Technical Bulletin TB-0607-CFP

Hawkeye Industries' Critical Flow Prover

The critical flow prover (CFP) device provides a means to determine gas flow rate, *Q*, using principles of adiabatic, frictionless compressible flow in the critical, or choked, condition.

Principles of Operation

A compressible fluid traveling at subsonic velocity through a duct of constant cross section will increase velocity when passing through a region of reduced cross-sectional area (in this case, an orifice) to satisfy mass flow continuity. To satisfy conservation of energy, the fluid pressure at the obstruction decreases (i.e. Venturi effect).

Maximum velocity at the obstruction is limited by the rate at which pressure waves can propagate through the fluid ("the speed of sound"), and the flow will not exceed this velocity at the obstruction. Known as choked, or critical flow, the orifice velocity remains constant over a wide range of downstream pressure and temperature conditions. Since volumetric flow is proportional velocity, the volume flow rate of a choked flow can be determined based solely on upstream absolute pressure and temperature.

Critical flow will occur as the ratio of the obstruction flow area to the duct flow area approaches zero, and the ratio of upstream to downstream pressure for air, assumed to be an ideal gas, is *0.528*[1]. That is, the downstream pressure must be *0.528* times the upstream pressure (or less) in order to have critical flow at the obstruction. For example, to have critical flow with an upstream pressure of *10 MPa*, the downstream pressure must be *5.28 MPa* or less.

Empirically, natural gas exhibits critical flow behavior with straight-edge orifice diameters less then *60%* of the pipe diameter, and ratio of absolute downstream to absolute upstream pressure between *0.56* and *0.58*. For example, a subsonic natural gas flow in a *50 mm* pipe at *10 MPa* will be critical through a *30 mm* (or smaller) orifice, and downstream pressure of *5.6 MPa* or less.

The critical flow prover device ensures choked flow over a wide range of downstream pressures, allowing the use of critical flow property relationships to determine flow rate. By using critical flow properties, variability as a result of fluctuating downstream conditions is negated, allowing flow rates to be computed based solely on upstream conditions.

Device Description

The Hawkeye Industries Critical Flow Prover consists of a tubular section, approximately *6* pipe diameters long, with a smooth inside diameter and standard *2 NPT* connection on the upstream end. The opposite end features a recess, with an o-ring face-seal, for a *1/4 in*. thick orifice plate, held in place by a knurled retention cap. Approximately one pipe diameter upstream of the orifice plate are a *1/2 NPT* and *1/4 NPT* pressure taps, suitable for gauge mounting and a thermowell.

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[1] Eq. 9.32, White, F.M., (1999). *Fluid Mechanics.* New York: WCB McGraw Hill.

Operating Information

The flow rate through the CFP is determined using the following equation:

$$Q = \frac{CP}{\sqrt{GT}} \qquad \text{(eq. 1)}$$

Where:
Q = Flow Rate (*10^3 ft^3 / 24 hr (aka Mcfh)* or *10^3 m^3 / d*)
C = Orifice Coefficient (empirically derived, see tables 1a and 1b)
P = Absolute Upstream Pressure (*psi* or *MPa*)
G = Specific Gravity of Gas (air = *1.0*)
T = Absolute Upstream Temperature (°*R* or *K*)
Note: Equation 1 assumes a perfect gas, and does not account for deviations from Boyle's Law behavior.

Units:

When determining flow rate in imperial units ([*Mcfh*], or [*10^3 ft^3/24hr*]) use the following units in Equation 1:
C: From Table 1a.
P: pounds per square inch [psi]
G: unitless
T: Rankine [°R]

Likewise, to determine flow rate in metric, or SI units ([*10^3 m^3/d*]) use the following units in equation 1:
C: From Table 1b.
P: Megapascals [MPa]
G: unitless
T: Kelvin [K]

Absolute Temperature:

Thermodynamic calculations require use of absolute temperature in computations. In imperial units, absolute temperature is measure in Rankine (°*R*), calculated using the following formula:

$$[°R] = [°F] + 459.67 \qquad \text{(eq. 2)}$$

Example: 60°F = 519.67 °R

Similarly in SI, absolute temperature is measured in Kelvin (*K*) and is calculated using the following formula:

$$[K] = [°C] + 273.15 \qquad \text{(eq. 3)}$$

Example: 17°C = 290.15 K

Table 1a.

Empirically Derived Orifice Coefficient

** IMPERIAL UNITS **

For 2 NPS Critical Flow Prover (2.00 in. bore)

Orifice Diameter (in.)	Coefficient, C	Variance (%)
1/16	1.524	3.61
3/32	3.355	1.14
1/8	6.301	2.25
3/16	14.47	3.88
7/32	19.97	3.82
1/4	25.86	1.88
5/16	39.77	2.13
3/8	56.58	2.74
7/16	81.09	2.33
1/2	101.8	2.29
5/8	154	1.56
3/4	224.9	1.03
7/8	309.3	2.31
1	406.7	2.09
1 1/8	520.8	1.26
1 1/4	657.5	3.61
1 3/8	807.8	2.05
1 1/2	1002	6.32

Table 1b.

Empirically Derived Orifice Coefficient

** METRIC (SI) UNITS **

For 2 NPS [60.3 mm] Critical Flow Prover (2.00 in. [50.8 mm] bore)

Orifice Diameter		Coefficient, C	Variance
(in.)	(mm)		(%)
1/16	1.6	4.666	3.61
3/32	2.4	10.27	1.14
1/8	3.2	19.29	2.25
3/16	4.8	44.30	3.88
7/32	5.6	61.14	3.82
1/4	6.4	79.17	1.88
5/16	7.9	121.8	2.13
3/8	9.5	173.2	2.74
7/16	11.1	248.3	2.33
1/2	12.7	311.7	2.29
5/8	15.9	471.5	1.56
3/4	19.1	688.5	1.03
7/8	22.2	946.9	2.31
1	25.4	1245	2.09
1 1/8	28.6	1594	1.26
1 1/4	31.8	2013	3.61
1 3/8	34.9	2473	2.05
1 1/2	38.1	3068	6.32

Tables 1a. and 1b. provide orifice coefficients for imperial units (a.) and metric (SI) units (b.). The coefficients were derived from equation 1, using a known flow rate, Q, at a temperature of 60°F [519.67 °R] and downstream pressure of 14.4 psia.

Graphical Representation:

The flow rate, in 10^3 ft^3/24hr (Mcfh), has been calculated at 14.4 psi and 60°F [519.67°R], and ploted on charts A1 through B4, with a line for each orifice size (listed on the chart margins). Chart series A is scaled to provide legible values for orifice diameters 1/4 in. and under, while the series B charts show full-scale flow values.

Similarly, the flow rates, in 10^3 m^3/d at 99.3 kPa and 16°C [289.15 K] have been calculated, and ploted on charts C1 through D4, with a line for each orifice size (listed on the chart margins). Chart series C is scaled to provide legible values for orifice diameters 1/4 in. and under, while the series D charts show full-scale flow values.

Flow Charts

Scaled to 1/4 in. Orifice Plate Full Flow (Imperial Units):

Table A1: Flow Rate vs. Upstream Pressure (100 psi),
Table A2: Flow Rate vs. Upstream Pressure (500 psi),
Table A3: Flow Rate vs. Upstream Pressure (1000 psi)
Table A4: Flow Rate vs. Upstream Pressure (3000 psi)

Full Scale Flow (Imperial Units):

Table B1: Flow Rate vs. Upstream Pressure (100 psi)
Table B2: Flow Rate vs. Upstream Pressure (100 psi)
Table B3: Flow Rate vs. Upstream Pressure (100 psi)
Table B4: Flow Rate vs. Upstream Pressure (100 psi)

Scaled to 1/4 in. Orifice Plate Full Flow (Metric Units):

Table C1: Flow Rate vs. Upstream Pressure (1 MPa)
Table C2: Flow Rate vs. Upstream Pressure (5 MPa)
Table C3: Flow Rate vs. Upstream Pressure (10 MPa)
Table C4: Flow Rate vs. Upstream Pressure (20 MPa)

Full Scale Flow (Metric Units):

Table D1: Flow Rate vs. Upstream Pressure (1 MPa)
Table D2: Flow Rate vs. Upstream Pressure (5 MPa)
Table D3: Flow Rate vs. Upstream Pressure (10 MPa)
Table D4: Flow Rate vs. Upstream Pressure (20 MPa)

