Gas-lift Valve Performance Testing

API RECOMMENDED PRACTICE 11V2
SECOND EDITION, MARCH 2001

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Upstream Segment

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Gas-lift Valve Performance Testing

0 Introduction

This Recommended Practice (RP) covers the test procedures for flow performance testing of wireline retrievable and tubing retrievable IPO (injection pressure operated), and PPO (production pressure operated) gas-lift valves. Injection pressure operated means that the largest force causing the ball and stem to move is supplied by injection pressure and production pressure is the major force for moving the ball and stem for PPO valves.

The 11V2 RP contains sections which:

a. Briefly describes each section (Section 1).
b. Provide Definitions and Abbreviations (Section 2).
c. Recommend dynamic test facility requirements (Section 3).
d. Recommend the test equipment and describe the test procedure necessary to determine bellows assembly load rate and maximum effective travel for a given valve (Section 4).
e. Describe the test procedure necessary to determine valve flow coefficients for the full range of stem travel (Section 5).
f. Describe two methods of obtaining the gas-lift valve performance curves (Section 6).
g. Recommend the number of tests required to develop a model or correlation to predict valve performance (Section 7).
h. Describe two methods that use the test data to predict performance at conditions other than those tested (Appendix A and B).
i. Describe a method for the analysis of probe test data obtained from Section 4 (Appendix C).
j. Describe a test procedure which yields the time constant of the test system described in Section 3 (Appendix D).

1 Scope

Test site recommendations (Section 3): This section outlines the equipment needed for testing valves to determine the following:

a. Valve flow coefficients (C_v).
b. Pressure drop ratio factor (X_t).
c. Gas-lift valve performance curves.

Gas-lift valve probe tests (Section 4): This test method is outlined for determining the stem travel as pressure is applied over the bellows area. The test results are combined with analysis (Appendix C) to allow the user to approximate the valve load rate over the range of expected practical application conditions. The test also defines the maximum effective valve stem travel.

Flow coefficient test procedure (Section 5): The test procedure recommends test methods required to determine the flow coefficient (C_v) as a function of stem travel. The test results, combined with analysis, allow the user to approximate the valve flow coefficient (C_v) and pressure drop ratio factor (X_t) over the range of expected practical application conditions.

Gas-lift valve performance test methods (Section 6): This test procedure lists the test methods recommended to measure valve performance (flow) for upstream and downstream pressures and other controlled conditions.

Use of test data (Section 7): This section recommends the number of tests which should be performed in order to acquire sufficient data to develop a model or correlation describing valve performance at conditions other than those tested. Reference is made to methods described in Appendices A and B.

Simplified flow performance model (Appendix A): This appendix describes a method of analysis of test data that will predict flow at conditions other than those tested. The model makes several simplifying assumptions concerning valve dynamics.

TUALP flow performance model (Appendix B): This appendix describes a method of analysis of test data that will predict flow at conditions other than those tested. The model was developed and is supported by the Tulsa University Artificial Lift Projects research program at the University of Tulsa.

Method to analyze probe test data (Appendix C): This appendix describes a mathematical method of analysis to determine loadrate and maximum effective travel when data is collected per Section 4.

Determination of test system time constant (Appendix D): This appendix gives the supporting explanation for the use of "ramp" functions in the test methods and describes how to determine a test systems time constant.

2 Definitions and Abbreviations

2.1 DEFINITIONS

2.1.1 A_b: Effective bellows area (in.^{2}) [cm^2].

2.1.2 A_p: Area based on the nominal port diameter (in.^{2}) [cm^2].

2.1.3 A_s: Area based on the diameter where the stem contacts the seat (in.^{2}) [cm^2].

2.1.4 B_{lr}: Bellows assembly load rate as per Section 4 (psi/in.) [kPa/cm].

2.1.5 C_v: Flow Coefficient as per Section 5.

2.1.6 dP: Differential pressure as defined in context (psi) [kPa].

2.1.7 dx: Distance stem has moved from seat (in.) [cm].

2.1.8 F_k: Specific heats factor equal to k/1.40.

2.1.9 ***H*:** A factor determined by the manufacturer to calculate the upstream test pressure for the Constant Injection Pressure Test

2.1.10 ***k*:** Ratio of specific heats of lift gas.

2.1.11 ***P*1:** Upstream gage pressure of test section (psig) [kPag].

2.1.12 ***P*2:** Downstream gage pressure of test section (psig) [kPag].

2.1.13 P_{vst}**:** Pressure required to achieve LST of GLV.

2.1.14 P_{iod}**:** Operating injection gage pressure at valve depth (psig) [kPag].

2.1.15 P_o**:** Upstream gage pressure for a constant downstream gage pressure and near zero gas flow rate (psig) [kPag].

2.1.16 P_{pd}**:** Flowing production gage pressure at valve depth (psig) [kPag].

2.1.17 P_{vc}**:** Measured or calculated upstream gage pressure when the downstream pressure is equal to the upstream pressure and near zero gas flow rate at 60°F (15.5°C) (psig) [kPag]. Referred to as Valve Closing Pressure at 60°F.

2.1.18 P_{vcT}**:** Measured or calculated upstream gage pressure when the downstream pressure is equal to the upstream pressure and near zero gas flow rate at a known temperature (psig) [kPag]. Referred to as Valve Closing Pressure at temperature.

2.1.19 P_{vo}**:** Measured or calculated gage pressure applied over the area A_b minus A_s required to initiate flow through a valve with zero gage pressure downstream at 60°F (15.5°C (psig) [kPag]. Referred to as Valve Opening Pressure at 60°F.

2.1.20 P_{voT}**:** Measured or calculated gage pressure applied over the area A_b minus A_s required to initiate flow through a valve with zero gage pressure downstream at a known temperature (psig) [kPag]. Referred to as Valve Opening Pressure at Temperature.

2.1.21 ***q*:** Measured flow rate in cubic feet per hour at SC (SCF/hr) [m^3/hr].

2.1.22 q_{gi}**:** Measured flow rate in thousands of cubic feet per day at SC (MSCFD) [SCMD].

2.1.23 S_g**:** Specific gravity of gas (Air = 1.0).

2.1.24 ***T*1:** Upstream gas temperature of test section (°F) [°C].

2.1.25 T_v**:** Temperature of valve at depth (°F) [°C].

2.1.26 ***x*:** Pressure ratio. The measured differential pressure across the test section divided by the absolute upstream pressure ($dP/(P1 + 14.7)$).

2.1.27 X_t**:** Pressure drop ratio factor. The largest pressure ratio (x) for a given upstream pressure at which a decrease in downstream pressure will not increase the flow rate. Critical flow occurs when F_k*X_t equals or exceeds the pressure ratio. Determined as per Section 5.

2.1.28 ***Y*:** Expansion factor.

2.1.29 ***Z*1:** Upstream compressibility factor.

2.2 ABBREVIATIONS

ASME	*American Society of Mechanical Engineers*
ANSI	*American National Standards Institute*
API	*American Petroleum Institute*
CIPT	*Constant injection pressure test*
CPPT	*Constant production pressure test*
DCV	*Downstream control valve*
ECV	*Equalizing control valve*
GLV	*Gas-lift valve*
GST	*Geometric Stem Travel for full opened condition*
IPO	*Injection pressure operated*
ISA	*Instrument Society of America*
LST	*Maximum effective stem travel from probe test*
MSCFD	*Thousands of standard cubic feet per day*
PPO	*Production pressure operated*
RP	*Recommended Practice*
SC	*Standard Conditions assumed to be 14.73 psia (101 kPa) and 60°F (15.5°C)*
SCFD	*Standard cubic feet per day*
SCMD	*Standard cubic meters per day*
UCV	*Upstream control valve*
VST	*Valve stem travel*

3 Test Site Recommendations

3.1 INTRODUCTION

This section outlines the testing facility necessary to perform gas-lift valve testing. The type testing anticipated will require a high-volume, high-pressure source of gas. It is suggested that the gas storage device be at least 100 ft^3 (cubic meter) and the pressure be at least 1500 psig (kPa).

Local, state, and national codes and practices should be followed when constructing the facility. The piping, valves, and surge vessels comprising the gas-lift valve testing system will be subjected to high pressure gas. As such, the fabrication, testing, and valve selections should adhere to the established codes governing piping systems and vessels.

Surge or other vessels with diameters exceeding 6 in. (152 mm) should adhere to ANSI/ASME Sec VIII D1-89, *Rules for Construction of Pressure Vessels Division 1* or Sec VIII D2-89, *Rules for Construction of Pressure Vessels Division 2—Alter-*

native Rules. These rules provide requirements for design, fabrication, inspection, and certification of applicable vessels.

The piping consisting of materials, wall thickness, and related pressure ratings, should adhere to ANSI/ASME B31.8-89, *Gas Transmission and Distribution Piping Systems* and subsequent addenda. Piping material should be specified as Grade B. Flanges should adhere to ANSI/ASME B16.5-88, *Pipe Flanges and Flanged Fittings* and errata; valves are covered by ANSI/ASME B16.34-88, *Valves—Flanged, Threaded, and Welded End*.

Note: API valves and flanges could be used but are covered by API Spec 6D *Specification for Pipeline Valves (Steel Gate, Plug, Ball, and Check Valves)*. These API flanges may not be interchangeable with ANSI/ASME flanges.

The design pressure for piping, valves, flanges, or pressure vessels should be at least 20% greater than the highest pressure anticipated during the gas-lift valve tests.

When tests are conducted using a test stand as described in this section, the maximum possible error associated with the calculation of the flow rate will be approximately 6% and could be less.

3.2 GENERAL DESCRIPTION

The flow test system includes, as a minimum, items shown in Figure 1 and listed below:

1. Test specimen.
2. Test section.
3. Throttling control valves.
4. Pressure surge tanks.
5. Flow measuring device.
6. Pressure sensors.
7. Temperature sensors.
8. Equalizing valves.

3.3 TEST SPECIMEN

3.3.1 Wireline Retrievable Valves

The test specimen consists of the components as listed below and shown in Figure 2.

1. The fully assembled test valve including the manufacturers recommended reverse flow valve.
2. With a compatible latch.
3. Installed and latched in a compatible receptacle.

3.3.1.1 Test Valve

The valve should be in the fully assembled condition as suggested by the manufacturer. Replacement of the external V-ring packing stacks with an alternate sealing means is permissible.

3.3.1.2 Latch

The latch should be compatible with the receptacle and valve.

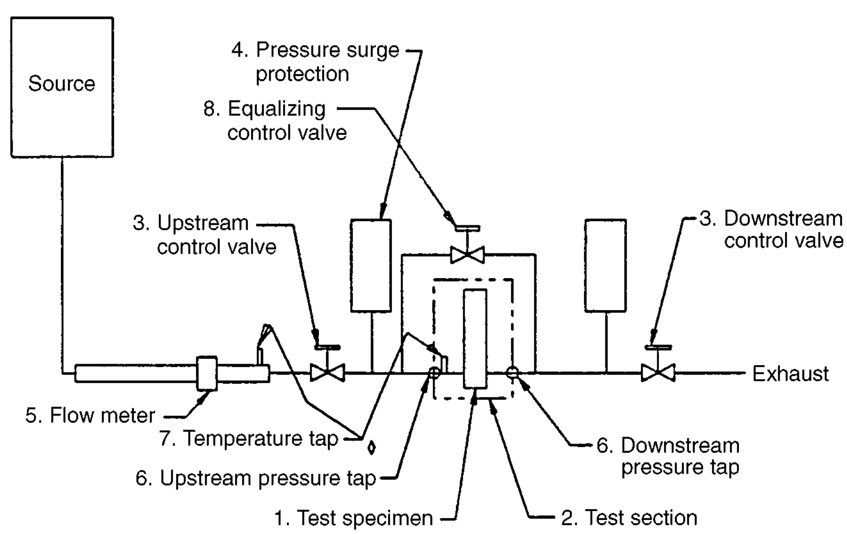


Figure 1—Basic Flow Test System Schematic

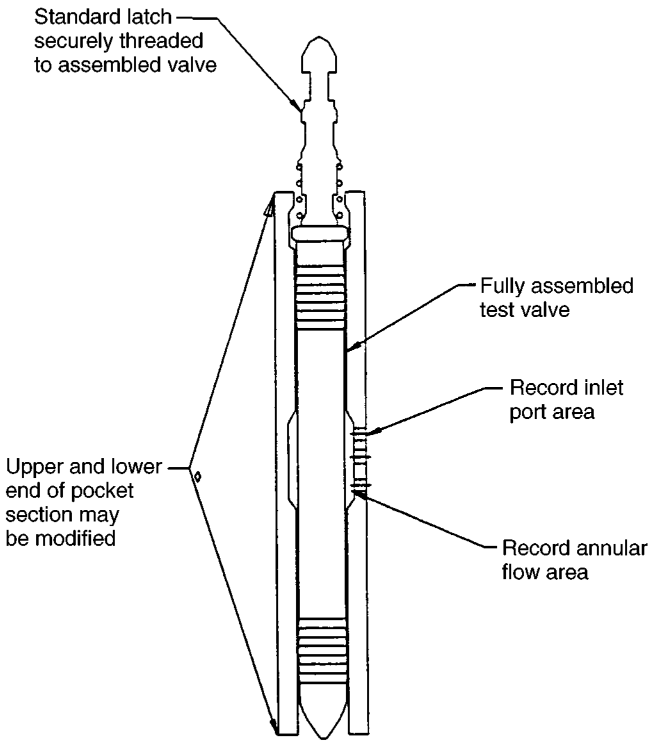


Figure 2—Wireline Retrievable Test Specimen

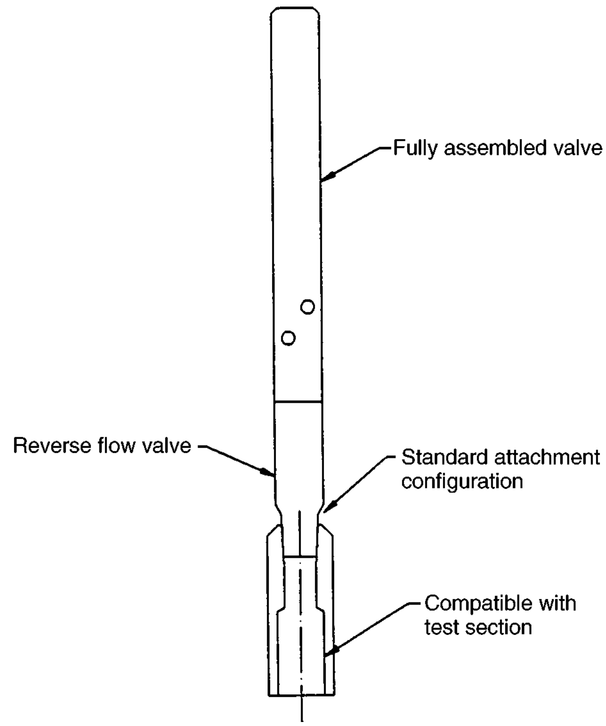


Figure 3—Tubing Retrievable Test Specimen

3.3.1.3 Valve Receptacle

The valve receptacle should be compatible with the valve and latch and should provide means to seal above and below the valve inlet ports. The inlet port area of the receptacle and the minimum annular flow area between the receptacle and valve inlet port should be recorded.

3.3.2 Tubing Retrievable Valves

The test specimen consists of the components as listed below and shown in Figure 3.

1. The fully assembled test valve including the manufacturers recommended reverse flow valve.
2. Threaded to a compatible receptacle for attachment to the test facility.

3.4 TEST SECTION

3.4.1 General

The test section includes the test specimen and all fixtures located between the upstream and downstream pressure measurement devices. The flow path through the test section should not pass through any chokes, close radius elbows or tees and be free of internal obstructions. Elbows should have a minimum 4 in. (10.16 cm) radius. Figures 4 and 5 show examples of test sections which comply with these recommendations.

3.4.2 Upstream Test Section

The test section upstream of the test specimen may extend no more than 24 in. (60.96 cm) from the test specimen and should have a minimum inside flow diameter of at least 1 in. (2.54 cm). The upstream test section should be plumbed to the test specimen such that an unobstructed annular chamber exists surrounding the inlet ports of the test specimen. This chamber should extend no less than $^1/_2$ in. (1.27 cm) above and below the inlet ports of the test specimen and should have an annular width of at least $^1/_4$ in. (0.64 cm).

3.4.3 Downstream Test Section

The test section downstream of the test specimen may extend no more than 24 in. (60.96 cm) from the test specimen and should have an inside diameter of at least 1.5 in. (3.81 cm). The downstream test section should be aligned such that the centerlines of the specimen and section are parallel and concentric. The downstream test section should have a straight extension of at least 6 in. (15.24 cm) length beginning at the test specimen.

3.5 THROTTLING CONTROL VALVES

3.5.1 General

Upstream and downstream throttling control valves are used to control the pressures acting on the test section. There is no restriction as to the style of these valves.

