



SURFACE VEHICLE RECOMMENDED PRACTICE

J2713™

SEP2024

Issued 2018-08
Revised 2024-09

Superseding J2713 AUG2018

(R) Direct Injection Gasoline Fuel Injector Characterization

RATIONALE

The use of uniform and 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 one accepted test 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 document will significantly enhance the ability of one test laboratory to accurately repeat and verify the results of another.

FOREWORD

A gasoline direct injection (GDI) fuel injector is an electrically actuated device that delivers a specific amount of fuel directly into the combustion chamber of an internal combustion engine. GDI system fuel pressures are more than an order of magnitude greater than port fuel injection (PFI) system pressures and continue to increase in newer systems. The amount of fuel delivered is controlled by the length of time the injector is open, as well as the differential pressure across that injector. The amount of time the injector is open is typically determined by an engine control module. A picture of a representative GDI injector is illustrated in Figure A1

GDI fuel injectors are typically used in four basic types of combustion systems - wall-guided tumble, wall-guided swirl, air-guided, or spray-guided - which are illustrated in Figure A4. Typically, both wall-guided types and air-guided GDI combustion systems employ a side-mounted injector located on the intake side of the combustion chamber, while spray-guided systems generally employ a vertically oriented injector that directs the spray perpendicular to the piston crown.

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1. SCOPE

This SAE Recommended Practice promotes uniformity in the evaluation and qualification tests conducted on gasoline direct injection (GDI) fuel injectors used in gasoline engine applications, where fuel pressures are typically well above 10 MPa. The document scope is limited to electrically actuated gasoline fuel injection devices used in automotive GDI systems and is primarily restricted to bench tests.

1.1 Purpose

The purpose of this document is to provide original equipment manufacturers and end users within the automotive industry with a neutral, unbiased test for each defined GDI injector performance parameter. The specific, stated purposes of SAE J2713 are to:

- a. Standardize the use of nomenclature specifically related to GDI injector performance evaluation.
- b. Define the parameters and key metrics that are associated with measuring the performance characteristics of GDI injectors.
- c. Establish detailed test procedures and recommend test equipment and methods to measure the key metrics in order to characterize GDI injectors.
- d. Establish the recommended data reduction and analytical procedures for the measurement and characterization of GDI injector performance.
- e. Establish the criteria for data reporting and the required accompanying information that shall be supplied 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 SAE publications shall apply.

2.2 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 J306	Automotive Gear Lubricant Viscosity Classification
SAE J308	Axle and Manual Transmission Lubricants
SAE J313	Diesel Fuels
SAE J1681	Gasoline, Alcohol, and Diesel Fuel Surrogates for Materials Testing
SAE J1703	Motor Vehicle Brake Fluid
SAE J1832	Low-Pressure Gasoline Fuel Injector
SAE J2715	Gasoline Fuel Injector Spray Measurement and Characterization

2.3 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 B117-19	Standard Practice for Operating Salt Spray (Fog) Apparatus
ASTM D56	Standard Test Method for Flash Point by Tag Closed Tester
ASTM D86	Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure
ASTM D445	Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (the Calculation of Dynamic Viscosity)
ASTM D471	Standard Test Method for Rubber Property-Effect of Liquid
ASTM D893	Standard Test Method for Insolubles in Used Lubricating Oils
ASTM D1298	Standard Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
ASTM D4806	Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as an Automotive Fuel
ASTM D4814	Standard Specification for Automotive Spark Ignition Engine Fuel
ASTM D6304	Standard Test Method for Determination of Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fischer Titration

2.4 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 16750-3	Road Vehicles - Environmental Conditions and Testing for Electrical and Electronic Equipment - Part 3: Mechanical Loads
ISO 1683:2015	Acoustics - Preferred Reference Values for Acoustical and Vibratory Levels
ISO 19438	Diesel Fuel and Petrol Filters for Internal Combustion Engines - Filtration Efficiency using Particle Counting and Contaminant Retention Capacity

2.5 Code of Federal Regulations (CFR) Publications

Available from United States Government Publishing 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
49 CFR 571.116	Federal Motor Vehicle Safety Standards - Motor Vehicle Brake Fluids

2.6 U.S. Government Publications

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

MIL-STD-810D	Environmental Test Methods and Engineering Guidelines
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3. BASIC CHARACTERISTICS, DEFINITIONS, AND ABBREVIATIONS

3.1 Basic Characteristics

The parameters in this section are used to describe and/or quantify the key functional and performance characteristics of a GDI injector. Figure 1 clearly illustrates the seven critical fuel pressure terms that are utilized throughout the document. It should be noted that the flow data used to generate the curve in Figure 1 was obtained using a representative GDI injector. The definitions in 3.2 define each of these fuel pressures, as well as additional nonpressure terms that are critical to the numerous tests that are used to characterize the GDI injector flow, performance, durability, and noise. A complete list of the abbreviations utilized within SAE J2713 is provided in 3.3.

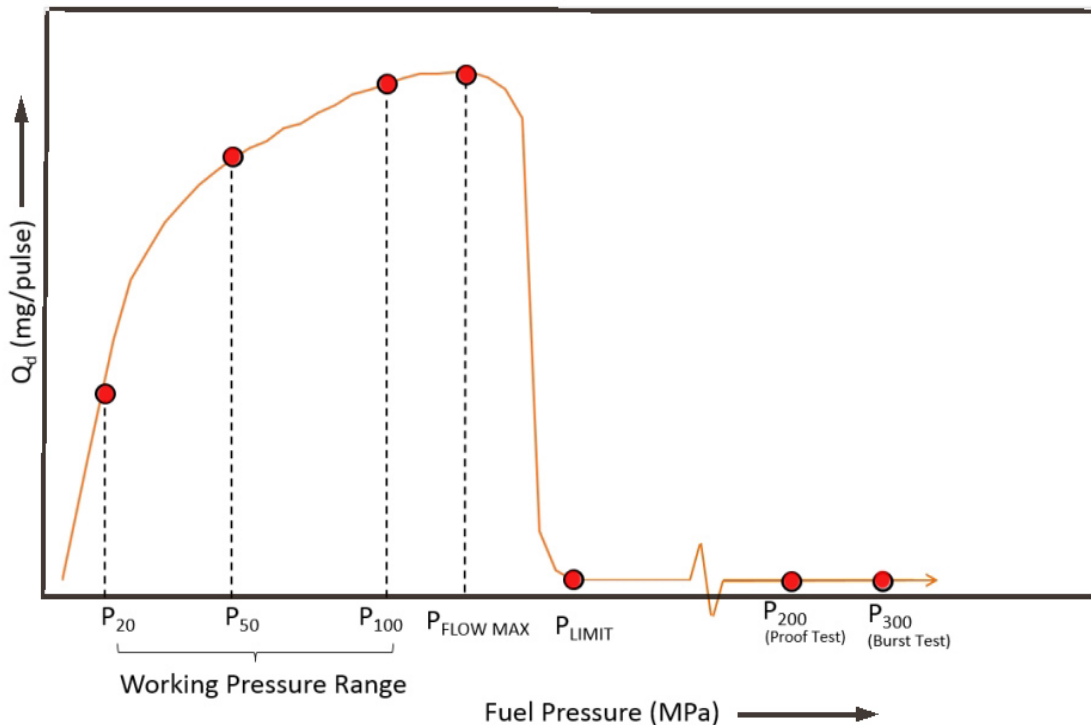


**Figure 1 - Representation of defined SAE J2713 GDI fuel pressures
(curve generated from actual GDI flow data)**

3.2 Definitions

3.2.1 P_{100}

This is the maximum pressure applied to the injector that the system will experience in typical operation. This is defined by the OEM for a given application. This is the maximum pressure at which the injector is typically characterized. The injector will still operate at pressures higher than P_{100} but may have degraded performance. This pressure, along with P_{50} and P_{20} , are the primary test pressures used to characterize performance in SAE J2713 and are expressed in megapascals (MPa).

3.2.2 P_{50}

This pressure is defined as 50% of P_{100} . This pressure is used to characterize the midrange performance of the injector and is expressed in megapascals (MPa).

3.2.3 P_{20}

This pressure is defined as 20% of P_{100} . This pressure is used to characterize the low-pressure performance of the injector and is expressed in megapascals (MPa).

3.2.4 PROOF TEST PRESSURE (P_{200})

This pressure is applied to an injector to verify functional robustness against elevated pressure. No permanent deformation or leakage should be observed at this pressure, and the injector shall function within specification subsequent to application and removal of this pressure. P_{200} is two times P_{100} and is expressed in megapascals (MPa).

