Recommended Practices for Core Analysis

6 Permeability Determination

6.1 INTRODUCTION

Permeability is a property of a porous medium and is a measure of its ability to transmit fluids. The measurement of permeability of a porous rock, or stratum, is a measurement of the fluid conductivity of the particular material. Permeability is the fluid-flow analog of electrical or thermal conductivity. The reciprocal of permeability represents the viscous resistivity that the porous medium offers to fluid flow when low flow rates prevail. This condition of flow is customarily called "viscous flow," or formally, "Stokes flow". Measurement of the flow of fluid through a sample in a particular direction yields permeability of the sample in that direction. The permeability of a homogeneous, isotropic medium is the same everywhere, and in all directions. However, real rocks are neither perfectly homogeneous nor isotropic.

6.1.1 Definitions

6.1.1.1 Darcy Flow

The mid-nineteenth century experiments and studies of Darcy¹ led to an empirical expression of the relationships among the variables involved in the flow of fluids through porous media, known now as Darcy's Law. Briefly, Darcy's Law states that the volumetric rate of flow per unit cross-sectional area of permeable medium (the volumetric flux) is directly proportional to the potential gradient, and inversely proportional to the viscosity of the fluid. The coefficient of proportionality is permeability. Thus, the potential gradient required for Stokes flow is equal to the product of the fluid's viscosity and volumetric flux, divided by the permeability of the rock. The potential gradient for horizontal liquid flow, or in any direction for practical measurements with low density gas, is equal to the pressure gradient.

6.1.1.2 Forchheimer Inertial Resistance

The work of Forchheimer² at the beginning of the twentieth century showed that Darcy's Law is a limiting case, restricted to low volumetric fluxes. At higher fluxes, Forchheimer observed that the potential gradient required for a given volumetric flux is greater than that predicted by Darcy's Law by an amount proportional to the product of the fluid's density and the square of its volumetric flux. The coefficient of proportionality, β , is the inertial resistivity of the porous medium. Inertial energy dissipation is due to innumerable accelerations (i.e., time-rates of change in the direction and magnitude of velocity) that a fluid undergoes as it travels tortuous paths through a porous medium. These accelerations cause second-

ary flow patterns, in which, part of the flow energy is converted to heat through viscous shear.

In a petroleum reservoir, especially away from a producing or injection well, volumetric fluxes are generally so low that Darcy's Law is applicable. However, high near-wellbore fluxes associated with high pressure gradients can cause nonnegligible inertial effects known as "rate-sensitive skins." These are particularly prevalent near gas-producing wellbores, and in perforations, where low gas viscosity permits very high fluxes.

In laboratory measurements of high permeability samples using gas (where inertial effects are most often observed), low volumetric fluxes require low pressure gradients, which can be difficult to measure accurately. Higher fluxes will cause the calculation of permeability to be low if Darcy's Law is employed. A procedure to estimate the maximum allowable pressure gradient as a function of permeability, to avoid significant permeability errors due to inertial resistance, is presented in 6.2.1.3. An alternative is to make multiple flow rate measurements and employ Forchheimer's equation to obtain both permeability and inertial resistivity of each sample. As a practical matter, this is most quickly accomplished with the pressure-transient technique presented in 6.4.1.1.

6.1.1.3 Klinkenberg Gas Slippage

Even when inertial effects are properly accounted for, the permeability of a porous medium to gas is dependent upon the mean free path of the flowing gas, hence among other things, upon its absolute pressure. This is due to a phenomenon known as slip, a fact first pointed out to the oil industry by Klinkenberg.³ Gas slippage had been overlooked or ignored by prior investigators of permeability despite theory and experimental data for slip in the flow of gases through small capillary tubes presented in scientific literature as early as 1875.⁴ When gas slippage is ignored, permeability calculated from the Forchheimer equation, or from Darcy's Law (provided that inertial resistance is negligible), is higher than that obtained using a non-reactive liquid. When expressed as a percentage, this difference is small for high permeability samples, but becomes progressively larger with decreasing permeability. It is minimized by using high mean pore pressures in gas permeability measurements.

To avoid the problem of obtaining pore-pressure-dependent gas permeabilities, Klinkenberg presented a method in which gas permeability measurements made at several different mean pore pressures can be extrapolated to infinite pore pressure. He showed that this extrapolated gas permeability (now called "Klinkenberg permeability", k_{∞}) is equal to the permeability obtained using a non-reactive liquid, such as a clean, refined hydrocarbon.

Permeability of rock samples, especially those that contain certain clays, can be altered when they are cleaned and dried in preparation for gas permeability measurements. Often, k_{∞} is higher in these samples than permeability measured using aqueous solutions. Special cleaning and/or drying techniques may be required.

6.1.1.4 Liquids

The use of liquids for permeability measurements eliminates the problem of gas slippage, and at reasonable and usual flow rates, inertial resistance is generally negligible. Thus, Darcy's Law can be used directly to calculate permeability from a single flow rate measurement. However, potential permeability alteration from interaction of rock constituents and liquids (especially aqueous solutions), fines movement, and microbial plugging requires special attention. Also, the liquid remaining in a sample may have to be removed before other measurements can be performed. Because of these problems, most routine permeability measurements have been made using gases. However, for some samples, such as those sensitive to drying techniques, liquid permeability measurements are considered to be the only acceptable alternative.

6.1.1.5 Confining Stress Dependence

Permeability of a porous medium is sensitive to the magnitude of net compressive stresses to which the medium is subjected, and to its stress history. As confining stresses are increased in a sample holder, the rock's permeability decreases. The decrease observed, when confining stresses are increased from 200 or 300 psi to several thousand psi, varies considerably-from just a few percent for reasonably permeable, well-cemented samples, to an order of magnitude or more for low permeability samples that contain micro fractures. In general, it is desirable to approximate reservoir stresses in laboratory permeability measurements to obtain values closer to expected in situ reservoir permeabilities. Additional, smaller permeability decreases may also be observed as a function of time after confining stresses are raised-due to creep. Creep is most prevalent at compressive stresses just lower than those that cause sample failure.

6.1.2 Unit of Permeability

6.1.2.1 Traditional Unit

In order to make practical use of the concept that porous media possess the measurable property of permeability, an arbitrary standard unit, the "darcy," has been defined. A porous medium has a permeability of one darcy when a single-phase fluid of one centipoise viscosity that completely fills the voids of the medium will flow through it under "conditions of Stokes flow" at a rate of 1 cm³/s per square centimeter of cross-sectional area under a pressure or equivalent hydraulic gradient of 1 atm/cm. "Condition of Stokes flow"

shall mean simply that "the rate of flow be sufficiently low to be directly proportional to the pressure or hydraulic gradient." The unit of permeability (the darcy), as a coefficient of proportionality between physical quantities, possesses dimensions of length squared. Permeability represents a property of the medium alone and is independent of the fluid, except as hereinafter qualified. For convenience the millidarcy sub-unit (equal to 0.001 darcy) may be used. The spelling of the plural forms of the unit have been standardized and established in the literature as "darcys" and "millidarcys." Although other sub-units are not recommended, the microdarcy (equal to 0.001 millidarcy or 10^{-6} darcy) is often used in conjunction with low-permeability gas sands. Also, the nanodarcy (equal to 0.001 microdarcy or 10^{-9} darcy) is often referred to for very tight rocks, such as micro fractured granite.

6.1.2.2 SI Unit

The fundamental SI unit of permeability, m², is defined as follows: a permeability of one meter squared will permit a flow of 1 m³/s of fluid of 1 Pa·s viscosity through an area of 1 m² under a pressure gradient of 1 Pa/m. One darcy equals 0.986923 x 10⁻¹² m². Because of the small exponent, this is an awkward unit for common usage. The Society of Petroleum Engineers of AIME preferred permeability unit is the micrometer squared (μ m²). One darcy (the traditional unit) equals 0.986923 μ m².