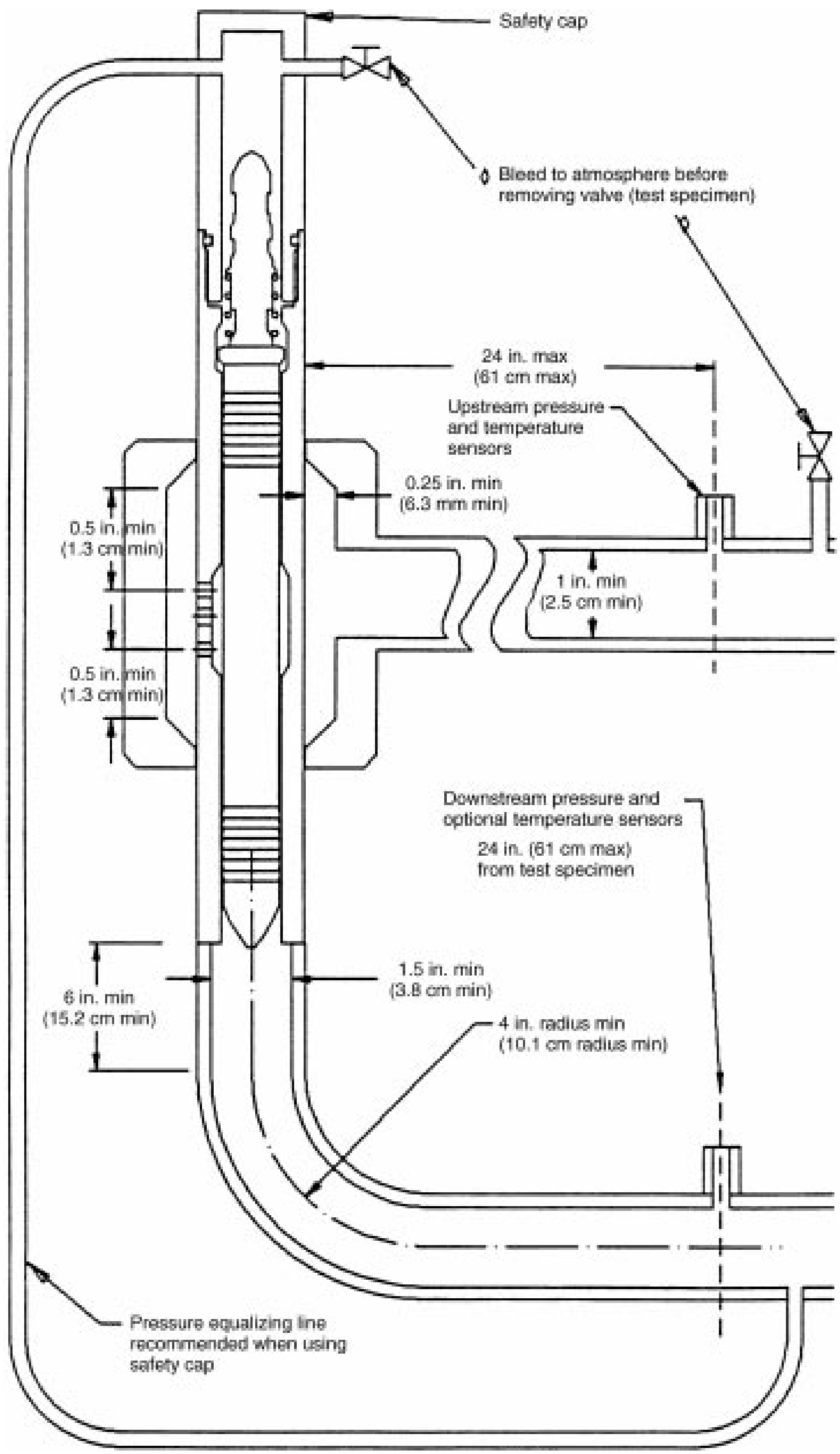


Figure 4—Test Section Example for Wireline Retrievable Valves

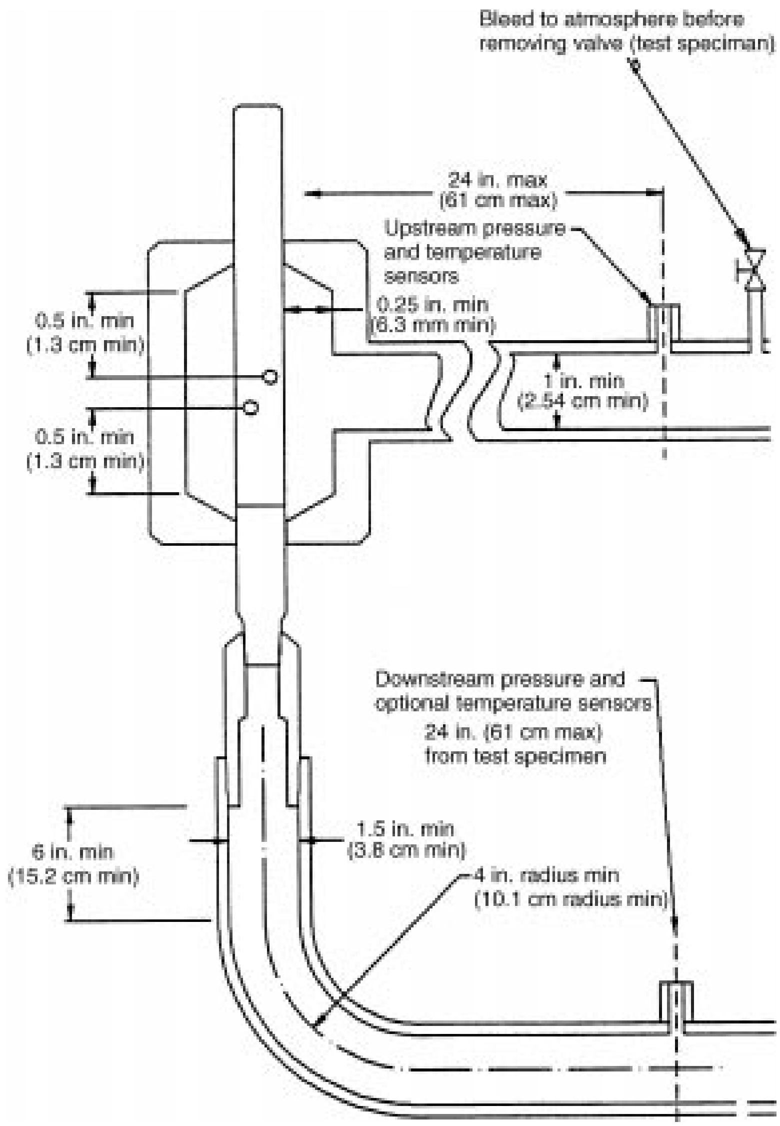


Figure 5—Test Section Example for Tubing Retrievable Valves

3.5.2 Capacity

Both control valves should be of sufficient flow rate and pressure capacity to exceed the flow rate and pressure capacity of the test specimen.

3.6 PRESSURE SURGE PROTECTION

3.6.1 General

Pressure surge protection is recommended on both the upstream and downstream side of the test section. The purpose of the pressure surge protection is to dampen the effects of a pressure surge that might occur as a result of valve performance. Pressure surge may cause serious damage to pressure gages and transducers and seriously hamper the ability to control and monitor a test.

3.6.2 Surge Tanks

Surge tanks can be used to gain an adequate amount of surge protection. These tanks should be plumbed into the test system outside of the test section such that they are each independently in full pressure communication with the upstream and downstream pressures acting on the test section. Optional control valves may be placed in the plumbing connecting the pressure surge tanks to the test system.

The volume of the pressure surge tanks should be no less than 2 ft^3 (0.057 m^3). It is preferred that the downstream pressure surge tank have twice the volume of the upstream pressure surge tank.

3.6.3 Alternative Methods

Alternative surge protection systems that reduce pressure surges in the test specimen to no more than 10 psig/sec (69 kPa/sec) are also permitted.

3.7 FLOW MEASUREMENT

3.7.1 Methods

The flow measurement instrument and/or method may be any device which meets the specified accuracy.

3.7.2 Accuracy

Flow rate should be determined within an error not exceeding ± 6% of actual flow rate. The resolution and repeatability of the method should be within ± 1% of actual flowrate. The measuring instrument should be selected and maintained to achieve the specified accuracy. The AGA Report No. 3, ANSI/API MPMS 14.31-1990, or GPA 8185-90 Part 1 methods of flowrate calculation along with a certified meter run will satisfy these recommendations.

3.8 PRESSURE TAPS

3.8.1 General

Two pressure taps are required. The location of these two pressure taps will define the upstream and downstream pressures acting on the test specimen. The location of these two taps define the beginning and end of the test section. The geometry of the tap should conform to the dimensions given in Figure 6.

3.8.2 Location

The upstream and downstream pressure taps should be located as near as possible to the test specimen but should be no more than 24 in. (60.96 cm) from the test specimen.

3.8.3 Orientation

When located on a horizontal run, the upstream and downstream taps should be located above a horizontal plane extending through the centerline of the pipe. The tap centerline should be perpendicular to the pipe centerline.

3.9 PRESSURE MEASUREMENT

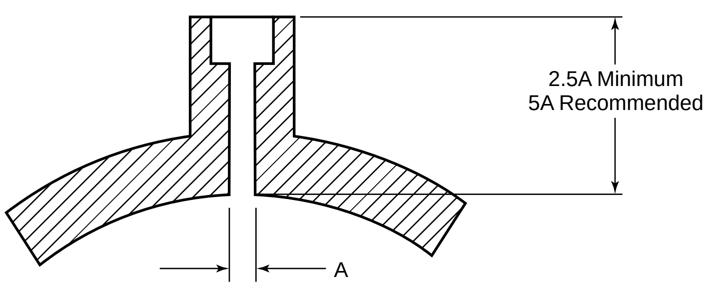
3.9.1 Accuracy

All pressure and pressure differential measurements should be selected with an accuracy such that any errors do not exceed ± 1% of actual value. Pressure measuring devices should be calibrated as frequently as necessary to maintain specified accuracy.

3.9.2 Pressure Reporting Requirements

The upstream and downstream test section pressure measurement should be visually displayed continuously to the operators controlling the test pressures at the test section.

A means should be provided to produce a hardcopy report of the pressures measured at both the upstream and downstream pressure taps of the test section. This means should report pressures within an accuracy of ± 2% of the pressure measurement devices.



Size of Pipe	A Not Exceeding	A Not Less Than
Less than 2 in.	1/4 in.	1/8 in.
2 in. to 3 in.	3/8 in.	1/8 in.
4 in. to 8 in.	1/2 in.	1/8 in.

Edge of hole must be clean and sharp or slightly rounded, free from burrs, wire edges, or other irregularities. In no case shall any fitting protrude inside the pipe.

Figure 6—Recommended Pressure Taps

3.10 TEMPERATURE TAPS

3.10.1 General

Two temperature taps are required. One temperature tap is required on the upstream side of the test section and another is required for the flow rate measurement device. An optional downstream temperature tap may be located on the downstream side of the test section.

3.10.2 Location

The upstream temperature tap should be located within the upstream side of the test section. The temperature tap used for flow rate measurement should be located as recommended by the manufacturer of the flow rate measurement device. There is no requirement for the location of the optional downstream temperature tap, however, it is recommended that if one is used, it be located within the downstream side of the test section.

3.10.3 Orientation

When located on a horizontal run, the temperature taps should be located above a horizontal plane extending through the centerline of the pipe.

3.11 TEMPERATURE MEASUREMENT

3.11.1 Accuracy

The devices used to measure gas temperature should not have an error exceeding ± 2°F (± 1.1°C) of actual value.

3.11.2 Measurement Requirements

The gas temperature should be measured at the flow rate measurement device and on the upstream portion of the test section.

3.11.3 Temperature Reporting Requirements

A means should be provided to produce a hardcopy report of the temperatures measured at both the flow rate measurement device and at the upstream portion of the test section. This means should report temperatures within an accuracy of ± 2% of the temperature being measured.

3.12 EQUALIZING VALVES

The method of accomplishing the tests may require that the upstream and downstream pressures be equalized prior to testing. The equalizing valve is positioned between the upstream and downstream test section and allows the ability to bypass the test specimen.

3.13 GAS SUPPLY

Air or some other compressible gas should be used as the basic fluid in this test procedure. Vapors which may approach their condensation points at the vena contracta of the specimen are not acceptable. Care should be taken to avoid formation of liquids or solids in the gas supply during the test.

3.14 DOCUMENTATION

The following information should be available as a means for demonstrating the compliance of the test apparatus with this recommendation. Data Form 1 is a convenient form that may be used for this purpose.

1. Schematic identifying the layout and location of items 1–8 of 3.2 and signed by the person in charge of testing.
2. Detail drawing of the test section showing:
   a. distance from upstream test section to test specimen.
   b. distance from downstream test section to test specimen.
   c. number and size of receptacle inlet ports and annular flow area between valve and receptacle for wireline retrievable fixtures.
   d. location and size of annular chamber around test specimen.
3. Type and capacity of throttling control valves.
4. Type and size of surge protection.
5. Type and accuracy of flow measurement device.
6. Type and accuracy of pressure measurement devices.
7. Type and accuracy of pressure recording hardcopy device.
8. Type and accuracy of temperature measurement devices.
9. Type and accuracy of temperature recording hardcopy device.

4 Gas-lift Valve Probe Test

4.1 INTRODUCTION

The purpose of the Gas-lift Valve Probe Test is to determine the relative "stiffness" of a gas-lift valve and to determine the maximum effective travel of the stem. When gas pressure is admitted to the tester, it must act on the full area of the valve bellows to lift the stem off the seat. When this pressure is increased, the stem lifts further from the seat. By using the Valve Probe Tester (see Figure 7), an accurate measure of the stem travel versus pressure can be determined and the results tabulated and plotted. The valve probe tester shown in Figure 7 is an example and is not intended to restrict the many possible devices which may be used to accomplish the test.

When the pressure is plotted as the ordinate and the stem travel as the abscissa, a relatively straight line will be generated for the effective stem travel. The slope of this line is an indication of the "stiffness" of the valve. The numerical value

API Recommended Practice 11V2 Data Form 1

1. Schematic of test apparatus attached (Y/N). ________________
   Items 1–8 of Paragraph 3.2 identified (Y/N).________________

2. Detail drawing of test section attached (Y/N). ________________
   Dimension from test specimen to upstream pressure gauge. ________________
   Dimension from test specimen to downstream pressure gauge. ________________
   Number of receptacle inlet ports. ________________
   Diameter of receptacle inlet ports. ________________
   Annular flow area between valve and receptacle. ________________
   Dimension from OD of test specimen to ID of annular chamber around test specimen. ________________
   Dimension from test specimen inlet ports to annular chamber seal. ________________

3. Upstream control valve description. ____
   Flow capacity of upstream control valve at full open position. ________________
   Downstream control valve description. ____
   Flow capacity of downstream control valve at full open position. ________________

4. Type of upstream pressure surge protection.

   Type of downstream pressure surge protection.

5. Type of flow measurement device. ____
   Type of Accuracy of flow measurement device. ____

6. Upstream pressure measurement device. ________________________ Accuracy ____________________
   Downstream pressure measurement device. ________________________ Accuracy ____________________
   Differential pressure measurement device. ________________________ Accuracy ____________________

7. Method of reporting and recording pressure measurements.

   Accureacy of pressure measurement recording device.

8. Upstream temperature measurement device. ________________________ Accuracy ____________________
   Downstream temperature measurement device. ____________________ Accuracy ____________________

9. Method of reporting and recording temperature measurements.

   Accuracy of temperature measurement recording device.

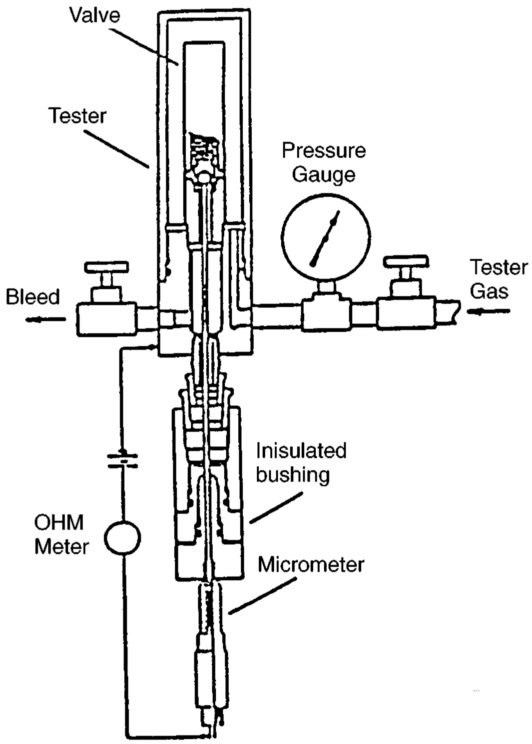


Figure 7—Typical Probe Tester

of the slope is called the Bellows Assembly Load Rate (B_{lr}) and is measured in psig/in. (kPa/cm). In this context, the "bellows assembly" includes the bellows and the gas-lift valve mechanism which applies a load to hold the valve stem on the seat. The higher the load rate, the "stiffer" the valve and inversely, the lower the load rate, the "softer" the valve.

If the above is done with the same valve, except that opening pressure (dome charge or spring setting) is varied, then the effect of dome charge pressure or spring setting on the bellows assembly load rate can be compared for the same type valve when set for different opening pressures.

The maximum effective stem travel and bellows assembly load rate are practical values that can be used to compare different types of valves or when evaluating the same valve under different load conditions and when designing the gas-lift installation.

4.2 EQUIPMENT REQUIRED

4.2.1 Gas-lift Valve Test Stand

Several typical test stands have been previously described in API Specification 11V1 Appendix B. The test stand must have a means for controlling and measuring the pressure applied to the gas-lift valve sleeve. The apparatus shown in Figure 7 is an example of a suitable test stand for the probe test.

4.2.2 Gas-lift Valve Sleeve

The sleeve must communicate pressure from a source to the valve without leaks. The source pressure should be communicated both above and below the valve seat when the valve is closed.

4.2.3 Gas-lift Valve Position Measurement Device

The measurement method must be capable of determining the stem position within ± 0.005 in. (.127 mm).

The position measurement device shown in Figure 7 is a micrometer probe designed to accurately measure the stem travel as a function of the pressure applied over the full area of the bellows. This device uses a micrometer in conjunction with an electrically conductive probe attached to the bottom of the valve. The electrically conductive probe contacts the end of the valve stem and must be electrically insulated from the valve body. The probe is attached to the barrel of the micrometer such that an adjustment of the micrometer will cause an equal adjustment of the probe. This device will meet the measurement accuracy requirements. Other methods of stem position measurement are also possible.

4.2.4 Pressure Gauge

The gauge used to measure pressure should have an accuracy such that measurement errors are no greater than ± 0.5% of value.

4.3 PROBE TEST PROCEDURE

4.3.1 Prepare the Valve for Testing

Nitrogen charged valves and combination valves (spring loaded and nitrogen charged) should be probe tested at opening pressures (P_{voT}) of 800 psig (5515 kPa), 1200 psig (8274 kPa), and at the manufacturer's maximum recommended pressure.

Spring loaded valves should be probe tested at the manufacturer's maximum recommended opening (P_{vo}) or closing pressure (P_{vc}).

4.3.2 Assemble the Test Equipment

Attach the position measurement device (micrometer/probe assembly) to the valve. Insert the valve and position measurement device into the proper sleeve in the valve test stand.

With reference to the micrometer/probe assembly, attach the ohmmeter as shown in Figure 7 with one lead attached to the micrometer barrel and the other lead attached to the gas-lift valve.

4.3.3 Calibrate the Position Measurement Device

Adjust the position measurement device to touch the valve stem when the valve stem is on the seat and no pressure is applied to the test sleeve. Record this micrometer reading opposite the zero pressure value on the data sheet. The stem travels will be computed by subtracting the micrometer reading for zero travel from each of the subsequent readings as the pressure is increased.

4.3.4 Perform the Probe Test

4.3.4.1 Increase pressure slowly to the test sleeve until the position measurement device indicates the stem is no longer touching the seat. This is the pressure at which the valve just opens when test pressure is applied across the full area of the bellows (P_{vcT}). Record this pressure.

With reference to the micrometer/probe assembly, this is indicated on the ohmmeter as a significant increase in the resistance reading.

4.3.4.2 Increase the pressure to the test sleeve in a convenient increment such as 10, 15, 20, or 25 psig (69, 103, 138, or 172 kPa).

Note: If the test pressure increment inadvertently exceeds the target pressure *DO NOT REDUCE* to the target pressure; instead, record the pressure obtained and continue with the test.

4.3.4.3 Adjust the position measurement device to determine the new stem position.

With reference to the micrometer/probe assembly, advance the probe with the micrometer barrel until it contacts the tip of the valve stem. This will be noted by a significant decrease in the ohmmeter resistance reading.

4.3.4.4 Record the pressure, and the stem position using Data Form 2.

4.3.4.5 Repeat steps 4.3.4.2 through 4.3.4.4 using the same pressure increment. These pressure increments should yield at least five recordings within the range of the maximum effective stem travel.

4.3.4.6 Decrease the pressure to the test sleeve in a convenient increment such as 10, 15, 20, or 25 psig (69, 103, 138, or 172 kPa).

With reference to the micrometer/probe assembly, before decreasing the pressure, retract the probe rod by reversing the micrometer barrel far enough to prevent stem tip contact during pressure decrease.

Note: If the test pressure increment is inadvertently allowed to drop to a value less than the target pressure *DO NOT INCREASE* to the target pressure; instead, record the pressure obtained and continue with the test.

4.3.4.7 Adjust the stem position measurement device to determine the new stem position.

With reference to the micrometer/probe assembly, advance the probe with the micrometer barrel until it contacts the tip of the valve stem. This will be noted by a significant decrease in the ohmmeter resistance reading.

4.3.4.8 Record the pressure, and the stem position using Data Form 2.

4.3.4.9 Repeat steps 4.3.4.6 through 4.3.4.8 using the same pressure increments until the valve stem is back on its seat (initial micrometer reading ± 0.005 in.). At least five stem positions should be recorded within the range of the maximum effective stem travel.

4.4 DETERMINING VALVE LOAD RATE

4.4.1 Plot the data on linear coordinate paper with the pressure readings on the vertical axis and the stem position readings on the horizontal axis as shown in Figure 8.

Note: On Figure 8 there are two (2) distinct regions of the plot where the slopes are different. The region identified as Slope A is the effective usable travel range of the valve. The region identified as Slope B is the travel range where the bellows has met a substantial resistance to travel and represents travel that is not normally usable. This additional resistance to travel can be the result of many different factors, but is usually the result of "bellows stacking".

The region of Slope A should extend from zero stem travel to the point where the slope of the load rate data turns sharply upward. This point will be visually determined.

4.4.2 Draw the best-fit straight line to the data of the region corresponding to Slope A. See Figure 9.

4.4.3 Calculate the slope of this best-fit straight line as follows: Slope = $(P1–P2)/dx$ (see Figure 9). The slope of this line is the Bellows Assembly Load Rate of the valve (B_{lr}).

4.4.4 The Bellows Assembly Load Rate (B_{lr}) documentation must include a graph showing ALL the data points, the best-fit straight line, and the B_{lr} calculation.

4.5 DETERMINING MAXIMUM EFFECTIVE STEM TRAVEL

4.5.1 The maximum effective stem travel is the greatest travel obtainable within the region of Slope A as shown in Figure 9.

Note: See Appendix C for detail explanation of Load Rate and Maximum Effective Stem Travel calculation.

4.6 DOCUMENTATION

The following documentation should be available to demonstrate the execution of the probe test per this section. Data Form 2 is a convenient method for recording the data.

1. Assembly drawing of the probe test equipment.
2. Type and accuracy of the pressure gage.
3. API designation of tested valve, manufacturers part number and dated assembly drawing of valve.

