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.

TO PLACE A DOCUMENT ORDER: **Tel: 877-606-7323 (inside USA and Canada)**
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE WEB ADDRESS: http://www.sae.org

For more information on this standard, visit
https://www.sae.org/standards/content/J2713_202409/

TABLE OF CONTENTS

1. SCOPE 6
1.1 Purpose 6

2. REFERENCES 6
2.1 Applicable Documents 6
2.2 SAE Publications 6
2.3 ASTM Publications 7
2.4 ISO Publications 7
2.5 Code of Federal Regulations (CFR) Publications 7
2.6 U.S. Government Publications 7

3. BASIC CHARACTERISTICS, DEFINITIONS, AND ABBREVIATIONS 8
3.1 Basic Characteristics 8
3.2 Definitions 8
3.3 Abbreviations 14

4. STANDARD TEST CONDITIONS 15
4.1 Test Conditions 15
4.1.1 Ambient Conditions 15
4.1.2 Test Fluid 15
4.1.3 Test Fluid Temperature 17
4.1.4 Injector Body Temperature 17
4.1.5 Fuel Pressures 17
4.1.6 Period (P) 17
4.1.7 Injection Pulse Width (IPW) 17
4.1.8 Injector Drivers and Waveforms 17
4.1.9 Injector Polarity 18
4.1.10 Fuel Supply Equipment 18
4.1.11 Instruments 18
4.1.12 Injector Position and Axis Orientation 18
4.2 Injector Preconditioning 18
4.2.1 Injector Flushing Operation 18
4.2.2 Injector Purging Operation 19
4.3 Flow Measurement 19
4.4 Summary of Standard Test Conditions 19

5. ELECTROMECHANICAL PERFORMANCE PARAMETERS 20
5.1 Overview of Electromechanical Performance Parameters 20
5.2 Injector Electrical Parameter Measurement Procedures 20
5.2.1 Coil Resistance (R) 20
5.2.2 Inductance (L) 21
5.2.3 Overview of Insulation Resistance 22
5.3 GDI Injector Opening and Closing Times 22
5.3.1 Overview of Injector Opening and Closing Times 22
5.3.2 Equipment Considerations for Injector Opening and Closing Time Testing 23
5.3.3 Test Conditions for Injector Opening and Closing Time Tests 24
5.3.4 Procedure for the Determination of Injector Opening and Closing Times 24
5.3.5 Data Reduction and Analysis for Injector Opening and Closing Time Tests 24
5.3.6 Data Reporting for Injector Opening and Closing Time Tests 24
5.4 GDI Injector Seat Tip Leakage 27
5.4.1 Overview of GDI Injector Fuel Leakage and Measurement Methods 27
5.4.2 Seat Tip Leakage Measurement using the FID Method 27
5.4.3 Requirements of the FID Analyzer Used for the Tip Leakage Test 28
5.4.4 Procedure for the FID Tip Leakage Test 29
5.4.5 Data Reduction and Analysis for FID Tip Leakage 32
5.4.6 Data Reporting for FID Tip Leakage 32
5.5 Overview of Static and Dynamic Flow Testing 33
5.5.1 Test Fluid Specified for Static and Dynamic Flow Testing 33

5.6 Static Flow Measurement 34
5.6.1 Procedure for the Static Flow Measurement Test 34
5.6.2 Data Reduction and Analysis for the Static Flow Test 34
5.6.3 Data Reporting for the Static Flow Test 34
5.7 Dynamic Verification Flow Measurement 34
5.7.1 Procedure for Dynamic Verification Flow Measurement 35
5.7.2 Data Reduction and Analysis for Dynamic Verification Flow Measurement 35
5.7.3 Data Reporting for Dynamic Verification Flow Measurement 35
5.8 Overview of Operating Flow Range Tests for LFR, DLFR, WFR, and DWFR 36
5.9 Linear Flow Range Test 37
5.9.1 Procedure for Measuring the Linear Flow Range 37
5.9.2 Data Reduction and Analysis for the Linear Flow Range 37
5.9.3 Regression Analysis for the Linear Flow Range 38
5.9.4 Generation of Percentage Difference from Linearity 39
5.9.5 Determination of the Limits of Linearity 40
5.9.6 Data Reporting for the Linear Flow Range 40
5.10 Dynamic Linear Flow Range Test 40
5.10.1 Procedure for Measuring the Dynamic Linear Flow Range 41
5.10.2 Data Reduction and Analysis for the Dynamic Linear Flow Range 41
5.10.3 Regression Analysis for the Dynamic Linear Flow Range 42
5.10.4 Generation of Percentage Difference from Dynamic Linearity 43
5.10.5 Determination of the Limits of Dynamic Linearity 44
5.10.6 Data Reporting for the Dynamic Linear Flow Range 44
5.11 Working Flow Range Test 45
5.11.1 Overview of the Working Flow Range and the Minimum Working Flow 45
5.11.2 Procedure for Measuring the Working Flow Range 45
5.11.3 Data Reduction and Analysis for the Working Flow Range 46
5.11.4 Generation of the Percentage Variability Curve 46
5.11.5 Determination of the Low and High Limits of the Working Flow Range 47
5.11.6 Data Reporting for the Working Flow Range 48
5.12 Dynamic Working Flow Range Test 49
5.12.1 Overview of the Dynamic Working Flow Range 49
5.12.2 Procedure for Measuring the Dynamic Working Flow Range 49
5.12.3 Data Reduction and Analysis for the Dynamic Working Flow Range 50
5.12.4 Generation of the Percentage Variability Curve 51
5.12.5 Determination of the Low and High Limits of the Dynamic Working Flow Range 51
5.12.6 Data Reporting for the Dynamic Working Flow Range 52
5.13 Minimum Time Between Injections (MTBI) 56
5.13.1 Procedure for the MTBI Test 57
5.13.2 Data Reduction and Analysis for MTBI Testing 58
5.13.3 Data Reporting for MTBI Testing 60
5.14 Shot-to-Shot (STS) Mass Flow Variation 63
5.14.1 Overview of the STS Variability Parameter 63
5.14.2 Test Equipment for STS Testing 63
5.14.3 Procedure for the STS Test 63
5.14.4 Data Reduction and Analysis for STS Testing 64
5.14.5 Data Reporting for STS Testing 65

6. ENVIRONMENTAL TESTS 67
6.1 External Fluid Compatibility Tests 67
6.1.1 Common Automotive Fluids for External Compatibility Tests 67
6.1.2 Procedure for the Common Automotive Fluid Compatibility Test 67
6.1.3 Data Reduction and Analysis for the External Fluid Compatibility Test 68
6.1.4 Data Reporting for the External Fluid Compatibility Test 68
6.2 Water Jet Test 68
6.2.1 Procedure for the Water Jet Test 68
6.2.2 Data Reduction and Analysis for the Water Jet Test 69
6.2.3 Data Reporting for the Water Jet Test 69
6.3 Steam Jet Test 69
6.3.1 Procedure for the Steam Jet Test 69

6.3.2 Data Reduction and Analysis for the Steam Jet Test 69
6.3.3 Data Reporting for the Steam Jet Test 70
6.4 Temperature Cycling Test 71
6.4.1 Procedure for the Temperature Cycling Test 71
6.4.2 Data Reduction and Analysis for the Temperature Cycling Test 72
6.4.3 Data Reporting for the Temperature Cycling Test 72
6.5 Hot Static Soak Test 72
6.5.1 Procedure for the Hot Static Soak Test 72
6.5.2 Data Reduction and Analysis for the Hot Static Soak Test 73
6.5.3 Data Reporting for the Hot Static Soak Test 73
6.6 Cold Static Soak Test 73
6.6.1 Procedure for the Cold Static Soak Test 73
6.6.2 Data Reduction and Analysis for the Cold Static Soak Test 73
6.6.3 Data Reporting for the Cold Static Soak Test 73
6.7 Thermal Shock Test 73
6.7.1 Procedure for the Thermal Shock Test 74
6.7.2 Data Reduction and Analysis for the Thermal Shock Test 75
6.7.3 Data Reporting for the Thermal Shock Test 75
6.8 Salt-Spray External Cyclic Corrosion Test 77
6.8.1 Design and Setup of Test Equipment for the Salt-Spray External Cyclic Corrosion Test 77
6.8.2 Procedure for the Salt-Spray External Cyclic Corrosion Test 77
6.8.3 Data Reduction and Analysis for the Salt-Spray External Cyclic Corrosion Test 79
6.8.4 Data Reporting for the Salt-Spray External Cyclic Corrosion Test 79

7. PHYSICAL TESTS 81
7.1 Overview of Physical Tests 81
7.2 Static Mechanical Testing 81
7.2.1 Overview of Static Mechanical Testing 81
7.2.2 Test Fixture Mounting Guidelines 81
7.2.3 Test Conditions for Physical Tests 82
7.2.4 Axial Load Tension Test 82
7.2.5 Axial Load Compression Test 83
7.2.6 Torsional Moment Test 83
7.2.7 Bending Moment Test 84
7.3 Operational Physical Tests 85
7.3.1 Overview of Operational Physical Tests 85
7.3.2 Vibration Test 85
7.3.3 Mechanical Shock Test 86
7.3.4 Proof-Pressure Test 87
7.3.5 Burst-Pressure Test 88

8. INJECTOR NOISE CHARACTERIZATION 90
8.1 Background on GDI Injector Noise Generation 90
8.2 GDI Noise Test Equipment 91
8.3 Test Conditions for GDI Injector Noise Measurement 92
8.4 Procedure for the GDI Noise Characterization Test 92
8.5 Data Reduction and Analysis of the Noise Data 93
8.6 Data Reporting for the Noise Test 93

9. BENCH DURABILITY TESTING 95
9.1 Test Equipment for Bench Durability Testing 95
9.2 List of Required Bench Durability Test Fuels 95
9.3 Optional Accelerated Wear Test Conditions and Fluids 96
9.4 Procedure for the Bench Durability Test 96
9.5 Frequency of Performance Audits 97
9.6 Data Reduction and Analysis for Bench Durability 97
9.7 Data Reporting for Bench Durability 97

10. TEST EQUIPMENT ... 99
10.1 Injector Driver Circuit ... 100
10.2 Flow Test Stand ... 100
10.3 Gasoline Bench Durability Test Stand ... 101

11. NOTES ... 103
11.1 Revision Indicator ... 103

APPENDIX A ADDITIONAL SYSTEM INFORMATION ... 104

Figure 1 Representation of defined SAE J2713 GDI fuel pressures (curve generated from actual GDI flow data) ... 8
Figure 2 GDI opening and closing response traces ... 23
Figure 3 Typical accelerometer mounting ... 24
Figure 4 Opening and closing response by injection rate meter ... 25
Figure 5 Schematic diagram of FID test stand for tip leakage test ... 28
Figure 6 Diagram of the FID test fixture for tip leakage ... 29
Figure 7 Injector nest fixture for GDI FID tip leakage measurement ... 31
Figure 8 Details of the nest fixture downstream of the tip ... 31
Figure 9A LFR regression and the percentage flow deviation ... 38
Figure 9B LFR regression and the percentage flow deviation (short-pulse-width region) ... 39
Figure 10 DLFR regression and the associated percentage flow deviation ... 42
Figure 11 DLFR regression and the associated percent flow deviations (short-pulse-width region) ... 43
Figure 12A GDI flow and percentage flow variability for WFR determination ... 46
Figure 12B GDI flow and percentage flow variability for WFR determination (short-pulse-width region) ... 47
Figure 13 GDI mean flow rate and the associated flow variability for a DWFR analysis ... 50
Figure 14 GDI mean flow rate and the associated flow variability for DWFR (short-pulse-width region) ... 51
Figure 15 Timing diagram for the MTBI test ... 57
Figure 16 Typical dataset for MTBI flow variation ... 60
Figure 17 Measured STS flow variation for a GDI injector ... 65
Figure 18 Temperature cycle test profile ... 72
Figure 19 Illustration of typical temperature confirmation data ... 74
Figure 20 Mechanical loading modes for physical testing ... 82
Figure 21A Representative GDI injector noise characterization test fixture ... 91
Figure 21B Fuel supply schematic for the GDI injector characterization test fixture ... 92
Figure 21C Period and pulse width protocol for injector noise measurement ... 93
Figure 22 Schematic of typical GDI injector driver circuit with a recirculation diode ... 100
Figure 23 Schematic of a recommended injector flow test stand ... 101
Figure 24 Schematic of a recommended bench durability test stand ... 102

Table 1 Comparison of properties and flow for n-heptane and the EPA emission test gasoline ... 16
Table 2 Physical property specifications for common test fluids ... 16
Table 3 Preconditioning procedure (flushing and purging) ... 18
Table 4 Listing of standard test conditions for all tests ... 20
Table 5 Electromechanical properties: data-reporting sheet ... 26
Table 6 Standard test conditions for the FID tip leakage test ... 30
Table 7 GDI injector FID tip leakage test: data-reporting sheet ... 33
Table 8 Types of GDI injector flow-range tests ... 36
Table 9 GDI injector flow test: data-reporting sheets ... 53
Table 10 Sample data set for minimum time between injections ... 59
Table 11 GDI MTBI: data-reporting sheet ... 61
Table 12 GDI shot-to-shot sample dataset ... 65
Table 13 GDI STS variability tests: data-reporting sheet ... 66
Table 14 Common automotive fluids for external compatibility tests ... 67
Table 15 External fluid compatibility tests: data-reporting sheet ... 70
Table 16 Thermal environmental tests: data-reporting sheet ... 75
Table 17 Salt-spray external cyclic corrosion test: data-reporting sheet ... 79
Table 18 GDI injector physical tests: data-reporting sheet ... 89
Table 19 GDI injector noise characterization: data-reporting sheet ... 94
Table 20 GDI injector bench durability tests: data-reporting sheet ... 98
Table 21 Recommended test equipment resolution and accuracy ... 102

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

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.

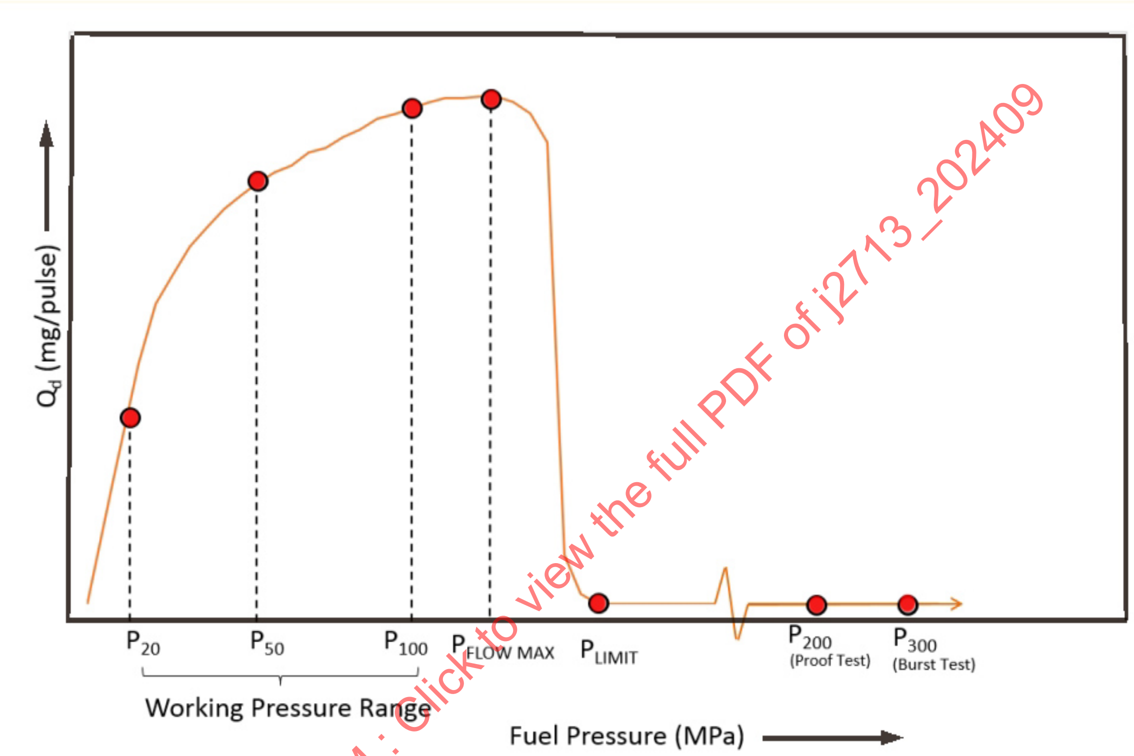

Figure 1 - Representation of defined SAE J2713 GDI fuel pressures (curve generated from actual GDI flow data)

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 ($P_{FLOW\ MAX}$)

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).

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

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 ±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 ±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*standard deviation/(corresponding mean flow) = 10%. This is also equivalent to 3*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*standard deviation/(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*standard deviation/(corresponding mean flow) = 10%. This is also equivalent to 3*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*standard deviation/(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*3*standard deviation/(corresponding mean flow), or alternatively as 100*3*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 ±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 mm^3/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 ± 5 kPa and a temperature of 21 °C ± 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 °C ± 2.0 °C.

4.1.4 Injector Body Temperature

The body temperature of the test injector should be stabilized at an ambient temperature of 21.0 °C ± 2.0 °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 °C ± 2.0 °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 ±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 VDC ± 1% 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.

a. Flush fluid temperature: 21.0 °C ± 2.0 °C.

b. Flush fluid pressure: P_{50} ± 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 °C ± 2.0 °C.

b. Purge fluid pressure: P_{50} ± 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 °C ± 2.0 °C. Caution should be taken to not physically touch the injector just before taking measurement as it may alter the injector coil temperature and affect the resistance readings.

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

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

5.2.1.3 Data Reduction and Analysis for Coil Resistance Measurement Test

None required.

5.2.1.4 Data Reporting for Coil Resistance Measurement Test

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

5.2.2 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 kHz ± 0.5%, with a potential of 1.0 Vrms.

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

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

5.2.2.3 Data Reduction and Analysis for Solenoid Inductance Measurement Test

None required.

5.2.2.4 Data Reporting for Solenoid Inductance Measurement Test

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

5.2.3 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.

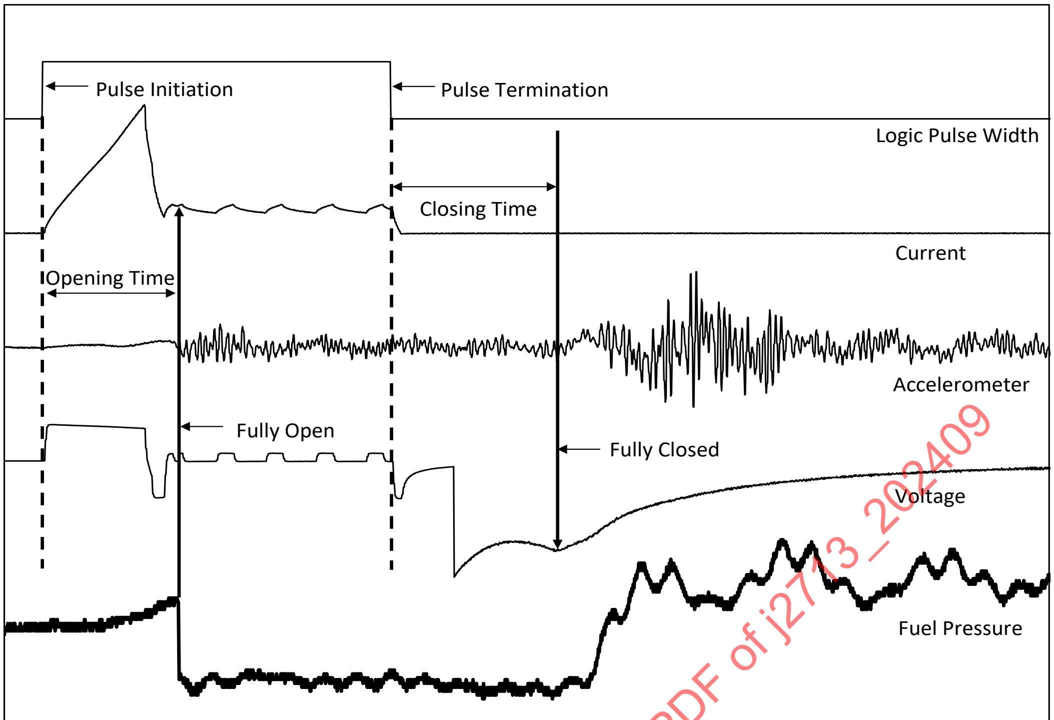

Figure 2 - GDI opening and closing response traces

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.

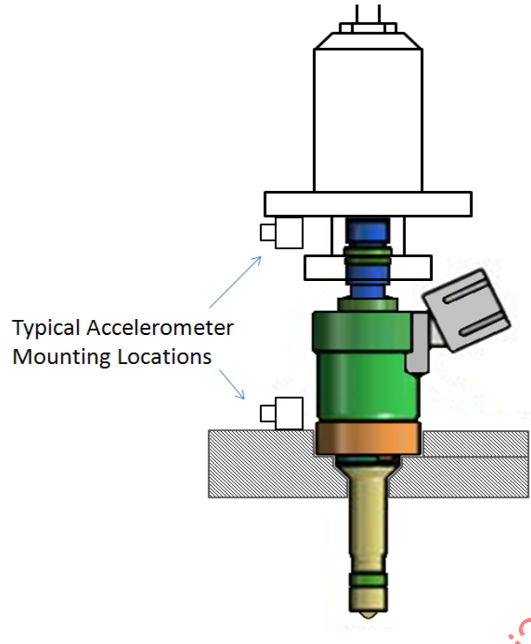

Figure 3 - Typical accelerometer mounting

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

a. 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.

b. 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

a. 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.

b. 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.

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

d. 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

a. 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.

b. If a measurement method other than an accelerometer is used, record the method used in the comments section of the data-reporting sheet.

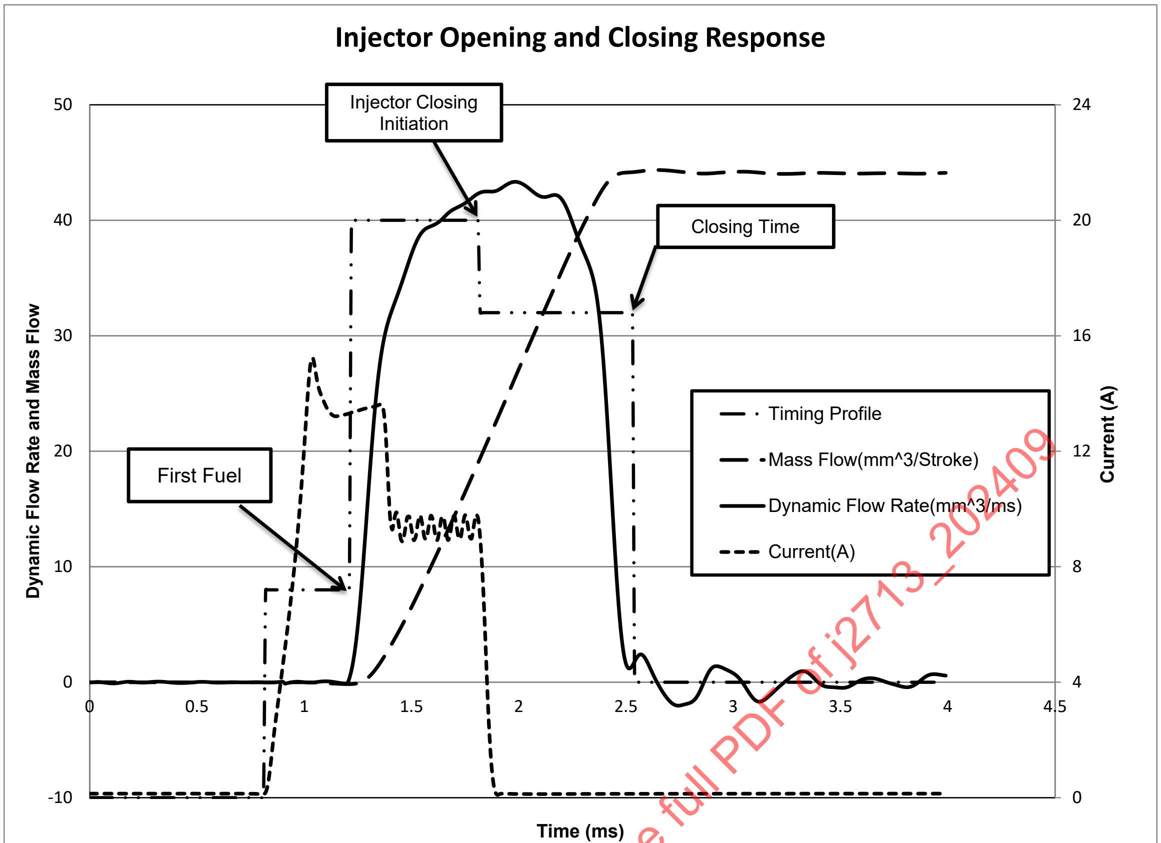

Figure 4 - Opening and closing response by injection rate meter

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

a. Analyzer type: Commercial FID analyzer.

b. Measurement repeatability: ±1% of the instrument full scale.

c. Response time: Within 1.5 seconds.

d. Zero drift: Within ±1% of the instrument full scale per 8 hours.

e. Calibration drift: Within ±1% of the instrument full scale per 8 hours.

f. Linearity: Within ±1% of the instrument full scale.

