INSTRUMENT ENGINEERS' HANDBOOK

Fourth Edition

Process Control and Optimization

VOLUME II

INSTRUMENT ENGINEERS' HANDBOOK

Fourth Edition

Process Control and Optimization

VOLUME II

Béla G. Lipták

EDITOR-IN-CHIEF

ISA–The Instrumentation, Systems, and Automation Society

Taylor & Francis
Taylor & Francis Group
Boca Raton London New York

A CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa plc.

This reference text is published in cooperation with ISA Press, the publishing division of ISA--Instrumentation, Systems, and Automation Society. ISA is an international, nonprofit, technical organization that fosters advancement in the theory, design, manufacture, and use of sensors, instruments, computers, and systems for measurement and control in a wide variety of applications. For more information, visit www.isa.org or call (919) 549-8411.

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-1081-4 (Hardcover)
International Standard Book Number-13: 978-0-8493-1081-2 (Hardcover)
Library of Congress Card Number 2003048453

Library of Congress Cataloging-in-Publication Data

Instrument engineers' handbook / Béla G. Lipták, editor-in-chief.
p. cm.
Rev. ed. of: Instrument engineers' handbook. Process measurement and analysis. ©1995 and Instrument engineers' handbook. Process control. ©1995.
Includes bibliographical references and index.
Contents: v. 2 Process control and optimization.
ISBN 0-8493-1081-4 (v. 2)
1. Process control--Handbooks, manuals, etc. 2. Measuring instruments--Handbooks, manuals, etc. I. Lipták, Béla G. II. Instrument engineers' handbook. Process measurement and analysis.

TS156.8 .I56 2003
629.8--dc21 2003048453

T&F informa

Taylor & Francis Group is the Academic Division of T&F Informa plc.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Dedicated to my colleagues, the instrument and process control engineers. It is hoped that by applying the knowledge found on these pages, we will make our industries more efficient, safer, and cleaner, and thereby will not only contribute to a happier future for all mankind, but will also advance the recognition and prestige of our profession.

CONTENTS

8 Control and Optimization of Unit Operations 1473

Appendix 2209

CONTRIBUTORS

The names of all the authors of all four editions of this handbook are listed at the beginning of each section of each chapter. Here, their academic degrees, titles, and positions that they held at the time of making their last contributions are also listed. Those authors who have participated in the preparation of this fourth edition are distinguished by an asterisk.

***JÁNOS ABONYI**	PhD, Assistant Professor, University of Veszprém, Hungary
ROBERT H. APPLEBY	BSMath, MSStat, Facilities Manager, Immaculate Conception Church
***JAMES B. ARANT**	BSChE, PE, Principal of J. B. Arant & Assoc. Consulting, U.S.A.
***TIBOR BAAN**	BME, CEO, Aalborg Instruments and Controls Inc.
MIGUEL J. BAGAJEWICZ	PhD, AIChe, Professor, University of Oklahoma, Norman, Oklahoma, U.S.A.
***STEVEN BAIN**	BscEE, PE, I&C Engineer, CH2M Hill
ROBERT J. BAKER	BS, Technical Director, Wallace & Tiernan Div. of Pennwalt Corp.
ROGER M. BAKKE	BS, MS, Senior Engineer, IBM Corp.
***ANDRÁS BÁLINT**	PhD, Assistant Professor, University of Veszprém, Hungary
***RUTH BARS**	PhD, Associate Professor, Budapest University of Technology and Economics, Hungary
CHET S. BARTON	PE, PSEE, Senior Process Automation Engineer, Jacobs Engineering, Baton Rouge, Louisiana, U.S.A.
***HANS D. BAUMANN**	PhDME, PE, President, H.B. Services Partners, LLC
CHESTER S. BEARD	BSEE, Author, Retired from Bechtel Corp.
***KEN BEATTY**	BSME, MEMME, Director of Advanced Product Development, Flowserve
***JONAS BERGE**	Engineer, SMAR, Singapore
JOHN W. BERNARD	BSChE, MSIE, PE, Manager, Systems Technology, The Foxboro Co.

***MICHAEL L. BERNS**	MSEE, PE, Electrical Engineer, Alcan Plastic Packaging
***PETER GRAHAM BERRIE**	PhD, Marketing Communications Manager, Endress + Hauser Process Solutions AG, Switzerland
***VIPUL BHSANAR**	BE, I&C Specialist, Consultant, Canada
PAUL B. BINDER	BSME, Program Manager, Leeds & Northrup
***TERRENCE BLEVINS**	MSEE, Principal Technologist, Emerson Process Management, U.S.A.
RICHARD W. BORUT	Senior Manager, M. W. Kellogg Co.
STUART A. BOYER	PE, BSc, EE, President, Iliad Engineering, Inc., Canada
***WALTER BOYES**	Editor in Chief, Control Magazine
AUGUST BRODGESELL	BSEE, President, CRB Systems Inc.
ROBERT D. BUCHANAN	BSCE, MS, Environmental Consultant
GEORGE C. BUCKBEE	PE, BSChE, MSChE, Control Engineer, Top Control, Clarks Summit, Pennsylvania, U.S.A.
ERIC J. BYRES	PE, Research Facility, British Columbia Institute of Technology, Canada
***FRED M. CAIN**	BSME, PE, Director of Engineering, Flowserve Corp.
ANTHONY M. CALABRESE	BSChE, BSEE, MSChE, PE, Senior Engineering Manager, M. W. Kellogg Co.
***OSCAR CAMACHO**	PhD, Professor, Universidad de Los Andes, Venezuela
BRYAN DELL CAMPBELL	BSEE, MEE, Electrical Engineer, Stanley Tools
DANIEL E. CAPANO	President, Diversified Technical Services, Inc., Stamford, Connecticut, U.S.A.
RICHARD H. CARO	BChE, MS, MBA, CMC Associates, Acton, Massachusetts, U.S.A.
***MICHAEL D. CHAPMAN**	AAS, Startup and Control System Eng. Supervisor, Bechtel Corp.
HARRY L. CHEDDIE	PE, BSc, Principal Engineer, Exida.com, Sarnia, Ontario, Canada.
***GEORGE S. CHENG**	PhD, Chairman, CTO, CyboSoft, General Cybernation Group, Inc.
***XU CHENG**	PhD, Emerson Process Management, Power and Water Solutions
WILLIAM N. CLARE	BSChE, MSChE, Engineering Manager, Automated Dynamics Corp.
SCOTT C. CLARK	BS, ChE, Project Engineer, Merck & Co., Inc., Elkton, Virginia, U.S.A.
JOHN R. COPELAND	BSEE, MSEE, PhDEE, Partner, Jackson Associates
ARMANDO B. CORRIPIO	BSChE, MSChE, PhDChE, PE, Professor of Chemical Engineering, Louisiana State University

NICHOLAS O. CROMWELL	BSChE, Principal Systems Architect, The Foxboro Co.
LOUIS D. DINAPOLI	BSEE, MSEE, Manager, Flowmeter Marketing and Technology, BIF Products of Leeds & Northrup Co.
ROBERT G. DITTMER	BSEE, Corporate Process Control Engineer, PPG Industries
ASEGEIR DRØIVOLDSMO	MS, Research Scientist, OECD Halden Reactor Project, Halden, Norway
SAMUEL G. DUKELOW	BSME, National Sales Manager, Bailey Meter Co.
***WATSON PARNELL DURDEN**	ASInstrTech, Systems Engineer, Westin Engineering
***RANDY A. DWIGGINS**	BCChE, MSSysE, PE, Performance Improvement Consultant, Invensys Systems
LAWRENCE S. DYSART	BSEE, Engineer, Robertshaw Controls Co.
SHIBI EMMANUEL	MTech, BTech, Head of I & C, Dar Al Riyablh Consultants, Al Khobar, Saudi Arabia
***HALIT EREN**	PhD, Curtin University of Technology, Australia
GEORG F. ERK	BSME, MSChE, PE, Consulting Engineer in Instrumentation and Control Systems, Retired from Sun Refining
EDWARD J. FARMER	BSEE, PE, President, Ed Farmer & Associates, Inc.
***BRIDGET ANN FITZPATRICK**	BSChE, MBA, Senior Consultant, Mustang Engineering
PAUL G. FRIEDMANN	BSChE, MSE, Control Consultant, CRB Systems
JEHUDA FRYDMAN	Manager, Electrical Engineering Section, Mobil Chemical Co., Plastics Div.
LUDGER FÜCHTLER	Dipl. Eng., Marketing Manager, Endress + Hauser Process Solutions AG, Reinach, Switzerland
***STEPHAN E. GAERTNER**	BSChE, PE, Sales Engineer, Clipper Controls
***WINSTON GARCIA-GABIN**	PhD, MSc, Professor, Universidad de Los Andes,Venezuela
***DAVID J. GARDELLIN**	BSME, PE, President and CEO of Onyx Valve Co.
CHARLES E. GAYLOR	BSChE, PE, Manager of Engineering Services, Hooker Chemical Corp.
***BRUCE J. GEDDES**	I&C Design Consultant, Calvert Cliffs Nuclear Power Plant
***JOHN PETER GERRY**	MSChE, PE, President, ExperTune Inc.
***ASISH GHOSH**	CE, MIEE, Vice President, ARC Advisory Group
***PEDRO M. B. SILVA GIRÃO**	Professor, Laboratótio de Medidas Eléctricas, Portugal
***ALAN CHARLES GIBSON**	BAS, ADE, Contract Instrument Engineer, Australia
***IAN H. GIBSON**	BSc, DipChE, Process, Controls & Safety Consultant, Australia

***RICHARD A. GILBERT**	PhD, Professor of Chemical Engineering, University of South Florida
DAVID M. GRAY	BSChE, Specialist Engineer, Leeds & Northrup Instruments
JOSEPH A. GUMP	BSChE, Process Panel Manager, Control Products Corp.
BHISHAM P. GUPTA	BS, MSME, DSc, PE, Instrument Engineer, Aramco,Saudi Arabia
BERNHARD GUT	Dipl. Eng. Informatik, Head of Department for Communications, Endress + Hauser GmbH + Co., Germany
***GÖRGY GYÖRÖK**	PhD, Vice Director, Budapest Polytechnic, Hungary
DIANE M. HANLON	BSEE, BSME, Engineer, E.I. DuPont de Nemours & Co.
HASHEM MEHRDAD HASHEMIAN	MSNE, ISA Fellow, President, Analysis and Measurement Services Corp., Knoxville, Tennessee, U.S.A.
HAROLD I. HERTANU	MSEE, PE, Senior Project Engineer, Malcolm Pirnie Inc.
***JENÖ HETHÉSSY**	PhD, Associate Professor, Budapest University of Technology and Economics, Hungary
CONRAD H. HOEPPNER	BSEE, MSEE, PhD, PE, President, Industrial Electronics Corp.
HAROLD L. HOFFMAN	BSChE, PE, Refining Director, Hydrocarbon Processing
PER A. HOLST	MSEE, Director of Computing Technology, The Foxboro Co.
***KARLENE A. HOO**	PhD, Associate Professor of Chemical Engineering,Texas Tech University
MICHAEL F. HORDESKI	BSEE, MSEE, PE, Control System Consultant, Siltran Digital
FRANKLIN B. HOROWITZ	BSChE, MSChE, PE, Process Engineer, Crawford & Russell Inc.
DAVID L. HOYLE	BSChE, Principal Field Application Engineer, The Foxboro Co.
DAVID W. HOYTE	MACantab, Consultant, IBM Corp.
JOHN C. HUBER	PhDEE, Laboratory Manager, 3M Co.
STUART P. JACKSON	BSEE, MSEE, PhD, PE, President, Engineering and Marketing Corp. of Virginia
RAJSHREE RANKA JAIN	BSChE, Applications Engineer, Capital Controls Co.
***JAMES EDWARD JAMISON**	BScChE, PE, Lead Engineer, Instrumentation, Electrical & Control Systems, OPTI Canada Inc.
***BRUCE ALAN JENSEN**	BS, MSChE, Technical Solutions Manager, Yokagawa Corp. of America
KENNETH J. JENTZEN	BSEE, MSEE, Manager, Project Engineering and Maintenance, Mobil Chemical Co.
DONALD R. JONES	BSME, PE, Consultant, Powell-Process Systems, Inc.