API Recommended Practice 11V2 Data Form 2

1. Assembly drawing of probe test apparatus attached (Y/N). ____________

2. Type of pressure measurement device. ______________________ Accuracy ____________

3. API designation for valve. ____________
   Manufacturers part number for valve. ______________
   Dated assembly drawing of valve attached (Y/N). ____________

4. Test data.
   Valve set pressure ________ P_{vo} or P_{vc}?

	Test Pressure (psig)	Stem Position: Actual	Stem Position: Corrected
1.	0		XXXXX
2.			
3.			
4.			
5.			
6.			
7.			
8.			
9.			
10.			
11.			
12.			
13.			
14.			
15.			
16.			
17.			
18.			
19.			
20.			

5. Graph attached showing test pressures and stem positions (Y/N). ____________
   Graph showing best-fit straight line (Y/N). ____________

6. Bellows assembly load rate (B_{lr}) __________ psig/inch

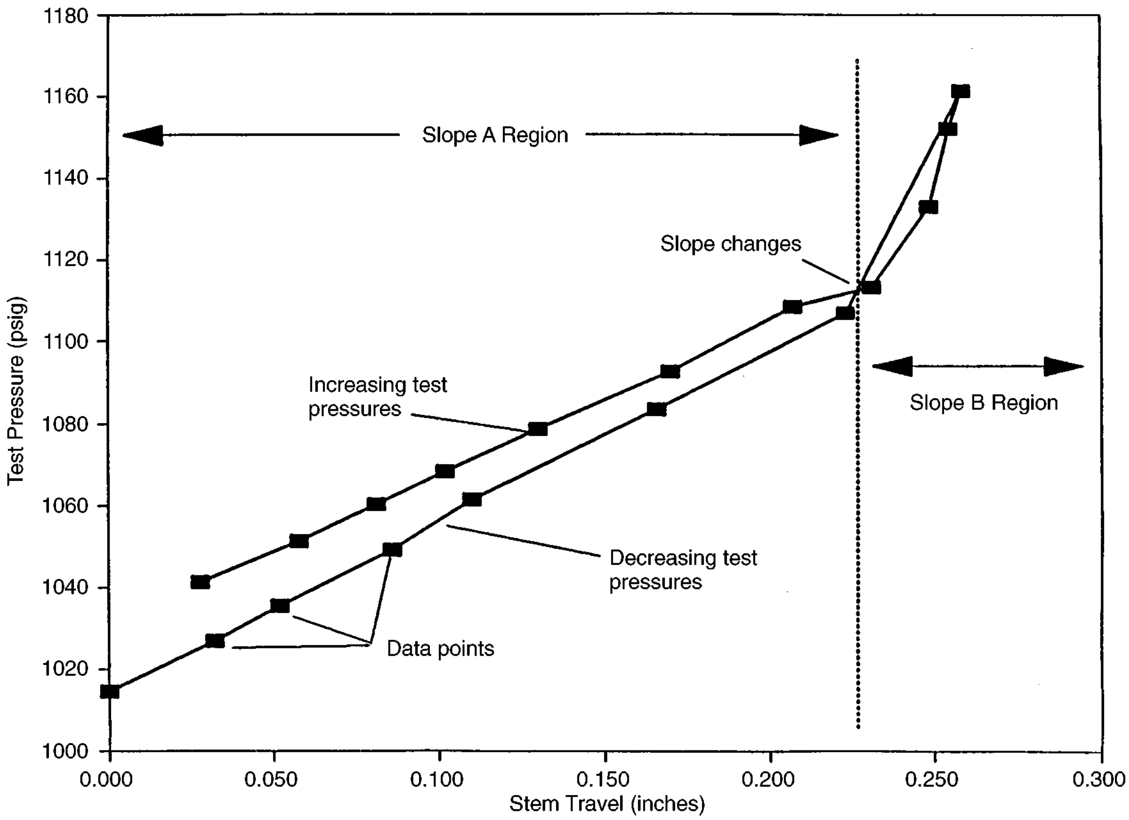


Figure 8—Typical Data from Probe Test

4. Test data including:
    a. Valve set pressure.
    b. Test pressures.
    c. Stem positions.
5. Graph showing:
    a. Tested pressures and stem positions.
    b. Best fit straight line.
6. Bellows assembly load rate (B_{lr}).
7. Maximum effective stem travel.
8. Date test performed.
9. Person in charge of the test.

5 Flow Coefficient Test Procedure

5.1 INTRODUCTION

The purpose of this procedure is to determine a gas-lift valve's flow capacity as a function of the valve's stem travel. When conducted properly the data from this test will allow accurate gas and liquid passage calculations at any pressure conditions. The valve's flow rate as a function of pressure collected per this section is geometry dependent and therefore is appropriate only for the particular configuration of the test specimen.

The test method described here requires the control of both upstream and downstream pressure. Experience has shown that practice may be required to obtain good data. Tests have been conducted showing that a slow and steady change in pressure during the test will yield more accurate data than when pressures are changed abruptly.

Two testing methods are possible. The *traditional* method of holding the upstream pressure constant and then abruptly changing the downstream pressure and the *ramp* method of holding the upstream pressure constant while slowly and continuously changing the downstream pressure. Both methods produce good results when conducted properly.

The *traditional* method requires that the system be stable before recording any readings. This is usually indicated by little or no change in flow rate for a period of time. This method can consume a considerable amount of time but can be accomplished with manually read gages or collected by transducers and data acquisition equipment.

The *ramp* method requires that the system time constant be determined (Appendix D) and that the data be collected by transducers and data acquisition equipment.

Tests have been conducted showing that slow and steady changes in pressure (ramp method) during the test will yield more accurate data than when pressures are changed abruptly (traditional method). This is due primarily to the ability of the

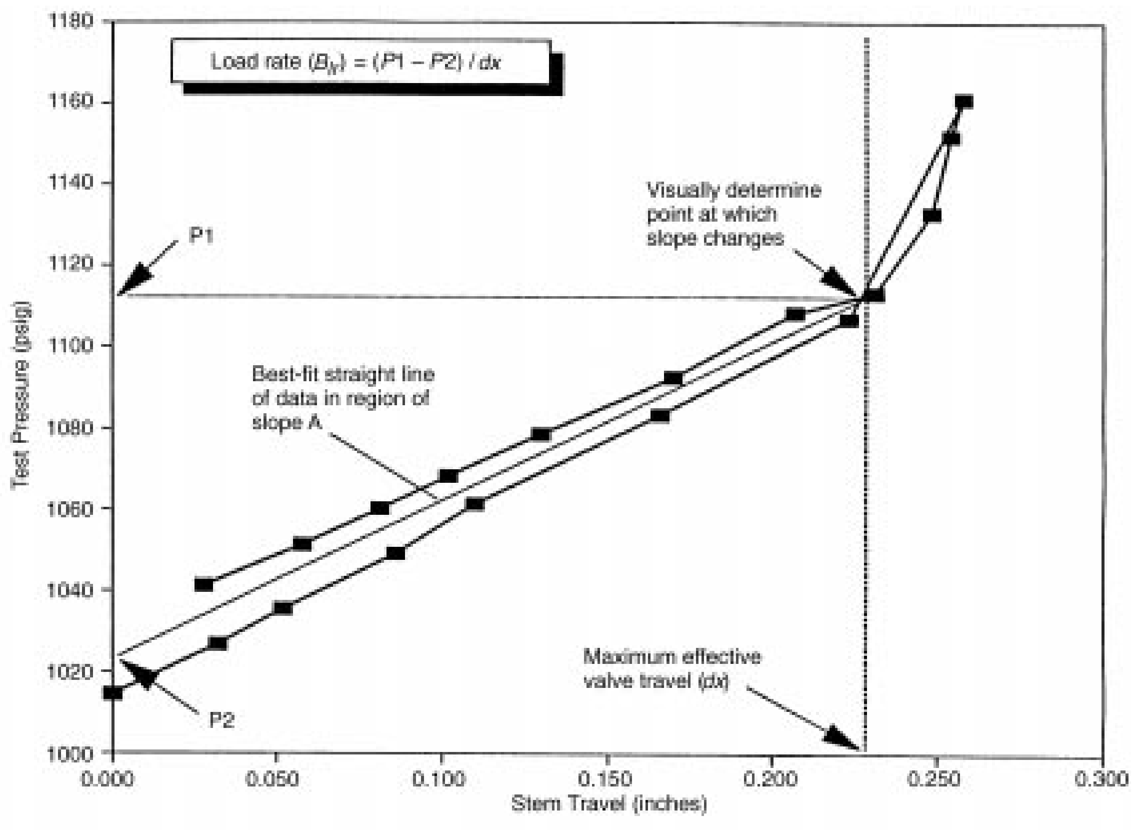


Figure 9—Determining Valve Loadrate (psig/inch)

tester to determine when the system is stable when using the traditional method.

When these tests are conducted using a test stand as described in Section 3 and data collected and analyzed as described in this section, the maximum possible error associated with the calculation of the flow coefficients will be approximately 9% and the maximum possible error associated with the calculation of the critical pressure ratio factor will be approximately 11% and could be less.

5.2 TEST SPECIMEN

5.2.1 Wireline Retrievable Test Specimen

The test specimen should include the following components.

1. A valve modified to include a feature which allows positive mechanical adjustment of the valve stem with respect to the seat. This feature must in no way affect the normal flow path through the valve. If the valve would normally include a reverse flow valve, the manufacturer's recommended reverse flow valve must be part of the valve assembly. See Figure 10.

2. A compatible latch securely threaded to the valve. The latch may be modified to allow easy access to the stem adjustment feature so long as the modification does not impair the ability of the latch to securely thread to the valve or to securely anchor the latch/valve assembly to the compatible receptacle.

3. The valve and latch shall be inserted into a compatible receptacle.

5.2.2 Tubing Retrievable Test Specimen

The test specimen should include the following components.

1. A valve modified to include a feature which allows positive mechanical adjustment of the valve stem with respect to the seat. This feature must in no way affect the normal flow path through the valve. If the valve would normally include a reverse flow valve, the manufacturer's recommended reverse flow valve must be part of the valve assembly.

2. The valve attached to a compatible receptacle.

5.2.3 Stem Position Measurement

The stem adjustment feature must allow measurement of the position of the stem with respect to the seat within ± 0.003 in. (± 0.076 mm). The position of the stem with respect to the seat will be defined as fully closed when the flow rate through the valve is less than 200 SCFD (5.66 SCMD) at expected test pressure conditions. At this position, the measurement of the stem position with respect to the seat is 0.000 in. (0.00 cm).

5.2.4 Required Stem Test Positions

At least five stem positions must be tested for each specific valve design and stem/seat configuration. At least one test must be conducted with the stem no more than 10% of its maximum effective travel from the seat and at least one test must be conducted with the stem at 100% of maximum effective travel. See 4.5 for a definition of maximum effective travel.

A minimum of three more stem position tests should be conducted at stem positions greater than 10% and less than 90% of maximum effective travel. These three stem positions should be chosen to obtain flow capacity data in the range of travel where flow rate is changing significantly.

5.3 FLOW COEFFICIENT TESTS

5.3.1 Definitions

See Section 2 of for abbreviations and definitions.

5.3.2 Test Pressure Range

For each stem position, a minimum of five well spaced pressure ratios (x) should be tested. The analysis of the test data may require additional tests. See 5.4 for clarification of the need for additional tests.

5.3.3 Measurement Requirements

For each of the pressure ratios (x) tested, measurements shall be made of flow rate, upstream test section gas temperature ($T1$), upstream test section pressure ($P1$), downstream test section pressure ($P2$), and stem position measurement.

Flow measurement should be made per 3.7, pressure measurements per 3.9, and temperature measurements per 3.10. Stem position measurements should be made per 5.2.3.

5.3.4 Test Method

5.3.4.1 Both upstream and downstream test section pressures ($P1$ and $P2$) must be equalized at some pressure greater than 100 psig (689 kPa) before each test. Both upstream and downstream test section pressure gauges must read within 2% of each other, and the flow measurement device must show less than 200 SCFD (5.66 SCMD) of flow.

5.3.4.2 Initiate flow such that the pressure ratio (x) at the test section is less than 0.05. Record the data per 5.3.3. When using the ramp method of testing, this data point will automatically be recorded. When using the traditional method, stabilize flow at this pressure ratio before recording the data.

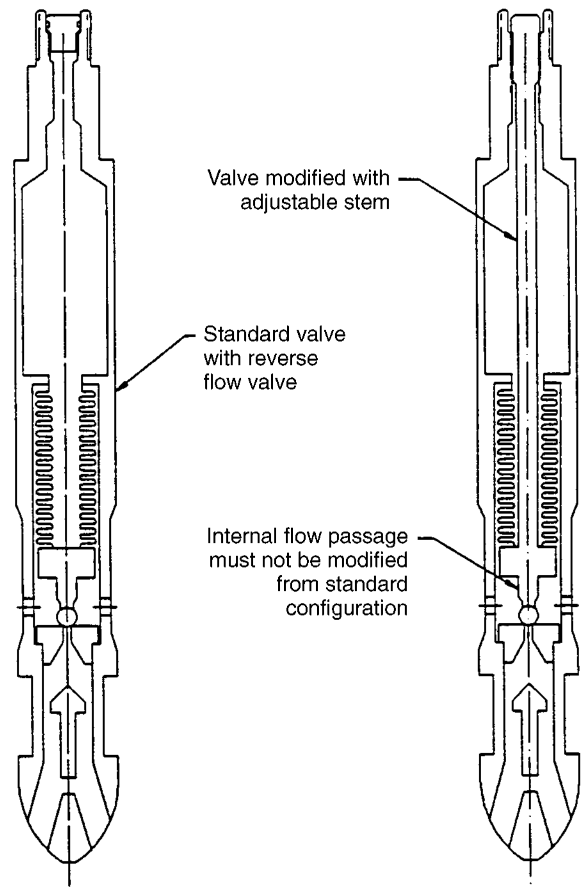


Figure 10—Modified Valve for Flow Coefficient Test

If using the traditional method, the data can be automatically recorded when using data acquisition equipment.

5.3.4.3 The pressure ratio (x) should be increased until critical flow is observed. Critical flow occurs when the flow rate no longer increases for a constant upstream pressure and a falling downstream pressure.

When using the ramp method, this is accomplished by holding the upstream pressure constant while slowly and continuously dropping the downstream pressure. (see Appendix D for an explanation concerning the rate of pressure change). Record the data per 5.3.3.

When using the traditional method, this is accomplished by holding the upstream pressure constant while changing the downstream pressure to a new value and then waiting until the system stabilizes. Record the data per 5.3.3.

5.3.4.4 At least three pressure ratios (x) in the range of 10% to 90% of the pressure ratio (x) observed for critical flow must be recorded per 5.3.3 above. Additional pressure ratios (x) may be tested within this range.

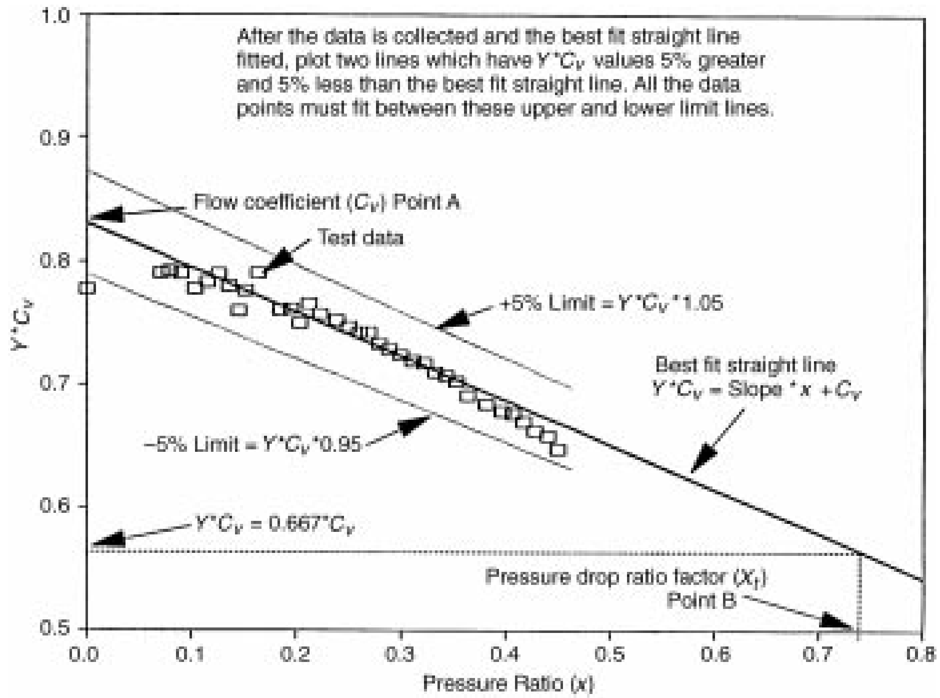


Figure 11—Flow Capacity Data Evaluation

5.4 DATA EVALUATION

5.4.1 Introduction

This section describes the procedure for evaluating the test data collected by the procedure given in section 5.3. This procedure will yield the flow coefficient (C_V) and the pressure drop ratio factor (X_t) for a given value at a given stem travel. See Figure 11.

5.4.2 Calculation

For each pressure ratio tested, find the product of Y^*C_V using the following equation.

$$Y^*Cv = q^*(Sg^*(T1+460)^*Z1/x)^{\frac{1}{2}}/[1360^*(P1+14.7)]$$

5.4.3 Analysis

The values calculated as Y^*C_V shall be plotted on linear coordinate paper with Y^*C_V on the vertical axis and the pressure ratio (x) on the horizontal axis. A best-fit straight line shall be fitted to the data. If any test data point deviates by more than 5% from the straight line, additional test data should be taken near that pressure ratio (x) to ascertain if the specimen truly exhibits anomalous behavior.

The accuracy of data collected at very low pressure ratios and small stem displacements is suspect. These data points may be ignored if at least five additional data points meet the criteria described above.

5.4.4 Determination of Flow Coefficient (C_V)

The value of C_V shall be read from the graph as the point on the vertical axis where the fitted straight line intersects the vertical axis. Note point A on Figure 11.

5.4.5 Determination of Pressure Drop Ratio Factor (X_t)

A horizontal line is projected from the vertical axis at a value of Y^*C_V = 0.667*C_V until it intersects the fitted straight line. A vertical line is then dropped from this intersection to the horizontal axis. The value of X_t is read on the horizontal axis as the point of intersection of the vertical line and the horizontal axis. Note point B on Figure 11.

Alternatively, the following equation could be used to determine X_t if the slope (M) of the straight line is known:

$$X_t = [0.667^*(Y^*C_v) - C_v]/M$$

5.4.6 Calculating the Expansion Factor (Y)

The value of the expansion factor (Y) is calculated as:

$$Y = 1 - x/(3^*F_k^*X_t)$$

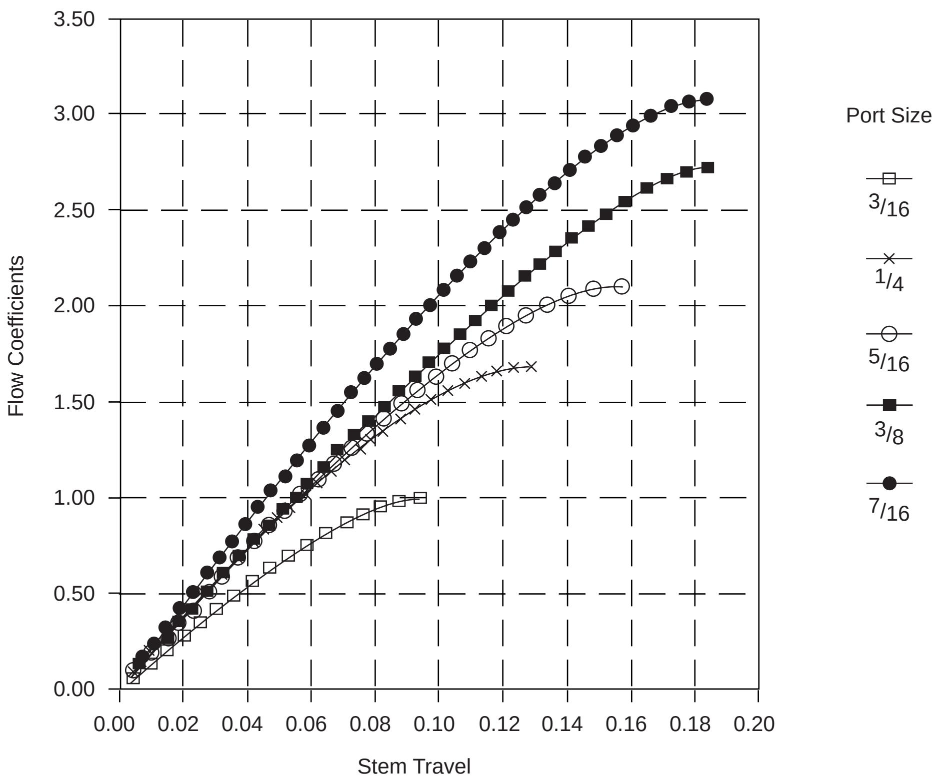


Figure 12—Flow Coefficients vs. Stem Travel

The computed value of the expansion factor (Y) may not exceed 1.0 and must be greater than or equal to 0.667. In addition, if x is greater than F_k*X_t then the value which must be used for x is F_k*X_t.

