of the best-fit line have been determined from the regression analysis, the linear flow rate values for all of the measurement test point values of IPW are to be calculated using either Equations 9 or 10. Following that, the percentage differences between the actual measured flow rate, Q_d, and the computed linear flow rate, Q_{dc}, are to be computed individually for all of the measured pulse width test values. The percentage deviation from linearity (LD) is determined from Equation 11 as the percent difference between the measured dynamic flow, Q_d, and the calculated linear dynamic flow, Q_{dc}, that is determined using the linear curve, divided by the calculated dynamic flow, and then multiplied by 100. It should be noted that each of the measured test points will have a different percentage deviation. When plotted, this will yield a curve of percentage deviation of the actual delivered flow from the idealized, linear flow.

$$\text{LD}\ (\%) = 100 * (Q_d - Q_{dc})/Q_{dc} \quad \text{(Eq. 11)}$$

An illustration of this percentage deviation curve is provided in the upper panel of Figure 16. It is shown as the curve with red solid circles as a plotting symbol. It should be noted that Figure 15 is a dual-purpose graph that is used to illustrate both the LFR and WFR calculations and nomenclature. Therefore, the highest curve with the solid black circles for plotting symbols in the upper portion of Figure 16 should be ignored for now, as that curve is part of the WFR data reduction which will be addressed in the subsections on WFR. For the representative lower curve in the upper portion of Figure 16, it may be noted that the percentage deviation from linearity is near zero for most PFI injectors over a large portion of the pulse width range, but normally deviates significantly from zero at very-small and very-large pulse widths. It may also be noted that, for most PFI injectors, at some small pulse width and low flow the actual flow will be more than 5.0% lower than the indicated linear flow. At large pulse widths and large flow, the actual flow will normally be greater than the indicated linear flow, but may or may not exceed the indicated linear flow by +5.0% or more. Injector operation within the limits of -5% and +5% of true linear flow is defined as near-linear operation. The values of pulse width where the deviation from linearity attains -5% or +5% will determine the limits of near-linear operation. Further, the ratio of these two limiting linear Q_{dc} flow rates at these two pulse-width values defines the numerical value of the flow range of near-linear operation for the test injector.

In conducting the remainder of the LFR data reduction and analysis it is helpful to note that the pulse-width value for which the percentage flow deviation crosses one of the ±5.0% band lines (normally the -5.0% band line) determines the minimum pulse-width at which the injector may be operated and still deliver fuel in the near-linear range. Similarly, the pulse width value for which the percentage flow deviation crosses one of the ±5.0% band lines (normally the +5.0% band line if it crosses at all) determines the maximum pulse width at which the injector may be operated and still deliver fuel in the near-linear range. If the high-flow deviation never crosses either of the band lines, the maximum pulse width is to be assigned as 10.0 ms, which yields the static flow for a test period of 10.0 ms. These two pulse-width values define the operating pulse-width range of the injector. The two flow rates that are computed from the linear regression line for these two limiting pulse-width values define the two limits of the near-linear flow range.

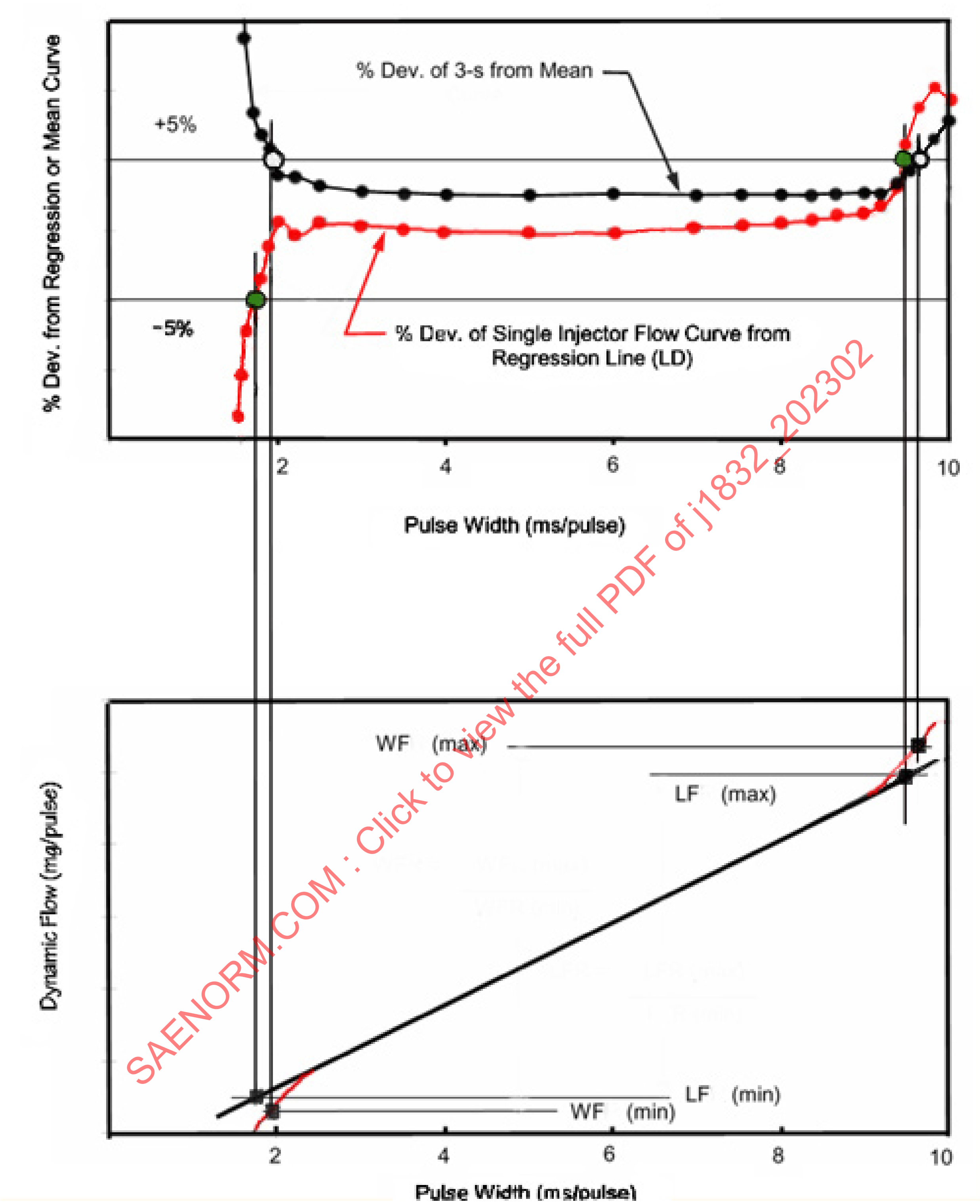


Figure 16 - Illustration of the calculation of LFR and WFR

5.7.3.3 Determination of the Limits of Linearity

From the linear-deviation plot, first examine the low-flow portion of the curve, identify the smallest test-point pulse width where the percentage deviation is still within the ±5.0% band lines. For most PFI injectors, this is normally just above the -5% band line. Then identify the next smaller test-point pulse width for which the percentage flow deviation first drops below -5.0%. These are the two low-flow IPW values to be used as the end points for a simple linear interpolation. The initial interpolation is to determine the precise low-flow IPW value at which the percentage flow deviation is exactly -5.0%. Use the two known test-point pulse-width values and the corresponding values of the percentage deviation from linearity at those two pulse-width values. Use a straight-line interpolation between these two test points to determine the lower-limit pulse width for linear flow, which is denoted as IPW_{min}. Once the value of IPW_{min} has been determined, the expected minimum linear fuel flow rate may be computed by inserting that particular IPW_{min} value into either Equations 9 or 10 using the values for slope and offsets that were determined earlier. This value of the linear flow will be designated as LF_{min}, which will be the lowest flow that the injector can deliver within the linear range.

Next, inspect the high-flow area of the plot of the percentage deviation from linearity and determine if either of the ±5% deviation band lines are exceeded at any of the high-flow test values of IPW. For most PFI injectors, this would be the +5.0% band line, if at all. If so, identify the largest pulse width for which the percentage deviation is still less than +5.0%. Then identify the next larger pulse width where the deviation first exceeds +5%. These are the two large-flow IPW values that are to be used as the end values for a linear interpolation. This interpolation is to determine the precise high-flow IPW value at which the percentage flow deviation is exactly +5%. If the high-flow percentage deviation DOES indeed cross one of the ±5.0% band lines, then perform a simple, straight-line linear interpolation using the two known IPW test points discussed above and the corresponding values of the percentage flow deviation from linearity at those two IPW values. The object of thos interpolation is to determine the pulse width that yields a percentage flow deviation of exactly +5.0%. This will be the IPW_{max} for linear flow. Once the value of IPW_{max} has been determined, the expected maximum linear fuel flow rate may be computed by inserting the IPW_{max} value into either Equations 9 or 10 using the values for slope and offsets that were determined earlier. This computed value of the linear flow will be LF_{max}, which will be the highest flow that the injector can deliver within the linear range. Note that if the percentage flow deviation does NOT cross either of the 5% band lines for any of the high-flow points, no interpolation of the high-flow data is to be performed. Instead, the value of IPW_{max} is to be assigned as 10.0 ms and the value of LF_{max} is to be assigned as the flow value that is computed by inserting 10.0 ms for the pulse width in Equation 10.

Once the values for LF_{max} and LF_{min} have been determined for an individual injector, the LFR value may be computed. Referring to Figure 16, the LFR is calculated from Equation 12 as the maximum linearized flow point, LF_{max}, divided by the minimum linearized flow point, LF_{min}. Note that these key points are denoted as LF(max) and LF(min) in the bottom portion of Figure 16.

$$\mathrm{LFR} = \mathrm{LF}_{\mathrm{max}}/\mathrm{LF}_{\mathrm{min}} \quad \text{(Eq. 12)}$$

For the case where multiple injectors are tested to ascertain the LFR, it should be noted that each individual injector will require a full, independent LFR determination, complete with its own flow curve, regression analysis, determination of the offsets and slope, the generation of the percentage deviation curve and the determination of the individual values of LF_{max} and LF_{min}. Thus, if five injectors are tested, there will be five separate regression analyses required and five individual values of LFR computed using Equation 12. Each individual LFR value is to be computed as described in this subsection, with each of the individual LFR value reported in the proper boxes at the top of Page 2 of the data reporting sheet. These individual LFR values for all of the tested injectors should then be averaged, as one number is desired that represents all of the tested injectors.

5.7.4 Data Reporting for the Linear Flow Range

As part of the LFR determination, the curve of fuel mass flow rate versus pulse width that is illustrated in the upper portion of Figure 16 is to be generated and attached to the data reporting sheet. If more than one injector is tested, the curve of fuel mass flow versus pulse width that is attached should be for one representative injector. The other curves of fuel mass flow rate versus pulse width that were generated do not have to be attached. Similarly, the computed slope, flow offset, and time (pulse-width) offset are to be recorded on the data reporting sheet for the single, representative injector, along with the serial number of the particular injector for which the data were generated. However, even though all of the detailed parameters associated with LFR determination have to be determined for each test injector, these values (except for the individual LFR value) do not have to be reported, just those of the representative injector. The percentage flow deviation curve for the representative test injector should have the pulse widths where the flow deviation is precisely +5.0% and -5.0% clearly indicated and separately recorded on Page 2 of the datasheet. The values of LF_{max} and LF_{min} are also to be reported on Page 2 of the data reporting sheet for the representative injector, along with the single, average value of LFR. If there is no high-flow test point for which the percentage flow deviation crosses either of the ±5.0% band lines, IPW_{max} is to be reported at 10.0 ms and LF_{max} is to be computed and reported using that value of IPW_{max} in Equation 10. This fact should be noted in the comments section of the data reporting sheet, although it is not to be considered as a test deviation. If there are no test deviations, the average of all of the individual LFR values is to be recorded in the proper box on Page 2 of the data reporting sheet as the SAE J1832 LFR value.

5.7.5 Overview of the Working Flow Range and the Minimum Working Flow

In order to perform the calibration of a fuel system on an engine, certain information on the statistical variation of flow among injectors of a given type must be known. The working flow range (WFR) is a dimensionless performance parameter that numerically quantifies the usable flow range of any subset of a population of new injectors of the same make and model. In this flow range there is a specified confidence level that any subset of injectors from the total population of all such injectors will deliver a fuel mass flow that is within a specified acceptable level of deviation. That acceptable level of deviation is normally specified as ±5.0% for PFI injectors throughout the automotive industry. The ±5.0% value is the limit of a statistical flow deviation parameter that is computed at each pulse width from the measured mean flow and the standard deviation of that flow. Thus the WFR may be thought of as a range of flow rates where the standard deviation of that flow is maintained within acceptable limits. This is particularly important at small pulse widths where very low flow rates are to be delivered. At very low flow rates, nearly all solenoid-energized PFI injectors exhibit not only a loss of linearity, but also a significant increase in the standard deviation of the flow delivered by a population of injectors.

For a sample population of 24 new injectors of the same make and model, the specification of 3.0 standard deviations sets a 99.7% statistical confidence level that the flow delivered at any flow value within the WFR range will be within ±5.0% of the mean flow of the entire population. If a larger number of injectors than 24 are tested, the confidence level will increase. Inherent in this statistical validity is the assumption that a normal distribution of production parts exists. Therefore, the interpretation of the final computed WFR value should take into account the various criteria that were used to select the test parts, such as serial production, various build dates, different build sites, or different tooling.

The WFR is determined by first computing the maximum working flow, WF_{max}, and the minimum working flow, WF_{min}, from the experimental flow data and the specified ±5.0% acceptability limit. The WFR value is determined by dividing the WF_{max} value by the WF_{min} value. It is important to note that the WF_{min} value is an important parameter in its own right, as it represents the lowest flow rate that can be reliably calibrated for use in the application. It is generally accepted that WF_{min} has more significance than WF_{max}, as the standard deviation of the delivered flow will increase markedly as the delivered flow is reduced to very small values, but may not increase significantly at very high flows near the static flow value. If there is no WFmax value for which the ±5.0% limit is exceeded, then the WF_{max} value is to be taken as the arithmetic average of the static flows of the 24 or more sample injectors that were tested.

5.7.6 Test Procedure for Measuring the Working Flow Range

The test to determine WFR is to be conducted using a set of at least 24 new injectors of a similar make and model. Normally these injectors are from serial production. More injectors than 24 can be used for the test set if desired. If criteria other than serial production are used to select the injectors in the set, the criteria should be indicated on the data reporting sheet.

a. All of the 24 or more injectors being tested are first to be pre-conditioned according to the procedures and test conditions in Table 2.

b. Each injector in the test set is to be flow-tested in a flow measurement test stand according to the standard test conditions specified in part 3 of the data reporting sheet. The flow rate of the standard test fluid is to be measured at a series of mid-range test points, all using an injection period (P) of 10.0 ms. The mid-range pulse width values are:

   Mid-range IPW values: 2.0, 2.2, 2.5, 3.0. 4.0, 5.0, 6.0. 7.0, 7.5, 8.0, 8.5, and 9.0 ms.

   In addition to these twelve mid-range test points, a number of high-flow and low-flow IPW values shall also be flow tested are fully described in the three subsequent steps.

c. To permit an accurate determination of the WFR following the testing, it is important to have enhanced pulse-width resolution in the areas of injector flow non-linearity, which normally occurs in the regions of very low and very high flow. Therefore, it is required that the injector flow be measured in finer increments of IPW in both of these regions. At the high-flow end of the curve the flow should be measured for a range of IPW values that start at 9.1 ms, and then continue upward on 0.1 ms increments until an IPW of 10.0 ms is tested. The fuel flow rate at this point will be the static flow rate of the injector. The specific IPW test points for each region are listed in steps (d) and (e), respectively. This adds ten flow test points for the high-flow region. The IPW values to be tested are:

   High-flow IPW values: 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7, 9.8, 9.9, and 10.0 ms.

d. The low-flow region of the flow curve is normally specified by a range of IPW values starting just slightly higher than the injector opening time (OT) and extending to an IPW value of 1.9 ms. For the low-flow test points, start with an IPW value that is the measured injector opening time, rounded up to the next higher 0.10 ms. Following that, measure the flow using IPW increments that are obtained by adding 0.10 ms to the previous IPW. Repeat until an IPW of 1.9 ms is attained. For example, for an OT of 0.56 ms, the low-flow test points would be:

   Low-flow IPW values: 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, and 1.9 ms.

e. Repeat steps (b) through (d) for the next injector in the WFR test set. Continue until all injectors in the WFR test set have been flow tested.