6.1.2.3 Typical Units Used in Hydrology

Most environmental engineers have a background in hydrology, in which the terms intrinsic permeability, hydraulic conductivity, and transmissivity are used. The physics of fluid flow that environmental engineers, core analysts, or petroleum engineers deal with is the same, but the language used by one group is often foreign to another group. This arises from different applications. Hydrologists most often deal with the flow of ground water in aquifers, in which water viscosity, density, and compressibility exhibit rather small variations. In these aquifers, it is often convenient to determine flow potential differences by measuring differences in liquid heads-the elevations to which water rises in small non-flowing test wells drilled into the aquifer. In the laboratory, an analogous measurement technique would be to attach a series of water manometers to a core sample through which water is flowing. The height of water in the manometer nearest the upstream end of the core would be greatest, and waterlevel elevations (from a horizontal reference) would be progressively lower further downstream.

In petroleum reservoirs, fluid properties vary widely, more than one fluid phase is usually present, and pressures are often too great to make manometric head measurements. Pressures are measured directly with pressure gauges or transducers. Thus, equations for these applications deal with pressures, not heads. Flow potentials must be calculated from pressures, flow rates, and fluid and rock properties through appropriate governing partial differential equations. Solution often requires numerical finite difference approximations of these equations.

6.1.2.3.1 Flow Potential Differences vs. Pressure Differences

It is important to understand that flow potential difference, not pressure difference, is the driving force for fluid flow, to know what flow potential is, and to ascertain when pressure differences can legitimately be used in flow equations. Relationships between flow potential and pressure are illustrated by Figure 6-1. Two tanks, each open to atmospheric pressure at its top and fitted with manometer tubes at several depths, are connected together by a small pipe. Each is partially filled with water to the same depth. Pressure in each tank at the airwater interface is atmospheric, and increases with depth.

We observe that the water level in every manometer tube is the same, and except for a very small capillary rise in each tube, it is the same as the water level inside the tanks. This water level in the manometer tubes is a measure of the flow potential inside the tanks, that is the same at every depth, even though pressure increases with depth. If pressure, alone, were the driving force for flow, higher pressure water from the bottom of a tank would flow upward, toward lower pressure. This is not observed. If we assume that the density of water everywhere in each tank is constant (a very close approximation), then flow potential, φ , everywhere is:

$$\varphi = p - \rho g z / C_4 \tag{1}$$

Where:

- p = pressure at depth z (below the water surface; z increases downward).
- ρ = density of the water.
- g =local acceleration of gravity.
- C_4 = conversion factor (found in Table 6-1) to make units consistent.

However, pressure at any depth in the tank is:

$$p = p_1 + \rho g z / C_4 \tag{2}$$

Where p_1 is the pressure at the air-water interface, atmospheric pressure in this case. Thus, combining Equations 1 and 2, we see that $\varphi = p_1$, and flow potential is the same at any depth. It is also the same in both tanks; so no flow occurs within or between tanks.

Condition 1:

- a. Both tanks are filled with water to same depth, and are open to atmospheric pressure.
- b. Water pressure increases in both tanks with increasing depth.
- c. However, flow potential (indicated by water levels in manometer tubes) is the same for all depths, and is the same in both tanks.
- d. Therefore, no flow occurs within or between tanks.

Condition 2:

- a. Air pressure above water in left tank is increased. Then vent is capped.
- b. Flow potential in left tank is increased as indicated by increased water levels in manometer tubes there.
- c. Water flows from left tank to right tank until water levels in manometer tubes are the same for both tanks.



Figure 6-1—Illustration of Flow Potential vs. Pressure Differences

	Units or Values of Constants										
Variable or Constant	SI	Preferred SPE	Traditional	Common Usage							
A, area perpendicular to flow	m ²	m ²	cm ²	cm ²							
b, Klinkenberg slip factor	Pa	Pa	atm	psi							
D, diameter of sample	m	m	cm	cm							
g, gravitational acceleration	m/s ²	m/s ²	cm/s ²	cm/s ²							
k, permeability	m^2		darcy	millidarcy							
L, length of sample	m	m	cm	cm							
M, gas molecular weight	kg/kg-mole	kg/kg-mole	g/g-mole	g/g-mole							
<i>P</i> , absolute pressure	Pa	Pa	atm	psia							
<i>p</i> , gauge pressure	Pa	Pa	atm	psig							
Δp , differential pressure	Pa	Pa	atm	psi							
q, volumetric flow rate											
r, radius of sample or seal	m	m	cm	cm							
S, compressive storage											
s, flow-direction distance	m	m	cm	cm							
<i>T</i> , absolute temperature	К	К	K	К							
V_p , pore volume											
V_{T} total reservoir volume											
v_s , volumetric flux	m/s	m/s	cm/s	cm/s							
β , inertial resistivity	m^{-1}	m^{-1}	cm^{-1}	ft1							
ρ , gas or liquid density	kg/m ³	kg/m ³	g/cm ³	g/cm ³							
μ , gas or liquid viscosity	Pa·s	Pa·s	ср	ср							
R, gas-law constant	8314	8314	82.05	1205.8							
C_1 , in Darcy or Forch. eq.	1.0	1.0	1.0	6.8046E-2							
C_2 , in Darcy or Forch. eq.	1.0	1.0E+12	1.0	1000.							
C_3 , constant in Forch. eq.	1.0	1.0	9.8692E-7	3.2379E-8							
C_4 , constant in eqs. with g	1.0	1.0	1.0133E+6	68 950.							

Table 6-1—Constants in Forchheimer or Darcy Equation with Various Sets of Units

Now, suppose air is pumped into the left tank through its vent so that air pressure above the water is greater than atmospheric pressure. Then the vent is capped. We would observe that water levels in all manometers attached to the left tank have risen equally. Except for the amount of water required to increase levels in the tubes, the water level inside the tank is unchanged. Initially, conditions in the right tank are unchanged. From the higher manometer levels in the left tank (indicated by dashed lines in Figure 6-1), relative to those in the right tank, we conclude that flow potential is higher in the former, even though water levels inside the two tanks are the same. Indeed, water flows from left to right until manometer levels are the same for both tanks. When flow ceases, the water level inside the left tank will be lower than in the right tank.

In laboratory single-phase gas permeability measurements, "gas head" differences are generally smaller than the accuracy of pressure measurements, and can be ignored. Therefore pressure differences or pressure gradients are very close approximations of flow potential differences or gradients in any flow orientation (horizontal or vertical). Conditions for single-phase liquid measurements are discussed in detail in 6.2.2. Pressure differences or gradients can be substituted for flow potential differences or gradients only in special, restricted situations.

6.1.2.3.2 Intrinsic Permeability

Intrinsic Permeability, k, as used by hydrologists is identical to permeability defined in 6.1.2.2, even though it is defined in terms of heads and kinematic viscosity, v, rather than dynamic viscosity, μ , used in the Darcy equation as defined in 6.1.2.1. Kinematic viscosity is equal to dynamic viscosity divided by density of the fluid. A porous medium has an intrinsic permeability of one unit of length squared if it will transmit in unit time a unit volume of fluid of unit kinematic viscosity through a cross section of unit area measured at right angles to the flow direction under a unit potential gradient. If SI units are used, intrinsic permeability has the unit of m².

6.1.2.3.3 Hydraulic Conductivity

Hydraulic conductivity, K, is not solely a property of a porous medium. It depends also upon the kinematic viscosity of the flowing fluid, and is appropriate only for ground water aquifers. Its units are those of velocity, usually feet per day or meters per day. A medium has a hydraulic conductivity of

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unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow. Hydraulic conductivity is related to permeability (or intrinsic permeability) by:

$$K = \frac{k\rho g}{\mu} \tag{3}$$

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Where k is permeability, and the other symbols are defined above. Any consistent set of units may be used in Equation 3. With SI units, K will have the unit of meters per second.