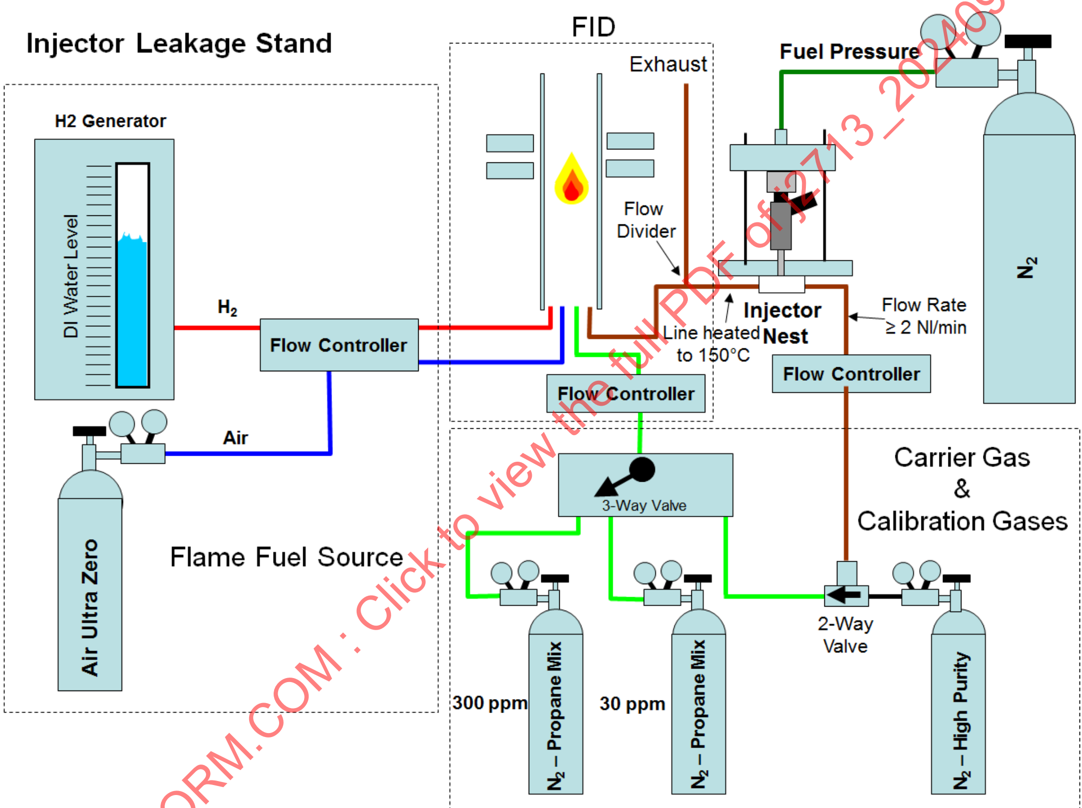

Figure 5 - Schematic diagram of FID test stand for tip leakage test

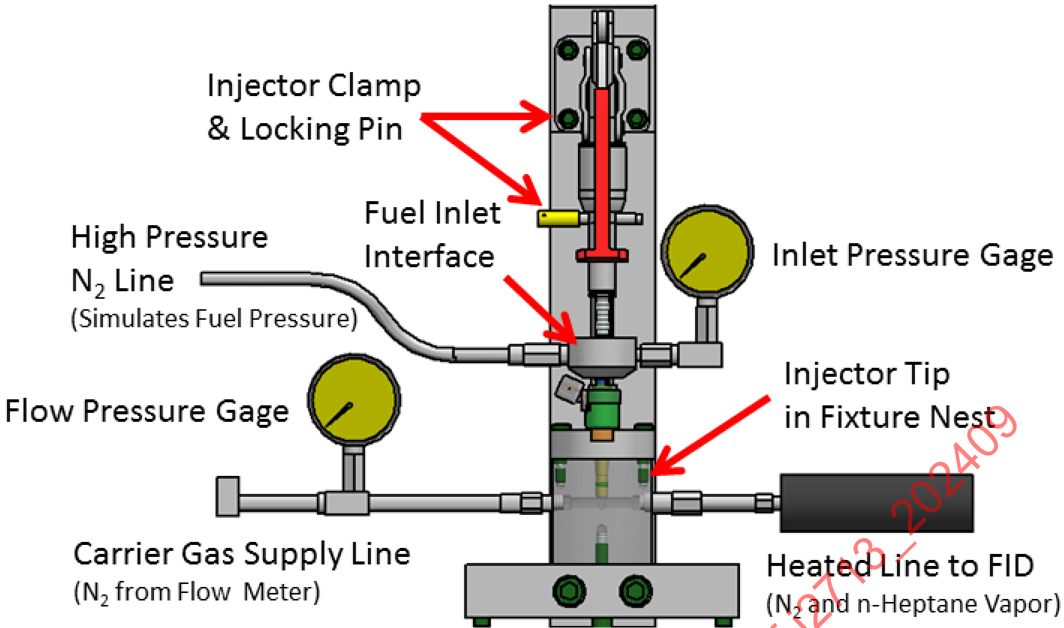

Figure 6 - Diagram of the FID test fixture for tip leakage

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

n. If the carrier gas flow rate is steady, record 20 seconds of data whether the FID reading is stable (within ±5%) or not. Record at a data rate of 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} ± 0.5%
Injector axis orientation	Vertical; tip down

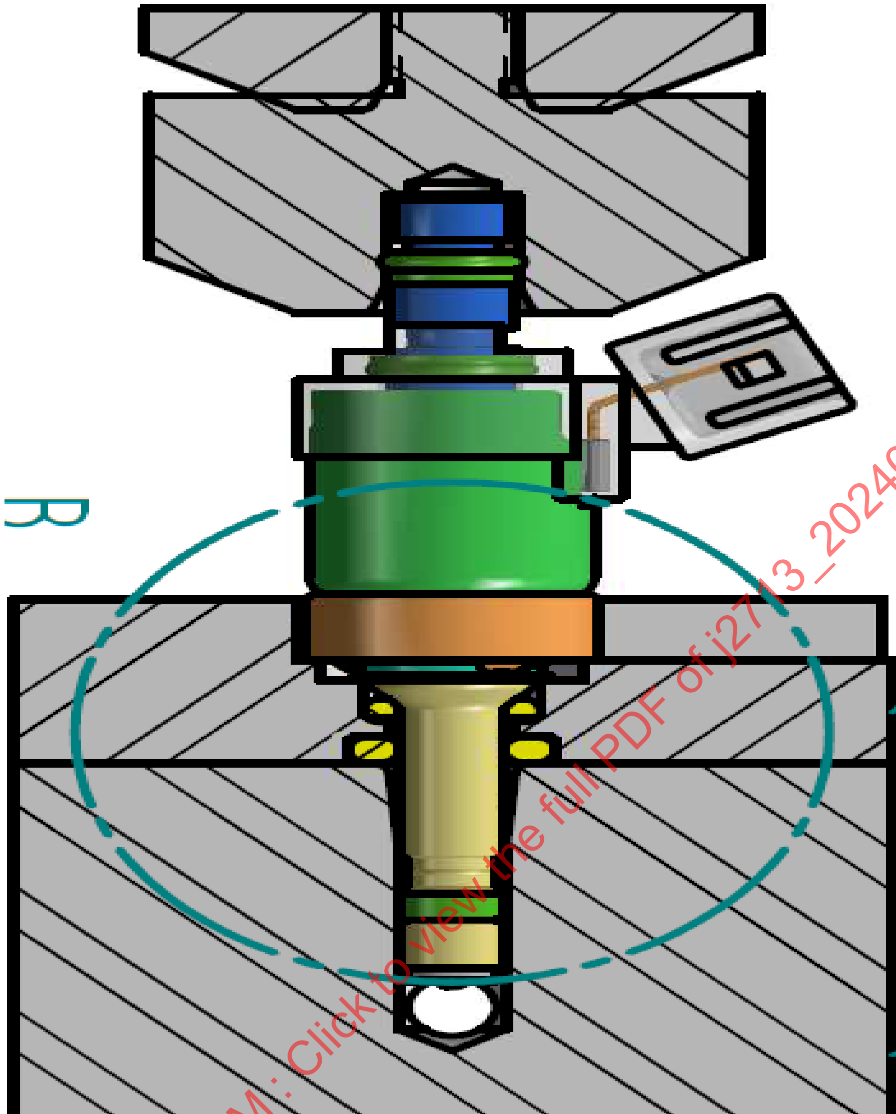

Figure 7 - Injector nest fixture for GDI FID tip leakage measurement

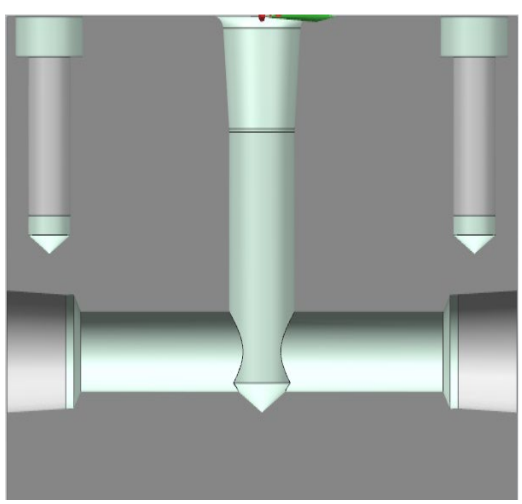

Figure 8 - Details of the nest fixture downstream of the tip

5.4.5 Data Reduction and Analysis for FID Tip Leakage

a. Determine the average of the 20 FID readings that were made at 1 per second.

b. 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.

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

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 ±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 °C ± 2.0 °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.

5.7.1 Procedure for Dynamic Verification Flow Measurement

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 described in 4.2.

b. Use n-heptane at a temperature of 21.0 °C ± 2.0 °C as the test fluid with a fuel pressure of P_{50}.

c. Operate the test injector using a specified dynamic verification flow pulse width of 1.0 ms and a period (P) of 10.0 ms (100 Hz). The use of a pulse width other than 1.0 ms is considered a test deviation and should be clearly noted in the specific test conditions section of the data-reporting sheet.

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

e. Repeat step (d) twice more for a total of three times for the same injector and record the three dynamic flow values that were obtained.

f. Repeat steps (b) through (e) for the next injector to be tested.

5.7.2 Data Reduction and Analysis for Dynamic Verification Flow Measurement

a. Convert the mass of fuel that was delivered for each of the three runs of 2000 injections for each injector into a mass of fuel delivered per injection event. If using a bulk collection method, this is achieved by dividing the total mass of fuel delivered in 20 seconds by 2000 injection events.

b. With each injection event considered as a "pulse," average the three independent values of milligrams per pulse for each tested injector. This average yields the value of the dynamic verification flow for the injector that was tested. Do this for each injector tested. Also, average all of the individual dynamic verification flow values (one per tested injector) to obtain the single, final value to be reported.

c. If using STS measurement equipment, average the results from the 2000 injection events.

5.7.3 Data Reporting for Dynamic Verification Flow Measurement

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 flow values that were measured, as well as the resultant dynamic verification flow value, which is the average of the three. The units are to be in milligrams per pulse. Repeat for each test injector using a new copy of the data-reporting sheet. Leave the row titled "Average of the Averages SAE J2713 Dynamic Verification Flow" blank for all but the last tested injector. For reporting on the 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 dynamic verification flow 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.

5.8 Overview of Operating Flow Range Tests for LFR, DLFR, WFR, and DWFR

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

As is shown in Table 8, there are four basic flow ranges that are commonly measured for a GDI injector. These are the LFR, DLFR, WFR, and the DWFR. The tests to determine all four of these ranges are described in this flow section. The usable operating flow range of a GDI injector, or a population of GDI injectors, at a single application pressure is normally represented by two main parameters, the LFR and the WFR. Both of these ranges represent a dimensionless ratio of a particular maximum operational flow rate in milligrams of fuel per injection divided by the corresponding minimum operational flow rate. The LFR is a performance parameter associated with a single injector, whereas the WFR is associated with a population of identical injectors. Thus, the WFR inherently includes the effects of part-to-part variations in fuel flow characteristics, whereas the LFR does not. The LFR defines a range of linear fuel delivery, whereas the WFR quantifies a fuel flow range within which any single injector or subset of injectors from the total population of identical injectors will deliver a metered flow that will be acceptably accurate.

Regarding the LFR, a more precise terminology than “linear range” would be the “near-linear range,” as the linear regression line through the flow data does not necessarily pass through each of the individual flow points. The two key parameters of LFR and WFR, as well as the associated key parameter of WF_{min}, are obtained by performing statistical operations on the flow test data that are obtained from the flow testing of either a single injector or a fairly large population of identical test injectors.

As illustrated in Table 8, many of the testing procedures are identical for both LFR and WFR evaluation, although the data reduction details differ. The two additional ranges of DLFR and the DWFR are for the complete fuel pressure spectrum that the GDI injector may utilize in service.

Table 8 - Types of GDI injector flow-range tests

Test	Quantity of Parts	Pressure	Comments
LFR	5 (or optionally more)	P_{50}	Has a ±5% acceptance bandwidth on flow.
DLFR	5 (or optionally more)	P_{20}, P_{100}	Has a ±5% acceptance bandwidth on flow. Accounts for the GDI fuel pressure range.
WFR	24 (or optionally more)	P_{50}	Has a +10% part-to-part flow variability limit.
DWFR	24 (or optionally more)	P_{20}, P_{100}	Has a +10% part-to-part flow variability limit. Accounts for the GDI fuel pressure range.

Another very important characteristic of a GDI fuel injector is the usable minimum and maximum fuel flow rates. The WFR and DWFR tests provide a measure of these flow rate limits. Depending on the system, the minimum and maximum flows may be measured at several different fuel pressures.

LFR and WFR are carryover tests from the characterization of port fuel injectors. These tests can be applied to GDI injectors, and their methodology forms the basis for the DLFR and the DWFR tests for a range of fuel pressures. This recognizes that direct injection fuel systems are variable pressure systems, as opposed to port fuel injection systems, which typically utilize a fixed, lower fuel pressure. DLFR is the primarily method for evaluating single injectors, whereas DWFR is the primary method for evaluating the flow performance of a population of GDI injectors that use a variable fuel pressure.

5.9 Linear Flow Range Test

5.9.1 Procedure for Measuring the Linear Flow Range

The test to determine the linear flow range of an injector is to be conducted using new injectors of the model of interest.

a. A minimum set of five new injectors of the same make and model from serial production is to be tested. Additional injectors of the same model may optionally be tested. Each injector shall be preconditioned according to the procedures and test conditions in 4.2.

b. The injector for LFR determination is to be flow tested in a flow measurement test stand at a pressure of P_{50}. The flow rate of the standard test fluid of n-heptane at a temperature of 21.0 °C ± 2.0 °C is to be measured at a series of midrange to long IPW test points, all using an injection period (P) of 10.0 ms. These pulse width values are:

   Midrange to long IPW values: 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, and 5.0 ms.

   In addition to these 13 midrange to long test points, a number of short IPW values shall also be flow tested. These are fully described in the two subsequent steps.

c. To permit an accurate determination of the LFR following the testing, it is important to have enhanced pulse-width resolution in the areas of injector flow non-linearity, which occurs in the regions of short pulse widths (very low flow). Therefore, it is required that the injector flow be measured in finer increments of IPW in this region.

d. The low-flow region of the flow curve is normally characterized by flow testing at a range of short IPW values starting just slightly higher than the injector OT and extending to an IPW value of 0.475 ms. For the short IPW test points using a fuel pressure of P_{50}, start with an IPW value that is the measured injector opening time rounded up to the next higher 0.025 ms. The procedure for measuring the OT is described in 5.3. Subsequent to measuring the initial low-flow test point, measure the flow using IPW increments that are obtained by adding 0.025 ms to the previous IPW. Repeat until an IPW of 0.475 ms is attained. For example, for a measured OT of 0.195 ms, the low-flow test points would be:

   Short IPW test points: 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375, 0.4, 0.425, 0.45, and 0.475 ms.

e. Repeat steps (b) through (d) for the next injector being tested for an LFR measurement.

5.9.2 Data Reduction and Analysis for the Linear Flow Range

As discussed in 5.8, the LFR for a single injector is a key performance parameter that is used to compare the linear performance between injectors of different design or manufacture. The LFR is the ratio of the maximum operational flow rate within the linear range at a fuel pressure of P_{50} to the minimum operational flow rate within the linear range for a single injector. Within this range there is a linear relationship between the commanded pulse width and the delivered fuel flow. As discussed in 5.8, a more precise terminology than “linear range” would be the “near-linear range.” Within the limits of the LFR, there is, in fact, a near-linear relationship between the pulse width and the resultant flow, as the LFR test specifies a 5% tolerance band on either side of the true linear curve. Thus, it is more accurate to state that the delivered flow is linear to within a maximum ±5% deviation when operating within the LFR.

5.9.3 Regression Analysis for the Linear Flow Range

All of the flow data obtained is to be plotted as the measured dynamic flow rate, Q_d, versus the commanded IPW. In order to quantify the deviation of the flow from linearity, a simple least-squares, linear regression analysis is to be performed on five specific midrange flow points, which are at IPW values of 1.0, 2.0, 3.0, 4.0, and 5.0 ms. Q_d and IPW are, respectively, the dependent and independent variables for the regression analysis. As illustrated in Figure 9A, this linear regression analysis will generate a best-fit linear line that passes among the five measured points. The linear regression line will pass below the origin of the plot, generating a slope for the line, as well as two offsets that are denoted as the "time offset" and the "flow offset." The determination of the values of the flow offset and the slope define the linear flow curve. Although the simple schematic drawing shows the resultant line passing through the five test points, in reality it will likely not pass through any of the five points exactly, as it is a "best-fit" line. Therefore, at each value of IPW there are actually two different flow rates; the first is the actual measured flow rate, Q_d, and the second is the flow rate computed by using the line that was generated by the regression analysis, Q_{dc}. The actual flow data will generally track the straight line of the linear flow curve quite well over the mid-flow portion of the data but will begin to deviate at the low-flow end of the flow curve.

The slope (m) of the resultant linear regression curve is the change in Q_{dc} per unit of pulse width based on the calculated linear regression flow curve (mg/ms). The time offset of the linear curve is the displacement of the calculated linear regression flow curve from the origin along the abscissa, or pulse width axis. The flow offset is the displacement of the calculated linear regression flow curve from the origin along the ordinate, or flow axis. The values of the slope, flow offset, and time offset will be obtained from the regression analysis. It should be noted that the actual flow data are denoted by Q_d, whereas the flows computed from the linear regression line are designated as Q_{dc}. The resultant best-fit line for the LFR may be expressed in terms of the flow offset as shown in Equation 11 or may alternatively be expressed in terms of the time offset as shown in Equation 12.

$$\text{Linear flow rate} = Q_{dc} = \text{Slope}*\text{IPW} - \text{Flow offset} \quad \text{(Eq. 11)}$$

$$\text{Linear flow rate} = Q_{dc} = \text{Slope}*(\text{IPW} - \text{Time offset}) \quad \text{(Eq. 12)}$$

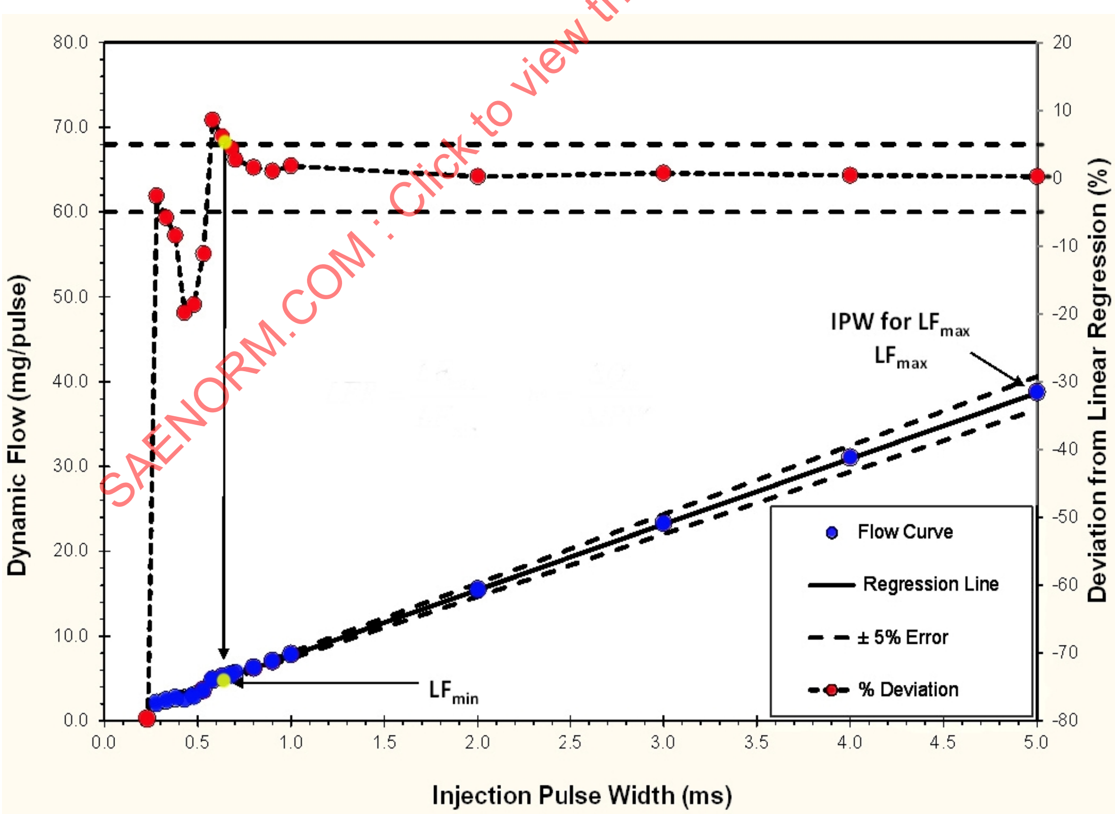

Figure 9A - LFR regression and the percentage flow deviation

5.9.4 Generation of Percentage Difference from Linearity

Once the slope and offsets of the best-fit line have been determined from the regression analysis, the linear flow rate values for all 25+ measurement test point values of IPW are to be calculated using either Equation 11 or 12. Following that, the percentage differences between the actual measured flow rate, Q_d, and the linear flow rate, Q_{dc}, are to be computed individually for all of the 25+ pulse width test values. The percentage deviation from linearity (LD) is determined from Equation 13 as the percent difference between the measured dynamic flow, Q_d, and the calculated linear dynamic flow, Q_{dc} (determined using the linear curve), divided by the calculated dynamic flow, and then multiplied by 100. It should be noted that each of the 25+ measured test points will likely have a different percentage deviation. When plotted, this will yield a curve of percentage deviation of the actual delivered flow from the idealized, linear flow.

$$LD\ (\%) = 100*(Q_d - Q_{dc})/Q_{dc} \quad \text{(Eq. 13)}$$

An illustration of this percentage deviation curve is provided in the upper portion of Figure 9A. The lower portion contains the regression curve and the limiting bandwidths, and the upper portion contains the curve of the percentage flow deviation for the P_{50} fuel test pressure. It may be noted that the percentage deviation from linearity is near zero for most GDI injectors over a large portion of the IPW range but normally deviates significantly from zero at very short IPW values, as is illustrated in Figure 9B. It may also be noted in Figure 9B that at some very short IPW values the actual flow will normally differ from the linear flow by 5% or more. Injector operation within the limits of -5% and +5% of true linear flow is defined as near-linear operation. The value of IPW where the flow deviation from linearity first exceeds either -5% or +5%, along with the value of Q_{dc} at an IPW of 5.0 ms, will determine the limits of near-linear operation. Further, the ratio of these two limiting linear Q_{dc} flow rates at these two IPW values defines the numerical value of the flow range of near-linear operation for the test injector.