5.7.7 Data Reduction and Analysis for the Working Flow Range

As discussed in the WFR Overview Subsection, the Working Flow Range (WFR) and WF_{min} are key parameters that quantify the limits of acceptable fuel delivery for a population of new injectors of the same make and model. The WFR is based on the measurement of a minimum sample of 24 injectors that is statistically intended as a representative sample of the total population of all manufactured injectors of that type and model. Inherent in this test is the specification in advance of a number of defined limits that determine both the detailed test procedure and the resultant meaning of the test results. For this WFR test, the combination of a minimum of 24 test samples, a limiting mean flow deviation limit of 5.0% and the specification of 3.0 standard deviations from the mean flow data at each value of IPW serve to statistically guarantee that the results of the test will reliably represent the total population of injectors with a confidence level of 99.7%.

The WFR defines the range of flow values that may be delivered by any manufactured injector of that type without exceeding the limiting flow deviations that were specified for the WFR test. The low-flow limit of WF_{min} and the high-flow limit of WF_{max} that were determined from the test and used to compute the WFR also define the lowest flow rate and the highest flow rate (for the 10 ms IPW that was tested) that can be reliably delivered by any subset of the entire population of these injectors. Thus, the two IPW values that correspond to WF_{min} and WF_{max} define the lowest and highest pulse widths that can be employed in the control system for that application. Unlike the LFR, the WFR is not based upon a linear regression curve, and therefore does not guarantee a linear relationship between the commanded pulse width and the delivered fuel flow of a group of injectors from a population. Instead, it is based upon a specified band that represents a limiting acceptable deviation in the mean flow rate delivered by any injector in that particular population.

5.7.7.1 Generation of Percentage Deviation Curve

At each of the 35+ test pulse widths (IPW), the local mean value of the measured flow and the value of the standard deviation (sigma) in flow are to be computed and tabulated. Next, for each tested value of IPW, the percentage deviation of the local 3.0*sigma value relative to the local measured mean flow rate is to be computed using 100*(3.0*sigma)/(local mean flow). These percentage deviations are then to be tabulated and plotted versus the test pulse width.

5.7.7.2 Determination of the Low and High Limits of the Working Flow Range

a. First inspect the low-flow area of the plot of percentage deviation versus pulse-width. Starting at an IPW of 5.0 ms and inspecting increasingly smaller pulse widths, identify the smallest test pulse width where the three-sigma percentage deviation is still within the ±5.0% band limits of the flow deviation. Then identify the next smaller test pulse width for which the deviation first exceeds one of these band limits. These are the two sets of low-flow test values (two IPW values, two corresponding flow deviation values and two corresponding mean flow rate values) that are to be used in two linear interpolations. The first interpolation is to determine the minimum pulse width of the WFR, which is IPW_{min}, and the second interpolation is to determine the minimum flow rate of the range, WF_{min}, that occurs at a pulse width of IPW_{min}. The first linear interpolation establishes the low-flow IPW value for which the percentage deviation is precisely 5.0%. This pulse width is to be designated as IPW_{min} for the working flow range. The second linear interpolation is to determine the fuel flow that is delivered at that pulse width of IPW_{min}. This will be designated as WF_{min}.

b. Perform the first linear interpolation for the low-flow parameter of IPW_{min}. At each of the two low-flow test pulse widths identified in step (a), linearly interpolate using as the end points the two percentage flow deviation values that are associated with the two low-flow pulse widths to compute the pulse width at which the flow deviation would be precisely 5.0%. This is IPW_{min}. Then perform a second linear interpolation using as the end points the two low-flow pulse widths and the two associated mean flow rates. Using the IPW_{min} value from the first interpolation as a target value, use the second interpolation to determine the expected mean flow rate that would be delivered at a pulse width of IPW_{min}. That mean flow rate will be designated as WF_{min}.

c. Repeat steps (a) and (b) except that the high-flow range will be examined. Start at a pulse width of 5.0 ms and examine increasingly larger pulse widths for the associated percentage flow deviation. The 5.0% band line may or may not be exceeded, depending upon the design of the particular injector. If it is not exceeded in the high-flow region, then skip to step (e). If the 5.0% flow deviation limit is exceeded, then two high-flow pulse widths are to be identified. The two pulse widths of interest in the high-flow region will be the largest IPW for which the deviation is still within the 5% band limits, and the next larger pulse width, which will have a flow deviation that lies outside of the band limits. The parameters being determined by the two linear regressions for the high-flow region will be IPW_{max} and WF_{max}.

d. If the band limits of ±5% were exceeded in the high-flow region, and IPW_{max} and WF_{max} were computed by interpolation in step (c), then skip to step (f).

e. If there is no high-flow IPW test point for which the 5.0% deviation line is exceeded, then the assigned value of WF_{max} is the arithmetic average of the measured static flow rates of the 24 or more injectors that were tested. In this operation the units of static flow are to be converted from g/s to milligrams of fuel delivered in each 10 ms period. Use this value of WF_{max} in computing WFR and for entry on the data reporting sheet. The assigned value of IPW_{max} for this case is to be 10.0 ms.

f. Again referring back to Figure 16, the WFR for a population of injectors is to be determined using Equation 13. In this equation, WFR is defined to be the delivered fuel rate at the maximum working flow point, WF_{max}, divided by the delivered fuel rate at the minimum working flow point, WF_{min}. For flow rates between these two values, all injectors in the population will deliver metered fuel rates that vary less than the 5.0% limit of the 3.0-sigma standard deviation. Note that WF_{max} and WF_{min} are also denoted as WF(max) and WF(min) in the bottom portion of Figure 16.

$$\mathrm{WFR} = \mathrm{WF_{max}}/\mathrm{WF_{min}} \qquad \text{(Eq. 13)}$$

The WFR value may also have interpretive value for prototype parts; however, it must be realized that prototype assembly may not be representative of the level of variation that may exist in mass production. If the distribution of the sample is not normal, or if a sample of less than 24 parts is used, the statistical confidence limit would be less than 99.7%, perhaps significantly less. Because of the number of possibilities for non-normal distributions and using less than 24 test injectors, the equations to be used are not provided in this document. Instead, it is suggested that one of many commercially available statistical packages be used to evaluate the WFR results for such cases. It is also noted that this would be considered as a significant test deviation, and that the WFR that was obtained would not be the SAE J1832 WFR.

5.7.8 Data Reporting for the Working Flow Range

For WFR reporting, a representative flow curve from one of the tested injectors is to be generated and attached to the data reporting sheet. The serial number of that representative injector is to be recorded on the data reporting sheet and on the plot. The plot of all of the flow data versus pulse width for all 24 or more test injectors is to be generated and attached to the data reporting sheet. If the injectors are not simply from serial production, the details of the selection criteria should be stated in the test comments section of the WFR data reporting sheet. Also, for all of the flow data for all 24 (or more) injectors, a tabulation of the local mean flow, the standard deviation and the three-sigma/mean flow percentage deviation is to be prepared and attached. A plot of the local three-sigma percentage deviation at each tested pulse width is also to be prepared and attached to the data reporting sheet. This plot is to clearly indicate the two pulse widths at low-flow and high-flow where the deviation lies outside of either the +5.0% or -5.0% limits. These particular pulse widths are the IPW values corresponding to the maximum working flow, WF_{max}, and to the minimum working flow, WF_{min}. If none of the deviations at the high-flow test points exceed the percentage limits, then WF_{max} is to assigned as the static flow, and the IPW at WF_{max} is to be assigned as 10.0 ms. The values of WF_{max}, WF_{min}, IPW for WF_{max}, IPW for WF_{min}, and the computed value of WFR are to be recorded on the data reporting sheet.

Table 9 - SAE data reporting sheet for PFI static and dynamic flow and flow range testing

SAE Data Reporting Sheet for PFI Static and Dynamic Flow and Flow Range Testing - Page 1 of 2				
Part 1: General Test Information				
Test name or log			Date of test	
Name of operator			Location of test	
File name of data archive				
Additional information				
Part 2: Information on Injector				
Injector manufacturer				
Injector description Nominal static flow rate (at pressure) Pintle/director single/dual spray type Bent/coaxial Multi-hole/single hole				
Injector part number				
Serial number of the representative injector			For a WFR test using 24 or more injectors, attach separate sheet with all serial numbers	
Additional S/Ns for static, set-point and LFR tests for more than one injector				
Part 3: Test Conditions	**Specific Test Conditions (if Not Standard)**		**Standard PFI Test Conditions**	
Test fluid			n-heptane	
Ambient temperature (°C)			21 ± 2	
Ambient pressure (kPaa)			100 ± 5	
Fluid temperature (°C)			21 ± 2	
Test fuel pressure (kPa)			P_{NORM} ± 0.5%	
Test pressure tolerance			±0.5%	
Injector temperature (°C)			21 ± 2	
Injection pulse width (ms)			2.5 ms ± 0.005 for set point flow tests. For LFR and WFR tests, use the specified series of IPWs from short to long	
Injection period (ms)			10 ± 0.2%	
No. of injectors tested	Static:	Set point:	LFR:	WFR:

Part 4: Description and Comments on Test Instruments or Test Deviations - Page 2 of 2					
Clarifying test comments and information					
Also WFR injector selection criteria					
Also any test deviations					
Part 5: Test Results FOR PFI Flow Testing					
Part 5A - Single Injector Flow Test Results (Static, Set-Point, and LFR Testing)					
Individual values for static flow if more than one injector					
Individual values for set-point if more than one injector tested					
Individual values for LFR if more than one injector tested					
Static flow rate value obtained from the average of three tests per injector and all injectors tested; if there are no test deviations, this is the SAE J1832 static flow					(g/s)
Set point flow rate value obtained from the average of three tests per injector and all injectors tested; if there are no test deviations, this is the SAE J1832 set point flow					(mg/pulse)
LFR value obtained from the percent deviation plot and average of individual LFRs if more than one injector tested; if there are no test deviations, this is the SAE J1832 LFR					
LFR Test: Values for a Representative Injector	**Units**				
LF_{min} value:					(mg/pulse)
LF_{max} value:					(mg/pulse)
Slope value:					(mg/ms)
Flow offset value:					(mg/pulse)
Time offset (along the IPW axis) value:					(ms/pulse)
IPW_{min} (for min LFR flow) for -5.0% linearity deviation:					(ms/pulse)
IPW_{max} (for max LFR flow) for +5.0% linearity deviation:					(ms/pulse)
Plot of flow data versus pulse width attached? Circle YES or NO	YES		NO		
Plot of % deviation from linearity versus pulse width attached? Circle YES or NO	YES		NO		
Part 5B - Flow Test Results for a Population of Injectors (WFR Testing)					
WF_{min} value:					(mg/pulse)
IPW_{min} for a 5.0% deviation from 3*sigma/mean flow					(ms/pulse)
WF_{max} value (use static flow if it does not attain 5.0%)					(mg/pulse)
IPW_{max} for a 5.0% deviation from 3*sigma/mean flow (use 10.0 ms/pulse if it does not reach 5.0%)					(ms/pulse)
WFR Value obtained from the percent deviation plot; if there are no test deviations, this is the SAE J1832 WFR					
Part 5C - Attachments					
Representative plot of flow data versus pulse width for one of the test injectors attached? Circle YES or NO	YES		NO		
Plot of all the flow data for all test injectors versus pulse width attached? Circle YES or NO	YES		NO		
Data listing and plot of 3-sigma % Deviation from the mean flow rate versus IPW attached? Circle YES or NO	YES		NO		
Sheet with all 24 (or more) serial numbers of the injectors tested in the WFR test attached? Circle YES or NO	YES		NO		

6. ENVIRONMENTAL TESTS

6.1 Overview of Environmental Testing

This series of tests has the goal of subjecting the injector to a range of internal fuel blends, corrosive external fluids and jet spray nozzles, temperature and thermal cycling, static hot and cold soak, as well as dynamic flow shift under vacuum and temperature, to quantify their influence on injector performance and functionality.

6.2 Internal Fuel Blend Compatibility Tests

This test series is used to determine the compatibility of internal fuel injector components with a wide range of fuel blends that represent fluids similar to those that could be present in the fuel system of the vehicle during the operating lifetime.

6.2.1 Fuel Blends for Internal Fuel Compatibility Tests

It is not practical to evaluate all possible fuel blends, therefore, at a minimum, the following ten reference fuel blends are recommended for this test. In the following list, a reference fuel blend is defined as a material representative of its particular group, which is sufficiently well defined in all respects so that supplies from different sources are essentially identical in action for which the test is intended (refer to ASTM D471).

a. ASTM Reference Fuel C with 15% methanol: Shall be 15% by volume reagent-grade methanol added to ASTM Reference Fuel C.

b. ASTM Reference Fuel C with 10% ethanol: Shall be 10% by volume reagent-grade ethanol added to ASTM Reference Fuel C.

c. ASTM Reference Fuel C with 22% ethanol: Shall be 22% by volume reagent-grade ethanol added to ASTM Reference Fuel C.

d. ASTM Reference Fuel C with 85% ethanol (If injectors are intended for FFV application): Shall be 85% by volume reagent-grade ethanol added to ASTM Reference Fuel C.

e. ASTM Reference Fuel C and corrosive water solution: Mix by volume, 98% ASTM Reference Fuel C and 2% corrosive water. Corrosive water is a solution formed by dissolving the following amounts of anhydrous sodium salts in 1 L of distilled water at 40 °C: first, sodium sulfate - 14.8 mg; second, sodium chloride - 16.5 mg; and third, sodium bicarbonate - 13.5 mg.

f. Oxidized fuel (sour gas): Shall be mixed according to the following procedure to achieve a peroxide number of 180 millimole/L: To obtain the test solution, dilute 60 mL of peroxide stock solution with 10 mL of copper ion stock solution and 930 mL of stock fuel. The stock fuel is a 50/50 mixture of n-heptane and toluene. The peroxide stock solution is obtained by diluting 335 mL of 90% by weight t-butyl hydroperoxide with 665 mL of n-heptane. The copper ion stock solution is obtained by using the mixing steps that are outlined below in the proper sequence. It should be noted that these chemicals are hazardous, and that the failure to follow proper procedures can result in a fire. Refer to the OSHA material safety data sheets for each of the materials:

  - First, add 10 mL of 12% copper ion concentrate solution to 990 mL of stock fuel.

  - Second, add 100 ml of the solution from the first step to 1040 mL of stock fuel.

  - Third, dilute 10 mL of the solution obtained in the second step with 990 mL of stock fuel.

6.2.2 Procedure for Internal Fuel Blend Compatibility Tests

A new set of injectors shall be used for each of the ten internal test fluids. Testing a single set of injectors with multiple test fluids is to be avoided.

a. A minimum set of five new injectors of the same make and model from serial production are to be tested. Pre-condition each test injector per Table 2.

b. The key operating parameters of Q_s, Q_{sp}, IR, R, and tip leakage shall be measured and recorded prior to any immersion in the internal test fluids. These tests should be performed using n-heptane fuel according to the procedures specified in the appropriate sub-sections of this document.

c. Fully empty the injector of the n-heptane used to measure the key operating parameters; then flush the injector, per Table 2, using the test fluid prior to the test.

d. Submerge the injector in the selected test fuel for 30 days at room temperature (21 °C) with the inlet port open and orientated in such a manner as to keep the injector full of the test fuel blend. The fuel blend within the injector is not pressurized for this test, nor is the electrical connector installed.

e. After 30 days, remove the injector and re-test for the key operating parameters of Q_s, Q_{sp}, IR, R, and tip leakage using n-heptane.

f. Repeat steps (c) through (e) on the next injector.

g. Repeat the test procedure for the next Internal test fluid using a new set of injectors.

6.2.3 Data Reduction and Analysis for Internal Fuel Compatibility Tests

Compute the parameter deviations from pre-submersion to post-submersion for the five performance test parameters of Q_s, Q_{sp}, IR, R, and tip leakage.

6.2.4 Data Reporting for Internal Fuel Compatibility Tests

The parameter deviations for Q_s, Q_{sp}, IR, R, and tip leakage resulting from the 30-day immersion in each internal test fluid are to be reported on the data reporting sheet. The Q_s and Q_{sp} deviations shall also be reported as a percentage change.

6.3 External Fluid Compatibility Tests

In this series of tests, the external surfaces of the PFI injector are to be placed in contact with a number of common fuels and automotive fluids such as E85, motor oil, brake fluid, anti-freeze, engine and brake cleaner, and battery electrolyte. Five key electrical and performance parameters are measured both prior to and after the exposure of the external injector surfaces to each of these test fluids.