5.4.7 Record of Flow Coefficient (C_v) versus Stem Travel

A graph of the flow coefficient (C_v) versus stem travel should be made on linear coordinates with C_v on the vertical axis and stem travel on the horizontal axis. The range of the stem travel axis should begin at 0.000 in. and extend to the maximum effective travel of the stem as determined in 4.5.

Each of the tested points should be identified with a symbol. A curve may be fitted to the data points using any method suggested by the manufacturer to obtain flow coefficients not tested. See Figure 12 for an example of flow coefficients plotted versus travel.

5.4.8 Record of Pressure Drop Ratio Factor (X_t) versus Stem Travel

A graph of the pressure drop ratio factor (X_t) versus stem travel should be made on linear coordinates with X_t on the vertical axis and stem travel on the horizontal axis. The range of the stem travel axis should begin at 0.000 in. and extend to the maximum effective travel of the stem as determined in 4.5.

Each of the tested points should be identified with a symbol. A curve may be fitted to the data points using a method recommended by the manufacturer to obtain pressure drop ratio factors not tested. See Figure 13 for an example of critical pressure ratios plotted versus travel.

5.5 USE Of C_v AND X_t TEST DATA

The flow coefficient shall be used in the following equation to compute flow rate.

$$q_{gi} = 32.64*C_v*(P_{iod} + 14.7)*Y*(x/(S_g*(T_v + 460)*Z1))^{\frac{1}{2}}$$

where

$$x = (P_{iod} - P_{pd})/(P_{iod} + 14.7).$$

In the above equation, use the actual pressure ratio (x) if it is less than F_k*X_t, otherwise, use F_k*X_t as the value of x.

5.5.1 Example For Using C_v and X_t to Compute Flow Rate

To calculate the flow rate through a gaslift valve using this equation you must know the amount of stem travel for the pressure conditions. This can be determined using either the Simplified Method (Appendix A) or any other correlation that

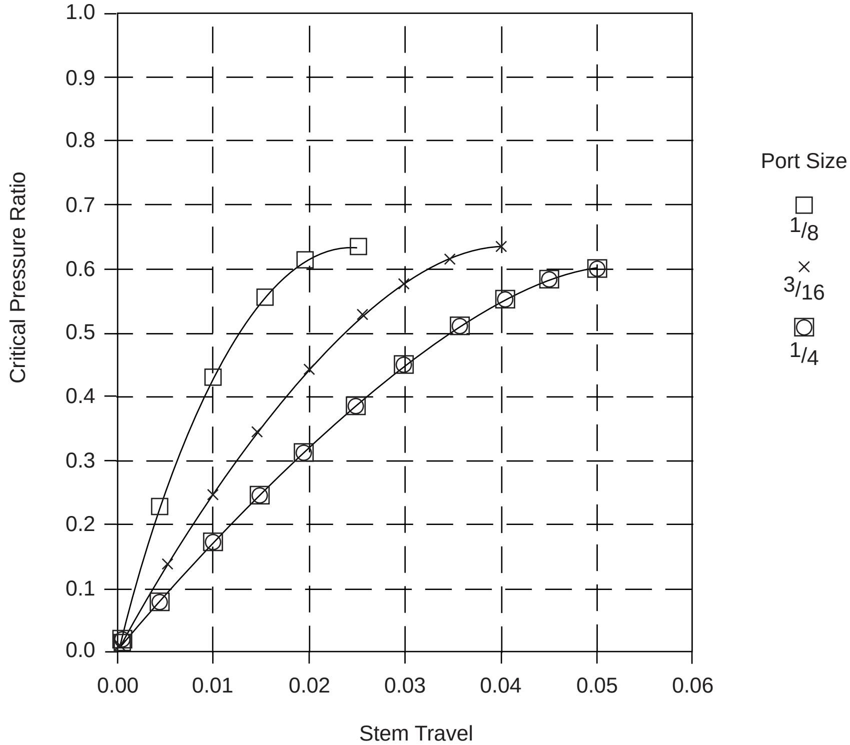


Figure 13—Critical Pressure Ratio vs. Stem Travel

calculates stem travel. You must also know the ratio of specific heats of the media used to test the flow coefficients. Assume the following:

- Figure 12 is a graph of the C_v versus travel for this valve.
- Figure 13 is a graph of the X_t versus travel for this valve.
- Test media ratio of Specific Heats = 1.4.
- Upstream pressure (P_{iod}) = 1000 psig.
- Downstream pressure (P_{pd}) = 850 psig.
- Natural Gas Specific Gravity (S_g) = 0.65.
- Temperature (T_v) = 150°F.
- Valve stem travel = 0.020.

1. Calculate the pressure ratio (x):

$$x = (1000 - 850)/(1000 + 14.7) = 0.1478$$

2. From Figure 13 determine the X_t for the valve at a travel of 0.020. Read X_t = 0.45.
3. Determine the ratio (F_k). The test media used a gas with a specific heat ratio of 1.4. Natural gas has a specific heat ratio of 1.3 therefore, F_k = 1.3/1.4 = 0.928
4. Determine if valve is in critical flow. If x is greater than X_t*F_k then the valve is choke and X_t*F_k must be used rather than x to compute flow rate. X_t*F_k = 0.45*0.928 = 0.417. The actual pressure ratio (.1478) is less than the critical pressure ratio factor (0.417) therefore, the valve is NOT in critical flow and the actual pressure ratio factor can be used to compute flow and the expansion factor.
5. Compute the expansion factor (Y)

$$Y = 1 - x/(3F_kX_t) = 1 - 0.1478/(3*0.928*0.45) = 0.882$$

6. From Figure 12 determine the C_v for the valve at a travel of 0.020. Read C_v = 0.40.
7. Compute the compressibility factor for pressure = 1000 and temperature = 150. $Z1$ = 0.95
8. Compute flow rate

$$Mscfd = 32.64*0.40*(1000 + 14.7)*0.882*(0.1478/(0.65*(150 + 460)*0.95))^{\frac{1}{2}} = 231$$

5.6 DOCUMENTATION

The following documentation should be available to record the execution of the test per this section. Data Form 3 is a convenient form to record the data.

1. The API designation of the tested valve and the manufacturer's part number and dated assembly drawing.
2. A drawing of the modified valve.
3. Maximum effective travel of valve (See 4.5).

API Recommended Practice 11V2 Data Form 3

1. API designation for valve. ____________
   Manufacturers part number for valve.____________
   Dated assembly drawing of valve attached (Y/N).____________
2. Drawing of modified valve attached (Y/N). ____________
3. Maximum effective travel of valve (per paragraph 4.5). ____________
4. Type of flow measurement device.____________________ Accuracy ____________
5. Upstream pressure measurement device.____________________ Accuracy ____________
   Downstream pressure measurement device.____________________ Accuracy ____________
   Differential pressure measurement device. ____________________ Accuracy ____________
6. Upstream temperature measurement device.____________________ Accuracy ____________
7. Stem travel.
8. Test Data

	Upstream psig	Downstream psig	Diff psi	Upstream Temp	Flowrate
1.					
2.					
3.					
4.					
5.					
6.					
7.					
8.					
9.					
10.					
11.					
12.					
13.					
14.					
15.					

9. Calculations

	Pressure ratio (x)	Y^*C_v	+5% limit	-5% limit
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				
12.				
13.				
14.				
15.				

   Coefficients of best-fit straight line. A______________ B________________
10. Graph showing data points and best-fit straight line attached (Y/N).____________
11. Flow Coefficient (C_v). ________________
12. Pressure drop ratio factor (X_t). ________________
13. Graph of flow coefficient versus stem travel attached (Y/N). ________________
14. Graph of pressure drop ratio factor versus stem travel attached (Y/N). ____________

4. Type and accuracy of flow rate measurement.
5. Type and accuracy of pressure measurement.
6. Type and accuracy of temperature measurement.
7. Stem travel.
8. Test data to include the following at each test point:
   a. Test section upstream pressure ($P1$).
   b. Test section downstream pressure ($P2$).
   c. Test section upstream temperature ($T1$).
   d. Flow rate.
9. Calculation of the following variables:
   a. Pressure ratio for each test point (x).
   b. Product of $Y*C_v$ for each test point as per 5.4.2.
   c. Coefficients of best fit straight line (i.e., coefficients A and B of $Y*C_v$ = A*x + B that best fits data).
   d. Plus 5% limit of each data point using the best fit straight line as reference.
   e. Minus 5% limit of each data point using the best fit straight line as reference.
10. Graph of data points and best fit straight line.
11. Flow coefficient (C_v).
12. Pressure drop ratio factor (X_t).
13. Graph of flow coefficient (C_v) versus stem travel.
14. Graph of pressure drop ratio factor (X_t) versus stem travel.
15. Location of test facility and test facility operator.
16. Media used for testing.
17. Date tested and person in charge of testing.

6 Gas-lift Performance Test

6.1 INTRODUCTION

Two test methods will be described.

One method describes the procedure for a live valve test when holding the production pressure constant at several values and at each value modifying the injection pressure to learn how the gas lift valve performs with changes in injection pressures. This will be referred to as the Constant Production Pressure Test (CPPT). (See Figure 14).

Another method describes the procedure for a live valve test when holding the injection pressure constant at several values and at each value modifying the production pressure to learn how the gas lift valve performs with the changes in production pressures. This will be referred to as the Constant Injection Pressure Test (CIPT). (See Figure 15).

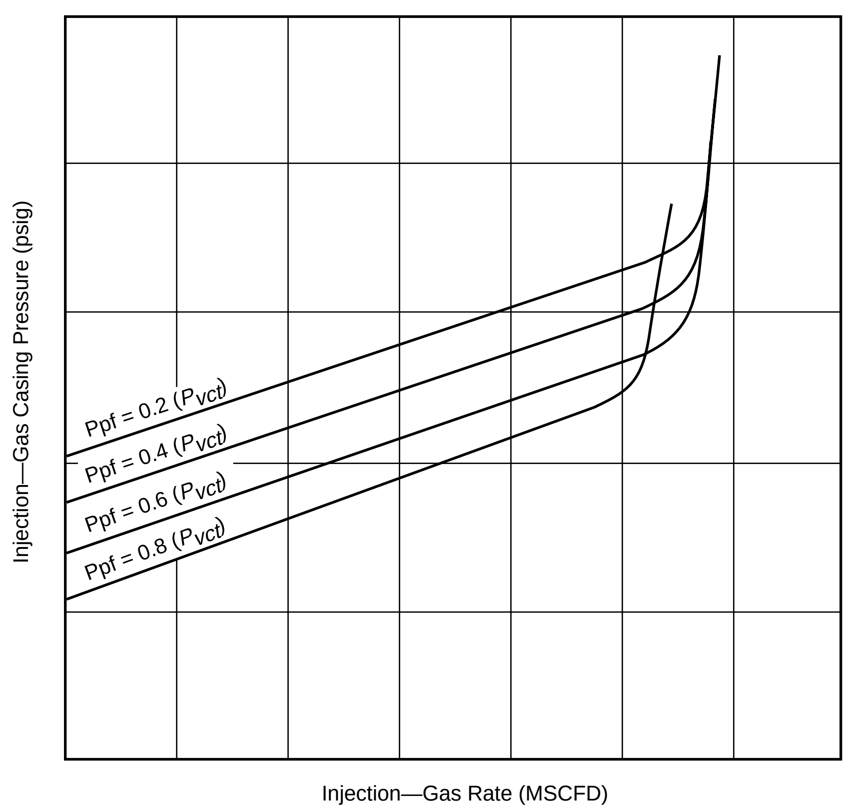


Figure 14—Typical Plot Data from Constant Production Pressure Test (CPPT)

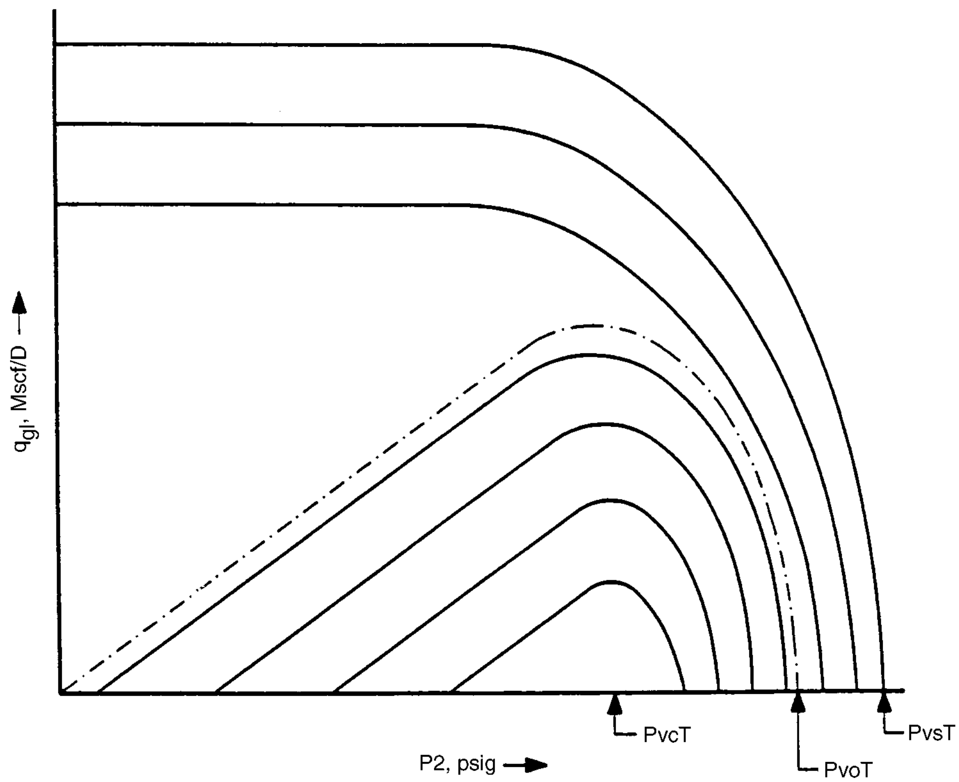


Figure 15—Typical Plot of Data from Constant Injection Pressure Test (CIPT) of Gas-lift Valve

These tests should be performed in a facility equivalent to that described in Section 3. The Gas-lift Valve (GLV) to be tested (test specimen) may be a nitrogen charged, spring loaded, or combination of spring loaded/nitrogen charged. It may be Injection Pressure Operated (IPO) or Production Pressure Operated (PPO) and it must comply with the test specimen in 3.3.

See Section 2 for abbreviations and definitions of several terms that follow. Figure 16 shows typical GLV performance characteristics on a three-dimensional graph of Upstream Pressure ($P1$), Downstream Pressure ($P2$) and Flow Rate (q_{gi}). The ability to plot data from either a Constant Injection Pressure Test (CIPT) or a Constant Production Pressure Test (CPPT) on the same three dimensional graph was verified by the API 11V2 Work Group in October 1991. Figure 16 illustrates how a GLV moves from the throttling flow regime through a regime of transition to the orifice flow regime as the $P1$ is increased. If q_{gi} and $P2$ are considered a vertical plane, that vertical plane will have a specific value of $P1$. Likewise, if q_{gi} and $P1$ are considered a vertical plane, that vertical plane will have a specific value of $P2$, which value may be visualized as one of the dashed isobar lines.

In summary, Figure 16 shows the results of a constant production pressure test (CPPT) using the dashed isobar lines as constant production pressure ($P2$) and changing the injection pressures ($P1$). And it also shows the results of a constant injection pressure test (CIPT) using the solid line curves as isobars for constant injection pressure ($P1$) as the production pressures ($P2$) are changed.

Two testing methods are possible. The *traditional* method of holding the upstream pressure constant and then abruptly changing the downstream pressure and the *ramp* method of holding the upstream pressure constant while slowly and continuously changing the downstream pressure. Both methods produce good results when conducted properly.

The *traditional* method requires that the system be stable before recording any readings. This is usually indicated by little or no change in flow rate for a period of time. This method can consume a considerable amount of time but can be accomplished with manually read gage. If using the traditional method, readings can be obtained using a data acquisition method.

The *ramp* method requires that the system time constant be determined (Appendix D) and that the data be collected by transducers and data acquisition equipment.

Tests have been conducted showing that slow and steady changes in pressure (ramp method) during the test will yield more accurate data than when pressures are changed abruptly (traditional method). This is due primarily to the ability of the tester to determine when the system is stable when using the traditional method.

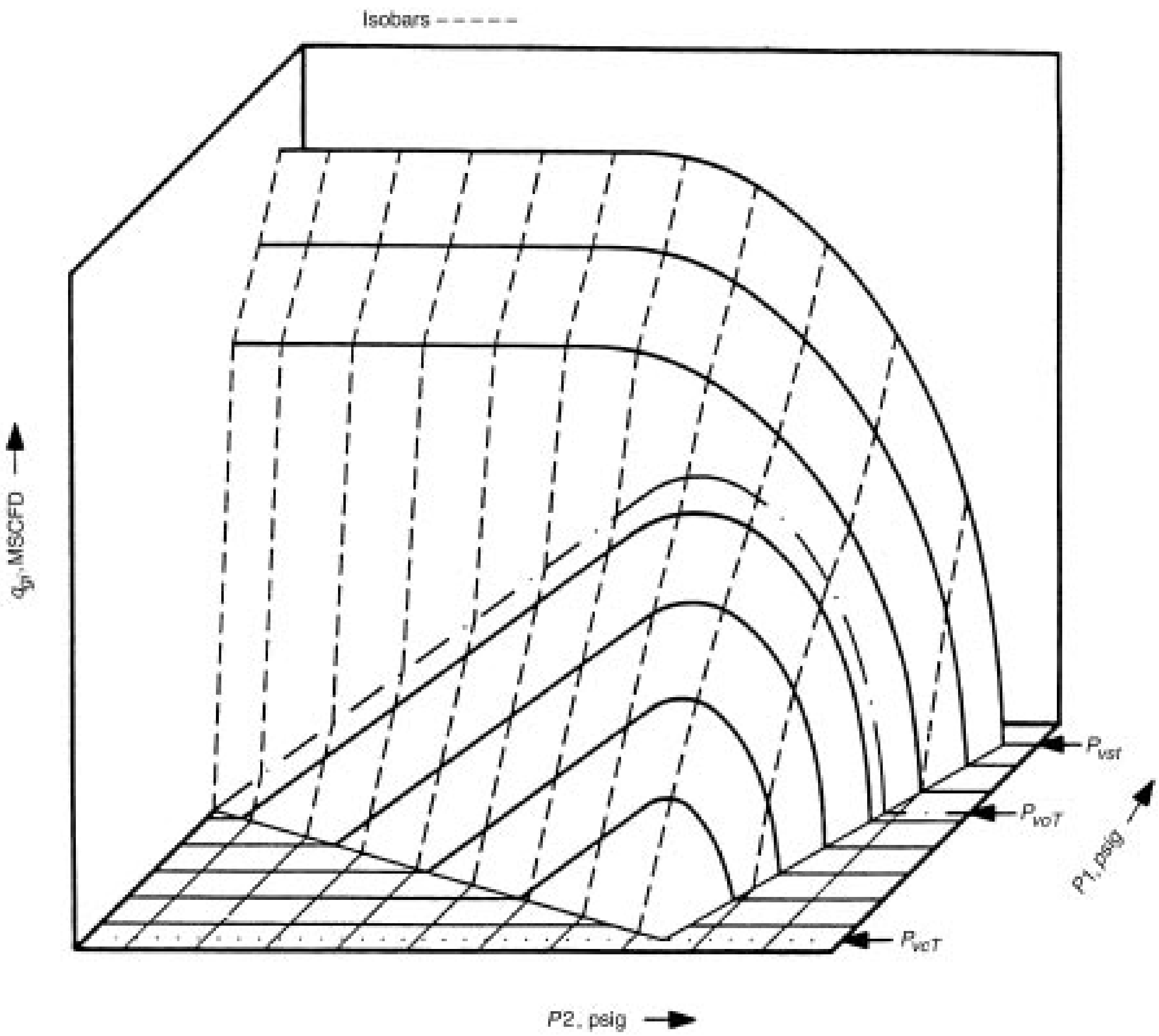


Figure 16—Three Axis Plot of Data from Constant Injection Pressure Test (CIPT) of Gas-lift Valve

6.2 FLOW PERFORMANCE TEST DOCUMENTATION

6.2.1 *Valve Description*: Record the manufacturer's name and an assembly or part number designation for the tested valve. Include the version number of the valve or date of manufacture.