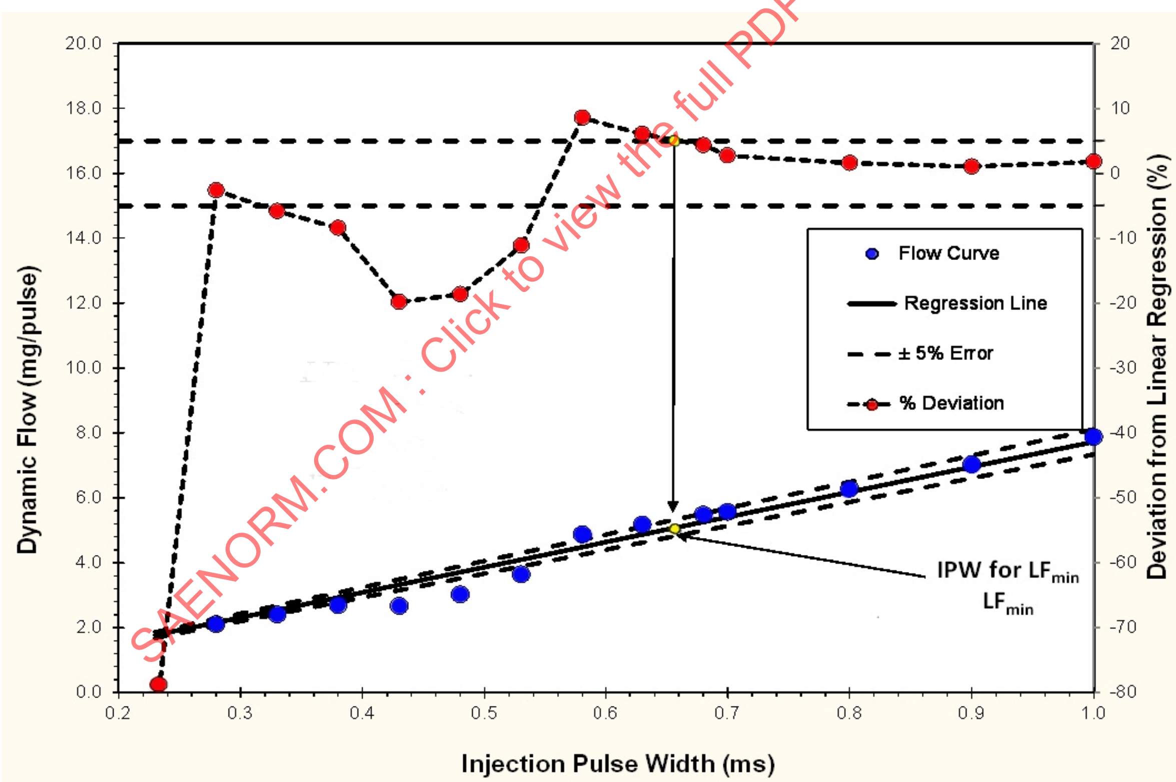

Figure 9B - LFR regression and the percentage flow deviation (short-pulse-width region)

5.9.5 Determination of the Limits of Linearity

a. Using the data from the P_{50} flow pressure test, review the linear-deviation plot. First, examine the short-pulse-width portion of the measured curve, using Figure 9B. Starting at 1.0 ms IPW, move left down the curve and identify the first test-point pulse width where the percentage deviation exceeds ±5.0%. Then identify the next longer test-point pulse width for which the deviation is within ±5.0%. These are the two IPW values to be used as the end points for a simple linear interpolation. The interpolation is to determine the precise IPW value at which the exact deviation is either +5% or -5.0%. Using the known test-point IPW values and the corresponding values of the percentage deviation from linearity at those IPW values, conduct a straight-line interpolation between these two test points to determine the IPW_{min} for linear flow. Once the value of IPW_{min} has been determined, the expected minimum linear fuel flow rate may be computed by inserting the IPW_{min} value into either Equation 11 or 12 using the values for slope and offsets that were determined earlier. This value of the linear flow will be designated as LF_{min}, which will be the lowest flow that the particular injector can deliver within the linear range.

b. For a GDI system, the maximum IPW available to actuate an injector is approximately 5 ms. This is determined as the available actuation time of an injector being 180 degrees out of 720 degrees of crank angle rotation at 6000 rpm. Operating at 6000 rpm provides a total of 20 ms of time per cycle. Therefore, 180/720 degrees is 25% of 20 ms, which equals 5 ms. Thus, the LF_{max} value for a GDI injector is chosen as the computed linear flow rate value, Q_{dc}, at 5.0 ms. The expected maximum linear fuel flow rate may be computed by inserting the IPW_{max} value into either Equation 11 or 12 using the values for slope and offsets that were determined earlier. This value of the linear flow will be LF_{max}, which will be the highest flow that the injector can deliver in the linear range.

c. Once the values for LF_{max} and LF_{min} have been determined for an individual injector, the LFR value may be computed. The LFR is calculated from Equation 14 as the maximum linearized flow point, $LF_{max,}$ divided by the minimum linearized flow point, LF_{min}.

$$LFR = LF_{max}/LF_{min} \qquad \text{(Eq. 14)}$$

5.9.6 Data Reporting for the Linear Flow Range

The general information on the test conditions and the tested injector is to be reported on Parts 1, 2, and 3 of the data-reporting sheet in Table 9. As part of the LFR determination, the measured flows, the computed flow deviations from linearity, and the serial number of the tested injector are to be reported on the Part 5-A data-reporting sheet in Table 9. These data are to be for a fuel pressure of P_{50} and for each specified test IPW. Also, the curves of flow rate and percentage flow deviation for each tested injector are to be generated and attached to the data-reporting sheet. The locations of LF_{min} and LF_{max} are to be clearly indicated on the flow curves. The computed slope, flow offset, and time offset (injection pulse-width offset) of the linear regression curve for the test injector are to be reported at the bottom of Part 5-A of the data-reporting sheet. The computed values for LF_{min}, $LF_{max,}$ and LFR for the test injector are to be reported on the bottom of Part 5-A of the datasheet and also on the data summary sheet in Part 5-D. Repeat for each test injector using a new copy of the data-reporting sheet. If n-heptane at a fuel pressure of P_{50} was employed for the test, and there are no other test deviations, these will be the SAE J2713 values for LF_{min} and LFR, and those values are to be entered in the boxes on 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.

In the box for SAE J2713 LFR on the left side of 5-D for the last tested injector, report the average of all of these measured LFR values. Then report the average of all of the LF_{min} values in that appropriate box. If n-heptane at a fuel pressure of P_{50} was utilized in the testing, and there are no other test deviations, then the average of all of the individual LFR values is to be reported in the proper box on the 5-D data-reporting sheet as the SAE J2713 LFR value, and the average of all of the individual LF_{min} values is to be reported in the proper 5-D box as the SAE J2713 LF_{min} value. If there are any test deviations, these should be noted in the test comments area of the datasheet, and the data is reported in the box in Part 5D for the data with test deviations.

5.10 Dynamic Linear Flow Range Test

The test to determine the dynamic linear flow range of an injector is to be conducted using new injectors of the model of interest.

5.10.1 Procedure for Measuring the Dynamic Linear Flow Range

a. A minimum set of five new injectors of the same make and model from serial production is to be tested. Additional injectors of the same model may optionally be tested. Each injector shall be preconditioned according to the procedures and test conditions described in 4.2. Next, the injector shall be tested at a fuel pressure of P_{20}, with one high-flow test point at an IPW of 5.0 ms at a fuel pressure of P_{100}.

b. The injector for DLFR determination is to be flow tested in a flow measurement test stand using a fuel pressure of $P_{20.}$ The flow rate of the standard test fluid of n-heptane at a temperature of 21.0 °C ± 2.0 °C is to be measured at a series of midrange to long IPW test points, all using an injection period (P) of 10.0 ms. These IPW test points are:

   Midrange to long IPW values: 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, and 5.0 ms.

   In addition to these IPW test points, a number of short IPW values shall also be flow tested at a fuel pressure of P_{20}. These are fully described in the two subsequent steps.

c. To permit an accurate determination of the DLFR following the testing, it is important to have enhanced pulse-width resolution in the areas of injector flow non-linearity, which occurs in this region of very low flow and short pulse widths. Therefore, it is required that the injector flow be measured in finer increments of IPW in this region.

d. The low-flow region of the flow curve is normally characterized by flow testing at a range of IPW values starting just slightly higher than the injector OT and extending to an IPW value of 0.475 ms. For the short-pulse-width test points at a fuel pressure of P_{20}, start with an IPW value that is the measured injector opening time rounded up to the next higher 0.025 ms. The procedure for measuring the OT is described in 5.3. Subsequent to measuring the initial short-pulse-width test point, measure the flow using IPW increments that are obtained by adding 0.025 ms to the previous IPW. Repeat until an IPW of 0.475 ms is attained. For example, for a measured OT of 0.195 ms, the short IPW test points would be:

   Short IPW values: 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375, 0.4, 0.425, 0.45, and 0.475 ms.

e. For a fuel pressure of $P_{100,}$ measure the fuel flow rate at an IPW of 5.0 ms.

f. Repeat steps (b) through (e) for the next injector being tested for a DLFR measurement.

5.10.2 Data Reduction and Analysis for the Dynamic Linear Flow Range

As discussed in 5.8, the DLFR for an individual injector is a key performance parameter that is used to compare the linear performance between injectors of different design or manufacture. The DLFR for a single injector is the ratio of the maximum operational flow rate within the linear range at P_{100} (which is at an IPW of 5.0 ms) to the minimum operational flow rate within the linear range at P_{20}.

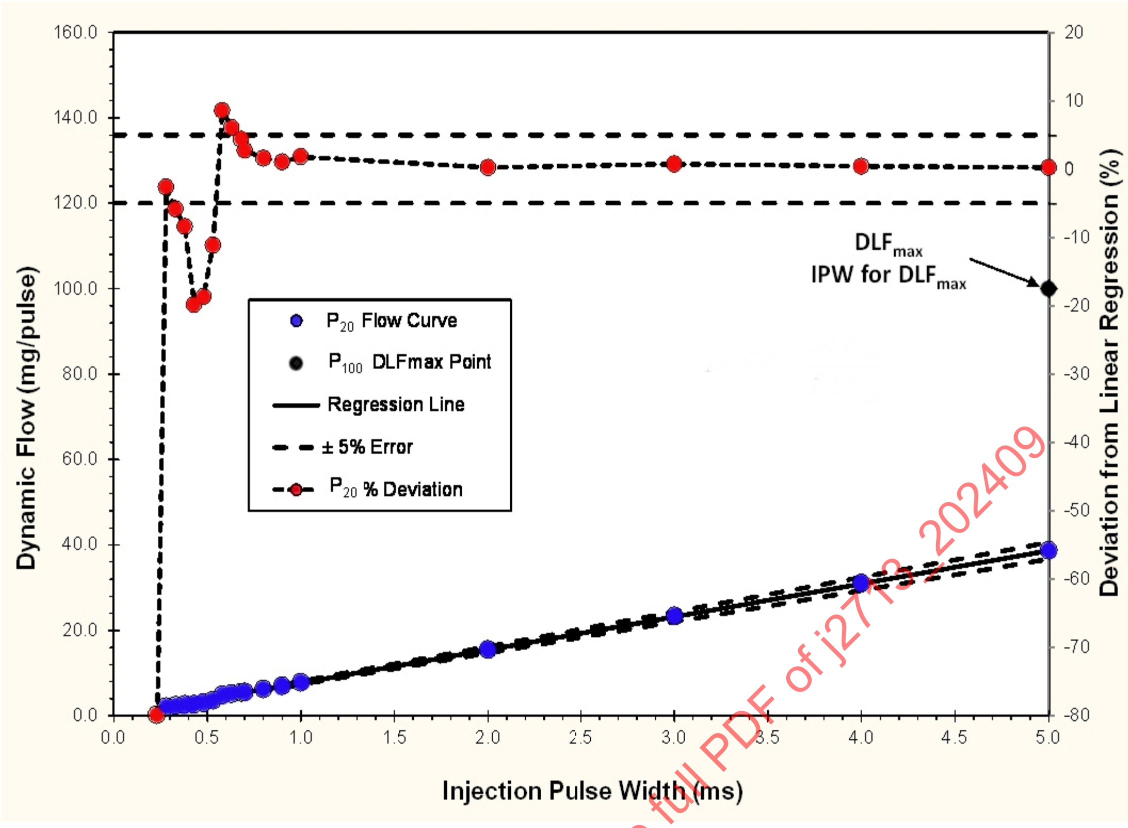

Figure 10 - DLFR regression and the associated percentage flow deviation

5.10.3 Regression Analysis for the Dynamic Linear Flow Range

All of the P_{20} flow data obtained is to be plotted as the measured dynamic flow rate, Q_d, versus the commanded IPW. In order to quantify the deviation of the flow from linearity, a simple least-squares, linear regression analysis is to be performed using five specified midrange and long IPW test points, which are at IPW values of 1.0, 2.0, 3.0, 4.0, and 5.0 ms. Q_d and IPW are, respectively, the dependent and independent variables for the regression analysis. This linear regression analysis will generate a best-fit linear line that passes among the five flow rates obtained at the five specified IPW points. Representative curves for a GDI injector are illustrated in Figure 10. The linear regression line will pass below the origin of the plot, generating a slope for the line, as well as two offsets that are denoted as the "time offset" and the "flow offset." The determination of the values of the flow offset and the slope will define the linear flow curve. Although the resultant linear flow line in Figure 10 may pass close to one or more of the measured flow test points, it will likely not pass through any of the five points exactly, as it is a "best-fit" line. Therefore, at each value of IPW there are actually two different flow rates; the first is the actual measured flow rate, Q_d, and the second is the flow rate, Q_{dc}, that is computed by using the line that was generated by the regression analysis. The actual flow data will generally track the straight line of the linear flow curve quite well over the midrange to long IPW portion of the flow data but will generally begin to deviate at the low-flow end of the flow curve.

The slope (m) of the resultant linear regression curve is the change in Q_{dc} per unit of injection pulse width based on the calculated linear regression flow curve (mg/ms). The time offset of the linear curve is the displacement of the calculated linear regression flow curve from the origin along the abscissa, or injection pulse width axis. The flow offset is the displacement of the calculated linear regression flow curve from the origin along the ordinate, or flow axis. The values of the slope, flow offset, and time offset may be obtained from the regression analysis. The resultant best-fit line for the linear flow rate may be expressed in terms of the flow offset as shown in Equation 11 or may alternatively be expressed in terms of the time offset as shown in Equation 12.

5.10.4 Generation of Percentage Difference from Dynamic Linearity

Once the slope and offsets of the best-fit line have been determined from the regression analysis for the P_{20} fuel pressure, the linear flow rate values for all 25+ measurement test point values of IPW are to be calculated using either Equation 11 or 12. Following that, the percentage differences between the actual measured flow rate, Q_d, and the linear flow rate, Q_{dc}, are to be computed individually for all of the 25+ IPW test values. The percentage deviation from linearity (LD) is determined from Equation 13 as the percentage difference between the measured dynamic flow, Q_d, and the calculated linear dynamic flow, Q_{dc}, that is determined using the linear curve, divided by the calculated dynamic flow, and then multiplied by 100. It should be noted that each of the 25+ measured test points for each pressure will have a different percentage deviation. When all of the data are plotted for the P_{20} fuel pressure, the curve of percentage deviation of the actual delivered flow from the idealized, linear flow will be obtained.

The percentage flow deviation curve for the P_{20} fuel pressure is provided in the upper portion of Figure 10, which contains actual flow data for a GDI injector. It may be noted that the percentage deviation from linearity is generally near zero for most GDI injectors over a large portion of the IPW range but normally deviates significantly from zero at very short injection pulse widths. The details of this short-pulse-width region of the flow curve are shown in Figure 11. It may also be noted in the upper portion of Figure 11 that at some very short IPW values the absolute difference between the actual measured flow rate and the indicated linear flow rate will be outside of the ±5% bandwidth limits. Injector operation within the limits of -5% and +5% of true linear flow is defined as near-linear operation. This value of IPW where the deviation from linearity attains either -5% or +5%, along with the Q_d value at a fuel pressure of P_{100} for an IPW of 5.0 ms, will determine the limits of near-linear operation. Further, the ratio of these two limiting flow rates at these two IPW values defines the numerical value of the DLFR of near-linear operation for the test injector.

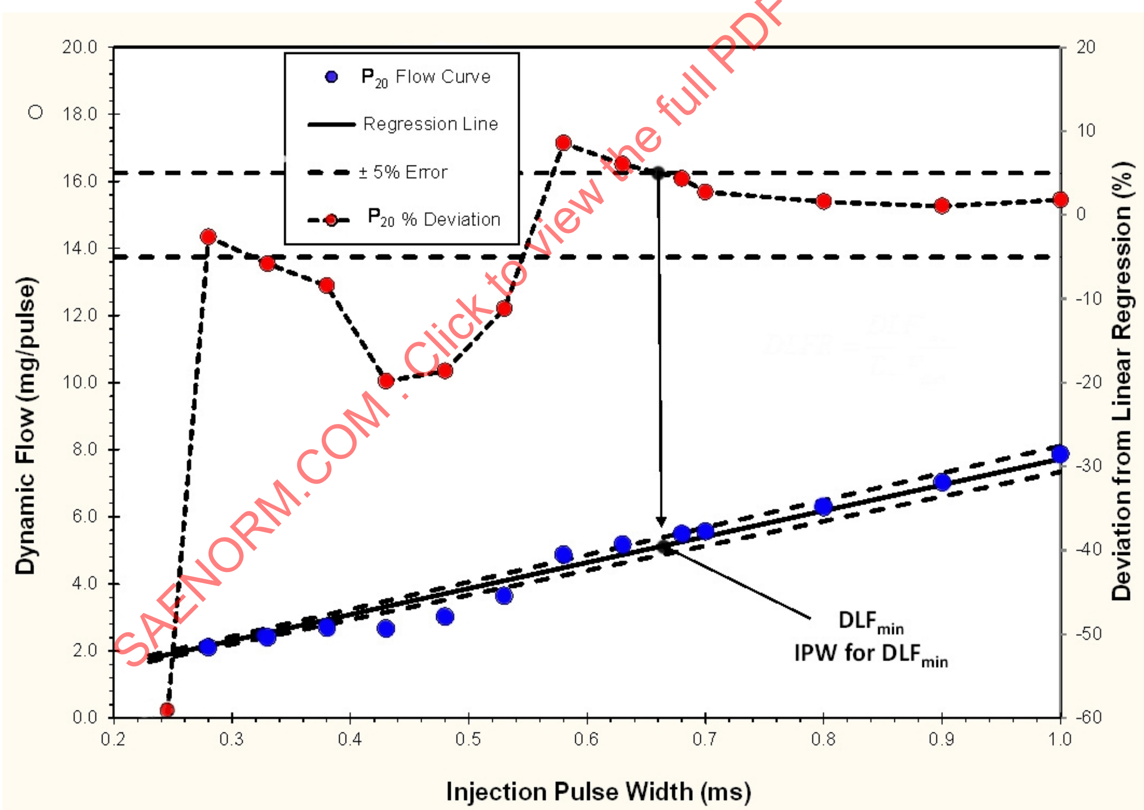

Figure 11 - DLFR regression and the associated percent flow deviations (short-pulse-width region)

5.10.5 Determination of the Limits of Dynamic Linearity

a. Using the data from the P_{20} test, review the linear-deviation plot. Starting at 1.0 ms IPW, move left down the curve and identify the first test-point pulse width where the percentage deviation exceeds ±5.0%. Then identify the next longer test-point pulse width for which the deviation is within ±5.0%. These are the two IPW values to be used as the end points for a simple linear interpolation. The interpolation is to determine the precise IPW value at which the exact deviation is either +5% or -5.0%. Use the known test-point IPW values and the corresponding values of the percentage deviation from linearity at those IPW values. Use a straight-line interpolation between these two test points to determine the IPW_{min} for linear flow. Once the value of IPW_{min} has been determined, the expected minimum linear fuel flow rate may be computed by inserting the IPW_{min} value into either Equation 11 or 12, using the values for slope and offsets that were determined earlier. This value of the linear flow will be designated as DLF_{min}, which will be the lowest flow that the injector can reliably deliver within the near-linear range.

b. For a GDI system, the maximum IPW available to actuate an injector is approximately 5 ms. This is determined as the available actuation time of an injector being 180 degrees out of 720 degrees of crank angle rotation at 6000 rpm. This engine speed yields a total of 20 ms of time per cycle. Thus, 180/720 degrees represents 25% of the total available time of 20 ms and corresponds to an IPW of 5 ms. So, the DLF_{max} value for a GDI injector is chosen as the measured fuel flow rate, Q_d, at an IPW value of 5.0 ms at P_{100}. This value will be DLF_{max}.

c. Once the values for DLF_{max} and DLF_{min} have been determined for an individual injector, the DLFR value may be computed. The DLFR is calculated from Equation 15 as the maximum linearized dynamic flow point, DLF_{max}, divided by the minimum linearized dynamic flow point, DLF_{min}.

$$DLFR = DLF_{max}/DLF_{min} \quad \text{(Eq. 15)}$$

d. Each individual injector will require a full, independent DLFR determination Thus, for the five injectors that have been tested, there will be five separate regression analyses required and five individual values of DLFR computed using Equation 15. Each of the individual DLFR values shall be reported in the proper boxes at the top of Part 5A of the data-reporting sheet. These individual DLFR values for all of the tested injectors should then be arithmetically averaged to obtain a single DLFR value for the test group.

5.10.6 Data Reporting for the Dynamic Linear Flow Range

The general information on the test conditions and the tested injector are to be reported in Parts 1, 2, and 3 of the data-reporting sheet in Table 9. As part of the DLFR determination, the measured flows, the computed flow deviations from linearity, and the serial number of the tested injector are to be reported on the Part 5-A data-reporting sheet in Table 9. These data are to be for a fuel pressure of P_{20} and for each specified test IPW. Also, the curves of flow rate and percentage flow deviation for the single tested injector are to be generated and attached to the data-reporting sheet. The locations of DLF_{min} and DLF_{max} are to be clearly indicated on the flow curves. The computed slope, flow offset, and time offset (injection pulse-width offset) of the linear regression curve for the test injector are to be reported at the bottom of Part 5-A of the data-reporting sheet. The computed values for DLF_{min}, DLF_{max}, and DLFR for the test injector are to be reported on the bottom of Part 5-A of the datasheet and also on the data summary sheet in Part 5-D. Repeat for each test injector using a new copy of the data-reporting sheet. If n-heptane at a fuel pressure of P_{20} was employed for the test and there are no other test deviations, these will be the SAE J2713 values for DLF_{min} and DLFR, and those values are to be entered in the boxes on Part 5-D of the data-reporting sheet in Table 9. If there are any test deviations, these should 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.

In Part 5-D of the last datasheet, the average of all of the individually computed LFR values is to be reported, along with the individual DLF_{min} and DLFR values that were calculated for that injector. In the box for SAE J2713 DLFR on the left side of 5-D, report the average of all of these measured DLFR values. Then report the average of all of the DLF_{min} values in that appropriate box. If n-heptane at a fuel pressure of P_{20} was utilized in the testing and there are no other test deviations, then the average of all of the individual DLFR values is to be recorded in the proper box on the 5-D data-reporting sheet as the SAE J2713 DLFR value, and the average of all of the individual DLF_{min} values is to be recorded in the proper 5-D box as the SAE J2713 DLF_{min} value. 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 5D for the data with test deviations.

5.11 Working Flow Range Test

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

In order to perform the calibration of a fuel system on an engine, certain information on the statistical variation of flow among injectors of a given type must be known. The WFR is a dimensionless performance parameter that numerically quantifies the usable flow range of any subset of a population of identical injectors. In this flow range there is a specified confidence level that any subset of injectors from the total population of all such injectors will deliver a fuel mass flow that is within a specified level of flow variability. That limiting level of flow variability is specified within this document as 10.0% of the value of a variability parameter that is computed from the measured flow rates of the population of 24 or more tested samples. This variability parameter is computed at each pulse width from the mean value of the 24 or more measured fuel flow rates and the computed standard deviation of those flow rates. Thus, the WFR may be thought of as a range of flow rates where the variability of that flow among identical new injectors of a particular model is maintained within a specified limit. This is particularly important at very short pulse widths where quite low flow rates are to be delivered. At these low flow rates, nearly all solenoid-energized GDI injectors exhibit not only a loss of linearity but also a significant increase in the standard deviation of the flow delivered by a population of those injectors.

For a sample population of 24 or more identical injectors from serial production, the specification of three standard deviations sets a 99.7% statistical confidence level that the flow delivered at any fuel flow value (and associated IPW) within the WFR will be within ±10.0% of the mean flow of the entire population. Inherent in this statistical validity is the assumption that a normal distribution of production parts exists. Therefore, the interpretation of the final computed WFR value should take into account the various criteria that were used to select the test parts, such as serial production, various build dates, different build sites, or different tooling.

The WFR defines the range of flow values that may be delivered by any newly manufactured injector of that type without exceeding the limiting flow variability that is specified for the WFR test. The low-flow IPW value that corresponds to WF_{min} defines the lowest pulse width that can be employed in the control system for that application. Unlike the LFR, the WFR is not based upon a linear regression curve and therefore does not guarantee a linear relationship between the IPW and the delivered fuel flow of a group of injectors from a population. Instead, it is based upon a specified upper limit on the variability in the mean flow rate delivered by any subset of injectors in that population.

