



SURFACE VEHICLE RECOMMENDED PRACTICE

J1832™

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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
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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 measured 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 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 $\pm 5.0\%$ 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 (%).

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

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 the 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.

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

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.

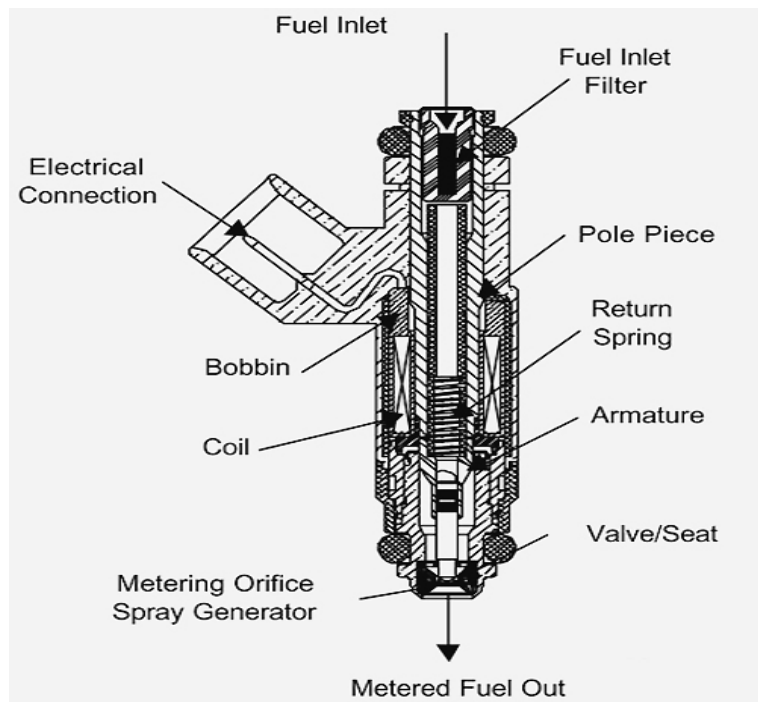


Figure 1 - Schematic cross section of a typical top-feed PFI injector

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.

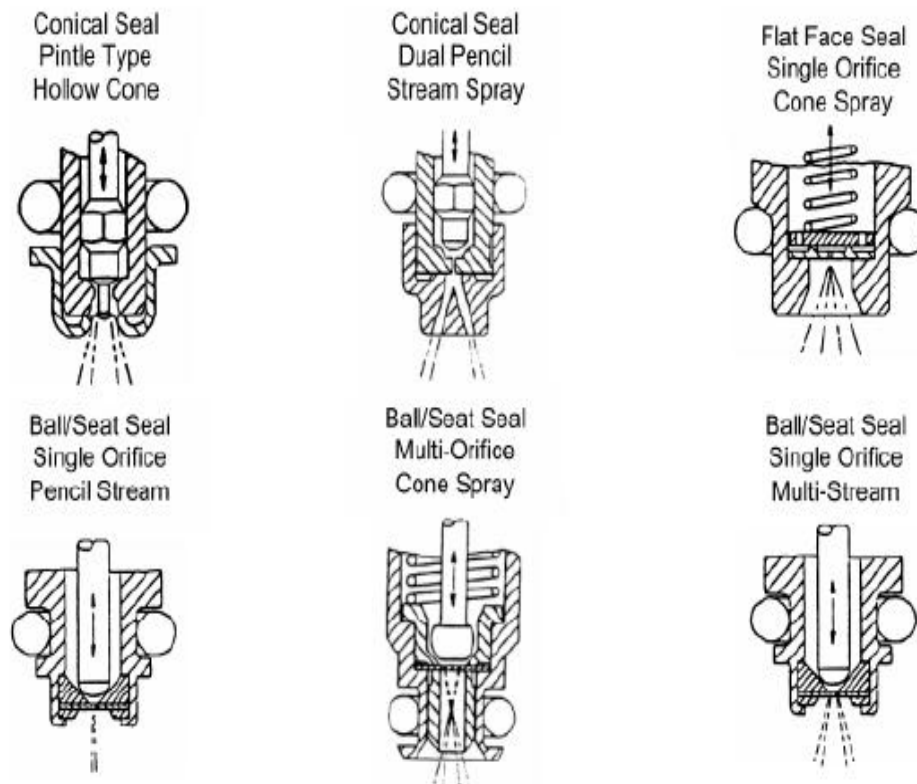


Figure 2 - Examples of PFI injector tip designs with various spray patterns

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.