6.1.2.3.4 Transmissivity

The transmissivity, *T*, of a ground water aquifer includes the thickness of the aquifer, *b*, and the kinematic viscosity of the confined water. Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It has the unit of length squared per unit time, often ft²/day, or m²/day. Transmissivity is equal to *Kb*. It can be calculated from permeability by:

$$T = \frac{k\rho g b}{\mu} \tag{4}$$

Definitions for intrinsic permeability, hydraulic conductivity, and transmissivity are taken from Lohman.⁴² Conversion factors for several sets of units can be found in *Ground Water* (1993).⁴³

6.1.3 Terminology

6.1.3.1 Specific Permeability

The definition of the standard unit of permeability requires that the porous medium contain only one homogeneous, single-phase fluid. The property of the medium so determined is properly termed specific permeability; but it shall simply be called permeability, and denoted by the symbol k. By this definition, the term permeability becomes a property solely of the porous medium; and the numerical value of permeability is constant and independent of the fluid used in the measurement. Whenever certain minerals and fluids are brought in contact and interaction results, or material is deposited from the fluid, this phenomenon, in effect, produces a new medium. The permeability of the new medium may differ from that of the unaltered medium. Whenever this occurs, it should be indicated clearly by appropriate references to both medium and fluid, e.g., "the permeability of Woodbine sand to salt water (fresh water, crude oil, heptane, etc., as the case may be)."

Uncorrected gas permeabilities are precluded from the above definition due to gas slippage effects. Gas permeabilities, which shall be called k_g (or k_{air} , k_{N2} , k_{He} , etc.) depend

upon the particular gas used in the permeability determination, and upon its mean pore pressure. Both must be specified to define the permeability of the medium. Only the Klinkenberg, slip-corrected gas permeability, when unaffected by high velocity (Forchheimer) effects, is constant and independent of the fluid used in the measurement.

Because the stress condition under which a measurement is made can have a significant effect upon permeability, it also should be specified. Examples are: k_{air} with a mean pore pressure of 32.3 psia and a radial confining stress of 400 psig; or k_{∞} at a net hydrostatic stress of 5,000 psi. The first specification implies that a gas permeability was obtained using air at an average absolute pore pressure of 32.3 psia, and that a pressure of 400 psig was applied to the rubber boot of the sample holder. The net radial stress is therefore 400 + 14.7 – 32.3, or about 382 psi. The net axial stress is unknown. In the second example, a Klinkenberg (slip-corrected) permeability was obtained that is independent of the gas used or its mean pore pressure (except as pore pressure affects net stress). Equal magnitude radial and axial ("hydrostatic") net stresses of 5,000 psi were applied during the measurement.

6.1.3.2 Effective and Relative Permeability

This manual of routine recommended practices deals only with single-phase permeability measurements. Therefore, effective permeability and relative permeability will only be defined. The effective permeability of a porous medium is a measure of its fluid conductivity to a particular phase of a multi-phase fluid system residing within the medium, where the saturation of each phase (the fraction of its total effective pore volume that is filled by each phase) is specified. Relative permeability is the ratio of the effective permeability of a particular fluid phase, at definite saturations of all phases, to some arbitrary reference permeability. The reference permeability can be the sample's specific permeability, its Klinkenberg permeability, the effective permeability of one of the fluid phases at a specified saturation condition, etc. The particular reference permeability used must be specified.

Book three of the five volume, *History of Petroleum Engineering* (API, 1961),³⁹ is a rich reference source for early work on laboratory permeability measurements, including the pioneering efforts of Fancher, Lewis, and Barnes,⁴⁰ and of Wyckoff, Botset, Muskat, and Reed.⁴¹

6.2 THEORY

Single-phase permeability measurements can be separated into four major categories: those utilizing flowing gas or liquid under steady-state or unsteady-state (transient) conditions. Equations for steady-state flow of gases and liquids are presented in this section. Several practical variations, each with particular advantages and limitations, will be outlined in 6.3, and the theory and application of transient pressure gas and liquid measurements are presented in 6.4. These are all considered to be direct measurements.

The permeability of a porous medium can also be inferred from empirical correlations using indirect measurements, such as those of inter granular porosity and grain size (Kozeny⁵ and Carman⁶); porosity and irreducible water saturation (Wyllie and Rose⁷); pore-throat and pore-size distribution by mercury injection or capillary pressure measurements (Swanson⁸, Katz and Thompson⁹, etc.); effective electrical conductivity (Archie¹⁰, Ondracek¹¹); transmissivity of acoustic waves (Biot¹²); electrokinetic emf (Moran¹³); etc. Because these can be less accurate and often more time consuming than making the direct measurements, they will not be considered here. All measurements are assumed to be conducted under isothermal conditions, which may require considerable technique and effort to achieve under certain circumstances. Also, even though temperature can affect permeability, most routine permeability measurements are made at, or near, room temperature.

Tables 6-2 and 6-3 are quick selection and reference guides for gas and liquid permeability determinations, respectively, using both steady-state and transient techniques. They list major advantages and disadvantages of each technique, its approximate permeability range, and particular application. They are intended to be a starting point only, and the reader is cautioned to be aware of details given in sections referenced by these tables.

Reference Section Numbers	Type of Measurement	Approx. Perm. Range, md	Apparatus or Application	Major Advantages	Major Limitations
6.3.1.1 6.3.1.1.1.1	Axial flow, steady state in core plugs	0.1- 10,000	Low pressure apparatus with manometers, orifice flow meters	Low capital cost; simple manual sys- tem; workhorse for decades; large data base for comparison	Labor intensive; high operating cost; low- stress perms; no slip correction; must check for inertial resistance
6.3.1.1 6.3.1.1.1.2	Axial flow, steady state in core plugs	0.1- 10,000	Apparatus with electronic sensors, high pressure. core holder	Can be automated; reservoir stresses can be approximated; better precision and accuracy than with manual system	Must make multiple measurements for gas slippage correction; must check to ensure negligible inertial resistance
6.4.1.1 B.6.8.2	Axial flow, pressure falloff in core plugs	0.001- 30,000	Wide range; med. to high stress measurements with corrections for <i>b</i> and β	Well adapted for automation; no flow meters required; can yield reservoir-condition perms (k_{∞}), and k_g	Higher capital cost for automated system with high accuracy pressure transducers and data acquisition system
6.4.1.3 D.6.8.4	Axial flow, pulse-decay in core plugs	.00001- 0.1	High stress apparatus for very low perms.	Only method for ultra-low perms; well adapted for automation; porosity can be determined in same apparatus	Requires high pressure, leak-tight system with high quality transducers and data acquisition system—higher capital cost
6.3.1.2	Probe perm., s.s., on whole core	1- 10,000	Zero stress, high density, localized measurements for heterogeneous cores	No plug preparation required (core slabbing recommended); relatively fast; can be automated or made portable	Zero stress, non slip corrected perms are high at low end of range; prone to high inertial resistance at high end
6.4.1.2 C.6.8.3	Probe perm., pressure falloff on whole core	0.001- 30,000	Zero stress, high density, localized measurements for heterogeneous cores	No plug preparation required (core slabbing recommended); very fast; automated; corrected for b , β	Zero stress perms are high, especially at low end of range; higher capital cost for automated system
6.3.1.3	Transverse, s.s. perm. in whole core	0.02- 500	Directional perm. in whole core (or plug) for k_{max} and k_{90*}	Can measure "horizontal" perm. in var- ious directions; averaging obtained using whole-core sample.	Cleaning and preparation of whole core sample more expensive; only k_g obtained without multiple measurements
6.3.1.4	Radial, s. s. perm. in whole core	0.01- 250	Average permeability in all radial directions in whole core samples	Measures average "horizontal" perme- ability in large sample	Difficult to prepare samples; no radial stress; perm. critically dependent on con- dition of central "wellbore"

Table 6-2—Quick Selection and Reference Guide for Permeability Measurements Using Gases*

*Major advantages of using gas rather than liquid:

- b. Non-reactive with rock; non-corrosive to equipment.
- c. No post-measurement cleanup required.
- d. Less prone than liquid to mobilizing fines in rock sample.
- e. Does not support microbial growth, nor require special filtration.
- a. Requires correction for gas slippage-especially with lower perms.
- b. Prone to significant high-velocity inertial resistance in high perm. rock.
- c. Necessary leak-tightness harder to achieve than with liquids.
- d. In some cases, may be less representative of permeability in reservoir.