5.11.2 Procedure for Measuring the Working Flow Range

The test to determine WFR is to be conducted using a set of at least 24 new, identical injectors from serial production. More injectors can be used for the test set if desired. 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.

a. All of the sample injectors shall be preconditioned according to the procedures and test conditions described in 4.2.

b. Each injector in the test set is to be flow tested in a flow measurement test stand at a fuel pressure of P_{50}. The flow rate of the standard test fluid is to be measured at a series of midrange to long IPW test points, all using an injection period (P) of 10.0 ms. These pulse width values are:

   Midrange to long IPW values: 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, and 5.0 ms.

   In addition to these 13 IPW test points, a number of short-pulse-width IPW values shall also be flow tested at a fuel pressure of P_{50} as described in the next steps.

c. The low-flow region of the flow curve is specified by a range of IPW values starting just slightly higher than the injector OT and extending to an IPW value of 0.475 ms. For the short-pulse-width test points, start with an IPW value that is the measured injector opening time rounded up to the next higher 0.025 ms. Following that, measure the flow using IPW increments that are obtained by adding 0.025 ms to the previous IPW. Repeat until an IPW of 0.475 ms is attained. For example, for an OT of 0.195 ms, the low-flow test points would be:

   Short-pulse-width IPW values: 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375, 0.4, 0.425, 0.45, and 0.475 ms.

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

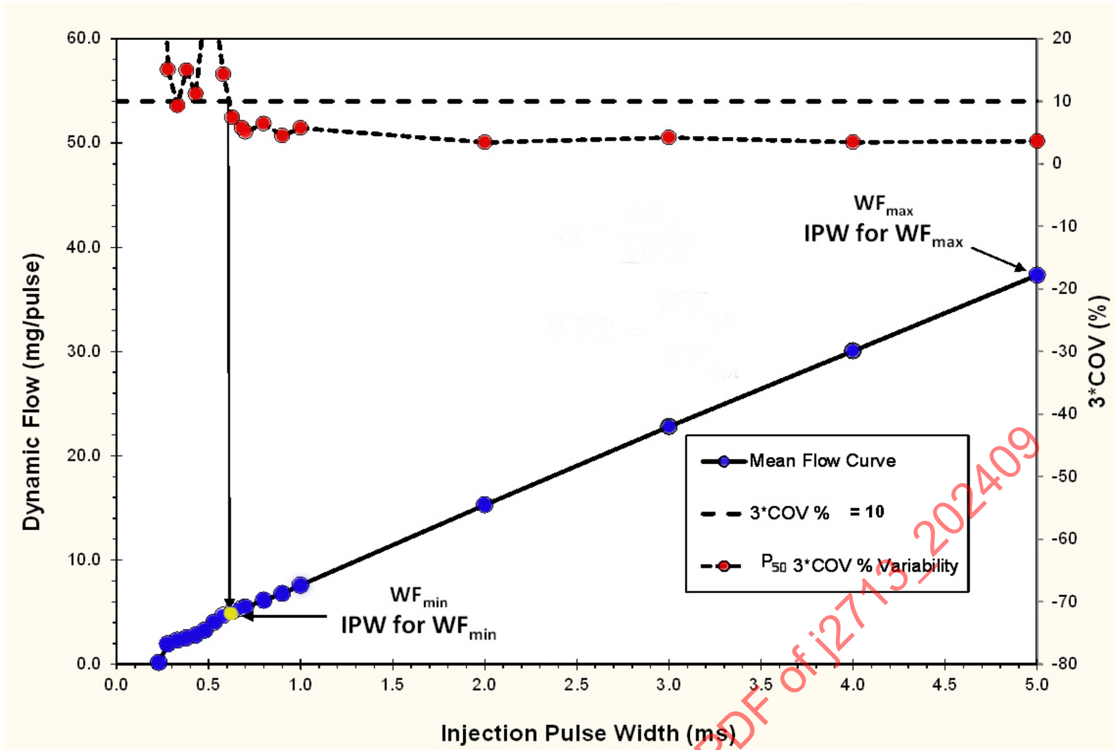

Figure 12A - GDI flow and percentage flow variability for WFR determination

5.11.3 Data Reduction and Analysis for the Working Flow Range

As discussed in 5.11.1, the WFR and WF_{min} are key parameters that quantify the limits of variability in fuel delivery for a population of identical injectors. The WFR is based on the measurement of a minimum sample of 24 injectors that is statistically intended as a representative sample of the total population of all manufactured injectors of that type and model. Inherent in this test is the specification in advance of a number of defined limits that determine both the detailed test procedure and the resultant meaning of the test results. For this WFR test, the combination of a minimum of 24 test samples and a 3*COV limit of 10% statistically guarantees that the results of the test will reliably represent the total population of injectors with a confidence level of 99.7%.

The WFR is determined by first computing the maximum working flow, WF_{max}, and the minimum working flow, WF_{min}, from the experimental flow data and the specified ±10.0% variability limits for flow variation. The WFR value is determined by dividing the WF_{max} value by the WF_{min} value. WF_{max} is obtained by determining the mean dynamic flow, Q_d, at the 5.0 ms IPW of the samples tested. It is important to note that the WF_{min} value is an important parameter in its own right, as it represents the lowest flow rate that can be reliably calibrated for use in the application.

5.11.4 Generation of the Percentage Variability Curve

For the set of 24 (or optionally more) injectors being tested, there will be 24 individual measured fuel flow rates for each one of the IPW values that are tested. Using standard statistical tools, compute the arithmetic mean (average) flow rate and the standard deviation (sigma) of those flow rates for those 24 measured flow rates at each IPW. These two values are referred to as the “corresponding” mean flow rate and the “corresponding” standard deviation of that particular set of 24 flow rates for one particular IPW value. Note that each IPW will have its own corresponding mean flow rate and corresponding standard deviation.

Next, for each tested value of IPW, calculate the corresponding percentage flow variability of the set of 24 flow rate values relative to three times the corresponding standard deviation, sigma. The flow variability of the set of all 24 measured flow rates at a particular IPW may be expressed as a percentage of three corresponding standard deviations by using Equation 16A. For convenience, the COV may be computed as the standard deviation divided by the arithmetic mean flow (see 3.2). This simplifies Equation 16A into Equation 16B. Each of these corresponding percentage flow variabilities (one for each IPW) is to be computed using either Equation 16A or 16B and is to be tabulated and plotted versus the IPW. The representative plots that are shown in the remainder of the flow subsection use the percentage 3.0*COV parameter from Equation 16B for plotting. Representative plots of these GDI data are shown in Figure 12A for the full-flow range and in Figure 12B for the short-pulse-width region.

$$\text{Corresponding percentage flow variability} = 100.0*(3.0*\text{Corresponding standard deviation})/(\text{Corresponding mean flow rate}) \quad \text{(Eq. 16A)}$$

$$\text{Corresponding percentage flow variability} = 100.0*(3.0*\text{COV}) \quad \text{(Eq. 16B)}$$

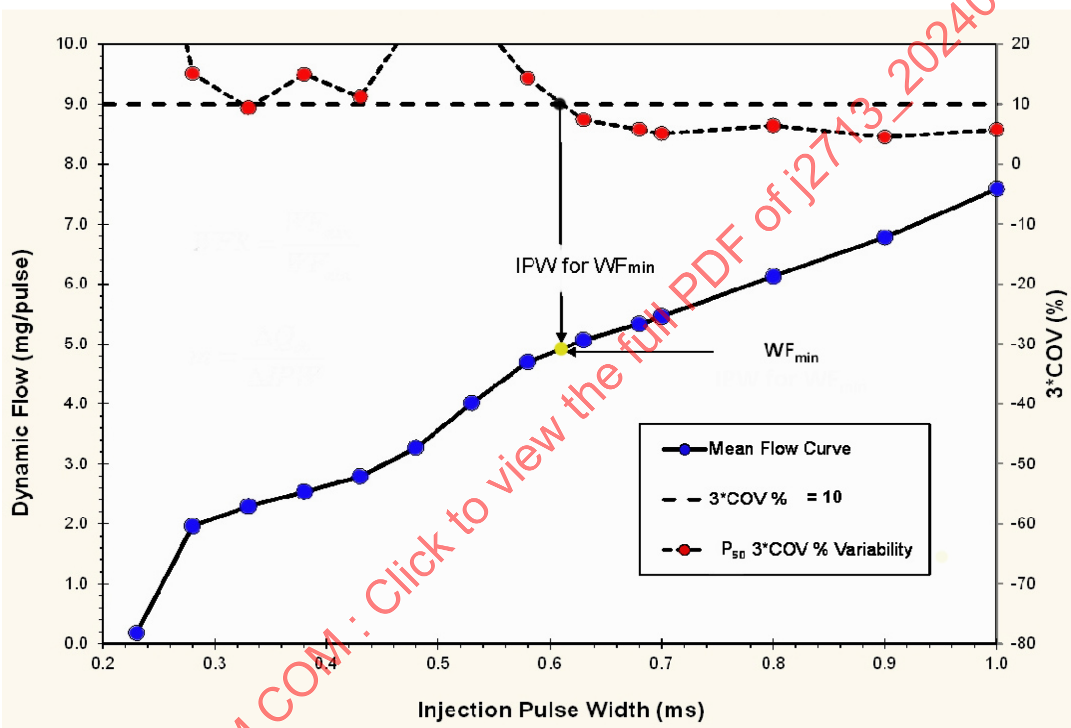

Figure 12B - GDI flow and percentage flow variability for WFR determination (short-pulse-width region)

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

a. First, inspect the short-pulse-width (low-flow) region of the percentage flow variability versus pulse-width plot. From the plot, starting at 1.0 ms PW, move left down the curve and first identify the highest IPW where the 3*COV percentage flow variability exceeds 10.0%. Then identify the next higher IPW for which that variability is less than 10.0%. These are the two low-flow IPW test values to be used for two linear interpolations. Identify the two flow variability values that are associated with these two test point IPW values and use the four values as the end points of a simple, linear interpolation. This first linear interpolation is to determine the precise low-flow IPW value at which the 3*COV percentage flow variability is exactly 10.0%. This is designated as IPW_{min} for the working flow range.

b. At each of the two short-pulse-width IPW values identified above, use the two associated mean flow rate values for a second linear interpolation. The second interpolation uses the same two low-flow IPW values along with their associated mean flow values as the interpolation end points. The purpose of the interpolation is to determine the expected mean flow delivered at a pulse width of IPW_{min}. This interpolated mean flow is to be designated as WF_{min}.

c. For a GDI system, the maximum IPW available to actuate an injector is approximately 5 ms. This is determined assuming that the available actuation time of an injector is 180 degrees out of 720 degrees of crank rotation at 6000 rpm. This engine speed yields a total of 20 ms of available time per cycle. Thus, 180/720 or 25% of 20 ms corresponds to an IPW of 5.0 ms. Therefore, the WF_{max} value for a GDI injector is specified in this document as the measured average flow rate value, Q_d, at an IPW of 5.0 ms.

d. The WFR for a population of injectors is to be determined using Equation 17. In this equation, WFR is defined as the delivered fuel rate at the maximum working flow point, WF_{max}, divided by the delivered fuel rate at the minimum working flow point, WF_{min}. For flow rates between these two values, all injectors in the population will deliver metered fuel rates that vary less than 10.0% of the 3*COV percentage variability.

$$WFR = WF_{max}/WF_{min} \quad \text{(Eq. 17)}$$

e. The WFR value may also have interpretive value for prototype parts; however, it must be realized that prototype assembly may not be representative of the level of variation that may exist in mass production. If the distribution of the sample is not normal, or if a sample of less than 24 parts is used, the statistical confidence limit would be less than 99.7%, perhaps significantly less. Because of the number of possibilities for non-normal distributions and using less than 24 test injectors, the equations to be used are not provided in this document. Instead, it is suggested that one of many commercially available statistical packages be used to evaluate the WFR results for such cases. It is also noted that this would be considered a significant test deviation and that the WFR that was obtained would not be the SAE J2713 WFR.

5.11.6 Data Reporting for the Working Flow Range

The general information on the test conditions and the details of the test injectors are to be reported in Parts 1, 2, and 3 of the data-reporting sheet in Table 9. As part of the WFR determination, the measured flows, the computed mean flows, the computed flow standard deviation, and the computed 3*COV percentage flow variability for those flows are to be reported for each test injector at each IPW test point. The raw flow data is to be reported on copies of Part 5-B of the data-reporting sheets. These data are for a fuel pressure of P_{50}. Use a copy of the Part 5-B portion of the data-reporting sheet for reporting the raw flow data for each eight injectors and record the eight serial numbers on that copy. Use three total copies of Part 5-B to report the measured data for all 24 injectors. The computed values for the mean flow, the standard deviation, and the 3*COV percentage flow variability are to be reported on the Part 5-C data-reporting sheet. Also, a plot containing the curves of flow rate and the 3*COV percentage flow variability for the test set of 24 (or more) injectors is to be generated and attached to the data-reporting sheet. The plot is to clearly indicate the low-flow pulse width where the percentage flow variability exceeds the 10.0% limit of 3*COV percentage variability and also the flow at the 5.0 ms pulse width. These particular pulse widths are the IPW values corresponding to the maximum working flow, WF_{max}, and to the minimum working flow, WF_{min}. The locations of WF_{min} and WF_{max} are to be clearly indicated on this plot.

The final computed values for WF_{min}, WF_{max}, and the IPW for WF_{min} and WFR are to be reported on Part 5-D of the datasheet. Part 5-D is a summary sheet for reporting all of the values of the flow parameters that were determined. If n-heptane at a fuel pressure of P_{50} was employed for the test and there are no other test deviations, these will be the SAE J2713 values for WF_{min} and WFR, and those values are to be entered in the indicated boxes on Part 5-D of the data-reporting sheet in Table 9. If there are any test deviations, these should be noted in the test comments area of the datasheet, and the data is reported in the box in Part 5D for the data with test deviations.

5.12 Dynamic Working Flow Range Test

5.12.1 Overview of the Dynamic Working Flow Range

In order to perform the calibration of a fuel system on an engine, certain information on the statistical variation of flow among injectors of a given type must be known. The DWFR is a dimensionless performance parameter that numerically quantifies the usable flow range of any subset of a population of identical injectors but includes flow at high and low fuel pressures. In this flow range there is a specified confidence level that any subset of injectors from the total population of all such injectors will deliver a fuel mass flow that is within a specified level of flow variability. For this GDI document the specified level of flow variability is 10.0%. The 10.0% value is the limit of a statistical flow-variability parameter that is computed at each pulse width from the measured mean flow rates of 24 or more injectors and the measured standard deviation of those 24 or more fuel flow rates. Thus, the DWFR may be thought of as a range of flow rates for a subset of identical injectors where the corresponding standard deviation of the collection of flow rates is maintained within a specified limit. This is particularly important at very short pulse widths where low flow rates are to be delivered. At these low flow rates, nearly all solenoid-energized GDI injectors exhibit not only a loss of linearity but also a significant increase in the standard deviation of the flows that are delivered by a population of injectors.

For a sample population of 24 new, identical injectors from serial production, the specification of three standard deviations sets a 99.7% statistical confidence level that the flow delivered at any flow value within the DWFR range will be within a 3*COV limit of 10.0% of the entire population. Inherent in this statistical validity is the assumption that a normal distribution of production parts exists. Therefore, the interpretation of the final computed DWFR value should take into account the various criteria that were used to select the test parts, such as serial production, various build dates, different build sites, or different tooling.

The DWFR is determined by first computing the dynamic maximum working flow, DWF_{max}, and the dynamic minimum working flow, DWF_{min}, from the experimental flow data and the specified 10.0% variability limit. The WFR value is determined by dividing the DWF_{max} value by the DWF_{min} value. As is done for linearity, DWF_{max} will be set as the mean dynamic flow value of Q_d at the 5.0 ms IPW of the samples tested at the maximum fuel pressure. It is important to note that the DWF_{min} value is an important parameter in its own right, as it generally represents the lowest fuel flow rate that can be reliably calibrated for use in the application.

5.12.2 Procedure for Measuring the Dynamic Working Flow Range

The test to determine DWFR is to be conducted using a set of at least 24 new, identical injectors from serial production. More injectors can be used for the test set if desired. If criteria other than serial production are used to select the injectors in the set, the criteria should be indicated in the comments section of the data-reporting sheet.

a. All of the 24 (or more) new injectors being tested shall be preconditioned according to the procedures and test conditions described in 4.2. Each injector shall be tested at P_{20}, with one high flow test point at an IPW of 5.0 ms at a fuel pressure of P_{100}.

b. The flow rate of the standard test fluid is to be measured at a series of midrange to long IPW test points, all using a fuel pressure of P_{20} and an injection period (P) of 10.0 ms. These IPW values are:

   Midrange to long IPW values: 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, and 5.0 ms.

   In addition to these 13 IPW test points, a number of short-pulse-width (low-flow) IPW values shall also be flow tested using a fuel pressure of P_{20} and an injection period (P) of 10.0 ms as described in the following step.

c. The short-pulse-width (low-flow) region of the flow curve is normally specified by a range of IPW values starting just slightly higher than the injector OT and extending to an IPW value of 0.475 ms. For the short-pulse-width test points, start with an IPW value that is the measured injector opening time rounded up to the next higher 0.025 ms. Following that, measure the flow using IPW increments that are obtained by adding 0.025 ms to the previous IPW. Repeat until an IPW of 0.475 ms is attained. For example, for a measured OT of 0.195 ms, the low-flow test points would be:

   Short-pulse-width IPW values: 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375, 0.4, 0.425, 0.45, and 0.475 ms.

d. Measure the fuel flow rate for the sample injector for a fuel pressure of P_{100} and a period (P) of 10.0 ms. Only one test point is required at this fuel pressure. That test point is for an IPW of 5.0 ms.

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

5.12.3 Data Reduction and Analysis for the Dynamic Working Flow Range

As discussed in 5.12.1, the DWFR and DWF_{min} are key parameters that quantify the limits of the variability of fuel delivery for a population of identical injectors. The DWFR is based on the measurement of a minimum sample of 24 injectors that is statistically intended as a representative sample of the total population of all manufactured injectors of that type and model. Inherent in this test is the specification in advance of a number of defined limits that determine both the detailed test procedure and the resultant meaning of the test results. For this DWFR test, a limiting mean flow variability limit of 10% at three standard deviations from the mean fuel flow rate value at each value of IPW serves to statistically guarantee that the results of the test will reliably represent the total population of injectors with a confidence level of 99.7%.

The DWFR defines the range of flow values that may be delivered by any new injector of that type without exceeding the limiting flow variability that was specified for the DWFR test. That is 10% for this recommended practice document. The low-flow limit of DWF_{min} that was determined from the test and used to compute the DWFR also defines the lowest flow rate that can be reliably delivered by any subset of the entire population of these injectors. Thus, the IPW value that corresponds to DWF_{min} defines the shortest pulse width that can be employed in the control system for that application. Unlike the DLFR, the DWFR is not based upon a linear regression curve and therefore does not guarantee a linear relationship between the IPW and the delivered fuel flow of a group of injectors from a population. Instead, it is based upon a specified limiting variability in the fuel flow rate delivered by any injector in that particular population.

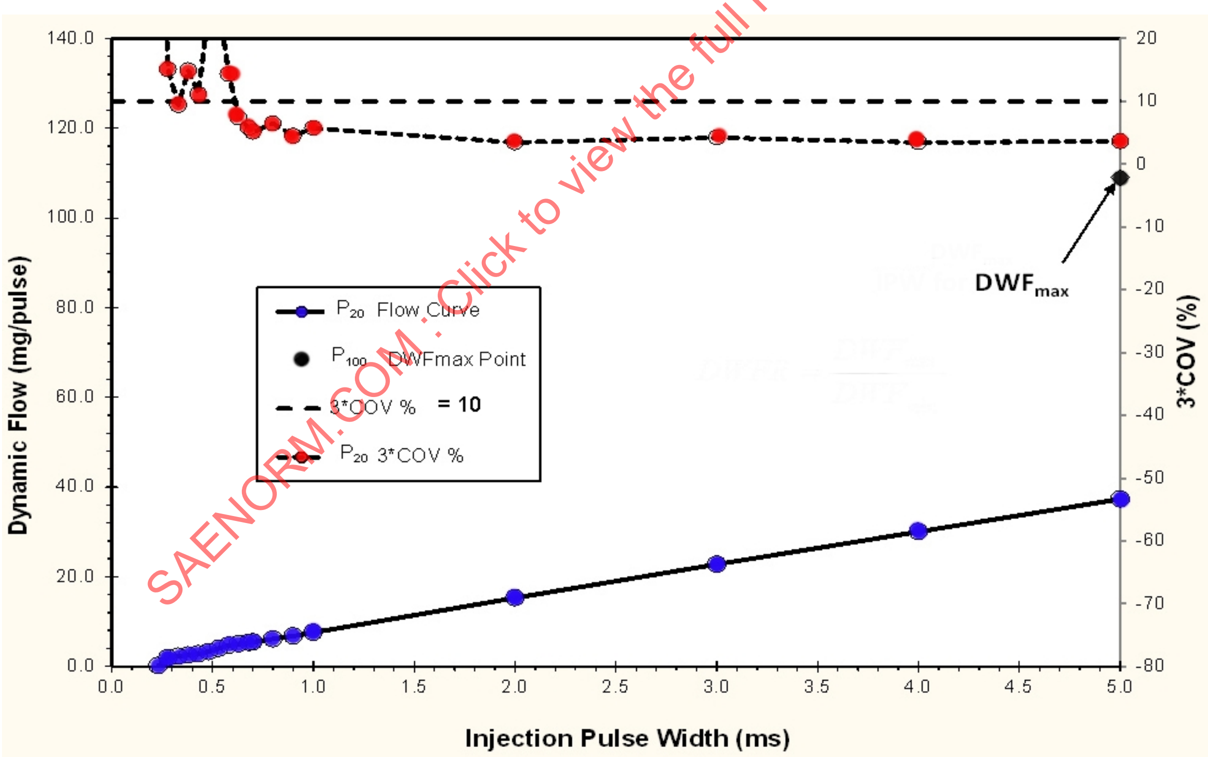

Figure 13 - GDI mean flow rate and the associated flow variability for a DWFR analysis

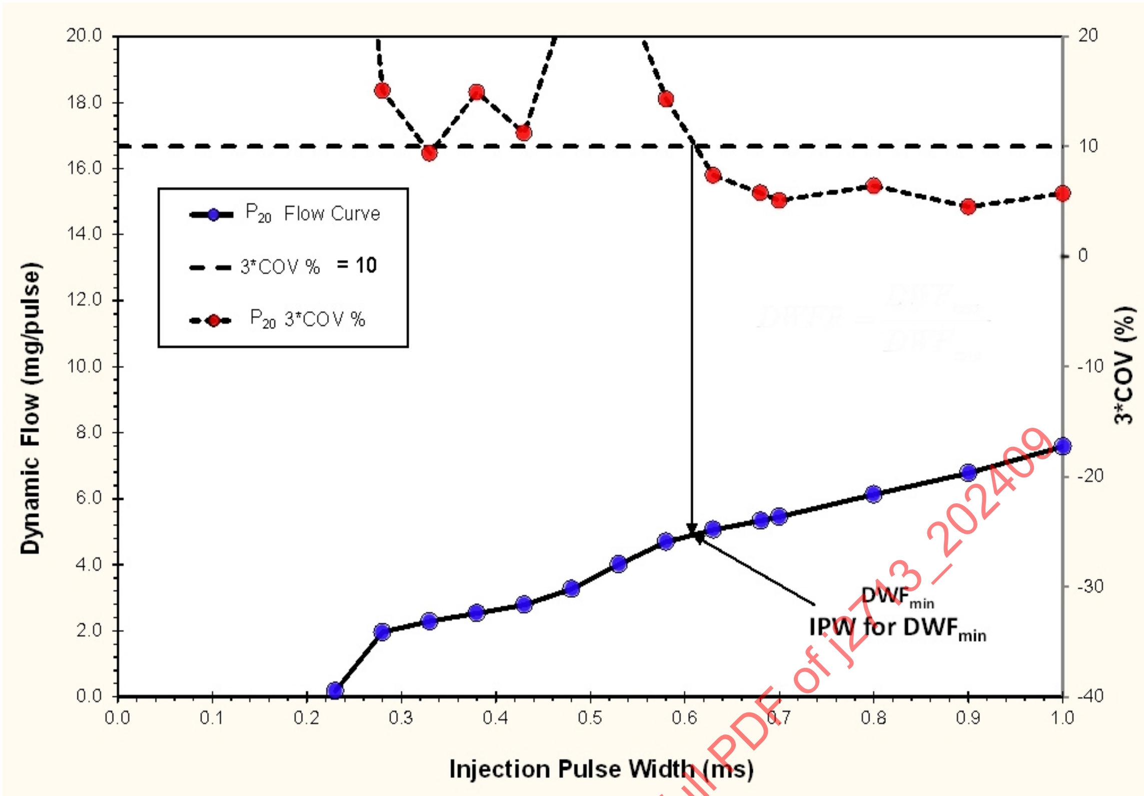

Figure 14 - GDI mean flow rate and the associated flow variability for DWFR (short-pulse-width region)

5.12.4 Generation of the Percentage Variability Curve

For the set of 24 (or optionally more) injectors being tested, there will be 24 measured fuel flow rates for each one of the IPW values tested. Using standard statistical tools, compute the arithmetic average flow rate and the standard deviation (sigma) of those flow rates for these 24 measured flow rates at each IPW. These two values are referred to as the "corresponding" mean flow rate and the "corresponding" standard deviation of that particular set of 24 (or more) flow rates for one particular IPW value. Note that each IPW will have its own corresponding mean flow rate and corresponding standard deviation.