BABU JOSEPH	PhDChE, Professor of Chemical Engineering, Washington University
VAUGHN A. KAISER	BSME, MSE, PE, Member of Technical Staff, Profimatics Inc.
***BABAK KAMALI**	BSEE, Control and Automation Designer, PSJ Co., Iran
LES A. KANE	BSEE, Mechanical/Electrical Editor, Hydrocarbon Processing
GENE T. KAPLAN	BSME, Project Design Engineer, Automated Dynamics Corp.
DONALD C. KENDALL	BSChE, MSChE, Senior Systems Analyst, The Foxboro Co.
***PRABHAKAR Y. KESKAR**	PhDEE, PE, Principal Technologist, CH2M Hill
CHANG H. KIM	BSChE, Senior Group Leader, UniRoyal Inc.
PAUL M. KINTNER	BSEE, MSEE, PhDEE, Manager, Digital Products,Cutler-Hammer Inc.
KLAUS H. KORSTEN	Dipl. Eng., Marketing Manager, Endress + Hauser Process Solutions AG, Reinach, Switzerland
***BÉLA LAKATOS**	MSc, PhD, Professor, University of Veszprém, Hungary
JAMES W. LANE	BSChE, MSChE, PE, Executive Director, Tenneco Inc.
***CULLEN G. LANGFORD**	BSME, PE. President, Cullen G. Langford Inc.
AVERLES G. LASPE	BS, PE, Senior Control Application Consultant, Honeywell Inc.
DONALD W. LEPORE	BSME, Design Engineer, The Foxboro Co.
CHENG S. LIN	DrEng, PE, Consultant, Tenneco Inc.
***KLAUS-PETER LINDNER**	Dipl. Inform., Specialist for New Technologies, Endress + Hauser GmBH + Co., Switzerland
***BÉLA LIPTÁK**	ME, MME, PE, Process Control Consultant
DAVID H. F. LIU	PhDChE, Principal Scientist, J. T. Baker Inc.
MICHAEL H. LOUKA	BS, Section Head, IFE Halden Virtual Reality Centre, Halden, Norway
ORVAL P. LOVETT JR.	BSChE, Consulting Engineer, E.I. DuPont de Nemours & Co.
DALE E. LUPFER	BSME, PE, Process Automation Consultant, Engel Engineering Co.
***MATTHEW H. MACCONNELL**	BSChE, MBA, PE, Technology Manager, Air Products and Chemicals, Inc.
***JÁNOS MADÁR**	MSCSChE, Research Assistant, University of Veszprém, Hungary
VICTOR J. MAGGIOLI	BSEE, Principal Consultant, E.I. DuPont de Nemours & Co.
CHARLES L. MAMZIC	BSME, CA. Director, Marketing and Application Engineering, Moore Products Inc.

***M. SAM MANNAN**	PhD, PE, Associate Professor of Chemical Engineering, Texas A&M University
ALAN F. MARKS	BSChE, PE, Engineering Specialist, Control Systems, Bechtel Petroleum Inc.
***EDWARD M. MARSZAL**	BSChE, CFSE, PE, Principal Engineer, Exida
FRED D. MARTON	Dipl. Eng., Managing Editor, Instruments and Control Systems
***GREGORY K. MCMILLAN**	MSEE, Professor, Washington University of Saint Louis
***RICK MEEKER**	Process Control Solutions, Inc.
DANIEL T. MIKLOVIC	ASNT, BSEE, MSSM, CMfgE, MIMC, Senior Consultant, H.A. Simons Ltd.
***HERBERT L. MILLER**	MSME, PE, Vice President, Control Components
FERENC MOLNÁR	MSEE, Department Manager, Chinoin Pharmaceutical and Chemical Works Ltd., Hungary
CHARLES F. MOORE	BSChE, MSChE, PhDChE, Professor of Chemistry, University of Tennessee
JOHN A. MOORE	BSChE, PE, Senior Application Specialist, Leeds & Northrup Instruments
RALPH L. MOORE	BSME, MSME, MSInstE, PE, Instrument Engineer, E.I. DuPont de Nemours & Co.
***DOUG MORGAN**	BSChE, Project Engineer, Control Systems International, U.S.A.
PAUL W. MURRILL	BSChE, MSChE, PhDChE, PE, Vice-Chancellor, Louisiana State University
THOMAS J. MYRON, JR.	BSChE, Senior Systems Design Engineer, The Foxboro Co.
MIKLÓS (NICHOLAS) NAGY	ME, Chief Engineer, Flygt Submersible Pump Co.
***MARK NIXON**	BSEE, Chief Architect, Delta V Control System, Emerson Process Management
***DAVID S. NYCE**	BSEE, MBA, Owner, Revolution Sensor Company
***SHINYA OCHIAI**	BSME, MSME, PhD, PE, Adjunct Professor, Texas A&M University
RICHARD H. OSMAN	PE, Engineering Manager, Robicon Corp.
GLENN A. PETTIT	Manager, Plastic Instrumentation, Rosemount Engineering Co.
***MICHAEL J. PIOVOSO**	PhD, PE, Associate Professor, Pennsylvania State University
WALLACE A PRATT, JR.	BSEE, Chief Engineer, HART Communication Foundation, Austin, Texas, U.S.A.
***SUBRAMANIUM RENGANATHAN**	PhD, Vice Chancellor, Bharath Institute of Higher Education and Research, Chennai, India
***R. RUSSELL RHINEHART**	PhDChE, Professor and Head, School of Chemical Engineering, Oklahoma State University
JAMES B. RISHEL	BSME, President, Corporate Equipment

HOWARD C. ROBERTS	BAEE, PE, Consultant, Lecturer at University of Colorado, Denver
***ALBERTO ROHR**	EE, Dr.Eng., Consultant, Italy
***RUBÉN DARIO ROJAS**	PhD, Universidad de Los Andes, Venezuela
DERRICK KEITH ROLLINS, SR.	BS, MS, PhD, AIChE, Associate Professor, Iowa State University, Ames, Iowa, U.S.A.
***MICHEL RUEL**	PE, President, Top Control
DOUGLAS D. RUSSELL	BSEE, MSEE, Group Leader, The Foxboro Co.
DONALD R. SADLON	BSEE, General Manager, Automated Dynamics Corp.
CHAKRA J. SANTHANAM	BSChE, MSChE, PE, Management Staff, Arthur D. Little Inc.
PÉTER SZILÁRD SCHERMANN	Senior Consultant at Comprimo BV and Professor of Process Dynamics, University of Groningen, the Netherlands
WALTER F. SCHLEGEL	BE, Assistant Chief Process Engineer, Crawford & Russell Inc.
PHILLIP D. SCHNELLE, JR.	BSEE, MSEE, PE, Technical Service Engineer, E.I. DuPont de Nemours & Co.
MICHAEL R. SHAFFER	PhD, PE, Adjunct Professor, Florida Institute of Technology
***FRANCIS GREGWAY SHINSKEY**	BSChE, Process Control Consultant
JOSEPH P. SHUNTA	PhDChE, PE, Principal Consultant, E.I. DuPont de Nemours & Co.
BURBINDER B. SINGH	BE, MBA, MCSE, Consultant Control Systems Engineer, Chicago, Illinois, U.S.A.
***ROBERT J. SMITH II**	EET, Plant Engineer, Rock-Tenn Co.
DAVID A STROBHAR	PE, SBHFE, President, Beville Engineering, Inc., Dayton, Ohio, U.S.A.
***ANGELA ELAINE SUMMERS**	PhD, PE, President, Sis-Tech Solutions, LLC
***GUSZTÁV SZECSÖ**	BSEE, MSEE, PhD. Professor of Control Engineering University of Miskolc, Hungary
JAMES E. TALBOT	BSEP, Senior Account Executive, Lewis, Gilman & Kynett
***JAMES F. TATERA**	BS, MBA, Senior Process Analysis Consultant, Tatera and Associates Inc., U.S.A.
MAURO C. TOGNERI	BSEE, President, Powell-Process Systems
***G. KEVIN TOTHEROW**	BSEE, President, Sylution Consulting
THOMAS H. TSAI	BSE, PE, Director, Tenneco Inc.
***ANN TUCK**	BSME, Senior Control Systems Engineer, Bechtel Corp.
***ISTVÁN VAJK**	PhD, Professor, Budapest University of Technology and Economics, Hungary
JÁNOS (JOHN) VENCZEL	BSEE, MSEE, Senior RF Engineer, Automation Industries

IAN VERHAPPEN	PE, BSCE, Engineering Associate, Syncrude Canada Lts., Fort McMurray, Alberta, Canada
***STEFANO VITTURI**	Dr. Eng., Italian National Council of Research, Italy
***HAROLD L. WADE**	PhD, President, Wade Associates, Inc.
MICHAEL H. WALLER	BME, SM, ME, PE, Associate Professor, Miami University
CHARLES G. WALTERS, JR.	BSEE, Electrical/Instrument Engineer, Geraghty and Miller Inc.
MARVIN D. WEISS	BSE, MSChE, Assistant Professor of Mechanical Engineering, Valpariso University
PETER ERIC WELLSTEAD	BSc, MSc, DSc, FIEE, CE, Reader in Control Engineering, University of Manchester, England
***CURT W. WENDT**	BSET, PE, I&C Group Leader, CDM
***HARRY H. WEST**	PhD, Research Associate, Texas A&M University
ANDREW C. WIKTOROWICZ	BS, PE, President, Automated Dynamics Corp.
THEODORE J. WILLIAMS	BSChE, MSChE, MSEE, PhDChE, PE, Professor of Engineering, Director of Purdue Laboratory for Applied Industrial Control, Purdue University
ROBERT A. WILLIAMSON	BSME, BA, PE, Supervisor, The Foxboro Co.
***JOHN WILSON**	BSChE, Business Manager, Fisher Controls International, LLC
***WILLY WOJSZNIS**	PhD, Technologist, DeltaV Advanced Control, Emerson Process Management, U.S.A.