6.3.1 Test Fluids for External Fluid Compatibility Testing

It is not practical to evaluate all variations of possible fluids that may come into contact with the external surfaces of a PFI injector over the operating lifetime. Therefore, a number of standard reference fluids are employed in testing. A reference fluid is defined as a material representative of its particular group, which is sufficiently well defined in all respects so that supplies from different sources are essentially identical in action for which the test is intended (refer to ASTM D471). The most commonly used reference fluids that are specified as external test fluids are listed as follows:

NOTE: If the 30-day immersion test for internal fluid compatibility has been performed for any of the first 10 fluids on this list, then the external fluid compatibility test may be skipped for that fluid.

a. ASTM Reference Fuel C with 40% by volume reagent-grade ethanol (E40) added.

b. ASTM Reference Fuel C with 15% by volume reagent grade MTBE (methyl tertiary butylether) added.

c. ASTM Reference Fuel C with 10% by volume reagent grade isopropyl alcohol added.

d. Emissions Test Fuel (E0): Shall be U.S. EPA emission data fuel (40 CFR 86.113).

e. Antifreeze 50%: Shall be an ethylene glycol based material as described in SAE J814 mixed with an equal volume of distilled water.

f. Automatic transmission fluid: Shall be Dextron III (General Motors Registered Trademark), Mercon (Ford Registered Trademark), or equivalent.

g. Axle and manual transmission lubricants: Gear oil API-GL-5 as described in SAE J308. (Viscosity as defined in SAE J306 may be specified at the option of the test engineer.)

h. Battery electrolyte: Shall be reagent-grade sulfuric acid diluted with distilled water to a specific gravity of 1.25 to 1.28.

i. Brake fluid: Is a mixture of polyglycols and cellosolves conforming to DOT-4 of 49 CFR 571.116.

j. Ethylene glycol monobutyl ether (butylcellosolve solvent): Technical grade.

k. Diesel fuel (No. 2): As described in SAE J313. The fluid shall have an aniline point of 60 to 70 °C. It is preferred that emissions-grade diesel fuel conforming to 40 CFR 86.113 be used.

l. Engine oil: Shall be ASTM Reference Oil No. 3.

m. Grease: Shall be an extended-lubrication-interval grease (lithium soap based) as noted in SAE J310. When tested according to ASTM D128, it shall contain not less than 4% by weight lithium (12-hydroxystearate type).

n. Power steering fluid: Shall be a commercial grade of power steering fluid.

o. Mineral spirits: This fluid shall be as described in Table 5.

p. Commercial engine cleaner.

q. Commercial brake cleaner.

r. Commercial windshield washer fluid.

s. Water (jet spray). Note: This has a separate test procedure.

t. Steam (jet spray). Note: This has a separate test procedure.

6.3.2 Procedure for External Fluid Compatibility Tests

A new set of five injectors shall be used for each of the external test fluids. Testing a single set of injectors with multiple test fluids is to be avoided.

a. A minimum set of five new injectors of the same make and model from serial production are to be tested for each fluid. Pre-condition each injector to be tested according to Table 2.

b. The key operating parameters of Q_s, Q_{sp}, IR, R, and tip leakage shall be measured and recorded prior to any application of any one of the external test fluids. These tests should be performed using n-heptane fuel according to the procedures specified in the appropriate sub-sections of this document.

c. Each injector to be tested shall have its inlet and outlet suitably sealed. The injector is to have its electrical connector fitted; however, it is not to be energized.

d. The injector shall have its exposed external surfaces thoroughly dampened with the test fluid either by spraying or by brush application. The injector shall then be allowed to stand for 24 hours at standard ambient temperature.

e. Upon completion of the 24-hour test period, the injector shall be degreased using a citrus-based cleaner. Inspect for external damage, such as corrosion or melted plastic.

f. Re-measure the values for Q_s, Q_{sp}, IR, R, and tip leakage for the test injector.

g. Repeat the test procedure for the next external compatibility test fluid using a new set of injectors.

6.3.3 Data Reduction and Analysis for External Fluid Compatibility Tests

Compute the parameter deviations from pre-test to post-test for the five performance test parameters of Q_s, Q_{sp}, IR, R, and tip leakage.

6.3.4 Data Reporting for External Fluid Compatibility Tests

The parameter deviations from pre-application to post-application for the five performance test parameters of Q_s, Q_{sp}, IR, R, and tip leakage are to be reported on the data reporting sheet. The Q_s and Q_{sp} deviations shall also be reported as a percentage change.

6.4 Water Jet Spray Test

6.4.1 Procedure for Water Jet Spray Test

A new set of five injector shall be used for the water jet spray test.

a. A minimum set of five new injectors of the same make and model from serial production are to be tested. Pre-condition each test injector according to Table 2.

b. Characterize the injector performance prior to spraying with the water jet by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage. These tests should be performed using the specified procedures in the appropriate sub-sections of this document.

c. Each injector shall have its inlet and outlet suitably sealed. The injector is to have its electrical connector fitted; however, it is not to be energized.

d. The exterior surface of the injector shall then be exposed to a high-pressure water jet that is typical of that present in commercial hand-operated car wash facilities. The water is to have a pressure of 10000 kPa, and is to be applied with the injector being at an approximate distance of 150 mm from the tip of the water jet. The application shall consist of momentary (1 second) exposures over various surfaces of the injector with a repeat rate of 20 exposures per minute (1 second on and 2 seconds off). This is to be continued for 10 minutes.

e. For a simulated lifetime exposure to high-pressure water jets, the procedure in step (d) should be repeated 39 more times for a total exposure of 40 10-minute spray events.

f. Upon completion of the high-pressure water spray test, the injector shall be dried using a clean cloth.

g. After the ten-minute test, re-measure the values for Q_s, Q_{sp}, IR, R, and tip leakage for the test injector. If the optional 400-minute test to simulate a lifetime exposure is performed, also re-measure Q_s, Q_{sp}, IR, R, and tip leakage after the completion of that test.

6.4.2 Data Reduction and Analysis for the Water Jet Spray Test

Compute the parameter deviations from pre-test to post-test for the five performance test parameters of Q_s, Q_{sp}, IR, R, and tip leakage. Do this for the 10-minute test, and also for the 400-minute lifetime simulation test if that test was conducted.

6.4.3 Data Reporting for the Water Jet Spray Test

The parameter deviations for Q_s, Q_{sp}, IR, R, and tip leakage resulting from the 10-minute water jet spray test are to be reported on the data reporting sheet. The Q_s and Q_{sp} deviations shall be reported as a percentage change. The parameter deviations for Q_s, Q_{sp}, IR, R, and tip leakage resulting from the 400-minute water jet spray test are also to be reported on the data reporting sheet if that optional test was performed. Indicate in the comments section of the data reporting sheet whether a 10-minute test or a 400-minute test, or both, were conducted.

6.5 Steam Jet Spray Test

6.5.1 Procedure for the Steam Jet Spray Test

A new set of five injectors shall be used for the steam jet spray test.

a. Pre-condition each test injector according to Table 2.

b. Characterize the injector performance prior to spraying with the steam jet by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage. These tests should be performed using the specified procedures in the appropriate sub-sections of this document.

c. Each injector shall have its inlet and outlet suitably sealed. The injector is to have its electrical connector fitted; however, it is not to be energized.

d. The exterior surface of the injector shall then be exposed to a steam jet, as is utilized in commercial steam cleaning equipment. The steam jet is to be sprayed over the exterior surface of the injector for 15 seconds.

e. For a simulated lifetime exposure to steam jets, the procedure in item (e) above should be repeated 19 more times for a total exposure of 20 15-second spray events (300 seconds). There should be a 1-minute cooling period after each steam jet spray event.

f. Upon completion of the 15 second steam-spraying session, re-measure the injector performance values of Q_s, Q_{sp}, IR, R, and tip leakage for the test injector. If the optional 300-second test to simulate a lifetime exposure is performed, also re-measure Q_s, Q_{sp}, IR, R, and tip leakage after the completion of that test.

6.5.2 Data Reduction and Analysis for the Steam Jet Spray Test

Compute the parameter deviations from pre-test to post-test for the five performance test parameters of Q_s, Q_{sp}, IR, R, and tip leakage. Do this for the 15-second test, and also for the 300-second lifetime simulation test if that test was conducted.

6.5.3 Data Reporting for the Steam Jet Spray Test

The parameter deviations for Q_s, Q_{sp}, IR, R, and tip leakage resulting from the 15-second steam jet spray Test are to be reported on the data reporting sheet. The Q_s and Q_{sp} deviations shall also be reported as a percentage change. The parameter deviations for Q_s, Q_{sp}, IR, R, and tip leakage resulting from the 300-second steam jet spray test are also to be reported on the data reporting sheet if that optional test was performed. Indicate in the comments section of the data reporting sheet whether a 15-second test or a 300-second test, or both, were conducted.

Table 10 - SAE data reporting sheet for environmental compatibility tests

SAE J1832 - Data Reporting Sheet for Environmental Compatibility Tests Internal - External - Water Jet - Steam Jet - Page 1 of 2			
Part 1: General Test Conditions			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on Injector and Injector Driver Module			
Injector manufacturer and design type			
Injector description			
Injector part number			
Additional information (static flow rate (at pressure), inward/outward, single/dual type, bent/coaxial, multi-hole, etc.)			

Part 3: Test Conditions	**Specific Test Conditions**	**Standard PFI Test Conditions**
Test fluid being tested		Various
Ambient temperature (°C)		21 ± 2
Ambient pressure (kPaa)		100 ± 5
Fluid temperature (°C)		21 ± 2
Test fuel pressure (kPa)		Not pressurized
Test pressure tolerance		N/A
Injector temperature (°C)		21 ± 2
Injection pulse width (ms)		Not operating
Injection period (ms)		Not operating

Part 4: Description and Comments on Equipment or Test Deviations - Page 2 of 2				
Test equipment details				
Test deviations				
Test Type Being Reported (Check One)	□ **Internal**	□ **External**	□ **Jet spray**	□ **Steam jet**
Test fluid:	Use Additional Blank Copies of This Data Sheet for Each Test Fluid			
#1 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#2 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#3 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#4 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#5 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#6 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#7 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				
#8 (SN) ________________	**Pre-Test Value**	**Post-Test Value**	**Deviation**	
Q_{sp} (mg/pulse)			%	
Q_s (g/s)			%	
IR (Ω)				
R (Ω)				
Leakage Rate (mm³/min)				

6.6 Salt-Spray External Cyclic Corrosion

This test procedure is utilized to determine the degree to which the test injector can withstand the effects of extensive external salt corrosion. This salt corrosion is highly likely to be encountered near seaside roadways and in locations that employ road salt to melt winter ice and snow coatings. The main source for the test equipment details such as the spray nozzles, corrosion coupons and the corrosion test chamber is the ASTM Standard B117 - ver. 19. The salt-spray external cyclic corrosion test consists of an ambient environment salt spray mist combined with a high humidity and high temperature drying interval for a set of five new test injectors of the same make and model. One 24-hour period is considered a cycle, assuming the mass loss of steel test coupons is within specified limits. The test duration is a total of 50 cycles, with the test monitored for sufficient corrosion potential by means of the measured mass loss of standardized steel corrosion coupons. The mass loss of the coupons is assumed to be linear throughout the test. A cosmetic inspection of the external surfaces of the injectors is conducted after ten cycles, and both an inspection and a retesting of the injector performance parameters is conducted after the completion of the test at 50 cycles. It should be noted that this test procedure differs from that in ASTM B117 - ver.19. This SAE J1832 test procedure is a thermal, cyclic corrosion test, whereas the test procedure indicated in ASTM B117 - ver.19 is not.

6.6.1 Design and Setup of Test Equipment for the Salt-Spray External Cyclic Corrosion Test

The corrosion test chamber requirements are outlined in 6.6. These requirements and guidelines are further described in ASTM B117 - ver.19, which also provides recommendations on the nozzle design for delivering the salt spray. However, any chamber and nozzle design that achieves the proper corrosion rate is permissible. The automated timings of the salt-spray injection period, the heat-and-humidity period and the high-temperature-drying period within a cycle shall also conform to the designated test procedure that is detailed in the subsections below.

Low-carbon steel monitoring coupons are utilized as part of this test to ensure that the corrosive environment provided for the injector samples is adequate. The monitoring coupons that are periodically weighed for corrosion mass loss are to be constructed of AISI 1006-1010 steel, and are to each be 25.4 x 50.8 mm in rectangular size, and may be either 1.59 mm or 3.18 mm thick. The expected mass loss of the coupons that will verify a sufficient degree of corrosiveness in the chamber is based upon the thickness chosen, and is outlined in ASTM B117 - ver. 19. Ten coupons are required for this 50-cycle corrosion test. The initial mass of each coupon shall be recorded on the data sheet prior to the start of the test. Coupons shall be mounted on a bracket and isolated from the bracket via plastic or nylon studs and nuts. The coupons shall be mounted at a 15 degree angle from the vertical and should not contact or shadow each other. The coupons should be placed a minimum of 5 mm apart, and shall be placed adjacent to the parts being tested so that they are subjected to the same corrosive environment.

The salt-solution used to create the spray mist in the test chamber has the following composition: It shall consist of de-ionized water containing 0.9% sodium chloride, 0.1% calcium chloride, and 0.25% sodium bicarbonate, with a pH that is between 6 and 8. An important note for the preparation of the salt-solution is that either the calcium chloride or the sodium bicarbonate must be dissolved separately in de-ionized water and then added to the mixture to avoid the formation of a solid precipitate that could later clog the spray nozzles during the test. Record the measured pH of the resulting solution.

6.6.2 Procedure for the Salt-Spray External Cyclic Corrosion Test

a. A set of five (minimum) new, injectors of the same make and model from serial production should be tested. Pre-production injectors may be utilized if that information is clearly listed in the comments section of the data reporting sheet. Pre-condition each injector to be tested according to Table 2. Photograph each of the five injectors prior to any testing.

b. Characterize the injector performance prior to starting the functional salt-spray external corrosion test by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage for each test injector that is to be tested in the salt-spray corrosion test chamber.

c. Each injector (hereinafter called a sample) shall have its inlet and outlet suitably sealed. Each injector sample is also to have its electrical connector fitted; however, the injector is not to be energized.

d. Samples shall be supported or suspended between 15 degrees and 30 degrees from the vertical, with any significant surface parallel to the principal direction of fog flow within the shed.

e. Samples shall be at least 30 mm from each other and 35 mm from any chamber wall.

f. The sample shall be so placed as to permit free settling of the spray fog on all samples, but avoiding the salt solution from one sample dripping onto another.

g. Expose the samples to the salt-spray fog in the shed for a 24-hour cycle. A test cycle consists of three phases, each eight hours in duration. The three phases of the test, in the order to be performed are:

1. Ambient conditions period (25 °C ± 3 °C, 40 to 50% RH) with salt spray mist.

2. Heat and humidity period (49 °C ± 3 °C, 95 to 100% RH).

3. High temperature drying period (60 °C ± 3 °C, <30% RH).

h. During phase 1, which is the salt-spray mist, the parts are to be sprayed at 2-hour intervals for a total of four spray events. The spray nozzles shall be capable of applying sufficient momentum to rinse away any residual salt from previous sprays, and shall spray a sufficient amount of salt-solution onto the parts to maintain wetness for 15 minutes.

i. The ramp time between phases 1 and 2 is to be 1 hour. The ramp time between phase 2 and 3 is to be 3 hours. The ramp time between phase 3 and the next repeat cycle of phase 1 is to be 2 hours. Periodically inspect the samples and the overall operation of the spray chamber as required in ASTM B117 - ver. 19. The opening of the chamber shall be limited to the frequency necessary to carry out the operations. Inspections should not be made more than twice a day for a total of 15 minutes. The positions of the samples may be varied during the inspection period if required.

j. Following the first cycle, repeat the test for additional cycles until ten cycles have been completed. As indicated in ASTM B117 - ver. 19, remove two coupons at the end of the tenth cycle and sandblast the corrosion by-product off of both of the coupons until the surface is again bare. After cleaning with either alcohol or acetone, then drying, weigh each of the two coupons on a precision scale and compute the decrease from the original mass. The mass loss should ideally be approximately linear throughout the test, with a total mass loss per coupon after 50 cycles of 4161 to 4825 mg for a 1.59 mm thick coupon and 4573 to 5230 mg for a 3.19 mm thick coupon. Assuming a linear mass loss, each coupon should be expected to lose 842 to 965 mg during each ten cycles of the test. If this mass loss is found to be either too high or low during each ten-cycle increment, then the spray volume of the salt-solution should be adjusted.

k. Also, at the end of the tenth cycle, the test samples are to be removed from the chamber for an early cosmetic inspection that will provide an indication of any early susceptibility to salt corrosion. As part of this early-cycle inspection, the condition of the exterior surfaces shall be visually assessed, and any evidence of surface corrosion, surface defects or blistering noted. Each injector is to be photographed and the photos clearly labeled as corresponding to the early cosmetic inspection. No performance test of the injectors is required after ten cycles.

l. At the completion of each of the 20th, 30th, and 40th cycles, remove two additional coupons and sandblast, clean and dry them. Weigh the coupons and record the value of the mass loss since the start of the test. Also to be noted, but not required to be recorded on the data reporting sheet, are the incremental mass losses of each coupon between the 10th and 20th cycles, the 20th and 30th cycles, and the 30th and 40th cycles. This is for monitoring the degree of corrosiveness of the test. The injectors are not to be removed from the test chamber, and no performance test is required after 20th, 30th, or 40th cycles.

m. Following the end of the 50th and final cycle of the salt-spray external cyclic corrosion test, remove the samples from the test chamber, wash them gently in water not warmer than 38 °C, and dry by blotting with absorbent paper.

n. Both a cosmetic examination and a performance test of each test injector are to be conducted as detailed in the data analysis and reporting subsection below.