Next, for each tested value of IPW, calculate the corresponding percentage variability of the set of 24 (or more) flow rate values relative to three times the corresponding standard deviation, sigma. The flow variability of the set of all 24 measured flow rates at a particular IPW may be expressed as a percentage of three corresponding standard deviations by using Equation 16A. For convenience, the COV may be computed as the standard deviation divided by the arithmetic mean flow (see 3.2). This simplifies Equation 16A into Equation 16B. Both Equations 16A and 16B are listed previously in the working flow range section. The representative plots that are shown in the remainder of the flow subsection use the percentage 3.0*COV parameter from Equation 16B for plotting. Each of these 24 percentage variabilities is to be tabulated using either Equation 16A or 16B and then plotted versus the IPW. Representative plots of these data are shown in Figures 13 and 14 for the full-flow range and for the short-pulse-width (low-flow) region, respectively.

5.12.5 Determination of the Low and High Limits of the Dynamic Working Flow Range

a. First, inspect the short-pulse-width (low-flow) region of the 3*COV percentage variability versus pulse-width plot of the data for P_{20} fuel pressure. From the plot in Figure 14, starting at 1.0 ms PW, move left down the curve and first identify the longest IPW duration where the 3*COV percentage variability exceeds 10.0%. Then identify the next longest IPW (to the right of the first IPW just determined) for which the variability is less than 10.0%. These are the two short-pulse-width IPW test values to be used for two linear interpolations. Identify the two flow variability values that are associated with these two test point IPW values and use these four values as the end points of a simple linear interpolation. This first linear interpolation is to determine the precise low-flow IPW value at which the percentage variability is exactly 10.0%. This is designated as IPW_{min} for the dynamic working flow range.

b. At each of the two short-pulse-width IPWs determined above, use the two associated mean flow rate values for a second linear interpolation. The second interpolation uses the same two low-flow IPW values along with their associated mean flow values as the interpolation end points. The purpose of the interpolation is to determine the expected mean flow delivered at a pulse width of IPW_{min}. This interpolated mean flow is to be designated as DWF_{min}.

c. For a GDI system, the maximum IPW available to fire an injector is approximately 5 ms. This is determined assuming that the available firing time of an injector is 180 degrees out of 720 degrees of crank angle rotation at 6000 rpm. This engine speed gives a total of 20 ms of time per cycle. Therefore, 180/720 or 25% of 20 ms corresponds to an IPW of 5 ms. Thus, the DWF_{max} value for a GDI injector is chosen as the average flow rate Q_d value at the 5.0 ms flow from the P_{100} fuel pressure data.

d. The DWFR for a population of injectors is to be determined using Equation 18. In this equation, DWFR is defined to be the delivered fuel rate at the maximum working flow point, DWF_{max}, divided by the delivered fuel rate at the minimum working flow point, DWF_{min}. For flow rates between these two values, all injectors in the population will deliver metered fuel rates that vary less than the 10.0% limiting value of the 3*COV variability.

$$DWFR = DWF_{max}/DWF_{min} \quad \text{(Eq. 18)}$$

e. The DWFR value may also have interpretive value for prototype parts; however, it must be realized that prototype assembly may not be representative of the level of variation that may exist in mass production. If the distribution of the sample is not normal, or if a sample of less than 24 parts is used, the statistical confidence limit would be less than 99.7%, perhaps significantly less. Because of the number of possibilities for non-normal distributions and using less than 24 test injectors, the equations to be used are not provided in this document. Instead, it is suggested that one of many commercially available statistical packages be used to evaluate the DWFR results for such cases. It is also noted that this would be considered as a significant test deviation and that the DWFR that was obtained would not be the SAE J2713 DWFR.

5.12.6 Data Reporting for the Dynamic Working Flow Range

The general information on the test conditions and the details of the test injectors are to be reported in Parts 1, 2, and 3 of the data-reporting sheet in Table 9. As part of the DWFR determination, the measured flows, computed mean flows, computed flow standard deviation, and computed 3*COV percentage flow variability for those flows are to be reported for each test injector at each IPW test point. The raw flow data are to be reported on copies of Part 5-B of the data-reporting sheet. These data are to be for a fuel pressure of P_{20}, with one data point taken at P_{100}. Use a copy of the Part 5-B portion of the data-reporting sheet for reporting the raw flow data for each eight injectors and record the eight serial numbers on that copy. Use three total copies of Part 5-B to report the measured raw flow data for all 24 injectors. Check the box for "DWFR" data reporting. The computed values for the mean flow, the standard deviation, and the 3*COV percentage flow variability are to be reported on the Part 5-C data-reporting sheet. Also, a plot containing the curves of flow rate and 3*COV percentage flow variability for the test set of 24 (or more) injectors is to be generated and attached to the data-reporting sheet. The plot is to clearly indicate the two key pulse widths for DWFR determination; one at low flow where the percentage flow variability equals the 10.0% limit of 3*COV and the other at the high-flow pulse-width point (5.0 ms IPW). These particular pulse widths are the IPW values corresponding to the maximum dynamic working flow, DWF_{max}, and to the minimum dynamic working flow, DWF_{min}. The locations of DWF_{min} and DWF_{max} are to be clearly indicated on this plot.

The final computed values for DWF_{min}, DWF_{max}, the IPW for DWF_{min}, and DWFR are to be reported on Part 5-D of the datasheet. Part 5-D is a summary sheet for reporting all of the values of the flow parameters that were determined. If n-heptane at a fuel pressure of P_{20} was employed for the test and there are no other test deviations, these will be the SAE J2713 values for DWF_{min} and DWFR, and those values are to be entered in the indicated boxes on Part 5-D of the data-reporting sheet in Table 9. If there are any test deviations, these should be noted in the test comments area of the datasheet, and the data is reported in the box in Part 5D for the data with test deviations.

Table 9 - GDI injector flow test: data-reporting sheets

SAE J2713 - Data-Reporting Sheets for GDI Flow Measurements for Static Flow, Verification Flow, and for the LFR, DLFR, WFR, and DWFR Flow Range Tests			Page 1
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	
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)		100.0 ± 5.0
Fluid temperature (°C)		21.0 ± 2.0
Fluid test pressures (MPa) Note: There are three different test pressures that are determined by the particular test.		P_{20} P_{50} P_{100}
Initial injector temp (°C)		21.0 ± 2.0
Injection pulse widths (ms)		Various; see test procedure IPW = LPW - driver delay
Injection period (ms)		10.0 ± 0.05
Injection pulses per test point		1000
Injector preconditioning		As per 4.2
Additional information		

Part 4: Description and Comments on Instruments or Test Deviations	
Instrument details	
Test deviations	

Part 5-A: Test Results for: LFR and/or DLFR							
Note: Use a new copy of this Part 5-A datasheet for each injector							
S/N of the Tested Injector:							
P50 Pressure: (MPa)			**LFR DATA**	**P20 Pressure: (MPa)**			**DLFR DATA**
Point	**IPW (ms)**	**Fuel Mass per Pulse (mg)**	**% Difference from Linear Flow**	**Point**	**IPW (ms)**	**Fuel Mass per Pulse (mg)**	**% Difference from Linear Flow**
1	0.200			1	0.200		
2	0.225			2	0.225		
3	0.250			3	0.250		
4	0.275			4	0.275		
5	0.300			5	0.300		
6	0.325			6	0.325		
7	0.350			7	0.350		
8	0.375			8	0.375		

9	0.400			9	0.400		
10	0.425			10	0.425		
11	0.450			11	0.450		
12	0.475			12	0.475		
13	0.500			13	0.500		
14	0.55			14	0.55		
15	0.60			15	0.60		
16	0.65			16	0.65		
17	0.70			17	0.70		
18	0.75			18	0.75		
19	0.80			19	0.80		
20	0.90			20	0.90		
21	1.00			21	1.00		
22	2.00			22	2.00		
23	3.00			23	3.00		
24	4.00			24	4.00		
25	5.00			25	5.00		
				26*	5.00		

*** Note: For the DLFR P_{100} test at 5.0 ms IPW.**

For the test injector

LFR Parameters	Results	DLFR Parameters	Results
Computed slope m (mg/ms)		Computed slope m (mg/ms)	
Computed flow offset (mg)		Computed flow offset (mg)	
Computed time offset (ms)		Computed time offset (ms)	
Minimum linear flow point, LF_{min} (mg/pulse)		Minimum dynamic LF point, DLF_{min} (mg/pulse)	
Maximum linear flow point, LF_{max} (mg/pulse)		Maximum DLF flow point, DLF_{max} (mg/pulse)	
$LFR = LF_{max}/LF_{min}$		$DLFR = DLF_{max}/DLF_{min}$	

Part 5-B: Tabulation of Raw Flow Data for: □ WFR OR □ DWFR (check one)

Pressure: (MPa)
Specify P_{50} or P_{20} — WFR uses P_{50} and DWFR uses P_{20} and 1 IPW using P_{100}

Note: Use a copy of this Part 5-B datasheet for each 8 of the 24 (or more) injectors (three copies). Use three copies for WFR results and three copies for DWFR.

Reporting of the Measured Mass of Fuel per Pulse (mg) for each 8 Injectors

(ms)		Measured Flow (mg/pulse)							
Point	**IPW**	**S/N**	**S/N**	**S/N**	**S/N**	**S/N**	**S/N**	**S/N**	**S/N**
1	0.200								
2	0.225								
3	0.250								
4	0.275								
5	0.300								
6	0.325								
7	0.350								
8	0.375								
9	0.400								
10	0.425								
11	0.450								
12	0.475								
13	0.500								
14	0.55								
15	0.60								
16	0.65								
17	0.70								

18	0.75								
19	0.80								
20	0.90								
21	1.00								
22	2.00								
23	3.00								
24	4.00								
25	5.00								
26*	5.00								

* Note: Point 26 is for the single P_{100} point for DWFR at 5.0 ms IPW.

Part 5-C: Tabulation of Computations for Mean Flow and Standard Deviation

These results for: □ WFR or □ DWFR (check one)

Pressure: _____ (MPa)
Specify P_{50} or P_{20} — WFR uses P_{50} and DWFR uses P_{20} and 1 IPW using P_{100}

Note: Use a copy of this Part 5-C datasheet for each test set of 24 injectors. Use one copy for WFR results and another copy for DWFR results.

Reporting of the Mean Flow (per pulse in mg) and the Standard Deviation

IPW (ms)		Mean Flow	Std Dev	3*COV % Variability	PW (ms)		Mean Flow	Std Dev	3*COV % Variability
.0.150					0.500				
0.175					0.550				
0.200					0.600				
0.225					0.650				
0.250					0.700				
0.275					0.750				
0.300					0.800				
0.325					0.900				
0.350					1.000				
0.375					2.000				
0.400					3.000				
0.425					4.000				
0.450					5.000				
0.475					5.000@P_{100}				

Part 5-D: Summary Sheet for All GDI Flow Parameters

Note: Use a new copy of this Part 5-D datasheet for each injector.

Parameter Reported	Value Being Reported for No Test Deviations	Units	Values Being Reported if There are Known Test Deviations
Verification flow test 1		(mg/pulse)	
Verification flow test 2		(mg/pulse)	
Verification flow test 3		(mg/pulse)	
SAE J2713 Dynamic Verification Flow (Average of the 3 individual flow values) (mg/pulse)		Dynamic Verification Flow if there are known test deviation(s) (mg/pulse)	
Average of the averages for all tested injectors (5 or more) SAE J2713 Dynamic Verification Flow Value (mg/pulse)		Average of the averages for Dynamic Verification Flow Value if there are known test deviation(s) (mg/pulse)	
Static flow test 1		(g/s)	
Static flow test 2		(g/s)	
Static flow test 3		(g/s)	
SAE J2713 Static Flow (Average of the 3 individual flow values) (g/s)		Static Flow Value if there are known test deviation(s) (g/s)	

Average of the averages for all tested injectors (5 or more) SAE J2713 Static Flow Value (g/s)		Average of the averages for Static Flow Value if there are known test deviation(s) (g/s)	
SAE J2713 LFR (Average of all the tested parts)		Average of the averages for LFR if there are known test deviations	
SAE J2713 LF_{min} (Average of all the tested parts) (mg/pulse)		Average of all the tested parts for LF_{min}, if there are known test deviation (mg/pulse)	
SAE J2713 DLFR (Average of all tested parts)		Average of the averages for DLFR, if there are known test deviations	
SAE J2713 DLF_{min} (Average of all the tested parts) (mg/pulse)		Average of all the tested parts for DLF_{min}, if there are known test deviations	
SAE J2713 WFR		WFR if there are known test deviations	
SAE J2713 WF_{min} (mg/pulse)		WF_{min} if there are known test deviations	
SAE J2713 WF_{min} IPW (ms)		WF_{min} IPW (ms) if there are known test deviations	
SAE J2713 DWFR		DWFR if there are known test deviations	
SAE J2713 DWF_{min} (mg/pulse)		DWF_{min} if there are known test deviations	
SAE J2713 DWF_{min} IPW (ms)		$DWFR_{min}$ IPW if there are known test deviations	
Test comments, including any deviations			
Data plots: Attach the required curves that are indicated in the data-reporting subsection of each test.			

5.13 Minimum Time Between Injections (MTBI)

This is a test for determining the minimum acceptable time between two identical, closely spaced injections for a GDI injector. The test is used to determine how closely these pulses can be spaced before their interaction causes a shift greater than 5% in the total delivered mass of fuel from that of two independent pulses. This MTBI value is used for comparison purposes only. It is acknowledged that it may be desirable to operate with a shorter time between injections than is indicated by the MTBI value for other reasons.

A 0.5 ms fixed pulse width is favored over a fixed mass quantity because it automatically approximates a typical standard engine load point, such as a light cruise road load for various sized injectors. This assumes that most injectors are sized similarly for their application.

As is illustrated in Figure 15, this test consists of injecting twice using two identical IPW values of 0.5 ms each while varying the time interval between the end of the first IPW and the beginning of the second. These two IPWs and the time between them constitute one injection set. For test purposes, the time between each two-pulse injection set is fixed at 50.0 ms, regardless of the time between IPWs. This means that the injection set frequency of 20.0 Hz does not change throughout the test. Each test point consists of the average of at least 1000 flow rate measurements of the two-pulse set.

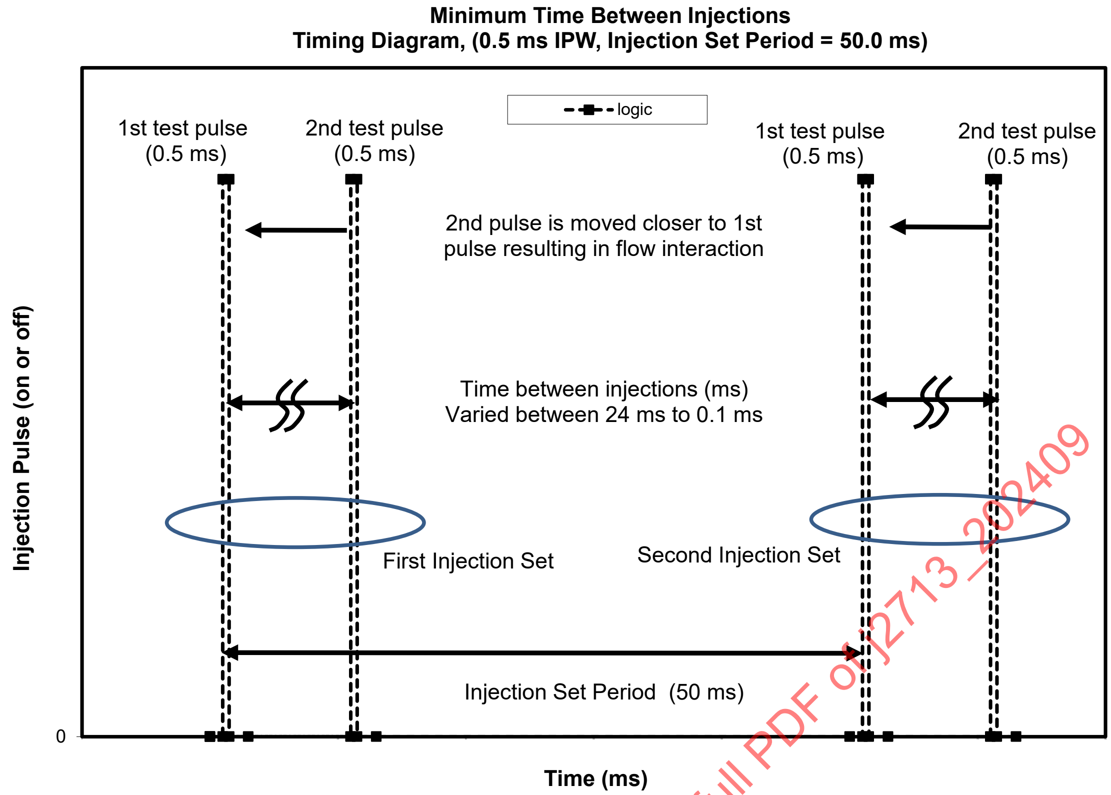

Figure 15 - Timing diagram for the MTBI test

5.13.1 Procedure for the MTBI Test

A minimum test set of five new injectors, of the same make and model, from serial production shall be tested. More injectors may be optionally tested if desired. 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. Preproduction injectors may be used in this test without deviation if this is clearly noted in the comments section of the data-reporting sheet. All of the test injectors shall be preconditioned as described in 4.2.

a. Install a test injector on a fuel flow stand having the measurement capabilities that are indicated in 10.2. Set the controller to provide two identical IPW pulses of 0.5 ms each, with an injection period, P, for the two-pulse set of 50.0 ms. As is shown in the MTBI timing diagram in Figure 15, the individual pulses in the two-pulse set shall be separated by a variable, controllable time interval that can be varied from 24.0 ms down to 0.1 ms. This time interval (TBI) is from the end of the first pulse in the set to the start of the second pulse.

b. Using n-heptane at a fuel pressure of P_{50} and a period (P) for the two-pulse set of 50.0 ms, measure the total delivered fuel flow rate for the two-pulse set for a series of TBI values. Measure at least 1000 occurrences of the two-pulse set. These TBI values are: 24.0, 15.0, 10.0, 5.0, 4.5, 4.0, 3.5, and 3.0 ms, followed by a short-TBI set from 2.5 to 0.1 ms in 0.1 ms increments. The order of testing shall be from the longest TBI to the shortest.

c. Repeat the test for a fuel pressure of P_{20}.

d. Repeat steps (a) through (c) for the next injector in the test set.

5.13.2 Data Reduction and Analysis for MTBI Testing

For each of the tested injectors, the fuel flow rates for each TBI test point are to be averaged over a minimum of 1000 injection-set cycles and computed and reported as that average in mg/pulse. For informational purposes, a representative set of actual GDI flow data is tabulated in Table 10 and is plotted in Figure 16. This illustrates that the longer the time interval between the two injection pulses, the lower the deviation in fuel mass delivery is expected to be. Therefore, fuel mass delivery deviations are expected to be near the lowest at TBI values of 24.0, 15.0, and 10.0 ms. The reference (ideal) mass flow for the fuel mass deviation calculation is determined by averaging the individual average mass delivered for each of the first three TBI test points (24.0, 15.0, and 10.0 ms). As may be seen from the tabulated data and the graph, as the time between injections becomes significantly shorter (less than 5.0 ms for the GDI injector in this illustration), the mass of fuel delivered by the two injection events begins to deviate significantly. This is normally due to an encroachment of the second pulse on the first pulse while the first is still in the ballistic range. As the TBI value is reduced, the total flow rate delivered by the two-pulse set decreases by a few percent until the TBI is reduced to about 3.0 ms. Beyond that point, a further decrease in TBI yields an increase in the fuel mass delivered. The delivered mass flow rate then increases rapidly as the TBI is decreased to 2.0 ms and further yet to 1.0 ms. For the P_{20} plot, the deviation in fuel mass delivery may be seen to exceed the +5.0% limit (relative to the ideal mass delivery value) at a TBI value of approximately 1.45 ms. For the representative GDI injector that was used to obtain the sample data, this 1.45 ms value would be the P_{20} SAE J2713 MTBI that is obtained. Similarly, the P_{50} SAE J2713 MTBI is 1.66 ms.

Table 10 - Sample data set for minimum time between injections

		P_{20} 0.5 ms test IPW		P_{50} 0.5 ms test IPW	
Test order	**Time Between Injections (ms)**	**Mass/set (mg)**	**Deviation from Ideal Flow (%)**	**Mass/set (mg)**	**Deviation from Ideal Flow (%)**
1	24.0	4.725	0.02%	10.500	0.33%
2	15.0	4.722	-0.05%	10.493	0.26%
3	10.0	4.725	0.02%	10.405	-0.58%
4	5.0	4.722	-0.05%	10.498	0.31%
5	4.5	4.682	-0.89%	10.479	0.13%
6	4.0	4.724	0.01%	10.339	-1.21%
7	3.5	4.716	-0.17%	10.200	-2.54%
8	3.0	4.653	-1.51%	10.170	-2.83%
9	2.5	4.590	-2.83%	10.200	-2.54%
10	2.4	4.577	-3.12%	10.300	-1.58%
11	2.3	4.590	-2.83%	10.350	-1.11%
12	2.2	4.635	-1.88%	10.400	-0.63%
13	2.1	4.658	-1.41%	10.450	-0.15%
14	2.0	4.680	-0.93%	10.500	0.33%
15	1.9	4.703	-0.45%	10.600	1.28%
16	1.8	4.725	0.02%	10.800	3.19%
17	1.7	4.770	0.98%	10.900	4.15%
18	1.6	4.860	2.88%	11.150	6.54%
19	1.5	4.905	3.83%	11.300	7.97%
20	1.4	5.018	6.21%	11.320	8.16%
21	1.3	5.085	7.64%	11.390	8.83%
22	1.2	5.094	7.83%	11.400	8.93%
23	1.1	5.126	8.50%	11.420	9.12%
24	1.0	5.130	8.60%	11.435	9.26%
25	0.9	5.139	8.79%	11.500	9.88%
26	0.8	5.146	8.93%	11.700	11.79%
27	0.7	5.175	9.55%	12.100	15.61%
28	0.6	5.265	11.45%	12.400	18.48%
29	0.5	5.445	15.26%	12.500	19.44%
30	0.4	5.580	18.12%	11.000	5.10%
31	0.3	5.625	19.07%	10.940	4.53%
32	0.2	4.950	4.79%	10.850	3.67%
33	0.1	4.875	3.20%	10.750	2.72%
	Ideal Mass Flow (average of first 3 test points)	**4.724**		**10.466**	

	P_{20}		P_{50}	
SAE_{2713} MTBI	**1.45**	(ms)	**1.66**	(ms)
Dynamic Flow @ MTBI	4.96	(mg/set)	10.99	(mg/set)
Maximum Deviation	19.07	(%)	19.44	(%)
TBI @ max deviation	0.3	(ms)	0.5	(ms)

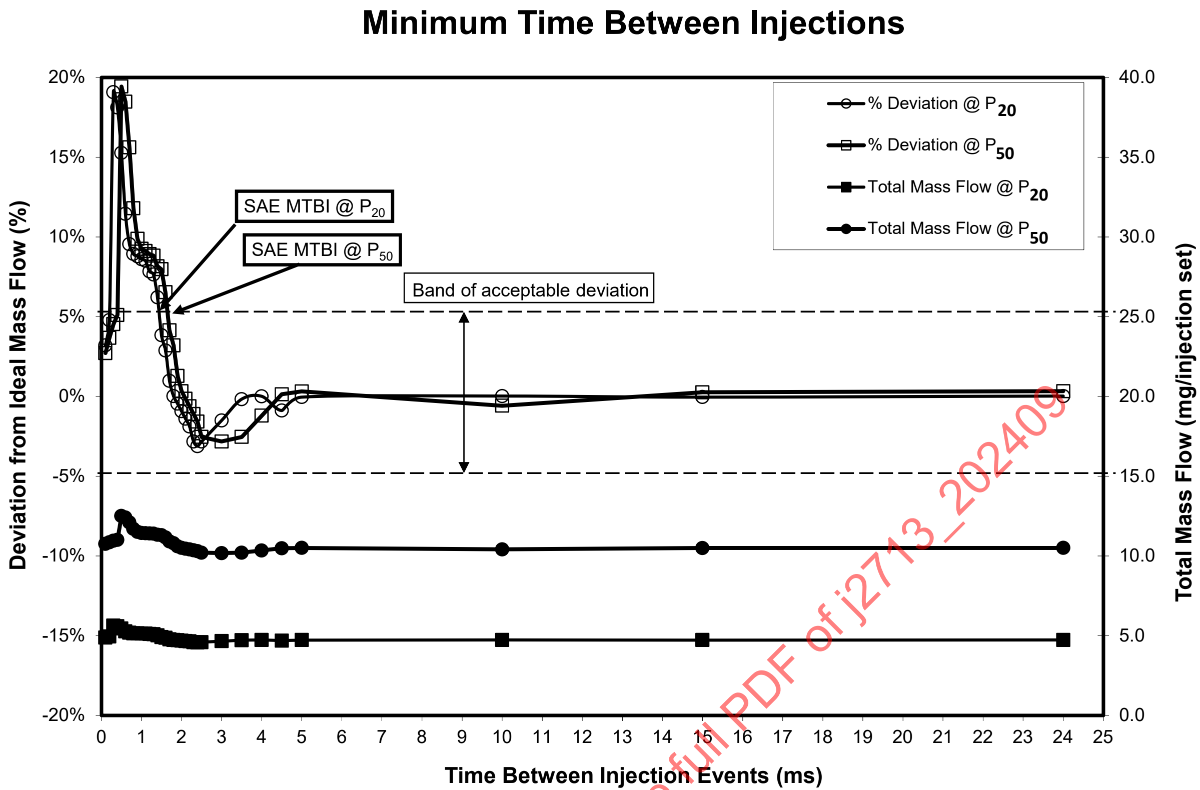

Figure 16 - Typical dataset for MTBI flow variation

5.13.3 Data Reporting for MTBI Testing

The SAE J2713 MTBI test values to be reported will be the largest value of TBI and the associated mean mass delivery per two-pulse injection set for which the TBI deviation exceeds 5% with respect to the ideal reference mass flow. For any larger TBI, the mass flow deviation will be less than 5%. This defines the SAE J2713 MTBI indicator of the operational lower boundary for the time between injections. A theoretically perfect injection system would have an MTBI of 0.1 ms, which could be approachable by piezoelectric GDI injectors but not likely by solenoid-actuated GDI injectors. If the deviation does not exceed the 5% limit for any value of TBI during the test, then the SAE J2713 MTBI is to be reported as 0.1 ms.