INTRODUCTION

This is the fourth edition of the *Instrument Engineers' Handbook* (*IEH*). This handbook serves the automation and control engineering (ACE) profession and has been published once every decade since 1969. The subject of the first volume is measurement; the second volume deals with control; and the third volume is devoted to the topics of software and digital networks.

In the introduction to each new edition, I give a summary of the key developments of the previous decade and point to the challenges we face in the coming decade. Before discussing the previous and the next decades, however, I will say a few words about the growing pains of the ACE profession. I will conclude this introduction with a brief summary of the history of this handbook.

AUTOMATION AND CONTROL ENGINEERING (ACE)

Ours is a very young profession. When the first edition of the *Instrument Engineers' Handbook* (*IEH*) was published, Marks' *Mechanical Engineers' Handbook* was in its fifth and Perry's *Chemical Engineers' Handbook* was in its sixth edition. It is partly for this reason that while people know what kind of engineer an ME or a ChE is, they have no idea what I do when I say that my field is process control or instrumentation. I just get a blank stare.

It is time for us to change that. The first step should be to use a name for our profession that people understand. It is time for our profession to develop a distinct identity.

When I was teaching at Yale, my course was offered under the Chemical Engineering Department. This was not because Yale had anything against our profession; it was simply because they did not know where to put my course. Even this handbook of mine proves the confusion about our identity, because Taylor & Francis publishes this handbook among its Electrical Engineering books. Once again, the reason is not that Taylor & Francis has something against our profession. No, the reason is that we have not yet developed our distinct identity.

"Automation" is a term that the wider public understands. Therefore, I would suggest that we consistently refer to our profession as Automation and Control Engineering (ACE). Together with that, the name of our professional society should also be changed to International Society of Automation (ISA). Another clarifying step could be to change the title of our society magazine from *InTech* to *AutomationTech* because "In" does not say much.

The potentials of the ACE profession are great. While as a profession we have been anonymous, we have already designed fully automated Mars explorers and fully optimized industrial plants. Now it is time to let the world know that we exist. It is time to add to the list of ME, EE, or ChE professional engineering licenses one for ACE engineers; it is time for universities to offer degrees in ACE engineering and for publishers to set up ACE departments.

We should not be shy about this. After all, no engineering profession can claim what we can. No engineering profession can offer to increase the global gross domestic product by trillions of dollars simply through optimization, without building a single new plant, while also *increasing* safety and *reducing* pollution. We can do that. We can increase productivity without using a single pound of additional raw material and without requiring a single additional BTU of energy. Yes, our profession does deserve a distinct identity.

DEVELOPMENTS OF THE LAST DECADE

These days, the computer is our main tool of control. The chapters of this volume describe how the computer is being used in optimizing our processes, providing self-diagnostics, and displaying status information in operator-friendly formats. Today, the World Wide Web provides access to great quantities of data; in the future it will also provide problem-solving capability, so that through the grid, every ACE engineer will have a supercomputer at his or her disposal.

During the last decade, the artificial separation between the roles of DCS, PLC, and PC packages has started to disappear because their separate roles of control (DCS), logic sequencing (PLC), or simulation, and business-related tasks (PC) are beginning to be integrated. I believe that in the near future DCS will simply mean digital control system. Once the digital bus protocols are integrated into a single global standard, the presently required interfacing cards (and the associated risk of mixup) will disappear, and therefore our control systems will become safer, simpler, and more effective.

In the paragraphs below I review some of the developments of the last decade.

Is the Age of the PID Over?

Designating a valve on a flow sheet as a temperature control valve (TCV) will not suspend the laws of nature, and this arbitrary designation will not, for example, prevent the valve from affecting the process pressure. Similarly, the number of available control valves in a process will not necessarily coincide with the number of process properties that need to be controlled. Multivariable herding or envelope control overcomes this limitation of uncoordinated single loop controllers and lets us control all variables that need to be controlled, while minimizing interactions.

The majority of our control loops are still keeping single process variables on set point, but the age of multivariable control has already arrived. In the majority of cases, we still tend to control levels, flows, and temperatures as if these single loops operated in a vacuum, but others are already recognizing that loops do interact and that the opening or closing of a control valve affects not only the one variable we are controlling. For these reasons, the decoupling of interactions based on relative gain calculations have become important tools in the tool boxes of ACE engineers.

Many of us have concluded that the single-loop mentality is wrong because our plants do not produce flows, levels, and temperatures; hence, the control of these variables should not be our ultimate goal. Our ultimate goal should be to optimize the productivity and safety of the whole plant. As a consequence, we are now thinking in terms of unit operation controllers. In these multivariable control systems, the total unit operation (be it a boiler, a distillation column, or a compressor) is being controlled.

The Set Point

Advances have also been made in rethinking the role of the set point. In one aspect, the single set point is often replaced by a set point gap, so that as long as the controlled variable is within that gap, the output is unaltered. This tends to stabilize sensitive loops, such as flow.

Another aspect in which the set point is treated differently today is its effect on the controller output. In many algorithms a change in set point does not change the proportional or derivative contributions to the output because the P and D modes act only on the measurement.

In other algorithms, while the set point change does affect the integral contribution to the output, the set point change is "feedforwarded" directly to the output to minimize reset windup. Reset windup is also minimized by external feedback, taken from the slave measurement in case of cascade loops, from the valve signal in case of selective loops, and from the inverse model in feedforward loops.

Dynamics and Dead Time

The dynamics of control are also better understood today. It is clear that for quarter amplitude damping the gain product of the loop should be about 0.5. This means that in order to keep this product constant, if the process gain doubles, the controller gain must be cut in half. This understanding is critical to the control of all nonlinear processes (heat transfer, chemical reaction, pH, etc.). Clearly understanding this goal also allows for gain adaptation based on either measurements or modeling.

Similarly, the role of dead time is also better understood today. Most ACE engineers know that the integral and derivative control modes must be tuned to match the dead time. Therefore, the control goal is to reduce the loop dead time to a minimum and keep it constant. If that is not possible because the process dead time must vary (transportation lag caused by displacing a fixed volume), it is necessary to match that variable dead time with adapted I and D settings. When the dead time is large, the regular PID algorithm is replaced with sample-and-hold or predictor algorithms.

Unit Operations Controllers

An already existing multipurpose reactor package (described in this volume) can be reconfigured through software modifications to become a stripper, distillation, or crystallizer unit controller. Other multivariable, envelope, and matrix control systems described in this volume are aimed at increasing the efficiency or the productivity of the process, while treating the individual variables — the temperatures, pressures, and levels — only as constraints.

There are hundreds of expert systems, all serving some form of optimization. From the perspective of their methods of operation, one can group them into model-based and model-free methods. They both control multivariable unit operations and because they both evaluate the total process, they also eliminate the interactions between the various controlled and manipulated variables.

Expert systems, which are used in unit operations controllers, are also useful in decoupling the interactions through relative gain and other techniques. Probably the greatest progress has occurred in the area of model-based control, which utilizes both steady-state and dynamic models and allows both for the prediction of process responses before they occur and for continual refinement of the model by empirical updating. In this regard neural networks, artificial intelligence, statistical process control, fuzzy logic, and empirical optimization strategies have all made some contribution.

Model-Based and Model-Free Control

Model-Based Control (MBC), Model Predictive Control (MPC), and Internal Model Control (IMC) are suited for the optimization of well-understood unit processes, such as heat transfer or distillation. Their performance is superior to that of model free systems because they are capable of anticipation and thereby can predict the process response to new situations. In this sense their performance is similar to that of feedforward control systems, while model-free systems behave in a feedback manner only.

The performance of a model-free expert system can be compared to the behavior of a tennis player. The tennis player does not necessarily understand Newton's laws of motion or the aerodynamic principles that determine the behavior of a tennis ball. The tennis player has simply memorized the results of a large number of past "process" responses. This is also the basis of most human learning. All the neural network–based software packages mimic this method of learning.

Neural networks, fuzzy logic, and statistical process control are all such model-free methods, which can be used without the need for knowing the mathematical model of the process. The major difference between fuzzy logic and neural networks is that the latter can only be trained by data, but not with reasoning. Fuzzy logic is superior from this perspective because it can be modified both in terms of the gain (importance) of its inputs and in terms of the functions of its inputs.

The main limitations of all model-free expert systems are their long learning period (which can be compared to the maturing of a child) and the fact that their knowledge is based solely on past events. Consequently, they are not prepared to handle new situations. Therefore, if the process changes, they require retraining because they can only anticipate repetitive events.

Artificial Neural Networks (ANN)

One of the tools used in building models is the Artificial Neural Network (ANN), which can usually be applied under human supervision or can be integrated with expert and/or fuzzy logic systems. Figure 1 shows a three-layer ANN network, which serves to predict the boiling point of a distillate and the Reid vapor pressure of the bottoms product of a