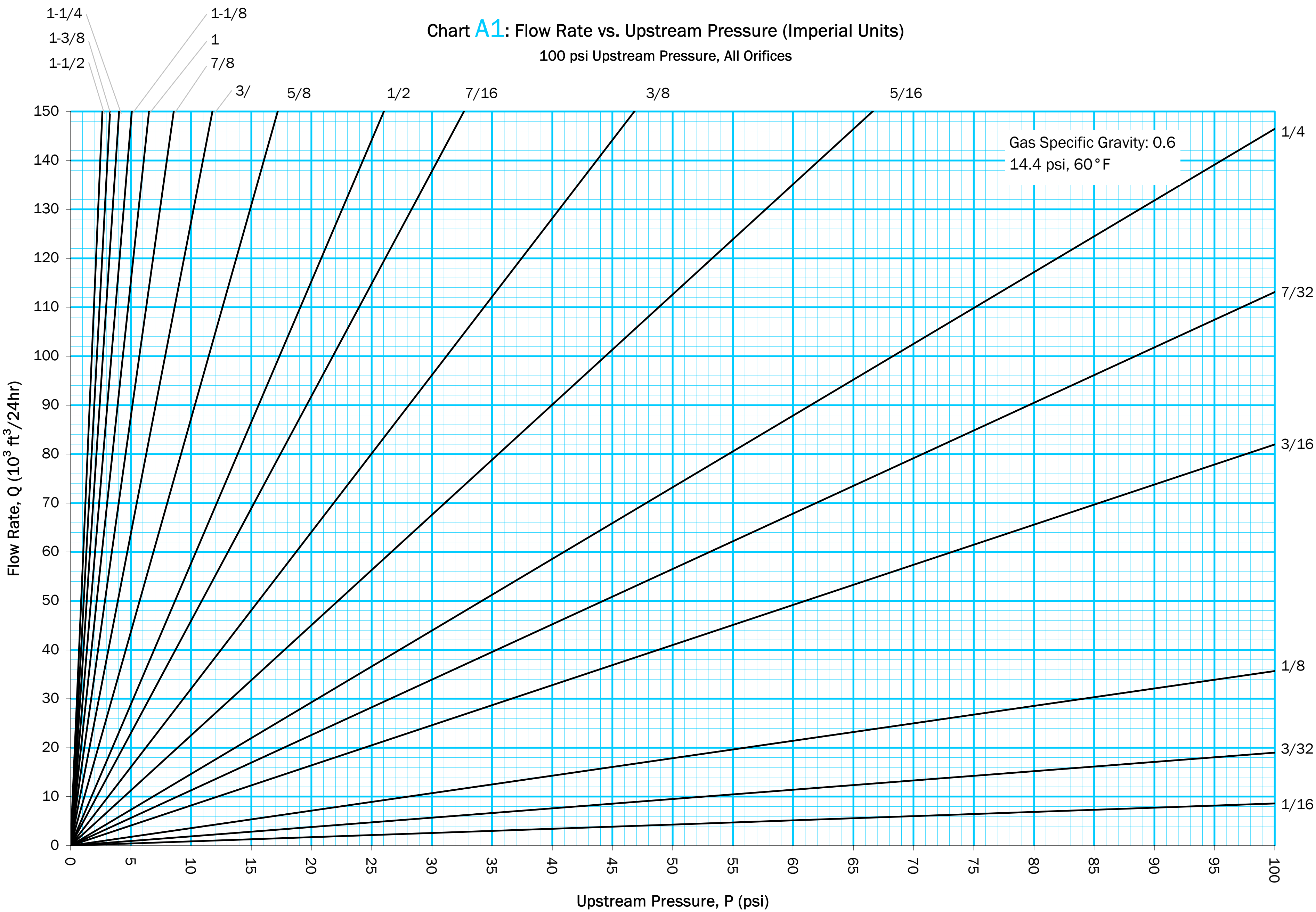


Chart A1: Flow Rate vs. Upstream Pressure (Imperial Units)
100 psi Upstream Pressure, All Orifices
Gas Specific Gravity: 0.6
14.4 psi, 60°F
1-1/4
1-3/8
1-1/2
1-1/8
1
7/8
3/
5/8
1/2
7/16
3/8
5/16
1/4
7/32
3/16
1/8
3/32
1/16
Flow Rate, Q (10^3 ft^3/24hr)
Upstream Pressure, P (psi)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

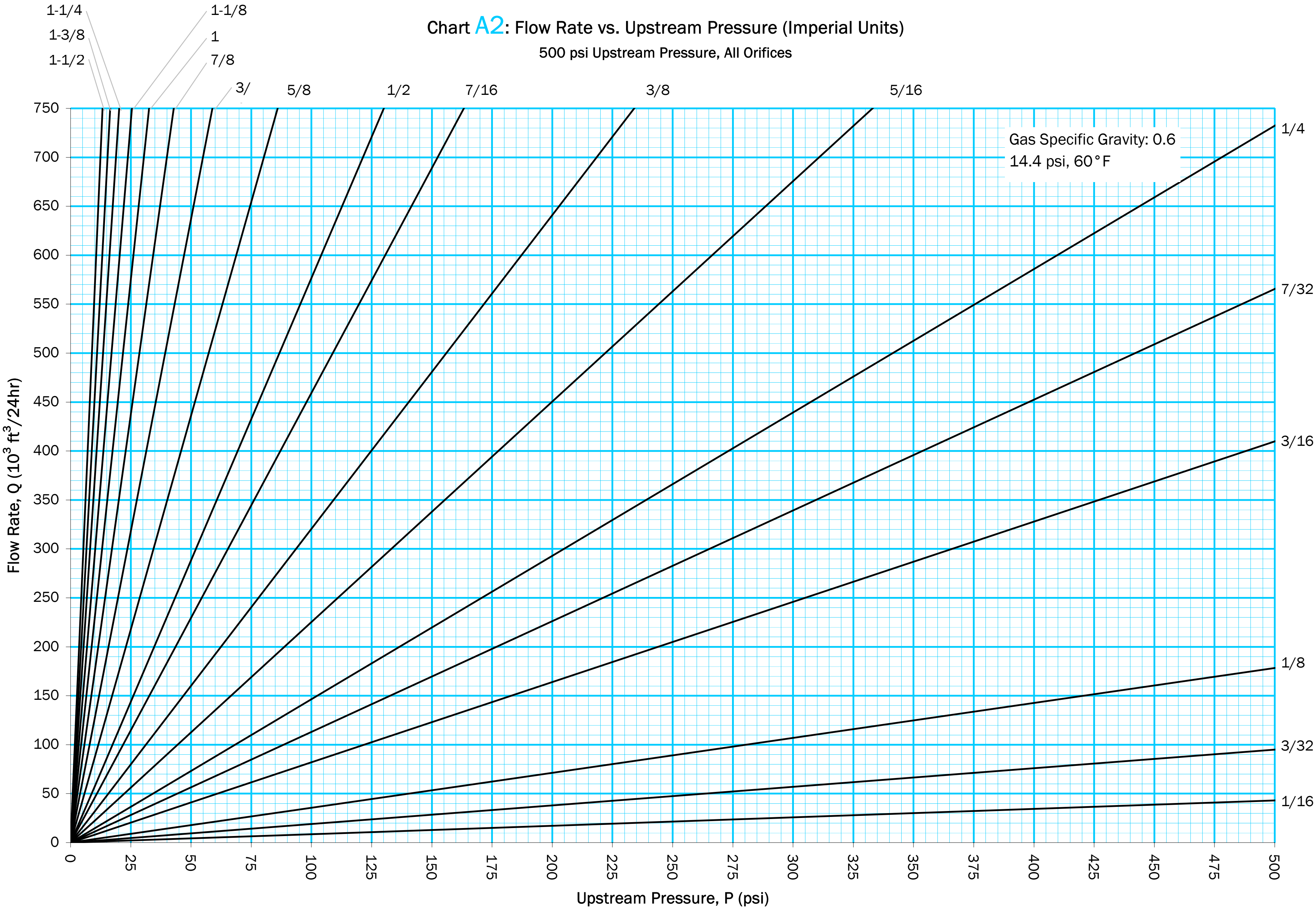
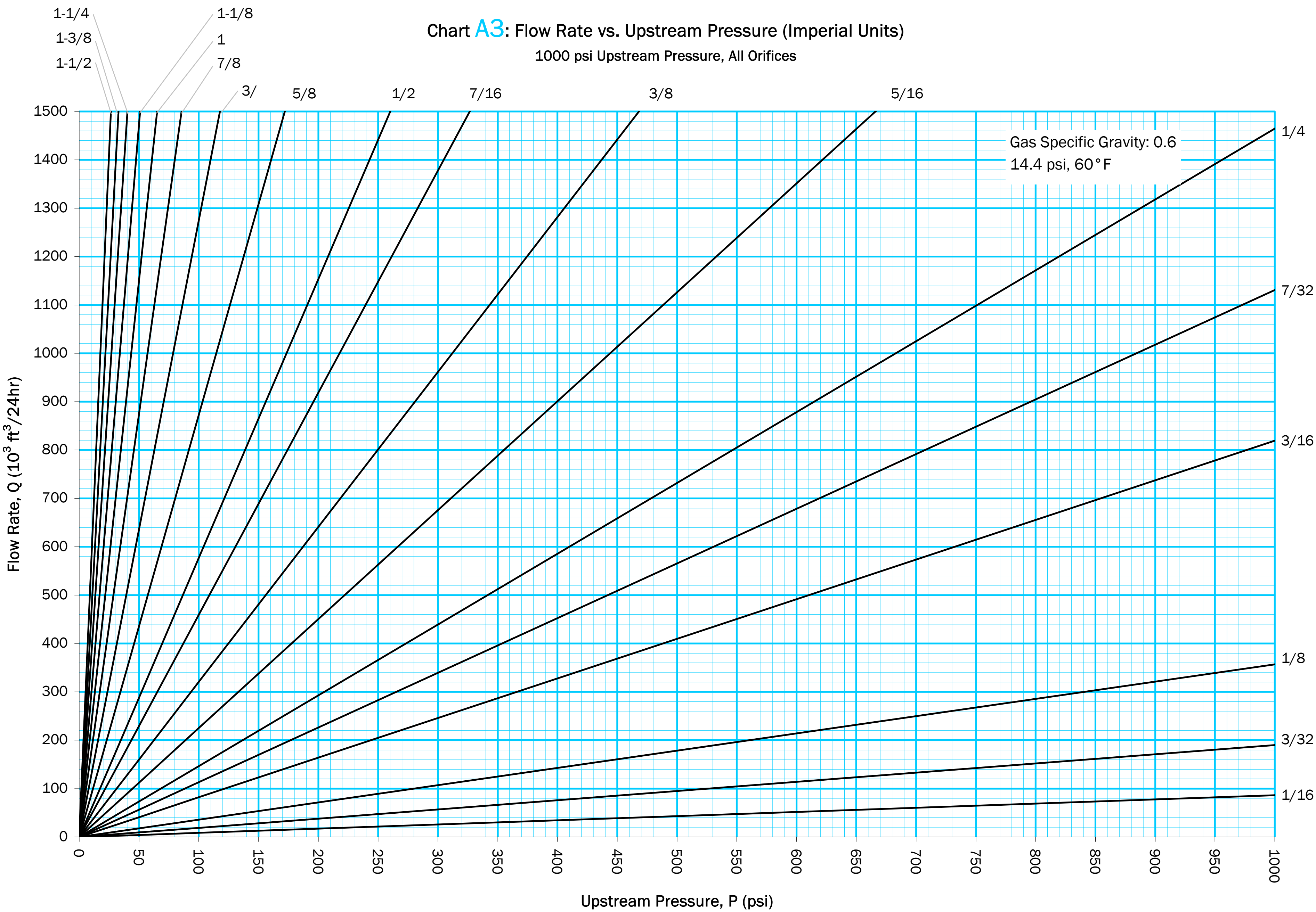