The MTBI value and the associated value of fuel mass delivery at that MTBI are to be determined and reported on the data-reporting sheet in Table 11, Part 5-B for each of the five tested injectors. The five values of MTBI and the five values of the associated fuel mass delivery are then each to be averaged to obtain the final values of MTBI and mass flow to report on data-reporting sheet Part 5-A. These final values will be the SAE J2713 MTBI test value and the associated fuel mass delivery. If there are no test deviations, these are to be recorded in the boxes that are so labeled. However, if there are test deviations, the values are to be recorded in the boxes below the SAE J2713 MTBI boxes, leaving the SAE J2713 MTBI boxes blank.

For each injector tested, the measured and tabulated mass flow data for the individual values of TBI that were tested are to be recorded on the data-reporting sheet Part 5-B. The serial number of each injector is to be recorded at the indicated position on the Part 5-B data-reporting sheet. Plots of the fuel mass delivered and the percentage deviation from ideal fuel mass delivery are to be prepared for each injector. These plots are to be generated for both the P_{50} and P_{20} fuel pressures and are to be attached to the data-reporting sheet.

Table 11 - GDI MTBI: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for GDI Minimum Time Between Injections (MTBI)				
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 (attach plot of current waveform to datasheet)				
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} and P_{20} both to within ±0.5%		
Initial injector temperature (°C)		21.0 ± 2.0		
Injection pulse width of an individual injection (ms)		1.0 ± 0.01		
Number of injection pulses in an injection set		2		
Injection period between injection sets (ms)		50.00 ± 0.05		
Number of injection sets measured for each test point		1000		
Injector preconditioning time		As per 4.2		
Additional information				
Part 4: Description and Comments on Instruments or Test Deviations				
Instrument details				
Test deviations				
Part 5-A: Reporting of Final Test Results for GDI Minimum Time Between Injections (MTBI)				
Reporting of the measured minimum time between injections for no test deviations: Average of the five individual values for each of the five tested injectors that are listed on the Part 5-B datasheet.	SAE J2713 minimum time between injections (ms)	SAE J2713 dynamic flow at MTBI (mg/pulse)		Other info
	MTBI for P_{50}:	Flow for P_{50}:		
	MTBI for P_{20}:	Flow for P_{20}:		
	Minimum time between injections (ms)	Minimum fuel delivery (mg/pulse)		

Measured minimum time between injections: For non-standard test conditions or IPW: If there are known test deviations, enter the results here and indicate deviations above in Part 4.			
Additional information			
Data plots	Attach plots of measured fuel mass delivered per two-pulse injection set and % deviation from ideal flow versus TBI for both P_{20} and P_{50}. Also attach plots of representative driver current waveform to datasheets.		

Part 5-B: Reporting of Detailed Mass Flow Data

Note: Use a new copy of this Part 5-D datasheet for each injector

Injector S/N

Measured Mass Flow Values

TBI Value (ms)	P_{20} Mass Flow	P_{20} Deviation from Ideal Flow (%)	P_{50} Mass Flow	P_{50} Deviation from Ideal Flow (%)
24.0				
15.0				
10.0				
5.0				
4.5				
4.0				
3.5				
3.0				
2.5				
2.4				
2.3				
2.2				
2.1				
2.0				
1.9				
1.8				
1.7				
1.6				
1.5				
1.4				
1.3				
1.2				
1.1				
1.0				

0.9				
0.8				
0.7				
0.6				
0.5				
0.4				
0.3				
0.2				
0.1				
Additional Information				
Data Plots	Attach plots of Measured Fuel Mass Delivered per two-pulse injection set and % Deviation from ideal flow versus TBI for both P_{20} and P_{50}. Also attach plots of representative driver current waveform to datasheets.			

5.14 Shot-to-Shot (STS) Mass Flow Variation

5.14.1 Overview of the STS Variability Parameter

This document provides a test for the minimum fuel mass flow delivery for a GDI injector that has a specified limiting mass flow variability among many injection events. The test is used to determine the minimum mass fuel delivery that can be achieved before the shot-to-shot mass flow variation equals 5% of 3*COV. At that value of fuel mass flow variability there is a corresponding mean value of the delivered mass of fuel per pulse, and there is also a specific value of the IPW. These are the values that are to be reported as the test results.

The test consists of measuring and documenting the changes in the COV in mass flow for a single GDI injector for a series of test points of increasing injection pulse width. A sample dataset is presented in Table 12 and is plotted in Figure 17.

The SAE STS test is for a single injection per cycle. It is recognized that multiple injections are commonly used in GDI systems; however, the basic case of the mass variation among many single injections must ideally be understood first. The SAE STS test is also defined for a single injector, not a population of injectors. It should be noted that this recommended practice document does not define an STS test procedure and data reduction for testing a population of injectors nor for multiple injections per pulse.

5.14.2 Test Equipment for STS Testing

There are currently three types of STS flow meters in common use. These are the rate tube, the positive displacement type, and the constant volume type. The SAE J2713 Recommended Practice test fluid to be used for STS testing is n-heptane

5.14.3 Procedure for the STS Test

A minimum test set of five new GDI injectors of the same make and model from serial production shall be tested. Additional injectors may be tested as desired. 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. As noted in 5.14.1, the basic STS test is performed on a single injector, and the results that are obtained are for that injector. The individual STS results for each of the five injectors are averaged to obtain the final numbers that are reported. More than five injectors may be tested if required, with the STS results for all tested injectors averaged. Preproduction injectors may be used in this test without deviation if this is clearly noted in the comments section of the data-reporting sheet. The possible use of a charge delay in the GDI driver must be addressed in the establishment of the pulse width that is used for testing. IPW is to be used, not LPW. These terms are defined in 3.2.

a. Each test injector shall be preconditioned as described in 4.2.

b. Use n-heptane at a temperature of 21 °C ± 2 °C as the test fluid unless it is precluded by the particular flow meter being used. If other than n-heptane is used, it shall be reported in the comments section of the data-reporting sheet.

c. Install one of the test injectors on a fuel flow stand that has one of the STS-capable flow measurement instruments connected.

d. The test fluid pressure is to be set to P_{50}, as specified by the GDI application. If required, other fuel pressures can be tested to determine the STS results for other fluid pressures, but only P_{50} is to be used for reporting the SAE J2713 STS values.

e. Set the injection period (P) to 50 ms, which is a 20 Hz injection frequency.

f. All testing shall be performed in the direction of increasing pulse widths (from low to high).

g. Determine the first-fuel pulse width: Start with an IPW of 0.150 ms and then increment the test IPW by +0.025 ms until a noticeable response is observed on the flow measurement instrument. Measure the delivered fuel mass for at least 200 injection pulses at that initial IPW.

h. After the first flowing pulse width, measure the delivered fuel mass for at least 200 injection pulses each for ten more IPW values that are each incremented by +0.050 ms above the first-fuel IPW (see Table 11 for an example dataset).

i. Add test points at IPW values of 0.600, 0.700, 0.800, and 0.900 ms if those values were not already part of the previous step.

j. Finally, measure the delivered fuel mass for at least 200 injection events for IPW values of 1.000 ms and 2.000 ms.

k. Using the test points determined in steps (g) through (j) on the first injector in the test set, complete the testing on the remaining injectors by repeating steps (a) through (f) for the next injector in the test set.

5.14.4 Data Reduction and Analysis for STS Testing

For each of the five (or more) injectors, the fuel flow COV for each pulse width is to be computed for the accumulated delivered mass flow data over 200 (or more) injection pulses. The mean and standard deviation of each set of the 200 delivered mass points are to be computed for each IPW value. The COV for this test is defined as the ratio of the standard deviation of the mass injected per pulse to the mean of the mass injected per pulse. Next, the percentage 3*COV values of that data are to be computed, as the 3*COV (%) parameter will be used to plot the data. This data reduction is repeated for each of the IPW values for each of the other test injectors.

Prepare a plot for the data from each test injector, with the delivered mass flow and percentage 3*COV (%) as Y-axes and the IPW values as the X-axis. For an injector, identify the longest IPW that yields a 3*COV (%) value that exceeds 5%. Then, using this IPW value and its associated 3*COV (%) value, as well as the next longer IPW value and its associated 3*COV (%) value (this value will be less than 5%), perform a linear interpolation to obtain the IPW value and the corresponding mean value of the delivered mass flow for which the 3*COV (%) value of fuel mass flow variability is exactly 5%. Then prepare plots and perform the linear interpolations for the other injectors in the test set. Determine the one injector in the test set that has the highest computed IPW for which the value of fuel mass flow variability is exactly 5%.

Table 12 - GDI shot-to-shot sample dataset

Test Order	IPW	Mass/Pulse (mg)	Standard Dev. (mg)	3*COV%
1	0.425	2.34	0.04	5.13
2	0.475	3.30	0.06	5.45
3	0.525	3.05	0.05	4.92
4	0.575	4.64	0.07	4.53
5	0.6	5.13	0.09	5.26
6	0.625	5.46	0.05	2.75
7	0.675	5.97	0.03	1.51
8	0.7	6.22	0.06	2.89
9	0.725	6.47	0.08	3.71
10	0.775	7.23	0.08	3.32
11	0.8	7.60	0.08	3.16
12	0.9	8.95	0.08	2.68
13	1	9.78	0.07	2.15
14	2	20.58	0.05	0.73

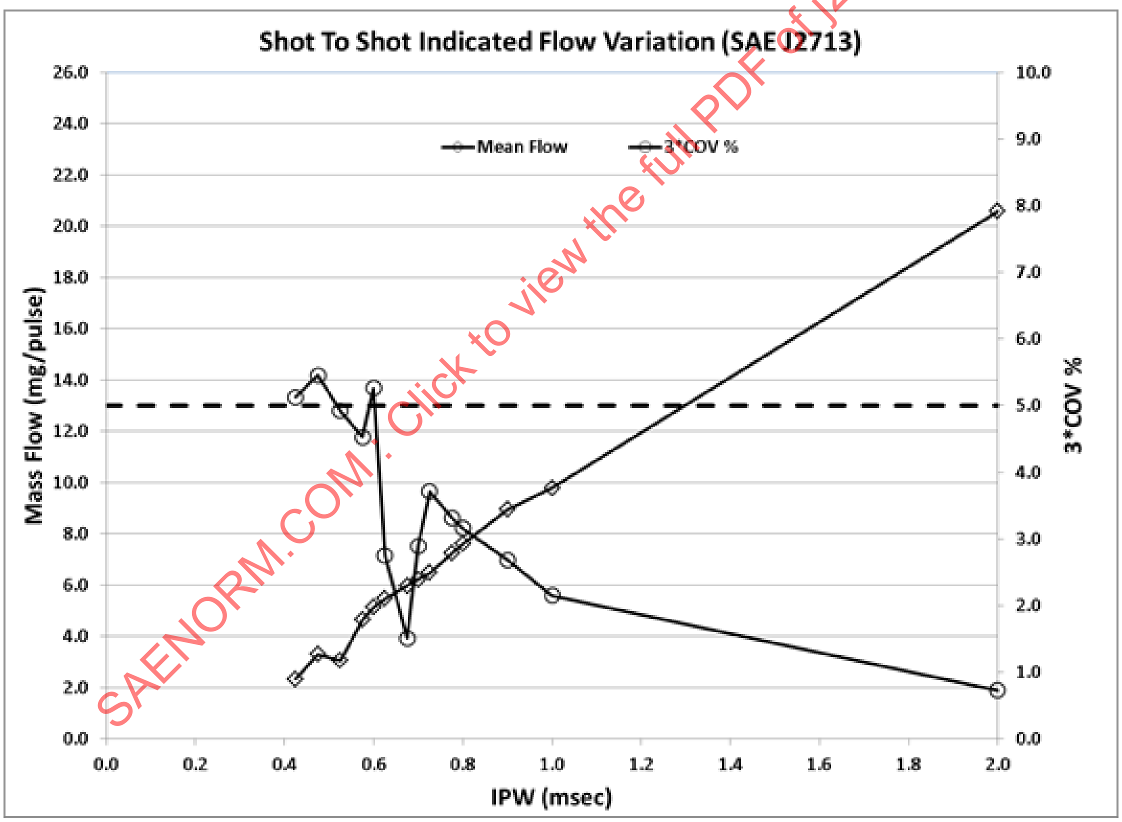

Figure 17 - Measured STS flow variation for a GDI injector

5.14.5 Data Reporting for STS Testing

Record the computed STS mean mass flow values, the standard deviation of those values, and the percentage 3*COV values for each IPW value on the STS data-reporting sheet, Part 5-B. Use a blank copy of Part 5-B for each test injector, with the injector serial number indicated at the top of each sheet. In Part 5-A of the data-reporting sheet, report the mean value of the delivered mass flow and the IPW for the one tested injector having the maximum IPW value. These are the SAE J2713 STS values if there are no test deviations.

Table 13 - GDI STS variability tests: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for Shot-to-Shot Fuel Mass Delivery Variation (Use one copy of this datasheet per injector)			
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:	
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
Pulses per injection set		200
Period between inject sets (ms)		50 ± 0.05
Injector axis orientation (degrees)		Vertical unless specified
Injector preconditioning time		As per 4.2
Additional information		

Part 4: Description and Comments on Instruments or Test Deviations	
Instrument details	
Test deviations	

Part 5-A: Final Test Results for Shot-to-Shot Fuel Mass Delivery Variation			
Shot-to-shot 3*COV variability of 5% in fuel mass delivered: For no test deviations, enter results in the boxes to the right:	SAE J2713 STS IPW (ms)	Mean fuel mass delivered: SAE J2713 STS fuel flow (mg/pulse)	
Shot-to-Shot 3*COV variability of 5% in fuel mass delivered: For nonstandard test conditions or for an additional fuel pressure, enter results in the boxes to the right: Fuel pressure = MPa	STS IPW (ms)	Mean fuel mass delivered at this STS test point (mg/pulse)	
Additional information			
Data plots	Attach curves of computed 3*COV (%) in delivered fuel mass per injection and mean fuel mass delivered per injection (mg/pulse) as a function of IPW. Also attach a graph of the injector driver current waveform.		

Part 5-B: Tabulation of STS Mass Fuel Delivery and 3*COV%			
Number of total pulses measured if greater than 200:			
Injector of ; injector s/n:			
Use a blank copy of this Part 5-B datasheet for each injector:			
Injection Pulse Width (ms)	**Mean Mass/Pulse (mg)**	**Standard Deviation (mg)**	**3*COV Variability (%)**
Lower IPW as needed			
0.425			

0.475			
0.525			
0.575			
0.600			
0.625			
0.675			
0.700			
0.725			
0.775			
0.800			
0.900			
1.000			
2.000			

6. ENVIRONMENTAL TESTS

6.1 External Fluid Compatibility Tests

This series of tests determines the compatibility of the external surface of a gasoline GDI injector, excluding external O-rings, with various external liquids and gases. This is to ensure that the external surfaces can withstand contact with common automotive fluids and cleaning procedures. It is not practical to evaluate all variations of test fluids and cleaning procedures; thus, a consensus list of such common test fluids is specified.

6.1.1 Common Automotive Fluids for External Compatibility Tests

A test fluid is defined as a material representative of its particular group, which is sufficiently well defined in all respects so that shop supplies from different sources are essentially identical (refer to ASTM D471). The most commonly used and recommended fluids are listed in Table 14.

Table 14 - Common automotive fluids for external compatibility tests

Fluid	Description
Automatic transmission fluid	Dexron III (General Motors Registered Trademark), Mercon (Ford Registered Trademark), or equivalent.
Engine oil	Commercially available SAE grades.
E10	ASTM Reference Fuel C with 10% ethanol shall be 10% by volume reagent-grade ethanol added to Fuel C.(1)
E85	ASTM Reference Fuel C with 85% ethanol (E85) shall be 85% by volume reagent-grade ethanol added to Fuel C(1)
M15	ASTM Reference Fuel C and 15% methanol shall be 15% by volume reagent-grade methanol added to Fuel C(1)
Diesel fuel	Diesel fuel (No. 2) as described by SAE J313. The fluid shall have an aniline point of 60 to 70 °C. It is preferred that emissions-grade diesel fuel conforming to 40 CFR 86.113 be used.
Axle and manual transmission lubricants	Gear oil API-GL-5 as described in SAE J308. (Viscosity as defined in SAE J306 may be specified at the option of the test engineer.)
Battery electrolyte	Reagent-grade sulfuric acid diluted with water to a specific gravity of 1.25 to 1.28.
Antifreeze	Ethylene glycol/water mixture in equal portions.
Brake fluid	Polyglycols and cellosolves per SAE J1703 and 49 CFR 571.116.
Engine cleaner	Commercially available engine cleaning solvent such as ethylene glycol monobutyl ether (Dow Butylcellosolve™ solvent), technical grade.
Windshield washer fluid	Commercially available washer fluid containing methanol or equivalent.

(1) Refer to ASTM D4814 for Reference Fuel C and ASTM D4806 for ethanol.

6.1.2 Procedure for the Common Automotive Fluid Compatibility Test

a. A minimum set of five new, identical injectors from serial production shall be tested for each fluid. More injectors can be optionally tested for any particular fluid if required. The testing of an injector with one fluid followed by another fluid is to be avoided. 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. Each of the five (or more) injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage both prior to and after completion of the compatibility tests.

b. Each of the test injectors shall have the inlet and outlet suitably sealed. The injector is to have the electrical connector fitted; however, it is not to be energized.

c. For battery acid exposure, the injector shall have its exposed surfaces dampened either by spraying or brush application and allowed to stand for 24 hours.

d. For all other test fluids, the five (or more) injectors shall be submerged together in the test fluid at standard ambient conditions for 24 hours.

e. Upon completion of the 24-hour period, the injector shall be degreased using a mild, citrus-based cleaner and then washed gently in water not warmer than 38 °C and then dried by blotting with an absorbent cloth.

6.1.3 Data Reduction and Analysis for the External Fluid Compatibility Test

Each tested injector shall be examined immediately after testing. The external surface condition shall be visually assessed. The surface of any nonmetallic part shall not be cracked, melted, or the markings defaced. Special attention should be paid to welded joints, crevices, and other areas that may be especially susceptible to corrosion or damage. The parameter deviations from pretest values to post-test values for Q_S, Q_{VF}, IR, R, and tip leakage are to be computed for each test injector and test fluid. The Q_S and Q_{VF} deviations are to be computed as percentage changes.

6.1.4 Data Reporting for the External Fluid Compatibility Test

Record observations of the visual appearance of the test samples on the data-reporting sheet in Table 15. The parameter values and the computed deviations for Q_S, Q_{VF}, IR, R, and tip leakage for each tested injector and test fluid shall also be recorded on the data-reporting sheet. The Q_S and Q_{VF} deviations shall be reported as a percentage change. Use a copy of the blank data-reporting sheet for each tested injector and test fluid. Photographs are to be attached to the data-reporting sheets.

6.2 Water Jet Test

In this test the injector is exposed to a water jet from a high-pressure spray nozzle that is typical of that present in commercial hand-operated car wash facilities. This nozzle should deliver a water jet pressure of approximately 10 MPa.

6.2.1 Procedure for the Water Jet Test

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the five (or more) injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to the water jet test.

b. Each of the test injectors shall have the inlet and outlet suitably sealed. The injector is to have the electrical connector fitted; however, it is not to be energized.

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

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

e. Upon completion of the water jet test, the five injectors shall be dried by blotting with an absorbent cloth.

f. Each of the five (or more) injectors shall be retested for Q_S, Q_{VF}, IR, R, and tip leakage after completion of the water jet test. If the optional 400-minute test to simulate a lifetime exposure is performed, also remeasure Q_S, Q_{VF}, IR, R, and tip leakage after the completion of that test.

6.2.2 Data Reduction and Analysis for the Water Jet Test

Following exposure to the water jet, visually inspect all of the samples and note any negative findings. Specific issues to look for include, but are not limited to, penetration of water at the electrical connector and any cracking of any external surfaces. The parameter deviations for Q_S, Q_{VF}, IR, R, and tip leakage resulting from the water jet test shall be computed for each injector. The Q_S and Q_{VF} deviations are to be computed as percentage changes. Do this for the 10-minute test and also for the 400-minute lifetime simulation test if that test was conducted.

6.2.3 Data Reporting for the Water Jet Test

All observations that resulted from the inspection of the test injectors are to be recorded on the data-reporting sheet in Table 15, with photographs taken of all injectors. All photographs are to be attached to the data-reporting sheets. The pretest and post-test parameter values, and the associated deviations that were computed for Q_S, Q_{VF}, IR, R, and tip leakage, shall be recorded on the data-reporting sheet. The Q_S and Q_{VF} deviations are to be recorded as percentage changes. The parameter deviations for Q_S, Q_{VF}, IR, R, and tip leakage resulting from the 400-minute water jet spray test are also to be reported on the data-reporting sheet if that optional test was performed. Indicate in the comments section of the data-reporting sheet whether a 10-minute test or a 400-minute test, or both, were conducted.

6.3 Steam Jet Test

In this test, the injector is exposed to a steam jet from a steam-cleaner nozzle, as is used in commercial equipment. This steam jet should deliver steam at an upstream pressure of approximately 7 MPa.

6.3.1 Procedure for the Steam Jet Test

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors may be optionally tested if required. 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. Each of the five (or more) injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to the steam jet test.

b. Each of the test injectors shall have the inlet and outlet suitably sealed. The injector is to have the electrical connector fitted; however, it is not to be energized.

c. The test shall consist of a 15-second steam jet exposure to a set of five (or more) closely spaced injectors that is repeated for a total of four exposures. The injector set is to be positioned at a distance of 150 mm from the steam jet nozzle tip.

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

e. Upon completion of the steam jet test, the five injectors shall be dried by blotting with absorbent cloth.

f. Each of the five (or more) injectors shall be retested for Q_S, Q_{VF}, IR, R, and tip leakage after completion of the steam jet test.