3.2.5 BURST TEST PRESSURE (P_{300})

This pressure is applied to an injector to verify structural integrity and resistance to bursting or leaking. The fuel injector is not expected to function normally after exposure to this pressure level, but it shall not exhibit a rupture or any external leakage. P_{300} is three times P_{100} and is expressed in megapascals (MPa).

NOTE: It is common to test for a burst failure pressure, which differs from the burst test pressure, by steadily increasing pressure until there is a structural failure. This burst failure pressure would be the actual point that an injector experiences structural failure. A method for testing burst failure pressure is not included in this document. For the purposes of this document, ensuring that the injector can withstand P_{300} is deemed to be sufficient.

3.2.6 MAXIMUM FLOW PRESSURE ($P_{\text{FLOW MAX}}$)

This is the pressure at which the maximum dynamic flow is obtained. This pressure is expressed in megapascals (MPa). As the fuel pressure is increased, the dynamic flow rate will increase throughout the working flow range. At some point above the working flow range, the flow will begin to decrease.

3.2.7 LIMIT PRESSURE (P_{LIMIT})

This is the minimum pressure at which the injector is unable to open. This pressure is expressed in megapascals (MPa). For inwardly opening injectors, the hydrostatic force of the fuel pressure tends to hold the injector closed. This force increases as the fuel pressure increases. At a pressure level of P_{LIMIT} , the injector is unable to open.

3.2.8 INDUCTANCE (L)

This 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. The unit of measurement is the millihenry (mH).

3.2.9 COIL RESISTANCE (R)

This is a measure of the resistance of the injector coil between the two coil terminal pins. The coil resistance is measured in ohms (Ω).

3.2.10 INSULATION RESISTANCE (IR)

This is a measure of the internal resistance between the injector body and the coil terminal pins. It is related to the potential failure of the insulation between the coil assembly and the case of the injector. The IR is measured in ohms (Ω).

3.2.11 OPENING TIME (OT)

This is the time required for the injector needle to first reach its fully opened position after initiation of the injection pulse width. The OT is recorded in milliseconds (ms).

3.2.12 CLOSING TIME (CT)

This is the time required for the injector needle to first reach its fully closed position after the termination of the injection pulse width signal. The CT is recorded in milliseconds (ms).

3.2.13 SHOT-TO-SHOT MASS FLOW VARIATION (STS)

This measures the pulse-to-pulse injection quantity variation versus injection pulse width (IPW) of a GDI injector. It is quantified and reported as the coefficient of variation (COV) percentage of the population of measured injection quantities. The STS will vary with the IPW value that is used for the test. The definition of the coefficient of variation of a set of numbers is provided in 3.2.44.

3.2.14 PERIOD (P)

This is the reciprocal of the frequency of injection; that is, the time elapsed between the beginning of one injection to the beginning of the next injection, expressed in milliseconds (ms).

3.2.15 LOGIC PULSE WIDTH (LPW)

This is the increment of time (ms) that the injectors are commanded to be energized during an injection period. This logic pulse width may include a driver pre-charge delay. See Section A.4 for more detailed information and diagrams that illustrate this.

3.2.16 INJECTION PULSE WIDTH (IPW)

This is the increment of time (ms) that the injectors are commanded to deliver fuel during an injection period. This injection pulse width does NOT include any pre-charge delay and may or may not be identical to LPW. See Section A.4 for more detailed information.

3.2.17 PRE-CHARGE DELAY PULSE WIDTH

This is the increment of time (ms) after initiation of the logic pulse before the peak current charge is applied to the injector coil. This delay time is typically used to provide a final peaking charge to the main capacitor in the injector driver circuitry and/or to apply a low-level current to the injector coil to reduce the OT. See Section A.4 for more detailed information.

3.2.18 STATIC FLOW RATE (Q_S)

This is the rate of fuel delivered by an injector, expressed in grams per second (g/s), when continuously energized in the fully opened position. It is the maximum flow rate of the injector and can be used to approximate the slope (m_a) of the injector flow curve. It shall be specified with the test pressure, which is typically 10 MPa unless otherwise specified by the manufacturer (example: static flow rate specification: 12.4 g/s at 10 MPa).

3.2.19 STATIC FLOW SHIFT

For a particular injector, the static flow 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 compute the change (shift) in the static flow that occurs subsequent to the test. This change in static flow, expressed in percent (%), is obtained by measuring the static flow both before and after the particular test, then computing the percentage shift. This may be computed from Equation 1.

$$\text{Static flow shift (\%)} = \left(\frac{\text{End of test } Q_S - \text{Start of test } Q_S}{\text{Start of test } Q_S} \right) \times 100 \quad (\text{Eq. 1})$$

3.2.20 DYNAMIC FLOW (Q_d)

This is the measured fuel delivered per pulse of the injector, expressed in milligrams per pulse (mg/pulse), when energized at a specified IPW.

3.2.21 TIME-OFFSET (X)

This is the displacement of the calculated linear regression flow curve from the origin along the IPW axis and is expressed in milliseconds (ms).

3.2.22 FLOW-OFFSET (Y)

This is the displacement of the calculated linear regression flow curve from the origin, as measured along the Q_d axis, and is expressed in milligrams per pulse (mg/pulse).

3.2.23 SLOPE (m)

This is the change in Q_d per unit of IPW based on the calculated linear regression flow curve for a specified fuel pressure and is computed using Equation 2. It is expressed in milligrams per millisecond (mg/ms).

$$m = \frac{\Delta Q_{dc}}{\Delta IPW} \quad (\text{Eq. 2})$$

3.2.24 DYNAMIC FLOW CALCULATED (Q_{dc})

This is the calculated fuel delivery per pulse of the fuel injector at a given pulse width and a known slope (m) and offset (either X or Y). The slopes and offsets are determined from a calculated linear flow curve that has been generated for a specified fuel pressure. It is computed using Equation 3 and is expressed in milligrams per pulse (mg/pulse).

$$Q_{dc} = m \cdot (IPW) - Y = m \cdot (IPW - X) \text{ mg/pulse} \quad (\text{Eq. 3})$$

3.2.25 DYNAMIC VERIFICATION FLOW PULSE WIDTH

This is the IPW value used to verify injector dynamic performance. This IPW value is specified as 1.0 ms for the verification flow tests in this document. This pulse width is used to establish Q_{VF} , the dynamic performance and offset characteristics of the fuel injector.

3.2.26 DYNAMIC VERIFICATION FLOW (Q_{VF})

This is the measured fuel delivered per pulse of the fuel injector in mg/pulse when energized at the dynamic verification flow pulse width at a fuel pressure of P_{50} . In this document, the dynamic verification pulse width is specified as 1.0 ms.

3.2.27 DYNAMIC VERIFICATION FLOW SHIFT

For a particular injector, the dynamic verification flow may be adversely affected by any number of the tests within this document, such as corrosion, physical, or durability tests. One important quantification of the effects of any one of those tests is to determine the change (shift) in the dynamic verification flow delivery that occurs due to the test. This change in dynamic verification flow, expressed in percent (%), is obtained by measuring the dynamic verification flow both before and after the particular test, then computing the percentage shift using Equation 4.

$$\text{Dynamic verification flow shift (\%)} = \left(\frac{\text{End of test } Q_{VF} - \text{Start of test } Q_{VF}}{\text{Start of test } Q_{VF}} \right) \times 100 \quad (\text{Eq. 4})$$

3.2.28 LINEARITY DEVIATION (LD)

Ideally, the flow from an injector should be both linear and directly proportional to pulse width over the full operating flow range of the injector. This is not the actual case, as flow offsets occur and significant deviation from linearity occurs at the lower extremity of the flow curve. In order to measure the deviation from linearity, a least squares regression analysis is normally performed using the fuel flow rate values that are obtained at five specified injection pulse widths. These IPW points are 1.0, 2.0, 3.0, 4.0, and 5.0 ms. The measured Q_d and the corresponding IPW value are, respectively, the dependent and independent variables. The resulting straight line is referred to as the linearized flow curve. As shown in Equation 5, the deviation from that linearity at some IPW point is then defined as the percent difference between the measured flow (Q_d) at that IPW and the flow that is calculated from the linear curve (Q_{dc}) divided by the calculated flow.

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

3.2.29 LINEAR FLOW MINIMUM (LF_{min})

This is the lowest flow the injector can deliver within the linear range at P_{50} . The lowest flow is prescribed by the measured flow deviating by $\pm 5.0\%$ from the linearized flow curve as is shown in Figures 9A and 9B.

3.2.30 LINEAR FLOW MAXIMUM (LF_{max})

This is the flow rate of the injector at 5 ms IPW and a fuel pressure of P_{50} .