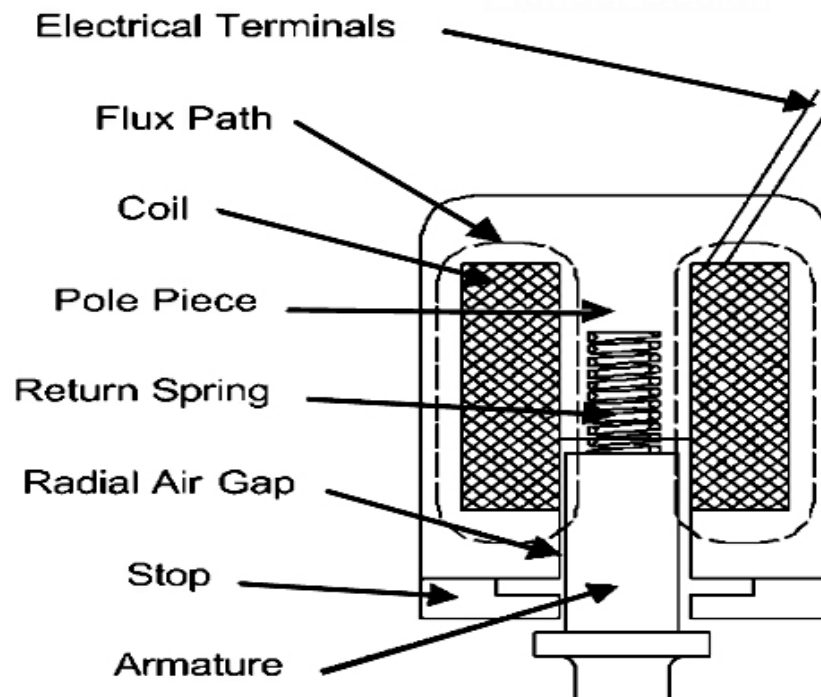


Figure 3 - Schematic diagram of the coil magnetic circuit



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.

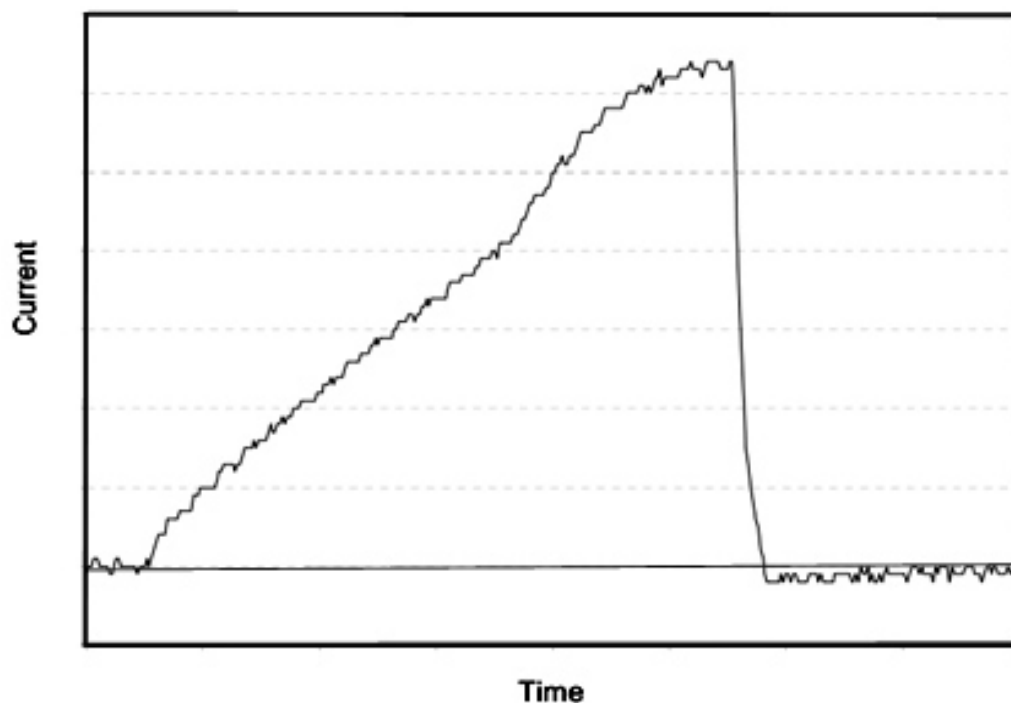


Figure 4 - Typical injector current trace for a saturated driver

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 $\pm 5.0\%$. 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.