6.3.2 Data Reduction and Analysis for the Steam Jet Test

Following exposure to the steam jet, visually inspect all of the samples and note any negative findings. Specific issues to look for include, but are not limited to, penetration of water at the electrical connector and any cracking of any external surfaces. The parameter deviations for Q_S, Q_{VF}, IR, R, and tip leakage resulting from the water jet test shall be computed. The Q_S and Q_{VF} deviations are to be computed as percentage changes. Do this for the 15-seconds test and also for the 300-second lifetime simulation test if that test was conducted.

6.3.3 Data Reporting for the Steam Jet Test

All observations that resulted from the inspection of the test injectors are to be recorded on the data-reporting sheet in Table 15, with photographs taken. All photographs are to be attached to the data-reporting sheets. The pretest and post-test parameter values and the associated parameter deviations that were computed for Q_S, Q_{VF}, IR, R, and tip leakage shall be recorded on the data-reporting sheet. The Q_S and Q_{VF} deviations are to be recorded as percentage changes. The parameter deviations for Q_S, Q_{VF}, IR, R, and tip leakage resulting from the 300-second steam jet test are also to be reported on the data-reporting sheet if that optional test was performed. Indicate in the comments section of the data-reporting sheet whether a 15-second test or a 300-second test, or both, were conducted.

Table 15 - External fluid compatibility tests: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for External Fluid Compatibility Tests			
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			
Additional information			
Part 3: Test Conditions			
Test being reported (check one): □ External fluids □ Water jet □ Steam jet	If an external fluid test, designate the test fluid here: □ 10 min Test □ 400 min Test □ 15 sec Test □ 300 sec Test		
Additional information			
Part 4: Description and Comments on Equipment or Test Deviations			
Test equipment details and test any deviations			
Part 5: Test Results			
Note: If reporting on an external fluid test, use a copy of this data-reporting sheet for each test fluid.			
Performance Parameter	**Pretest**	**Post-Test**	**Change**
Inj #1 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Visual observations			
Inj #2 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Visual observations			
Inj #3 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			

Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Visual observations			
Inj #4 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Visual observations			
Inj #5 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Visual observations			
Overall Test Comments			
Record test observations and attach photographs below			

6.4 Temperature Cycling Test

The temperature cycle test is designed to evaluate and quantify any changes in injector performance that result from exposure to extreme temperature cycle test conditions.

6.4.1 Procedure for the Temperature Cycling Test

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2. In addition, each of the test injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any temperature cycling testing.

b. The temperature cycling test shall be conducted on a test bench that is capable of operating the injectors inside a thermal chamber at elevated temperatures. The test cycle is illustrated in Figure 18. The injectors are to be operational (injecting fuel) only during segments E through G of the cycle, not during A to E.

c. The test fuel is to be ASTM Reference Fuel C with 10% by volume reagent-grade ethanol, with a fresh supply of test fuel used at the start of every test. The fuel pressure for the test is to be set to P_{50}, with an IPW of 1.20 ms and a period (P) of 7.0 ms.

d. The designated test cycle shown in Figure 18 is to be repeated for a total of 175 cycles.

e. Following the completion of 175 designated temperature cycles, each of the test injectors shall be retested for Q_S, Q_{VF}, IR, R, and tip leakage.

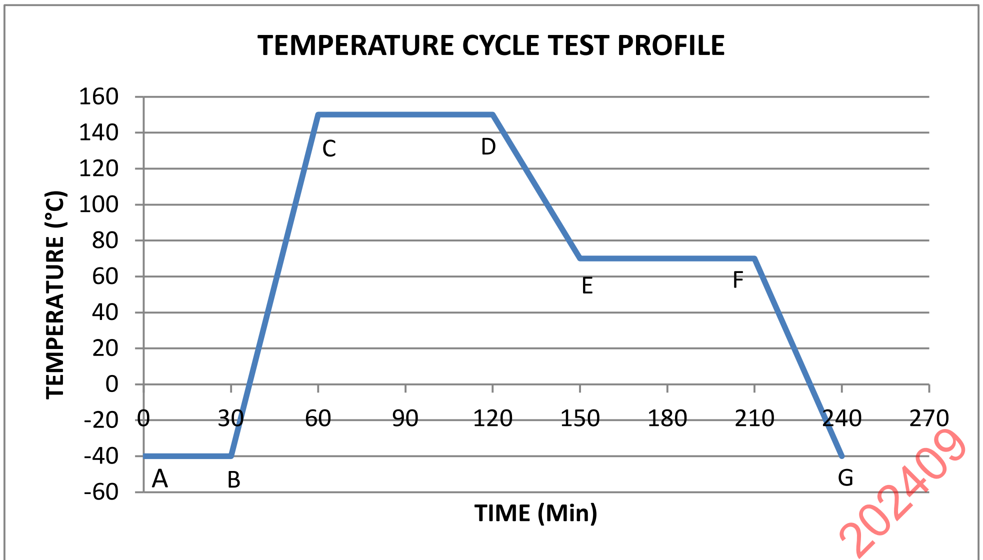

Figure 18 - Temperature cycle test profile

6.4.2 Data Reduction and Analysis for the Temperature Cycling Test

For each test injector, the changes in Q_S, Q_{VF}, IR, R, and tip leakage from the start to the completion of 175 cycles of the temperature cycling test shall be computed. The changes in Q_S and Q_{VF} shall each be computed as a percentage.

6.4.3 Data Reporting for the Temperature Cycling Test

For each test injector, the pretest and post-test parameter values of Q_S, Q_{VF}, IR, R, and tip leakage and the associated parameter deviations from the start to the completion of the temperature cycling test shall be recorded on the data-reporting sheet in Table 16. The deviations in Q_S and Q_{VF} for each parameter shall each be recorded on the data-reporting sheet as a percentage change.

6.5 Hot Static Soak Test

This procedure is designed to evaluate and quantify any changes in injector performance that result from a prolonged exposure to an extreme high-temperature condition.

6.5.1 Procedure for the Hot Static Soak Test

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2. In addition, each of the test injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any hot static soak testing.

b. Drain and dry each test injector with dry compressed air or nitrogen following the initial measurements for Q_S, Q_{VF}, IR, R, and tip leakage.

c. Insert the test injectors into a heated, stabilized air environment having a temperature of 150 °C ± 2 °C. The duration of this high-temperature exposure is to be 720 hours. In this hot static soak test, the injectors are dry and are not operated.

d. Following the 720-hour exposure, allow the injectors to cool to room temperature and remeasure each one for Q_S, Q_{VF}, IR, R, and tip leakage.

6.5.2 Data Reduction and Analysis for the Hot Static Soak Test

For each test injector, the changes in Q_S, Q_{VF}, IR, R, and tip leakage from the start to the completion of 720 hours of high-temperature exposure shall be computed. The changes in Q_S and Q_{VF} shall each be computed as a percentage.

6.5.3 Data Reporting for the Hot Static Soak Test

For each test injector, the pretest and post-test parameter values of Q_S, Q_{VF}, IR, R, and tip leakage and the associated parameter deviations from the start to the completion of 720 hours of high-temperature exposure shall be recorded on the data-reporting sheet in Table 16. The computed deviations in Q_S and Q_{VF} shall each be recorded as a percentage change.

6.6 Cold Static Soak Test

This procedure is designed to evaluate any changes in injector performance that result from a prolonged exposure to an extreme low-temperature condition.

6.6.1 Procedure for the Cold Static Soak Test

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2. In addition, each of the test injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any cold static soak testing.

b. Drain and dry each test injector with dry compressed air or nitrogen following the initial measurements for Q_S, Q_{VF}, IR, R, and tip leakage.

c. Insert the test injectors into a cold, stabilized air environment having a temperature of -40 °C ± 2 °C. The duration of this cold-temperature exposure is to be 720 hours. In this cold static soak test, the injectors are dry and are not operated.

d. Following the 720-hour exposure, allow the injectors to warm to room temperature and remeasure each one for Q_S, Q_{VF}, IR, R, and tip leakage.

6.6.2 Data Reduction and Analysis for the Cold Static Soak Test

For each test injector, the changes in Q_S, Q_{VF}, IR, R, and tip leakage from the start to the completion of 720 hours of cold-temperature exposure shall be computed. The deviations in Q_s and Q_{VF} shall each be computed as a percentage change.

6.6.3 Data Reporting for the Cold Static Soak Test

For each test injector, the pretest and post-test parameter values of Q_S, Q_{VF}, IR, R, and tip leakage and the associated parameter deviations from the start to the completion of 720 hours of cold-temperature exposure shall be recorded on the data-reporting sheet in Table 16. The computed deviations in Q_S and Q_{VF} shall each be recorded as a percentage change.

6.7 Thermal Shock Test

This procedure is designed to evaluate any changes in injector performance that result from a series of extreme thermal shocks that occur when the injector is not operating. This test can be performed with commercially available automatic thermal shock equipment or by manually moving the test parts between two environmental chambers in close proximity. The chambers must be of the forced air type to ensure rapid temperate transition of the test parts. The transition time must be verified through temperature measurements on the first and final cycle. This thermal shock test is performed dry, with no test fluid or injector actuation.

6.7.1 Procedure for the Thermal Shock Test

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2. In addition, each of the test injectors shall be tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any thermal shock testing.

b. Drain and dry each test injector with dry compressed air or nitrogen following the initial measurements for Q_S, Q_{VF}, IR, R, and tip leakage.

c. Set up the chamber(s) for 130 °C ± 2 °C and -40 °C ± 2 °C. The cycle starts in the cold chamber and shall soak for 30 minutes. The transfer between the cold to hot condition shall take place in under 3 minutes. The hot soak period is 30 minutes starting after the transition period. The hot to cold transition shall then be completed in under 3 minutes. This transition is the end of a single cycle. The transition time is confirmed by measuring the airstream temperature within 300 mm of the test parts. The air temperature shall achieve at least 90% of the temperature transition within 3 minutes (total transition is 170 °C, so the 90% transition would be when the temperature reaches 113 °C or -23 °C, depending on transition direction). The air temperature shall also reach the ±2 °C steady state chamber temperature tolerance within 15 minutes. The temperature transition data shall be taken with precision data recording equipment at one sample per second or faster. The temperature transition data shall be confirmed for the first and last full cycles with the full test load in place. In the case of using two separate chambers, the temperature probe shall be moved with the test parts from one chamber to another, and the physical transfer shall be done within 3 minutes (from the door on the first chamber being opened to the door on the second chamber being closed). See Figure 19 for a sample illustration of typical temperature confirmation data.

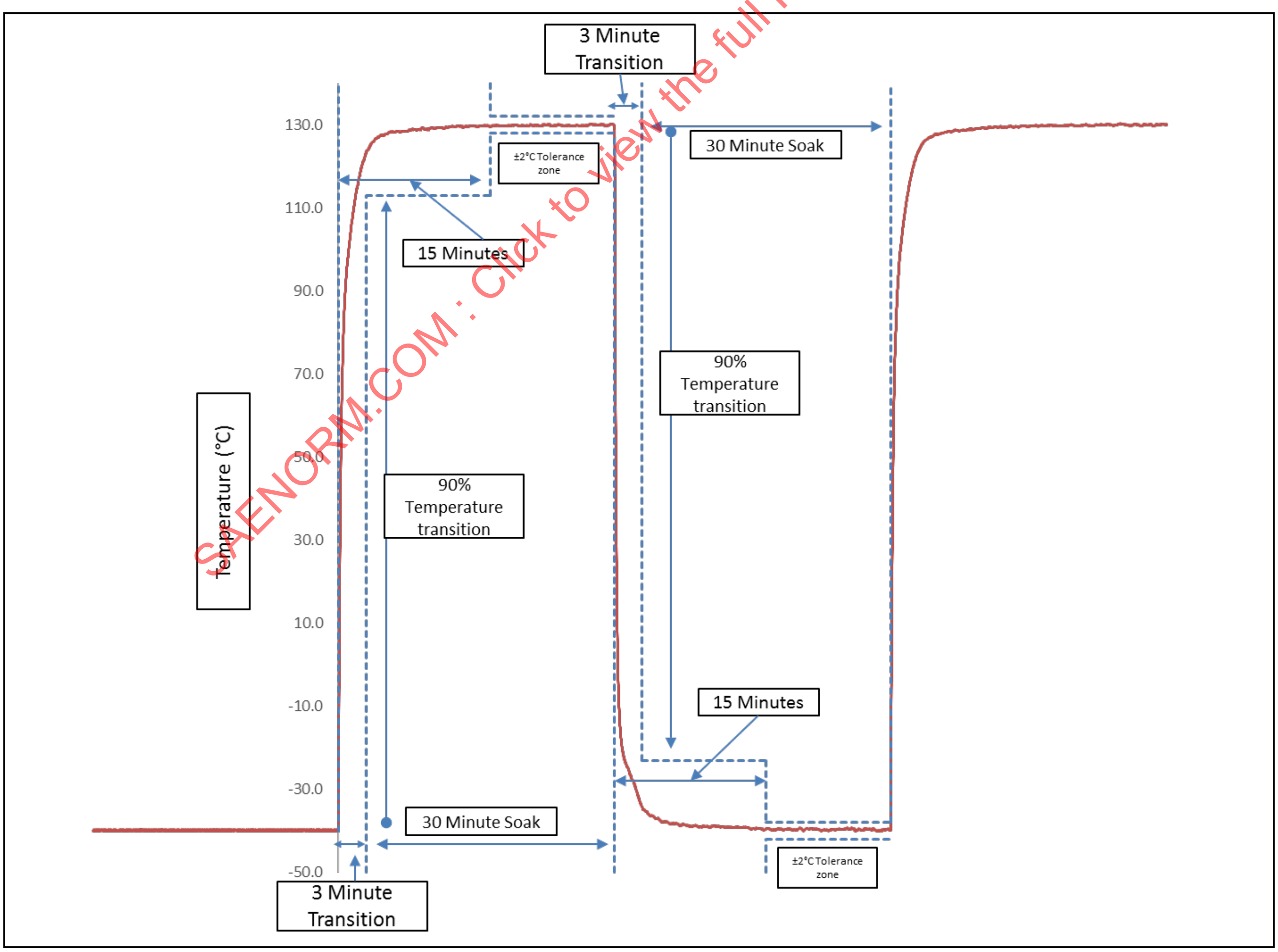

Figure 19 - Illustration of typical temperature confirmation data

d. Repeat this thermal shock cycle for a total number of 200 cycles.

e. Following the completion of the 200 cycles, allow the injectors to return to room temperature and remeasure each one for Q_S, Q_{VF}, IR, R, and tip leakage.

6.7.2 Data Reduction and Analysis for the Thermal Shock Test

For each test injector, the changes in Q_S, Q_{VF}, IR, R, and tip leakage from the start to the completion of 200 cycles of thermal shock shall be computed. The deviations in Q_S and Q_{VF} shall each be computed as a percentage change.

6.7.3 Data Reporting for the Thermal Shock Test

For each test injector, the pretest and post-test parameter values of Q_S, Q_{VF}, IR, R, and tip leakage and the associated parameter deviations from the start to the completion of 200 cycles of thermal shock shall be recorded on the data-reporting sheet in Table 16. The computed deviations in Q_S and Q_{VF} shall each be recorded as a percentage change. Temperature confirmation data from the first and final full cycle shall be appended to the data-reporting sheet.

Table 16 - Thermal environmental tests: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for Temperature Cycle, Hot and Cold Static Soak, and Thermal Shock			
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	
Additional information	

Part 3: Test Conditions		
Test Being Reported	**Tested Temperatures**	**Standard Test Temperatures**
□ Temperature cycle □ Hot static soak □ Cold static soak □ Thermal shock		□ See profile in test procedures □ 150 °C ± 2 °C □ -40 °C ± 2 °C □ -40 °C ± 2 °C to 130 °C ± 2 °C
Additional information		

Part 4: Description and Comments on Equipment or Test Deviations	
Test equipment details	
Test deviations	

Part 5: Test Results for Temperature Cycle, Hot and Cold Static Soak, and Thermal Shock			
Performance Parameter	**Pretest Value**	**Post-Test Value**	**Change**
Inj #1 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Observations			
Inj #2 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			

Observations			
Inj #3 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Observations			
Inj #4 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Observations			
Inj #5 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Observations			
Inj #6 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Observations			
Inj #7 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip Leakage (mm^3/min)			
Observations			
Inj #8 (SN):			
Q_{VF} (mg/pulse)			%
Q_S (g/)			%
Insulation resistance IR (ohms)			
Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Observations			
Record test observations and attach photographs below			

6.8 Salt-Spray External Cyclic Corrosion Test

This test procedure is utilized to determine the degree to which the test injector can withstand the effects of extensive external salt corrosion. This type of corrosion is likely to occur in geographical locations that employ road salt to melt winter ice and snow coatings and also on seaside roadways. The main source for the test equipment details, such as the spray nozzles, corrosion coupons, and the corrosion test chamber, is ASTM B117-19. The salt-spray external cyclic corrosion test consists of cycles of ambient environment salt-spray mist combined with a high-humidity and high-temperature drying interval for a set of new test injectors of the same make and model. One 24-hour period is considered a cycle, assuming the mass loss of steel test coupons is within specified limits. The test duration is a total of 50 cycles, with the test monitored for sufficient corrosion potential by means of the measured mass loss of standardized steel corrosion coupons. The mass loss of the coupons is ideally to be linear with test time throughout the test, and this can be monitored and adjusted if required. A visual inspection of the external surfaces of the injectors is conducted after ten cycles, and both an inspection and a retesting of the injector performance parameters is conducted after the completion of the test at 50 cycles. It should be noted that this test procedure differs from that in ASTM B117-19. This SAE J2713 test procedure is a thermal, cyclic corrosion test, whereas the test procedure indicated in ASTM B117-19 is not.

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

The cyclic corrosion test consists of cycles of ambient temperature, salt mist, high humidity, and elevated drying-temperature conditions. The test chamber for conducting this test shall be capable (at a minimum) of providing the high humidity (up to 100% RH) and the elevated drying temperature (60 °C ± 2 °C at <30% RH) required to run the cyclic corrosion test for 24 hours per day, preferably in an automated cycle. A tank, pump, and specific spray nozzles for delivering the salt spray are also required. Valuable information on the design of these equipment items may be found in ASTM B117-19. However, any chamber and nozzle design that achieves the proper corrosion rate is permissible. Although the salt mixture mist can be applied manually, it is preferred that the corrosion chamber be capable of automatically applying a controlled and timed salt spray to thoroughly wet the parts and rinse away any previous salt accumulation in a cyclic manner. The automated timings of the salt-spray injection period, the heat-and-humidity period, and the high-temperature-drying period within a cycle shall also conform to the designated test procedure that is detailed in the subsections below.

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

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

6.8.2 Procedure for the Salt-Spray External Cyclic Corrosion Test

a. A set of five (minimum) new injectors of the same make and model from serial production shall 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. Preproduction injectors may be utilized in this test without deviation if that information is clearly listed in the comments section of the data-reporting sheet. Precondition each injector to be tested according to the procedure in 4.2. Photograph each of the five injectors prior to any testing.

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

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

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

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

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

g. Expose the samples to the salt-spray fog in the shed for a 24-hour cycle. A test cycle consists of three phases, each 8 hours in duration. The three phases of the test, in the order to be performed, are:

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

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

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

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

i. The ramp time between phases 1 and 2 is to be 1 hour. The ramp time between phases 2 and 3 is to be 3 hours. The ramp time between phase 3 and the next repeat cycle of phase 1 is to be 2 hours. The ramp time is included at the beginning of that cycle's 8-hour time period. Periodically inspect the samples and the overall operation of the spray chamber as required in ASTM B117-19. The opening of the chamber shall be limited to the frequency necessary to carry out the operations. Inspections should not be made more than twice a day for a total of 15 minutes. The positions of the samples may be varied during the inspection period if required.

j. Following the first cycle, repeat the test for additional cycles until ten cycles have been completed. As indicated in ASTM B117-19 on the procedure regarding coupons, remove two coupons at the end of the tenth cycle and sandblast the corrosion by-product off of both until the surface is again bare. After cleaning with either alcohol or acetone and then drying, weigh each of the two coupons on a precision scale and compute the decrease from the original mass. The mass loss should ideally be approximately linear throughout the test, with a total mass loss per coupon after 50 cycles of 4161 to 4825 mg for a 1.59-mm-thick coupon and 4573 to 5230 mg for a 3.18-mm-thick coupon. Assuming a linear mass loss, each 1.59-mm-thick coupon should be expected to lose 832 to 965 mg during each ten cycles of the test, and each 3.18-mm-thick coupon should lose 915 to 1046 mg in that same test period. If this mass loss is found to be either too high or low during each ten-cycle increment, then the spray volume of the salt solution should be adjusted accordingly.

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

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

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

n. For each test injector, both a visual examination and a performance test are to be conducted for Q_s, Q_{VF}, IR, R, and tip leakage after the 50th and final cycle.

6.8.3 Data Reduction and Analysis for the Salt-Spray External Cyclic Corrosion Test

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

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

For each test injector, the post-test (after 50 cycles) parameter deviations of Q_S, Q_{VF}, IR, R, and tip leakage from the measured pretest values are to be computed. The Q_S and Q_{VF} deviations are to be computed as percentage changes.

6.8.4 Data Reporting for the Salt-Spray External Cyclic Corrosion Test

For each test injector, the pretest and post-test parameter values of Q_S, Q_{VF}, IR, R, and tip leakage and the associated parameter deviations from the measured pretest values are to be recorded on the data-reporting sheet in Table 17. The Q_S and Q_{VF} deviations are to be recorded as percentage changes. Use additional blank copies of Pages 2 and 3 of the data-reporting sheets if more than five injectors are tested.

Table 17 - Salt-spray external cyclic corrosion test: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for the Salt-Spray External Cyclic Corrosion Test			**Page 1 of 3**
Part 1: General Test Information			
Test name or log		Date of test	
Name of operator		Time of test	
File name of data archive		Location of test	
Additional information			
Part 2: Information on Injector and Injector Driver Module			
Injector manufacturer and design type			
Injector description			
Injector part number			
Additional information			
Part 3: Test Conditions	**Specific Test Conditions**	**Standard Test Conditions**	
Salt solution pH		6 to 8	
Ambient temperature (°C)		Phase 1: 25 °C ± 3.0 °C Phase 2: 49 °C ± 3.0 °C Phase 3: 60 °C ± 3.0 °C	
Relative humidity (%RH)		Phase 1: 40 to 50%RH Phase 2: 95 to 100%RH Phase 3: <30%RH	
Additional information			
Part 4: Description and Comments on Equipment or Test Deviations			
Test equipment details			

Test deviations	

Part 5-A: Test Results for Test Coupon Mass in the Functional Salt-Spray External Corrosion Test			
Sample Coupon Tested	Initial Mass (mg)	Final Mass (mg)	Mass Loss (mg)
1		(mg) After 10 cycles	
2		(mg) After 10 cycles	
3		(mg) After 20 cycles	
4		(mg) After 20 cycles	
5		(mg) After 30 cycles	
6		(mg) After 30 cycles	
7		(mg) After 40 cycles	
8		(mg) After 40 cycles	
9		(mg) After 50 cycles	
10		(mg) After 50 cycles	
Total mass loss for all ten coupons after all 50 cycles (g):			

Part 5-B: Test Results for Performance Parameters in the Salt-Spray External Cyclic Corrosion Test			Page 2 of 3
Performance Parameter			
Inj #1 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Inj #2 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Inj #3 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Inj #4 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/ min)			
Inj #5 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Inj #6 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Inj #7 (SN):	Pretest	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			

R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Inj #8 (SN):	Pre-Test	Post 50 Cycles	Change
Q_{VF} (mg/pulse)			%
Q_S (g/s)			%
IR - Insulation resistance (ohms)			
R - Coil resistance R (ohms)			
Tip leakage (mm^3/min)			
Comments on any of the performance test results			

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

7. PHYSICAL TESTS

7.1 Overview of Physical Tests

The purpose of physically testing GDI injectors is to measure the changes, if any, in a number of key injector performance parameters after being subjected to these defined static and non-static forces. These physical tests consist of two main classes, which are static mechanical loading tests and operational (non-static) physical tests. Fuel injectors are subjected to various mechanical loads during manufacturing, testing, handling, and installation in the vehicle fuel system. During actual vehicle service, the injector is also subjected to various non-static shock and vibrational loads. These loads may occur while installed on the engine or during injector removal and cleaning. The injector may also be inadvertently subjected to various degrees of overpressure, for which it must maintain body integrity.

7.2 Static Mechanical Testing

7.2.1 Overview of Static Mechanical Testing

During manufacture, installation, and servicing, fuel injectors are subjected to various static mechanical forces and moments. These loads take the form of axial compression, axial tension, bending moments, and applied torsional loads, as illustrated in Figure 20. The purpose of static mechanical testing is to ensure that the injector can be subjected to a series of defined loadings and still perform within acceptable limits that are defined by the OEM and the end user.

7.2.2 Test Fixture Mounting Guidelines

Axial load, bending moment, and torsional loads are applied to the injector during installation and removal to overcome the resistance of seals used for the purpose of sealing, thermal and mechanical isolation, and compensation for part variations. They are also subjected to loads resulting from mounting the fuel rail and/or retaining the injector.

