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# NATURAL GAS RESERVOIR ENGINEERING

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CHI U. IKOKU

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*The Pennsylvania State University*

**JOHN WILEY & SONS**

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# PREFACE

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This book presents concepts and applications of reservoir engineering principles essential to optimum development of natural gas reservoirs. It is based on courses taught at The University of Tulsa, The Pennsylvania State University, and adult education seminars in the United States and overseas.

The development of a natural gas field always depends on the reservoir and well characteristics as well as the equipment performance. A systems approach is emphasized throughout the book, since change in any component of the field production system will affect the performance of the other components. This book is arranged so that it can be used as a text or reference work for students and practicing engineers, geologists, and managers in the crude oil and natural gas production industry.

Chapter 1 discusses methods of estimating nonassociated, associated, and dissolved gas and abnormally pressured gas reserves. Reserves estimation and performance prediction for gas-condensate reservoirs are treated in Chapter 2. A comprehensive and rigorous treatment of production decline curve analysis is given in Chapter 3.

In Chapters 4 and 5 the theory and application of gas well testing are discussed. Well test analysis is an important subject in reservoir engineering, since it enables us to obtain reservoir parameters that could be used to predict future reservoir performance. Chapter 4 considers deliverability or back-pressure testing of gas wells. Chapter 5 discusses pressure transient analysis for gas wells. Both the pressure-squared technique and the pseudo-pressure function or real gas potential technique are treated and compared.

The systems approach is used to determine optimum gas field development strategies in Chapter 6; examples of reservoir performance techniques and field development patterns are presented. Chapter 7 extends some of the techniques of gas transmission and gas reservoir engineering to the storage of natural gas.

Much of the material on which this book is based was drawn from the publications of the Society of Petroleum Engineers of the American Institute of Mining, Metallurgical and Petroleum Engineers, the American Gas Association, the Division of Production of the American Petroleum Institute, and the Gas Processors Suppliers Association. Tribute is due to these organizations and also to a host of schools and authors who sponsor programs and have contributed to petroleum literature in various other publications.

## **viii Preface**

I am indebted to my students, whose enthusiasm for the subject has made teaching a pleasure. To my colleagues who have adopted this material in various petroleum and natural gas engineering departments in the United States and overseas, I express my gratitude for their constructive criticisms and comments that became textbook inputs. I thank Peggy Conrad for typing the manuscript.

I would like to express my appreciation to the editorial staff of John Wiley, including Merrill Floyd and Deborah Herbert, for their patience and politeness. I thank Cindy Stein-Lapidus and the members of Wiley's production staff for a fine job.

Chi U. Ioku

# NOMENCLATURE

## QUANTITIES IN ALPHABETICAL ORDER

(\*) Dimensions: L = length, m = mass, q = electrical charge, t = time, and T = temperature.

(\*\*) To avoid conflicting designation in some cases, use of reserve symbols and reserve subscripts is permitted.

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimen- sions*
air requirement	$a$	$F_a$	
angle	$\alpha$ alpha	$\beta$ beta	
angle	$\theta$ theta	$\gamma$ gamma	
angle, contact	$\theta_c$ theta	$\gamma_c$ gamma	
angle of dip	$\alpha_d$ alpha	$\theta_d$ theta	
area	$A$	$S$	$L^2$
Arrhenius reaction rate velocity constant	$w$	$z$	$L^3/m$
breadth, width, or (primarily in fracturing) thick- ness	$b$	$w$	$L$
burning-zone advance rate	$v_b$	$V_b, u_b$	$L/t$
capillary pressure	$P_c$	$P_c, p_c$	$m/Lt^2$
charge	$Q$	$q$	$q$
coefficient, convective heat transfer	$h$	$h_h, h_T$	$m/t^3T$
coefficient, heat transfer, interphase convective (use $h$ , or convective coefficient symbol, with pertinent phase subscripts added)			$m/t^3T$
coefficient, heat transfer, overall	$U$	$U_T, U_\theta$	$m/t^3T$
coefficient, heat transfer, radiation	$I$	$I_T, I_\theta$	$m/t^3T$
components, number of	$C$	$n_c$	
compressibility	$c$	$k, \kappa$ kappa	$Lt^2/m$
compressibility factor	$z$	$Z$	
concentration	$C$	$c, n$	various

Courtesy of Society of Petroleum Engineers of  
American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc.