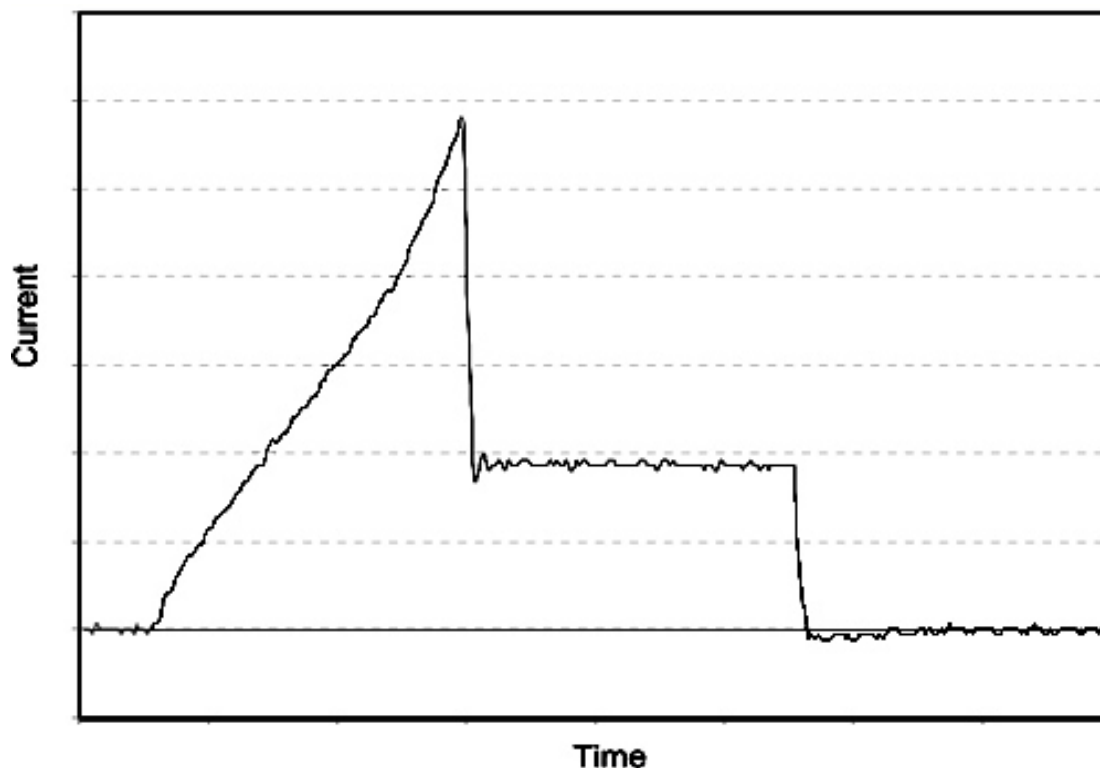


Figure 5 - Typical injector current trace for a peak-and-hold driver

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 $\pm$ 5 kPa abs and a temperature of 21 $^{\circ}$ C $\pm$ 2.0 $^{\circ}$ 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 $21\text{ °C} \pm 2.0\text{ °C}$.

4.4 Injector Temperature

The body temperature of the test injector should be stabilized at an ambient temperature of $21\text{ °C} \pm 2.0\text{ °C}$ 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 $21\text{ °C} \pm 2.0\text{ °C}$ 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 $\pm 0.5\%$ 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 $\pm 0.005\text{ ms}$.

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 $14.0\text{ VDC} \pm 0.05\text{ VDC}$ 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	10% by volume max
Aromatics	35% by volume max
Saturates	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 $21\text{ }^{\circ}\text{C} \pm 2.0\text{ }^{\circ}\text{C}$. 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 $\pm 0.01\text{ }\Omega$.
- 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 $1.0\text{ kHz} \pm 0.5\%$, with a potential of $1.0\text{ V}_{\text{rms}}$.
- d. Conduct the inductance measurement using the Wheatstone Bridge. The unit of measurement is the millihenry (mH), with a resolution of $\pm 0.01\text{ mH}$.
- 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.