3.2.31 LINEAR FLOW RANGE (LFR)

This number expresses the numerical value of the linear operating range of the injector. It is computed using Equation 6 as LF_{max} divided by the minimum linearized flow point, LF_{min} . The linear flow range is a carryover performance parameter from port fuel injector testing that can be applied to GDI injectors, and it forms the basis for the multiple-fuel-pressure test for GDI injectors.

$$LFR = LF_{max} / LF_{min} \quad (\text{Eq. 6})$$

3.2.32 DYNAMIC LINEAR FLOW MINIMUM (DLF_{min})

This is the lowest flow the injector can deliver within the linear range at a fuel pressure of P_{20} . The lowest flow is prescribed by the measured flow at a fuel pressure of P_{20} deviating by $\pm 5.0\%$ from the linearized flow curve as is shown in Figure 10.

3.2.33 DYNAMIC LINEAR FLOW MAXIMUM (DLF_{max})

This is the mean flow (mg/pulse) delivered by the GDI fuel injector at an IPW of 5 ms and a fuel pressure of P_{100} . Only one flow point at P_{100} is required to determine this parameter.

3.2.34 DYNAMIC LINEAR FLOW RANGE (DLFR)

The dynamic linear flow range (DLFR) is an extension of LFR in that the test fuel pressure is varied from P_{20} to P_{100} to extend the fuel delivery range as opposed to testing at a single fixed pressure of P_{50} as is done for LFR. This recognizes that most direct injection fuel systems operate using variable pressure systems as opposed to port fuel injection systems, which normally operate with a fixed, lower pressure. The DLFR test is the primary flow test for evaluating the expected operating range of a single GDI fuel injector that operates over a range of fuel pressures. This ratio is also useful in comparing the linear performance between injectors of different design or manufacturer. The DLFR test is primarily applied for evaluating the operating range of a single injector in the case where the measurement of a population is impractical. The DLFR is determined by dividing DLF_{max} by DLF_{min} , as shown in Equation 7.

$$DLFR = DLF_{max} / DLF_{min} \quad (\text{Eq. 7})$$

3.2.35 WORKING FLOW MINIMUM (WF_{min})

This is the mean flow value, expressed in milligrams per pulse (mg/pulse), in the low IPW region of the flow curve, which is delivered at a fuel pressure of P_{50} from a group of 24 (or more) identical fuel injectors, and satisfies the criterion that $3 \times \text{standard deviation} / (\text{corresponding mean flow}) = 10\%$. This is also equivalent to $3 \times \text{COV} = 10\%$. This WF_{min} value typically occurs at an IPW value less than 1.0 ms. If there are multiple fuel deliveries that satisfy $3 \times \text{standard deviation} / (\text{corresponding mean flow}) = 10\%$, the largest of these fuel deliveries shall be used.

3.2.36 WORKING FLOW MAXIMUM (WF_{max})

This is the mean flow value (mg/pulse) that is delivered from a group of 24 (or more) identical fuel injectors at an IPW of 5 ms and a fuel pressure of P_{50} .

3.2.37 WORKING FLOW RANGE (WFR)

This is the flow range that quantifies the flow variation limits of a population of 24 (or more) injectors tested at a single fixed pressure of P_{50} , with no linearity requirement. This range number recognizes that linear performance is less important for contemporary GDI applications, as nearly any repeatable non-linearity can be modeled and predicted with modern computing power. The WFR test is a carryover test from port fuel injector characterization that can be applied to GDI injectors. The working flow range is computed using Equation 8 by dividing the maximum flow value by the minimum flow value as obtained at a fuel pressure of P_{50} .

$$WFR = WF_{\max} / WF_{\min} \quad (\text{Eq. 8})$$

3.2.38 DYNAMIC WORKING FLOW MINIMUM (DWF_{min})

This is the mean flow (mg/pulse) in the low IPW region of the flow curve that is delivered at a fuel pressure of P_{20} by a test group of 24 (or more) identical fuel injectors and satisfies the criterion that $3 \times \text{standard deviation} / (\text{corresponding mean flow}) = 10\%$. This is also equivalent to $3 \times \text{COV} = 10\%$. This DWF_{min} value typically occurs at an IPW value less than 1.0 ms. If there are multiple deliveries that satisfy $3 \times \text{standard deviation} / (\text{corresponding mean flow}) = 10\%$, the largest of these deliveries shall be used.

3.2.39 DYNAMIC WORKING FLOW MAXIMUM (DWF_{max})

This is the mean flow (mg/pulse) delivered by a test group of 24 (or more) identical fuel injectors at an IPW of 5.0 ms and a fuel pressure of P_{100} .

3.2.40 DYNAMIC WORKING FLOW RANGE (DWFR)

This is an extension of WFR in that the fuel pressure is varied at specified values as opposed to testing at a single, fixed pressure. This recognizes that most direct injection fuel systems operate at various fuel pressures as opposed to port fuel injection systems, which are lower pressure systems that generally operate at a fixed pressure. The test for DWFR is the primary flow test for evaluating a population of 24 (or more) GDI fuel injectors. The DWFR is obtained by using Equation 9 to compute the ratio of the flow at P_{100} at a 5 ms IPW (DWFR_{max}) divided by the flow at P_{20} (DWFR_{min}), at which the percentage flow variability among the 24 (or more) test injectors attains a value of 10%. This percentage flow variability is obtained from the flow data and is expressed as $100 \times 3 \times \text{standard deviation} / (\text{corresponding mean flow})$, or alternatively as $100 \times 3 \times \text{COV}$, where COV is the Coefficient of Variation. The DWFR is useful in comparing the part-to-part variation in dynamic performance between injectors of different design or manufacturer.

$$DWFR = DWF_{\max} / DWF_{\min} \quad (\text{Eq. 9})$$

3.2.41 MINIMUM TIME BETWEEN INJECTIONS (MTBI)

This is the minimum acceptable time between two injection events having equal IPW values. The test is used to determine how closely pulses can be spaced before their interaction causes a flow shift greater than 5%. The minimum time between injections is the time interval between pulses that yields a combined indicated mass flow deviation for the two events that exceeds a $\pm 5\%$ deviation from the mass flow that is obtained when the two pulses are very far apart in time.

3.2.42 SEAT TIP LEAKAGE

This is the mass quantity of fuel that escapes from the sealed valve seat of a pressurized, non-energized injector. This is measured in mm³/min of n-heptane. GDI injectors generally have metal-to-metal sealing surfaces for durability reasons. In order to reduce deposit formation, evaporative and hydrocarbon emissions, and to maintain the fuel pressure, ideally no fuel should escape the injector until it is energized. This requires a leak-tight interface between the mating surfaces of the valve seat components.

3.2.43 STANDARD DEVIATION (SIGMA)

The standard deviation of the values in a dataset of numbers, Sigma, is the square root of the variance of the set of numbers, with the variance being the mean of the sum of the squares of the quantity of each dataset number minus the mean of all of the dataset numbers. It is also commonly denoted as σ .

3.2.44 COEFFICIENT OF VARIATION (COV)

The coefficient of variation of a dataset of numbers, COV, is obtained by dividing the standard deviation of the set of numbers by the arithmetic mean value of those same numbers. This is sometimes denoted as “CV” in statistics.

3.3 Abbreviations

These are additional abbreviations that are within the text of this document but are not listed in 3.2.

A	amperes
A/F	air-fuel ratio
BJT	bipolar junction transistor
CCW	counterclockwise
cP	centipoise measurement of fluid viscosity
cSt	centistokes measurement of fluid viscosity
CW	clockwise
E85	gasoline blend containing 85% ethanol
Exx	any gasoline blend containing xx% ethanol
ECU	engine control unit
EPA	Environmental Protection Agency
FET	field-effect transistor
FID	flame ionization detector
GDI	gasoline direct injection
h	hours
HC	hydrocarbon
IGBT	insulated gate bipolar transistor
kPa	general pressure level in kilopascals
kPaa	absolute pressure value in kilopascals
kPag	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
Mxx	any gasoline blend containing xx% methanol
NL	normal liters
OEM	original equipment manufacturer
P	period
PFI	port fuel injection
ppm	parts per million
RH	relative humidity
rms	root mean square
rpm	revolutions per minute
s	seconds
TBI	time between injections
UBHCs	unburned hydrocarbons
V	volts

4. STANDARD TEST CONDITIONS

4.1 Test Conditions

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

4.1.1 Ambient Conditions

The testing shall be performed at an ambient pressure of 100 kPa $\pm$ 5 kPa and a temperature of 21 °C $\pm$ 2 °C.