Chart A2: Flow Rate vs. Upstream Pressure (Imperial Units)
500 psi Upstream Pressure, All Orifices
Gas Specific Gravity: 0.6
14.4 psi, 60°F
1-1/4
1-3/8
1-1/2
1-1/8
1
7/8
3/
5/8
1/2
7/16
3/8
5/16
1/4
7/32
3/16
1/8
3/32
1/16
Flow Rate, Q (10^3 ft^3/24hr)
Upstream Pressure, P (psi)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
25
75
125
175
225
275
325
375
425
475

Chart A3: Flow Rate vs. Upstream Pressure (Imperial Units)

1000 psi Upstream Pressure, All Orifices



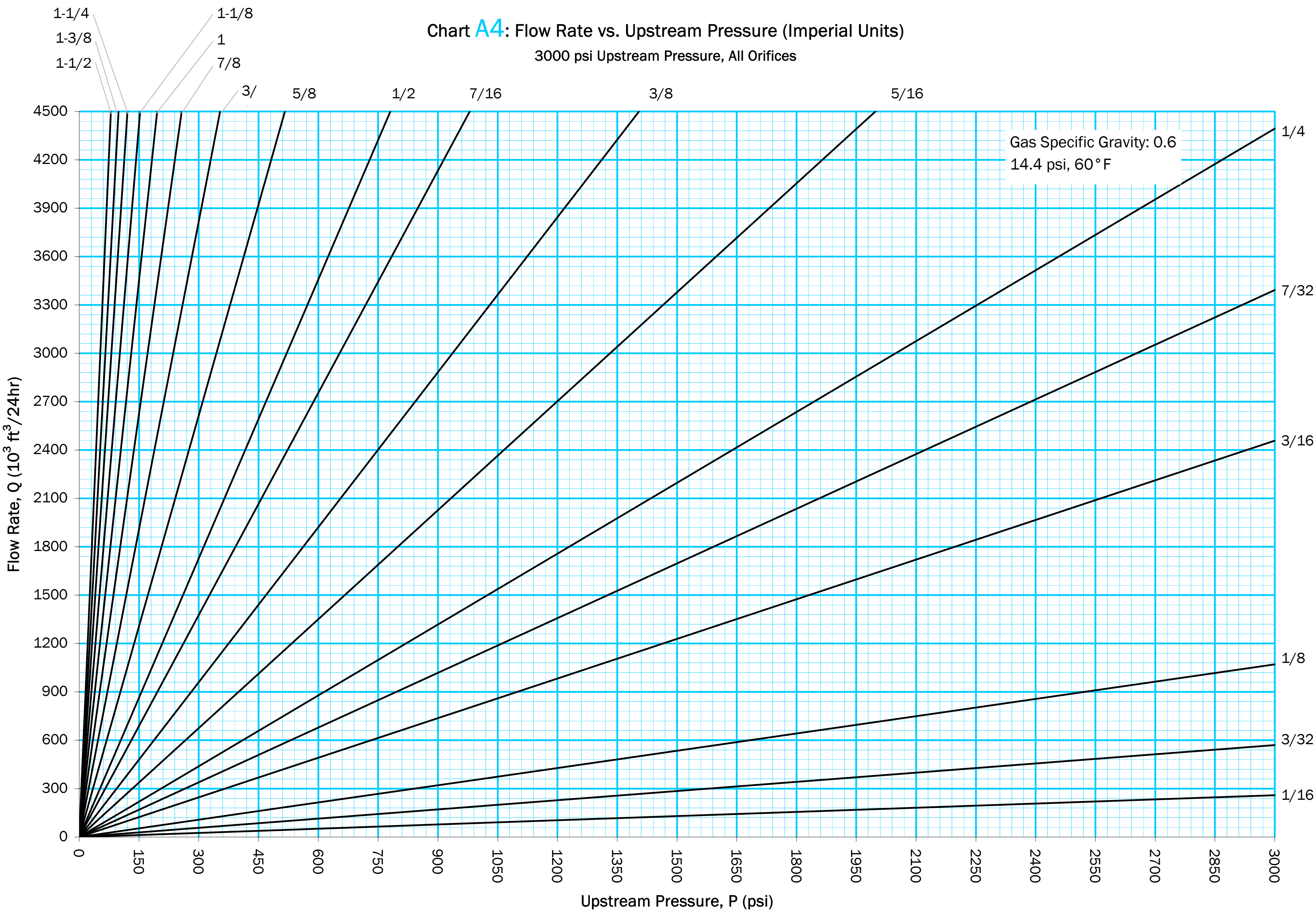


Chart A4: Flow Rate vs. Upstream Pressure (Imperial Units)
3000 psi Upstream Pressure, All Orifices
1-1/4
1-3/8
1-1/2
1-1/8
1
7/8
3/
5/8
1/2
7/16
3/8
5/16
1/4
7/32
3/16
1/8
3/32
1/16
Gas Specific Gravity: 0.6
14.4 psi, 60°F
Flow Rate, Q (10^3 ft^3/24hr)
4500
4200
3900
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
0
150
300
450
600
750
900
1050
1200
1350
1500
1650
1800
1950
2100
2250
2400
2550
2700
2850
3000
Upstream Pressure, P (psi)

Chart B1: Flow Rate vs. Upstream Pressure (Imperial Units)