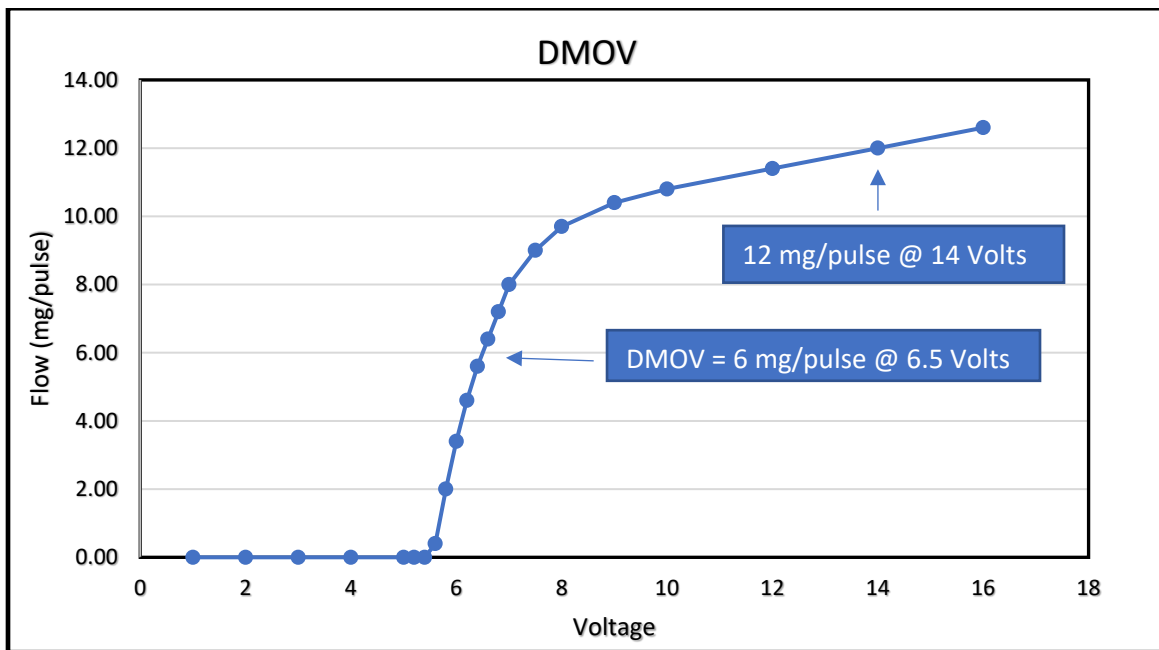


Figure 6 - Dynamic minimum operating voltage (DMOV)

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 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.
- Establish the standard test conditions listed on the data reporting sheet in this section.
- Measure the parameters of Q_s , Q_{sp} , R , IR , and tip leakage for the injector prior to the application of any overload voltage.
- 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} .
- 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.
- 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.

