



International Association of Chemical Engineers

# Encyclopedia of Chemical Processing and Design

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**66**

**Wastewater Treatment  
with Ozone to Water and  
Wastewater Treatment**

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MARCEL DEKKER, INC.

NEW YORK • BASEL

**Library of Congress Cataloging in Publication Data**

Main entry under title:

Encyclopedia of chemical processing and design.

Includes bibliographic references.

1. Chemical engineering—Dictionaries 2. Chemistry,  
Technical—Dictionaries. I. McKetta, John J.  
II. Cunningham, William Aaron.

Tp9.E66 660.2'8'003

75-40646

ISBN: 0-8247-2617-0

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MARCEL DEKKER, INC.  
270 Madison Avenue, New York, New York, 10016

Current printing (last digit):  
10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

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- Steve Cappos** National Sales Manager, Fluid Systems Corporation, San Diego, California: *Water Treatment, Zero Discharge, Reverse Osmosis*
- Boy Cornils, Ph.D.** Hoechst AG, Frankfurt, Germany: *Water-Soluble (Aqueous-Phase) Catalysis*
- Vikas R. Dhole** General Manager Development, Linnhof March Ltd., Targeting House, Rudheath Norwich, Cheshire, England: *Water, Process, Reuse Maximizing*
- Joseph T. Echols, Ph.D.** Professor of Chemistry, Pfeiffer College, Misenheimer, North Carolina: *Water, Cooling Tower, Treatment with Ozone*
- Brad Fleming** Glitsch, Inc., Dallas, Texas: *Water Stripping, Refineries and Chemical Plants*
- James D. Garber, Ph.D., P.E.** Professor and Head, Chemical Engineering Department, University of Southwest Louisiana, Lafayette, Louisiana: *Water Production Rate for Condensate Wells*
- Deepak Garg** Environmental Engineer, ENSR Consulting and Engineering Company, Houston, Texas: *Water, Storm, Management*
- Gary E. Geiger** Consultant, Global Technology Department, Betz Water Management Group, Horsham, Pennsylvania: *Water, Cooling, Corrosion, and Deposition Control*
- Mikel E. Goldblatt, P.E.** Technical Advisor, Betz Dearborn, Horsham, Pennsylvania: *Water Conservation Projects, Justification*
- Kapil Gupta** Process Manager, Reliance Industries Ltd., Patalganga, Mumbai, India: *Water, for Process Cooling*
- Allan D. Holiday** Process Editor, Chemical Engineering, New York, New York: *Water Reuse*
- John W. Hornbrook, Ph.D.** Cawley, Gillespie & Associates, Inc., Houston, Texas: *Waterflood Predictions*

- Mark L. Hunter** Project Engineer, Amoco Corporation, Worldwide Engineering and Construction, Whiting, Indiana: *Wastewater Treatment Plant, Renovation*
- B. G. Kelkar, Ph.D.** Professor of Petroleum Engineering, The University of Tulsa, Tulsa, Oklahoma: *Waterflood Predictions*
- Thomas M. Kenny** President, Ogontz Corporation, Willow Grove, Pennsylvania: *Water, Freezing Conditions*
- Christian W. Kohlpaintner, Ph.D.** Celanese GmbH, Werk Ruhrchemie, Oberhausen, Germany: *Water-Soluble (Aqueous-Phase) Catalysis*
- Sheng H. Lin, Ph.D.** Chairman, Chemical Engineering Department, Yuan Ze Institute of Technology, Taouyan, Taiwan, Republic of China: *Wastewater Treatment with Ozone*
- Béla G. Lipták, Ph.D.** Former Yale Professor and President of Lipták Associates P.C., Stamford, Connecticut: *Water Treatment Controls*
- John J. McKetta, Ph.D., P.E.** The Joe C. Walter Professor of Chemical Engineering, The University of Texas at Austin, Austin, Texas: *Water Content of Hydrocarbon Liquids and Vapors; Estimation; Water Content of Natural Gases; Water, Properties of*
- S. T. Mayne, Ph.D.** Radiation Disposal Systems, Inc., Misenheimer, North Carolina: *Water, Cooling Tower, Treatment with Ozone*
- Takeyoshi Nagaoka** Director, Nagaoka USA, Houston, Texas: *Water, Magnetic*
- Harusuke Naito** Naito Bio-Science Labs Inc., Houston, Texas: *Water, Magnetic*
- Joel Nedrow** Project Engineer, Toledo Refinery, BP Oil Company, Toledo, Ohio: *Water, Storm, Underground Storage Tanks*
- R. Benson Pair** Chief Environmental Technology Engineer, M. W. Kellogg Company, Houston, Texas: *Water, Storm, Management*
- Bipin S. Parekh, Ph.D.** Senior Consulting Engineer, Millipore Corporation, Bedford, Massachusetts: *Water, Production of, Ultrapure*
- Nand Ranchandani** Operations Research Engineer, Linnhof March Ltd., Targeting House, Rudheath Norwich, Cheshire, England: *Water, Process, Reuse Maximizing*
- James R. Reinhardt, Ph.D.** Professor, Chemical Engineering Department, University of Southwest Louisiana, Lafayette, Louisiana: *Water Production Rate for Condensate Wells*
- Christian Schlimm, Ph.D.** Vereins und Westbank AG, Hamburg, Germany: *Wastewater Treatment, Reductive Dehalogenation of Chlorinated Hydrocarbons*
- Andrew W. Sloley** Glitsch, Inc., Dallas, Texas: *Water Stripping, Refineries and Chemical Plants*
- Alan L. Smith** Senior Technical Consultant, Calgon Corporation, Pittsburgh, Pennsylvania: *Water Treatment, Zero Discharge, Chemical Treatment*
- Richard A. Tainsh** Technology Development Engineer, Linnhof March Ltd., Targeting House, Rudheath Norwich, Cheshire, England: *Water, Process, Reuse Maximizing*
- Arthur H. Tuthill** President, Tuthill Associates Inc., Blacksburg, Virginia: *Water and Design Factors, Effect on Performance of Piping Materials*
- Morris Anthony Vivona, P.E.** Director, Water and Wastewater, ICF Kaiser Engineers, Inc., Houston, Texas: *Water, Storm, Pollution Prevention Design; Water and Wastewater Treatment*