100 psi Upstream Pressure, Orifices 5/16 and Larger

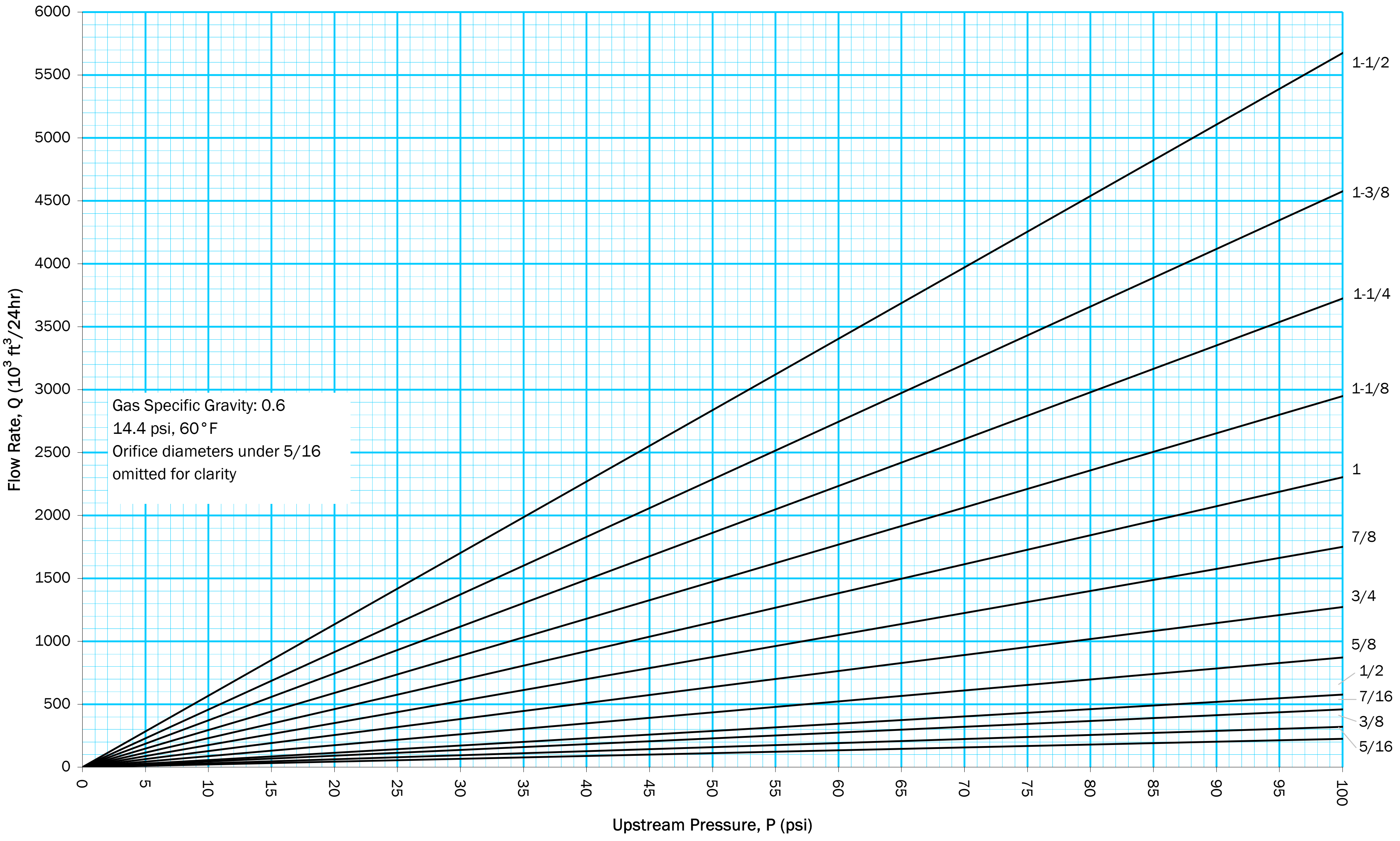


Chart B2: Flow Rate vs. Upstream Pressure (Imperial Units)

500 psi Upstream Pressure, Orifices 5/16 and Larger

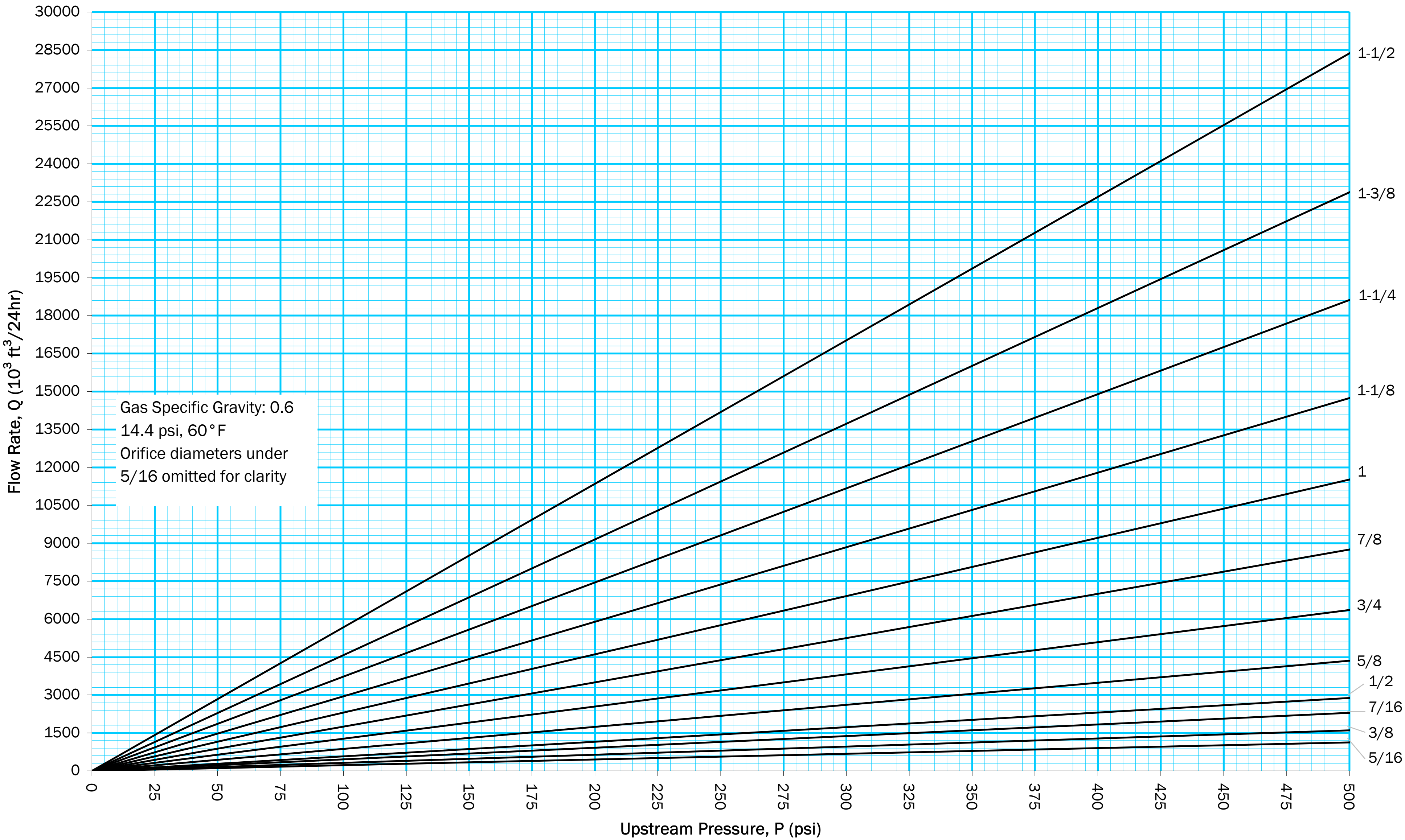


Chart B3: Flow Rate vs. Upstream Pressure (Imperial Units)