4.1.2 Test Fluid

Normal heptane (n-heptane) is specified as the standard test fluid 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 GDI performance tests result in an SAE J2713 performance parameter providing n-heptane has been used along with the other specified standard conditions. Any other test fluid may optionally be used, such as mineral spirits or a solvent. 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 J2713 parameter. There are some exceptions to this, such as with 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 shall 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 GDI 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 multicomponent hydrocarbon fuels that are found in the field. n-heptane was selected as the best compromise based on 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 comparison with n-heptane is illustrated in Table 1 for the EPA emission test gasoline, whereas a comparison of the properties of n-heptane with those of mineral spirits and indolene clear is provided in Table 2. 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 yield 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 approximately a 4% lower static flow rate than that of the U.S. EPA emission test gasoline, 40 CFR 86.113.

Table 1 - Comparison of properties and flow for n-heptane and the EPA emission test gasoline

	Viscosity (20 °C) Centipoise	Specific Gravity (20 °C)	Static Flow (g/s)	Dynamic Verification Flow (mg/pulse)
40 CFR 86.113	0.468	0.75	9.323	8.934
n-heptane	0.438	0.68	8.978	8.651
% Difference	-6.41	-9.33	-3.7	-3.2

Table 2 - 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
Calculated dynamic viscosity at 20 °C (68 °F) (ASTM D445)	0.418 to 0.438 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.

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 in gasoline. Therefore, repeated flow testing that results in partial evaporation of the test fluid does not change the physical properties of the remaining fluid. 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,” which has a flash point that exceeds 43 °C. The use of such a liquid requires a laboratory-to-factory floor calibration step in which a flow rate of 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.

4.1.3 Test 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 $21.0\text{ °C} \pm 2.0\text{ °C}$.

4.1.4 Injector Body Temperature

The body temperature of the test injector should be stabilized at an ambient temperature of $21.0\text{ °C} \pm 2.0\text{ °C}$ prior to any preconditioning procedure that may be required prior to some tests. If preconditioning is not specified, the injector body temperature should be stabilized at $21.0\text{ °C} \pm 2.0\text{ °C}$ prior to the test.

4.1.5 Fuel Pressures

Unless otherwise specified for a particular test, the fuel pressure at the injector inlet should be P_{50} . It is to be maintained within $\pm 0.5\%$ of this value throughout the test. If there is no particular application pressure associated with the injector that is being tested, then 10 MPa should be used as the default value for P_{100} . The actual fuel pressure used should be recorded on the data-reporting sheet in the SI units of MPa.

4.1.6 Period (P)

The injection period is defined in 3.2.14, and the standard value of P specified for a test depends upon the particular test. Typical injection periods are 10 ms, 20 ms, and 50 ms, and the particular value to be used will be stated in the corresponding test procedure and on the corresponding data-reporting sheet. The injection period shall be held within ± 0.001 ms.

4.1.7 Injection Pulse Width (IPW)

The injection pulse width is defined in 3.2.16, and the standard value of IPW specified for a test depends upon the type of test being conducted. In general, a specific value of IPW is specified for each of the various tests within this document, with the particular value being stated in the corresponding test procedure and on the corresponding data-reporting sheet. Thus, careful attention must be given to setting the IPW to the required test value. The IPW shall be held within ± 0.001 ms.

4.1.8 Injector Drivers and Waveforms

The type of injector driver used in testing is to be determined by the specified application and is to be of instrument-grade quality. The voltage supplied to the driver shall be $14.0\text{ VDC} \pm 1\% \text{ VDC}$ unless otherwise specified by the application. The driver type and any unique operating characteristics, such as pre-charge, boost voltage, peak current, hold current, and time delays, shall be recorded on the injector performance data sheet. Details on injector driver waveforms can be found in Section A.4.

4.1.9 Injector Polarity

The injector polarity shall be maintained throughout all testing and be the same as that used in the application.

4.1.10 Fuel Supply Equipment

The equipment used to supply the injector with fuel may vary depending on the injector design and the particular injector test being conducted. Consult the particular test description and procedure.

4.1.11 Instruments

The test instruments shall be operated and stabilized per the manufacturers' recommendations.

4.1.12 Injector Position and Axis Orientation

The axis of the injector shall be mounted vertically with the spray tip down unless otherwise designated in the appropriate test procedure.

4.2 Injector Preconditioning

Total preconditioning consists of two separate procedures: flushing and purging. The injector and the test apparatus shall 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 3. For both procedures, the injector should be operated at an injector pulse width of 1.5 ms and a period of 10.0 ms. Flushing requires at least 10000 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 3 - Preconditioning procedure (flushing and purging)

Procedure	Purpose	Test Conditions	Discard Fluid?
Flushing	Clear the injector of any shipping fluids and contaminants	IPW = 1.5 ms Period = 10.0 ms No. of pulses = 10000 (minimum) (Minimum test time = 60 seconds)	Yes
Purging	Clear the injector of air bubbles and vapor	IPW = 1.5 ms Period = 10.0 ms No. of pulses = 2000 (minimum) (Minimum test time = 20 seconds)	Optional

4.2.1 Injector Flushing Operation

Flush the injector and test apparatus with test fluid to remove all air, vapors, contaminants, and shipping fluids. This procedure is necessary for new injectors, when changing test fluid types during a test, or following a long period of storage. The injector is to be flowed for a minimum of 10000 pulses at 1.5 ms IPW and 10 ms P. For some tests, such as shot-to-shot (STS) flow, which utilize a rate meter, it may not be possible to operate at a period of 10 ms. For these tests, it is permissible to use a longer period. Discard the flush fluid after the flush procedure.

- Flush fluid temperature: $21.0\text{ }^{\circ}\text{C} \pm 2.0\text{ }^{\circ}\text{C}$.
- Flush fluid pressure: $P_{50} \pm 1.0\%$.

4.2.2 Injector Purging Operation

Purge the injector and test apparatus with test fluid to remove all air and vapors. This procedure is normally performed after the injector is initially placed into the test fixture. Flow the test injectors for a minimum of 2000 pulses at 1.5 ms IPW and 10 ms P. For certain tests, such as shot-to-shot flow, which utilize a rate meter, it may not be possible to operate at a period of 10 ms. For these tests, it is permissible to use a longer period. Discarding the purged fluid is optional.

- a. Purge fluid temperature: $21.0\text{ }^{\circ}\text{C} \pm 2.0\text{ }^{\circ}\text{C}$.
- b. Purge fluid pressure: $P_{50} \pm 1.0\%$.

4.3 Flow Measurement

The flow rate may be measured by either volume or mass flow, with the latter being the preferred method. The data should be reported in mass flow units - expressed in grams per second (g/s) for static or milligrams per pulse (mg/pulse) for dynamic points - and all pertinent information shall be recorded (number of pulses, fuel mass, etc.). Prior to flow measurement, the injector shall be preconditioned as described in 4.2.

NOTE: The dynamic flow measurement shall always precede the static flow measurement.

4.4 Summary of Standard Test Conditions

The summary of all standard test conditions is provided in Table 4. Any deviations from the recommended test conditions described in Table 4 must be recorded and clearly noted.

Table 4 - Listing of standard test conditions for all tests

Parameter	Flow - Gasoline Direct Injection Tests					Non-Flow Gasoline Direct Injection Tests			
	Preconditioning	Flow Testing	STS and MTBI	Opening and Closing	Noise	Thermal Tests	Mech Shock and Vibration	External Fluid Compatibility	Seat Tip Leak
Test fluid	n-heptane	n-heptane	n-heptane	n-heptane	n-heptane solvent or spirits	N/A	Stoddard solvent	N/A	n-heptane
Ambient temperature (°C)	21.0 ± 2.0					21.0 ± 2.0			
Ambient pressure (kPa)	100 ± 5					100 ± 5			
Fluid temperature (°C)	21.0 ± 2.0					21.0 ± 2.0			
Initial injector temperature (°C)	21.0 ± 2.0					21.0 ± 2.0			
Fluid pressure (MPa)	P ₅₀ to within ±0.5%	P ₅₀ to within ±0.5%	P ₅₀ and P ₂₀ ± 0.5%	P ₅₀ to within ±0.5%	P ₂₀ to within ±0.5%	N/A	P ₅₀ to within ±0.5%	N/A	P ₅₀ to within ±0.5%
Injection pulse width (ms)	Purge 2000 pulses at 5.0 Flush 10000 pulses at 5.0	Various as specified in procedure	STS Various as specified in procedure MTBI 0.5	1.0	1.0	N/A	N/A	N/A	N/A
Injection period (ms)	10.0	10.0	50.0 ± 0.05	50.0 ± 0.05	1000 minimum	N/A	N/A	N/A	N/A
Flow measurement	To be reported in mass flow units (g/s or mg/pulse)					N/A	N/A	N/A	mm ³ /min
Injector axis orientation	Vertical unless specified by application				Vertical	Vertical	Vertical and Horizontal	Vertical	Vertical
Injector electrical connector orientation	Specified by application					Specified by application			

5. ELECTROMECHANICAL PERFORMANCE PARAMETERS

5.1 Overview of Electromechanical Performance Parameters

Changes in selected electromechanical properties of electrically actuated solenoid fuel injectors are a key element of many test procedures in this document. The requirement to measure electromechanical properties both before and after a designated test is a common theme. This permits the changes in electromechanical properties resulting from the test to be determined. The particular parameters tend to be sensitive to temperature fluctuations, thus additional attention to temperature control may be required.