6.2.2 *Stem-Seat and Bellows Dimensions*: Record effective bellows area, port ID, stem-tip description and seat-bevel configuration.

6.2.3 *Valve Specifications*: Record ratio of stem-seat contact area to effective bellows areas (A_s/A_b).

6.2.4 *Profile of Equivalent Flow Area versus Stem Travel*: Define a curve representing equivalent flow area versus stem travel on the basis of the surface area of the frustrum of a right circular cone for the stem and seat geometry in 6.2.2 from zero stem travel to a maximum equivalent flow area equal to the port area. This curve defines the fully open stem travel. Figure 17 is an example of the equivalent flow area versus stem travel.

6.2.5 The test rack set pressure of the valve must be defined in psig at 60°F. The valve set pressure may be the P_{vo} or P_{vc} as designated by the manufacturer.

6.2.6 A probe test of the valve as defined in Section 4 must be performed and a copy of Data Form 2 included with the documentation.

6.3 PREPARATION FOR CONSTANT PRODUCTION PRESSURE TEST (CPPT)

6.3.1 Establish the maximum valve stem travel (VST) for calculating the increase in injection pressure for the constant production pressure tests. Maximum VST is the lesser of

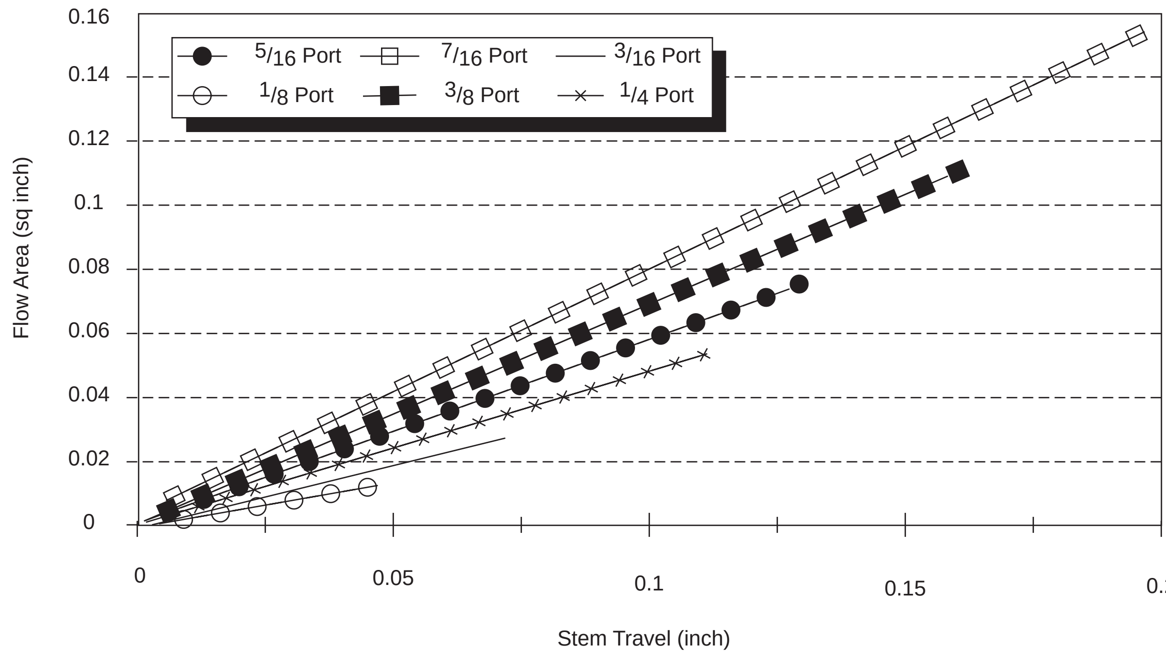


Figure 17—Geometric Flow Area vs. Port Size

either the Loadrate Stem Travel (LST) or Geometric Stem Travel (GST). LST is determined from the probe test of the valve (see Appendix C) and is measured in Section 4. GST is based on the physical geometry of the valve stem tip (usually a carbide ball) and its seat as described in 6.2.4. GLV is the VST required to attain an equivalent area (surface area of the frustrum of a right circular cone generated by the stem tip moving away from its seat) that is equal to the valve port area.

6.3.2 Calculate the required maximum increase (*dP*) in the upstream test section pressure (*P*1) above the initial valve opening pressure (P_o) to achieve maximum valve stem travel VST for a constant downstream test section pressure (*P*2). This maximum increase in the injection pressure (*dP*) is constant for a given GLV and for all values of *P*2. If the maximum VST is equal to or greater than the LST, the *dP* increase above the valve closing pressure (P_{vc}) to attain the LST from the probe test is used in the calculations. If the VST is equal to or greater than the GST, the GLV bellows load rate (B_{lr}) from the probe test and the GST are used in the calculations.

$$\text{For VST = LST: Max } dP = \{1.2(\text{probe } dP)\}/\{1 - A_s/A_b\}$$

$$\text{For VST = GST: Max } dP = 1.2(\text{VST})B_{lr}$$

6.3.3 Calculate the incremental delta pressure (*dP*) values above the upstream initial valve opening pressure (P_o) for the constant downstream test section pressure (*P*2) tests. A minimum of 4 equally spaced test *dP* values over the full range including the maximum *dP* (Max *dP*) calculated in 6.3.2 is recommended. For example, use 25, 50 and 75 percent of Max. *dP* and Max. *dP*.

6.3.4 Install the gas-lift valve in the test fixture and determine the valve opening pressure (P_{voT}) at the tester gas temperature with a downstream test section pressure (*P*2) equal to 0 psig (0 kPa gauge). Record the P_{voT}.

6.3.5 Since the tested valve closing pressure (P_{vcT}) can be difficult to accurately measure in the test fixture, calculate the P_{vcT} for selecting the values of downstream test section pressures (*P*2) in 6.3.6 by using the following equation:

$$P_{vcT} = P_{voT}(1 - A_s/A_b)$$

6.3.6 Calculate at least 4 equally spaced values for downstream test section pressures (*P*2) based on the valve closing pressure (P_{vcT}) that will define the full range of operation of the injection-pressure-operated valve. Suggested values of *P*2 for the full range of operation are 20, 40, 60 and 80 percent of P_{vcT}.

6.4 PERFORMING THE CONSTANT PRODUCTION PRESSURE TEST

6.4.1 Adjust the upstream and downstream control valves for a near zero gas rate through the gas-lift valve for the calculated downstream test section pressure (*P*2). Record the upstream initial valve opening pressure (P_o) and its corresponding $P2$.

6.4.2 Calculate the upstream test section pressure ($P1$) based on the upstream initial valve opening pressure (P_o) for the set constant downstream test section pressure ($P2$) from 6.4.1 and the value of delta pressure (dP) from 6.3.3.

$$P1 = P_o + dP$$

6.4.3 Increase the upstream test section pressure ($P1$) to the $P1$ calculated in 6.4.2. After stable flow conditions are attained, record the proper values on Data Form 4 to calculate the stabilized gas flow rate, the upstream test section gas temperature ($T1$), $P1$, and the $P2$ which should remain constant for each higher $P1$ test. An alternate method as described in Appendix D can be used as follows. Increase the upstream test section pressure ($P1$) from P_o to $P1 = P_o$ + Max dP in a slow and continuous ramp. The length of time for the test must be greater than 5 time constants and the slope of the increase in $P1$ should be as constant as possible.

6.4.4 Check the valve opening pressure with zero downstream pressure (P_{voT}) following the final highest upstream test section pressure test based upon the maximum dP from 6.3.2 for the constant test downstream test section pressure ($P2$). If the P_{voT} varies more than 0.5% from the P_{voT}, tested in 6.3.4, then repeat the test beginning at 6.4.3 for the last $P2$.

6.4.5 Select the next downstream test section pressure ($P2$) and repeat 6.4.1 through 6.4.4 until the final constant $P2$ test series has been concluded.

6.4.6 Plot the upstream initial valve opening pressure (P_o) from 6.4.1, and calculate the gas flow rate (q_{gi}) for each test and graph the data with the upstream test section pressure ($P1$) as a function of q_{gi} for each constant downstream test section pressure ($P2$). The curves will appear as shown in Figure 14.

6.5 PERFORMING CONSTANT INJECTION PRESSURE TEST (CIPT)

6.5.1 Place the test specimen in the test section as defined in 3.4. Measure the valve opening pressure at temperature (P_{voT}). Record P_{voT} and the temperature. Since the valve closing pressure (P_{vcT}) can be difficult to accurately measure in the test fixture, calculate the P_{vcT} as follows:

$$P_{vcT} = P_{voT}(1 - A_s / A_b)$$

Record the calculated P_{vcT}.

6.5.2 Charge the basic flow test system with valve opening pressure at temperature, (P_{voT}). Be sure to close the equalizing control valve ECV after charging the system. The GLV will be open with P_{voT} upstream and downstream.

6.5.2.1 Adjust the upstream pressure to $P1 = P_{voT} - (0.1)*(P_{voT} - P_{vcT})$ while reducing downstream pressure ($P2$) from P_{voT} to 0.9 $P1$. Stabilize $P2$ at 0.9 $P1$. Record the proper values as indicated on Data Form 4.

6.5.2.2 Decrease the downstream pressure ($P2$) in equal increments so that at least 6 flow rates have been stabilized and measured; and the GLV has closed or the $P2$ has been reduced to zero psig.

Note: As in the probe test, it is important to keep the $P2$ in a decreasing mode. If when approaching a desired $P2$, and it is inadvertently passed, do not go back up to the desired $P2$, but instead stabilize at a slightly lower $P2$.

An alternate method as described in Appendix D can be used as follows. Decrease the downstream test section pressure ($P2$) from $P1$ to zero psig in a slow and continuous ramp. The length of time for the test must be greater than 5 time constants and the slope of the decrease in $P2$ should be as constant as possible. Record at least 6 flow rates during the ramp test.

6.5.2.3 The upstream pressure ($P1$) must be maintained within 5 psi of target value while testing at the downstream pressures ($P2$) above.

6.5.2.4 Check P_{voT} after the test. It must be within 0.5% of initial P_{voT}. Record this P_{voT} and the temperature at the end of the test.

6.5.2.5 Recharge the basic flow test system to an upstream pressure:

$$P1 = P_{voT} - (0.25)(P_{voT} - P_{vcT})$$

Reduce downstream pressure ($P2$) to 0.9 $P1$ and stabilize. Record the proper values as indicated on Data Form 4. Repeat 6.5.2.2 through 6.5.2.4.

6.5.2.6 Recharge the basic flow test system to an upstream pressure:

$$P1 = P_{voT} - (0.5)(P_{voT} - P_{vcT})$$

Reduce downstream pressure ($P2$) to 0.9 $P1$ and stabilize. Record the proper values as indicated on Data Form 4. Repeat 6.5.2.2 through 6.5.2.4.

6.5.2.7 Recharge the basic flow test system to an upstream pressure:

$$P1 = P_{voT} - (0.65)(P_{voT} - P_{vcT})$$

Reduce downstream pressure ($P2$) to 0.9 $P1$ and stabilize. Record the proper values as indicated on Data Form 4. Repeat 6.5.2.2 through 6.5.2.4.

API Recommended Practice 11V2 Data Form 4

API Valve Identification: ______________________________ Set P_{vo}= ______________ psig at 60°F

Vendor name, assembly number, and description ______________________________________

Bellows area= ______________ sq. in. Stem-seat area= ______________ sq. in. Port Bore= ______________ in.

Probe test date: ______________ Max. EffectiveTravel= ______________ in. for ΔP= ______________ psi

Avg. Bellows assembly load rate= ______________ psi/in. Name of technician: ______________

Performance test date: ______________ Meter tube ID= ________ in. Gas Gravity= ______________

Time begin test: ______________ P_{vot}= ______________ psig @ ________ °F

Time end test: ______________ P_{vot} ______________ psig @ ________ °F

	Gas Orifice Meter Tube Data					Gas-lift Valve Fixture Data			
Test No.	Orifice Bore ID in.	Pressure psig	Diff. in. water	Flowing Temp. °F	Computer Gas Rate MSCFD	Upstream Pressure psig	Downstream Pressure psig	Inlet Temp. °F	Delta P Across Valve psi

6.5.3 Test the valve at upstream pressures ($P1$) greater than the valve opening pressure (P_{voT}) (the orifice flow regime). Calculate a maximum dP above P_{voT} using 6.3.1 and 6.3.2.

6.5.3.1 Recharge the basic flow test system to an upstream pressure:

$$P1 = P_{voT} + \text{maximum } dP$$

Reduce downstream pressure ($P2$) to 0.9 $P1$ and stabilize. Record the proper values as indicated on Data Form 4. Repeat 6.5.2.2 through 6.5.2.4. Obtain at least two $P2$'s that are less than half the upstream pressure.

6.5.3.2 Recharge the basic flow test system to an upstream pressure:

$$P1 = P_{voT} + (0.5)(\text{maximum } dP)$$

Reduce downstream pressure ($P2$) to 0.9 $P1$ and stabilize. Record the proper values as indicated on Data Form 4. Repeat 6.5.2.2 through 6.5.2.4. Obtain at least two $P2$'s that are less than half the upstream pressure.

6.5.3.3 If the valve manufacturer intends for the valve to be used in a well only in the throttling flow regime, he may elect to use only a small fraction of maximum dP in 6.5.3.1.

6.5.4 Plot the data. The plot will have the form shown in Figure 15. Be sure to include the valve closing pressure (P_{vcT}) as an integral part of the plotted data.

6.5.5 Data accumulation. If data is accumulated manually, use the convenient Data Form 4.

7 Recommended Tests to Develop Correlations

The use of test data for the purpose of predicting valve performance at conditions other than those tested will require the development of models or correlations. This RP describes the type of tests and the manner of performing those tests which will give the information needed to develop a model. All or part of these tests could be used to develop a model. Suggestions on the quantity of tests required to develop a model are given in the following paragraphs.

7.1 PROBE TESTS

Section 4 describes the procedure to be followed to determine a valve's bellows assembly load rate (B_{lr}) and the valve's maximum effective valve stem travel. Section 4 also describes the number of tests and the set pressures to be tested.

7.2 FLOW COEFFICIENT TESTS

Section 5 describes the procedures to be followed to determine a valve's flow coefficient (C_v) and pressure drop ratio factor (X_t) as a function of the maximum effective valve stem travel. The number of tests required to determine a valve's full range of operation are recommended in Section 5. When performed correctly, the procedures given in Section 5 will give data applicable for any range of pressure and for any type of gas.

7.3 GAS-LIFT VALVE PERFORMANCE TESTS

Section 6 describes the procedures to be followed to obtain the dynamic valve performance characteristics for a valve with a given set pressure. To obtain sufficient data to develop a model, additional tests are required at different set pressures.

The test procedures described in Section 6 should be performed on a valve set at a minimum of three set pressures. Two of these set pressures should be the manufacturer's minimum and maximum recommended set pressures and the third set pressure should be an intermediate pressure. The chosen set pressures should be at least 200 psig (1379 kPa) apart.

For example, a valve recommended for operation between 600 psig (4137 kPa) and 1800 psig (12410 kPa) should preferably be tested at 600, 1200, and 1800 psig (4137, 8274, and 12410 kPa) set pressures.

7.4 USE OF TEST DATA

The test procedures described in the previous sections will yield sufficient data to develop a model of valve performance which can be used to predict gas passage at conditions other than those tested. Two example models are presented in Appendices A and B. Additional models are also possible but will not be described here.

Appendix A is a simplified model which uses the test data collected as per Sections 4 and 5. This model makes several assumptions concerning the stem position during flowing conditions and may not be appropriate for gas passage prediction under all circumstances. The simplified model does not require data collected per Section 6. If data from Section 6 were collected, it could be used to "modify" the simplified model to account for the dynamic pressures occurring inside the valve and thus produce a more accurate model. The method of use of the data from Section 6 to "modify" the simplified model is beyond the scope.

Appendix B is a model which uses the test data collected as per Section 6. It relies on a statistical correlation of a multitude of dynamic valve tests. This model does not require the use of data as collected per Sections 4 and 5.

APPENDIX A—SIMPLIFIED MODEL

A.1 Simplified Model

The model described in the following paragraphs is simplified and will use the data collected in Sections 4 and 5. This model is based on the following assumptions.

1. The measured downstream pressure at the test section is assumed to work on the ball/seat contact area.
2. The areas acted upon by both upstream and downstream pressure remains constant.
3. The static force balance equation is used to determine the stem position.

The amount of error in calculated stem position increases as the port sizes increase. Accuracy of flow rate prediction is within approximately ± 30% for ports of 3/16 in. or less. This statement of accuracy is based upon only a limited comparison of tested values from a 1 in. IPO valve. Accuracy for other valves could be different.

An improvement to the simplified model would also include the data obtained in Section 6 to more accurately define dynamic stem position during flowing conditions.

A.2 Determine Stem Position

For the anticipated subsurface pressure and temperature conditions, determine the valve's static stem position using the static force balance equation which includes a term for the travel and load rate of the valve. For example, the static force balance equation for a nitrogen or spring loaded valve would be as follows:

$$P_{vcT} * A_b + B_{lr} * A_b * dx = P_{iod} * (A_b - A_s) + P_{pd} * A_s$$

$$dx = [P_{iod} * (A_b - A_s) + P_{pd} * A_s - P_{vcT} * A_b] / B_{lr} * A_b$$

A.3 Determine C_v and X_t

From the graph of C_v versus stem travel, read the flow coefficient (C_v) for the static stem travel computed in A.2. From the graph of X_t versus stem travel read the pressure drop ratio factor (X_t) for the static stem travel computed in A.2.

A.4 Calculate Flow rate

Use the following formula to calculate flow rate:

$$q_{gi} = 32.64 * C_v * (P_{iod} + 14.7) * Y * [x / ((T_v + 460) * S_g * Z)]^{\frac{1}{2}} \quad 1$$

where

x = $(P_{iod} - P_{pd})/(P_{iod} + 14.7)$ or $F_k * X_t$ whichever is less[1],

Y = $1 - [x/(3 * F_k * X_t)]$ and $F_k = k/1.40$[1],

k = Ratio of specific heat of lift gas.

A.5 Example of use of Simplified Method

Assume you are using a 1 in. IPO valve with 3/16 in. port. The upstream pressure (P_{iod}) is 925 psig, the downstream pressure (P_{pd}) is 450 psig, the P_{vo} = 825 psig, the temperature at depth is 150°F, and the specific gravity of the gas is 0.65. Figure 12 can be used as the Flow Coefficient curve and Figure 13 can be used for the Critical Pressure Ratio curve.

A.5.1 DETERMINE STEM POSITION

Compute P_{voT} at a temperature of 150°F. This can be approximated as follows. If a manufacturer's temperature correction chart is available, this should be used rather than the approximate method shown below. Also a chart of the compressibility factor for nitrogen should be used to determine Z.

$$P_{voT} = Ptro * Z * (\text{Temperature at depth} + 460) / (60 + 460)$$

$$P_{voT} = 825 * 0.95 * (150 + 460) / (60 + 460) / 0.95 = 919\text{psig}$$

$$P_{vcT} = P_{voT} * (A_b - A_p) / A_p$$

$$P_{vcT} = 919 * (0.31 - 0.0276) / 0.31 = 837\text{psig}$$

Use the static force balance equation to compute a stem position. At a P_{vcT} of 837 this valve has a loadrate of 935 psig/in. Use the valve manufacturer's tested loadrate at temperature. This valve has an effective stem travel of 0.085 in. Use the valve manufacturer's maximum effective stem travel whenever possible.

$$dx = [P_{iod} * (A_b - A_s) + P_{pd} * A_s - P_{vcT} * A_b] / B_{lr} * A_b$$

$$dx = [925 * (0.31 - 0.0276) + 450 * 0.0276 - 837 * 0.31] / 935 * 0.31 = 0.049$$

The computed stem travel (dx = 0.049) cannot exceed the maximum effective stem travel (LST = 0.085). In our case, this does not happen, however, if the computed stem travel was calculated to be greater than the LST, then the LST should be used in the following equations.

[1]Instrument Society of America Standard S75.02 or latest revision.