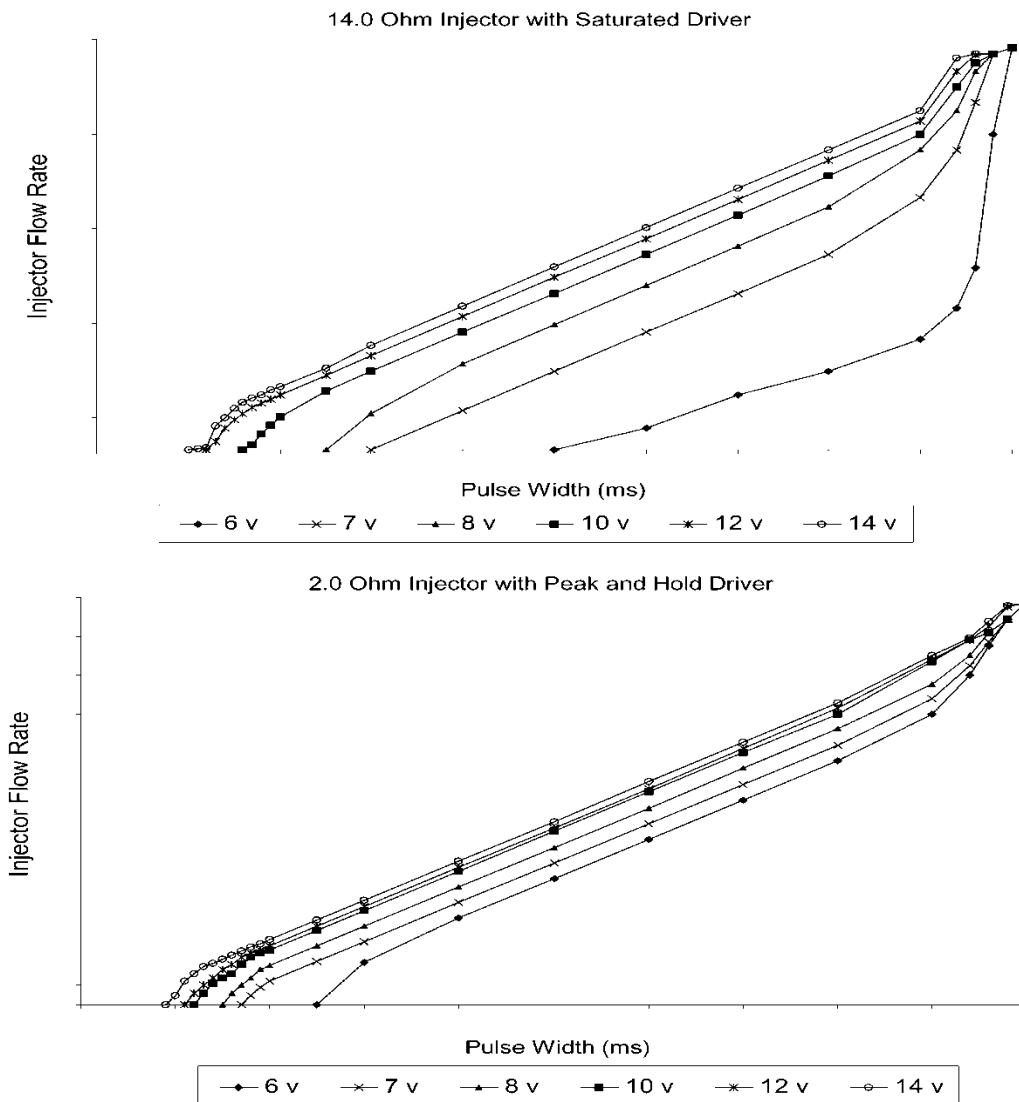


Figure 7 - Typical measured curves of voltage sensitivity

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

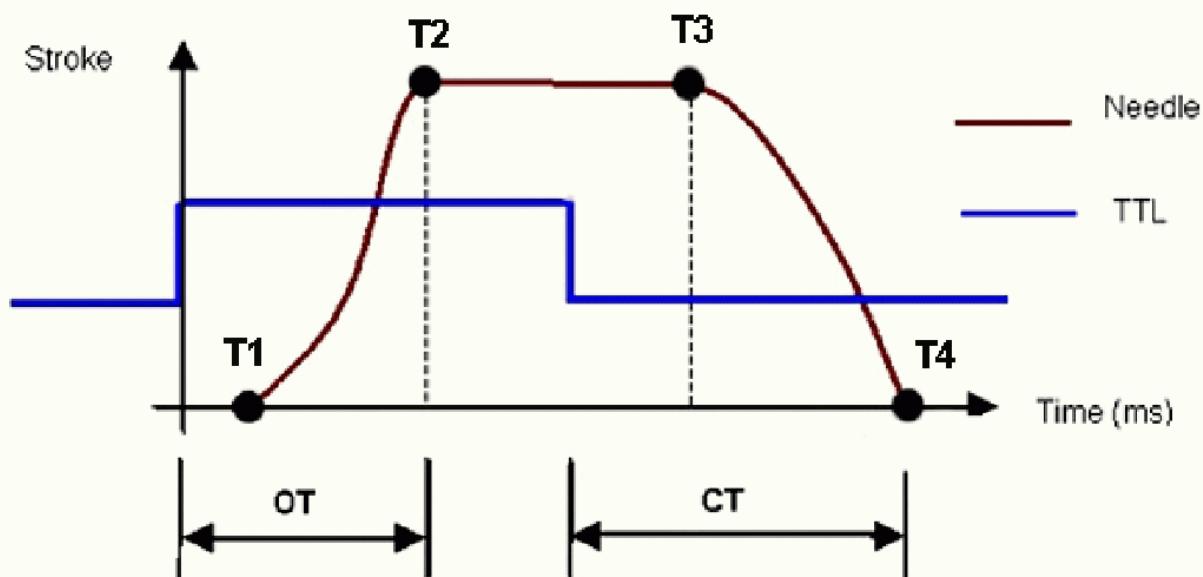


Figure 8 - Representation of needle movement relative to the logic pulse

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.