5.2 Injector Electrical Parameter Measurement Procedures

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, GDI injector solenoid designs consist of low-resistance coils. The low-resistance design is typically 0.5 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 preproduction, 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 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 preproduction, 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 Vrms .
- 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 Overview of Insulation Resistance

The test for insulation 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 and that the conductor-to-case clearance has been adequately maintained. The IR is also commonly measured after any mechanical integrity or environmental testing to ensure that the insulating abilities of the injector coil assembly have not been degraded.

In most vehicle applications, a positive DC voltage is applied to one of the injector terminals (high side) while the other terminal is connected to ground (low side), completing the circuit. In a situation where the IR breaks down, the injector could misfire, not fire at all, or in the worst case be continuously energized and flood the engine. This depends heavily on where the coil assembly is shorted (high or low side) and the manner in which the injector drive circuit current is monitored.

5.2.3.1 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 preproduction, 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.

5.2.3.2 Data Reduction and Analysis for Insulation Resistance Measurement Test

None required.

5.2.3.3 Data Reporting for Insulation Resistance Measurement Test

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

5.3 GDI Injector Opening and Closing Times

5.3.1 Overview of Injector Opening and Closing Times

The opening time (OT) of an injector is a measure of the time required for the injector needle to first reach its fully opened position after initiation of the injector logic pulse.

NOTE: The OT is not to be confused with the “determination of first fuel” (refer to SAE J2715). The determination of first fuel is an indication of the time at which the injector needle first begins to open and the presence of fuel spray exiting the nozzle is visually observed.

Closing time (CT) is the time required for the injector needle to first reach its fully closed position after the termination of the injector logic pulse. Both the OT and CT are to be reported in milliseconds. These parameter values provide a relative indication of the combined mechanical and magnetic response time. The total time to open and close the injector also provides a relative measure of the usable IPW range of the injector. A typical dynamic response trace is illustrated in Figure 2.

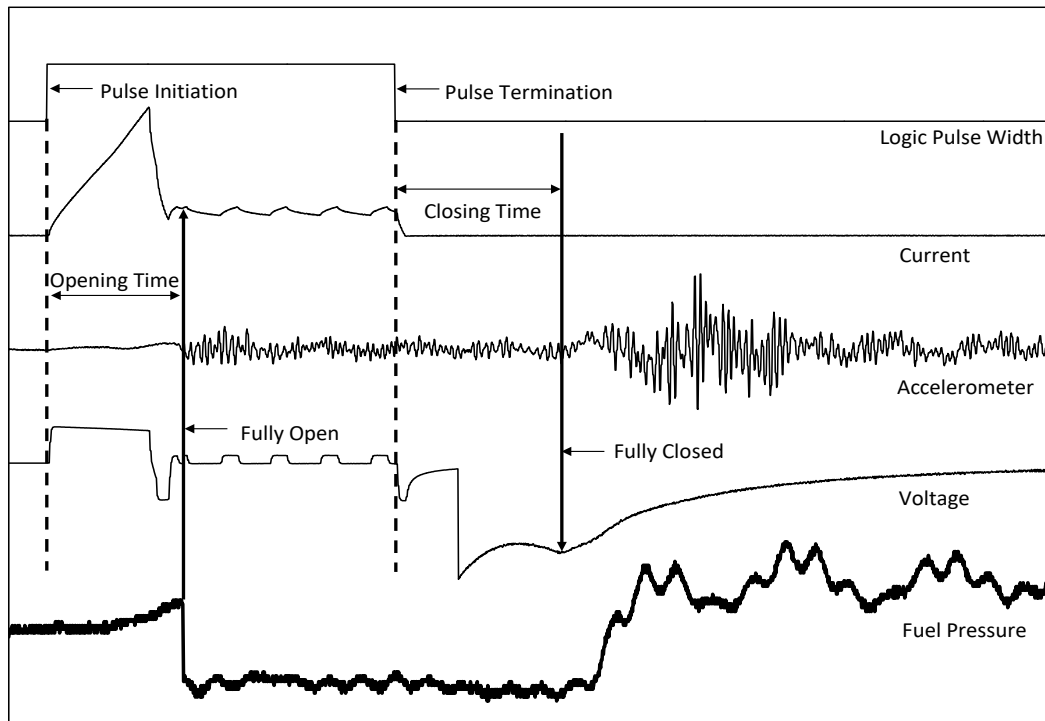


Figure 2 - GDI opening and closing response traces

5.3.2 Equipment Considerations for Injector Opening and Closing Time Testing

- a. The preferred method of measuring the OT and CT intervals is with the use of an oscilloscope and a precision, fast-response accelerometer that is mounted either directly on the injector body or within 25.0 mm of it. The accelerometer should have a response of at least 10 kHz or higher. A representative mounting of the accelerometer on the test fixture is shown in Figure 3.
- b. For injectors having a decoupled needle (armature), it may be difficult to detect the needle motion using an accelerometer. Alternate methods include the use of a dynamic pressure transducer for both OT and CT, the inflection in the current trace for OT, the inflection in the voltage trace for CT, or an injection rate meter as illustrated in Figure 4.

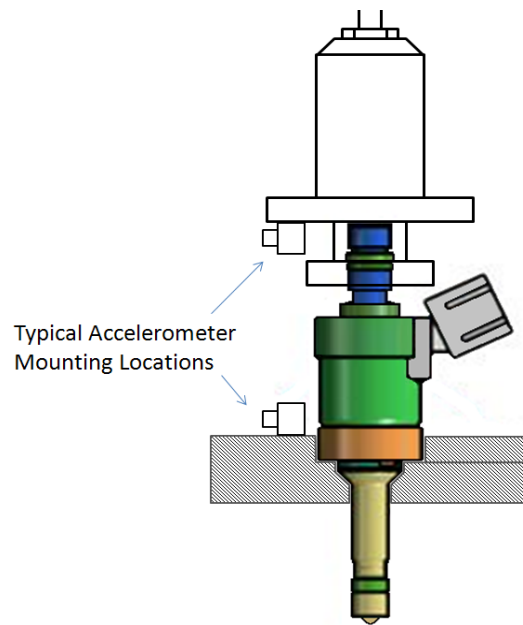


Figure 3 - Typical accelerometer mounting

5.3.3 Test Conditions for Injector Opening and Closing Time Tests

The tests are to be conducted at a fuel pressure of P_{50} . The standard test conditions are provided in Table 4 and on the data-reporting sheet in Table 5.

5.3.4 Procedure for the Determination of Injector Opening and Closing Times

- Precondition the test injector according to the procedure listed in 4.2. Then initiate the test for OT and CT using a preselected pulse width of 1.0 ms and a period of 50 ms.
- Each injection should have two distinct acceleration events as depicted in Figure 2. Record the accelerometer trace, the logic pulse, the voltage applied to the injector, the current through the injector, and the pressure maintained at the inlet of the injector for a minimum of 100 consecutive injection events.

5.3.5 Data Reduction and Analysis for Injector Opening and Closing Time Tests

- Determine the OT of each of the injection events by measuring the time between the start of the logic pulse width (LPW) and the first rise on the first set of the accelerometer signal waveforms.
- Determine the CT of each of the injection events by measuring the time between the end of the LPW and the first movement on the second set of accelerometer signal waveforms.
- Calculate the average and standard deviation of the OT for all injection events.
- Calculate the average and standard deviation of the CT for all injection events.

5.3.6 Data Reporting for Injector Opening and Closing Time Tests

- Record the calculated averages and standard deviations for OT and CT on the data-reporting sheet in Table 5 for electromechanical properties. The values should be reported in milliseconds.
- If a measurement method other than an accelerometer is used, record the method used in the comments section of the data-reporting sheet.