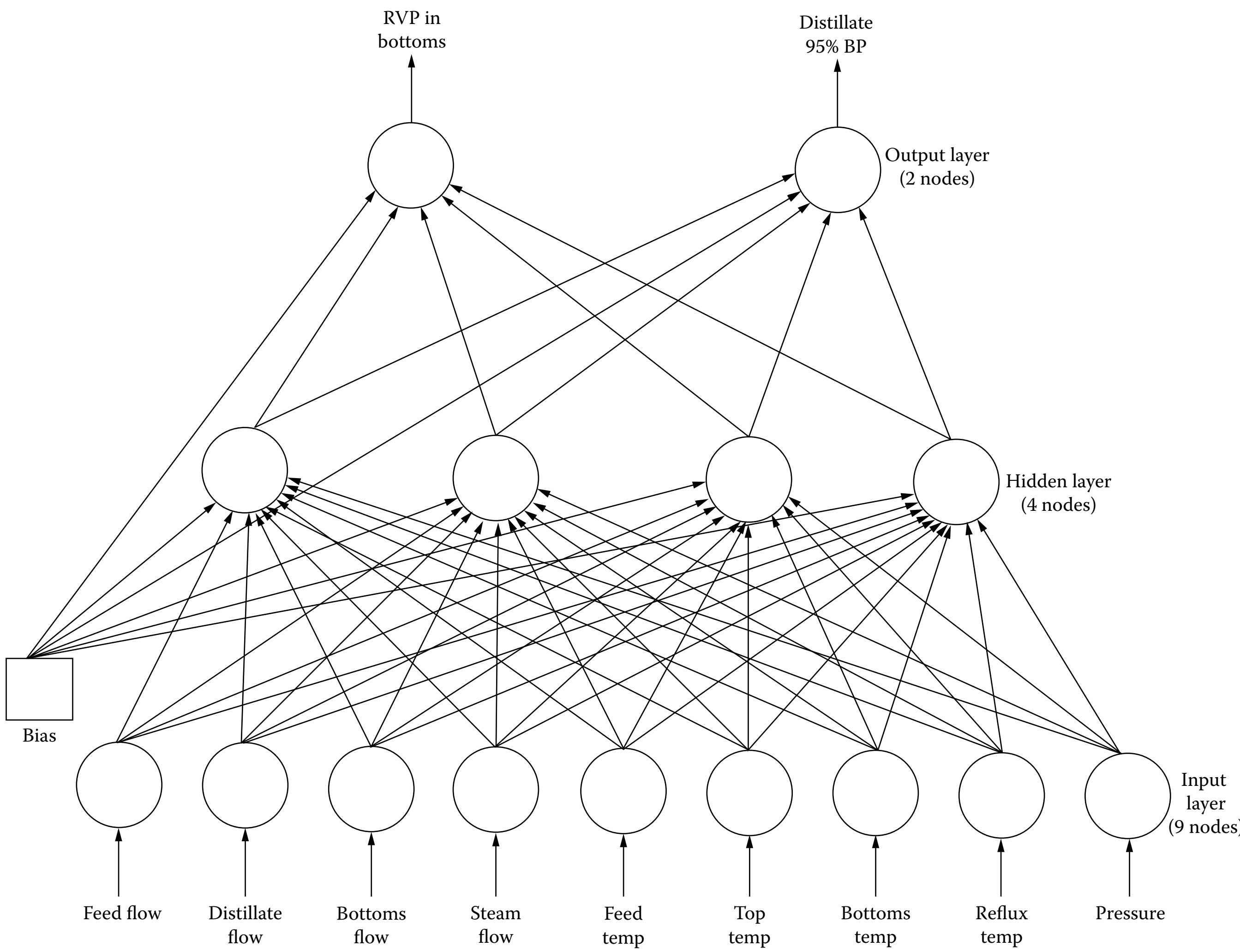

FIG. 1
A three-layer artificial neural network (ANN) can be used to predict the quality of overhead and bottoms products in a distillation column.

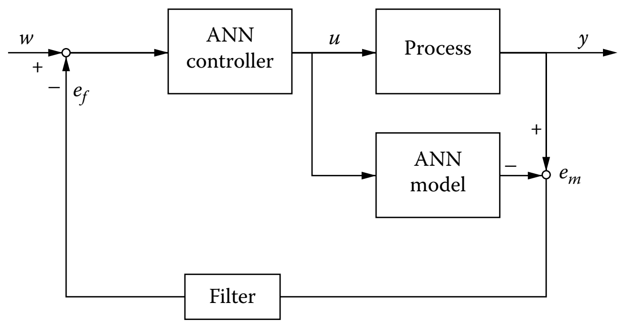

FIG. 2
The use of an artificial neural network in an IMC (Internal Model Control) application.

column. Such predictive ANN models can be valuable because they are not limited by either the unreliability or the dead time of analyzers.

The "personality" of the process is stored in the ANN network by the way the processing elements (nodes) are connected and by the importance assigned to each node (weight). The ANN is "trained" by example and therefore it contains the adaptive mechanism for learning from examples and to adjust its parameters based on the knowledge that is gained through this process of adaptation. During the "training" of these networks, the weights are adjusted until the output of the ANN matches that of the real process.

Naturally, these networks do need "maintenance" because process conditions change; when that occurs, the network requires retraining. The hidden layers help the network to generalize and even to memorize.

The ANN network is also capable of learning input/output and inverse relationships. Hence it is useful in building Internal Model Control (IMC) systems based on ANN-constructed plant models and their inverses. In a neural controller (Figure 2), the ANN can be used in calculating the control signal.

Herding Control

When a large number of variables is involved, model free herding control can be considered. This approach to control can be compared to the herding of sheep, where the shepherd's dog goes after one animal at a time and changes the direction or speed of the whole herd by always influencing the behavior of the least cooperative sheep.

I have successfully applied such herding algorithms in designing the controls of the IBM headquarters building in New York City. By herding the warm air to the perimeter (offices with windows) from the offices that are heat generators even in the winter (interior offices), the building became self-heating. This was done by changing the destination of the return air from one "hot" office at a time (the one that was the warmest in the building) and simultaneously opening the supply damper of the "coldest office" to that same header.

I have also applied the herding algorithm to optimize the process of computer chip manufacturing by eliminating the minute pressure differences that can cause dust-transporting drafts, which in turn can ruin the chips.

In general, herding control is effective if thousands of manipulated variables exist and they all serve some common goal.

Common-Sense Recommendations

While evaluating and executing such sophisticated concepts as optimized multivariable control, the ACE engineer's best friend is common sense and our most trusted teacher is still Murphy, who says that anything that can go wrong, will. In order to emphasize the importance of common sense, I will list here some practical recommendations:

- Before one can control a process, one must fully understand it.
- Being progressive is good, but being a guinea pig is not. Therefore, if the wrong control strategy is implemented, the performance of even the latest digital hardware will be unacceptable.
- An ACE engineer is doing a good job by telling plant management what they need to know and not what they like to hear.
- Increased safety is gained through backup. In case of measurement, reliability is increased by the use of multiple sensors, which are configured through median selectors or voting systems.
- If an instrument is worth installing, it should also be worth calibrating and maintaining. No device can outperform the reference against which it was calibrated.
- All man-made sensors detect relative values, and therefore the error contribution of references and compensators must always be included in the total error.
- Sensors with errors expressed as percent of the actual reading are preferred over those with percent of full-scale errors. If the actual percent of reading error increases as the reading moves down-scale, the loop performance will also deteriorate.
- It is easier to drive within the limits of a lane than to follow a single line. Similarly, control is easier and more stable if the single set point is replaced by a control gap.
- Process variables should be allowed to float within their safe limits as they follow the load. Constancy is the enemy of efficiency. Optimization requires efficient adaptation to changing conditions.
- Trust your common sense, not the sales literature. Independent performance evaluation based on the recommendations of international and national users' associations (SIREP-WIB) should be done *before* installation, not after it. The right time for "business lunches" is *after* start-up, not before the issue of the purchase order.
- Annunciators do not correct emergencies; they just throw those problems that the designers did not know how to handle into the laps of the operators. The smaller the annunciator, the better the design.

FUTURE NEEDS

I have already mentioned such needs as the establishment of our professional identity as automation and control engineers (ACE) or the need to integrate DCS, PLC, and PC hardware into a new digital control system (DCS+) that incorporates the features of all three. I have also briefly mentioned the need for bringing order into our "digital Babel" and to stop the trend toward software outsourcing (selling DCS systems without some software packages), which is like selling violins without the strings.

I would not be surprised if, by the end of the 21st century, we would be using self-teaching computers. These devices would mimic the processes taking place in our children's brains, the processes that allow babies to grow into Einsteins by learning about their environment. These devices would be watching the operation of a refinery or the landing and takeoff of airplanes and eventually would obtain as much knowledge as an experienced operator or pilot would have.

If this comes to pass, some might argue that this would be a step forward because machines do not forget; do not get tired, angry, or sleepy; and do not neglect their job to watch a baseball game or to argue with their spouse on the phone. This might be so, yet I would still prefer to land in a human-piloted airplane. I feel that way because I respect Murphy more than most scientists and I know that he is right in stating that "anything that can happen, will." For this reason, the knowledge of the past, which is the knowledge of the computer, might still not be enough.

In addition to new control tools, we will also have new processes to control. Probably the most important among these will be the fuel cell. The fuel cell is like a battery, except that it does not need recharging because its energy is the chemical energy of hydrogen, and hydrogen can come from an inexhaustible source, namely water. In order to gain the benefits of tripling the tank-to-wheel efficiency of our transportation systems while stopping global warming, we will have to learn to control this new process. The challenge involves not only the control of the electrolytic process that splits the water by the use of solar energy, but also the generation, storage, and transportation of liquid or slurry hydrogen.

As I was editing this reference set for the fourth time, I could not help but note the new needs of the process control industry, which are the consequences of the evolution of new hardware, new software, and new process technologies. Here, in the paragraphs that follow, I will describe in more detail what I hope our profession will accomplish in the next decade.

Bringing Order to the "Digital Babel"

In earlier decades, it took time and effort to reach agreement on the 3- to 15-PSIG (0.2- to 1.0-bar) pneumatic and later on the 4- to 20-mA DC standard current signal range. Yet when these signal ranges were finally agreed upon, the benefit was universal because the same percentage of full scale measurement was represented by the same reading on every device in the world.

Similarly, the time is ripe for a single worldwide standard for all digital I/O ranges and *digital communication protocols.* The time is ripe for such an internationally accepted digital protocol to link all the digital "black boxes" and to eliminate the need for all interfacing.

By so doing, we could save the time and effort that are being spent on figuring out ways to interconnect black boxes and could invest them in more valuable tasks, such as enhancing the productivity and safety of our processing industries.

Networks and Buses

Protocol is the language spoken by our digital systems. Unfortunately, there is no standard that allows all field devices to communicate in a common language. Therefore the creation and universal acceptance of a standard field bus is long overdue.

There is nothing wrong with, say, the Canadians having two official languages, but there is something wrong if a pilot does not speak the language of the control tower or if two black boxes in a refinery do not speak the same language. Yet the commercial goal of manufacturers to create captive markets resulted in some eight protocols. These control-oriented communication systems are supported by user groups, which maintain Internet sites as listed below:

AS-Interface	www.as-interface.com
DeviceNet	www.odva.org
HART	www.hartcomm.org
PROFIBUS	www.profibus.org
Found. Fieldbus	www.fieldbus.org
OPC Foundation	www.opcfoundation.com
WorldFIP	www.worldfip.org
ControlNet	www.controlnet.com
MODBUS	www.modbus.org
Ethernet TCP/IP*	www.industrialethernet.com

*TCP - Transmission control protocol
IP - Internet protocol

During the last decade, HART has become the standard for interfacing with analog systems, while Ethernet was handling most office solutions. SCADA served to combine field and control data to provide the operator with an overall view of the plant. While there was no common DCS fieldbus protocol, all protocols used Ethernet at the physical and TCP/IP at the Internet layer. MODBUS TCP was used to interface the different DCS protocols.

The layers of the communication pyramid were defined several ways. OSI defined it in seven (7) layers, #1 being the physical and #7 the application layer (with #8 being used for the "unintegrated," external components). The IEC-61512 standard also lists seven levels, but it bases its levels on physical size: (1) control module, (2) equipment, (3) unit, (4) process cell, (5) area, (6) site, and (7) enterprise.

As I noted earlier, in the everyday language of process control, the automation pyramid consists of four layers: #1 is the level of the field devices, the sensors and actuators; #2 is control; #3 is plant operations; and #4 is the level of business administration.

Naturally, it is hoped that in the next decade, uniform international standards will replace our digital Babel, so that we once again can concentrate on controlling our processes instead of protecting our plants from blowing up because somebody used the wrong interface card.

Software Outsourcing

Another problem in the last decade was the practice of some DCS vendors to sell their "violins without strings," to bid their packages without including all the software that is needed to operate them.