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Major disadvantages:

a. Easy to use-does not require special saturation techniques.

Reference Section Numbers	Type of Measurement	Approx. Perm. Range, md	Apparatus or Application	Major Advantages	Major Limitations
6.3.2.2	Axial, s.s. flow in plugs using liquid heads	1000- 40,000	Gravity flow of liquid through high perm., cylindrical core plugs	Simple, low cost equipment (but does require electronic balance for flow rate determination)	Low back pressure—difficult to ensure that no gas remains in core plug.
6.3.2.1	Axial flow, steady state in core plugs	0.1- 20,000	Apparatus with electronic sensors, high pressure. core holder, imposed	Can be automated; reservoir stresses can be approximated; may be most representative measurement of perm. in reservior	Corrosion resistant, moderate to high pres- sure pumping and control equipment is expensive
6.4.2.1 E.6.8.5	Axial flow, pulse-decay in core plugs	.00001- 0.1	High stress apparatus for very low perms.	Only method for ultra-low perms; well adapted for automation; no flow meters required: rate is calc. from $\Delta p \& t$	Requires high pressure, leak-tight system with high quality transducers and data acquisition system—high capital cost
6.3.2.1 6.3.1.3.1	Transverse, s.s. flow in whole cores	0.005- 500	Directional perm. in whole core (or plug) for k_{max} and k_{90*}	Can measure "horizontal" perm. in various directions; averaging obtained using whole-core sample.	Same as for s.s. axial flow (above); clean- ing, preparation and handling of whole core sample more expensive
6.3.1.4 6.3.1.4.2	Radial, steady state flow in whole cores	0.002- 250	Average permeability in all radial directions in whole core samples	Measures average "horizontal" per- meability in large sample	Same as above; difficult to prepare samples; no radial stress; perm. critically dependent on condition of central "wellbore"

Table 6-3—Quick Selection and Reference Guide for Permeability Measurements Using Liquids

6.2.1 Steady-State Permeability Equations For Gases

The general equation for steady-state gas permeability measurements will be presented first. It includes provision for gas slippage and inertial resistance effects, which become somewhat complicated and require more measurements than is usually practicable using steady-state measurements. However it serves to unify the theory of gas measurements and provides principles and guidelines for use of the Darcy equation, which is the basis for the practical steady-state cases that follow.

Unlike liquids, gases are highly compressible. Also, under normal laboratory conditions, the density of gas is sufficiently low that gravity effects may be ignored in making permeability measurements. The viscosity of air, nitrogen, or helium (see Tables 6-4, 6-5, and 6-6, respectively) is less than $1/_{50}$ that of water at room temperature. Therefore, volumetric fluxes of gases are correspondingly higher for a given pressure gradient, and can deviate from conditions of Stokes flow, demanded by Darcy's Law. Finally, the phenomenon of gas slippage, or the Klinkenberg effect, requires special treatment. Because of these differences, the point of departure for developing equations pertaining to the measurement of permeability using gases is the differential form of the Forchheimer equation, into which the Klinkenberg relationship will be inserted:

Where:

s = distance along the direction of flow.

 q_s = volumetric rate of gas flow through area A per unit time.

A = area perpendicular to the flow of gas.

 $\frac{dP}{ds}$ = pressure gradient along s to which q_s / A refers.

 μ = dynamic gas viscosity.

- k_e = apparent permeability of the medium to a particular gas.
- β = coefficient of inertial resistivity.
- ρ = gas density.

The constants C_1 , C_2 , and C_3 allow for various sets of dimensions to be used in the gas-flow equations that follow. Table 6-1 shows values of these constants for SI, preferred-SPE, traditional, or common-usage dimensions. Note that an upper case *P* appears in the equation above. This non-standard symbol denotes that the pressure is *absolute*. A lowercase *p* is used to denote a *gauge* or *differential* pressure in any equation below. These conventions have been adopted in this document because of the confusion between the two pressures, and the frequent error made when a measured gaugepressure is not converted to an absolute pressure when required. Thus, in keeping with this convention:

$$P = p + P_a \tag{6}$$

Where P_a is the true ambient barometric pressure, converted to the proper units (not the barometric pressure from the local airport, which has been converted to sea-level pressure).

The density of a real gas is:

$$\frac{dP}{ds} = \frac{C_2 \mu q_s}{C_1 A k_g} + \frac{C_3 \beta \rho_s^2}{C_1 A^2} \tag{7}$$

				Vis	cosity of air	at one atmosp	ohere, microp	oises				
			Tempera	ature, °F					Tempera	ature, °C		
plus	50°F	60°F	70°F	80°F	90°F	100°F	0°C	10°C	20°C	30°C	40°C	50°C
0	176.8	179.6	182.3	185.0	187.7	190.4	171.8	176.8	181.8	186.6	191.4	196.2
1	177.1	179.9	182.6	185.3	188.0	190.6	172.3	177.3	182.3	187.1	191.9	196.6
2	177.4	180.1	182.9	185.6	188.2	190.9	172.8	177.8	182.8	187.6	192.4	197.1
3	177.7	180.4	183.1	185.8	188.5	191.2	173.3	178.3	183.2	188.1	192.9	197.6
4	177.9	180.7	183.4	186.1	188.8	191.4	173.8	178.8	183.7	188.6	193.3	198.0
5	178.2	181.0	183.7	186.4	189.0	191.7	174.3	179.3	184.2	189.0	193.8	198.5
6	178.5	181.2	184.0	186.6	189.3	192.0	174.8	179.8	184.7	189.5	194.3	198.9
7	178.8	181.5	184.2	186.9	189.6	192.2	175.3	180.3	185.2	190.0	194.7	199.4
8	179.0	181.8	184.5	187.2	189.8	192.5	175.8	180.8	185.7	190.5	195.2	199.9
9	179.3	182.1	184.8	187.4	190.1	192.8	176.3	181.3	186.2	191.0	195.7	200.3

Table 6-4—Viscosity of Air (for Degrees F and C) at One Atmosphere*

*Calculated from Sutherland's equation:

$$\mu_{air} = \frac{14.969T^{1.5}}{T+120}$$

Where: T is absolute temperature, degrees Kelvin (degrees Celsius + 273), and μ_{air} is the viscosity of air at one atmosphere pressure, micropoises. Multiply by 1.0 E-04 to convert to centipoises, or by 1.0 E-07 to convert to Pa·s. Constants are based on work of Montgomery³⁵ and Birge³⁶.