6.6.3 Data Analysis and Reporting for the Salt-Spray External Cyclic Corrosion Test

Each test injector shall be examined and photographed after 50 cycles of testing. The final external surface condition shall be visually assessed and noted for any observable surface corrosion, surface defects, and blistering. Special attention should be paid to welded joints and other areas that may be particularly susceptible to corrosion. For the purpose of the salt spray test only, a “significant” surface is defined as an area designated to be coated that can be touched by a 6.35 mm diameter ball. All other surfaces shall be considered as “non-significant.” The size, number, and locations of red rust spots, blisters, and surface defects on all significant surfaces are to be recorded. The supporting photographs should also clearly indicate any red rust spots, blisters, and surface defects.

The expected average mass loss per coupon after 50 cycles should be in the range of 4161 to 4825 mg for a 1.59 mm thick coupon and 4573 to 5230 mg for a 3.19 mm thick coupon. This is 41.61 to 48.25 grams for all ten coupons. If the total measured mass loss for the ten total coupons does not fall into this range, the actual total mass loss should be listed as a test deviation in Section 4 of the data reporting sheet. This deviation is indicative of a corrosive environment during the test that is either too corrosive (excessive mass loss) or not corrosive enough (insufficient mass loss).

Following the completion of 50 cycles of the salt-spray external corrosion test and the cosmetic examination, each of the injectors in the test set shall be tested for Q_s, Q_{sp}, IR, R, and tip leakage. The parameter deviations from the measured pre-test values are to be computed and reported on the data reporting sheet. The Q_s and Q_{sp} deviations are also to be reported as a percentage change. Use additional blank copies of Pages 2 and 3 of the data reporting sheet if more than eight injectors are tested.

Table 11 - SAE data reporting sheet for functional salt spray external cyclic corrosion test

SAE J1832 - Data Reporting Sheet for Functional Salt Spray External Cyclic Corrosion Test - Page 1 of 3			
Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on Injector and Injector Driver Module			
Injector manufacturer and design type			
Injector description			
Injector part number			
Additional information			
Part 3: Test Conditions	**Specific Test Conditions**	**Standard Test Conditions**	
Salt solution pH		6 to 8	
Ambient temperature (°C)		Phase 1: 25 °C ± 3.0 °C Phase 2: 49 °C ± 3.0°C Phase 3: 60 °C ± 3.0°C	
Relative humidity (% RH)		Phase 1: 40 to 50% RH Phase 2: 95 to 100% RH Phase 3: <30% RH	
Additional information			
Part 4: Description and Comments on Equipment or Test Deviations			
Test equipment details			
Test deviations			
Part 5A: Test Results for Test Coupon Mass in the Functional Salt Spray External Corrosion Test			
Sample Coupon Tested	**Initial Mass (mg)**	**Final Mass (mg)**	**Mass Loss (mg)**
1		(mg) after 10 cycles	
2		(mg) after 10 cycles	
3		(mg) after 20 cycles	
4		(mg) after 20 cycles	
5		(mg) after 30 cycles	
6		(mg) after 30 cycles	
7		(mg) after 40 cycles	
8		(mg) after 40 cycles	
9		(mg) after 50 cycles	
10		(mg) after 50 cycles	
Total mass loss for all ten coupons after all 50 cycles (grams):		g	

Part 5B: Test Results for Performance Parameters in the Functional Salt Spray External Corrosion Test - Page 2 of 3			
Performance Parameter			
#1 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			**%**
Q_s (g/s)			**%**
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#2 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#3 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#4 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			**%**
Q_s (g/s)			**%**
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#5 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#6 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#7 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
#8 (SN):	Pre-Test	Post 50 cycles	Change
Q_{sp} (mg/pulse)			**%**
Q_s (g/s)			**%**
IR - Insulation resistance (Ω)			
R - Coil resistance R (Ω)			
Tip leakage (mm³/min)			
Comments on any of the performance test results			

Part 5C: Salt-Spray Test: Injector Serial Numbers and Results of Cosmetic Examinations - Page 3 of 3		
Injector Number and Serial Number	**Comments on Cosmetic Exam at 10 Cycles (Early Susceptibility)**	**Comments on Final Cosmetic Exam after 50 Cycles**
1 - S/N:		
2 - S/N:		
3 - S/N:		
4 - S/N:		
5 - S/N:		
6 - S/N:		
7 - S/N:		
8 - S/N:		
Record test cosmetic observations above. Attach photographs taken initially, and after 10 cycles and 50 cycles.		

6.7 Temperature Cycle Test

This test procedure is designed to evaluate the effect of repeated cycles of significantly elevated operating temperatures (simulated hot soaks), followed by injector operation during the cool-down period. Five key performance parameters of Q_s, Q_{sp}, IR, R, and tip leakage are measured before and after 140 of these temperature cycles in order to quantify any changes. If fluid purge is required for pre-test conditioning, take great care to ensure that all fluid is purged; otherwise, fuel residue may affect response time.

6.7.1 Procedure for the Temperature Cycle Test

a. A minimum set of five new injectors of the same make and model from serial production should be tested. Pre-condition each injector according to Table 2.

b. Characterize the injector performance prior to any testing by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage.

c. The test shall be conducted using a test fuel of ASTM Reference Fuel C with 10% reagent-grade ethanol by volume added. The ethanol must meet the requirements listed in ASTM D4806. Set the fuel pressure to P_{NORM} and maintain this pressure level throughout the temperature cycle.

d. The temperature cycling test shall be conducted on a test bench capable of operating the injectors inside a thermal chamber at elevated temperatures. Expose the injector set to the thermal cycle shown in Figure 17. The injectors are to be operated only during segment E-G of the cycle, using an IPW of 2.0 ms and a period of 7.0 ms.

e. Repeat the test cycle in Figure 17 a total of 140 times.

f. Following the 140 temperature cycles, re-measure the values for Q_s, Q_{sp}, IR, R, and tip leakage for each tested injector.

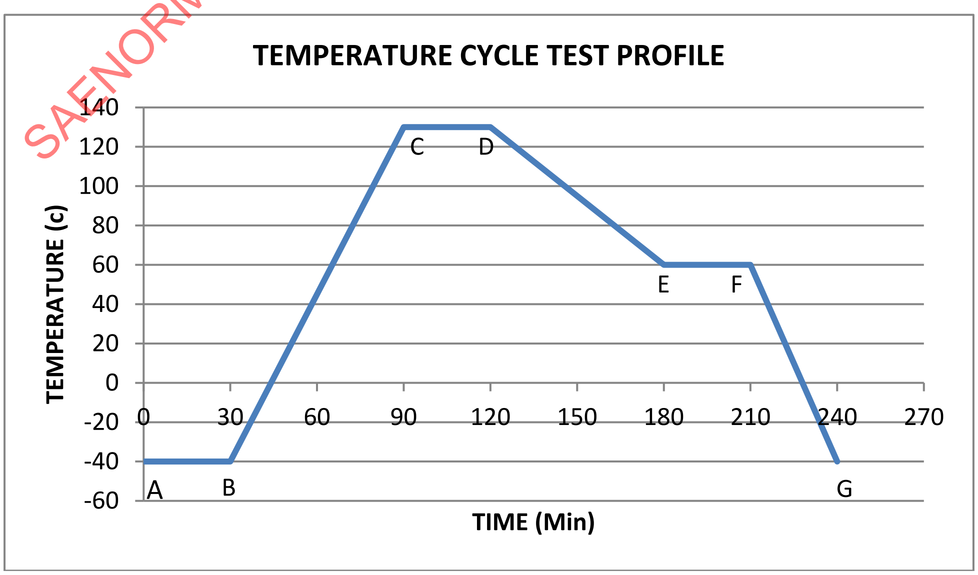


Figure 17 - Test time schedule for the temperature cycle test

6.7.2 Data Reduction and Analysis for Temperature Cycle Test

Compute the deviations between the pre-test and post-test values for Q_s, Q_{sp}, IR, R, and tip leakage for each injector tested. The deviations in Q_s and Q_{sp} are to be computed as percentage changes.

6.7.3 Data Reporting for Temperature Cycle Test

Record the deviations in Q_s, Q_{sp}, IR, R, and tip leakage from the initial pre-test values on the data reporting sheet for each of the tested injectors. The deviations in Q_s and Q_{sp} are also to be reported as percentage changes.

6.8 Hot Static Soak Test

This procedure is designed to evaluate injector performance when exposed to a constant elevated test condition without the injector being operated. The key performance parameters of Q_s, Q_{sp}, IR, R, and tip leakage are measured before and after the test in order to quantify any changes that occur. If fluid purge is required for pre-test conditioning, take great care to ensure that all fluid is purged; otherwise, fuel residue may affect response time.

6.8.1 Procedure for the Hot Static Soak Test

a. A minimum set of five new injectors of the same make and model from serial production should be tested. Pre-condition each injector according to Table 2.

b. Characterize the injector performance prior to any testing by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage.

c. Purge all fluids from the injector and expose all five injectors to a stabilized ambient of 150 °C ± 2 °C for 16 hours. During this period, the injectors are not operated.

d. Monitor IR and R at the soak temperature to ensure continuity at elevated temperature.

e. Following the 16-hour test period, cool the set of injectors to 21 °C ± 2 °C and re-measure the values for Q_s, Q_{sp}, IR, R, and tip leakage.

6.8.2 Data Reduction and Analysis for Hot Static Soak Test

For each test injector, compute the deviations in the measured values of Q_s, Q_{sp}, IR, R, and tip leakage from the pre-test to the post-test. The deviations in Q_s and Q_{sp} are to be computed as percentage changes.

6.8.3 Data Reporting for Hot Static Soak Test

Record the measured deviations in Q_s, Q_{sp}, IR, R, and tip leakage from the initial values on the data reporting sheet for each of the tested injectors. The deviations in Q_s and Q_{sp} are also to be reported as percentage changes.

6.9 Cold Static Soak Test

This procedure is designed to evaluate injector performance when exposed to a constant low temperature test condition without the operation of the injector. Key performance parameters, Q_s, Q_{sp}, IR, R, and tip leakage are measured before and after the test in order to quantify any changes.

6.9.1 Procedure for the Cold Static Soak Test

a. A minimum set of five new injectors of the same make and model from serial production should be tested. Pre-condition each injector according to Table 2.

b. Characterize the injector performance prior to any testing by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage.

c. Purge all fluids from the injector and expose the entire set of five injectors to a stabilized ambient of -40 °C ± 2 °C for 16 hours. During this period, the injectors are not operated.

d. Monitor IR and R at the soak temperature to ensure continuity at reduced temperature.

e. Following the 16-hour test period, allow the set of test injectors to return to the room temperature of 21 °C ± 2 °C and re-measure the values for Q_s, Q_{sp}, IR, R, and tip leakage.

6.9.2 Data Reduction and Analysis for Cold Static Soak Test

Compute the deviations between the pre-test and post-test values of Q_s, Q_{sp}, IR, R, and tip leakage for each test injector. The deviations in Q_s and Q_{sp} are to be computed as percentage changes.

6.9.3 Data Reporting for Cold Static Soak Test

Record the deviations in Q_s, Q_{sp}, IR, R, and tip leakage from the initial values on the data reporting sheet for each of the tested injectors. The deviations in Q_s and Q_{sp} are also to be reported as percentage changes.

6.10 Cyclic Thermal Shock Test

This procedure is designed to evaluate injector performance when exposed to extreme thermal shocks without the operation of the injector. Key performance parameters, Q_s, Q_{sp}, IR, R, and tip leakage are measured before and after the test in order to quantify any changes. If fluid purge is required for pre-test conditioning, take great care to ensure that all fluid is purged; otherwise, fuel residue may affect response time.

6.10.1 Procedure for the Cyclic Thermal Shock Test

a. A minimum set of five new injectors of the same make and model from serial production should be tested. Pre-condition each injector according to Table 2.

b. Characterize the injector performance prior to any testing by measuring the values for Q_s, Q_{sp}, IR, R, and tip leakage.

c. Purge all fluids from the injector.

d. Expose the entire set of five injectors to a stabilized ambient of -40 °C ± 2 °C for a minimum of 0.5 hour. During this and subsequent steps, the injectors are not operated.

e. As quickly as the test apparatus will allow, but not to exceed 30 seconds, transfer the five injectors to a stabilized ambient of 130 °C ± 2 °C for a minimum of 0.5 hour. Due to the desired short transfer time it is recommended that two test chambers in close proximity be utilized, with one maintained at -40 °C and the other at 130 °C. This would allow a simple and rapid transfer of test parts.

f. Complete steps (d) and (e) 200 times.

g. Following the 200 cycles, allow the set of test injectors to return to room temperature (21 °C ± 2 °C) and re-measure the values for Q_s, Q_{sp}, IR, R, and tip leakage.

6.10.2 Data Reduction and Analysis for Cyclic Thermal Shock Test

Compute the deviations between the pre-test and post-test values of Q_s, Q_{sp}, IR, R, and tip leakage for each test injector. The deviations in Q_s and Q_{sp} are to be computed as percentage changes.

6.10.3 Data Reporting for Cyclic Thermal Shock Test

Record the deviations in Q_s, Q_{sp}, IR, R, and tip leakage from the initial values on the data reporting sheet for each tested injector. The deviations in Q_s and Q_{sp} are also to be reported as percentage changes.

Table 12 - SAE data reporting sheet for temperature cycle, hot static soak, cold static soak, and thermal shock tests

SAE J1832 - Data Reporting Sheet for Temperature Cycle Test, Hot Static Soak Test, Cold Static Soak Test, and Cyclic Thermal Shock Test - Page 1 of 2			
Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on Injector and Injector Driver Module			
Injector manufacturer and design type			
Injector description			
Injector part number			
Additional information			
Part 3: Test Conditions			
Test Type Being Run (check)	Tested Temperatures		Standard Test Temperatures
□ Temperature cycle □ Hot static soak □ Cold static soak □ Thermal shock			See profile in test procedures 150 °C ± 2 °C -40 °C ± 2 °C -40 °C ± 2 °C to 130 °C ± 2 °C
Test fuel for temperature cycle	ASTM Reference Fuel C with 10% reagent-grade ethanol by volume added		
Additional information			
Part 4: Description and Comments on Equipment or Test Deviations			
Test equipment details			
Test deviations: Note any deviations from the specified conditions or procedures			

Part 5: Test Results for Temperature Cycle, Hot Static Soak, Cold Static Soak, and Thermal Shock Tests - Page 2 of 2			
Performance Parameter	Pre-Test Value	Post-Test Value	Change
INJ #1 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #2 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #3 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #4 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #5 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #6 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #7 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
INJ #8 (SN):			
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
Insulation resistance IR -Ω			
Coil resistance R (Ω)			
Tip leakage (mm^3/min)			
Comments and observations			
	Use additional copies of this datasheet for each test type and for more than eight injectors in a test		

6.11 Dynamic Flow Shift Test

Fuel injectors exhibit varying degrees of “rich and lean shifts” when subjected to varying levels of manifold pressures at the outlet of the injector. A “rich shift” can occur during an engine over-run condition of high manifold vacuum and small injector pulse width, whereas a “lean shift” can occur during a throttle tip-in maneuver that follows an over-run condition. This tip-in condition of low manifold vacuum and a large injector pulse width results in an excessive fuel condition. There also can be an elevated positive pressure in the intake manifold in forced induction applications (turbocharger or supercharger). Similarly, the delivered fuel mass flow rate can be affected by the temperature of the fuel and the injector body, as this change in temperature results in a change in fuel density and viscosity. During a morning start in very cold climates the temperature can be in the vicinity of -30 °C, and during a start after a hot soak on a summer day more than 100 °C may be experienced.