1000 psi Upstream Pressure, Orifices 5/16 and Larger

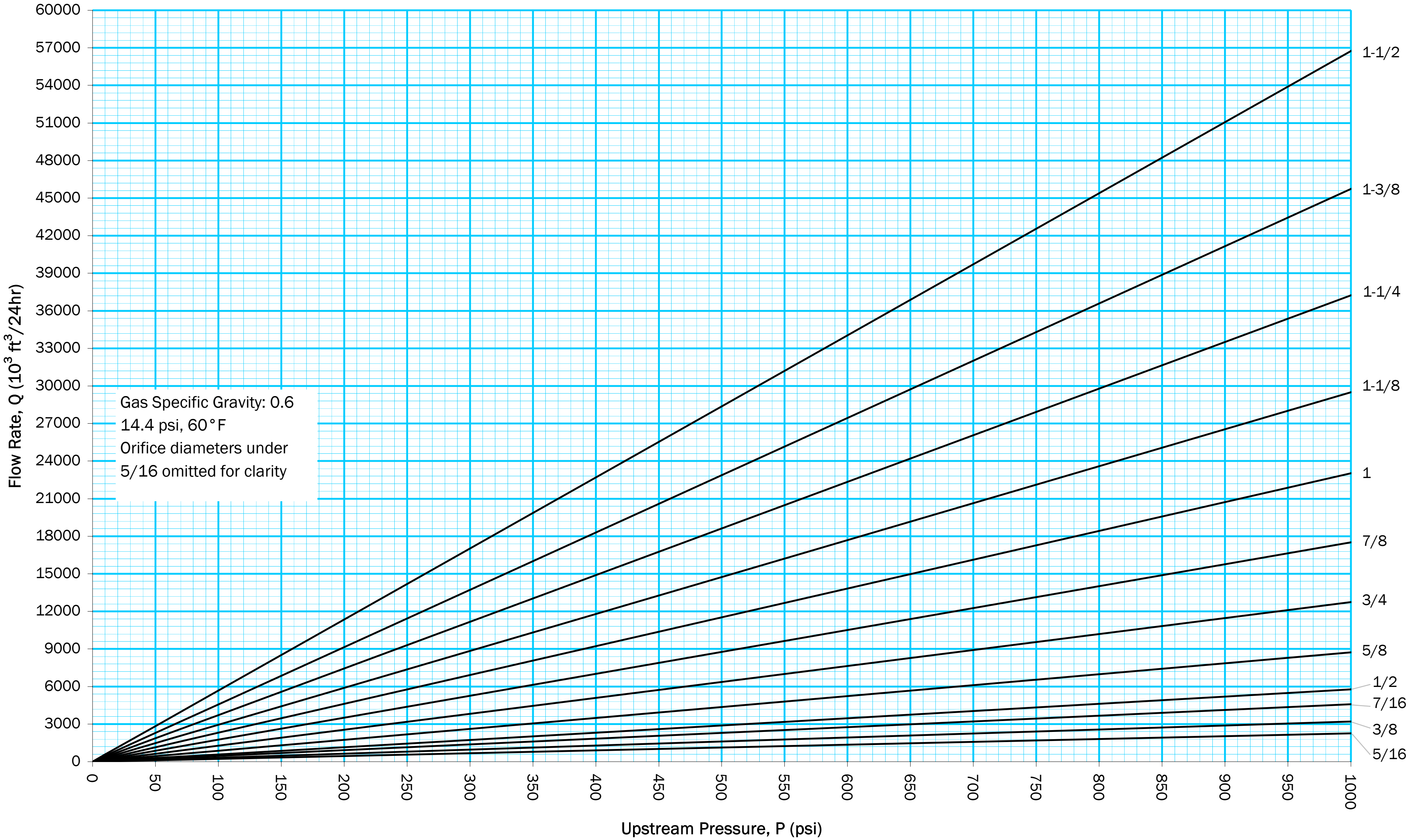
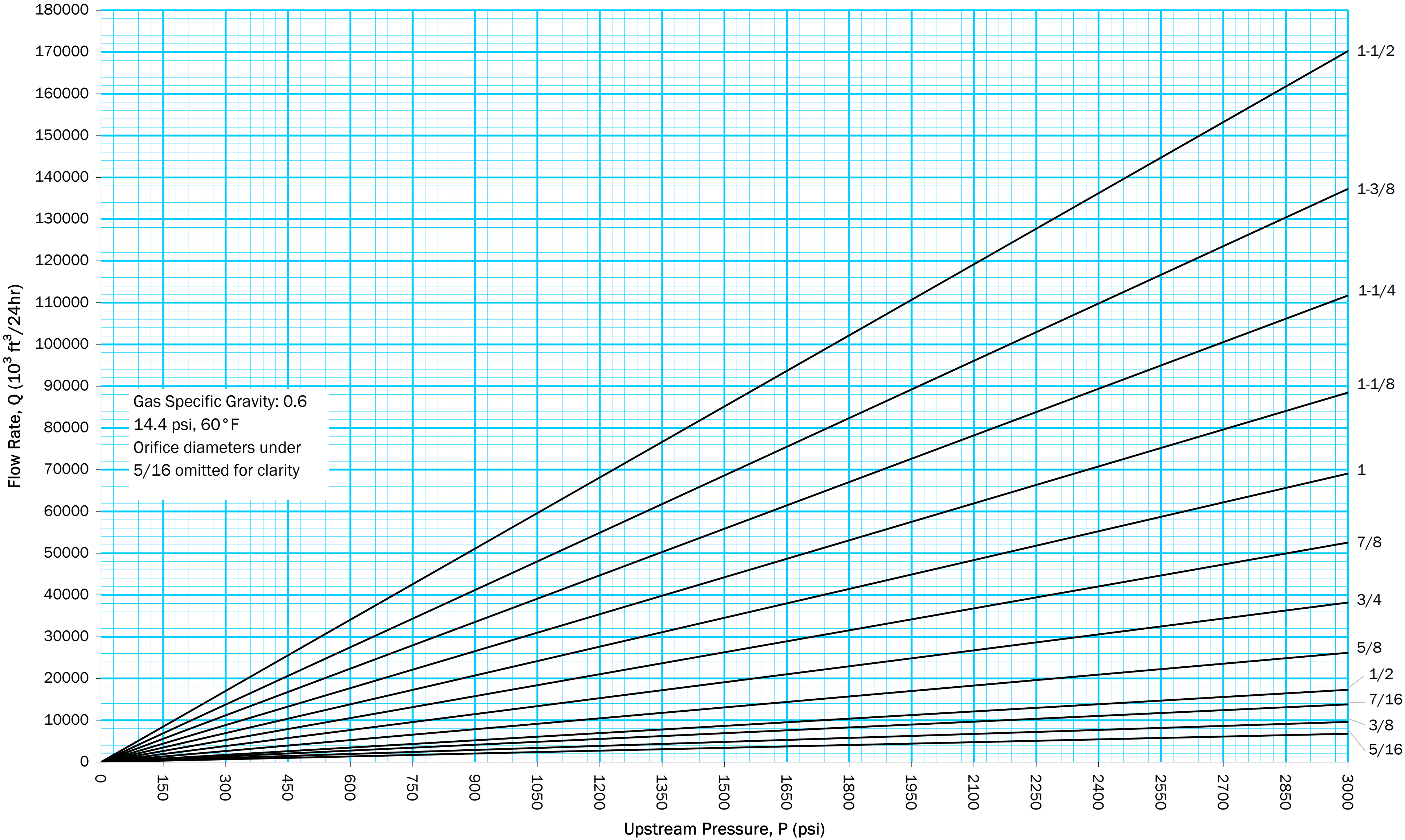


Chart B4: Flow Rate vs. Upstream Pressure (Imperial Units)