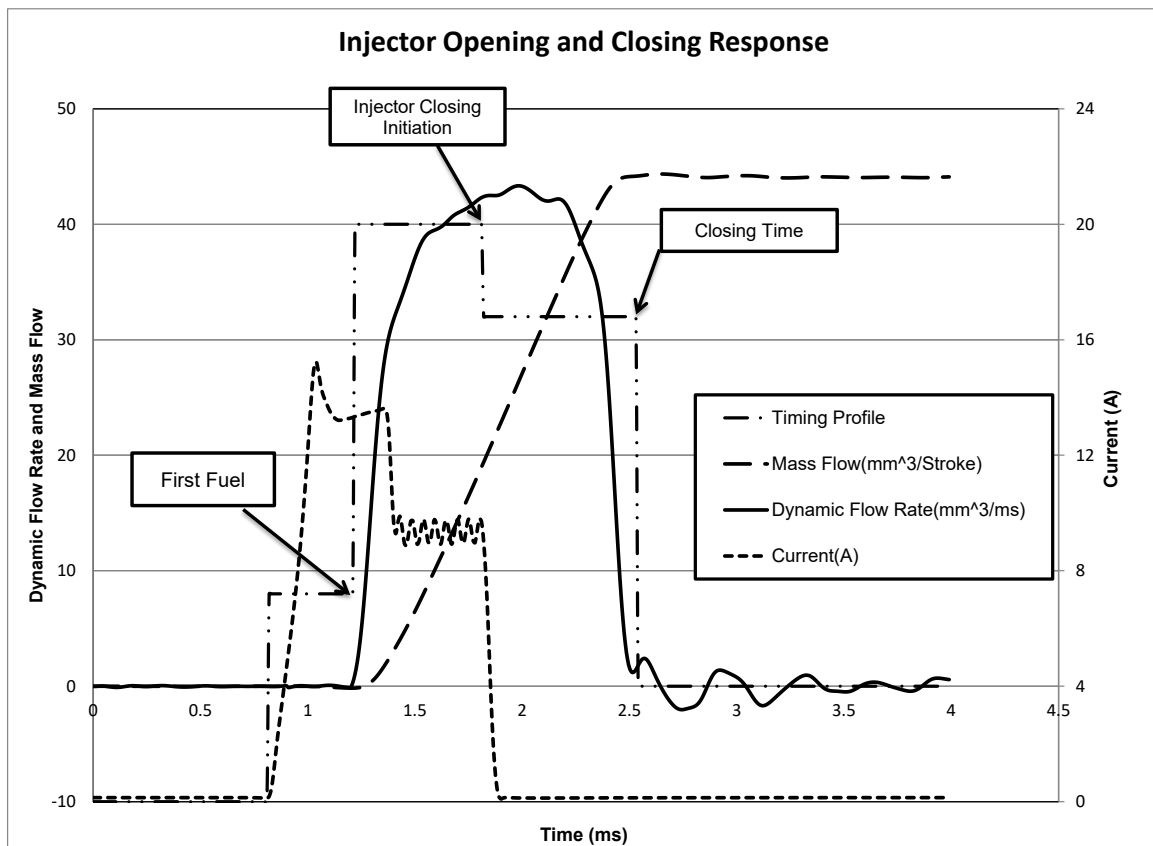


Figure 4 - Opening and closing response by injection rate meter

Table 5 - Electromechanical properties: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for GDI Injector Electromechanical Properties - Opening Time, Closing Time, Coil Resistance, Inductance, and Insulation Resistance			
Part 1: General Test Logistics			
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			
Injector serial number			
Injector driver type (current waveform - attach to data-reporting sheet)			
Injector driver charge delay time (if any) (ms)			
Additional information			
Part 3: Test Conditions	Specific Test Conditions	Standard Test Conditions	
Test fluid		n-heptane	
Ambient temperature (°C)		21.0 ± 2.0	
Ambient pressure (kPa)		100 ± 5	
Fluid temperature (°C)		21.0 ± 2.0	
Fluid pressure (MPa)		P ₅₀ to within ±0.5%	
Initial injector temperature (°C)		21.0 ± 2.0	
Injection pulse width (ms)		1.0 ± 0.001	
Injection period (ms)		50.0 ± 0.001	
Injector axis orientation (degrees)		Vertical unless specified	
Injector preconditioning time (seconds)		As per 4.2	
Additional information			
Part 4: Description and Comments on Instruments or Test Deviations			
Instrument details			
Test deviations			
Part 5: Test Results for GDI Injector Electromechanical Properties			
Opening time (ms) and associated standard deviation (ms) as obtained from the time trace; this is the SAE J2713 opening time if there are no test deviations		Opening time (ms) and associated standard deviation (ms) as obtained from the time trace if there are known test deviations:	
Closing time (ms) and associated standard deviation (ms) as obtained from the time trace; this is the SAE J2713 closing time if there are no test deviations		Closing time (ms) and associated standard deviation (ms) as obtained from the time trace if there are known test deviations:	
Coil resistance as obtained from the bridge (ohms) - denoted as (R)			
Insulation resistance as obtained from the ohmmeter (ohms) - denoted as (IR)			
Solenoid inductance as obtained from the Wheatstone bridge (mH) - denoted as (L)			
Data plots	Attach curves of injector driver current waveform and opening time and closing time traces		

5.4 GDI Injector Seat Tip Leakage

5.4.1 Overview of GDI Injector Fuel Leakage and Measurement Methods

Historically, two types of leakage are discussed for fuel injectors: body leakage and seat tip leakage. With the advent of greatly improved injector design and welding practices, body leakage measurements from GDI injectors are no longer a discriminating performance factor. Zero body leakage is expected and required. Therefore, only seat tip leakage is covered in this document. Fuel leakage from the interface between the injector and the rail is important but is a fuel system test and therefore is not covered in this document.

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 in order to prevent or significantly minimize fuel leakage. This, in turn, eliminates or minimizes the presence of unmetered fuel in the combustion chamber and reduces the tendency for deposit formation at the injector tip. The seat tip leakage rate that may occur during operation on the vehicle will vary with fuel pressure, injector temperature, and any heat-soak duration and may result in an imprecise A/F ratio, injector deposits, and elevated levels of unburned hydrocarbons (UBHCs).

Over the past decades, both gaseous and hydraulic test methods have been developed for measuring tip leakage. Three widely used gaseous test methods are the bubble-rise, pressure-decay, and helium methods. The bubble-rise and pressure-decay methods both use dry nitrogen as the test medium. With increasingly stringent leak specifications, ensuring that the internal sealing surfaces are dry is difficult. Not having total dryness can increase the uncertainty of these gaseous test methods, and they are generally not recommended for GDI tip leakage measurements. Hydraulic-test measurements eliminate the need for drying these internal surfaces, and they do provide a direct correlation to fuel leakage. Further, measurement using a flame ionization detector (FID) provides the capability of measuring the very small leak rates that are commonly encountered in contemporary GDI injectors. Therefore, this document recommends the use of an HC FID analyzer for GDI injector tip leakage measurement.

The SAE J2713 seat tip leakage is defined as the leakage at P_{50} . However, the loading on the injector needle/seat interface varies, and the needle can change accordingly, resulting in a nonlinear leak rate as a function of pressure. Therefore, other optional test pressures may be utilized (such as low-pressure electric pump pressure, idle fuel pressure, and/or fuel pressure at road-load conditions).

5.4.2 Seat Tip Leakage Measurement using the FID Method

This document defines the test method that is to be utilized to determine the seat tip leakage of a GDI injector. The injector to be tested is filled with n-heptane and pressurized. It is to be mounted in a special test fixture, as is illustrated in Figure 6, with a known flow rate of nitrogen passed over the injector tip. The flow path around the injector tip is designed such that all leaking fuel is evaporated. The resultant HC concentration of the flow stream is then measured with an FID analyzer. The analyzer is calibrated prior to the test with a calibration gas (propane) spanning the appropriate measurement range as shown in Figure 5. The sampling stream flow rate is maintained constant during the measurement. A heated sample line between the injector and the FID is required to avoid possible HC condensation within the system. The FID analyzer measures the parts per million of hydrocarbons in the nitrogen stream, and, knowing the nitrogen flow rate and the measured HC concentration, this value may then be converted into the equivalent cubic millimeters per minute of fuel leakage.

The FID tip leak test may be conducted in a non-explosion-proof environment because of the small quantities of n-heptane required. Typically, the injector is filled with n-heptane at a separate station in an explosion-proof environment. It is then brought to the leak test stand and pressurized to the correct measurement pressure with nitrogen above the n-heptane. Therefore, only the internal injector volume is filled with n-heptane. The measured value is the average HC concentration.

NOTE: An HC FID analyzer is recommended in SAE J2713 for GDI injector leakage measurement. However, if an FID analyzer is not available for testing, then one of the seven archival, alternative test procedures described in Section A.5 may be utilized. If this is done, the type of archival test utilized should be clearly indicated on the data-reporting sheet in the comments area. The use of one of these archival tests would not be considered as a test deviation.