A.5.2 DETERMINE C_V AND X_t

Use Figure 12 as the flow coefficient curve. Compute the C_V using the curve fit for a stem travel of 0.049.

$$C_v = 219.3*dx\text{^}3 - 149.04*dx\text{^}2 + 22.58*dx$$

$$C_v = 219.3*0.049\text{^}3 - 149.04*0.049\text{^}2 + 22.58*0.049 = 0.774$$

If the stem travel exceeds 0.095 in., then the maximum C_V should be used rather than the computed C_V. In our case, this does not occur, so use C_V = 0.774.

Use Figure 13 as the Critical Pressure Ratio Factor curve. Compute X_t using the curve fit for a stem travel of 0.049.

$$X_t = 734.4*dx\text{^}3 - 178.3*\mathrm{dx}\text{^}2 + 15.12*dx$$

$$X_t = 734.4*0.049\text{^}3 - 178.3*0.049\text{^}2 + 15.12*0.049 = 0.40$$

A.5.3 CALCULATE THE FLOW RATE

1. Calculate the pressure ratio (x)

$$x = (P1 - P2)/(P1 + 14.7)$$

$$x = (925 - 450)/(925 + 14.7) = 0.505$$

2. Determine if the valve is in critical flow. If x is greater than X_t then the valve is in critical flow and X_t must be used rather than x to compute flow rate. X_t = 0.40 and the actual pressure ratio is 0.505. This is greater than X_t and therefore, the valve is in critical flow and X_t must be used in the equation.
3. Compute the expansion factor (Y)

$$Y = 1 - x/(3*F_k*X_t)$$

$$Y = 1 - 0.4/(3*(1.3/1.4)*0.4) = 0.641$$

4. Compute the compressibility factor for natural gas at 925 psig and 150F or obtain from a chart.

$$Z = 0.95$$

5. Compute the flow rate

$$\mathrm{MSCFD} = 32.64*C_v*(P_{iod} + 14.7)*Y*\mathrm{sqrt}[x/((T_v + 460)*S_g*\mathrm{Z})]$$

$$\mathrm{MSCFD} = 32.64*0.774*(925 + 14.7)*0.641*\mathrm{sqrt}[0.4/((150 + 460)*0.65*0.95)] = 496$$

APPENDIX B—TUALP MODEL FOR GAS LIFT VALVE PERFORMANCE

This method developed by TUALP (Tulsa University Artificial Lift Projects) and has been documented in the literature. (See reference list at the end of this Appendix). This method represents an alternate approach to the simplified model presented in Appendix A. Also, the TUALP model does not use load rate data that were measured as per Section 4.

B.1 Introduction

This appendix describes a cost effective procedure to predict the dynamic performance of injection pressure operated gas-lift valves. The recommended procedure is based on an extensive study of gas-lift valve performance conducted at the Tulsa University Artificial Lift Projects. [1-10]

The expected accuracy for injection operated gas-lift valves was studied by using the standard error of the estimate, and qualitatively reviewing the pattern of data. The largest percentage deviations between the model and experimental data occur near the ends of the curves that describe very low rates of flow, but where the absolute deviation is comparably small. The numbers reported here are a safe upper bound over the range of data for any port size.

	Nitrogen Charged	Spring Loaded
Orifice	± 5%	± 5%
Variable Area	± 30%	± 15%

These uncertainties are based on numerous tests. Some 3967 data points were taken on 1 inch valves, including 1560 on the Camco BK, 477 on the Camco BK 1, 1112 on the McMurry-Hughes JR-STD, and 818 on the Teledyne-Merla NM 16R. An additional 2590 data points were gathered on the Camco R-20 1.5 inch valve, and more limited data were acquired on the McMurry-Hughes VR-STD and the Teledyne-Merla LN-20R. In each case the data points were distributed over a wide range of flow conditions and port sizes. For the 1 inch valves there were 158 orifice flow curves and 95 variable area curves. Absolute percentage errors are reported because they are dimensionless. For orifice flow errors seldom exceed 13%, while some variable area flows exhibited large percentage errors at low flow rates, in rare cases as high as 93%. Nevertheless, the values given above will serve well in cases of interest in the field.

The test data are collected by the procedure given in Section 6.5 of 11V2. This Appendix is divided as follows:

- Section B.1 contains the introduction.
- Section B.2 distinguishes the orifice regime from the variable flow regimes for injection pressure operated gas-lift valves.
- Section B.3 develops the coefficients for the orifice flow model.
- Section B.4 develops the coefficients for the variable area model.
- Section B.5 describes the transition between the orifice and variable area flow regimes.
- Section B.6 describes the procedure used to calculate the gas flow rate using the orifice flow model.
- Section B.7 describes the procedure used to calculate the gas flow rate using the variable area flow model.

B.2 Flow Regimes for Gas-lift Valve Performance

Figure B-1 illustrates the two categories of flow: orifice and variable area. Both categories are further subdivided into two regimes based on the slope of the characteristic curve. Both categories exhibit a regime in which the rate of gas flow through the valve increases as differential pressure across the valve increases. This behavior appears in the figure as the right side of the characteristic curve where the slope is negative, because the injection pressure is held constant for a given curve, and the production pressure is plotted on the horizontal axis. Thus, increasing the production pressure toward the level of the injection pressure is equivalent to decreasing the differential pressure, and the negative sloping line intersects the abscissa where the differential pressure falls to zero. For the orifice flow category, convention dictates that we call this regime subcritical flow. For the variable area flow category, we call it "below maximal flow" or "submaximal flow". The root word maximal is used because the maximum of the variable area curve does not necessarily occur at the "critical" flow point. Furthermore, the word "below" refers to the differential pressure rather than the production pressure.

The distinction between the two categories of flow is determined by the left side of the characteristic curve for production pressures below a critical value, P_{pd}, for orifice flow or P_{pdmax} for variable flow. In orifice flow the slope of the curve is zero, which means that no matter how much the differential pressure increases by dropping the production pressure, the rate of flow does not change. Thus, in orifice flow, we call this regime critical flow. The variable area flow, on the other hand, exhibits decreased flow as differential pressure increases, to the limit that flow ceases altogether when the differential pressure becomes too great. Again referring to the differential pressure rather than the production pressure, we call this regime "supermaximal" flow. The production pressure that corresponds to the differential pressure at which the valve shuts off flow completely is called P_{pdc}, the valve closing pressure.

Figure B-4 shows the relationship between the two categories. Injection pressure is plotted on the third axis. Orifice flow occurs when the injection pressure exceeds a transition pressure, P_{tran}. Variable area flow occurs when production

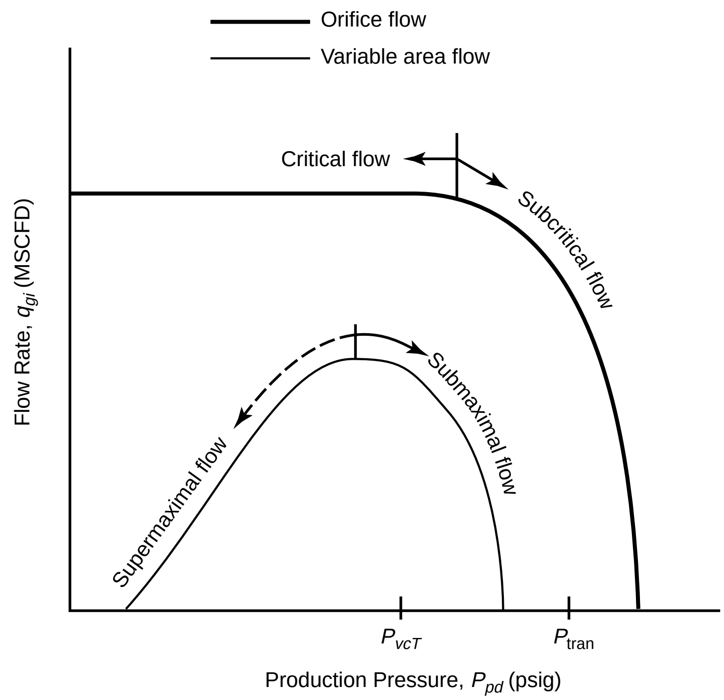


Figure B-1—Flow Regimes for Gas-lift Valve Performance

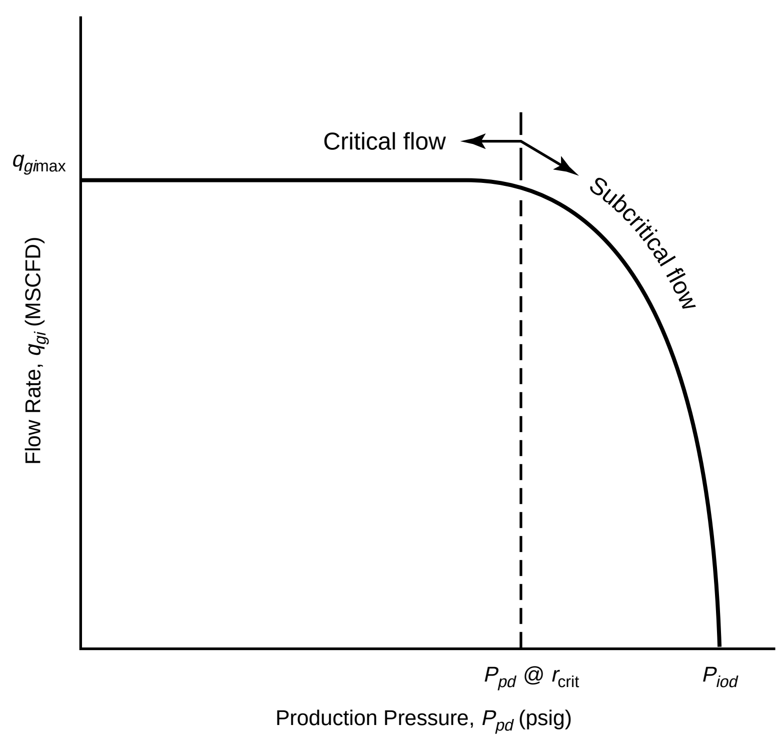


Figure B-2—Orifice Flow Regime

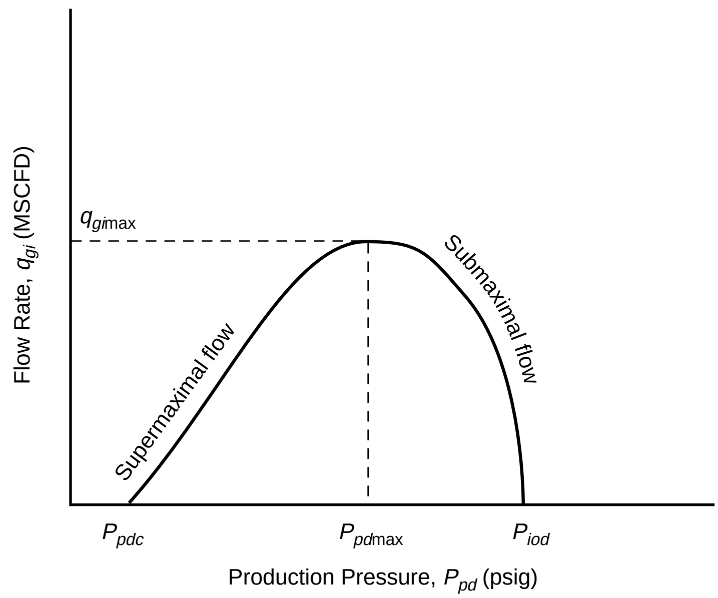


Figure B-3—Variable Area Flow Regime

pressure is less than the transition pressure but greater than the valve closing pressure.

B.3 The Orifice Flow Regime

The equation used to predict the throughput of a GLV in orifice flow is:

$$q_{gi} = 1241 A_p C_d Y \sqrt{\frac{P_{iod}(P_{iod} - P_{pd})}{T_v Z_v S_g}} \qquad \text{(B.3.1)}$$

where

q_{gi} = flow rate, MSCFD,

A_p = Port area, in.^{2},

Y = Expansion factor,

C_d = Experimental discharge coefficient that incorporates the term $\sqrt{(1-\beta^4)}$,

β = Ratio of port area to the inlet flow area,

S_g = Gas gravity (Air =1),

T_v = Injection temperature, °R,

Z_v = Compressibility factor at valve conditions,

P_{iod} = Injection pressure, psia,

P_{pd} = Production pressure, psia.

Note: P_{iod} and P_{pd} are in psia for equation B.3.1

A minimum of two experimentally determined orifice flow curves generated using one valve closing pressure, P_{vcT}, and two different injection pressures are needed to calculate the product C_dY for each port size. The valve closing pressure should be near the middle of the expected range of operation, and the two injection pressures should span the expected range of operation. The two injection pressures must be greater than the transition pressure, P_{tran}, corresponding to the chosen valve closing pressure, P_{vcT}, as discussed in Section B.5 and 6.5.3. The following steps establish the procedure that should be used to determine the product C_dY from the experimental data for each port size:

a. For each measured data point, back-calculate the product C_dY from Equation B.3.1:

$$C_yD = \frac{q_{gi}}{1241 A_p} \sqrt{\frac{T_v Z_v S_g}{P_{iod}(P_{iod} - P_{pd})}} \qquad \text{(B.3.2)}$$

where

P_{iod} and P_{pd} are in psia.

b. For each port size, plot C_dY against the dimensionless pressure ratio, $(P_{iod} - P_{pd})/P_{iod}K$, as shown in Figure B-5. K is the ratio of specific heat at constant pressure to constant volume (Air = 1.4). The pressures P_{iod} and P_{pd} are in psia.

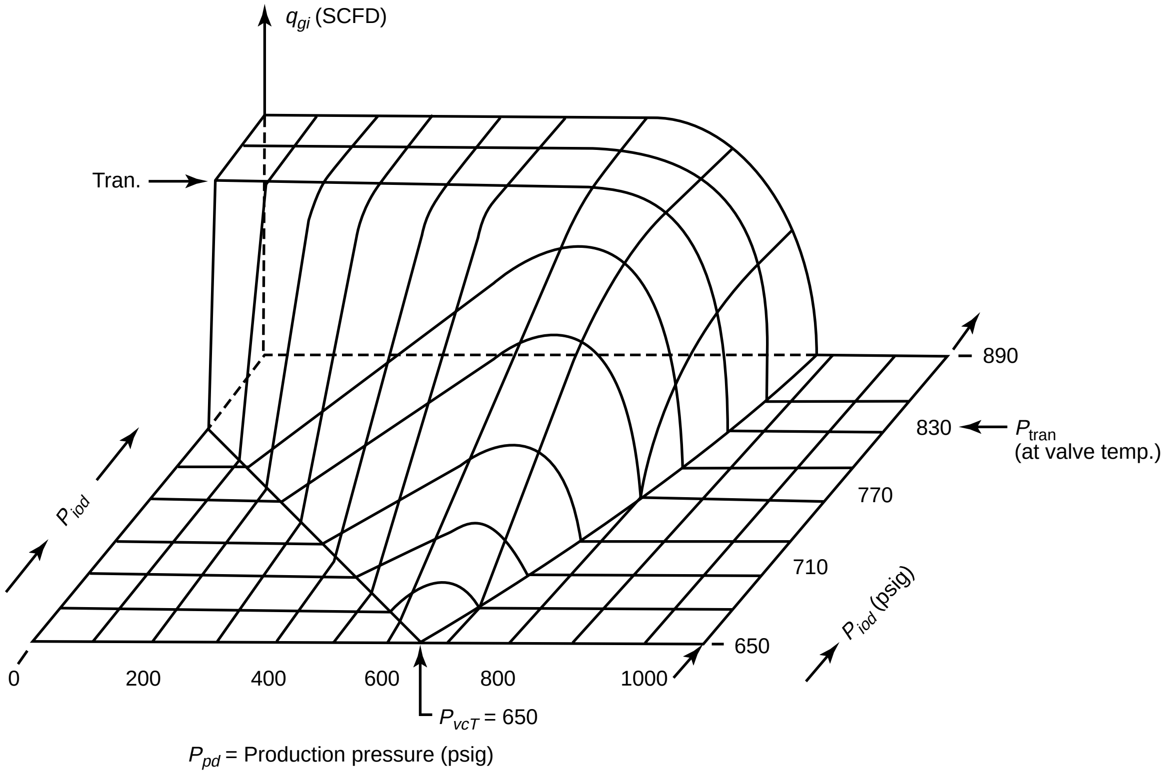


Figure B-4—Idealized Three-Dimensional Nitrogen Charged Gas-lift Valve Performance

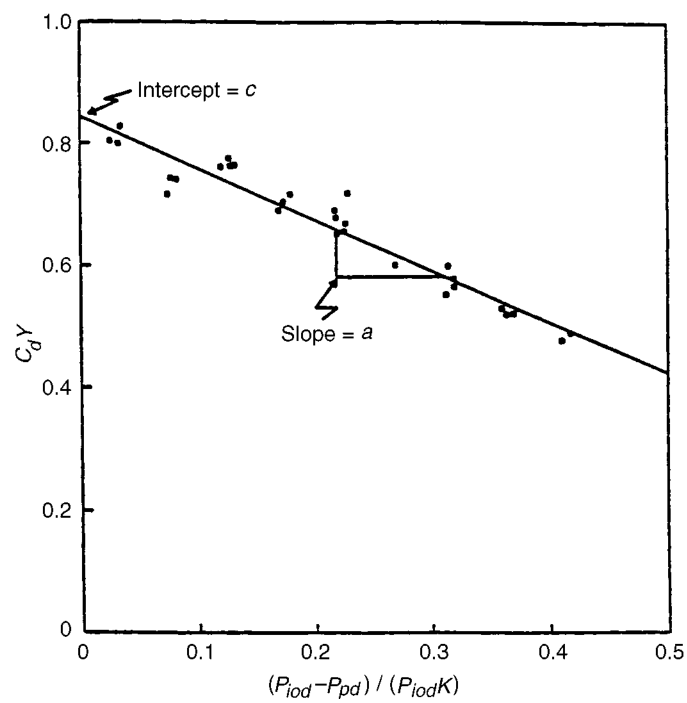


Figure B-5—Product C_dY vs. $(P_{iod} - P_{pd})/(P_{iod}K)$ for a Gas-lift Valve with a 0.25 in. (0.635 cm) Port

c. Draw a best fit straight line through the data. Obtain the slope, *a*, and the intercept, *c*, of the straight line. Thus, the equation for C_dY will be:

$$C_dY = a(P_{iod} - P_{pd})/(P_{iod}K) + c \qquad \text{(B.3.3)}$$

For the example show in Figure B-5, $a = -0.838$ and $c = 0.844$.

d. The critical pressure ratio, r_{crit}, for the orifice flow curve, at which the gas flow rate, $q_{gi\max}$, becomes constant and independent of the decreasing production pressure, can be determined graphically from a plot of $(q_{gi\max} - q_{gi})/(P_{iod} - P_{pd})$ versus the pressure ratio P_{pd}/P_{iod} where P_{pd} and P_{iod} are in psia. For the example considered in Figure B-6, the critical pressure ratio, r_{crit}, is 0.67. Thus, the production pressure at which the flow becomes constant is:

$$P_{pd}@r_{\text{crit}} = r_{\text{crit}}P_{iod} \qquad \text{(B.3.4)}$$

For

$$P_{pd} < P_{pd}@r_{\text{crit}} \qquad \text{(B.3.5)}$$

the flow will be in critical orifice flow and for

$$P_{pd} > P_{pd}@r_{\text{crit}} \qquad \text{(B.3.6)}$$

the flow will be in subcritical orifice flow.

B.4 Variable Area Flow Regime

At least four experimentally determined variable area flow curves are required to predict the variable area flow performance of a valve for each port size. In order to insure that the correlation covers the expected possible range of operating pressures, use two valve closing pressures, P_{vcT}, one at the lower end and one at the upper end of the expected range of operation. For each valve closing pressure, P_{vcT}, two corresponding injection pressures, P_{iod}, should then be used. The injection pressures are chosen to be greater than the valve closing pressure, P_{vcT}, but less than the transition pressure, Ptran, at the corresponding P_{vcT} in order to insure that the valve will operate in the variable area flow region. The selection of the test pressures is also discussed in 6.5.3.