- Marek Wasilewski** Senior Software Design Engineer, Linnhof March Ltd., Targeting House, Rudheath Norwich, Cheshire, England: *Water, Process, Reuse Maximizing*
- Albert H. Wehe** Consultant, Raleigh, North Carolina: *Water Content of Natural Gases*
- Guy E. Weismantel** President, Weismantel International, Kingwood, Texas: *Water, Produced Water*
- Ernest Wiebus, Ph.D.** Celanese GmbH, Werk Ruhrchemie, Oberhausen, Germany: *Water-Soluble (Aqueous-Phase) Catalysis*
- Carl L. Yaws, Ph.D.** Professor, Department of Chemical Engineering, Lamar University, Beaumont, Texas: *Water Solubility of Organic Chemicals*
- Kuo L. Yeh** Assistant Manager of Manufacturing, Chinese Petroleum Company, Taoyuan, Taiwan, Republic of China: *Wastewater Treatment with Ozone*
- Adam Zanker, Ch.E., M.Sc.** Senior Research Engineer, Oil Refineries, Ltd., Haifa, Israel: *Water, Alkalinity Calculations; Water Flow Over Weirs; Water Flow Under Gates of a Dam*

# Conversion to SI Units

To convert from	To	Multiply by
acre	square meter (m <sup>2</sup> )	$4.046 \times 10^3$
angstrom	meter (m)	$1.0 \times 10^{-10}$
are	square meter (m <sup>2</sup> )	$1.0 \times 10^2$
atmosphere	newton/square meter (N/m <sup>2</sup> )	$1.013 \times 10^5$
bar	newton/square meter (N/m <sup>2</sup> )	$1.0 \times 10^5$
barrel (42 gallon)	cubic meter (m <sup>3</sup> )	0.159
Btu (International Steam Table)	joule (J)	$1.055 \times 10^3$
Btu (mean)	joule (J)	$1.056 \times 10^3$
Btu (thermochemical)	joule (J)	$1.054 \times 10^3$
bushel	cubic meter (m <sup>3</sup> )	$3.52 \times 10^{-2}$
calorie (International Steam Table)	joule (J)	4.187
calorie (mean)	joule (J)	4.190
calorie (thermochemical)	joule (J)	4.184
centimeter of mercury	newton/square meter (N/m <sup>2</sup> )	$1.333 \times 10^3$
centimeter of water	newton/square meter (N/m <sup>2</sup> )	98.06
cubit	meter (m)	0.457
degree (angle)	radian (rad)	$1.745 \times 10^{-2}$
denier (international)	kilogram/meter (kg/m)	$1.0 \times 10^{-7}$
dram (avoirdupois)	kilogram (kg)	$1.772 \times 10^{-3}$
dram (troy)	kilogram (kg)	$3.888 \times 10^{-3}$
dram (U.S. fluid)	cubic meter (m <sup>3</sup> )	$3.697 \times 10^{-6}$
dyne	newton (N)	$1.0 \times 10^{-5}$
electron volt	joule (J)	$1.60 \times 10^{-19}$
erg	joule (J)	$1.0 \times 10^{-7}$
fluid ounce (U.S.)	cubic meter (m <sup>3</sup> )	$2.96 \times 10^{-5}$
foot	meter (m)	0.305
furlong	meter (m)	$2.01 \times 10^2$
gallon (U.S. dry)	cubic meter (m <sup>3</sup> )	$4.404 \times 10^{-3}$
gallon (U.S. liquid)	cubic meter (m <sup>3</sup> )	$3.785 \times 10^{-3}$
gill (U.S.)	cubic meter (m <sup>3</sup> )	$1.183 \times 10^{-4}$
grain	kilogram (kg)	$6.48 \times 10^{-5}$
gram	kilogram (kg)	$1.0 \times 10^{-3}$
horsepower	watt (W)	$7.457 \times 10^2$
horsepower (boiler)	watt (W)	$9.81 \times 10^3$
horsepower (electric)	watt (W)	$7.46 \times 10^2$
hundred weight (long)	kilogram (kg)	50.80
hundred weight (short)	kilogram (kg)	45.36
inch	meter (m)	$2.54 \times 10^{-2}$
inch mercury	newton/square meter (N/m <sup>2</sup> )	$3.386 \times 10^3$
inch water	newton/square meter (N/m <sup>2</sup> )	$2.49 \times 10^2$
kilogram force	newton (N)	9.806
kip	newton (N)	$4.45 \times 10^3$
knot (international)	meter/second (m/s)	0.5144
league (British nautical)	meter (m)	$5.559 \times 10^3$
league (statute)	meter (m)	$4.83 \times 10^3$
light year	meter (m)	$9.46 \times 10^{15}$