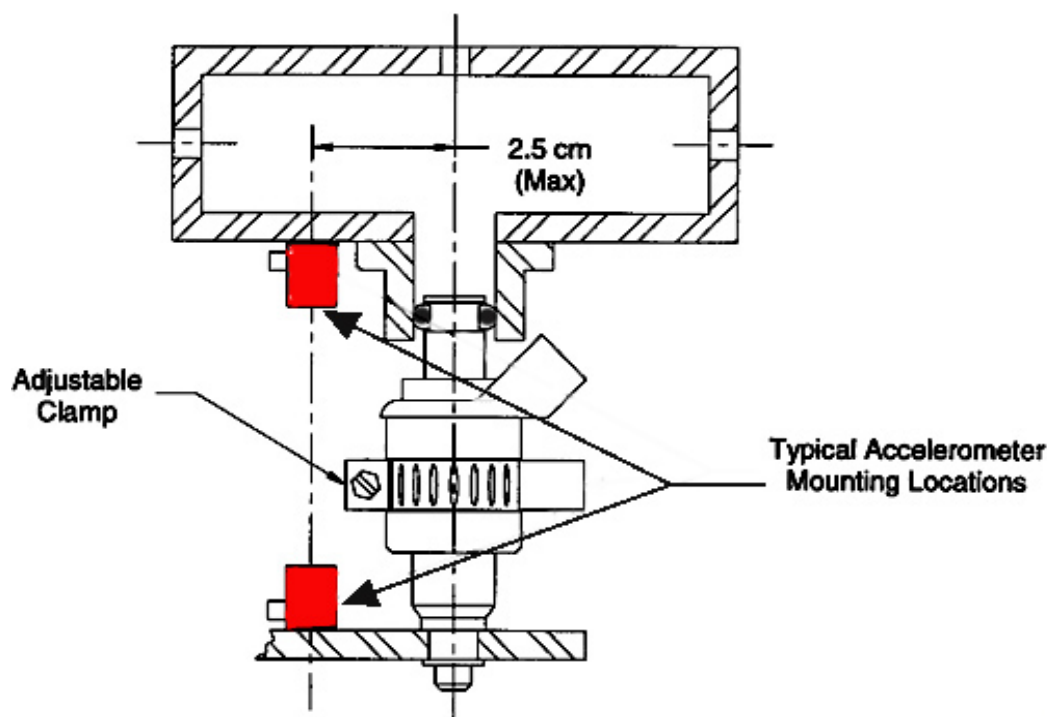


Figure 9 - Accelerometer mounting locations for OT and CT tests

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.