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimen- sions*
condensate or natural gas liquid content	$C_L$	$c_L, n_L$	various
conductivity	$\sigma$ sigma	$\gamma$ gamma	various
conductivity, thermal (always with additional phase or system subscripts)	$k_h$	$\lambda$ lambda	$mL/t^3T$
contact angle	$\theta_c$ theta	$\gamma_c$ gamma	
damage ratio ("skin" conditions relative to forma- tion conditions unaffected by well operations)	$F_s$	$F_d$	
density	$\rho$ rho	$D$	$m/L^3$
depth	$D$	$y, H$	$L$
diameter	$d$	$D$	$L$
diffusion coefficient	$D$	$\mu$ mu, $\delta$ delta	$L^2/t$
dimensionless fluid influx function, linear aquifer	$Q_{LD}$	$Q_{LD}$	
dispersion coefficient	$K$	$d$	$L^2/t$
displacement	$s$	$L$	$L$
displacement ratio	$\delta$ delta	$F_d$	
distance between adjacent rows of injection and production wells	$d$	$L_d, L_2$	$L$
distance between like wells (injection or produc- tion) in a row	$a$	$L_a, L_1$	$L$
distance, length, or length of path	$L$	$s, l$ script l	$L$
efficiency	$E$	$\eta$ eta, $e$	
electrical resistivity	$\rho$ rho	$R$	$mL^3/tq^2$
electromotive force (voltage)	$E$	$V$	$mL^2/t^2q$
elevation referred to datum	$Z$	$D, h$	$L$
encroachment or influx rate	$e$	$i$	$L^3/t$
energy	$E$	$U$	$mL^2/t^2$
enthalpy (always with phase or system subscripts)	$H$	$I$	$mL^2/t^2$
enthalpy (net) of steam or enthalpy above reser- voir temperature	$H_s$	$I_s$	$mL^2/t^2$
enthalpy, specific	$h$	$i$	$L^2/t^2$
entropy, specific	$s$	$\sigma$ sigma	$L^2/t^2T$
entropy, total	$S$	$\sigma_t$ sigma	$mL^2/t^2T$
equilibrium ratio	$K$	$k, F_{eq}$	
fluid influx function, linear aquifer, dimensionless	$Q_{LD}$	$Q_{LD}$	
flow rate or flux, per unit area (volumetric ve- locity)	$u$	$\psi$ psi	$L/t$
flow rate or production rate	$q$	$Q$	$L^3/t$
fluid (generalized)	$F$	$f$	various
flux	$u$	$\psi$ psi	various
force	$F$	$Q$	$mL/t^2$
formation volume factor	$B$	$F$	
fraction gas	$f_g$	$F_g$	
fraction liquid	$f_L$	$F_L, f_l$	
frequency	$f$	$\nu$ nu	$1/t$