3000 psi Upstream Pressure, Orifices 5/16 and Larger



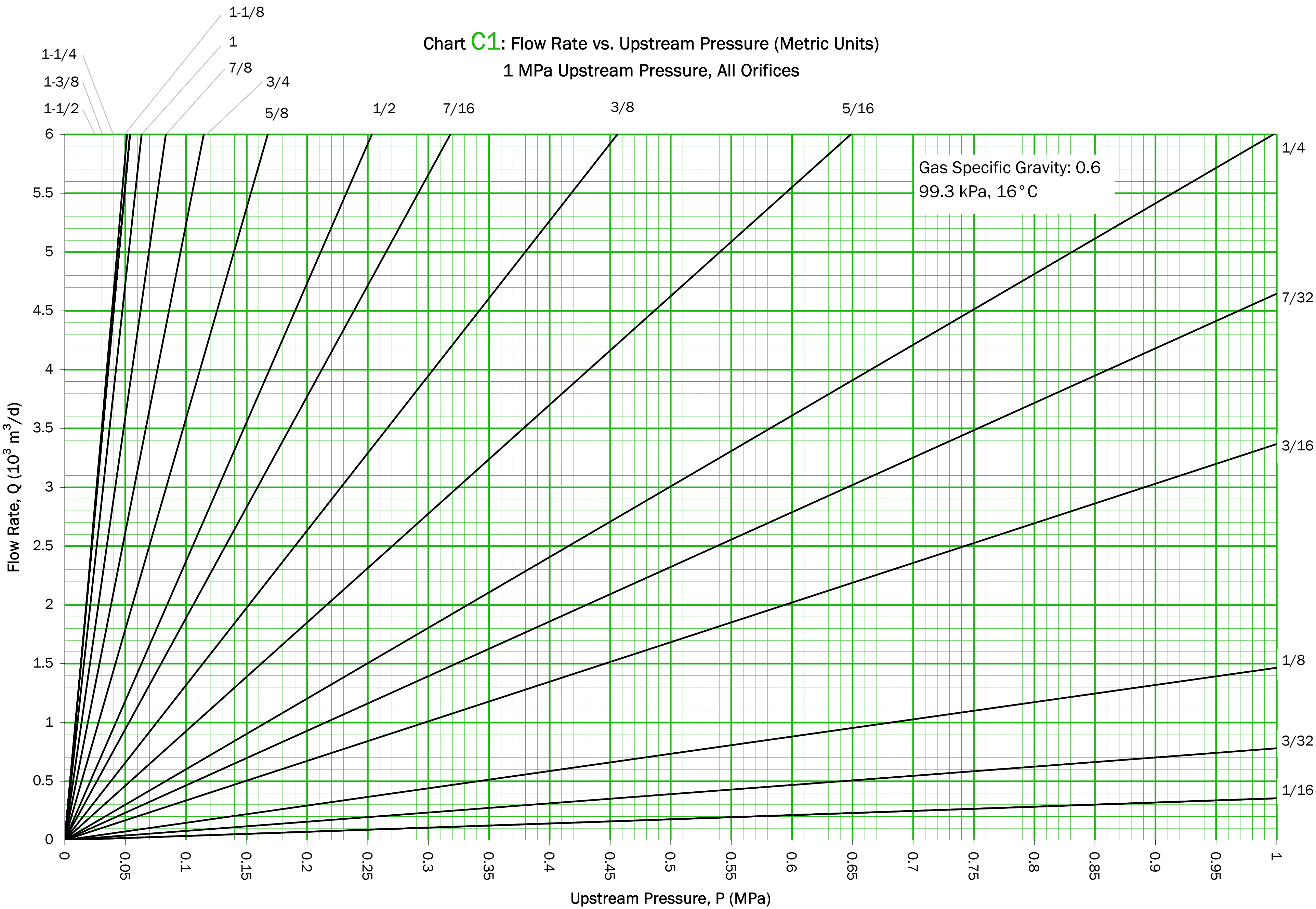


Chart C1: Flow Rate vs. Upstream Pressure (Metric Units)
1 MPa Upstream Pressure, All Orifices
Gas Specific Gravity: 0.6
99.3 kPa, 16°C
1-1/8
1
7/8
3/4
5/8
1-1/4
1-3/8
1-1/2
1/2
7/16
3/8
5/16
1/4
7/32
3/16
1/8
3/32
1/16
Flow Rate, Q (10^3 m^3/d)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
Upstream Pressure, P (MPa)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

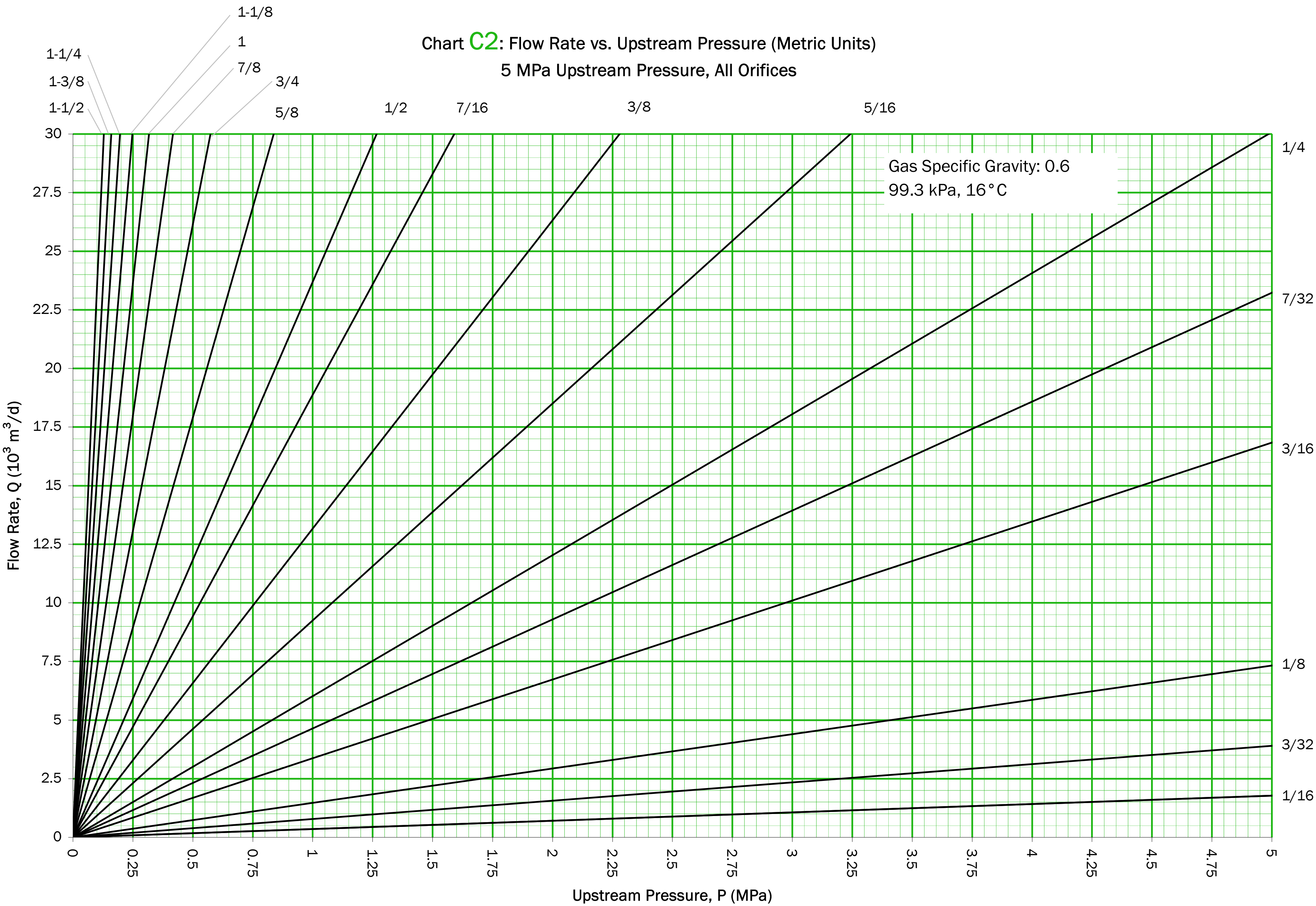


Chart C2: Flow Rate vs. Upstream Pressure (Metric Units)
5 MPa Upstream Pressure, All Orifices
Gas Specific Gravity: 0.6
99.3 kPa, 16°C
1-1/8
1
7/8
3/4
5/8
1-1/4
1-3/8
1-1/2
1/2
7/16
3/8
5/16
1/4
7/32
3/16
1/8
3/32
1/16
Flow Rate, Q (10³ m³/d)
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
3.5
3.75
4
4.25
4.5
4.75
5
Upstream Pressure, P (MPa)