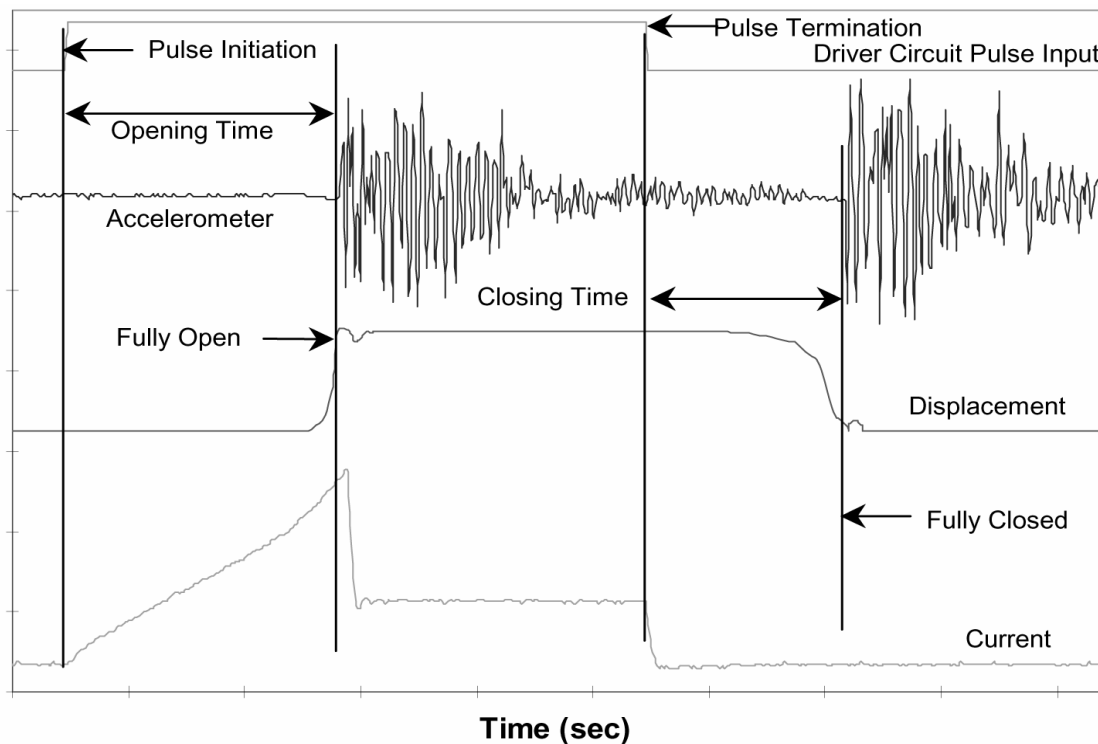


Figure 10A - Typical opening and closing events with peak and hold driver

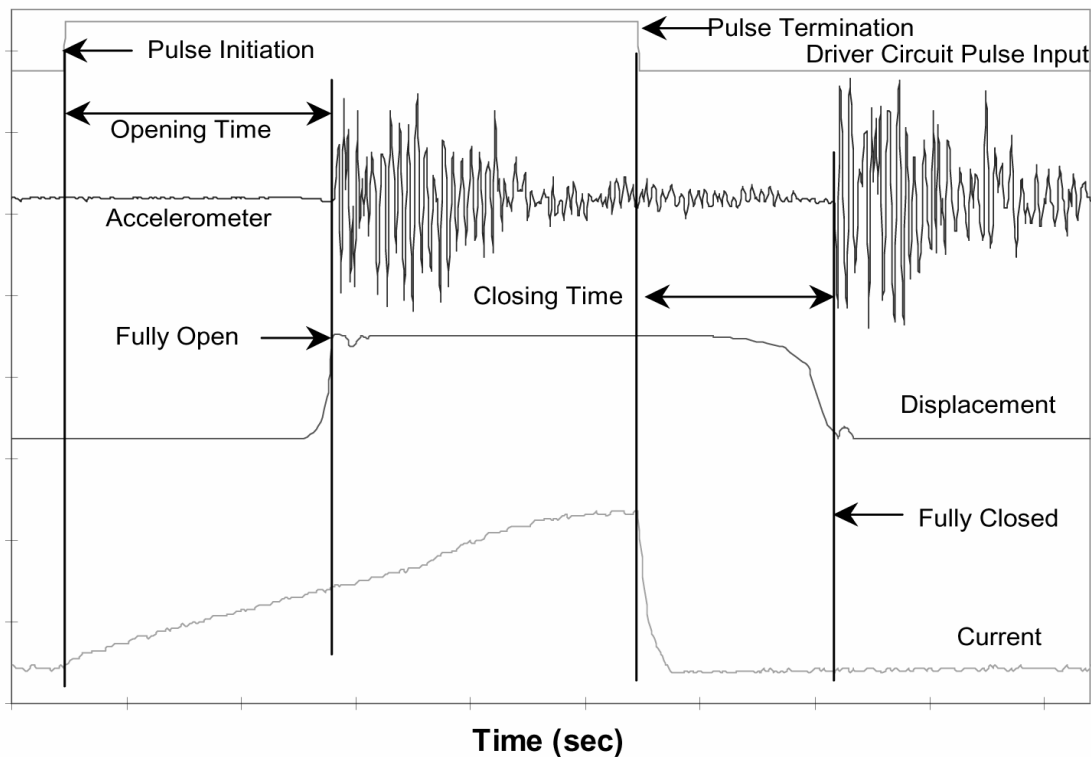


Figure 10B - Typical opening and closing events with saturated driver

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

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