5.4.3 Requirements of the FID Analyzer Used for the Tip Leakage Test

- Analyzer type: Commercial FID analyzer.
- Measurement repeatability: $\pm 1\%$ of the instrument full scale.
- Response time: Within 1.5 seconds.
- Zero drift: Within $\pm 1\%$ of the instrument full scale per 8 hours.
- Calibration drift: Within $\pm 1\%$ of the instrument full scale per 8 hours.
- Linearity: Within $\pm 1\%$ of the instrument full scale.

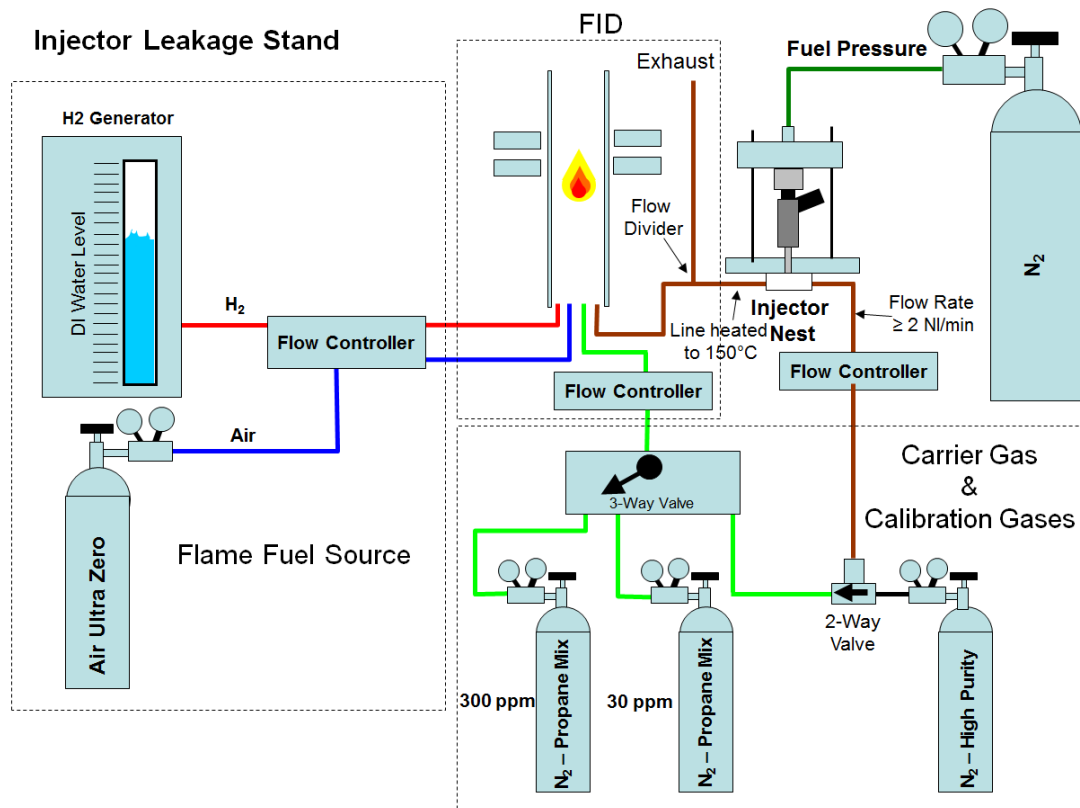


Figure 5 - Schematic diagram of FID test stand for tip leakage test

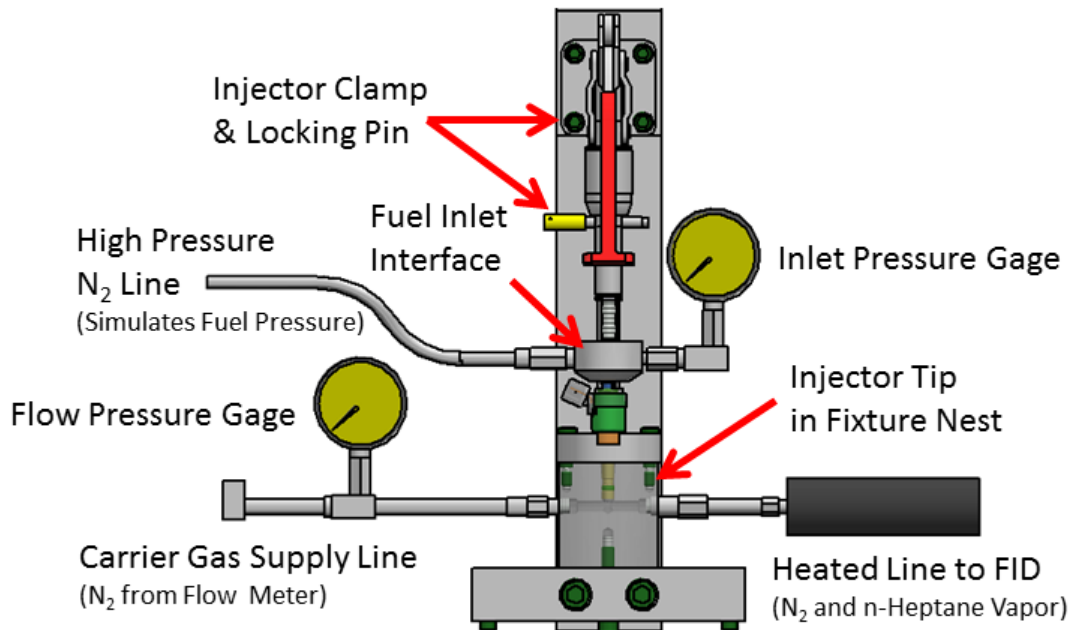


Figure 6 - Diagram of the FID test fixture for tip leakage

5.4.4 Procedure for the FID Tip Leakage Test

- a. FID calibration: First, conduct a three-point calibration of the FID instrument. See Figure 5 for the schematic of the FID test stand and Figure 6 for the FID injector test fixture that is in that stand. Note in Figure 5 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 GDI 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 steps (b), (c), and (d) 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 is to be tested. If the injectors are obtained from other than serial production, the source and selection method shall be entered in the comments section of the data-reporting sheet. Precondition each of these injectors according to the procedures in 4.2. 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 in Table 4 (also shown in Table 6 for convenience) and on the data-reporting sheet for tip leakage. Note any deviations in the comments section of the data-reporting sheet.

- h. When removing the injector from the preconditioning 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.
- i. The injector is then mounted in an FID injector nest fixture, which is depicted in Figure 7. This is, in turn, mounted in the overall FID test fixture that is shown in Figure 6. A close-up view of the downstream portion of the nest fixture is shown in Figure 8. When installed as illustrated, pressurized nitrogen may be later applied to the injector fuel inlet at the designated test pressure to pressurize the test fuel and to initiate the process of tip leakage. Once the injector is installed, and without fuel pressurization, obtain a verification of zero indicated leakage. The nest is designed to have the nitrogen gas flow around the tip of the injector such that any and all leaking fuel evaporates and is carried to the analyzer 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: first, 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. Second, the injector exhibits a gross leak. To verify the leak, test with an alternate method (non-FID) to determine if the injector is a gross leaker. Third, 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_{50} 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_{50} .
- m. Let the FID measurement stabilize such that the reading from the FID does not vary by more than $\pm 5\%$. 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 $\pm 5\%$) or not. Record at a data rate of 1 per second (1 Hz).

Table 6 - Standard test conditions for the FID tip leakage test

Test Parameter	Standard Value
Test fluid	n-heptane
Ambient pressure (kPa)	100 ± 5
Ambient temperature (°C)	21 ± 2
Fluid temperature (°C)	21 ± 2
Injector temperature (°C)	21 ± 2
Fluid pressure (MPa)	$P_{50} \pm 0.5\%$
Injector axis orientation	Vertical; tip down