How sensitive the mass metering ability of an injector is to the manifold pressure and fuel temperature is related to the injector design, the fuel system components, the ambient air temperature and the properties of the fuel being utilized. The extent to which manifold-vacuum induced flow shifts and fuel-temperature induced flow shifts affect drivability is best evaluated in a running vehicle; however, these effects can be evaluated using an environmental flow stand which has the capability of changing and maintaining a range of fuel temperatures and downstream air pressure levels. A schematic representation of such a flow stand is depicted in Figure 18. This type of fuel flow stand permits the determination of the percentage shift (deviation) in the delivered fuel flow rate, Q_{fs}, as a function of the fuel temperature and downstream pressure level.

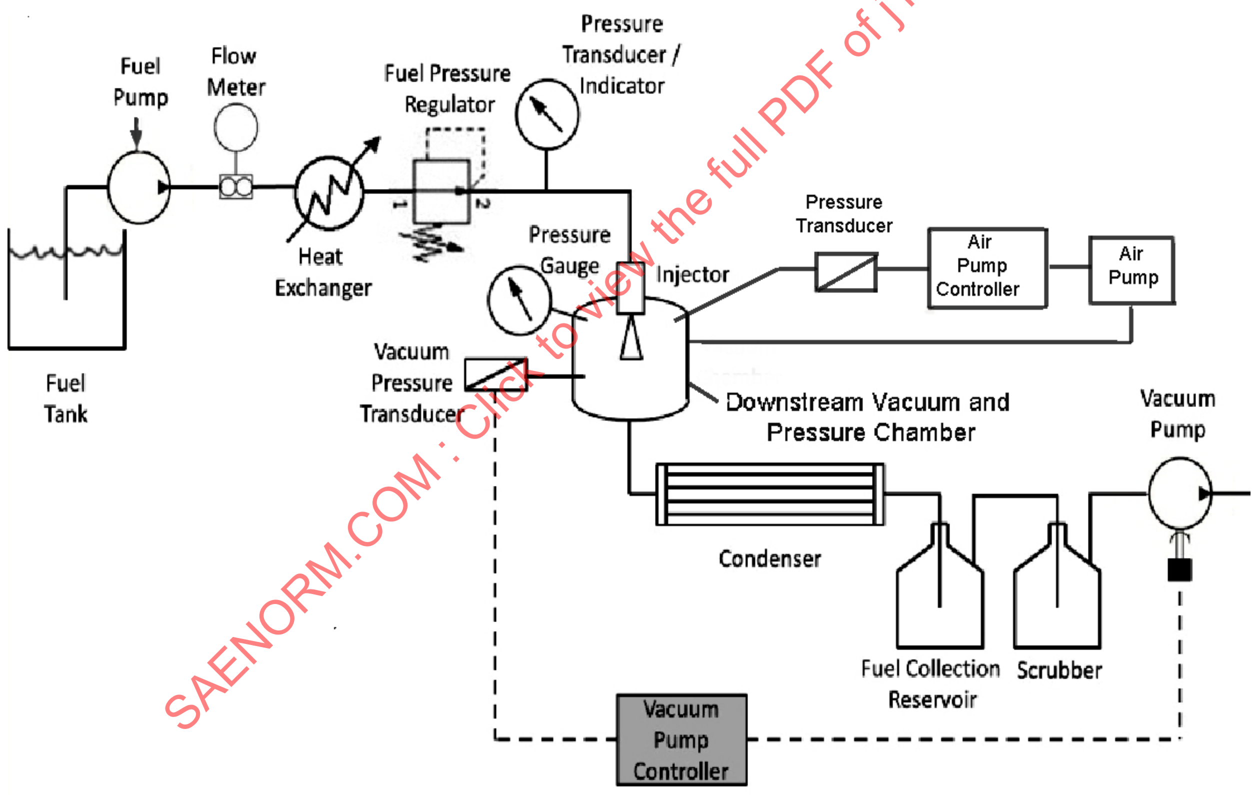


Figure 18 - Schematic of environmental flow stand for the measurement of PFI dynamic flow characteristics

6.11.1 Procedure for the Dynamic Flow Shift Test

a. A minimum set of five new injectors of the same make and model from serial production should be tested. If the test is conducted using pre-production injectors, this should be indicated in the comments section of the data reporting sheet. Pre-condition each injector according to Table 2.

b. Measure the baseline dynamic flow rates of one of the test injectors at the following operating conditions:

- Test fuel and temperature: n-heptane at 21 °C ± 2 °C.
- Test fuel pressure: P_{NORM}.
- A downstream absolute ambient air pressure value of 100 kPa (zero vacuum).
- An IPW of 2.5 ms.
- An injection period of 10 ms (100 injections per second).

c. Note that a mass flow rate of n-heptane measured for standard ambient conditions is designated as Q_{std}. Thus, these measured dynamic flow rates will be the baseline Q_{std} values to be used in Equation 2 for the 2.5 ms IPW test series.

d. For that same test injector, repeat the test using the larger IPW value of 5.0 ms to obtain the baseline dynamic flow for an IPW of 5.0 ms. These dynamic flow rates will be the baseline Q_{std} values to be used in Equation 2 for the 5.0 ms IPW test series.

e. Repeat steps (b) through (d) for each of the test injectors to obtain the baseline dynamic flow rates at pulse widths of both 2.5 ms and 5.0 ms for the entire set of test injectors.

f. For IPW values of both 2.5 ms and 5.0 ms, measure the dynamic flow rates, Q_d, of all of the test injectors for all combinations of the six temperatures and the three downstream pressure levels (five for forced induction) that are listed below in this step. These tests are to be performed for an IPW of 10 ms. This will be either 34 or 58 additional tests for each injector, as 21 °C and ambient pressure will have already been run. Thus, for each of the six temperatures, either three or five different downstream pressure levels will be used. These dynamic flow rates will be the Q_d values to be used in Equation 2 during data reduction. The fuel and injector temperatures to be tested are -30, 0, 21, 50, 75, and 100 °C. For each of these temperatures test at a downstream air pressure of ambient (zero vacuum), and at the downstream negative pressure levels of 40 kPa (vacuum) and 85 kPa (vacuum). If the injector model being tested is intended for a turbocharger or supercharger application, also test at the positive (boost) downstream air pressure values of +100 kPa (gauge) and +50 kPa (gauge). These two additional boost downstream pressures do not have to be tested if a forced-induction system is not part of the intended application. Just leave those spaces blank on the data reporting sheet.

g. In regard to the order of the tests that are called for in step (g), it may be more efficient to run all of the test injectors and required downstream pressures and pulse widths at a particular flow stand fuel temperature first, then switching to the next test temperature. This might avoid changing and stabilizing the test stand temperature hundreds of times. This is an acceptable alternative test order if utilized, and does not have to be reported as a test deviation.

6.11.2 Data Reduction and Analysis for the Dynamic Flow Shift Test

Compute the percentage shift in the measured dynamic flow rate, Q_{fs}, from the measured Q_d and Q_{std} values for each of the test injectors for each combination of temperature and downstream air pressure. Use Equation 14 for this computation. This equation from 3.2.7 is repeated here for convenience. Perform this calculation for both the 2.5 ms and 5.0 ms IPW test data.

$$\text{Dynamic flow shift percentage} = Q_{fs} = 100 * (Q_d - Q_{std})/Q_{std} \quad \text{(Eq. 14)}$$

where:

Q_{std} = the injector dynamic flow at a standard fuel temperature and a standard (ambient) downstream pressure

Q_d = the injector dynamic flow at the non-standard fuel temperature or non-standard downstream pressure being tested

6.11.3 Data Reporting for the Dynamic Flow Shift Test

Use a copy of the proper blank data reporting sheet for each tested injector. The data sheet to be copied is the second page of the two pages that are shown. Report the individual percentage deviations, Q_{fs}, that were computed for each combination of temperature and pressure in the proper indicated spaces on the data reporting sheet for each of the tested injectors. Note any deviations from the recommended test procedure. Attach these extra data reporting sheets (at least eight of them) to the first (initial) page of the data reporting sheet.

Table 13 - SAE data reporting sheet for dynamic flow shifts resulting from changes in environmental conditions

SAE J1832 - Data Reporting Sheet for Dynamic Flow Shifts Resulting from Changes in Environmental Conditions - Page 1 of 2			
Part 1: General Test Information This Datasheet is for Injector _____ of _____			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on Injector			
Injector manufacturer			
Injector description Static flow rate (@pressure) Inward/outward single/dual type Bent/coaxial Multi-hole			
Injector part number			
Injector serial number			
Additional information			
Part 3: Test Conditions	**Specific Test Conditions**	**Standard PFI Test Conditions**	
Test fluid		n-heptane	
Ambient temperature (°C)		21 ± 2	
Ambient pressure (kPaa)		100 ± 5	
Fluid temperature (°C)		21 ± 2	
Test fuel pressure (kPa)		P_{NORM} ± 0.5%	
Test pressure tolerance		±0.5%	
Injector temperature (°C)		21 ± 2	
Injection pulse width (ms)		2.5 and 5.0 ± 0.005 - dependent upon test	
Injection period (ms)		10 ± 0.01	
Part 4: Description and Comments on Test Instruments or Test Deviations			
Comments and clarifying information			
Test deviations present and any instabilities observed during testing			

Part 5: Test Results for Dynamic Flow Shifts Resulting from Changes in Environmental Conditions (Injector Operating Temperature and/or Downstream Vacuum or Pressure) - Use a new blank copy of this data reporting sheet for each injector - Page 2 of 2							
Injector Number _____ of _____ Total				**Injector S/N:**			
Pressure (kPa)	Temp (°C)	Q_d (mg/pulse)	% Flow Shift	Pressure (kPa)	Temp (°C)	Q_d (mg/pulse)	% Flow Shift
0	21			0	21		
2.5 ms IPW				5.0 ms IPW			
40 vacuum				40 vacuum			
85 vacuum	21			85 vacuum	21		
+50 *				+50 *			
+100 *				+100 *			
40 vacuum				40 vacuum			
85 vacuum				85 vacuum			
0	-30			0	-30		
+50 *				+50 *			
+100 *				+100 *			
40 vacuum				40 vacuum			
85 vacuum				85 vacuum			
0	0			0	0		
+50 *				+50 *			
+100 *				+100 *			
40 vacuum				40 vacuum			
85 vacuum				85 vacuum			
0	50			0	50		
+50 *				+50 *			
+100 *				+100 *			
40 vacuum				40 vacuum			
85 vacuum				85 vacuum			
0	75			0	75		
+50 *				+50 *			
+100 *				+100 *			
40 vacuum				40 vacuum			
85 vacuum				85 vacuum			
0	90			0	90		
50 *				50 *			
100 *				100 *			
* Optional for forced induction applications.							

7. PHYSICAL TESTS

Fuel injectors are subjected to various mechanical loads during manufacturing, testing, handling, installation, and removal from the vehicle fuel system. The injector is also subjected to various shock and vibrational loads during operation in actual vehicle service. The purpose of physical testing is to ensure that the injector flow performance, electrical characteristics, and fuel leakage will exhibit no flow and electrical changes when undergoing these mechanical loadings.

7.1 Overview of All Physical Tests

A port fuel injector is typically subjected to an axial load, a bending moment and a torsional load during installation and removal. This is required to overcome the resistance of O-rings or other elastomeric members that are used for the purpose of sealing, and for thermal and mechanical isolation. The injector is also subjected to loads resulting from mounting and removing the fuel rail and/or installing and removing an injector in the rail. The spectrum of such physical tests is normally divided into two classes. The first class consists of those involving forces and moments, which are the axial load, torsional moment, and bending moment tests. The forces and torques are normally applied by pushing and twisting the upper half of the injector relative to the stationary lower half, as the upper half of most current PFI injector designs contain the electrical connector and the lower half contains the fuel metering section. For the force and moment tests, the injector is devoid of fluid, is uncapped and the electrical connector is not installed. The second class of physical tests is denoted as the operational physical tests, and consists of tests for vibration, mechanical shock, proof pressure, and burst pressure. This class of physical tests is addressed in 7.7 through 7.10.3.

7.2 Test Fixtures for Force and Moment Physical Tests

Several representative test fixtures are illustrated in this section, as one fixture design will likely not accommodate all injector designs. This is because of the significant variety of injector designs and mounting methods that are in use. The specific fixture that is employed for a given physical test in the series must accommodate the particular injector design and application that is being tested. Thus, the test fixtures that are employed may necessarily differ slightly from the generic fixtures that are illustrated and described in the following sections. This is not to be considered a test deviation.

7.3 Common Test Steps for Force and Moment Physical Tests

It is not intended that multiple loading tests be applied to an injector prior to measuring the operational changes. The intent is to have one test type applied to one new injector, with the next test in the series applied to another new unit of that same type of injector. Therefore, do not apply all six loading tests to a single injector, and then measure the flow or leakage changes. Use one new injector for each separate test. The only permitted exception to this is if a combined vibration and shock test is utilized. Those two tests may be applied to one injector.

For all force-and-moment physical tests, each individual test is to be performed on a minimum of five new injectors of the same make and model from serial production. The procedure for all physical tests is to first pre-condition each new test injector according to Table 2. Next, measure Q_s, Q_{sp}, R, IR, and tip leakage for each new injector prior to any physical testing. The flow measurement procedures for those parameters are listed in 5.6, 5.2, and 5.5, respectively. Then, all test fuel is to be removed from the injector and one of the Force-and-moment physical tests is performed as described in the corresponding procedure for that test in the subsections below. Finally, following the completion of that individual physical test, the injector is to be retested for R and IR, then reinstalled on the flow test bench, refilled with test fuel, and the flow parameters of Q_s and Q_{sp} are to be remeasured. Next, the injector is to be reinstalled on the tip leakage test bench, refilled with the tip-leakage test fluid, and the tip leakage re-measured. A minimum set of five new injectors of the same make and model from serial production are to be tested in this manner. More injectors may be optionally tested if required.

7.4 Axial Load Test

7.4.1 Procedure for Axial Load Test

a. A minimum test set of five new injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. The injectors should be pre-conditioned according to Table 2.

b. Prior to any axial load being applied, measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage according to the procedures outlined in 5.5, 5.2, and 5.6.

c. The injector to be tested shall be drained of any test fluid, and shall have the injector fuel inlet port open and the tip uncapped. The electrical connector is not to be installed.

d. Mount the injector in an axial test fixture that is representative of the application mounting. A typical fixture is illustrated in Figure 19.

e. Subject the injector to a force of 600 N applied along the longitudinal axis of the injector, as is depicted by the small arrow at the top of Figure 19. The force is to be steadily applied for a duration of 1 minute.

f. Following the axial load test, inspect the injector body and re-measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage as outlined in 5.5, 5.2, and 5.6.

g. Repeat the test for the next injector in the set.

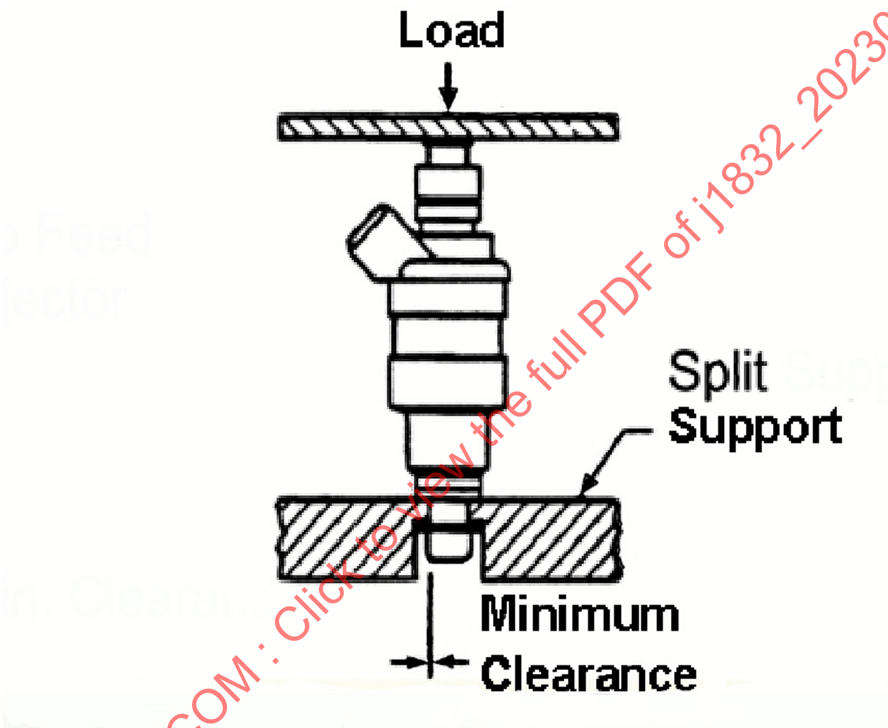


Figure 19 - Representative axial load test fixture

7.4.2 Data Reduction and Analysis for the Axial Load Test

For each of the five or more test injectors, compute the deviations in Q_s, Q_{sp}, R, IR, and tip leakage from the pre-test values to the post-test values. The deviations in Q_s and Q_{sp} shall also be computed as a percentage change.