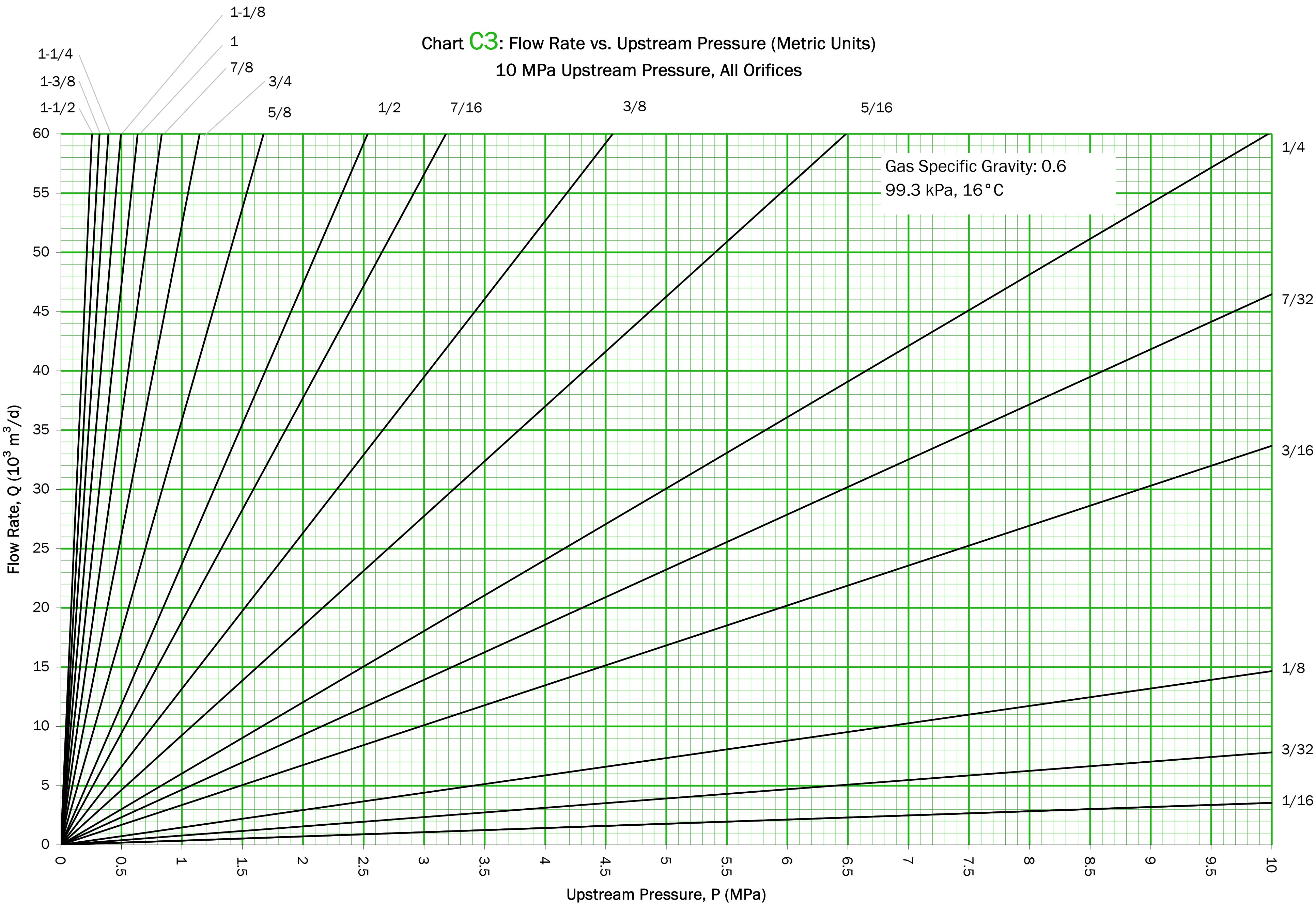


Chart C3: Flow Rate vs. Upstream Pressure (Metric Units)
10 MPa Upstream Pressure, All Orifices
1-1/8
1
7/8
3/4
5/8
1-1/4
1-3/8
1-1/2
1/2
7/16
3/8
5/16
1/4
7/32
3/16
1/8
3/32
1/16
Gas Specific Gravity: 0.6
99.3 kPa, 16°C
Flow Rate, Q (10³ m³/d)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
Upstream Pressure, P (MPa)

Chart C4: Flow Rate vs. Upstream Pressure (Metric Units)
20 MPa Upstream Pressure, All Orifices

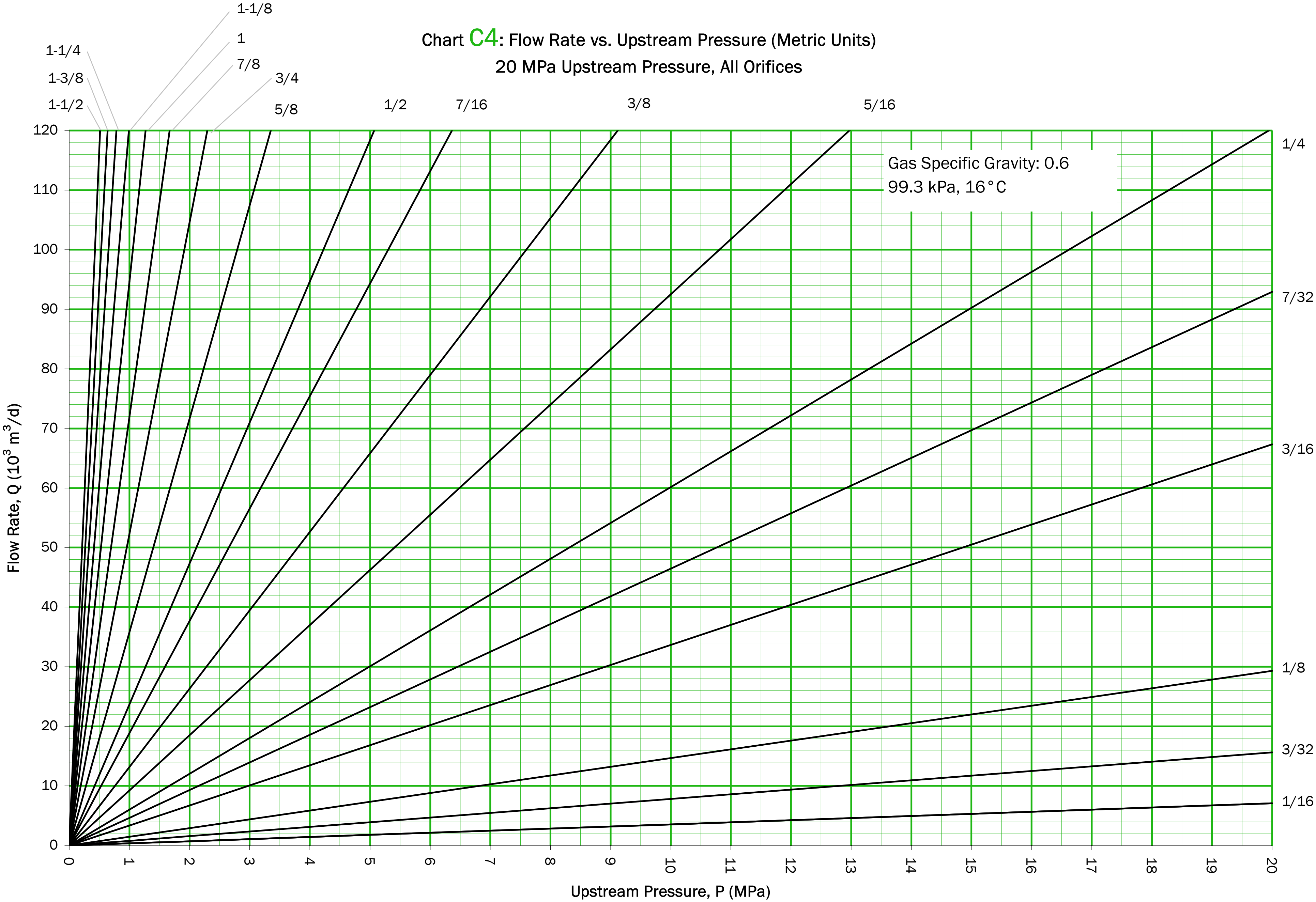


Chart D1: Flow Rate vs. Upstream Pressure (Metric Units)