Table 6-5—Viscosit	v of Nitroaen	(for Degrees F	and C) at One Atmosph	ere*
	,	1.0 0 g. 0 0 0 .		/	

				Vis	cosity of air	at one atmosp	ohere, microp	oises					
			Tempera	ature, °F		Temperature, °C							
plus	50°F	60°F	70°F	80°F	90°F	100°F	0°C	10°C	20°C	30°C	40°C	50°C	
0	171.3	173.8	176.4	178.9	181.4	183.8	166.6	171.3	175.9	180.4	184.8	189.2	
1	171.5	174.1	176.6	179.1	181.6	184.1	167.1	171.7	176.3	180.8	185.2	189.6	
2	171.8	174.3	176.9	179.4	181.9	184.3	167.5	172.2	176.8	181.3	185.7	190.0	
3	172.0	174.6	177.1	179.6	182.1	184.6	168.0	172.7	177.2	181.7	186.1	190.5	
4	172.3	174.8	177.4	179.9	182.3	184.8	168.5	173.1	177.7	182.2	186.6	190.9	
5	172.5	175.1	177.6	180.1	182.6	185.1	168.9	173.6	178.1	182.6	187.0	191.3	
6	172.8	175.3	177.9	180.4	182.8	185.3	169.4	174.0	178.6	183.0	187.4	191.8	
7	173.1	175.6	178.1	180.6	183.1	185.5	169.9	174.5	179.0	183.5	187.9	192.2	
8	173.3	175.9	178.4	180.9	183.3	185.8	170.3	174.9	179.5	183.9	188.3	192.6	
9	173.6	176.1	178.6	181.1	183.6	186.0	170.8	175.4	179.9	184.4	188.7	193.0	

*Calculated from Sutherland's equation:

$$\mu_{N_2} = \frac{13.85T^{1.5}}{T+102}$$

Where: T is absolute temperature, degrees Kelvin (degrees Celsius + 273), and μ_{N_2} is the viscosity of nitrogen at one atmosphere pressure, micropoises. Multiply by 1.0 E-04 to convert to centipoises, or by 1.0 E-07 to convert to Pa·s. Constants are based on the work of Licht and Stechert³⁷. The viscosity of nitrogen at temperatures reasonably close to 25°C and pressures to 253 atmospheres can be calculated from:

$$\mu_{N_2}[T, P] = \mu_{N_2}[T, 1] - 0.12474 + 0.123688P + 1.05452E - 03P^2 - 1.5052E - 06P^3$$

Where: $\mu_{N_2}[T, 1]$ is the viscosity of nitrogen at one atmosphere pressure (from the tables above), micropoises, and *P* is pressure, atmospheres. The pressure dependence is fitted to the data of Gracki, *et al.*³⁴ to within a maximum deviation of 0.1%. Pressure dependence at 0°C and 50°C is nearly the same as at 25°C.

Table 6-6—Viscosity of Helium (for Degrees F and C) at One Atmosphere*

				Vis	cosity of air	at one atmos	ohere, microp	oises							
Temperature, °F								Temperature, °C							
plus	50°F	60°F	70°F	80°F	90°F	100°F	0°C	10°C	20°C	30°C	40°C	50°C			
0	191.7	194.2	196.8	199.3	201.8	204.4	187.0	191.7	196.3	200.8	205.4	209.8			
1	191.9	194.5	197.0	199.6	202.1	204.6	187.5	192.1	196.7	201.3	205.8	210.3			
2	192.2	194.7	197.3	199.8	202.3	204.9	187.9	192.6	197.2	201.7	206.3	210.7			
3	192.4	195.0	197.5	200.1	202.6	205.1	188.4	193.1	197.6	202.2	206.7	211.2			
4	192.7	195.3	197.8	200.3	202.9	205.4	188.9	193.5	198.1	202.7	207.1	211.6			
5	193.0	195.5	198.1	200.6	203.1	205.6	189.3	194.0	198.6	203.1	207.6	212.0			
6	193.2	195.8	198.3	200.8	203.4	205.9	189.8	194.4	199.0	203.6	208.0	212.5			
7	193.5	196.0	198.6	201.1	203.6	206.1	190.3	194.9	199.5	204.0	208.5	212.9			
8	193.7	196.3	198.8	201.3	203.9	206.4	190.7	195.4	199.9	204.5	208.9	213.4			
9	194.0	196.5	199.1	201.6	204.1	206.6	191.2	195.8	200.4	204.9	209.4	213.8			

*Calculated from:

$$\mu_{He} = 187.0 \left(\frac{T}{273.1}\right)^{0.685}$$

Where: T is absolute temperature, degrees Kelvin (degrees Celsius + 273), and μ_{He} is the viscosity of helium at one atmosphere pressure, micropoises. Multiply by 1.0 E-04 to convert to centipoises, or by 1.0 E-07 to convert to Pa·s. Constants are from Chapman and Cowling³⁸.

According to the data of Gracki, *et al.*³⁴ the viscosity of helium at 25°C passes through a very shallow minimum with pressure. At 37 atm. it is 0.43 percent lower than at 1 atm., and at 158 atm., its viscosity is 0.17 percent higher than at 1 atm.

Where z is the gas deviation factor, which is equal to 1.0 for an ideal gas. Values of z as functions of temperature and pressure are given in Tables 6-7, 6-8, and 6-9 for air, nitrogen, and helium, respectively. They are calculated from the Beat-tie-Bridgeman equation of state¹⁴. See Table 6-1 for values of the universal gas-law constant, R, for the various sets of units. M is the gas molecular weight. Temperature in Equation 7 is absolute, in degrees Kelvin:

$$T = {^{\circ}C} + 273.15$$

= (°F - 32)/1.8 + 273.15 (8)

6.2.1.1 Treatment of the Gas Slippage Factor

The Klinkenberg relationship, written as a point function (i.e., pertaining to a particular point in a sample, not an average value) is:

$$k_g = k_{\infty} \left(1 + \frac{b}{P} \right) \tag{9}$$

Note that k_g depends upon pressure. Therefore it cannot be treated as a constant when the Forchheimer (or Darcy) equation is integrated. In Equation 9, *b* must have the same units as those of the pressure used.

Unfortunately, the gas slippage factor, b, is partly a rock property and partly a gas property, which has caused confusion and some problems. For example, a b measured using air, but not indicated as such, might be misused in calculations involving a different gas with significantly different properties. It is a fairly simple procedure to separate the gas properties from the slip factor, so that only the rock-dependent property remains. According to Klinkenberg³, *b* is related to the mean free path of gas molecules, $\overline{\lambda}$, by the relationship:

$$\bar{\lambda} = \frac{br}{4cP} \tag{10}$$

But, from the kinetic gas theory¹⁵, the mean free path is given by:

$$\bar{\lambda} = \frac{1.881\mu}{P} \sqrt{\frac{RT}{M}} \tag{11}$$

In Equations 10 and 11, any consistent units may be used. From these two equations, and adjusting for the units given below, we obtain:

$$b = \left[99.5\mu \sqrt{\frac{T}{M}}\right] \left(\frac{c}{r}\right) \tag{12}$$

Where:

- P = absolute gas pressure.
- R = universal gas law constant.
- b = Klinkenberg gas slippage factor, psi. (The constant 99.5 becomes 6.77 if b has the unit of atm).
- μ = gas viscosity, cp.