7.4.3 Data Reporting for the Axial Load Test

The measurements of Q_s, Q_{sp}, R, IR, and tip leakage that were obtained both before and after the axial load test are to be reported on the data reporting sheet under the appropriate test. The changes in Q_s and Q_{sp} are also to be reported as percentage changes. Use a different Page 2 of the data reporting sheet for each test injector, and note on that page the serial number of the injector being reported upon.

7.5 Torsional Moment Test

7.5.1 Procedure for Torsional Moment Test

a. A minimum test set of five new injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. The injectors should be pre-conditioned according to Table 2.

b. Prior to any torsional moment being applied, measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage according to the procedures outlined in 5.5, 5.2 and 5.6.

c. The injector to be tested shall be drained of any test fluid, and shall have the injector fuel inlet port open and the tip uncapped. The electrical connector is not to be installed.

d. Mount the injector in a torsional moment test fixture that is representative of the application mounting. The central portion of the injector body is to be clamped and fixed. A typical fixture is illustrated in Figure 20.

e. Subject the injector to a torsional moment of 0.6 Nm that is applied both at the fuel-inlet end and the tip end, as is depicted by the moment arrows at the top and bottom of Figure 19. These moments are to be about the longitudinal axis of the injector and are to be applied for a duration of 5 seconds.

f. Following the torsional moment test, inspect the injector body and re-measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage in 5.5, 5.2, and 5.6.

g. Repeat the test for the next injector in the set.

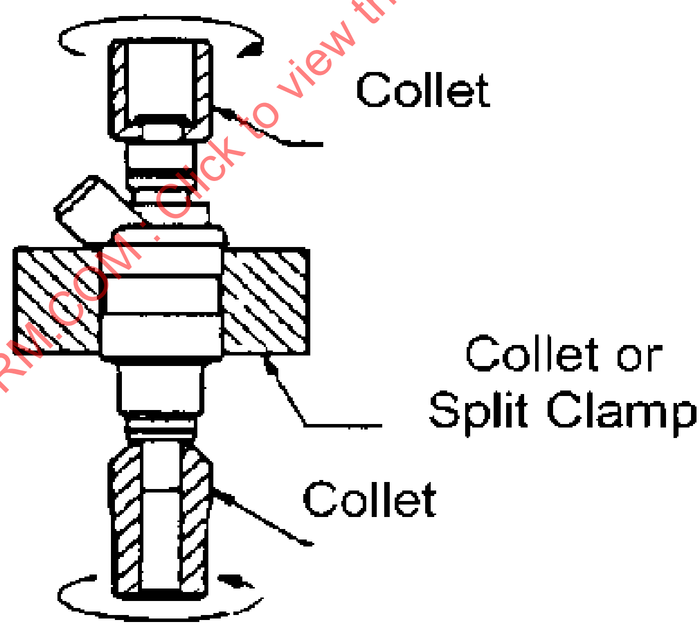


Figure 20 - Representative torsional moment test fixture

7.5.2 Data Reduction and Analysis for the Torsional Moment Test

For each of the five or more test injectors, compute the deviations in Q_s, Q_{sp}, R, IR, and tip leakage from the pre-test values to the post-test values. The deviations in Q_s and Q_{sp} shall also be computed as a percentage change.

7.5.3 Data Reporting for the Torsional Moment Test

The measurements of Q_s, Q_{sp}, R, IR, and tip leakage that were obtained both before and after the torsional moment test are to be reported on the data reporting sheet under the appropriate test. The changes in Q_s and Q_{sp} are also to be reported as percentage changes. Use a different Page 2 of the data reporting sheet for each test injector, and note on that page the serial number of the injector being reported upon

7.6 Bending Moment Test

7.6.1 Procedure for Bending Moment Test

a. A minimum test set of five new injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. The injectors should be pre-conditioned according to Table 2.

b. Prior to any bending moment being applied, measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage according to the procedures outlined in 5.5, 5.2, and 5.6.

c. The injector to be tested shall be drained of any test fluid, and shall have the injector fuel inlet port open and the tip uncapped. The electrical connector is not to be installed.

d. Mount the injector in a bending moment test fixture that is representative of the application mounting. The central portion of the injector body is to be clamped and fixed. A typical fixture is illustrated in Figure 21.

e. Subject the injector to a bending moment of 6.0 Nm by means of a horizontal force that is applied at the O-ring groove of the fuel inlet. This is depicted by the arrows at the top of Figure 21. This horizontal force that creates the bending moment is to be applied for a duration of 30 seconds.

f. Following the bending moment test, inspect the injector body and re-measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage as outlined in 5.5, 5.2, and 5.6.

g. Repeat the test for the next injector in the set.

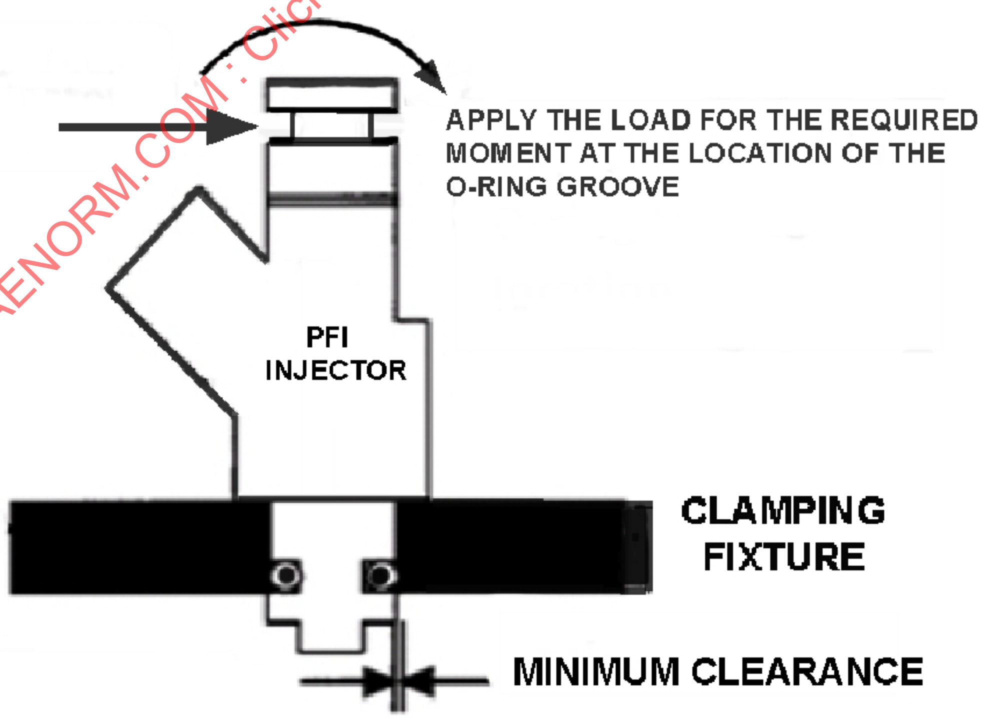


Figure 21 - Locations for clamping and loading for the bending moment test

7.6.2 Data Reduction and Analysis for the Bending Moment Test

For each of the five or more test injectors, compute the deviations in Q_s, Q_{sp}, R, IR, and tip leakage from the pre-test values to the post-test values. The deviations in Q_s and Q_{sp} shall also be computed as a percentage change.

7.6.3 Data Reporting for the Bending Moment Test

The measurements of Q_s, Q_{sp}, R, IR, and tip leakage that were obtained both before and after the Bending Moment test are to be reported on the data reporting sheet under the appropriate test. The changes in Q_s and Q_{sp} are also to be reported as percentage changes. Use a different Page 2 of the data reporting sheet for each test injector, and note on that page the serial number of the injector being reported upon.

7.7 Overview of Operational Physical Tests

The second class of physical tests deal with the vibration, mechanical shock and overpressure that a PFI injector may be subjected to during an operating lifetime. This class of tests addresses the further significant stresses that can be applied to a PFI injector during a normal lifetime of operation on an engine. Engine vibration can be severe, with significant g-forces. Fuel overpressure may possible occur due to a system malfunction, and mechanical shock can occur due to dropping the injector or striking it with metal tools.

The operational physical tests consist of the vibration, mechanical shock, proof pressure and burst pressure tests. In this class of physical tests, all tests are performed on five new injectors of the same make and model from serial production, with only one test performed on any one injector. Therefore, do not apply all four operational physical tests to a single injector, and then measure the flow or leakage changes. With the exception of the combined vibration and mechanical shock tests noted below, use one new injector for each separate test. In each operational physical test, the injector is filled with Stoddard solvent. Note that it is not to be filled with n-heptane. In some operational physical tests, the injector is capped, but not pressurized (vibration and mechanical shock) and in other tests it is pressurized (proof and burst pressure). In none of the operational physical tests is the injector operated, although the electrical connector and the wiring harness are installed for the vibration and mechanical shock tests.

7.8 Vibration Test

The vibration test methodology and durations will follow the ISO 16750-3 standard for engine-mounted components. The vibration schedule is to be sine-on-random with the frequency controlled over the range of 5 to 2000 Hz. The sinusoidal tone portion of the test should also follow Table 1 of the ISO-16750-3 standard (which is for components mounted directly on the engine of passenger vehicles). The combined test schedule should follow Table 2 (sine spectrum) and Table 3 (random spectrum) in ISO 16750-3. If an application-specific vibration schedule is available, this may be substituted without deviation for the ISO 16750-3 sine-on-random profiles if it is clearly noted on the data reporting sheet. Any deviations from these protocols shall be reported on the data reporting sheet.

7.8.1 Procedure for the Vibration Test

The vibration test fixture should duplicate the application mounting; the fixture must allow for the pressurization of fluid in the injector to P_{NORM}, and must permit the collection of any fluid lost from the injector tip. Accelerometers should be placed on the injector housing that is aligned with the injector longitudinal axis. The injector electrical wiring harness shall be connected to the injector during testing. Fill the injector and fixture with Stoddard solvent for the purpose of simulating the mass only. After filling with Stoddard solvent, ensure that any trapped air is removed. On a vibration table, vibrate the injector in each of the three axes (first longitudinal, then lateral, then vertical). A picture or sketch of the accelerometer locations should be included on the data sheet for each axis.

If both mechanical shock and vibration tests are to be conducted, it is recommended to run the vibration and mechanical shock tests as combined sequential tests on each of the three individual axes. This would be longitudinal vibration followed by longitudinal mechanical shock, then repeating for the lateral axis, then for the vertical axis. The injector performance parameters of Q_s, Q_{sp}, and tip leakage shall be measured prior to and following the combined series of vibration and mechanical shock tests that were just described.

a. A minimum test set of five new, injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. The injectors should be pre-conditioned according to Table 2.

b. Prior to any vibration testing or combined Vibration and Shock testing, measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage according to the procedures outlined in 5.6, 5.2, and 5.5 of this document.

c. The injector to be tested shall be filled with Stoddard solvent for mass purposes only, and shall have the fuel inlet and tip capped. The test fluid can be pressurized or not pressurized as needed, to simulate in vehicle mounting and operation. The electrical connector and the wiring harness are to be installed, however the injector is not to be operated.

d. Mount the injector in a vibration-shock test fixture that has an injector mounting that is representative of the application. A typical fixture is illustrated in Figure 22. The accelerometers on this fixture should be placed at the same relative location as was utilized for any vibration data acquisition on the vehicle. Any collection of data on vehicle vibration should include the extremes that may be encountered in field use.

e. Using a controlled vibration test facility, vibrate the injector in each of the three axes (first longitudinal, then lateral, and then vertical). The vibration schedule is to be random with the frequency controlled over the range of 5 to 2000 Hz, based upon the actual vehicle application. The test duration is to be 22 hours per axis. The test may be optionally accelerated per the random vibration practices described in the reference document MIL-STD-810-D if clearly noted in the comments section of the data reporting sheet.

f. Following the vibration or combined vibration-shock test, inspect the injector body and re-measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage.

g. Repeat the test for the next injector in the set.

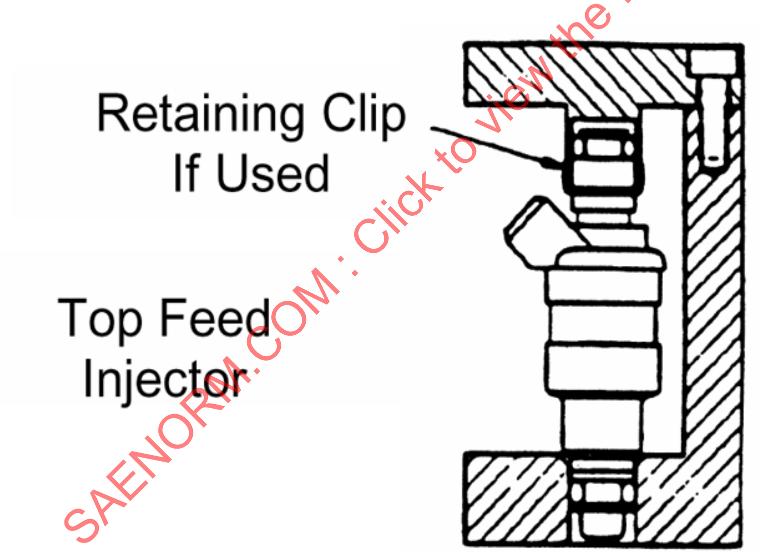


Figure 22 - Fixture for both shock and vibration testing

7.8.2 Data Reduction and Analysis for the Vibration Test

For each of the five or more test injectors, compute the deviations in Q_s, Q_{sp}, R, IR, and tip leakage from the pre-test values to the post-test values. The deviations in Q_s and Q_{sp} shall be computed as a percentage change.

7.8.3 Data Reporting for the Vibration Test

For each of the five or more test injectors, record the pre-test and post-test values, and their deviations, for Q_s, Q_{sp}, R, IR, and tip leakage on the data reporting sheet. The deviations in Q_s and Q_{sp} shall also be reported as a percentage. Use a different Page 2 of the data reporting sheet for each of the test injectors, and note on that page the serial number of the injector being reported.

7.9 Mechanical Shock Test

7.9.1 Procedure for the Mechanical Shock Test

The mechanical shock test shall consist of a 50 g shock pulse having a half-sine shape with a pulse width of 11.0 to 14.0 ms. The number of shock pulses shall be 18 in total, and shall be comprised of six pulses in each of the three mutually perpendicular axes.

a. A minimum test set of five new injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. The injectors should be pre-conditioned according to Table 2 in this document.

b. Prior to any mechanical shock or combined vibration-shock testing, measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage according to the procedures outlined in 5.6, 5.2, and 5.5 of this document.

c. The injector to be tested shall be filled with Stoddard solvent for mass purposes only, and shall have the injector fuel inlet port and tip capped. The test fluid is not to be pressurized. The electrical connector and the wiring harness are to be installed, however the injector is not to be operated.

d. Mount the injector in a vibration-shock test fixture that has an injector mounting that is representative of the application. A typical fixture is illustrated in Figure 22. The accelerometers on this fixture should be placed at the same location as per vehicle data acquisition.

e. Perform impacts that provide 50 g of input acceleration load, each lasting for a duration of 11 to 14 ms. Perform this six times with the injector in the vertical position (valve tip pointing downward), six times with the injector in the horizontal position with connector pointing up and six times with the injector in the horizontal position with the connector pointing to the side.

f. Following the mechanical shock test or the combined vibration-shock test, re-measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage.

g. Repeat the test for the next injector in the set.

7.9.2 Data Reduction and Analysis for the Mechanical Shock Test

For each of the five or more test injectors, compute the deviations in Q_s, Q_{sp}, and tip leakage from the pre-test values to the post-test values. The deviations in Q_s and Q_{sp} shall be computed as a percentage change.

7.9.3 Data Reporting for the Mechanical Shock Test

For each of the five or more test injectors, record the pre-test and post-test values, and their deviations, for Q_s, Q_{sp}, R, IR, and tip leakage on the data reporting sheet. The deviations in Q_s and Q_{sp} shall also be reported as a percentage. Use a different Page 2 of the data reporting sheet for each of the test injectors, and note on that page the serial number of the injector being reported.