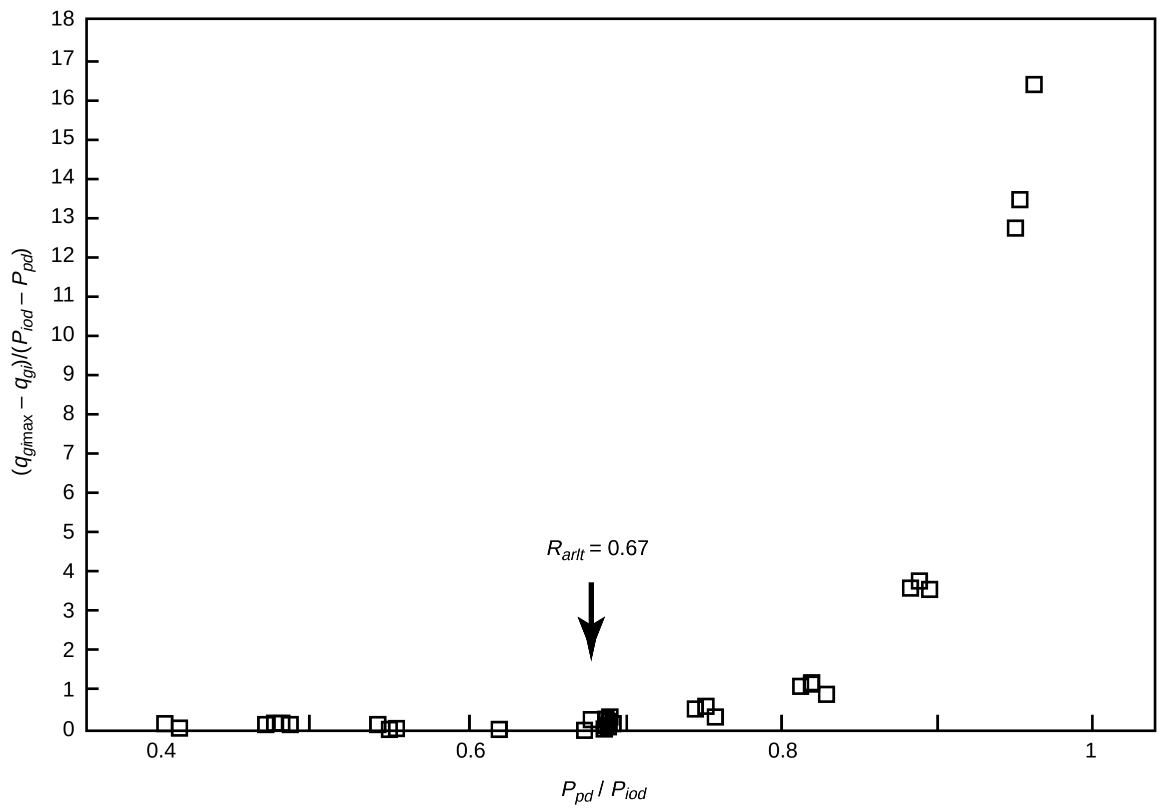


Figure B-6—The Critical Pressure Ratio is 0.67 at $(q_{gi\max} - q_{gi})/(P_{iod} - P_{pd}) = 0$ for a 0.25 in. (0.635 cm) Port

The following steps establish the procedure that should be used to determine the coefficients that describe the variable area flow performance for a given valve and port size. In the first five steps, a through e, the coefficients are determined to predict variable area flow when P_{pd} exceeds the production closing pressure, P_{pdc}, but is less than P_{pdmax}. Step f determines the parameters needed to predict the flow rate when P_{pd} is greater than P_{pdmax} but less than P_{iod}. Step g examines the tubing effect factor, F_e.

a. Determine the extrapolated production closing pressure for each variable area flow curve. This is not the same closing pressure that is predicted by the standard force balance equation. The extrapolated production pressure is obtained from each experimental variable area flow curve by extrapolating the slope of the variable area flow curve as shown in Figure B-7. For this example, P_{pdc} = 250 psig (1724 k Pa).

b. For each variable area curve, determine the maximum flow rate $q_{gi\max}$. For the experimental variable area curve shown in Figure B-7, $q_{gi\max}$ = 415 MSCFD (11,749 m^3 /D).

c. For each tested data point, plot the normalized flow rate $q_{gi}/q_{gi\max}$ against the normalized pressure, N, where:

$$N = (P_{pd} - P_{pdc}) / (P_{iod} - P_{Pdc}) \qquad \text{(B.4.1)}$$

The values of all variable area flow curves should be superimposed on one graph, as shown in Figure B-8. Next, determine the normalized pressure, $N_{\max}$, that corresponds to the maximum normalized flow rate, as illustrated in Figure B-8. For this example, $N_{\max}$ = 0.55.

d. For each variable area flow curve, calculate the production pressure, $P_{pd\max}$, at which maximum normalized flow rate occurs. This is done by substituting $N_{\max}$ determined in Step c into Equation B.4.1 and solving for $P_{pd\max}$:

$$P_{pd_{\max}} = N_{\max}(P_{iod} - P_{pdc}) + P_{pdc} \qquad \text{(B.4.2)}$$

For this example, $P_{pd\max}$ = 470 psig (3.240k Pa).

e. Determine the slope of each variable area flow curve when Ppd is between P_{pdc} and $P_{pd\max}$ using the equation:

$$\text{slope} = q_{gi_{\max}} / (P_{pd_{\max}} - P_{pdc}) \qquad \text{(B.4.3)}$$

Then fit a straight line through the slope data and determine the coefficients m and b:

$$\text{slope} = mP_{vcT} + b$$

For example, from Figure B-9, the coefficients m and b were determined to be: m = 0.00127 MSCFD/psi/psi and b = 1.25 MSCFD/psi.

Note: the calculated slope can be either positive or negative, depending on the variable area response of the valve.

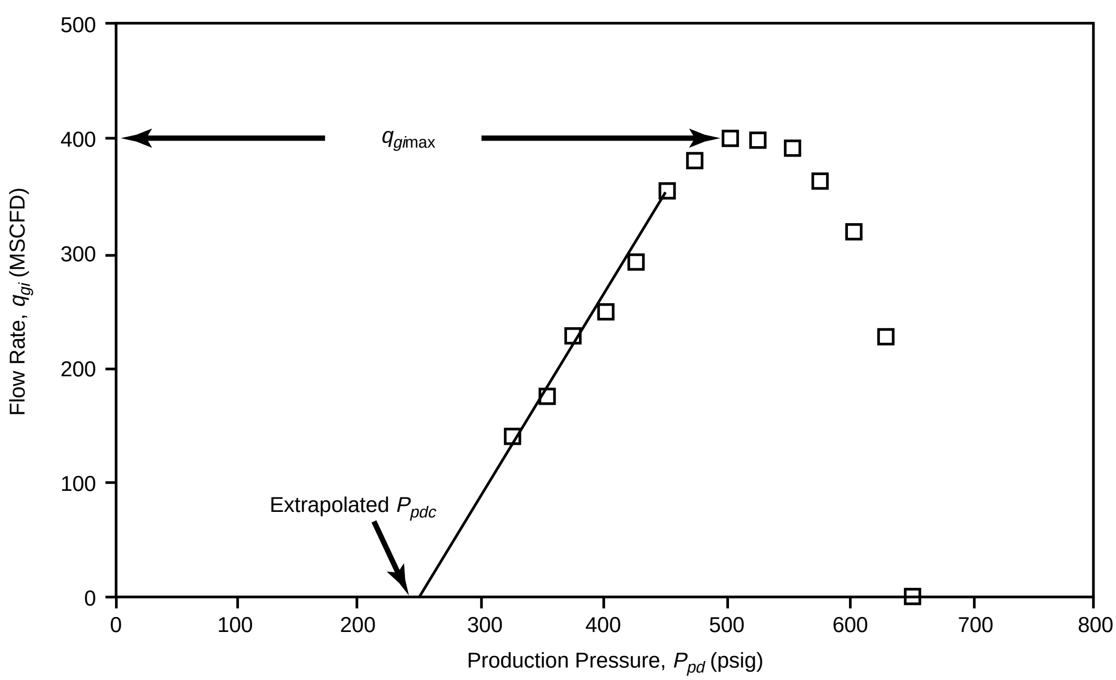


Figure B-7—Determining P_{pdc} and $q_{gi\max}$ from the Experimental Throttling Flow Curve

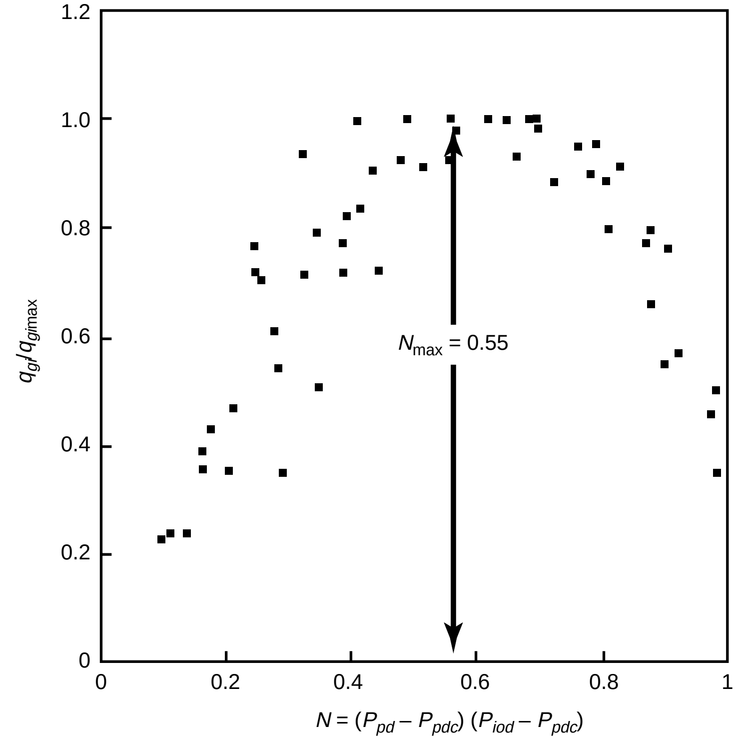


Figure B-8—The Plot of $q_{gi} - q_{gimax}$ vs. N Determines the Coefficient N_{max}

f. For each variable area flow curve and a specific port size, calculate the dynamic tubing sensitivity factor, F_e, from the force balance equation:

$$F_e = (P_{iod} - P_{vcT})/(P_{iod} - P_{pdc})$$

Note: the dynamic tubing sensitivity factor is different from R, which is the ratio of the seat area to the bellows area. The final F_e is calculated by averaging the tubing sensitivity factors for all of the variable area curves. For the example considered, the average F_e was determined to be 0.09.

B.5 The Transition between Orifice and Variable Area Flow

The transition between orifice and variable area flow regimes for a specific port size and valve closing pressure, can be calculated from the following equation:

$$P_{tran} = P_{vcT}(1 + F_e)$$

Another criterion that can be used to determine the transition pressure is to assume that the transition occurs at the test rack opening pressure, P_{voT}, at the given temperature.

Thus:

$$P_{tran} = P_{voT} = \frac{P_{vcT}}{1 - R}$$

The above two equations may result in somewhat different predictions of the transition pressure. Equation 6.5.2 is recommended over Equation 6.5.4.

B.6 Step by Step Procedure to Calculate the Gas Flow Rage Using the Orifice Flow Model

This section outlines a step by step procedure to calculate the gas flow rate for a valve operating in the orifice flow regime using the current model. For a given valve, port size, A_p, valve closing pressure, P_{vcT}, injection pressure, P_{iod}, production pressure, P_{pd}, flowing temperature, T_v, and gas properties, the flow rate is calculated as follows:

a. Determine if the operating conditions will result in orifice flow, i.e., if $P_{iod} > P_{tran}$, which was calculated using either Equation B.5.2 or Equation B.5.3. If this is the case, then pro-

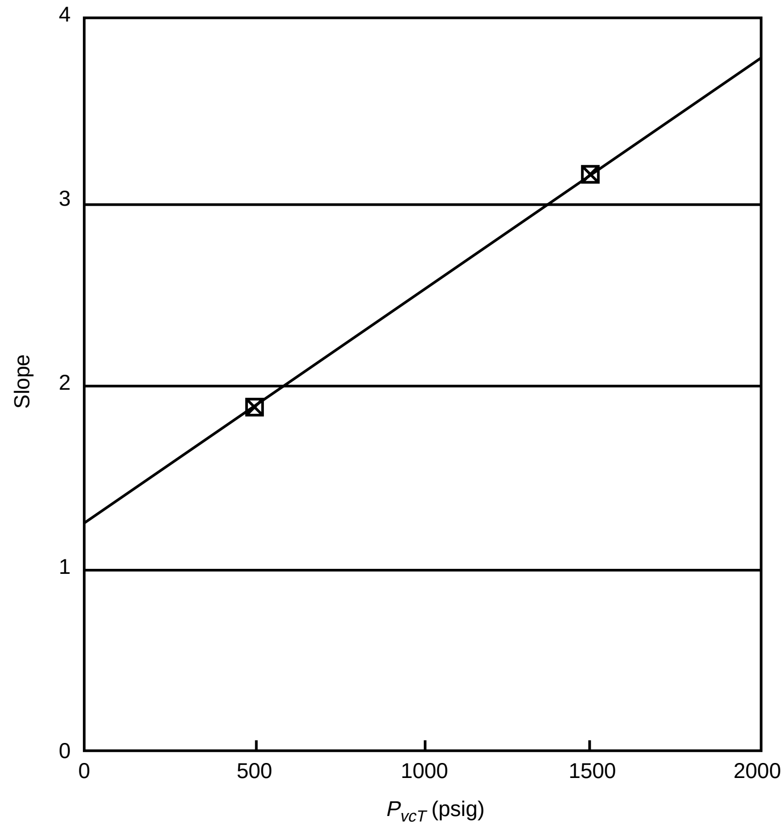


Figure B-9—The Slope of Throttling Flow Curve vs. P_{vcT} for a Valve with a 0.25 in. (0.635 cm) Port

ceed with the calculations for orifice flow, otherwise go to Section B.7.

b. Calculate the production pressure at the critical pressure ratio using Equation B.3.4:

$$P_{pd}@r_{\text{crit}} = r_{\text{crit}}P_{iod} \quad \text{(B.6.1)}$$

c. Compare the production pressure, P_{pd}, to the calculated production pressure at r_{crit} for the selected valve and port size. If

$$P_{pd} > P_{pd}@\text{r}_{\text{crit}} \quad \text{(B.6.2)}$$

then use P_{pd} to calculate the flow rate, q_{gi}, from Equations B.6.4 and B.6.5. However, if

$$P_{pd} < P_{pd}@\text{r}_{\text{crit}} \quad \text{(B.6.3)}$$

then replace P_{pd} with $P_{pd}@r_{\text{crit}}$ in Equations B.6.4 and B.6.5.

d. Use the appropriate value of P_{pd} determined in Step c to calculate the product C_dY using equation B.3.3:

$$C_dY = a(P_{iod} - P_{pd})/(P_{iod}K) + c \quad \text{(B.6.4)}$$

where a and c are determined in Step c of Section B.3.

e. Use this value of C_dY and the value of P_{pd} determined in Step c to calculate the resulting gas flow rate for orifice flow from Equation B.3.1:

$$q_{gi} = 1241 A_p C_d Y \sqrt{\frac{P_{iod}(P_{iod} - P_{pd})}{T_v Z_v S_g}} \quad \text{(B.6.5)}$$

Note: The pressures P_{pd} and P_{iod} should be converted to psia for Section B.6.

B.7 Step by Step Procedure to Calculate the Gas Flow Rage Using the Variable Area Flow Model

This section outlines a step by step procedure to calculate the gas flow through the valve in variable area flow:

a. Determine if the conditions favor variable area flow, i.e., if $P_{iod} < P_{tran}$ where P_{tran} was calculated using either Equation B.5.2 or B.5.3. If variable area flow is indicated, then proceed to calculated the resulting variable area flow rate. Otherwise, go to Section B.6.

b. Calculate the production closing pressure using the coefficient F_e (determined from Equation B.4.6) for the given valve and port size:

$$P_{pdc} = P_{iod} - (P_{iod} - P_{vcT})/F_e \qquad \text{(B.7.1)}$$

c. Calculate $P_{pd\max}$ with the $N_{\max}$ corresponding to the valve and port size, using Equation B.4.2. ($N_{\max}$ is determined in Step c of Section B.4):

$$P_{pd_{\max}} = N_{\max}(P_{iod} - P_{pdc}) + P_{pdc} \qquad \text{(B.7.2)}$$

d. If $P_{pdc} < P_{pd} < P_{pd\max}$, proceed with Steps e, f and g. Otherwise, when $P_{pd} > P_{pd\max}$, go to Step h.

e. For variable area flow performance in the supermaximal region, calculate the slope of the variable area using the coefficients *m* and *b* calculated in Step c of B.4 for the specific valve and port size:

$$\text{slope} = mP_{vcT} + b \qquad \text{(B.7.3)}$$

f. Finally, calculate the flow rate:

$$q_{gi} = \text{slope}(P_{pd} - P_{pdc}) \qquad \text{(B.7.4)}$$

g. If the flow tests were conducted at a different temperature, Tm, than the injection temperature, T_v, or the gas gravity of the injection gas, S_g, differs from the gas gravity, S_{gm}, used to perform the flow performance tests (which is usually air), then a correction should be made to the flow rate calculated in Step f:

$$q_{gi} = q_{gi}\ \text{(Step f)}\ \sqrt{\frac{T_m Z_M S_{gm}}{T_v Z_v S_g}} \qquad \text{(B.7.5)}$$

where

Z_m = Compressibility of the gas at T_m and P_{iod},

Z_v = Compressibility of the injected gas at T_v and P_{iod},

S_{gm} = Gravity of the gas used to conduct the flow tests, (Air = 1),

S_g = Gas gravity of the injected gas, (Air = 1),

T_m = Temperature at which the flow measurements were conducted, °R,

T_v = Injection temperature, °R.

h. When P_{pd} is greater than $P_{pd\max}$ but is less than P_{iod} and the flow is in submaximal region, the flow rate is calculated with a corrected orifice flow equation. The procedure to determine the correction factor is given as follows:

First, calculate $q_{gi\max}$ (variable area) using Equation B.7.1 through B.7.5 by letting $P_{pd} = P_{pd\max}$. Next, calculate q_{gi} (orifice flow) using equations B-6.4 through B.6.5, with $P_{pd} = P_{pd\max}$. Finally calculate the correction factor:

$$\text{Cor. Fac.} = \frac{q_{gi_{\max}}(\text{variable area})}{q_{gi}(\text{orifice flow } @P_{pd} = P_{pd_{max}})}$$

i. If Piod > $P_{pd} > P_{pd\max}$, the flow rate is calculated using a corrected orifice flow equation. The procedure followed is to calculate C_dY from Equation B.6.5 using the values of a and c determined in Section B.3 and the production pressure, P_{pd}:

$$C_d Y = a(P_{iod} - P_{pd})/(P_{iod}\ K) + c \qquad \text{(B.7.6)}$$

j. Use this value of C_dY, and calculate an orifice flow rate using the orifice Equation C.6.5:

$$q_{gi} = 1241 A_p C_d Y \sqrt{\frac{P_{iod}(P_{iod} - P_{pd})}{T_v Z_v S_g}} \qquad \text{(B.7.7)}$$

Note: The pressures P_{pd} and P_{iod} should be converted to psia for Equations B.7.6 and B.7.7.

k. Finally, correct the orifice flow rate calculated in Step j to a variable area flow rate by using the appropriate correction factor, calculated in Step h of this section.

$$q_{gi_{\text{corr}}} = \text{Cor. Fac. } q_{gi} \qquad \text{(B.7.8)}$$

B.8 References

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5. Sagar, R. K. "An Improved Dynamic Model of Gas-lift Valve Performance," MS thesis, The University of Tulsa, Tulsa, OK (1991).
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APPENDIX C—METHOD TO ANALYZE PROBE TEST DATA

A simple calculation technique is given for determining load rate and maximum LST (Load Rate Stem Travel) for a gas lift valve. The data needed to perform this calculation are measured during the probe test as described in Section 4. Applying this technique yields a consistent, reproducible value for load rate and maximum LST. Also, this technique can be programmed to run on a computer.

C.1 Assumptions

1. At least four data points of measured values are required.
2. Each data point in the set must have unique values of stem travel and system pressure.

Note: Ignore early data point in your set of measured data if these data shows a large (almost infinite) increase in slope at the smallest values of stem travel.

3. Starting at the smallest value of stem travel and system pressure; all points in the data set must continually increase.
4. All data below the point of maximum LST are fit to a linear ($y = m_A x + b_A$) relationship. Also all data above this point are fit to a separate linear ($y = m_B x + b_B$) relationship. Where m_A and m_B are the slopes of these two lines and b_A and b_B are the y-intercepts.
5. Also the measured slopes and intercepts must be unique(i.e., $m_A\ m_B$ and $b_A\ b_B$).