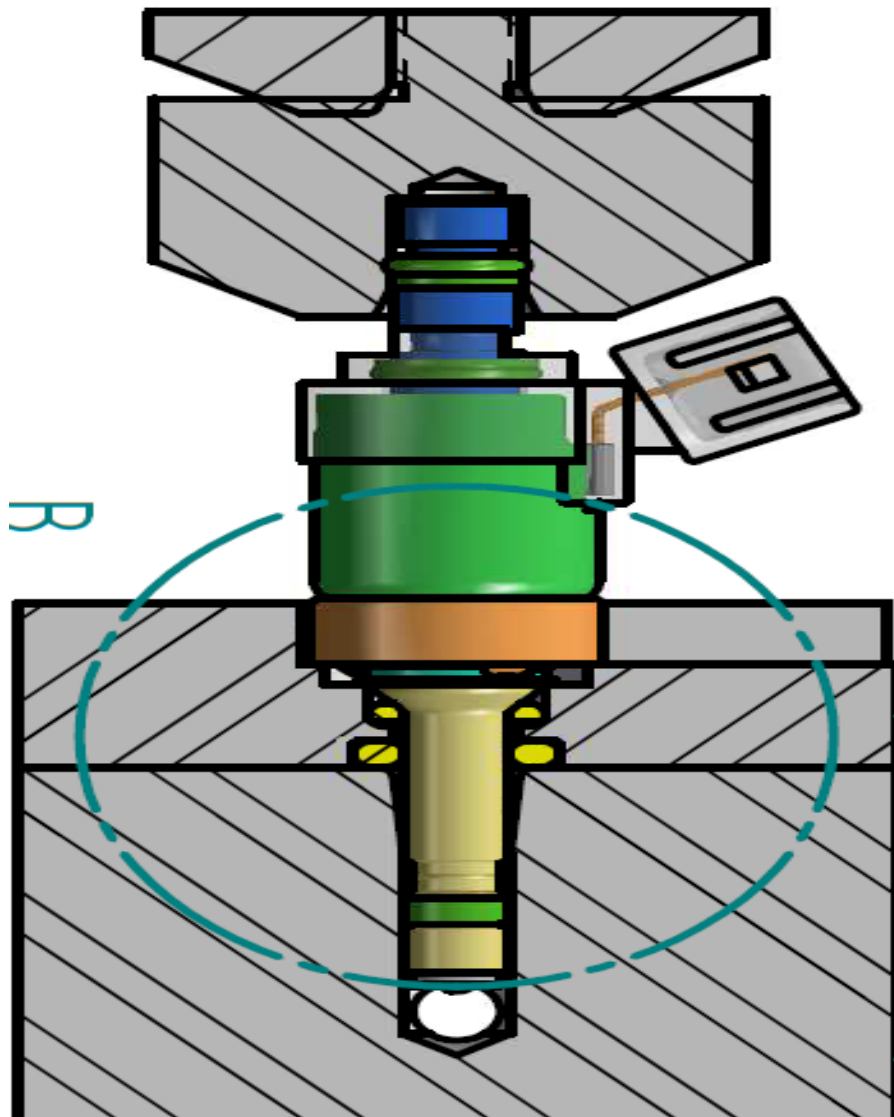


Figure 7 - Injector nest fixture for GDI FID tip leakage measurement

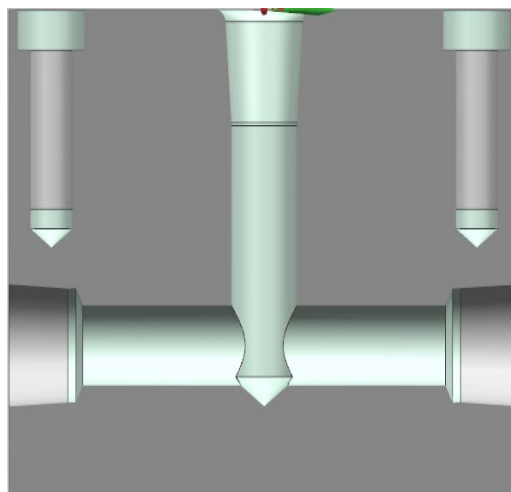


Figure 8 - Details of the nest fixture downstream of the tip

5.4.5 Data Reduction and Analysis for FID Tip Leakage

- Determine the average of the 20 FID readings that were made at 1 per second.
- For HC analyzers that report in carbon parts per million, use the FID ppm measurement and Equation 10 to convert the carbon ppm reading to an equivalent 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.

$$q_{\text{LEAK}} = q_c \times \frac{1000 \text{ mL}}{1 \text{ L}} \times \frac{1 \text{ mol}}{22400 \text{ mL}} \times \frac{c}{10^6} \text{ Carbon} \times \frac{3 \text{ carbon}}{1 \text{ propane}} \times \frac{1 \text{ n hept}}{7 \text{ carbon}} \times \frac{100.204 \text{ g}}{1 \text{ mol}} \times \frac{1 \text{ mL}}{0.68376 \text{ g}} \times \frac{1000 \text{ }\mu\text{L}}{1 \text{ mL}} \quad (\text{Eq. 10})$$

where:

q_c = carrier gas flow rate in NL/min

c = concentration of carbon in ppm

q_{LEAK} = leak rate in mm^3/min (note: this is the same as microliters/minute)

5.4.6 Data Reporting for FID Tip Leakage

Record the resultant leakage rate on the FID tip leakage data-reporting sheet in Table 7. The units are to be in mm^3/min . If the readings were stable to within $\pm 5\%$, 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 J2713 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 J2713 FID tip leakage rate.

Table 7 - GDI injector FID tip leakage test: data-reporting sheet

SAE Data-Reporting Sheet for FID Tip Leakage Measurements for GDI			
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 P ₁₀₀			
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 (kPa)			100 ± 5
Fluid temperature (°C)			21 ± 2
Fuel test pressure (MPa)			P ₅₀ ± 0.5%
Test pressure tolerance			±0.5%
Injector temperature (°C)			21 ± 2
Data sampling rate			1 Hz
Pressurization medium			Air or nitrogen
Part 4: Specific Instrument Information and Test Parameters			
Additional info/comments			
Deviations and instabilities			
Part 5: Test Results			
Recording of the measured average tip leakage rate for the final 20 seconds of data			
If there are no test deviations, record the measured FID leakage rate here:		For any test deviations or for non-stable data, record the measured FID leakage rate here:	mm ³ /min
This is the: SAE J2713 FID Tip Leakage Rate:	mm ³ /min		

5.5 Overview of Static and Dynamic Flow Testing

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. Since the introduction of direct 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.

5.5.1 Test Fluid Specified for Static and Dynamic Flow Testing

n-heptane is the preferred standard test fluid for the fuel flow tests in this 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 safely with actual hydrocarbons as the test fluid. However, most of the industry now utilizes n-heptane as the flow test fluid of choice, and the majority of tests within SAE J2713 specify this. In those cases where n-heptane is specified and cannot be utilized, another fluid may be used that is compatible with the flow test equipment, and this can be specified as a test deviation on the data-reporting sheet.

5.6 Static Flow Measurement

The static flow, Q_s , is an important GDI injector flow parameter that quantifies the maximum flow capacity of the injector. It is a key parameter in determining the applicability of a particular injector model to a specified engine application. The static flow is reported in grams per second.

5.6.1 Procedure for the Static Flow Measurement Test

This test procedure is for a single injector rather than for a population of injectors. If the injectors are from preproduction, this shall be stated in the comments section of the data-reporting sheet.

- a. A minimum set of five new injectors of the same make and model from serial production is to be tested. The test may be optionally repeated for additional injectors of the same model. Precondition each injector to be tested according to the procedure in 4.2.
- b. Use n-heptane at a temperature of $21.0\text{ }^{\circ}\text{C} \pm 2.0\text{ }^{\circ}\text{C}$ as the test fluid, with a fuel pressure of P_{50} .
- 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 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.
- f. Repeat steps (b) through (e) for the next injector to be tested.

5.6.2 Data Reduction and Analysis for the Static Flow Test

Compute the average of the three independent static flow rates that were measured for each of the test injectors to obtain its individual static flow. Then compute the average of all the individual computed static flow values (one per tested injector) to obtain the single, final static flow value to be reported. The units of the reported Q_s are to be in grams per second (g/s).

5.6.3 Data Reporting for the Static Flow Test

The general information on the test conditions and the injector that is tested are to be reported on Parts 1, 2, and 3 of the flow data-reporting sheet in Table 9. This includes the serial number of that injector. Also, record on the data-reporting sheet in Part 5-D the injector serial number and the three static flow rate values that were measured, as well as the resultant static flow value, which is the average of the three. The units are to be in grams per second. Repeat for each test injector using a new copy of the data-reporting sheet. Leave the row titled "Average of the Averages SAE J2713 Static Flow" blank for all but the last tested injector. For that last tested injector, if n-heptane at a fuel pressure of P_{50} was employed for the test and there are no other test deviations, this will be the SAE J2713 static flow that was determined for that particular test injector, and that value is to be entered in that box in Part 5-D of the data-reporting sheet in Table 9. If there are any test deviations, these shall be noted in the test comments area of the datasheet, and the data is reported in the box in Part 5-D for data with test deviations.

5.7 Dynamic Verification Flow Measurement

The dynamic verification flow, Q_{VF} , is a key parameter that indicates the fuel flow rate at a specified pulse width. This is an important GDI parameter for determining the suitability of a specific injector design to a particular engine application. The dynamic verification flow is normally reported in milligrams per injection or in milligrams per pulse.