7.10 Overview of Proof-Pressure Testing

The proof pressure is an elevated level of fuel pressure that the fuel injector may be subjected to and still operate properly once the normal fuel pressure is reestablished. The fuel injector is not expected to function at the proof pressure, but shall function properly after exposure to this pressure without damage. The objective of this test is to ascertain the amount of permanent change in key performance parameters that results from the application of the proof pressure. The proof pressure is normally specified by the injector manufacturer and is typically twice the normal operating pressure for that injector (2.0 times P_{NORM}). Another reason for performing the proof pressure test is to verify that the fuel injector body is capable of withstanding the specified proof pressure at 21 °C ± 2.0 °C for 5 minutes without structural failure, internal damage, or external visual leakage. A minimum set of five new injectors of the same make and model from serial production is to be tested, and the test fluid utilized shall be Stoddard solvent.

7.10.1 Procedure for the Proof-Pressure Test

a. A minimum test set of five new injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. The injectors should be pre-conditioned according to Table 2 of this document.

b. Prior to any proof-pressure testing, measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage according to the procedures outlined in 5.6, 5.2, and 5.5.

c. The injector to be tested shall be filled with the test fluid (Stoddard solvent at 21 °C), and shall have the fuel inlet connected to a pressure vessel containing Stoddard solvent at 21 °C that is pressurized by means of nitrogen gas acting on a bladder. During this test, the injector is not operated, as the electrical connector is not installed.

d. Mount the injector onto a fixture that is placed within a safe containment vessel. Next, gradually increase the nitrogen pressure on the bladder until the fluid pressure within the injector attains 2.0 times P_{NORM}. Maintain that pressure level for five minutes. Observe and record any visible fluid leakage.

e. Reduce the fluid pressure back to zero and remove the injector from the fixture.

f. Following the proof-pressure test, re-measure the key performance parameters of Q_s, Q_{sp}, R, IR, and tip leakage for the test injector.

g. Repeat the test for the next injector in the set.

7.10.2 Data Reduction and Analysis for the Proof Pressure Test

For each of the five or more test injectors, compute the deviations in Q_s, Q_{sp}, R, IR, and tip leakage from the pre-test values to the post-test values. The deviations in Q_s and Q_{sp} shall be computed as a percentage change.

7.10.3 Data Reporting for the Proof Pressure Test

For each of the five or more test injectors, record the pre-test and post-test values and their deviations for Q_s, Q_{sp}, R, IR, and tip leakage on the data reporting sheet. The deviations in Q_s and Q_{sp} shall also be reported as a percentage. Use a different Page 2 of the data reporting sheet for each of the test injectors, and note on that page the serial number of the injector being reported.

7.11 Overview of Burst Pressure Testing

The objective of bust pressure testing is to determine that the fuel injector is able to withstand an applied pressure of three times the normal operating fuel pressure (3.0 times P_{NORM}) without bursting or leaking. The fuel injector is not expected to function normally after exposure to this pressure level, but it must not exhibit a rupture or any external leakage. To facilitate leak detection during and following the test, the test fluid shall be doped with a dye tracer that fluoresces either wet or dry when exposed to an ultraviolet light. A minimum set of five new injectors of the same make and model from serial production is to be tested, and the test fluid used shall be Stoddard solvent.

7.11.1 Procedure for the Burst Pressure Test

a. A minimum test set of five new injectors of the same make and model from serial production should be tested. Pre-production injectors may be used without deviation if this is clearly noted in the comments section of the data reporting sheet. Pre-conditioning of the injectors is not required.

b. Prepare a quart of Stoddard solvent for detection of liquid leakage by means of an ultraviolet light by adding a suitable dopant that fluoresces when exposed to ultraviolet light.

c. The injector to be tested shall be filled with the test fluid containing the dopant (Stoddard solvent at 21 °C), and shall have the fuel inlet connected to a pressure vessel containing the same Stoddard solvent at 21 °C that is pressurized by means of nitrogen gas acting on a bladder. During this test, the injector is not operated, as the electrical connector is not installed.

d. Mount the injector onto a fixture within a safe containment vessel that permits a visualization of the injector with an ultraviolet light. Gradually increase the nitrogen pressure on the bladder until the fluid pressure within the injector attains 3.0 times P_{NORM}. Maintain that pressure level for 5 minutes.

e. During the 5-minute pressurization period, examine the entire body of the test injector with an ultraviolet light for evidence of any external leakage. After 5 minutes, reduce the pressure to P_{NORM} and continue the examination.

f. After completing a thorough examination, remove all pressurization of the Stoddard solvent and remove the injector. Note the location and extent of any observed external leakage or body damage.

g. Repeat the test for the next injector in the set.

7.11.2 Data Reduction and Analysis for the Burst-Pressure Test

None required.

7.11.3 Data Reporting for the Burst-Pressure Test

For each of the five or more injectors that were tested, record on the data reporting sheet whether or not any external damage or leakage of any type was detected. Use a different Page 2 of the data reporting sheet for each of the test injectors, and note on that page the serial number of the injector being reported.

Table 14 - SAE data reporting sheet for PFI injector physical tests

SAE J1832 - Data Reporting Sheet for PFI Injector Physical Testing - Page 1 of 2			
Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on PFI Injector and PFI Injector Driver Type			
Injector manufacturer			
Injector description			
Injector part number		(enter injector S/N on Page 2 of the datasheet)	
Injector driver type			
Part 3: Test Conditions	**Force-and Moment Physical Test Types**	**Operational Physical Test Types**	
** Physical tests being reported (Circle all those being reported)	Axial loading bending moment torsional loading	Vibration proof pressure shock burst pressure	
Conditions for Physical Tests	**Specific Test Conditions**	**Standard Test Conditions**	
Ambient temperature (°C)		21 ± 2	
Ambient pressure (kPaa)		100 ± 5	
Fluid temperature (°C)		21 ± 2	
Fluid pressure for testing (kPa)		Normal pressure (P_{NORM}), ±0.5%	
Injector period (P) for flow testing before and after (ms)		10.0 ± 0.01	
Injection pulse width for flow testing before and after (ms)		2.5 ± 0.005	
Part 4: Description and Comments on Equipment or Test Deviations			
Comments and information			
Test deviations present			

Part 5: Specific Test Measurements for Physical Tests - Use New Page 2 for Each Injector - Page 2 of 2			
Injector serial number: ____________________		Injector in Test Series Number _____ of _____	
Axial Loading Test	Pre-Test Value	Post-Test Value	Deviation
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
R (Ω)			(Ω)
IR (Ω)			(Ω)
Tip leakage rate (mm^3/min)			(mm^3/min)
Torsional Moment Test	Pre-Test Value	Post-Test Value	Deviation
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
R (Ω)			(Ω)
IR (Ω)			(Ω)
Tip leakage rate (mm^3/min)			(mm^3/min)
Bending Moment Test	Pre-Test Value	Post-Test Value	Deviation
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
R (Ω)			(Ω)
IR (Ω)			(Ω)
Tip leakage rate (mm^3/min)			(mm^3/min)
Vibration Test	Pre-Test Value	Post-Test Value	Deviation
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
R (Ω)			(Ω)
IR (Ω)			(Ω)
Tip leakage rate (mm^3/min)			(mm^3/min)
Shock Test	Pre-Test Value	Post-Test Value	Deviation
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
R (Ω)			(Ω)
IR (Ω)			(Ω)
Tip leakage rate (mm^3/min)			(mm^3/min)
Proof Pressure Test	Pre-Test Value	Post-Test Value	Deviation
Q_{sp} (mg/pulse)			%
Q_s (g/s)			%
R (Ω)			(Ω)
IR (Ω)			(Ω)
Tip leakage rate (mm^3/min)			(mm^3/min)
Burst Pressure Test	Circle One	Circle One	
External leakage observed? (mm^3/min)	No leakage	Yes, leakage observed	Comment:
Additional Test Comments			
Additional information and test comments; indicate the name of the test being commented upon			
Attachments and data plots	None required		

8. INJECTOR NOISE MEASUREMENT

8.1 Overview of PFI Injector Noise

Acoustical noise from a low-pressure port fuel injector (PFI), often described as a ticking noise, is generated by the opening and/or closing events of the fuel shut-off valve within the injector. The injector noise is most audible in a vehicle during the idle and fast-idle operating conditions when the masking from other engine and vehicle noises are low. This can be either the stable, hot-idle condition or may be the cold-idle condition during the transient engine warm-up.

The noise generated by the opening and closing events of the PFI injector is radiated directly from its housing, unless the injector is directly mounted on its face to the intake manifold. Unlike direct gasoline injectors, the mechanical vibrations generated by these events in a PFI injector are unlikely to excite the neighboring structures due to the very low operating fuel pressure. Other noises that may be misdiagnosed as injector noise are normally found to be generated by pressure pulsations from the injector opening and closing events interacting with the hydraulic resonances of the fuel system. This is commonly referred to as "fuel line hammer."

Due to the structural asymmetry of the injector housing, the noise radiated by the PFI injector is very directional. Hence, the sound pressure level measured using one or two microphones is insufficient to characterize the overall noise generated by these injectors. Therefore, the most appropriate technique for characterizing port fuel injector noise is to measure the sound pressure level using multiple microphones on an imaginary spherical or hemispherical surface around the injector, and then calculating the total sound power radiated by the injector. In order to calculate the sound power, the procedures described in the ISO 3744 and ISO 3745 documents are used.

8.2 Test Equipment Requirements for PFI Noise Measurement

The noise that is radiated from an operating PFI injector shall be measured with the injector isolated from its application environment. The injector shall be mounted in a way that ensures that the noise measured is only the direct, airborne, radiated noise from the injector. The injector mounting shall represent the application-relevant boundary conditions, which include a rail cup with a mounting clip at the top, as well as a receiving cup at the tip of the injector. If the microphones are attached to a frame for ease of measurement, then such a frame shall be isolated from the fixture using elastomeric elements. N-heptane is the nominal test fluid; however, if a non-flammable fluid is deemed to be necessary for the test chamber, then such a fluid having physical properties that are similar to those of either n-heptane or standard pump gasoline may be utilized without a test deviation. Some alternate fluids meeting this criteria are Stoddard solvent and mineral spirits.

The noise measurement should preferentially be performed in either a fully anechoic or a hemi-anechoic chamber according to the procedures outlined in ISO 3745. If this test environment cannot be accessed, then a free-field environment using a reflecting plane may be employed. The procedures for this test environment are outlined in ISO 3744. These ISO standards are both titled, "Acoustics - Determination of Sound Power Levels and Sound Energy Levels of Noise Sources using Sound Pressure," where ISO 3744 is an engineering method for an essentially free-field environment using a reflecting plane, and ISO 3745 is a precision method employed for anechoic rooms and hemi-anechoic rooms. As is noted in both ISO 3744 and ISO 3745, the radiated noise from the injector shall be measured over the entire spherical surface around the injector or over a hemispherical surface that has a reflecting plane, with the injector mounted near the reflecting plane. As indicated, the measurement may be performed with either a single microphone or with multiple microphones. An example of the use of six microphones mounted in a half-circle configuration within a hemi-anechoic test chamber is illustrated in Figure 23. The rotation of this plane of microphones to eight discrete measurement locations (every 45 degrees) is outlined in the test procedure in the subsequent subsection. When the measurements are performed in a hemi-anechoic chamber, the injector shall be mounted at least 1.0 m above the chamber floor. All horizontal reflecting surfaces in the test setup or the chamber floor should be treated with sound absorbing material of at least 100 mm thickness.

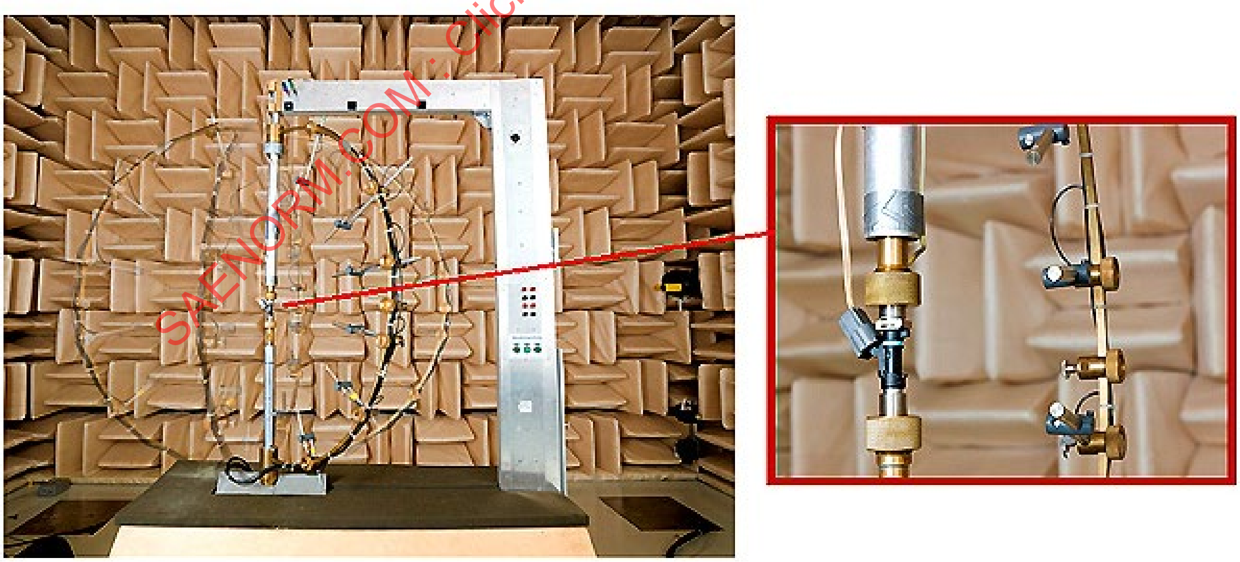


Figure 23 - Representative test facility and fixture for PFI noise testing

The sound power that quantifies the resultant injector noise shall be calculated from these microphone measurements using a procedure similar to that outlined in ISO 3744 (2010-10-01) or in ISO 3745 (2012-3-15). If there is excessive background noise from equipment that is employed to operate the PFI injector, a correction for the background noise shall be performed using the average of all microphone positions at the respective 1/3 octave band, as is noted in ISO 3744. The computed values of sound power shall be presented as a 1/3 octave band spectrum from 1000 to 16000 Hz. A single value of the A-weighted sound power shall then be computed and reported in dB(A).

As the sound power is a characteristic of the component and it is independent of the distance at which the sound pressure is measured, the choice of the radius of the measurement sphere upon which the microphones are placed, be it 0.3 m or 0.5 m, is not critical. However, the accuracy of the measurement for the lowest frequency of interest will be degraded as the sphere radius is diminished. For the frequency range from 1000 to 16000 Hz, experience has verified that six microphones mounted on a semicircular arc of a radius of not less than 0.3 m that is sequentially indexed to every 45 degrees location around the test injector will provide a sufficient spatial resolution and accuracy to determine the sound power from a PFI injector. A representative test setup for PFI noise measurement over a spherical surface around the injector in a hemi-anechoic chamber is illustrated in Figure 23. This type of setup is to be tested according to ISO 3745. Conversely, a test setup in free space using a reflecting plane shall be tested according to ISO 3744.

8.3 PFI Noise Test Parameters and Test Conditions

a. The nominal test fluid is n-heptane. Stoddard solvent or mineral spirits may be used if necessary without a deviation. On the data reporting sheet, specify the test fluid type that is utilized.

b. The test fuel pressure shall be P_{NORM} ± 0.5%.

c. The ambient air temperature shall be maintained at 21 °C ± 2 °C.

d. The fuel temperature shall be maintained at 21 °C ± 2 °C.

e. The relative humidity in the test chamber shall be maintained below 65%.

f. The injection pulse width (IPW) shall be set to 4.0 ms.

g. The period (P) shall be set to 100 ms (ten injections per second). This corresponds to an engine speed of 1200 rpm.

h. The pulse width in step (f) and the period in step (g) are the SAE J1832 standard test conditions for the SAE J1832 noise measurement, any other test conditions may be alternatively used if desired; for example, a 200 ms period that represents a stable, hot-idle speed of 600 rpm may be used, as long as this test deviation is clearly indicated on the data reporting sheet. It should be noted that only the use a 4.0 ms pulse width and a period of 100 ms will lead to the SAE J1832 noise value. The optional testing of any other pulse width or period will yield a noise value on the data reporting sheet, but it is not to be indicated as the SAE J1832 noise value.