To treat software as an extra and not to include the preparation of the unique control algorithms, faceplates, and graphic displays in the basic bid can lead to serious problems. If the plant does not hire an engineering firm or system integrator to put these strings onto the DCS violin, the plant personnel usually cannot properly do it and the "control music" produced will reflect that. In such cases the cost of plugging the software holes can exceed the total hardware cost of the system.

The cause of another recurring problem is that the instructions are often written in "computerese."

In some bids, one might also read that the stated cost is for "hardware with software license." This to some will suggest that the operating software for the DCS package is included. Well, in many cases it is not; only its license is.

Similarly, when one reads that an analyzer or an optimization or simulation package needs "layering" or is in the "8th layer," one might think that the bid contains eight layers of fully integrated devices. Well, what this language often means is that the cost of integrating these packages into the overall control system is an extra.

So, on the one hand, this age of plantwide digital networks and their associated advanced controls has opened the door for the great opportunities provided by optimization. On the other hand much more is needed before the pieces of the digital puzzle will conveniently fit together, before these "stringless violinists" can be integrated into a good orchestra of automation.

Connectivity and Integration

Utilizing our digital buses, one can plug in a PC laptop or use a wireless hand tool and instantly access all the data, displays, and intelligence that reside anywhere in a DCS network. This capability, in combination with the ability for self-tuning, self-diagnosing, and optimizing, makes the startup, operation, and maintenance of our plants much more efficient.

The modern control systems of most newly built plants consist of four levels of automation. In the field are the intelligent and self-diagnosing local instruments (sensors, valves, motors, safety devices). This first level is connected by a number of data highways or network buses to the next level in this automation pyramid, the level of control. The third level is plant operations, and the fourth is the enterprise-wide business level.

The functions of the DCS workstations include control/operation, engineering/historian, and maintenance functions, while the enterprise-wide network serves the business functions. In addition, wireless hand tools are used by the roving operators, and external PCs are available to engineers for their process modeling and simulation purposes.

HARDWARE-RELATED IMPROVEMENTS NEEDED

I will discuss below some of the areas in which the next decade should bring improvements in the quality and intelligence of the components that make up our control systems. I will discuss the need for better testing and performance standards and the improvements needed in the sensors, analyzers, transmitters, and control valves. I will place particular emphasis on the potentials of "smart" devices.

Meaningful Performance Standards

The professional organizations of automation and control engineers (ACE) should do more to rein in the commercial interests of manufacturers and to impose uniform performance testing criteria throughout the industry. In the sales literature today, the meanings of performance-related terms such as inaccuracy, repeatability, or rangeability are rarely based on testing, and test references are rarely defined. Even such terms as "inaccuracy" are frequently misstated as "accuracy," or in other cases the error percentages are given without stating whether they are based on full scale or on actual readings. It is also time for professional societies and testing laboratories to widely distribute their findings so that these reliable third-party test results can be used by our profession to compare the performance of the various manufacturers' products.

We the users should also require that the manufacturers always state not only the inaccuracy of their products but also the rangeability over which that inaccuracy statement is valid. In other words, the rangeability of all sensors should be defined as the ratio between those maximum and minimum readings for which the inaccuracy statement is still valid.

It would also be desirable to base the inaccuracy statements on the performance of at least 95% of the sensors tested and to include in the inaccuracy statement not only linearity, hysteresis, and repeatability but also the effects of drift, ambient temperature, over-range, supply voltage variation, humidity, radio frequency interface (RFI), and vibration.

Better Valves

In the next decade, much improvement is expected in the area of final control elements, including smart control valves.

This is because the performance of the control loop is much affected not only by trim wear in control valves but also by stem sticking caused by packing friction, valve hysteresis, and air leakage in the actuator. The stability of the control loop also depends on the gain of the valve during the tuning of the loop.

In order for a control loop to be stable, the loop is tuned (the gain of the controller is adjusted) to make the gain product of the loop components to equal about 0.5. If the control valve is nonlinear (its gain varies with the valve's opening), the loop will become unstable when the valve moves away from the opening where it was when the loop was tuned. For this reason, the loop must be compensated for the gain characteristics of the valve; such compensation is possible only if the valve characteristics are accurately known.

For the above reasons, it is desirable that the users and the professional societies of ACE engineers put pressure on the manufacturers to accurately determine the characteristics of their valves. The other performance capabilities of the final control elements also need to be more uniformly defined. This is particularly true for the rangeability of control valves. For example, a valve should be called linear only if its gain (Gv) equals the maximum flow through the valve (Fmax) divided by the valve stroke in percentage (100%) throughout its stroke.

The valve manufacturers should also be required to publish the stroking range (minimum and maximum percentages of valve openings) within which the valve gain is what it is claimed to be (for a linear valve it is Fmax/100%). Similarly, valve rangeability should be defined as the ratio of the minimum and maximum valve Cvs, at which the valve characteristic is still what it is specified to be.

Smarter Valves

A traditional valve positioner serves only the purpose of maintaining a valve at its intended opening. Digital valve controllers, on the other hand, provide the ability to collect and analyze data about valve position, valve operating characteristics, and valve performance trending. They also provide two-way digital communication to enable diagnostics of the entire valve assembly and instrument. Section 6.12 in this handbook and the following Web pages provide more information: Metso Automation (http://www.metsoautomation.com/), (http://www.emersonprocess.com/fisher/products/fieldvue/dvc/index.html)

The potentials of smart valves are likely to be further increased and better appreciated in the next decade. The main features of a smart valve include its ability to measure its own:

- Upstream pressure
- Downstream pressure
- Temperature
- Valve opening position
- Actuator air pressure

Smart valves will also eliminate the errors introduced by digital-to-analog and analog-to-digital conversions and will guarantee the updating of their inputs about 10 times per second. In addition, they will be provided with the filters required to remove the errors caused by turbulence in these readings. As a consequence, smart valves will also be able to measure the flow, by solving equations, such as the one below for liquid flow:

$$Q = \frac{C_v}{\sqrt{\frac{SP\,GRAV}{\Delta P_A}}}$$

where

Q = Flow rate (GPM)
F_L = Recovery coefficient
C_v = Flow capacity factor
P_1 = Upstream pressure (PSIA)
P_v = Liquid vapor press (PSIA)
P_c = Critical pressure (PSIA)
ΔP_A = Valve pressure drop (PSI) or

If Choked:

$$\Delta P_A = F_L^2\left[P_1 - \left(0.96 - 0.28\sqrt{\frac{P_V}{P_C}}\right)\right]P_V$$

The smart valves of the coming decade will hopefully not only measure their own flows but will also measure them over a rangeability that exceeds most flowmeters (from 25:1 to over 100:1) because they in effect are variable-opening orifices.

If the sensors of the intelligent control valve are connected to a PID chip mounted on the valve, the smart valve becomes a local control loop. In that case, only the operator's displays need to be provided remotely, in a location that is convenient for the operator. In such a configuration, it will be possible to remotely reconfigure/recalibrate the valve as well as to provide it with any limits on its travel or to diagnose stem sticking, trim wear, or any other changes that might warrant maintenance.

"Smarter" Transmitters, Sensors, and Analyzers

In the case of transmitters, the overall performance is largely defined by the internal reference used in the sensor. In many cases there is a need for multiple-range and multiple-reference units. For example, pressure transmitters should have both atmospheric and vacuum references and should have sufficient intelligence to automatically switch from one to the other on the basis of the pressure being measured.

Similarly, d/p flow transmitters should have multiple spans and should be provided with the intelligence to automatically switch their spans to match the actual flow as their measurement changes.

The addition of "intelligence" could also increase the amount of information that can be gained from such simple detectors as pitot tubes. If, for example, in addition to detecting the difference between static and velocity pressures, the pitot tube was able to also measure the Reynolds number, it would be able to approximate the shape of the velocity profile. An "intelligent pitot tube" of such capability could increase the accuracy of volumetric flow measurements.

Improved On-Line Analyzers

In the area of continuous on-line analysis, further development is needed to extend the capabilities of probe-type analyzers. The needs include the changing of probe shapes to obtain self-cleaning or to improve the ease of cleaning by using "flat tips." The availability of automatic probe cleaners should also be increased and the probe that is automatically being cleaned should be made visible by the use of sight flow indicators, so that the operators can check the cleaner's effectiveness.

More and more analyzers should become self-calibrating, self-diagnosing, and modular in their design. In order to lower maintenance costs, analyzers should also be made more modular for ease of replacement and should be provided with the intelligence to identify their defective modules. The industry should also explore the use of multiple-probe fiber-optic analyzers with multiplexed shared electronics.

Improving Operators' Displays

The control rooms of the coming decades will be more operator-friendly and more enterprise-wide optimization oriented. The human-machine interfaces (HMIs) in the control rooms are only as good as the ability of the operators to use them.

The hand, the psychological characteristics, the hearing, and color discrimination capability of the human operator must all be part of the design. Even more importantly, the design should also consider the personality and education of the average operator. Therefore, a well-designed HMI is the operator's window on the process.

In past decades, the operator's window on the process was little more than the faceplate of an analog controller and an annunciator. Today, when a single operator is expected to oversee the operation of processes having hundreds if not thousands of variables, the operator must be provided with diagnostic, trend, and historical data in an easily understandable and familiar format.

For that purpose, it is advisable to provide in the control room a large display panel, on which (as one of the options) the operation of the whole plant can be displayed. Using that graphic flowsheet, the operator should have the ability to focus in on any unit operation of interest. As the operator focuses in on smaller and smaller sections of the plant, the information content of the display should increase. In the process of "focusing," the operator must be able to select subsystems, individual loops, or loop components, such as a single control valve. At each level of scale, the display should identify all abnormal conditions (by color and flashing), while providing all the trend and status data for all related variables.

Another essential feature of modern control systems is their suitability for smooth growth of the plant. This capability is very important in process control because plants are ever expanding and therefore their control systems must also grow with the expansions. A modular approach to operator stations makes the expansion of the plant easier.

Optimization and Advanced Controls

In some ways we have already passed the age of the single-loop PID control. Yet in the coming decade much more improvement is expected both in multivariable unit operations control and in model-based optimization.

We all know that it is time to stop controlling flows, pressures, and temperatures and to start controlling and optimizing pumping stations, boilers, and chemical reactors. In the next decade, hopefully we will see the development of the universal software package for the various unit operations that can be adapted to specific plants just by the entering of design data for the particular process.

Plant-Wide Modeling and Optimization

In addition to its role in providing better control, process modeling and simulation can also improve the training of operators. If the simulation model is accurate and if it integrates the dynamics of the process with that of its control system, it can be used to train operators for plant startup without risking the consequences of their inexperience. Needless to say, the building of good models is expensive, but once prepared, they are very valuable.

Business- or enterprise-wide optimization includes the model of not only the manufacturing process, but also the optimization of the raw material supply chain and of the packaging and product distribution chain. This is a higher and more important level of optimization because it requires the simultaneous consideration of all areas of optimization and the finding of enterprise-wide operation strategies, which will keep all areas within their optimum areas of operation.