C.2 Hysteresis

Data measured from both increasing and decreasing system pressures, commonly show some hysteresis in the data. Possible cause(s) of this hysteresis has not been documented by the industry and will not be discussed in this RP. A suggested way to handle multiple data sets is to analyze each data set separately and calculate average values for load rate and maximum LST.

C.3 Calculation Procedure

The probe test data are plotted using a linear x- and y-scaled axis. The values of system pressure are plotted on the vertical y axis and stem travel are plotted on the horizontal x axis. Assume that there are no data points in the set.

Sort data from lowest to highest values for valve stem travel. Data point 1 has the lowest value of stem travel and point n has the highest.

Use the last two data points to define an initial guess for line B. Calculate the slope and intercept as:

$$\text{slope: } m_B = (y_n - y_{(n-1)})/(x_n - x_{(n-1)})$$

$$\text{Intercept: } b_B = y_n - (m_B x_n)$$

If the data set contains only four points then calculate the slope and intercept of line A as:

$$\text{slope: } m_A = (y_2 - y_1)/(x_2 - x_1)$$

$$\text{Intercept: } b_A = y_1 - (m_A x_1)$$

If their are more than four data points you must decide to what line the next (n – 2) data point belongs. Perform linear regression on data points {n – 2, n – 3, n – 4, ...} in order to calculate m_A and b_A for the line A defined as $y = m_A x + b_A$.

Calculate the shortest distance from point (n – 2) to lines A and B using the following equations, where i = A for line A and i = B for line B.

$$x_i = (y_{(n-2)} - b_i)/m_i$$

$$y_i = m_i x_{(n-2))} + b_i$$

$$x = |x_i - x_{(n-2)}|$$

$$y = |y_i - y_{(n-2)}|$$

$$= \tan^{-1}(y/x)$$

$$d = x \sin(\ )$$

Variable d is the shortest distance between point (n – 2) and line i .

If the distance between line B and point (n – 2) is less than the distance between line A and point (n – 2) then assume (n – 2) belongs to line B. Otherwise assume point (n – 2) belongs to line A.

Perform linear regression analysis again to re-compute slope and intercept of lines A and B. Include the (n–2) data point in the appropriate line as determined in step 6.

Repeat steps 4, 5, 6 and 7 for data points {n – 3, n – 4, n – 5, ...} in place of the (n – 2) data point, until a point belonging to line A is found.

Note: In most cases the number of data points used to define line B is smaller than the points used to define line A. By starting with the (n–2) data point and working backwards towards data point 3, you can minimize the total calculations required.

Calculate the x value for the point of intersection between lines A and B using the following equation:

$$\text{maximum LST} = (b_B - b_A)/(m_A - m_B)$$

The value of m_A (slope of line A) is also the load rate.

C.4 Example Calculation

Table C.4.1—Data Points used in Example Calculation

#	Stem Travel (in.)	Pressure (psig)
1= n – 10	0	450
2= n – 9	0.019	460
3= n – 8	0.032	470
4= n – 7	0.055	480
5= n – 6	0.070	490
6= n – 5	0.079	500
7= n – 4	0.102	550
8= n – 3	0.116	600
9= n – 2	0.126	650
10= n – 1	0.134	700
11= n	0.147	800

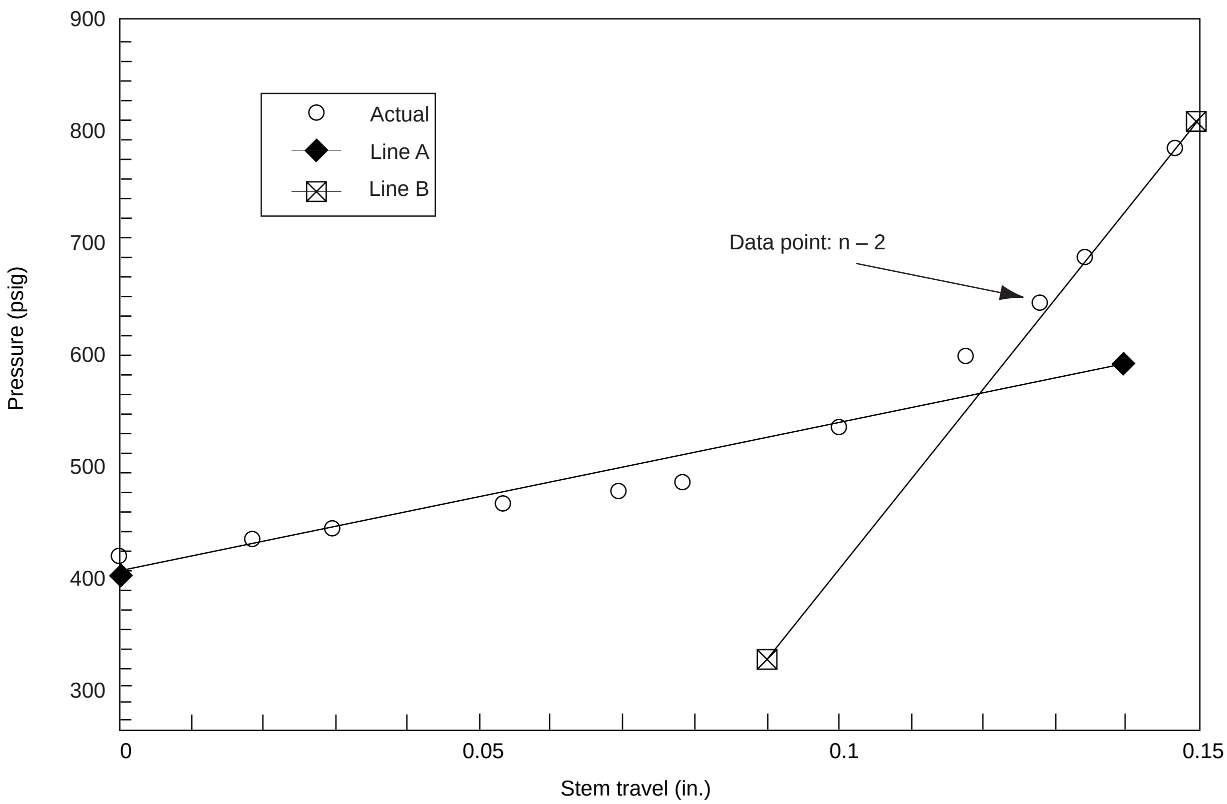

Figure C-1—First Estimate of Lines A and B Shows that Data Point n – 2 is Closest to Line B

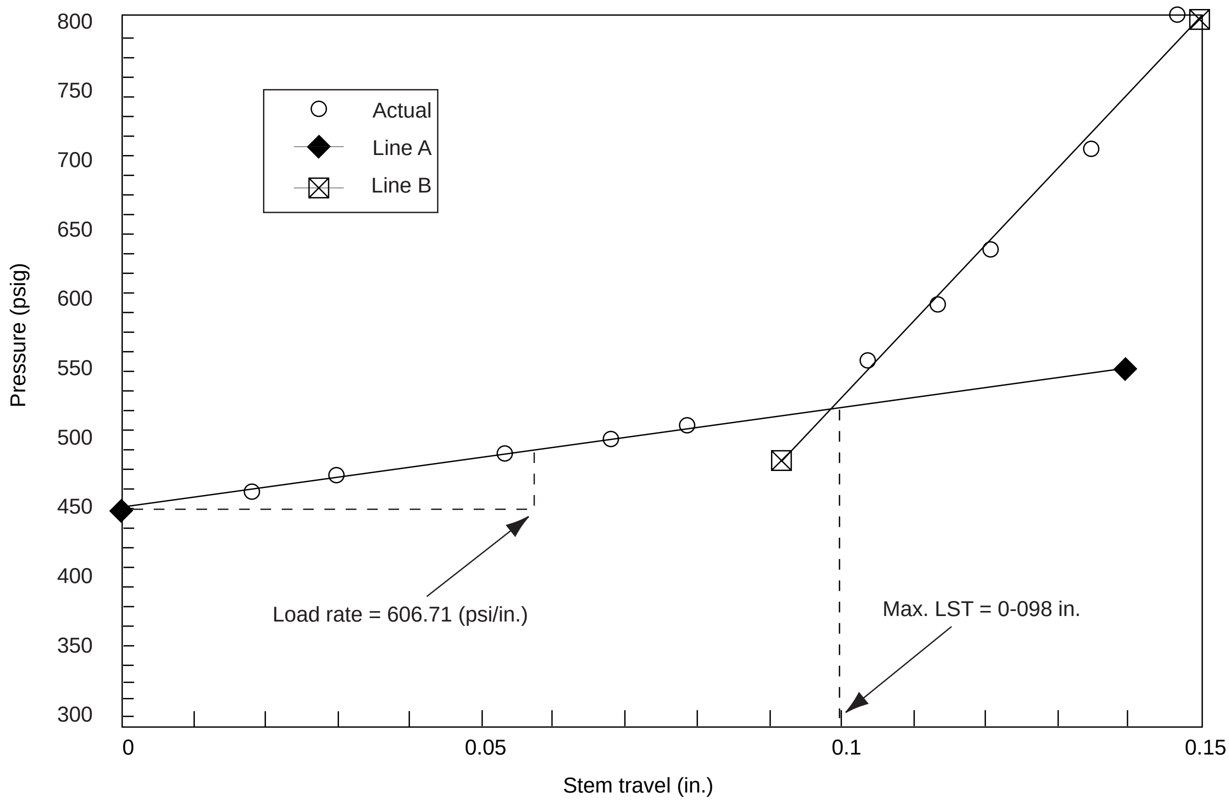

Figure C-2—Final Estimate of Load Rate and Maximum LST.
First Six Data Points Define Line A and Last Five Points Define Line B

APPENDIX D—USE OF A RAMP FUNCTION IN THE DYNAMIC GAS LIFT VALVE TEST

This appendix describes how to design and use a constant ramp change in pressure during the dynamic gas lift valve test procedures documented in Section 6 and the flow coefficient test procedure documented in Section 5. This ramp method helps ensure that the valve data collected represent the behavior of the gas lift valve at steady state conditions. Also, using this ramp method helps minimize the cost for performing a dynamic test since the volume of gas supplied and time needed to perform the test are minimized.

Note: It is assumed that all data collected during the dynamic tests are electronically recorded. Data recorded manually will probably not be accurate enough to apply the ramp method described in this Appendix. If the test system is not equipped with an electronic data logger or if for some other reason a constant ramp cannot be maintained during valve tests, then pressure can be changed as a series of discrete steps. See section D.4 at the end of this Appendix.

D.1 Background and Theory of Approach

Prior to discussing how to design and perform the constant ramp method, it will be helpful to define terms such as steady state and system time constant.

D.1.1 STEADY STATE

The components of a gas lift test system: gas lift valve, pressure gauges, lengths of pipe, etc., do not react instantaneous to changes in system pressure. For these components there will always have a measurable lag between the time an external step change in pressure is applied and the time required for the system to reach "Steady State."

Strictly speaking, a system reaches "Steady State" only after waiting an infinite amount of time. However for practical purposes, a gas lift test system is assumed to reach "Steady State" when values of *P*1 (upstream injection pressure), *P*2 (downstream production pressure), and flow rate are changing by only small random fluctuations. It is assumed that this random error will not significantly effect the calculations where these data are used. To see if this error is really important a sensitivity analysis on the specific gas-lift design calculations that use the test data may be required.

D.1.2 SYSTEM TIME CONSTANT

A study done using an actual gas lift valve and test section showed that the transient behavior of this system can be approximated by a first order response. See API memo: *Verification of Constant Injection Pressure Test Procedures in Gas-lift Valve Performance Testing,* by T. A. Hyde, August 24, 1993. The governing equations for a first order response are as follows:

Discharging system: (i.e., constant injection pressure tests)

$$P_2(t) = P_{1\max} * e^{(-t/h)}$$

where

$P_2(t)$ = Downstream system pressure (psig) as a function of time,

$P_{1\max}$ = Maximum upstream system pressure (psi),

t = Time (sec),

h = System time constant (sec).

The system time constant (*h*) is a physical parameter that varies with system geometry and physical properties of the gas. This time constant (*h*) can be used to determine how close the measured values are to steady state. For example, after an elapsed time of 1*t*, 2*t*, 3*t*, 4*t*, and 5*t*, the test system has reached 63.2%, 85.6%, 95%, 98% and 99% of steady state respectively.

In some cases the accuracy of the calculations can be improved by fitting the experimental data to a second order response. This analysis requires a curve fit of the experimental data and calculation of several empirical constants. For example in the case of the discharging test system, the following second order equation applies:

$$P_2(t) = A_1 * e^{(-t_1/h)} + A_2 * e^{(-t_2/h)}$$

where

$P_2(t)$ = Downstream system pressure (psig) as a function of time,

A_1, A_2 = Empirical constants determined by curve fitting data (psig),

t = Time (sec),

h = System time constants (sec) also found by curve fitting data.

It is also worth noting that increasing the capacity of surge tanks and overall pipe volume in the test system helps dampen out fluctuations in system pressure. This feature makes it easy for the operator to control the system pressures and read the pressure gauges and flow meters during a dynamic test. However, the trade-off for increasing this system volume is that it also acts to increase the system time constant. As this time constant increases, longer periods of time in order are required to ensure that measured data represent steady state conditions. The end result is an increased cost in terms of time and gas volume required.

D.2 Measuring System Time Constant

This section illustrates how to measure the system time constant for a typical discharging test system. This example assumes a first order response. This test must be performed on the test system configuration to be used for valve testing. DO NOT install a valve in the test section for this test. Make sure the bypass valve is closed before beginning.

D.2.1 STEP BY STEP PROCEDURE

1. Close the downstream valve in the test system.
2. Open the upstream valve in the test system so that both upstream and downstream pressures are equal at 850 psig (i.e., $P1_{max} = P2(t)$ at $t = 0$).
3. Start the data acquisition equipment and collect data at frequencies of no more than 2-second intervals. Open the downstream valve as rapidly as possible.
4. When $P2(t)$ is at atmospheric pressure or is changing by only small random fluctuations the test is complete.
5. Plot $P2$ as a function of time as shown in Figure D-1.
6. Calculate the first order time constant (t) either by finding the time required to decrease from an initial value of $P2 = P1_{max}$ at $t = 0$ to $P2(t) = (100 – 63.2)/100 * (P1_{max}$ – Lowest value of $P2(t)$). For example, $P2(t) = (100–63.2)/100 * (850 – 0) = 313$ psig. As an alternative, data can be curve fit to Equation D.1.0.

D.3 Using the System Time Constant to Design a Ramp for the Dynamic Test

Once the system time constant has been determined as described in D.2, it can be used to design a ramp function for carrying out the dynamic valve test as documented in Section 6 or the flow coefficient test as documented in Section 5. The ramp function is basically a constant rate linear decrease in downstream pressure $P2(t)$ over time as upstream pressure $P1_{max}$ is held constant.

Note: The duration of this ramp needs to be at least five time constants (5) to ensure that data recorded are within 99% of steady state.

Generally, a longer duration of this ramp is more conservative and provides more assurance that data are measured at steady state. Figure D-2 illustrates a ramp function design where the time constant was measured to be nine seconds. (i.e., = 9 sec.)

Deviations from linearity in the ramp function can be caused by a failure to maintain upstream pressure $P1_{max}$ constant or by rapid changes in the downstream pressure. These deviations in linearity cause error in the test data. To reduce this error design for a longer ramp with a gentler slope.

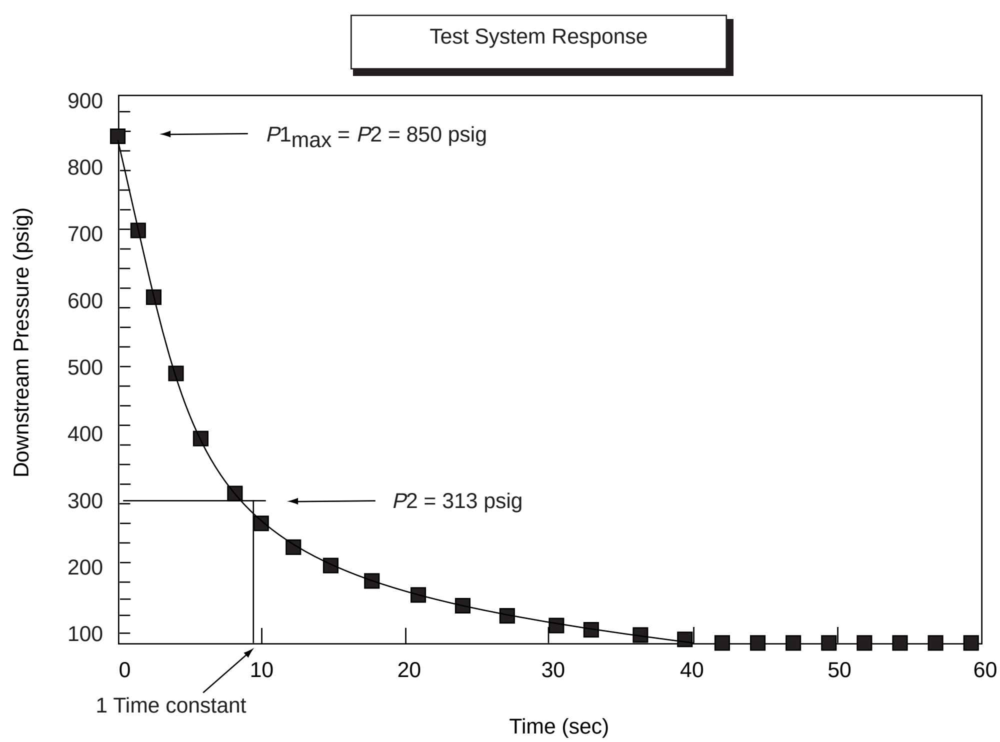

Figure D-1—Typical First Order Response for a Discharging Test System

D.4 Using a Series of Discrete Steps as an Alternate to the Ramp Method

An alternate procedure to the constant ramp method is to take the drops in system pressure as a series of discrete steps.

While this discrete step method generates less data, takes longer to run and requires more gas, it may be necessary to resort to this method if a constant ramp is too difficult to obtain or if electronic data recording capabilities are not available.

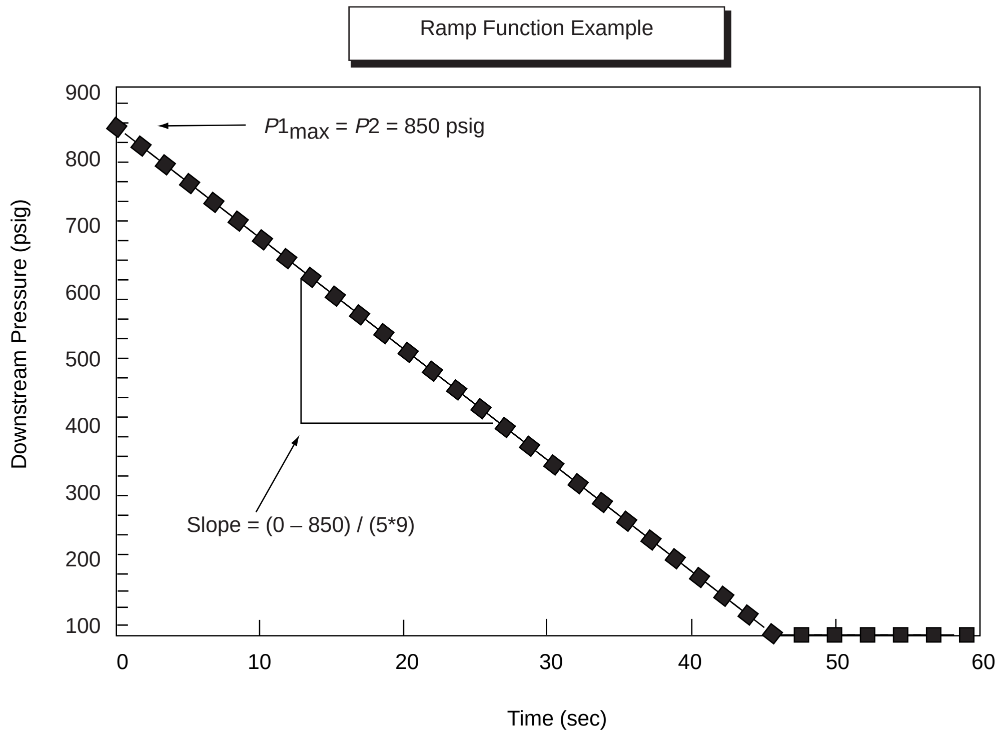

Figure D-2—Dynamic “Live” Valve Test Designed Using Constant Ramp Method

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