8.4 Test Procedure for Injector Noise Measurement

a. A set of five new injectors of the same make and model from serial production is to be tested.

b. In order to remove all gases from the fuel supply system and ensure that the injector induced noise has stabilized, pre-condition each test injector as per the procedure in Table 2. However, extend the flush duration to 3 minutes and the purge duration to 10 minutes.

c. Measure the background noise in the test environment. This is to be done without the operation of the injector, but with the operation of all other auxiliary equipment required during the injector operation. The background noise shall be measured at all microphone measurement locations planned for the measurements with the injector operating. If the data suggests that the background noise cannot be regarded as unchanging with test duration, then it is required that the sound pressure level shall be measured and recorded each time a new injector is measured in order to capture any shift in the background noise of the auxiliary equipment used for the test, such as the fuel pump.

d. Set the test conditions for the injector operation as noted in the subsection on noise test parameters.

e. Set the position of the semicircular arc of microphones. Six microphones equally spaced are recommended. Energize the injector and record the sound pressure level for a minimum of 10 seconds at each microphone measurement point.

f. Rotate the semicircular arc of microphones by 45 degrees and repeat step (e). Then rotate by additional 45 degree increments until eight total increments have been measured around the injector.

g. Repeat steps (b) through (f) for the four additional new injectors from series production.

8.5 Sound Pressure Level Calculations for Background and Injector Noise Measurements

a. From the measured sound pressure at each measurement position i, calculate A-weighted sound pressure levels, $L_{pi}(f)$, for each 1/3 octave band from 1000 to 16000 Hz. Perform these calculations for both the background and injector noise measurements.

For each 1/3 octave band calculate an average sound pressure level, $L_p(f)$, over all measurement positions. The average for sound pressure level values is computed as a logarithmic average using Equation 15. These calculations are to be made for the sound pressure level associated with both the background and injector noise measurements.

$$L_p(f) = 10\log_{10}\left[\frac{1}{N_M}\sum_{i=1}^{N_M} 10^{0.1Lpi\,(f)}\right] \quad \text{(Eq. 15)}$$

where:

i = the measurement location (microphone position) identification number

N_M = the total number of measurement locations (microphone positions)

f = the center frequency of the 1/3 octave band, in Hz

Using Equation 16, compute the overall sound pressure level ($\overline{L}_p$) in dB(A) for the frequency range from 1000 Hz to 16000 Hz as the logarithmic sum of the sound pressure levels at each of the 1/3 octave bands calculated above, $L_p(f)$.

$$\overline{L}_p = 10\lg\left[\sum_{f=1000}^{16000} 10^{0.1Lp(f)}\right] \quad \text{(Eq. 16)}$$

Perform these calculations for both the background and injector noise measurements. The sound pressure level value at each 1/3 octave band center frequency (f) from 1000 to 16000 Hz is designated for the injector noise as $L_{p\text{-injector}}(f)$ and as $L_{p\text{-background}}(f)$ for the background noise. The overall total sound pressure level value for the injector noise is designated as $\overline{L}_{p-\text{injector}}$ and as $\overline{L}_{p-\text{background}}$ for the background noise.

b. If the sound pressure level for the injector operation noise, $L_{p\text{-injector}}(f)$, is at least 15 dB higher than that for the background noise $L_{p\text{-background}}(f)$ at each of the respective 1/3 octave band center frequencies, then no further calculation is necessary. However, if the difference $L_{p\text{-injector}}(f)$ - $L_{p\text{-background}}(f)$ is less than 15 dB at any frequency, then see 8.8 for additional calculations that must be made for the background noise correction. However, it is recommended that the background noise be reduced to stay at least 15 dB below the injector noise levels through modifications to the test setup itself, rather than adopting the background noise correction methodology of 8.8.

8.6 Sound Power Level Calculations for the Injector Noise from the Sound Pressure Levels.

Using Equation 17, compute the sound power level ($L_w(f)$) for each 1/3 octave band center frequency (f) from the average sound pressure level ($L_p(f)$) in step (b) of 8.5.

$$L_w(f) = L_p(f) + 10\log_{10}\left(\frac{S_1}{S_0}\right) \quad \text{(Eq. 17)}$$

where:

S_1 = the area of the spherical measurement surface; for example, in a spherical surface measurement technique, S_1 is $4\pi r^2$ in m^2 and r is the radius of the measurement sphere, in meters

S_0 = the reference area, 1 m^2

Using Equation 18, compute the overall sound power level ($\bar{L}_w$) in dB(A) for the frequency range from 1000 to 16000 Hz as the logarithmic sum of sound power levels at each of the 1/3 octave bands calculated above, $L_w(f)$.

$$\bar{L}_w = 10\log_{10}\left[\sum_{f=1000}^{16000} 10^{0.1Lw(f)}\right] \quad \text{(Eq. 18)}$$

Note that this is referred to as the overall sound power value of the injector. Since the sound pressure level values, $L_p(f)$, used in the calculations in step (a) of 8.6 are already A-weighted, the overall sound power value thus obtained is also A-weighted, and is to be expressed in dB(A).

8.7 Data Reporting for Noise Measurements and Calculations

Report the following on the data reporting sheets that are numbered 1 through 4:

a. On Data Reporting Sheet 1, record the ambient room temperature, ambient pressure and percent relative humidity present in the chamber during the test.

b. On Data Reporting Sheet 1, record the injector needle lift (µm), the static flow capacity (g/s) and the measured flow per pulse at the test conditions (mg/pulse).

c. On Data Reporting Sheet 1, record the detailed test conditions used for the noise measurement test, including the injector fluid pressure, pulse width, period, fluid type and fluid temperature. Report any deviations from the noted standard conditions in the comments section of the Data Reporting Sheet 1. Note that the use of Stoddard solvent or mineral spirits in place of n-heptane is not a test deviation.

d. On Data Reporting Sheet 1, record the number of microphones used, the number of microphone locations, the measurement radius (meters) of the microphone array and the microphone spacing in degrees.

e. On Data Reporting Sheets 2, 3, and 4, identify each test injector by recording the associated serial number.

f. On Data Reporting Sheet 2, Part 4A, record the measured sound pressure level for the background noise ($L_{p\text{-background}}(f)$) at each 1/3 octave band center frequency f from 1000 to 16000 Hz. Also report the overall sound pressure level value for the background noise level value $\bar{L}_{p-\text{background}}$ in the same datasheet. If the background noise was found to be non-stationary and time-varying, and was recorded once before each injector measurement, then report the sound pressure level values from each one of these measurements on the datasheet.

g. On Data Reporting Sheet 2, Part 4B, record the measured sound pressure level for the injector noise ($L_{p\text{-injector}}(f)$) at each 1/3 octave band center frequency f from 1000 to 16000 Hz, for each injector. Also report the overall sound pressure level value, $\bar{L}_{p-\text{injector}}$, for each injector at the bottom of the same Data Reporting Sheet.

h. If the background noise correction methodology of 8.6 is utilized, then on Data Reporting Sheet 3, Part 4C, record the corrected sound pressure level for the injector noise ($L_{p\text{-corrected}}(f)$) at each 1/3 octave band center frequency f from 1000 to 16000 Hz for each injector. Also record the overall corrected sound pressure level value for each injector ($\bar{L}_{p-\text{corrected}}$) at the bottom of the same Data Reporting Sheet. Further, the use of this correction methodology is to be clearly indicated by circling “YES” on the last row (Part 6H) of the Data Reporting Sheet.

i. On Data Reporting Sheet 3, Part 3, record the computed sound power level at each 1/3 octave band from 1000 to 16000 Hz ($L_w(f)$). Also record the associated overall sound power level ($\bar{L}_w$) value in dB(A), for each tested injector at the bottom of the same Data Reporting Sheet.

j. As requested on Data Reporting Sheet 4, Parts 6A and 6B, for each tested injector, plot the A-weighted 1/3 octave band sound pressure level values for the injector noise, $L_{p\text{-injector}}(f)$, or for $L_{p\text{-corrected}}(f)$ if a background noise correction is utilized. Also plot the A-weighted 1/3 octave band sound power level values for the injector noise ($L_w(f)$). Label the plots with the serial number of the injector being reported on.

k. Attach the two 1/3 octave band plots to the six Data Reporting Sheets.

l. On Data Reporting Sheet 4, Parts 6C and 6D, record the five overall sound pressure values and the five overall sound power values from the bottom of Data Reporting Sheets 2 and 3. Use Sheet 3 instead of 2 if the background noise correction was employed. Arithmetically average the five overall sound pressure values to obtain the final test result for sound pressure. Similarly, arithmetically average the five overall sound pressure values to obtain the final test result for sound power.

m. Enter the final sound pressure value in box 6E. If there are no test deviations indicated at the bottom of Data Reporting Sheet 1, enter the final sound pressure value in box 6G as the SAE J1832 measured sound power. If there were any deviations during the test as indicated at the bottom of Data Reporting Sheet 1, then enter the final sound pressure value in box 6F.

8.8 Equations for Background Noise Correction

The purpose of background noise correction is to provide an accurate estimation of the sound power generated by the PFI injectors. If the background noise is higher, the estimated sound power level of the injectors will be higher. For example, if the background noise, as measured in sound pressure level, is only 6 dB less than that of the injector noise at each 1/3 octave band, then the estimated sound power level of the injector would be 1.3 dB higher than if there was no background noise. This would imply that the injector is louder than it actually is.

Therefore, verify that the sound pressure level at each 1/3 octave band from 1000 to 16000 Hz is 15 dB above the background sound pressure level at the respective 1/3 octave band measured in Step (c) of 8.4. If the sound pressure level for the injector operation noise measurement is at least 15dB or higher than that for the background noise measurement at each 1/3 octave band center frequency, then the sound power level calculation will be within 0.1 dB accuracy.

If the difference between the sound pressure level for the injector operation noise measurement and the background noise measurement is less than 15 dB, then the accuracy of sound power level estimated will be compromised. Hence, either some changes in the test environment or test equipment setup should be made in order to reduce the background noise (recommended solution), or a correction to the background noise should be applied using the formulas mentioned below.

The sound pressure level used in step (b) of 8.5 shall be corrected for background noise levels using Equation 19.

$$L_{p-\text{corrected}}(f) = L_{p-\text{injector}}(f) - K_1(f) \qquad \text{(Eq. 19)}$$

where:

$$K_1(f) = -10\log_{10}(1 - 10^{-0.1\Delta Lp(f)}) \qquad \text{(Eq. 20)}$$

$$\Delta L_p(f) = L_{p-\text{injector}}(f) - L_{p-\text{background}}(f) \qquad \text{(Eq. 21)}$$

Note that $K_1(f)$ is the correction factor in dB for the background noise sound pressure level average at all microphone positions over the measurement surface for each 1/3 octave band center frequency, f.

The overall corrected sound pressure value, $\bar{L}_{p-corrected}$, is the logarithmic sum of the corrected sound pressure levels at each of the 1/3rd Octave bands calculated above, $L_{p\text{-corrected}}(f)$, and may be computed using Equation 22. Note that all sound pressure level values shall be A-weighted. This applies to each microphone location and for all of the measurements for both background noise and the injector operating noise. Therefore, all of the corrected sound pressure levels and the sound power values are also A-weighted.

$$\bar{L}_{p-corrected} = 10 * Lg\left[\sum 10^{0.1\,Lp-corrected(f)}\right]f = \ 1000 \text{ to } 16000 \qquad \text{(Eq. 22)}$$

If the background noise correction methodology described in 8.8 is employed, this shall be indicated on the last row of Part H of Data Reporting Sheet 6.

Table 15 - SAE datasheet for PFI noise testing

SAE J1832 - Datasheet for PFI Noise Testing - Page 1 of 4			
Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Test location	
Additional information			
Part 2: Information on Injector and Injector Driver Module			
Injector manufacturer and type	Enter INJ S/N on Page 2		
Injector description			
Injector part number			
Injector needle lift			(µm)
Injector driver type			
Driver charge delay e (if any)			(ms)
Injector static flow at P_{NORM}			(g/s)
Injector flow rate at the noise test conditions			(mg/pulse)
Part 3: Test Conditions	**Specific Test Conditions**	**Standard Test Conditions**	
Test fluid		n-heptane, Stoddard solvent, or mineral spirits - specify the fluid	
Ambient temperature (°C)		21.0 ± 2.0	
Ambient pressure (kPaa)		100 ± 5	
Relative humidity (%)		28 ± 8	
Fluid temperature (°C)		21.0 ± 2.0	
Fluid pressure (kPa)		P_{NORM} ± 0.5%	
Initial injector temp (°C)		21.0 ± 2.0	
Injection pulse width (ms)		4.0 ± 0.005	
Injection period (ms)		100.0 ± 0.5	
Injector axis orientation (degrees)		Vertical ± 2 (tip down)	
Injector pre-conditioning?		Yes, as per 6.2	
Number of microphones used on the semicircular arc		6 (recommended)	
Microphone spacing on the semicircular arc (degrees)		First microphone 15 degrees from vertical, then every 30 degrees (recommended)	
Measurement locations and spacing for the semicircular arc of microphones		8 recommended; every 45 degrees	
Microphone radius (meters)		0.30 (recommended)	
Microphone type/model			
Listing of any test deviations or comments			

Part 4 (A): SAE J1832 - Datasheet for PFI Noise Testing - Page 2 of 4 Sound Pressure Level Values, $L_{p\text{-}background}$, for the Background Noise Measurements					
Injector manufacturer, type, and model:					
Injector serial numbers:	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5
Number of measurement locations and the measurement method: (check one) No. of measurement locations: __________	□ Spherical surface □ Hemispherical surface, with reflecting plane □ Other (specify) ________				

Sound Pressure Value in 1/3 Octave Band Center Frequencies - Background					
1/3 octave band center freq, f (Hz)	$L_{p\text{-}background}$ (f) - A-Weighted Sound Pressure Level, dB(A) re 20 µPa				
	Before Test of Injector 1	Before Test of Injector 2	Before Test of Injector 3	Before Test of Injector 4	Before Test of Injector 5
Column A	Column B	Column C	Column D	Column E	Column F
1000 Hz					
1250					
1600					
2000					
2500					
3150					
4000					
5000					
6300					
8000					
10000					
12500					
16000 Hz					
Overall sound pressure level, $\overline{L}_{p-background}$, dB(A)					

Part 4 (B): SAE J1832 - Datasheet for PFI Noise Testing Sound Pressure Level ($\overline{L}_{p-injector}$), dB(A) for Injector Noise Measurements					
Injector manufacturer name:					
Injector type and model:					
Injector serial numbers:	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5

Sound Pressure Value in 1/3 Octave Band Center Frequencies - Injectors					
1/3 octave band center freq, f (Hz)	$L_{p\text{-}injector}$(f) - A-Weighted Sound Pressure Level, dB(A) re 20 µPa				
	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5
Column A	Column G	Column H	Column I	Column J	Column K
1000 Hz					
1250					
1600					
2000					
2500					
3150					
4000					
5000					
6300					
8000					
10000					
12500					
16000 Hz					
Overall sound pressure level, $\overline{L}_{p-injector}$, dB(A)					

Part 4 (C): SAE J1832 - Datasheet for PFI Noise Testing - Page 3 of 4 Note: Use if Correction for Excessive Background Noise is Required: Sound Pressure Level, $L_{p\text{-corrected}}$, for Injector Noise Measurement with Correction for Background Noise					
Manufacturer name:					
Injector type/model:					
Injector serial numbers:	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5
Corrected Sound Pressure Values at 1/3 Octave Band Center Frequencies Corrected					
1/3 octave band center freq, f (Hz)	$L_{p\text{-corrected}}(f)$ - A-Weighted Sound Pressure Level, dB(A) re 20 µPa				
	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5
Column A	Column G	Column H	Column I	Column J	Column K
1000 Hz					
1250					
1600					
2000					
2500					
3150					
4000					
5000					
6300					
8000					
10000					
12500					
16000 Hz					
Overall sound pressure level, $\overline{L}_{p-corrected}$, dB(A)					

Part 5: SAE J1832 - Datasheet For PFI Noise Testing Sound Power Level ($\overline{L}_w$), dB(A) for Injector Noise Measurements					
Manufacturer name:					
Injector type/model:					
Injector serial numbers:	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5
Sound Power Values in 1/3 Octave Band Center Frequencies - Injectors					
1/3 octave band center freq, f (Hz)	$L_w(f)$ - A-Weighted Sound Power Level, dB(A) re 1 pW				
	Injector 1	Injector 2	Injector 3	Injector 4	Injector 5
Column A	Column L	Column M	Column N	Column O	Column P
1000 Hz					
1250					
1600					
2000					
2500					
3150					
4000					
5000					
6300					
8000					
10000					
12500					
16000 Hz					
Overall sound power level, $\overline{L}_w$, dB(A)					