Plant-wide optimization also involves more than the optimization of the unit processes because it must also consider documentation, maintenance, production scheduling, and quality management considerations. Plant-wide optimization requires the resolution of the conflicting objectives of the operations and strategies.

Naturally, it should be kept in mind that modeling and optimization can only be achieved when the control loops are correctly tuned, the measurements are sampled fast enough, and interactions between loops have been eliminated.

Efficiency and Productivity Controllers

This handbook already describes a large number of methods to increase the efficiency of unit operations. For example, in the section describing the methods of pumping station optimization, it is pointed out that the lifetime operating cost of a pumping station is about a *hundred times higher than its initial cost.* The returns on the optimization of other unit operations are similar, although not that high. It is for this reason that in the coming decade, optimization is expected to increase.

When using multivariable envelopes for unit operation optimization, the individual variables of levels, pressures, and temperatures become only constraints, while the overall goal is to maximize the efficiency or productivity of the controlled process. New software packages are needed to "educate" and give "personality" to today's multivariable controllers to transform these general-purpose units into chemical reactor, distillation tower, compressor, or any other type of unit operation controllers.

Unit Operation Controllers of the Future

The next decade could bring a building-block approach to control systems. In this approach all "empty boxes" could be very similar, so that a unit operations controller that was, say, to optimize a dryer, could be converted to control an evaporator or a pumping station just by loading into it a different software package and connecting a different set of I/Os. Once the particular software package was loaded, the unit controller would be customized by a menu-driven adapter package, organized in a question-and-answer format.

During the customization phase, the user would answer questions on piping configuration, equipment sizes, material or heat balances, and the like. Such customization software packages could not only automatically configure and tune the individual loops but could also make the required relative gain calculations to minimize the interaction among them.

HISTORY OF THE HANDBOOK

The birth of this handbook was connected to my own work: In 1962 — at the age of 26 — I became the Chief Instrument Engineer at Crawford & Russell, an engineering design firm specializing in the building of plastics plants. C&R was growing and with it the size of my department also increased. Yet, at the age of 26 I did not dare to hire experienced people because I did not feel secure enough to lead and supervise older engineers.

So I hired fresh graduates from the best engineering schools in the country. I picked the smartest graduates and I obtained permission from C&R's president, Sam Russell, to spend every Friday afternoon teaching them. In a few years C&R not only had some outstanding process control engineers but had them at relatively low salaries.

By the time I reached 30, I felt secure enough to stop disguising my youth. So I shaved off my beard and threw away my phony, thick-rimmed eyeglasses, but my Friday's notes remained. They still stood in a 2-foot-tall pile on the corner of my desk.

"Does Your Profession Have a Handbook?"

In the mid-1960s an old-fashioned Dutch gentleman named Nick Groonevelt visited my office and asked: "What is that pile of notes?" When I told him, he asked: "Does your profession have a handbook?" "If it did, would I bother to prepare all these notes?" I answered with my own question. (Actually, I was wrong in giving that answer, because Behar's *Handbook of Measurement and Control* was already available, but I did not know about it.) "So," Nick proposed, "let me publish your notes and then the instrument engineers will have a handbook!" In 1968 the first edition of the *Instrument Engineers' Handbook* (*IEH*) was published.

In 1968, the Soviet tanks — which I fought in 1956 in Budapest — were besieging Prague, so I decided to dedicate the three volumes of the *IEH* to the Hungarian and Czech freedom-fighters. A fellow Hungarian-American, Edward Teller, wrote the preface to the first edition; Frank Ryan — the editor of *ISA Journal* — wrote the introduction. Because of the publication of the first edition of the *IEH*, in 1973 I was elected the youngest ISA fellow ever.

Later Editions

By the end of the 1970s the world of process control had changed. Pneumatics were on the way out, and new solutions like DCS control and on-line analyzers proliferated. It was time to revise the handbook. The second edition was published in 1985. It was well received.

By the mid-1990s the handbook was ready for another updated edition. By that time the process control market was becoming globalized, "smart" instruments had evolved, and such hardware inventions as fiber-optic probes and throttling solenoid valves proliferated. So I stopped teaching at Yale, cut back on consulting, and prepared the third edition. In this edition I also added a third volume to the two-volume set to cover all the evolving digital software packages, communication networks, buses, and optimization packages.

Work on the fourth edition of the *IEH* started in the new millenium, and the first volume on measurement and analysis was published in 2003. The second volume is in your hands now.

During the nearly four decades of its existence, the *Instrument Engineers' Handbook* (*IEH*) has become the most widely used reference source for the automation and control (ACE) engineering profession. During this period, our experience and our knowledge of control principles have penetrated all the fields of modern science and technology. I hope that the three volumes of the *IEH* will continue to play a major role in spreading this knowledge and understanding.

The Contents of the *IEH* Volumes

In 1968, this handbook started out as a two-volume reference set and, in that respect, it has not changed. The first volume still deals with measurement, the second with control. What is new is that the third volume deals with digital networks and software systems.

This fourth edition updates the information content of the previously published sections, incorporates the new developments of the last decade, and broadens the horizons of the work from an American to a global perspective. In the first volume, one chapter was devoted to each major measured variable including the detection of flow, level, temperature, pressure, density, viscosity, weight, composition, and safety sensors. Each subchapter (section) was devoted to the discussion of a different method of making that measurement.

This second volume of the *IEH* deals with process control and covers both control hardware and control strategies. The hardware discussed includes transmitters, controllers, control valves, and displays, including the design of control rooms. The chapters on control systems provide in-depth coverage both of the theory of control and of the unit processes of pumping, distillation, chemical reaction, heat transfer, and many others. The individual sections (subchapters) begin with a flowsheet symbol and if the subject matter is a hardware item, start with a feature summary.

This summary provides quick access to specific information on the available sizes, suppliers, ranges, and inaccuracies of the devices covered in that section. The reader is advised to turn to the section of interest and, based on the information in the feature summaries, decide whether the costs, inaccuracies, and other characteristics meet the requirements of the particular application.

We know that there is no greater resource than the combined knowledge and professional dedication of a well-educated new generation. We live in an age when technology can make the difference in overcoming the social and environmental ills on this planet. We live in an age when an inexhaustible and nonpolluting energy technology must be developed. It is hoped that this handbook will make a contribution toward these goals and in addition will also improve the professional standing of automation and control engineers around the world.

Béla Lipták
Stamford, Connecticut
(*liptakbelaieh4@aol.com*)

DEFINITIONS

Absolute (Dynamic) Viscosity (μ) Constant of proportionality between applied stress and resulting shear velocity (Newton's hypothesis).

Absorbance (*A*) Ratio of radiant energy absorbed by a body to the corresponding absorption of a blackbody at the same temperature. Absorbance equals emittance on bodies whose temperature is not changing. ($A = 1 - R - T$, where R is the reflectance and T is the transmittance.)

Absorption The taking in of a fluid to fill the cavities in a solid.

Accumulation In safety and relief valve terminology, accumulation is the pressure increase over the maximum allowable working pressure of a tank or vessel during discharge through the pressure relief valve. It is given either in percentage of the maximum allowable working pressure or in pressure units such as pounds per square inch or in bars.

Accuracy See **Inaccuracy**, which is the term used in this handbook.

Adaptive Control See **Control, Adaptive**

Admittance (*A*) The reciprocal of the impedance of a circuit. The admittance of an AC circuit is analogous to the conductance of a DC circuit. (Units: siemens.)

Adsorption The adhesion of a fluid in extremely thin layers to the surfaces of a solid.

Alarm A signal designed to alert, inform, guide, or confirm deviations from acceptable system status.

Alpha Curve In resistance bulb terminology, it is the relationship of the resistance change of an RTD vs. temperature. In European alpha curves, the alpha value is 0.00385 ohms per degree C, while in American curves it is 0.00392.

Ampacity The current (amperes) a conducting system can support without exceeding the temperature rating assigned to its configuration and application.

Amperometric Titration Titration in which the end point is determined by measuring the current (amperage) that passes through

Amperometry The process of performing an amperometric titration. The current flow is monitored as a function of time between working and auxiliary electrodes while the voltage difference between them is held constant; in other designs, the current is monitored as a function of the amount of reagent added to bring about titration of an analyte to the stoichiometrically defined end point. Also called constant potential voltametry.

Amplifier A device that enables an input signal to control a signal source independent of the signal and is thus capable of delivering an output that is related to and is greater than the input signal.

Apparent Viscosity Viscosity of a non-Newtonian fluid under given conditions. Same as consistency.

Approach The different between the wet-bulb temperature of the ambient air and the water temperature leaving a cooling tower. The approach is a function of cooling tower capacity; a large cooling tower will produce a closer approach (colder leaving water) for a given heat load, flow rate, and entering air condition. (Units: °F or °C.)

Artificial Neural Networks (ANNs) An ANN can learn complex functional relations by generalizing from a limited amount of training data; hence, it can thus serve as black-box model of nonlinear, multivariable static and dynamic systems and can be trained by the input–output data of these systems. ANNs attempt to mimic the structures and processes of biological neural systems.

They provide powerful analysis properties such as complex processing of large input/output information arrays, representing complicated nonlinear associations among data, and the ability to generalize or form concepts–theory.

Attenuation Loss of communication signal strength.

Auto-Manual Station A device that enables an operator to select either the output of a controller or a manually generated signal.

Backlash In mechanical devices, it is the relative movement between interacting parts that results from the looseness of these parts when motion is reversed.

Backplane Physical connection between individual components and the data and power distribution buses inside a chassis.

Backpressure In relief and safety valve terminology, it is the pressure on the discharge side of a pressure relief valve. This pressure is the sum of the superimposed and the built-up backpressures. The superimposed backpressure is the pressure that exists in the discharge piping of the relief valve when the valve is closed.

Balanced Safety Relief Valve A safety relief valve with the bonnet vented to atmosphere. The effect of backpressure on the performance characteristics of the valve (set pressure, blow-down, and capacity) is much less than on a conventional valve. The balanced safety relief valve is made in three designs: (1) with a balancing piston, (2) with a balancing bellows, and (3) with a balancing bellows and an auxiliary balancing piston.

Balling Degrees Unit of specific gravity used in the brewing and sugar industries.

Balun (Balanced/Unbalanced) A device used for matching characteristics between a balanced and an unbalanced medium.

Band Pass Filter An optical or detector filter that permits the passage of a narrow band of the total spectrum. It excludes or is opaque to all other wavelengths.

Bandwidth Data carrying capacity, the range of frequencies available for signals. The term is also used to describe the rated throughput capacity of a given network medium or protocol.

Barkometer Degrees Unit of specific gravity used in the tanning industry.

Baseband A communication technique where only one carrier frequency is used to send one signal at a time. Ethernet is an example of a baseband network. Also called narrow-band. Contrast with **Broadband**.

Basic Control Continuously executed algorithms that drive the process or equipment to a specified state and keep it there, such as indicators, regulatory and device controls, and interlocks.

Batch A quantity of material produced by the single execution of a batch process. A batch also refers to the intermediate materials during the manufacturing process.

Baumé Degree A unit of specific gravity used in the acid and syrup industry.