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimen- sions*
fuel consumption	$m$	$F_F$	various
fuel deposition rate	$N_R$	$N_F$	$m/L^3t$
gas (any gas, including air)—always with identifying subscripts	$G$	$g$	various
gas in place in reservoir, total initial	$G$	$g$	$L^3$
gas-oil ratio, producing (if needed, the reserve symbols could be applied to other gas-oil ratios)	$R$	$F_g, F_{go}$	
general and individual bed thickness	$h$	$d, e$	$L$
gradient	$g$	$\gamma$ gamma	various
heat flow rate	$Q$	$q, \Phi$ phi <sub>cap</sub>	$mL^2/t^3$
heat of vaporization, latent	$L_v$	$\lambda_v$ lambda	$L^2/t^2$
heat or thermal diffusivity	$\alpha$ alpha	$\alpha, \eta_h$ eta	$L^2/t$
heat transfer coefficient, convective	$h$	$h_h, h_T$	$m/t^3T$
heat transfer coefficient, interphase convection (use $h$ , or convective coefficient symbol with pertinent subscripts added)			$m/t^3T$
heat transfer coefficient, over-all	$U$	$U_T, U_0$	$m/t^3T$
heat transfer coefficient, radiation	$I$	$I_T, I_0$	$m/t^3T$
height (elevation)	$Z$	$D, h$	$L$
height (other than elevation)	$h$	$d, e$	$L$
hydraulic radius	$r_H$	$R_H$	$L$
index of refraction	$n$	$\mu$ mu	
influx (encroachment) rate	$e$	$i$	$L^3/t$
influx function, fluid, linear aquifer, dimensionless	$Q_{LID}$	$Q_{lID}$	
initial water saturation	$S_{wi}$	$\rho_{wi}$ rho, $S_{wi}$	
injectivity index	$I$	$i$	$L^4t/m$
intercept	$b$	$Y$	various
interfacial or surface tension	$\sigma$ sigma	$y, \gamma$ gamma	$m/t^2$
interstitial-water saturation in oil band	$S_{wo}$	$S_{wb}$	
irreducible water saturation	$S_{iw}$	$\rho_{iw}$ rho, $S_{iw}$	
kinematic viscosity	$\nu$ nu	$N$	$L^2/t$
length	$L$	$s, I$ script I	$L$
length, path length, or distance	$L$	$s, I$ script I	$L$
mass flow rate	$w$	$m$	$m/t$
mobility ratio	$M$	$F_\lambda$	
mobility ratio, diffuse-front approximation, $[(\lambda_D + \lambda_d)_{swept}/(\lambda_d)_{unswept}]$ ; $D$ signifies displacing; $d$ signifies displaced; mobilities are evaluated at average saturation conditions behind and ahead of front	$M_S$	$M_{Dd}, M_{su}$	
mobility ratio, sharp-front approximation, $(\lambda_D/\lambda_d)$	$M$	$F_\lambda$	
mobility ratio, total, $[(\lambda_t)_{swept}/(\lambda_t)_{unswept}]$ ; "swept" and "unswept" refer to invaded and uninvaded regions behind and ahead of leading			



Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimen- sions*
edge of a displacement front	$M_i$	$F_{\lambda_i}$	
mobility, total, of all fluids in a particular region of the reservoir; e.g., $(\lambda_o + \lambda_g + \lambda_w)$	$\lambda_t$ lambda	$\Lambda$ lambda <sub>cap</sub>	$L^3t/m$
modulus, bulk	$K$	$K_b$	$m/Lt^2$
modulus of elasticity in shear	$G$	$E_s$	$m/Lt^2$
modulus of elasticity (Young's modulus)	$E$	$Y$	$m/Lt^2$
mole fraction gas	$f_g$	$F_g$	
mole fraction liquid	$f_L$	$F_L, f_l$	
molecular refraction	$R$	$N$	$L^3$
moles, number of	$n$	$N$	
moles of liquid phase	$L$	$n_L$	
moles of vapor phase	$V$	$n_v$	
moles, total	$n$	$n_t, N_t$	
number (of moles, or components, or wells, etc.)	$n$	$N$	
oil (always with identifying subscripts)	$n$	$n$	various
oil in place in reservoir, initial	$N$	$n$	$L^3$
oxygen utilization	$e_{O_2}$	$E_{O_2}$	
path length, length, or distance	$L$	$s, l$ script I	$L$
permeability	$k$	$K$	$L^2$
Poisson's ratio	$\mu$ mu	$\nu$ nu, $\sigma$ sigma	
porosity	$\phi$ phi	$f, \epsilon$ epsilon	
pressure	$p$	$P$	$m/Lt^2$
production rate or flow rate	$q$	$Q$	$L^3/t$
productivity index	$J$	$j$	$L^4t/m$
quality (usually of steam)	$f_s$	$Q, x$	
radial distance	$\Delta r$	$\Delta R$	$L$
radius	$r$	$R$	$L$
radius, hydraulic	$r_H$	$R_H$	$L$
ratio, damage ("skin" conditions relative to for- mation conditions unaffected by well opera- tions)	$F_s$	$F_d$	
ratio initial reservoir free gas volume to initial reservoir oil volume	$m$	$F_{Fo}, F_{go}$	
ratio, mobility	$M$	$F_{\lambda}$	
ratio, mobility, diffuse-front approximation, [ $(\lambda_D + \lambda_d)_{\text{swept}}/(\lambda_d)_{\text{unswept}}$ ]; $D$ signifies dis- placing; $d$ signifies displaced; mobilities are evaluated at average saturation conditions be- hind and ahead of front	$M_{\bar{S}}$	$M_{Dd}, M_{su}$	
ratio, mobility, sharp-front approximation, $(\lambda_D/\lambda_d)$	$M$	$F_{\lambda}$	
ratio, mobility, total, [ $(\lambda_r)_{\text{swept}}/(\lambda_r)_{\text{unswept}}$ ]; "swept" and "unswept" refer to invaded and uninvaded regions behind and ahead of leading edge of a displacement front	$M_t$	$F_{Nt}$	
reaction rate constant	$k$	$r, j$	$L/t$

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimen- sions*
reciprocal formation volume factor, volume at standard conditions divided by volume at reservoir conditions	$b$	$f, F$	
reciprocal permeability	$j$	$\omega$ omega	$1/L^2$
resistance	$r$	$R$	$mL^2/tq^2$
resistance	$r$	$R$	various
resistivity, electrical	$\rho$ rho	$R$	$mL^3/tq^2$
saturation	$S$	$\rho$ rho, $s$	
saturation, water, initial	$S_{wi}$	$\rho_{wi}$ rho, $s_{wi}$	
saturation, water, irreducible	$S_{iw}$	$\rho_{iw}$ rho, $s_{iw}$	
skin effect	$s$	$S, \sigma$ sigma	
skin (radius of well damage or stimulation)	$r_s$	$R_s$	$L$
slope	$m$	$A$	various
specific gravity	$\gamma$ gamma	$s, F_s$	
specific heat (always with phase or system subscripts)	$C$	$c$	$L^2/t^2T$
specific heats ratio	$\gamma$ gamma	$k$	
specific injectivity index	$I_s$	$i_s$	$L^3t/m$
specific productivity index	$J_s$	$j_s$	$L^3t/m$
specific volume	$v$	$v_s$	$L^3/m$
specific weight	$F_{wv}$	$\gamma$ gamma	$m/L^2T^2$
stimulation radius of well (skin)	$r_s$	$R_s$	$L$
strain, normal and general	$\epsilon$ epsilon	$e, \epsilon_n$ epsilon	
strain, shear	$\gamma$ gamma	$\epsilon_s$ epsilon	
strain, volume	$\theta$ theta	$\theta_v$ theta	
stress, normal and general	$\sigma$ sigma	$s$	$m/Lt^2$
stress, shear	$\tau$ tau	$s_s$	$m/Lt^2$
surface tension	$\sigma$ sigma	$y, \gamma$ gamma	$m/t^2$
temperature	$T$	$\theta$ theta	$T$
thermal conductivity (always with additional phase or system subscripts)	$k_h$	$\lambda$ lambda	$mL/t^3T$
thermal cubic expansion coefficient	$\beta$ beta	$b$	$1/T$
thermal or heat diffusivity	$\alpha$ alpha	$a, \eta_b$ eta	$L^2/t$
thickness (general and individual bed)	$h$	$d, e$	$L$
time	$t$	$\tau$ tau	$t$
total mobility of all fluids in a particular region of the reservoir; e.g., $(\lambda_o + \lambda_g + \lambda_w)$	$\lambda_t$ lambda	$\Lambda$ lambda <sub>cap</sub>	$L^3t/m$
total mobility ratio, $[(\lambda_t)_{\text{swept}}/(\lambda_t)_{\text{unswept}}]$ ; "swept" and "unswept" refer to invaded and uninvaded regions behind and ahead of leading edge of a displacement front	$M_t$	$F_{\lambda t}$	
transfer coefficient, convective heat	$h$	$h_h, h_T$	$m/t^3T$
transfer coefficient, heat, interphase convective (use $h$ , or convective coefficient symbol with pertinent phase subscripts added)			$m/t^3T$
transfer coefficient, heat, overall	$U$	$U_T, U_0$	$m/t^3T$