P.			Z-Factors f	or Air at Tem	peratures (Des	grees F) of:			P.			Z-Factors for	or Air at Tem	peratures (De	prees C) of:		
nsia	55	60	65	70	75	80	85	90	nsia -	0	5	10	15	20	25	30	35
0	1 00000	1.00000	1.00000	1.00000	1.00000	1.00000	1 00000	1.00000	0	1.00000	1.00000	1.00000	1.00000	1 00000	1.00000	1.00000	1.00000
10	0.99968	0.99970	0.99972	0.99973	0.99975	0.99977	0.99979	0.99980	10	0.99957	0.99962	0.99966	0.99969	0.99973	0.99976	0.99979	0.99982
20	0.99935	0.99970	0.999/2	0.999/13	0.99951	0.99954	0.99957	0.99961	20	0.99915	0.99902	0.99900	0.00030	0.99946	0.99952	0.99979	0.99964
20	0.00004	0.00010	0.00015	0.00021	0.00026	0.00031	0.00036	0.00041	20	0.00873	0.00996	0.00907	0.00008	0.00010	0.00028	0.00037	0.00046
40	0.99904	0.99910	0.99913	0.99921	0.99920	0.99931	0.99930	0.99941	30	0.99873	0.99880	0.99897	0.99908	0.99919	0.99928	0.99937	0.99940
40 50	0.99872	0.99880	0.99888	0.99895	0.99902	0.99909	0.99910	0.99922	40 50	0.99831	0.99848	0.99804	0.99878	0.99892	0.99903	0.99917	0.99928
50	0.99840	0.99830	0.99800	0.99809	0.99878	0.99887	0.99895	0.99903	50	0.99790	0.99811	0.99830	0.99848	0.99800	0.99882	0.99897	0.99911
70	0.99809	0.99821	0.99833	0.99844	0.99834	0.99803	0.99875	0.99884	70	0.99748	0.99773	0.99797	0.99819	0.99839	0.99839	0.99870	0.99893
80	0.99778	0.99792	0.99800	0.99818	0.99831	0.99843	0.99834	0.99800	70 80	0.99707	0.99730	0.99704	0.99789	0.99813	0.99830	0.99837	0.99870
00	0.99747	0.99703	0.99779	0.99793	0.99808	0.99821	0.99834	0.99847	80	0.99000	0.99700	0.99731	0.99700	0.99788	0.99813	0.99837	0.99839
90	0.99717	0.99733	0.99732	0.99709	0.99784	0.99800	0.99813	0.99829	90	0.99020	0.99003	0.99098	0.99731	0.99782	0.99791	0.99818	0.99843
110	0.99087	0.99700	0.99720	0.99744	0.99702	0.99779	0.99795	0.99811	110	0.99585	0.99027	0.99000	0.99703	0.99737	0.99709	0.99798	0.99820
120	0.99037	0.99078	0.99099	0.99720	0.99739	0.99738	0.99770	0.99793	120	0.99545	0.99391	0.99034	0.99074	0.99712	0.99747	0.99779	0.99810
120	0.99027	0.99031	0.99073	0.99093	0.99717	0.99737	0.99737	0.99778	120	0.99303	0.99333	0.99002	0.99040	0.99087	0.99723	0.99701	0.99794
140	0.99597	0.99023	0.99048	0.99071	0.99094	0.99710	0.99738	0.99738	140	0.99400	0.99320	0.99571	0.99018	0.99002	0.99703	0.99742	0.99778
140	0.99508	0.99590	0.99022	0.99048	0.99072	0.99090	0.99719	0.99741	140	0.99420	0.99485	0.99539	0.99590	0.99038	0.99082	0.99724	0.99702
150	0.99539	0.99308	0.99397	0.99024	0.99031	0.99070	0.99701	0.99724	150	0.99387	0.99430	0.99308	0.99303	0.99013	0.99001	0.99703	0.99747
170	0.99510	0.99541	0.99572	0.99372	0.99001	0.99001	0.99029	0.99030	100	0.99349	0.99413	0.99477	0.99535	0.99389	0.99040	0.99087	0.99732
170	0.99481	0.99313	0.99347	0.99378	0.99008	0.99037	0.99004	0.99091	170	0.99310	0.99381	0.99447	0.99308	0.99300	0.99019	0.99070	0.99717
100	0.99433	0.99488	0.99322	0.99333	0.99387	0.99017	0.99040	0.99073	180	0.99272	0.99347	0.99410	0.99481	0.99342	0.99399	0.99032	0.99702
200	0.99423	0.99402	0.99498	0.99555	0.99300	0.99398	0.99629	0.99039	190	0.99234	0.99313	0.99380	0.99433	0.99319	0.99379	0.99033	0.99087
200	0.99397	0.99430	0.99474	0.99310	0.99343	0.99379	0.99011	0.99043	200	0.99190	0.99279	0.99550	0.99428	0.99490	0.99339	0.99018	0.99073
210	0.99309	0.99410	0.99430	0.99466	0.99323	0.99300	0.99394	0.99627	210	0.99139	0.99240	0.99327	0.99402	0.99475	0.99339	0.99001	0.99039
220	0.99342	0.99383	0.99420	0.99400	0.99303	0.99342	0.99377	0.99012	220	0.99121	0.99212	0.99297	0.00251	0.99430	0.99320	0.99384	0.99043
230	0.99313	0.99300	0.99405	0.99443	0.99465	0.99323	0.99300	0.99390	230	0.99084	0.99180	0.99208	0.99331	0.99428	0.99300	0.99508	0.99031
240	0.99288	0.99333	0.99380	0.99423	0.99403	0.99303	0.99344	0.99381	240	0.99048	0.99147	0.99239	0.99320	0.99400	0.99481	0.99332	0.99017
250	0.99201	0.99310	0.99337	0.99402	0.99445	0.99487	0.99528	0.99500	250	0.99011	0.99113	0.99211	0.99300	0.99384	0.99402	0.99535	0.99004
200	0.99233	0.99285	0.99334	0.99381	0.99420	0.99470	0.99311	0.99332	200	0.98973	0.99082	0.99182	0.99275	0.99302	0.99444	0.99320	0.99540