Bay The area between two bents of lines of framing members; usually longitudinal.

Bent A line of structural framework composed of columns or ties; a bent may incorporate diagonal bracing members; usually transverse.

Blackbody The perfect absorber of all radiant energy that strikes it. A blackbody is also a perfect emitter. Therefore, both its absorbance and emissivity (E) are unity. A blackbody radiates energy in predictable spectral distributions and intensities, which are a function of the blackbody's absolute temperature.

Black Box Model See **Empirical Model**.

Blowdown In case of cooling towers, it is the water discharged to control the concentration of impurities in circulated water. (Units: percentage of circulation rate.)

Blowdown (Blowback) In relief valves, it is the difference between the set pressure and the reseating (closing) pressure of a pressure relief valve, expressed in percent of the set pressure, in bars, or in pounds per square inch.

Bode Diagram A plot of the logarithm of gain or magnitude ratio and a plot of the logarithm of phase angles against the logarithm of frequency for a transfer function.

Boiling Point Rise This term expresses the difference (usually in °F) between the boiling point of a constant composition solution and the boiling point of pure water at the same pressure. For example, pure water boils at 212°F (100°C) at 1 atmosphere, and a 35% sodium hydroxide solution boils at about 250°F (121°C) at 1 atmosphere. The boiling point rise is therefore 38°F (21°C). In a Dühring plot, the boiling point of a given composition solution is plotted as a function of the boiling point of pure water.

Bolometer Thermal detector that changes its electrical resistance as a function of the radiant energy striking it.

Bonding The practice of creating safe, high capacity, reliable electrical connectivity between associated metallic parts, machines, and other conductive equipment.

Brightness Pyrometer A device that uses the radiant energy on each side of a fixed wavelength of the spectrum. This band is quite narrow and usually centered at 0.65 microns in the orange-red area of the visible spectrum.

British Thermal Unit (BTU) The amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit at or near 60° Fahrenheit.

Brix Degree A specific gravity unit used in the sugar industry.

Broadband A communication technique that multiplexes multiple independent signals simultaneously, using several distinct carriers. A common term in the telecommunication industry to describe any channel having a bandwidth greater than that of a voice-grade channel (4 kHz). Also called wideband. Contrast with **Baseband**.

BTU "Dry" The heating value of a gas expressed on a "dry basis." The common assumption is that pipeline gas contains 7 pounds (or less) of water vapor per million standard cubic feet.

BTU "Saturated" The heating value of a gas expressed on the basis that the gas is saturated with water vapor. This state is defined as the condition when the gas contains the maximum amount of water vapor without condensation, when it is at base pressure and 60°F.

Bubble Point The temperature at which a mixture of liquids first starts to boil.

Built-Up Backpressure In connection with safety relief valves, the variable backpressure that develops as a result of flow through the pressure relief valve after it opens. This is an increase in pressure in the relief valve's outlet line caused by the pressure drop through the discharge headers.

Burning In combustion-related terminology, burning is when the flame does not spread or diffuse but remains at an interface where fuel and oxidant are supplied in proper proportions.

Calibrate To ascertain the outputs of a device corresponding to a series of input values that the device is to receive, measure, or transmit.

Calibration Cycle The application of known values as inputs to a device and the registering of the corresponding output readings over the range of that device, in both ascending and descending directions.

Calibration Traceability The relationship of the calibration of an instrument to that of one or more instruments calibrated and certified by a national standardizing laboratory.

Campaign The total production run of one product, for example, for a single order or season, consisting of one or more lots.

Capacitance (*C*) The amount of charge, in coulombs, stored in a system necessary to raise the potential difference across it 1 volt; represented by the SI unit farad.

Capacitor Device consisting of two conductors electrically isolated by an insulator. The conductors are called plates, and the insulator is referred to as the dielectric. The larger the capacitor, the smaller its impedance, and the more AC current will flow through it.

Cascade Control See **Control, Cascade**.

Characteristic Impedance The impedance that, when connected to the output terminals of a transmission line appear to be infinitely long, for there are no standing waves on the line, and the ratio of voltage to current is the same for each point of the line [nominal impedance of wave-guide].

Chatter Rapid, abnormal reciprocating variations in lift during which the disc contacts the seat.

Chronopotentiometry When the potential difference between a metallic measuring electrode and a reference electrode is monitored as a function of time. At the measuring electrode an oxidation or reduction of a solution species is taking place.

Closing Pressure (Reseat Pressure) In relief and safety valve terminology, the pressure, measured at the valve inlet, at which the valve closes, flow is substantially shut off, and there is no measurable lift.

Coax Jargon meaning "coaxial cable," consisting of a center wire surrounded by low K insulation, surrounded by a second shield conductor. It has low capacitance and inductance for transmission of high-frequency current.

Co-Current Operation The process feed and steam (or other utility fluid) follow parallel paths through such processes as an evaporator train.

Countercurrent Operation The feed and steam enter the evaporator train at opposite ends.

Cold Differential Test Pressure (CDTP) The pressure at which the PRV is adjusted to open during testing. The CDTP setting includes the corrections required to consider the expected service temperature and backpressure.

Cold Junction See **Reference Junction**.

Combustion Air Requirement Index (CARI) This dimensionless number indicates the amount of air required (stoichiometrically) to support the combustion of a fuel gas. Mathematically the Combustion Air Requirement Index is defined by the equation below:

$$\text{CARI} = \frac{\text{Air/Fuel Ratio}}{\sqrt{\text{SG}}}$$

Common Mode Interference See **Interference, Common Mode**.

Common Mode Rejection The ability of a circuit to discriminate against a common mode voltage.

Common Mode Voltage A voltage of the same polarity relative to ground on both sides of a differential input.

Common Resource An equipment entity that services more than one unit, either simultaneously (shared-use resource) or one at a time (exclusive-use resource).

Compliance The reciprocal of stiffness.

Conductance (*G*) The reciprocal of resistance. (Units: Siemens [formerly "mhos"].)

Conductivity (*g*) The reciprocal of resistivity. All solids and liquids have some degree of conductivity. For the purpose of this section, any material above 1 micro Siemen/cm will be considered to be conductive (this includes most metals and water with any ions).

Conformity The degree or closeness to which one curve approximates another curve. Conformity can be expressed as independent, terminal based, or zero based. Independent conformity is obtained when the calibration curve is so positioned as to minimize the maximum deviation between it and the specified curve. Terminal-based conformity is obtained when the two curves are so positioned that their readings coincide at zero and full span. Zero-based conformity is when they coincide only at zero.

Consistency In terms of viscosity, the resistance of a substance to deformation. It is the same as viscosity for a Newtonian fluid and the same as apparent viscosity for a non-Newtonian fluid.

Constant Backpressure In connection with safety relief valves, the backpressure that does not change under any condition of operation, whether the pressure relief valve is closed or open.

Control Action For a controller, the nature of the change in the output of the controller, which is affected by the controller's input.

Control Action, Derivative (Rate) (*D*) A control action in which the controller output is proportional to the rate of change of the input.

Control Action, Integral (Reset) (*I*) A control action in which the controller output is proportional to the time integral of the input. In this case the rate of change of the controller output is proportional to the input.

Control Action, Proportional (*P*) A control action in which there is a continuous linear relationship between the controller's output and its input.

Control, Cascade Control configuration in which the output of one controller (the "master") is the set point of another controller (the "slave").

Control, Differential Gap Control in which the output of the controller remains at a minimum or maximum value until the controlled variable reaches the top limit of a band or gap, at which point the output reverses and stays in that state until the controlled variable crosses the bottom limit of the gap. At that point, the controller output returns to its original condition.

Control, Feedback Control in which a measurement is compared to a set point to produce an error signal. This error is acted upon in such a way as to reduce the magnitude of the error.

Control, Feedforward Control in which one or more conditions that are outside the feedback loop and have an influence on the controlled variable are converted into some corrective action in order to minimize the deviations from the set point of the controlled variable.

Control Horizon The number of future manipulated variable moves that are taken into account in developing the optimal MPC solution.

Controlled Variable The variable that is detected to originate the feedback signal for the controller.

Controller, Direct Acting A controller that increases its output signal when its measured variable (input signal) increases.

Controller, On-Off A two-position controller, of which one of the two discrete output signal values is zero.

Controller, Program A controller that automatically adjusts its set point to follow a prescribed program.

Controller, Ratio A controller that maintains a predetermined ratio between two variables.

Controller, Reverse Acting A controller that decreases its output signal as the value of its measured variable (input signal) increases.

Controller, Sampling A controller using intermittent readings of the controlled variable (error or set point) to affect control action.

Controller, Self-Operated (Regulator) A controller that derives the required energy for its operation from the system that it controls.

Controller, Time Schedule A controller in which the set point (or the reference-input signal) automatically follows some predetermined time schedule.

Control Module A set of equipment and functions that can carry out basic control. For example, a control loop consisting of one or more sensors, actuators, and control functions is a control module. It is also the lowest-level equipment grouping that acts as a single entity from a control standpoint, but cannot execute procedural elements. May be an individual measurement (with suitable signal conditioning or state names) or a grouping of directly coupled actuators with their associated measurements, alarms, and control actions, including subordinate Control Modules as appropriate. Examples are an uncontrolled temperature, a flow control loop, an automatic block valve with limit switches, or a header containing interlocked (mutually exclusive) block valves.

Control, Optimizing Control that does not hold the controlled variable constant but seeks and maintains a value of the controlled variable that will result in the most advantageous operation of the process.

Control Recipe An equipment-specific recipe that defines the production of a single batch. It is usually derived from a master recipe.

Control, Supervisory Control in which a supervisory controlled periodically applies some corrective action, such as set point changes, to a number of controllers.

Control System, Multi-Variable A control system that uses two or more process variable measurement signals to affect control.

Control, Time Proportioning Control in which the outputs are periodic pulses whose duration is varied in relation to the actuating error signal.

Control, Velocity Limiting Control in which the rate of change of some variable is prevented from exceeding a predetermined limit.

Conventional Safety Relief Valve A safety relief valve with the bonnet vented either to atmosphere or internally to the discharge side of the valve. The performance characteristics (set pressure, blow-down, and capacity) are directly affected by changes of the backpressure on the valve.

Coordination Control Control functions existing at multiple levels to schedule batches and manage recipes, procedural control execution, equipment entity allocation, and batch data.

Corner Frequency In the asymptotic form of the Bode diagram, that frequency that is indicated by a break point. It is the junction of two confluent straight lines asymptotic to the log gain curve.

Coulometry A process of monitoring analyte concentration by detecting the total amount of electrical charge passed between two electrodes that are held at constant potential or when constant current flow passes between them.

Countercurrent Operation The process feed and steam (or other utility fluid) enter at opposite ends as they flow through such processes as an evaporator train.

Counterflow Cooling Tower A cooling tower in which the airflow is in the opposite direction from the fall of water through the water cooling tower.

CPVC (Chlorinated Polyvinyl Chloride) A low cost, reasonably inert polymer used for some noninsertion sensors. It is easily solvent-welded. The max temperature range is about 225°F.