Quantity	SPE Standard	Reserve SPE Letter Symbols**	Dimen- sions*
transfer coefficient, heat, radiation	$I$	$I_T, I_0$	$m/t^3T$
utilization, oxygen	$e_{O_2}$	$E_{O_2}$	
velocity	$v$	$V, u$	$1L/t$
viscosity	$\mu$ mu	$\eta$ eta	$m/Lt$
volume	$V$	$v$	$L^3$
volumetric velocity (flow rate or flux, per unit area)	$u$	$\psi$ psi	$L/t$
water (always with identifying subscripts)	$W$	$w$	various
water in place in reservoir, initial	$W$	$w$	$L^3$
water saturation, initial	$S_{wi}$	$\rho_{wi}$ rho, $s_{wi}$	
water saturation, irreducible	$S_{iw}$	$\rho_{iw}$ rho, $s_{iw}$	
wave number	$\sigma$ sigma	$\bar{v}$	$1/L$
weight	$W$	$w, G$	$mL/t^2$
wet-gas content	$C_{wg}$	$c_{wg}, n_{wg}$	various
width, breadth, or (primarily in fracturing) thick- ness	$b$	$w$	$L$
work	$W$	$w$	$mL^2/t^2$

### Subscripts

Subscript	SPE Standard	Reserve SPE Letter Subscripts**
air	$a$	$A$
atmospheric	$a$	$A$
average or mean saturation	$\bar{S}$	$\bar{\rho}$ rho, $\bar{s}$
band or oil band	$b$	$B$
base	$b$	$r, \beta$ beta
boundary conditions, external	$e$	$o$
breakthrough	$BT$	$bt$
bubble point or saturation	$b$	$s$
burned or burning	$b$	$B$
calculated	$C$	calc
capillary (usually with capillary pressure, $P_c$ )	$c$	$C$
casing or casinghead	$c$	$cg$
contact (usually with contact angle, $\theta_c$ )	$c$	$C$
core	$c$	$C$
cumulative influx (encroachment)	$e$	$i$
damage or damaged (includes "skin" conditions)	$s$	$d$
depleted region, depletion	$d$	$\delta$ delta
dispersed	$d$	$D$
dispersion	$K$	$d$
displaced	$d$	$s, D$
displacing or displacement	$D$	$s, \sigma$ sigma