1 MPa Upstream Pressure, Orifices 5/16 and over

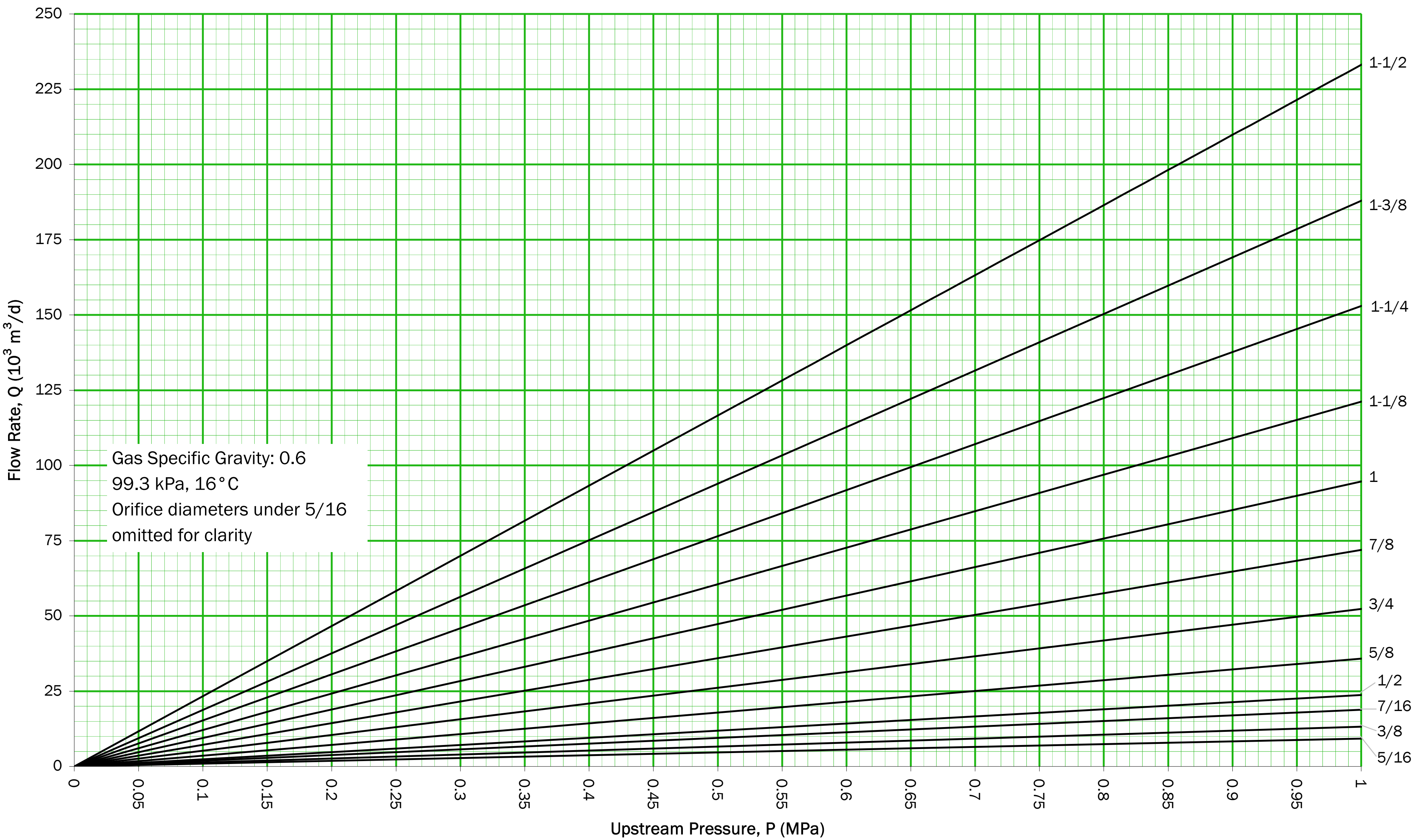
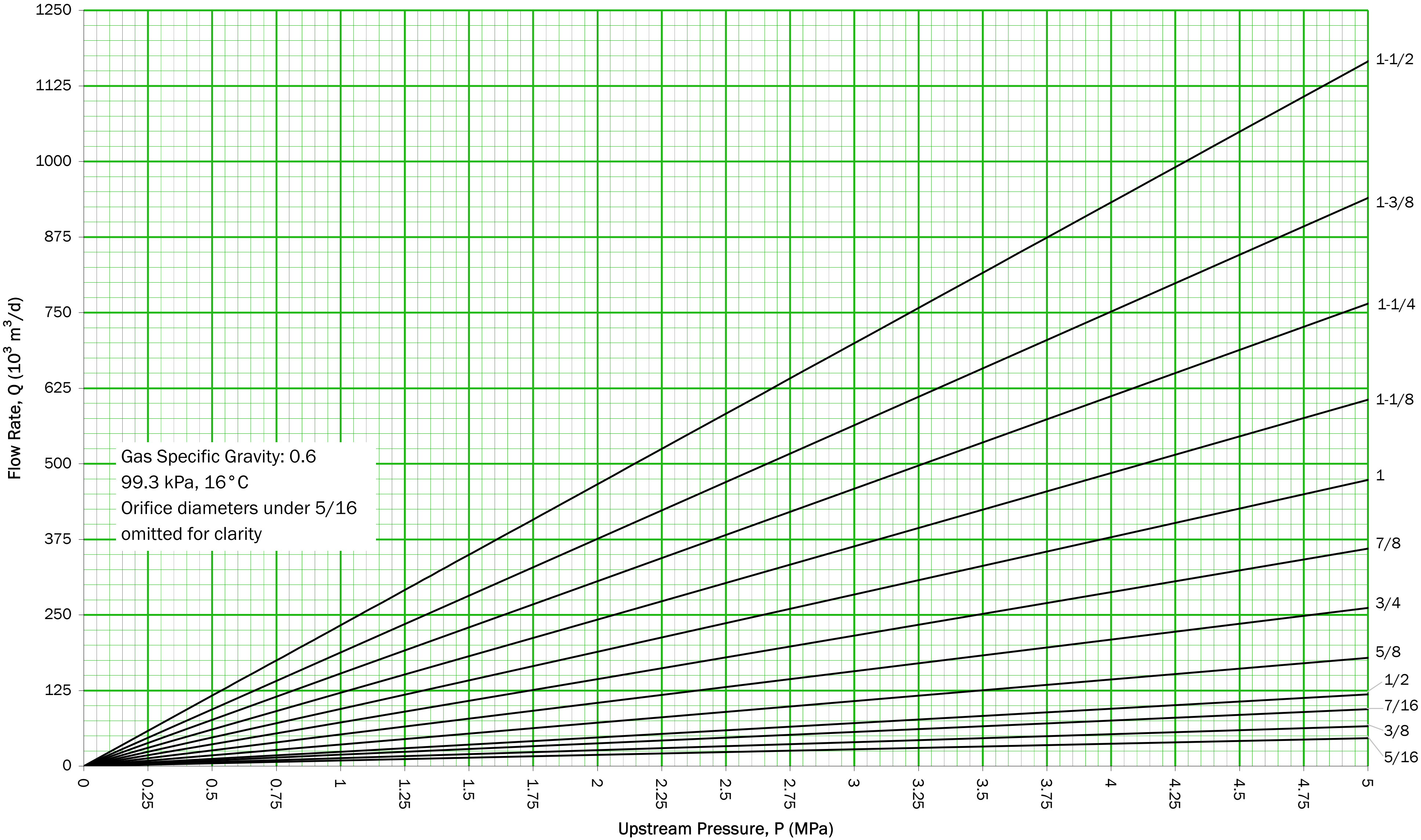


Chart D2: Flow Rate vs. Upstream Pressure (Metric Units)

5 MPa Upstream Pressure, Orifices 5/16 and over



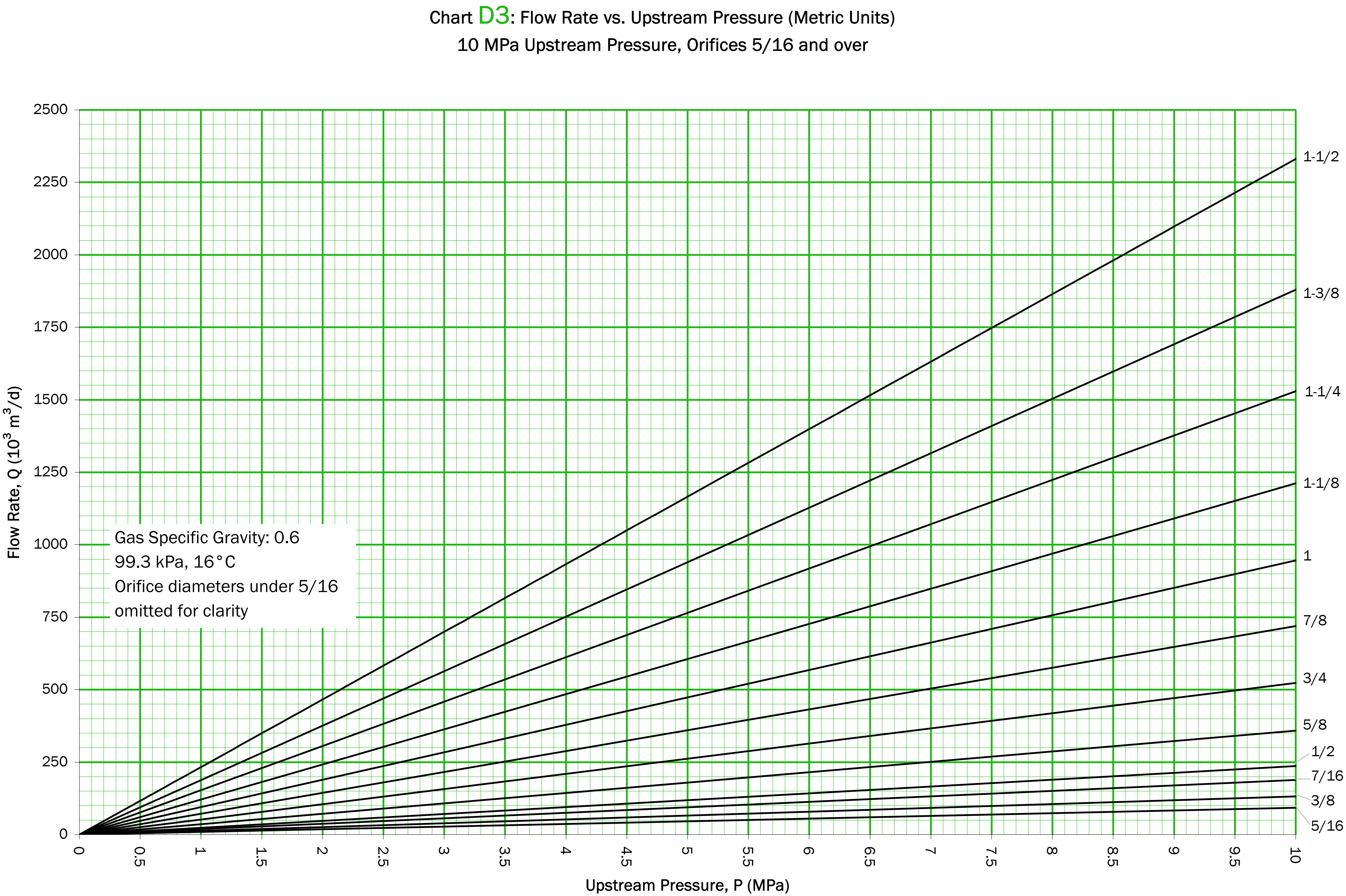


Chart D3: Flow Rate vs. Upstream Pressure (Metric Units)
10 MPa Upstream Pressure, Orifices 5/16 and over
Flow Rate, Q (10³ m³/d)
Upstream Pressure, P (MPa)
Gas Specific Gravity: 0.6
99.3 kPa, 16°C
Orifice diameters under 5/16
omitted for clarity
1-1/2
1-3/8
1-1/4
1-1/8
1
7/8
3/4
5/8
1/2
7/16
3/8
5/16
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10

Chart D4: Flow Rate vs. Upstream Pressure (Metric Units)

20 MPa Upstream Pressure, Orifices 5/16 and over