400	0.99132	0.99190	0.99240	0.99299	0.99331	0.99401	0.99449	0.99490	400	0.98833	0.98937	0.99071	0.99178	0.99278	0.99371	0.99439	0.99340
500	0.98691	0.98908	0.99041	0.99112	0.99180	0.99240	0.99.09	0.99370	400 500	0.98498	0.98000	0.98812	0.98932	0.99084	0.99207	0.99321	0.99428
600	0.98070	0.98770	0.98801	0.98948	0.99032	0.99113	0.99190	0.99203	500	0.98190	0.98591	0.98378	0.98731	0.98913	0.99004	0.99200	0.99337
700	0.98480	0.98398	0.98703	0.98808	0.98907	0.99002	0.99094	0.99183	700	0.97911	0.98149	0.98370	0.98370	0.98707	0.98943	0.99112	0.99208
800	0.98322	0.98430	0.98575	0.98092	0.98805	0.98913	0.99020	0.99122	800	0.97002	0.97935	0.98189	0.98425	0.98045	0.98850	0.99041	0.99219
000	0.98185	0.98329	0.98407	0.98000	0.98728	0.98850	0.98908	0.99082	800	0.97442	0.977503	0.98033	0.98301	0.98547	0.98777	0.98992	0.99192
1000	0.98074	0.98233	0.98380	0.98332	0.98073	0.98809	0.98939	0.99003	1000	0.97233	0.97393	0.97908	0.98202	0.98474	0.98728	0.98903	0.99185
1100	0.97989	0.98103	0.98329	0.98489	0.98042	0.98790	0.98932	0.99009	1100	0.97093	0.97405	0.97809	0.98129	0.98420	0.98702	0.98900	0.99200
1200	0.97931	0.98118	0.98297	0.98470	0.98035	0.98794	0.98947	0.99094	1200	0.90905	0.97300	0.97737	0.98061	0.98401	0.98099	0.98977	0.99233
1200	0.97900	0.98099	0.98290	0.98474	0.98690	0.98821	0.98984	0.99141	1200	0.96800	0.97293	0.97674	0.98000	0.98402	0.98762	0.99010	0.99291
1400	0.97894	0.98137	0.98350	0.98555	0.98090	0.98809	0.99122	0.99206	1400	0.96363	0.97234	0.97683	0.98004	0.98474	0.98702	0.99070	0.99368
1500	0.97913	0.98193	0.98550	0.98535	0.98835	0.98940	0.99722	0.99290	1500	0.96756	0.97241	0.97003	0.98095	0.98545	0.98015	0.99760	0.99580
1600	0.97901	0.98193	0.98505	0.98030	0.98835	0.99033	0.99223	0.99403	1500	0.96779	0.97230	0.97780	0.98147	0.98545	0.98915	0.99200	0.99580
1700	0.98032	0.98275	0.98505	0.98728	0.90069	0.99781	0.99/85	0.99682	1700	0.96832	0.97259	0.97867	0.98220	0.98040	0.99024	0.99535	0.99870
1800	0.98128	0.98505	0.98752	0.98990	0.99009	0.99281	0.99405	0.99849	1800	0.96013	0.97365	0.97807	0.98325	0.98996	0.99135	0.99525	1.00043
1000	0.98248	0.98555	0.98909	0.90153	0.99218	0.99430	0.98827	1.00034	1900	0.97021	0.97590	0.98116	0.98604	0.98890	0.99300	0.99000	1.00045
2000	0.98558	0.98828	0.90088	0.99337	0.99576	0.99805	1.00026	1.00238	2000	0.97021	0.97738	0.98276	0.98004	0.00238	0.99669	1,00069	1.00442
2100	0.98747	0.90020	0.99287	0.99540	0.99784	1 00018	1.00020	1.00250	2100	0.97320	0.97912	0.98460	0.98968	0.99440	0.99879	1.00287	1.00668
2200	0.98957	0.99237	0.99506	0.99764	1.00011	1.00249	1.00245	1.00400	2200	0.97508	0.98109	0.98666	0.99182	0.99662	1.00108	1.00207	1.00008
2200	0.90957	0.99237	0.99500	1.00006	1.00257	1.00249	1.00730	1.00953	2200	0.97500	0.98320	0.98803	0.99416	0.99002	1.00103	1.00525	1.01167
2400	0.99109	0.99472	1.00002	1.00000	1.00237	1.00490	1.00750	1.00955	2300	0.97120	0.98571	0.90095	0.99410	1.00161	1.00554	1.00775	1.01440
2400	0.99440	1.00000	1.00002	1.00200	1.00520	1.00703	1.00998	1.01225	2400	0.97957	0.98935	0.99141	0.99070	1.00/38	1 00800	1 01328	1.01440
2500	1 00000	1.00000	1.00277	1.00545	1 01005	1.013/3	1.01202	1.01810	2500	0.98/07	0.90055	0.99410	1 00233	1.00732	1.00079	1.01528	1 02030
2000	1.00000	1.00291	1.00570	1.00050	1.01095	1.01545	1.01301	1.02124	2000	0.98700	0.99120	1 00003	1.00235	1.007.52	1.01190	1.01027	1.02050
2800	1.00507	1.00399	1.00079	1.01/40	1.01407	1.01055	1.01094	1.02124	2700	0.96799	0.99423	1.00003	1.00341	1.01042	1.0193/	1.01941	1.02545
2000	1.00051	1.00925	1.01204	1.01915	1.02074	1.01203	1.02222	1.02794	2000	0.99120	1 00086	1.00527	1.00000	1.01708	1.02175	1.02209	1.02074
2200	1.007/1	1.01204	1.01040	1.01015	1.02074	1.02525	1.02005	1.02/24	2200	0.00920	1.00080	1.00007	1.01200	1.02062	1.02175	1.02010	1.03260
5000	1.01347	1.01019	1.01900	1.02109	1.02420	1.02070	1.02717	1.03147	5000	0.22020	1.004444	1.01025	1.01302	1.02005	1.02327	1.02704	1.05507