On most designs, the upper half of the injector contains the electrical connector and the lower half the fuel metering section. The loads are usually applied to the injector by pushing and twisting the upper half relative to the lower half. One fixture design will not accommodate all injectors because of the variety of injector designs and mounting methods in use. The fixture must take into account the specific injector design and application. Therefore, the loads and fixtures used may deviate from those recommended in the following sections.

7.2.3 Test Conditions for Physical Tests

All tests are to be conducted at a room and injector body temperature of 21.0 °C ± 2.0 °C.

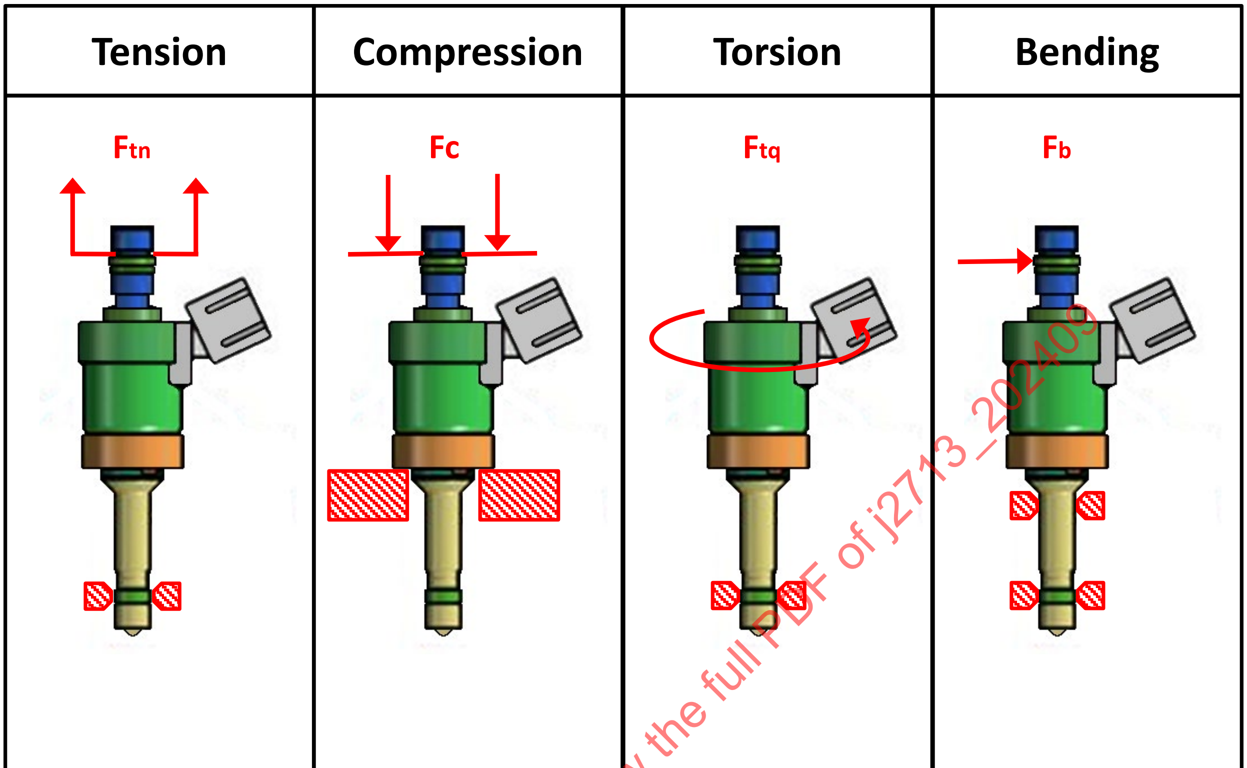

Figure 20 - Mechanical loading modes for physical testing

7.2.4 Axial Load Tension Test

7.2.4.1 Axial Load Tension Test Procedure (Related to Injector Removal)

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2 and then tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any static mechanical tests.

b. Each test injector shall be drained of any test fluid and shall have the fuel inlet port open and the tip uncapped. The electrical connector is not to be installed. Each test injector shall be mounted in a suitable fixture with the body fixed according to the appropriate diagram in Figure 20.

c. A tension of 220 N ± 10 N shall be applied to the upper housing via the O-ring groove for 15 minutes along the longitudinal axis of the injector.

d. Following the axial load tension test, retest each injector to obtain the post-test values of Q_S, Q_{VF}, IR, R, and tip leakage.

7.2.4.2 Data Reduction and Analysis for Axial Load Tension Test

Inspect each test injector under a microscope and note any cracks or visible plastic deformation on the connector. Also, for each injector, compute the percentage changes in Q_S and Q_{VF} and the change in R, IR, and tip leakage.

7.2.4.3 Data Reporting for Axial Load Tension Test

On the data-reporting sheet in Table 18, record the values of Q_S, Q_{VF}, IR, R, and tip leakage that were measured for each test injector both before and after the test. Record the percentage changes in Q_S and Q_{VF} and the changes in R, IR, and tip leakage for each injector. Also, record observations of any cracks or visible plastic deformations that occurred during the test, plus any other relevant observations of the effects of the tests. Use an extra blank copy of Page 2 of the data-reporting sheet for each injector.

7.2.5 Axial Load Compression Test

7.2.5.1 Axial Load Compression Test Procedure (Related to Injector Installation)

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2 and then tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any static mechanical tests.

b. Each test injector shall be drained of any test fluid and shall have the injector inlet port open and the inlet tip uncapped. The electrical connector is not to be installed. Each test injector shall be mounted in a suitable fixture with the body fixed according to the appropriate diagram in Figure 20. The injector shall be resting on a fixture similar to the cylinder head of the application, with the tip constrained accordingly.

c. A compressive load of 3500 N ± 10 N shall be applied to the upper housing via the O-ring groove for 15 minutes along the longitudinal axis of the injector.

d. Following the axial load compression test, retest each injector to obtain the post-test values of Q_S, Q_{VF}, IR, R, and tip leakage.

7.2.5.2 Data Reduction and Analysis for Axial Load Compression Test

Inspect each test injector under a microscope and note any cracks or visible plastic deformation on the connector. Also, for each injector, compute the percentage changes in Q_S and Q_{VF} and the change in R, IR, and tip leakage.

7.2.5.3 Data Reporting for Axial Compression Tension Test

On the data-reporting sheet in Table 18, record the values of Q_S, Q_{VF}, IR, R, and tip leakage that were measured for each test injector both before and after the test. Record the percentage changes in Q_S and Q_{VF} and the changes in R, IR, and tip leakage for each injector. Also, record observations of any cracks or visible plastic deformations that occurred during the test, plus any other relevant observations of the effects of the tests. Use an extra blank copy of Page 2 of the data-reporting sheet for each injector.

7.2.6 Torsional Moment Test

7.2.6.1 Torsional Moment Test Procedure

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2 and then tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any static mechanical tests.

b. Each test injector to be tested shall be drained of any test fluid and shall have the injector fuel inlet port open and the tip uncapped. The electrical connector is not to be installed. Each test injector shall be mounted in a suitable fixture with the body fixed according to the appropriate diagram in Figure 20.

c. A torsional moment of 4.5 Nm ± 0.1 Nm shall be applied to the connector housing using a flat clamp (or by hand). This torsional moment shall be applied for a duration of 5 seconds about the longitudinal axis of the injector.

d. Following the torsional moment test, retest each injector to obtain the post-test values of Q_S, Q_{VF}, IR, R, and tip leakage.

7.2.6.2 Data Reduction and Analysis for Torsional Moment Test

Inspect each test injector under a microscope and note any cracks or visible plastic deformation on the connector. Also, for each injector, compute the percentage changes in Q_S and Q_{VF} and the change in R, IR, and tip leakage

7.2.6.3 Data Reporting for Torsional Moment Test

On the data-reporting sheet in Table 18, record the values of Q_S, Q_{VF}, IR, R, and tip leakage that were measured for each test injector both before and after the test. Record the percentage changes in Q_S and Q_{VF} and the changes in R, IR, and tip leakage for each injector. Also, record observations of any cracks or visible plastic deformations that occurred during the test, plus any other relevant observations of the effects of the tests. Use an extra blank copy of Page 2 of the data-reporting sheet for each injector.

7.2.7 Bending Moment Test

7.2.7.1 Bending Moment Test Procedure

a. A minimum set of five new, identical injectors from serial production shall be tested. More injectors can be optionally tested if required. 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. Each of the test injectors shall be preconditioned as per the procedures described in 4.2 and then tested for Q_S, Q_{VF}, IR, R, and tip leakage prior to any static mechanical tests.

b. Each test injector to be tested shall be drained of any test fluid and shall have the injector fuel inlet port open and the tip uncapped. The electrical connector is not to be installed. Each test injector shall be mounted in a suitable fixture with the body fixed according to the appropriate diagram in Figure 20.

c. Apply a load such that a bending moment of 30 Nm ± 0.5 Nm is applied at the injector groove for 30 seconds while the injector is restrained as it would be by the cylinder head. In order to achieve a bending moment of 30 Nm, the magnitude of the load applied to the injector groove will vary with the length of the injector. A shorter injector will require a higher load than a longer injector.

d. Following the bending moment test, retest each injector to obtain the post-test values of Q_S, Q_{VF}, IR, R, and tip leakage.

7.2.7.2 Data Reduction and Analysis for Torsional Moment Test

Inspect each test injector under a microscope and note any cracks or visible plastic deformation on the connector. Also, for each injector, compute the percentage changes in Q_S and Q_{VF} and the change in R, IR, and tip leakage.

7.2.7.3 Data Reporting for Torsional Moment Test

On the data-reporting sheet in Table 18, record the values of Q_S, Q_{VF}, IR, R, and tip leakage that were measured for each test injector both before and after the test. Record the percentage changes in Q_S and Q_{VF} and the changes in R, IR, and tip leakage for each injector. Also, record observations of any cracks or visible plastic deformations that occurred during the test, plus any other relevant observations of the effects of the tests. Use an extra blank copy of Page 2 of the data-reporting sheet for each injector.

7.3 Operational Physical Tests

The second class of physical tests deals with the vibration, mechanical shock, and overpressure that a GDI injector may be subjected to during an operating lifetime. This class of tests addresses the further significant stresses that can be applied to a GDI injector during a normal lifetime of operation on an engine. Engine vibration can be severe, with significant g-forces, particularly for a GDI injector that is mounted directly on the cylinder head. In addition, fuel overpressure may possibly occur due to a system malfunction, and mechanical shock can occur inadvertently due to dropping the injector or striking it with metal tools.

7.3.1 Overview of Operational Physical Tests

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

7.3.2 Vibration Test

7.3.2.1 Overview of the Vibration Test

The vibration test methodology and durations shall follow the ISO 16750-3 standard for engine-mounted components. The vibration schedule is to be sine-on-random with the frequency controlled over the range of 5 to 2000 Hz. The sinusoidal tone portion of the test should also follow Table 1 of the ISO 16750-3 standard, which is for components mounted directly on the engine of passenger vehicles. The combined test schedule should follow Table 2 (sine spectrum) and Table 3 (random spectrum) in ISO 16750-3. If an application-specific vibration schedule is available, this may be substituted without deviation for the ISO 16750-3 sine-on-random profiles if it is clearly noted on the data-reporting sheet. Any deviations from these protocols shall be reported on the data-reporting sheet. The vibration test may be optionally accelerated per the random vibration practices described in MIL-STD-810D if clearly noted in the comments section of the data-reporting sheet.

7.3.2.2 Procedure for the Vibration Test

The vibration test fixture should duplicate the application mounting and must permit the collection of any fluid lost from the injector tip. If both mechanical shock and vibration tests are to be conducted, it is recommended to run the vibration and mechanical shock tests as combined sequential tests on each of the three individual axes. This would be longitudinal vibration followed by longitudinal mechanical shock, then repeating for the lateral axis, and then for the vertical axis.

a. A minimum test set of five new injectors of the same make and model from serial production shall 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. Preproduction injectors may be used in this test without deviation if this is clearly noted in the comments section of the data-reporting sheet. The injectors shall be preconditioned as described in 4.2.

b. Prior to any vibration testing or combined vibration and shock testing, measure the key performance parameters of Q_S, Q_{VF}, R, IR, and tip leakage according to the procedures outlined in the appropriate subsections of this document.

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

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

e. Using a controlled vibration test facility, vibrate the injector in each of the three axes (first longitudinal, then lateral, and then vertical). The vibration test schedule for the sine and random vibrations shall be controlled over the frequency range of 5 to 2000 Hz according to ISO 16750-3 or customized to the application-specific vibration schedule as mentioned earlier. The recommended test duration is a minimum of 22 hours per axis.

f. If a combined vibration-shock test is being conducted, then proceed to 7.3.3.2 (c) to conduct the shock test, and then return to 7.3.3.2 (g) after the shock test is completed.

g. Following the vibration test (or the combined vibration-shock test), inspect the injector body and remeasure the key performance parameters of Q_S, Q_{VF}, R, IR, and tip leakage.

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

7.3.2.3 Data Reduction and Analysis for the Vibration Test

For each of the five (or optionally more) test injectors, compute the deviations in Q_S, Q_{VF}, R, IR, and tip leakage from the pretest values to the post-test values. The deviations in Q_S and Q_{VF} shall be computed as a percentage change.

7.3.2.4 Data Reporting for the Vibration Test

For each of the five or more test injectors, record the pretest and post-test values, and their deviations, for Q_S, Q_{VF}, R, IR, and tip leakage on the data-reporting sheet in Table 18. The deviations in Q_S and Q_{VF} shall be reported as a percentage change. Use a different Page 2 of the data-reporting sheet for each of the test injectors, and note on that page the serial number of the injector being reported.

7.3.3 Mechanical Shock Test

7.3.3.1 Overview of the Mechanical Shock Test

The mechanical shock test subjects the injector to sudden loads that may be expected to occur during a lifetime of operation in the field. The injector is expected to perform as designed after experiencing a defined series of shock loadings that could occur, such as those that may result from dropping the injector on a concrete floor during a cleaning operation. This test subjects the injector to that defined series of shock loadings and ascertains the amount of change, if any, in a set of key performance parameters.

7.3.3.2 Procedure for the Mechanical Shock Test

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

a. A minimum test set of five new injectors of the same make and model from serial production shall 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. Preproduction injectors may be used in this test without deviation if this is clearly noted in the comments section of the data-reporting sheet. The injectors shall be preconditioned as described in 4.2.

b. Prior to any mechanical shock or combined vibration-shock testing, measure the key performance parameters of Q_S, Q_{VF}, R, IR, and tip leakage according to the procedures outlined in the appropriate subsections of this document.

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

d. Mount the injector in a vibration-shock test fixture that has an injector mounting that is representative of the application. The accelerometers on this fixture should be placed at the same location as was utilized for any vehicle data acquisition.

e. Perform impacts that provide a series of 50-g acceleration loads, with each impact load lasting for a duration of 11 to 14 ms. Perform this three times with the injector in the vertical position (valve tip pointing downward), three times in the vertical position (valve tip pointing upward), three times with the injector in the horizontal position (the connector pointing up), three times with the injector in the horizontal position (the connector pointing down), three times with the injector horizontal (the connector pointing to the left), and three times with the injector horizontal (the connector pointing to the right).

f. Following the mechanical shock test or the combined vibration-shock test, remeasure the key performance parameters of Q_S, Q_{VF}, R, IR, and tip leakage.

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

7.3.3.3 Data Reduction and Analysis for the Mechanical Shock Test

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

7.3.3.4 Data Reporting for the Mechanical Shock Test

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

7.3.4 Proof-Pressure Test

7.3.4.1 Overview of the Proof-Pressure Test

The proof pressure is an elevated level of fuel pressure that the fuel injector may be subjected to and for which the injector will operate properly once a lower operating fuel pressure is reestablished. The fuel injector is not expected to function normally while at the proof pressure but shall function properly after exposure to this pressure and the subsequent relaxation of this pressure. The objective of this test is to ascertain the level of permanent change in selected key performance parameters that results from the application of the proof pressure. The proof test pressure is P_{200}. Another reason for performing the proof-pressure test is to verify that the fuel injector body is capable of withstanding the specified proof pressure at a temperature of 21.0 °C ± 2.0 °C for 5 minutes without structural failure, internal damage, or external visual leakage.

7.3.4.2 Procedure for the Proof-Pressure Test

a. A minimum test set of five new injectors of the same make and model from serial production shall 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. Preproduction injectors may be used in this test without deviation if this is clearly noted in the comments section of the data-reporting sheet. The injectors shall be preconditioned as described in 4.2.

b. Prior to any proof-pressure testing, measure the key performance parameters of Q_S, Q_{VF}, R, IR, and tip leakage according to the procedures outlined in the appropriate subsections of this document.

c. The injector to be tested shall be filled with the test fluid (Stoddard solvent at 21.0 °C ± 2.0 °C) and shall have the fuel inlet connected to a pressure vessel containing Stoddard solvent at 21.0 °C ± 2.0 °C that is pressurized by means of nitrogen gas acting on a bladder. The tip of the injector shall be capped. During this test, the injector is not operated as the electrical connector is not installed.

d. Mount the injector onto a fixture that is placed within a safe containment vessel. Next, gradually increase the nitrogen pressure on the bladder until the fluid pressure within the injector reaches P_{200}. Maintain that pressure level for 5 minutes. Observe and record any visible fluid leakage during that time period.

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

f. Following the proof-pressure test, remeasure the key performance parameters of Q_S, Q_{VF}, R, IR, and tip leakage for the test injector.

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

7.3.4.3 Data Reduction and Analysis for the Proof-Pressure Test

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

7.3.4.4 Data Reporting for the Proof-Pressure Test

For each of the five or more test injectors, record the pretest and post-test values and their deviations for Q_S, Q_{VF}, R, IR, and tip leakage on the data-reporting sheet in Table 18. The deviations in Q_S and Q_{VF} shall be reported as a percentage. Use a different Page 2 of the data-reporting sheet for each of the test injectors, and note on that page the serial number of the injector being reported.

7.3.5 Burst-Pressure Test

7.3.5.1 Overview of the Burst-Pressure Test

The objective of burst-pressure testing is to determine that the fuel injector is able to withstand an applied pressure of P_{300} without bursting or leaking. The fuel injector is not expected to function normally after exposure to this pressure level, but it should not exhibit a rupture or any external leakage of fuel. To facilitate leak detection during and following the test, the test fluid shall be doped with a dye tracer that fluoresces either wet or dry when exposed to an ultraviolet light.

7.3.5.2 Procedure for the Burst-Pressure Test

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

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

c. The injector to be tested shall be filled with the test fluid containing the dopant (Stoddard solvent at 21.0 °C ± 2.0 °C) and shall have the fuel inlet connected to a pressure vessel containing the same Stoddard solvent at 21.0 °C ± 2.0 °C that is pressurized by means of nitrogen gas acting on a bladder. The tip of the injector shall be capped. During this test, the injector is not operated as the electrical connector is not installed.

d. Mount the injector onto a fixture within a safe containment vessel that permits a visualization of the injector with an ultraviolet light. Gradually increase the nitrogen pressure on the bladder until the fluid pressure within the injector reaches P_{300}. Maintain that pressure level for 5 minutes.

e. During the 5-minute dwell at P_{300}, examine the entire body of the test injector with an ultraviolet light for evidence of any external leakage. After 5 minutes, reduce the pressure to P_{100} and continue the examination for any damage or external leakage.

f. After completing a thorough examination, remove all pressurization of the Stoddard solvent and remove the injector.

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

7.3.5.3 Data Reduction and Analysis for the Burst-Pressure Test

None required.

7.3.5.4 Data Reporting for the Burst-Pressure Test

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

Table 18 - GDI injector physical tests: data-reporting sheet

SAE J2713 - Data-Reporting Sheet for GDI Injector Physical Tests							**Page 1 of 2**
Part 1: General Test Information							
Test name or log			Date of test				
Name of operator			Time of test				
File name of data archive			Location of test				
Additional information							
Part 2: Information on GDI Injector and GDI Injector Driver Type							
Injector manufacturer							
Injector description							
Injector part number			(enter injector S/N on Page 2 of the datasheet)				
Injector driver type							
Part 3: Test Conditions	**Force and Moment Physical Test Types**			**Operational Physical Test Types**			
** Physical tests being reported (circle all those being reported)	Axial loading	Torsional loading	Bending moment	Vibration	Proof pressure	Shock	Burst pressure
Conditions for Physical Tests	**Specific Test Conditions**			**Standard Test Conditions**			
Ambient temperature (°C)				21 ± 2			
Ambient pressure (kPa)				100 ± 5			
Fluid temperature (°C)				21 ± 2			
Fluid pressure for burst testing				P_{300} ± 1.5%			
Fluid pressure for proof testing				P_{200} ± 1.5%			
Shock profile				50-g half-sine for 11-14 ms			
Vibration profile				Sine-on-random per ISO 16750-3			
Injector period (P) for flow testing before and after (ms)				10.0 ± 0.01			
Injection pulse width for flow testing before and after (ms)				0.5 ± 0.010			
Part 4: Description and Comments on Equipment or Test Deviations							
Comments and information							
Test deviations present							

Part 5: Specific Test Measurements for Physical Tests			**Page 2 of 2**
Use New Page 2 for Each Injector			
Injector serial number:		Injector in test series: Number of	
Axial Loading Test	Pretest Value	Post-Test Value	Deviation
Q_{VF} (mg/pulse)			%
Q_s (g/s)			%
R (ohms)			(Ohms)
IR (ohms)			(Ohms)
Tip leakage rate (mm³/min)			(mm³/min)
Torsional Moment Test	Pretest Value	Post-Test Value	Deviation
Q_{VF} (mg/pulse)			%
Q_s (g/s)			%
R (ohms)			(Ohms)
IR (ohms)			(Ohms)
Tip leakage rate (mm³/min)			(mm³/min)
Bending Moment Test	Pretest Value	Post-Test Value	Deviation
Q_{VF} (mg/pulse)			%

Q_s (g/s)			%
R (ohms)			(Ohms)
IR (ohms)			(Ohms)
Tip leakage rate (mm^3/min)			(mm^3/min)
Vibration Test	Pretest Value	Post-Test Value	Deviation
Q_{VF} (mg/pulse)			%
Q_s (g/s)			%
R (ohms)			(Ohms)
IR (ohms)			(Ohms)
Tip leakage rate (mm^3/min)			(mm^3/min)
Shock Test	Pretest Value	Post-Test Value	Deviation
Q_{VF} (mg/pulse)			%
Q_s (g/s)			%
R (ohms)			(Ohms)
IR (ohms)			(Ohms)
Tip leakage rate (mm^3/min)			(mm^3/min)
Proof Pressure Test	Pretest Value	Post-Test Value	Deviation
Q_{VF} (mg/pulse)			%
Q_s (g/s)			%
R (ohms)			(Ohms)
IR (ohms)			(Ohms)
Tip leakage rate (mm^3/min)			(mm^3/min)
Burst Pressure Test	Circle One	Circle One	
External leakage observed? (mm^3/min)	No leakage	Yes, leakage observed	Comment:
Additional Test Comments			
Additional information and test comments: Indicate the name of the test being commented upon			
Attachments and data plots	None required		

8. INJECTOR NOISE CHARACTERIZATION

8.1 Background on GDI Injector Noise Generation

Direct injection engines have higher noise levels than port fuel injection engines because the injector opening and closing events generate high mechanical and hydraulic forces due to the elevated operating fuel pressure. This noise is most noticeable during engine idle operation. In almost all types of GDI engines, the fuel injectors are relatively small in size and are inserted deep into the cylinder head, where they are hardly visible. Therefore, the resultant “injector noise” is mainly a result of the structure-borne and fluid-borne excitations caused by the injectors and not the noise radiated directly from the injectors.

The structure-borne excitations from the injector to its mating component in the engine can best be measured using a fast-response force transducer. This force exerted by the injector is responsible for exciting various structural resonances of the engine components, which then indirectly radiate as the airborne noise from the engine. Irrespective of whether the injector is directly mounted to the cylinder head or directly coupled to the fuel rail through a clamp, the force exerted by the injector to its mating interface is the same. Therefore, the procedure described in this recommended practice is based on the premise that the measurement of force using a force transducer between the injector housing and a rigid base is the critical measure for characterizing the structure-borne noise generated by an injector to the engine structure, irrespective of its transfer path.

The fluid pressure pulsations generated by the injector are responsible for exciting the fluid modes, also known as acoustic modes or cavity modes, of the fuel rail and fuel lines. Depending upon the construction of the flow passages inside the injector and the actuation of the injector needle, the pressure pulsations generated by the injector and transmitted to the fuel rail cavity will vary substantially. The measurement of fluid pressure using a pressure transducer at the inlet of the injector will be sufficient to characterize the fluid-borne excitations induced by the injector.