Subscript	SPE Standard	Reserve SPE Letter Subscripts**
entry	<i>e</i>	<i>E</i>
equivalent	<i>eq</i>	<i>EV</i>
estimated	<i>E</i>	est
experimental	<i>E</i>	<i>EX</i>
fill-up	<i>F</i>	<i>f</i>
finger or fingering	<i>f</i>	<i>F</i>
flash separation	<i>f</i>	<i>F</i>
fraction or fractional	<i>f</i>	<i>r</i>
fracture, fractured, or fracturing	<i>f</i>	<i>F</i>
free (usually with gas or gas-oil ratio quantities)	<i>F</i>	<i>f</i>
front, front region, or interface	<i>f</i>	<i>F</i>
gas	<i>g</i>	<i>G</i>
gross	<i>t</i>	<i>T</i>
heat or thermal	<i>h</i>	<i>T</i> , $\theta$ theta
hole	<i>h</i>	<i>H</i>
horizontal	<i>H</i>	<i>h</i>
hydrocarbon	<i>h</i>	<i>H</i>
imbibition	<i>I</i>	<i>i</i> script i
influx (encroachment), cumulative	<i>e</i>	<i>i</i>
injected, cumulative	<i>i</i>	<i>I</i>
injection, injected, or injecting	<i>i</i>	inj
inner or interior	<i>i</i>	$\iota$ iota, <i>i</i> script i
interface, front region, or front	<i>f</i>	<i>F</i>
interference	<i>I</i>	<i>i</i> , <i>i</i> script i
invaded	<i>i</i>	<i>I</i>
invaded zone	<i>i</i>	<i>I</i>
invasion	<i>I</i>	<i>i</i>
irreducible	<i>i</i>	<i>i</i> script i, $\iota$ iota
linear, lineal	<i>L</i>	<i>I</i> script I
liquid or liquid phase	<i>L</i>	<i>I</i> script I
lower	<i>I</i> script I	<i>L</i>
mean or average saturation	$\bar{S}$	$\bar{\rho}$ rho, $\bar{s}$
mixture	<i>M</i>	<i>m</i>
mobility	$\lambda$ lambda	<i>M</i>
nonwetting	<i>nw</i>	<i>NW</i>
normalized (fractional or relative)	<i>n</i>	<i>r</i> , <i>R</i>
oil	<i>o</i>	<i>n</i>
outer or exterior	<i>e</i>	<i>o</i>
permeability	<i>k</i>	<i>K</i>
pore (usually with volume, $V_p$ )	<i>p</i>	<i>P</i>
production period (usually with time, $t_p$ )	<i>p</i>	<i>P</i>
radius, radial, or radial distance	<i>r</i>	<i>R</i>
reference	<i>r</i>	<i>b</i> , $\rho$ rho
relative	<i>r</i>	<i>R</i>
reservoir	<i>R</i>	<i>r</i>

Subscript	SPE Standard	Reserve SPE Letter Subscripts**
residual	$r$	$R$
saturation, mean or average	$\bar{S}$	$\bar{\rho}$ rho, $\bar{s}$
saturation or bubble point	$b$	$s$
segregation(usually with segregation rate, $q_s$ )	$s$	$S, \sigma$ sigma
shear	$s$	$\tau$ tau
skin (stimulation or damage)	$s$	$S$
slip or slippage	$s$	$\sigma$ sigma
solid(s)	$s$	$\sigma$ sigma
stabilization (usually with time)	$s$	$S$
steam or steam zone	$s$	$S$
stimulation (includes "skin" conditions)	$s$	$S$
storage or storage capacity	$S$	$S, \sigma$ sigma
strain	$\epsilon$ epsilon	$e$
surface	$s$	$\sigma$ sigma
swept or swept region	$s$	$S, \sigma$ sigma
system	$s$	$\sigma$ sigma
temperature	$T$	$h, \theta$ theta
thermal (heat)	$h$	$T, \theta$ theta
total, total system	$t$	$T$
transmissibility	$T$	$t$
treatment or treating	$t$	$\tau$ tau
tubing or tubing head	$t$	$tg$
unswept or unswept region	$u$	$U$
upper	$u$	$U$
vaporization, vapor, or vapor phase	$v$	$V$
velocity	$v$	$V$
vertical	$V$	$v$
volumetric or volume	$V$	$v$
water	$w$	$W$
weight	$W$	$w$
wellhead	$wh$	$th$
wetting	$w$	$W$

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