Table 6-7—Gas Law Deviation Factors for Air, Calculated from Beattie-Bridgemann Equation of State¹⁴

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Р,			Z-Factors f	or Air at Tem	peratures (De	grees F) of:			Р,	Z-Factors for Air at Temperatures (Degrees C) of:							
psia	55	60	65	70	75	80	85	90	psia	0	5	10	15	20	25	30	35
0	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	0	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
10	0.99975	0.99977	0.99979	0.99981	0.99983	0.99984	0.99986	0.99987	10	0.99965	0.99969	0.99973	0.99977	0.99980	0.99983	0.99986	0.99989
20	0.99950	0.99954	0.99958	0.99962	0.99965	0.99969	0.99972	0.99975	20	0.99930	0.99939	0.99946	0.99954	0.99960	0.99967	0.99973	0.99978
30	0.99926	0.99932	0.99938	0.99943	0.99948	0.99953	0.99958	0.99963	30	0.99896	0.99908	0.99920	0.99931	0.99941	0.99950	0.99959	0.99968
40	0.99902	0.99910	0.99917	0.99925	0.99932	0.99938	0.99945	0.99951	40	0.99862	0.99878	0.99894	0.99908	0.99922	0.99934	0.99946	0.99957
50	0.99878	0.99888	0.99897	0.99907	0.99915	0.99924	0.99932	0.99940	50	0.99828	0.99849	0.99868	0.99886	0.99903	0.99919	0.99933	0.99947
60	0.99855	0.99867	0.99878	0.99889	0.99899	0.99909	0.99919	0.99928	60	0.99795	0.99819	0.99843	0.99864	0.99884	0.99903	0.99921	0.99937
70	0.99832	0.99845	0.99858	0.99871	0.99883	0.99895	0.99906	0.99917	70	0.99761	0.99790	0.99817	0.99843	0.99866	0.99888	0.99909	0.99928
80	0.99809	0.99824	0.99839	0.99854	0.99868	0.99881	0.99894	0.99906	80	0.99729	0.99762	0.99792	0.99821	0.99848	0.99873	0.99896	0.99918
90	0.99786	0.99804	0.99820	0.99837	0.99852	0.99867	0.99882	0.99896	90	0.99696	0.99733	0.99768	0.99800	0.99830	0.99858	0.99885	0.99909
100	0.99764	0.99783	0.99802	0.99820	0.99837	0.99854	0.99870	0.99885	100	0.99664	0.99705	0.99744	0.99779	0.99813	0.99844	0.99873	0.99900
110	0.99742	0.99763	0.99784	0.99803	0.99822	0.99841	0.99858	0.99875	110	0.99632	0.99677	0.99719	0.99759	0.99795	0.99830	0.99862	0.99892
120	0.99720	0.99743	0.99766	0.99787	0.99808	0.99828	0.99847	0.99866	120	0.99601	0.99650	0.99696	0.99739	0.99779	0.99816	0.99851	0.99883
130	0.99698	0.99724	0.99748	0.99771	0.99793	0.99815	0.99836	0.99856	130	0.99569	0.99623	0.99672	0.99719	0.99762	0.99802	0.99840	0.99875
140	0.99677	0.99704	0.99730	0.99755	0.99779	0.99803	0.99825	0.99847	140	0.99538	0.99596	0.99649	0.99699	0.99745	0.99789	0.99829	0.99867
150	0.99656	0.99685	0.99713	0.99740	0.99766	0.99790	0.99814	0.99837	150	0.99508	0.99569	0.99626	0.99680	0.99729	0.99776	0.99819	0.99860
160	0.99636	0.99667	0.99696	0.99725	0.99752	0.99779	0.99804	0.99829	160	0.99478	0.99543	0.99604	0.99660	0.99713	0.99763	0.99809	0.99852
170	0.99615	0.99648	0.99680	0.99710	0.99739	0.99767	0.99794	0.99820	170	0.99448	0.99517	0.99582	0.99642	0.99698	0.99750	0.99799	0.99845
180	0.99595	0.99630	0.99663	0.99695	0.99726	0.99756	0.99784	0.99812	180	0.99418	0.99491	0.99560	0.99623	0.99683	0.99738	0.99790	0.99838
190	0.99576	0.99612	0.99647	0.99681	0.99713	0.99744	0.99775	0.99804	190	0.99389	0.99466	0.99538	0.99605	0.99667	0.99726	0.99780	0.99831
200	0.99556	0.99595	0.99631	0.99667	0.99701	0.99734	0.99765	0.99796	200	0.99360	0.99441	0.99517	0.99587	0.99653	0.99714	0.99771	0.99825
210	0.99537	0.99577	0.99616	0.99653	0.99689	0.99723	0.99756	0.99788	210	0.99331	0.99416	0.99496	0.99569	0.99638	0.99703	0.99763	0.99819
220	0.99518	0.99560	0.99601	0.99639	0.99677	0.99713	0.99747	0.99781	220	0.99303	0.99392	0.99475	0.99552	0.99624	0.99691	0.99754	0.99813
230	0.99500	0.99544	0.99586	0.99626	0.99665	0.99703	0.99739	0.99774	230	0.99275	0.99368	0.99454	0.99535	0.99610	0.99680	0.99746	0.99807
240	0.99482	0.99527	0.99571	0.99613	0.99654	0.99693	0.99730	0.99767	240	0.99247	0.99344	0.99434	0.99518	0.99596	0.99669	0.99738	0.99802
250	0.99464	0.99511	0.99557	0.99600	0.99643	0.99683	0.99722	0.99760	250	0.99220	0.99321	0.99414	0.99502	0.99583	0.99659	0.99730	0.99796
260	0.99446	0.99495	0.99542	0.99588	0.99632	0.99674	0.99715	0.99754	260	0.99193	0.99298	0.99395	0.99485	0.99570	0.99649	0.99722	0.99791
300	0.99378	0.99435	0.99489	0.99541	0.99591	0.99639	0.99686	0.99731	300	0.99089	0.99208	0.99320	0.99424	0.99520	0.99611	0.99695	0.99774
400	0.99230	0.99304	0.99375	0.99443	0.99508	0.99571	0.99632	0.99691	400	0.98851	0.99008	0.99154	0.99289	0.99416	0.99534	0.99644	0.99747
500	0.99112	0.99202	0.99289	0.99372	0.99453	0.99530	0.99604	0.99675	500	0.98647	0.98839	0.99018	0.99185	0.99339	0.99484	0.99618	0.99744
600	0.99024	0.99130	0.99232	0.99330	0.99424	0.99514	0.99601	0.99685	600	0.98478	0.98704	0.98914	0.99109	0.99291	0.99460	0.99618	0.99766
700	0.98967	0.99088	0.99204	0.99315	0.99422	0.99525	0.99624	0.99720	700	0.98343	0.98602	0.98841	0.99064	0.99271	0.99464	0.99644	0.99811
800	0.98940	0.99074	0.99204	0.99328	0.99447	0.99562	0.99672	0.99779	800	0.98244	0.98532	0.98800	0.99048	0.99279	0.99494	0.99694	0.99881
900	0.98943	0.99091	0.99232	0.99368	0.99499	0.99625	0.99746	0.99862	900	0.98180	0.98496	0.98789	0.99061	0.99315	0.99550	0.99769	0.99974
1000	0.98976	0.99136	0.99289	0.99436	0.99577	0.99713	0.99844	0.99969	1000	0.98151	0.98493	0.98810	0.99104	0.99378	0.99632	0.99869	1.00090
1100	0.99039	0.99209	0.99373	0.99530	0.99681	0.99826	0.99966	1.00100	1100	0.98156	0.98522	0.98861	0.99176	0.99468	0.99740	0.99993	1.00229
1200	0.99131	0.99311	0.99484	0.99651	0.99811	0.99964	1.00112	1.00254	1200	0.98196	0.98583	0.98942	0.99276	0.99585	0.99873	1.00141	1.00390
1300	0.99251	0.99441	0.99623	0.99797	0.99965	1.00126	1.00281	1.00430	1300	0.98270	0.98676	0.99053	0.99403	0.99728	1.00030	1.00312	1.00574
1400	0.99399	0.99597	0.99787	0.99969	1.00144	1.00312	1.00474	1.00629	1400	0.98376	0.98800	0.99193	0.99558	0.99897	1.00212	1.00505	1.00778
1500	0.99575	0.99780	0.99976	1.00165	1.00346	1.00521	1.00688	1.00849	1500	0.98515	0.98955	0.99362	0.99740	1.00091	1.00417	1.00721	1.01004
1600	0.99777	0.99988	1.00191	1.00385	1.00572	1.00751	1.00924	1.01090	1600	0.98686	0.99138	0.99558	0.99947	1.00308	1.00645	1.00958	1.01249
1700	1.00005	1.00221	1.00429	1.00628	1.00820	1.01004	1.01181	1.01351	1700	0.98886	0.99350	0.99780	1.00179	1.00550	1.00894	1.01215	1.01514
1800	1.00258	1.00479	1.00690	1.00894	1.01089	1.01277	1.01458	1.01631	1800	0.99117	0.99589	1.00028	1.00435	1.00813	1.01165	1.01493	1.01/98
1900	1.00535	1.00/59	1.009/4	1.01181	1.01379	1.01570	1.01754	1.01930	1900	0.99375	0.99855	1.00301	1.00/15	1.01099	1.01457	1.01790	1.02100
2000	1.00834	1.01061	1.01279	1.01489	1.01690	1.01883	1.02069	1.02248	2000	0.99661	1.00147	1.00598	1.01017	1.01406	1.01768	1.02105	1.02419
2100	1.01150	1.01385	1.01005	1.01816	1.02019	1.02214	1.02402	1.02582	2100	0.99973	1.00463	1.00918	1.01340	1.01/33	1.02098	1.02439	1.02/56
2200	1.01499	1.01/29	1.01950	1.02163	1.02367	1.02563	1.02/52	1.02934	2200	1.00310	1.00802	1.01259	1.01684	1.02079	1.02447	1.02/89	1.03108
2300	1.01862	1.02093	1.02315	1.02528	1.02/33	1.02930	1.03119	1.03301	2300	1.00670	1.01163	1.01622	1.02047	1.02444	1.02812	1.03156	1.034/6
2400	1.02244	1.02475	1.02097	1.02910	1.03115	1.03312	1.03501	1.03084	2400	1.01053	1.01546	1.02004	1.02430	1.02826	1.03195	1.03538	1.03859
2500	1.02645	1.02875	1.03096	1.03309	1.03513	1.03/10	1.03899	1.04081	2500	1.01458	1.01949	1.02405	1.02830	1.03225	1.03593	1.03936	1.04256
2600	1.03063	1.03292	1.03512	1.03/24	1.03927	1.04123	1.04311	1.04492	2600	1.01882	1.02371	1.02824	1.03247	1.03640	1.04006	1.04348	1.04666
2700	1.0349/	1.03725	1.03943	1.04153	1.04355	1.04550	1.04/36	1.04916	2700	1.02326	1.023/1	1.00824	1.03247	1.03640	1.04006	1.04348	1.04666
2800	1.03947	1.04173	1.04389	1.04597	1.047/97	1.04990	1.05175	1.05353	2800	1.02/88	1.03267	1.03/13	1.04128	1.04515	1.04875	1.05211	1.05524
20000		1 11/16/35	1 0 / 849	1 05054	1.05252	1 115443	1.05626	1 05802	2900	103267	1 037/40	1 11/11/81	1 1/1501	1 11/10/73	1.115/3/20	1 05661	1.0507/1

Table 6-8—Gas Law Deviation Factors for Nitrogen, Calculated from Beattie-Bridgemann Equation of State¹⁴

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RECOMMENDED PRACTICES FOR CORE ANALYSIS

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