To convert from	To	Multiply by
liter	cubic meter (m <sup>3</sup> )	0.001
micron	meter (m)	$1.0 \times 10^{-6}$
mil	meter (m)	$2.54 \times 10^{-6}$
mile (U.S. nautical)	meter (m)	$1.852 \times 10^3$
mile (U.S. statute)	meter (m)	$1.609 \times 10^3$
millibar	newton/square meter (N/m <sup>2</sup> )	100.0
millimeter mercury	newton/square meter (N/m <sup>2</sup> )	$1.333 \times 10^2$
oersted	ampere/meter (A/m)	79.58
ounce force (avoirdupois)	newton (N)	0.278
ounce mass (avoirdupois)	kilogram (kg)	$2.835 \times 10^{-2}$
ounce mass (troy)	kilogram (kg)	$3.11 \times 10^{-2}$
ounce (U.S. fluid)	cubic meter (m <sup>3</sup> )	$2.96 \times 10^{-5}$
pascal	newton/square meter (N/m <sup>2</sup> )	1.0
peck (U.S.)	cubic meter (m <sup>3</sup> )	$8.81 \times 10^{-3}$
pennyweight	kilogram (kg)	$1.555 \times 10^{-3}$
pint (U.S. dry)	cubic meter (m <sup>3</sup> )	$5.506 \times 10^{-4}$
pint (U.S. liquid)	cubic meter (m <sup>3</sup> )	$4.732 \times 10^{-4}$
poise	newton second/square meter (N · s/m <sup>2</sup> )	0.10
pound force (avoirdupois)	newton (N)	4.448
pound mass (avoirdupois)	kilogram (kg)	0.4536
pound mass (troy)	kilogram (kg)	0.373
poundal	newton (N)	0.138
quart (U.S. dry)	cubic meter (m <sup>3</sup> )	$1.10 \times 10^{-3}$
quart (U.S. liquid)	cubic meter (m <sup>3</sup> )	$9.46 \times 10^{-4}$
rod	meter (m)	5.03
roentgen	coulomb/kilogram (c/kg)	$2.579 \times 10^{-4}$
second (angle)	radian (rad)	$4.85 \times 10^{-6}$
section	square meter (m <sup>2</sup> )	$2.59 \times 10^6$
slug	kilogram (kg)	14.59
span	meter (m)	0.229
stoke	square meter/second (m <sup>2</sup> /s)	$1.0 \times 10^{-4}$
ton (long)	kilogram (kg)	$1.016 \times 10^3$
ton (metric)	kilogram (kg)	$1.0 \times 10^3$
ton (short, 2000 pounds)	kilogram (kg)	$9.072 \times 10^2$
torr	newton/square meter (N/m <sup>2</sup> )	$1.333 \times 10^2$
yard	meter (m)	0.914

# Bringing Costs up to Date

Cost escalation via inflation bears critically on estimates of plant costs. Historical costs of process plants are updated by means of an escalation factor. Several published cost indexes are widely used in the chemical process industries:

- Nelson Cost Indexes (*Oil and Gas J.*), quarterly
- Marshall and Swift (M&S) Equipment Cost Index, updated monthly
- CE Plant Cost Index (*Chemical Engineering*), updated monthly
- ENR Construction Cost Index (*Engineering News-Record*), updated weekly
- Vatavuk Air Pollution Control Cost Indexes (VAPCCI) (*Chemical Engineering*), updated quarterly

All of these indexes were developed with various elements such as material availability and labor productivity taken into account. However, the proportion allotted to each element differs with each index. The differences in overall results of each index are due to uneven price changes for each element. In other words,

**TABLE 1** *Chemical Engineering* and Marshall and Swift Plant and Equipment Cost Indexes since 1950

Year	CE Index	M&S Index	Year	CE Index	M&S Index
1950	73.9	167.9	1973	144.1	344.1
1951	80.4	180.3	1974	165.4	398.4
1952	81.3	180.5	1975	182.4	444.3
1953	84.7	182.5	1976	192.1	472.1
1954	86.1	184.6	1977	204.1	505.4
1955	88.3	190.6	1978	218.8	545.3
1956	93.9	208.8	1979	238.7	599.4
1957	98.5	225.1	1980	261.2	659.6
1958	99.7	229.2	1981	297.0	721.3
1959	101.8	234.5	1982	314.0	745.6
1960	102.0	237.7	1983	316.9	760.8
1961	101.5	237.2	1984	322.7	780.4
1962	102.0	238.5	1985	325.3	789.6
1963	102.4	239.2	1986	318.4	797.6
1964	103.3	241.8	1987	323.8	813.6
1965	104.2	244.9	1988	342.5	852.0
1966	107.2	252.5	1989	355.4	895.1
1967	109.7	262.9	1990	357.6	915.1
1968	113.6	273.1	1991	361.3	930.6
1969	119.0	285.0	1992	358.2	943.1
1970	125.7	303.3	1993	359.2	964.2
1971	132.3	321.3	1994	368.1	993.4
1972	137.2	332.0	1995	381.1	1027.5
			1996	381.7	1039.2
			1997	386.5	1056.8



**TABLE 2** Nelson-Farrar Inflation Petroleum Refinery Construction Indexes since 1946  
(1946 = 100)

Date	Materials Component	Labor Component	Miscellaneous Equipment	Nelson Inflation Index
1946	100.0	100.0	100.0	100.0
1947	122.4	113.5	114.2	117.0
1948	139.5	128.0	122.1	132.5
1949	143.6	137.1	121.6	139.7
1950	149.5	144.0	126.2	146.2
1951	164.0	152.5	145.0	157.2
1952	164.3	163.1	153.1	163.6
1953	172.4	174.2	158.8	173.5
1954	174.6	183.3	160.7	179.8
1955	176.1	189.6	161.5	184.2
1956	190.4	198.2	180.5	195.3
1957	201.9	208.6	192.1	205.9
1958	204.1	220.4	192.4	213.9
1959	207.8	231.6	196.1	222.1
1960	207.6	241.9	200.0	228.1
1961	207.7	249.4	199.5	232.7
1962	205.9	258.8	198.8	237.6
1963	206.3	268.4	201.4	243.6
1964	209.6	280.5	206.8	252.1
1965	212.0	294.4	211.6	261.4
1966	216.2	310.9	220.9	273.0
1967	219.7	331.3	226.1	286.7
1968	224.1	357.4	228.8	304.1
1969	234.9	391.8	239.3	329.0
1970	250.5	441.1	254.3	364.9
1971	265.2	499.9	268.7	406.0
1972	277.8	545.6	278.0	438.5
1973	292.3	585.2	291.4	468.0
1974	373.3	623.6	361.8	522.7
1975	421.0	678.5	415.9	575.5
1976	445.2	729.4	423.8	615.7
1977	471.3	774.1	438.2	653.0
1978	516.7	824.1	474.1	701.1
1979	573.1	879.0	515.4	756.6
1980	629.2	951.9	578.1	822.8
1981	693.2	1044.2	647.9	903.8
1982	707.6	1154.2	622.8	976.9
1983	712.4	1234.8	656.8	1025.8
1984	735.3	1278.1	665.6	1061.0
1985	739.6	1297.6	673.4	1074.4
1986	730.0	1330.0	684.4	1089.9
1987	748.9	1370.0	703.1	1121.5
1988	802.8	1405.6	732.5	1164.5
1989	829.2	1440.4	769.9	1195.9
1990	832.8	1487.7	797.5	1225.7
1991	832.3	1533.3	827.5	1252.9