Cross-Flow Cooling Tower A cooling tower in which airflow through the fill is perpendicular to the plane of the falling water.

Crystallography How the atoms are arranged in the object; a direct relation exists between these arrangements and materials properties (conductivity, electrical properties, strength, etc.).

Curie (Ci) A unit of radiation source size, corresponding to 37 billion disintegrations per second.

Damping The progressive reduction or suppression of oscillation in a device or system.

Damping Factor In the case of the free oscillation of a second-order linear system, it is the ratio of the greater by the lesser of a pair of consecutive swings of the output in opposite directions (without sign) about an ultimate steady-state value.

Data Servers A standard interface to provide data exchange between field devices and data clients.

Deadband The range through which an input can be varied without causing an observable change in the output. Deadband is the range through which the measurand may be varied by reversing direction without producing an observable response in the output signal.

Dead Time See **Time, Dead**.

Dead Zone See **Zone, Dead**.

Deflagration or Explosion A process where the flame front advances through a gaseous mixture at subsonic speeds.

Deionized Water Water of extremely high purity, with few ions to carry current. If exposed to air for any significant period, it will have a conductivity of about 5 micro Siemens/cm due to dissolved CO_2.

Demultiplexing Separating of multiple input streams that were multiplexed into a common physical signal back into multiple output streams.

Derivative Gain See **Gain, Derivative**.

Derivative Time See **Time, Derivative**.

Design Pressure This pressure is equal to or less than the maximum allowable working pressure. It is used to define the upper limit of the normal operating pressure range.

Detonation A process where the advancement of the flame front occurs at supersonic speeds.

Device Description (DD) In digital systems, a clear and unambiguous, structured text description that allows full utilization/operation of a field device by a host/master without any prior knowledge of the field device.

Device Description Language (DDL) In the Foundation fieldbus technology concept, it is the definition and description of function blocks and their parameters.

Dew Point Saturation temperature of a gas–water vapor mixture.

Dew Point Temperature (DPT) The temperature at which condensation begins if air is cooled under constant pressure.

Dielectric A material that is an electrical insulator or in which an electric field can be sustained with a minimum of dissipation of power. Dielectric materials include metal-oxides, plastics, and hydrocarbons.

Dielectric Compensation A scheme by which changes in insulating liquid composition or temperature can be prevented from causing any output error. It requires a second sensor and homogeneous liquid.

Dielectric Constant A unit expressing the relative charge storage capability of various insulators. Full vacuum is defined as 1.0, and all gases are indistinguishable from each other for practical purposes. TFE has a dielectric constant of 2.0, cold water about 80. It has no units because it is the ratio of the dielectric constant of a substance to that of vacuum. For the dielectric values of selected materials refer to Table 3.3p of the first volume of this handbook.

Diode A two-terminal electronic (usually semiconductor) device that permits current flow predominantly in only one direction.

Direct Acting Controller See **Controller, Direct Acting**.

Discontinuity An abrupt change in the shape [or impedance] of a wave-guide [creating a reflection of energy].

Distance/Velocity Lag A delay attributable to the transport of material or to the finite rate of propagation of a signal.

Dither A useful oscillation of a small magnitude, which is introduced to overcome the effect of friction, hysteresis, or recorder pen clogging.

Drift An undesired change in the output of a device, which occurs over time and is unrelated to the input, the environment, or the load. In the case of cooling towers it is the water loss due to liquid droplets entrained in exhaust air. Usually under 0.2% of circulated water flow rate.

Drift Eliminator An assembly constructed of wood or honeycomb materials that serves to remove entrained moisture from the discharged air.

Droop See **Offset**.

Dry-Bulb Temperature (TDB) The temperature of air measured by a normal thermometer.

Dust-Ignition-Proof Enclosed in a manner to exclude ignitable amounts of dust or amounts that might affect performance. Enclosed so that arcs, sparks, or heat otherwise generated or liberated inside of the enclosure will not cause ignition of exterior accumulations or atmospheric suspensions of dust.

Dynamic Gain See **Gain, Dynamic**.

Dynamic Matrix A matrix built from step responses to predict the changes in the process output that result from the moves of the manipulated variable over the control horizon.

Economy In case of the evaporation process, this term is a measure of steam use and is expressed in pounds of vapor produced per pound of steam supplied to the evaporator train. For a well-designed evaporator system the economy will be about 10% less than the number of effects; thus, for a triple-effect evaporator the economy will be roughly 2.7.

Effective Coefficient of Discharge This is a coefficient used to calculate the minimum required discharge area of the PRV.

Electrochemical Process The changes in voltage or current flow that occur between two electrodes in a solution (electrolyte) over time. The oxidation or reduction of the analyte provides data that are related to concentration.

Electrolytic Probe Probe that is similar to a galvanic probe, except that a potential is applied across the electrodes and the electrodes are not consumed. Dissolved oxygen detection is a primary application of this type of probe.

Electromagnetic Wave (Energy) A disturbance that propagates outward from any electric charge that oscillates or is accelerated; far from the charge it consists of vibrating electric and magnetic fields that move at the speed of light and are at right angles to each other and to the direction of motion.

Electron Microscope A scientific instrument that uses a beam of highly energetic electrons to examine objects on a very fine scale.

Element, Final Control The controlling element that directly changes the value of the manipulated variable. It can be a control valve, a damper, an electric power modulator, or a variable-speed pump.

Element, Primary The element that converts the measured variable into a form which can be measured.

Elevated Range, Elevation See **Range, Suppressed Zero**.

Elevation, Zero See **Zero Elevation**.

Emissivity or Emittance (*E*) The emissivity of an object is the ratio of radiant energy emitted by that object divided by the radiant energy that a blackbody would emit at that same temperature. If the emittance is the same at all wavelengths, the object is called a gray body. Some industrial materials change their emissivity with temperature and sometimes with other variables also. Emissivity always equals absorption and it also equals 1 minus the sum of reflectance and transmittance:

$$(E = A = 1 - T - R)$$

Empirical Model This type of model can be used for processes for which no physical insight is available or used. This model structure belongs to families that are known to have good flexibility and have been "successful in the past." The parameters of the models are identified based on measurement data. A complete mechanistic model is constructed from *a priori* knowledge.

Equipment Control The procedural, basic, and coordination control capability that enables an equipment entity to perform its function. It is not part of a recipe but may be directed by a recipe.

Equipment Entity A set of process and control equipment and associated control capability that has been grouped together to provide some specified process or equipment functionality.

Equipment Module A group of equipment that can carry out a finite number of specific minor processing activities. An equipment module may include one or more control modules. It is typically centered around a piece of process equipment, such as a weigh tank, heat exchanger, filter, or weighing scale. It is an equipment entity incorporating necessary devices, control modules, and application-specific states and modes to execute some basic process-oriented task or group of tasks. It may include equipment procedural elements (typically phase logic) and/or subordinate equipment modules but may not overlap other equipment modules. Examples are a common (exclusive-use) weigh tank, a recirculation/transfer pump within a unit, and a shared-use ingredient dosing system.

Equivalent Time Sampling (ETS) The process that captures high-speed electromagnetic events in real time (nanoseconds) and reconstructs them into an equivalent time (milliseconds), which allows easier measurement with present electronic circuitry.

Ergonomics An empirical approach to the study of human–machine interactions, with the objective of improving efficiency and reducing strain and discomfort of the operator.

Error The difference between the measurement signal and its ideal value. A positive error denotes that the indication of the instrument is greater than the ideal value.

Error, Systematic An error which, when a number of measurements are made under the same conditions, measuring the same value of a given quantity, either remains constant or varies according to some definite law when conditions change.

Error, Zero The error of a device when it is operating at the lower range-value, which is commonly referred to as its zero.

Ethernet A baseband local area network specification developed by Xerox Corporation, Intel, and Digital Equipment Corporation to interconnect computer equipment using coaxial cable and transceivers.

Evaporation Loss Water evaporated from the circulating water into the atmosphere in the cooling process. (Unit: percentage of total GMP.)

Excitation, Maximum The maximum excitation that can be applied to a device at rated operating conditions without causing damage or performance degradation beyond specified tolerances.

Exception Handling Procedures and functions that deal with conditions outside the normal or desired behavior of a process.

Explosion Proof All equipment that is contained within enclosures that are strong enough to withstand internal explosions without damage and tight enough to confine the resulting hot gases so that they will not ignite the external atmosphere. This is the traditional method of protection and is applicable to all sizes and types of equipment.

Fan Pitch The angle a fan blade makes with the plane of rotation. (Unit: degrees from horizontal.)

Fan Stack (Cylinder) Cylindrical or modified cylindrical structure in which the fan operates. Fan cylinders are used on both induced draft and forced draft axial-flow propeller-type fans.

Farad (*F*) A unit of capacitance. Because this is a very large unit, a unit equal to one trillionth of a farad (called a pico Farad, symbol: "pF") is commonly used in RF circuits.

Feedback Control See **Control, Feedback**.

Feedforward Control See **Control, Feedforward**.

FEP (Fluorinated Ethylene Propylene) A fluorocarbon that is extremely chemically inert, melts at a reasonable temperature, and can be plastic-welded fairly easily. Hard to bond with adhesives. Max. temperature range limited to the 300°F (150°C) area.

Fieldbus An all-digital, two-way, multi-drop communications system for instruments and other plant automation equipment.

Firewall A router or access server, designated as a buffer between any public networks and a private network.

Flash Point The lowest temperature at which a flammable liquid gives off enough vapors to form a flammable or ignitable mixture with air near the surface of the liquid or within the container used. Many hazardous liquids have flash points at or below room temperature. They are normally covered by a layer of flammable vapors that will ignite in the presence of a source of ignition.

Fluidity Reciprocal of absolute viscosity; unit in the cgs system is the rhe, which equals 1/poise.

Floutter Rapid, abnormal reciprocating variations in lift, during which the disc does not contact the seat.

Forced Draft Cooling Tower A type of mechanical draft water cooling tower in which one or more fans are located at the air inlet to force air into the tower.

Forman Vocal-tract resonance.

Formula A part of recipe that include process inputs, process parameters, and process outputs. The list of process inputs, outputs, and data (operating set points, reported values, timing, etc.) required to execute the batch procedure.

Frequency, Damped The frequency of a damped oscillatory response of a system resulting from a nonoscillatory stimulus.

Frequency Response Characteristics The frequency-dependent relation, both in terms of gain and phase, between steady-state sinusoidal inputs and the resulting steady-state sinusoidal outputs.

Fuel Cells Cells that convert the chemical energy of fuels such as hydrogen into electrical energy, while the electrode and the electrolyte remain unaltered. Fuel is converted at the anode into hydrogen ions, which travel through the electrolyte to the cathode, and electrons, which travel through an external circuit to the cathode. If oxygen is present at the cathode, it is reduced by these electrons, and the hydrogen and oxygen ions eventually react to form water.

Function Block A logical processing unit of software that has one or more input and output parameters.

Fuzzy Logic Modeling This type of model is used for processes that are not fully understood. It is a linguistically interpretable rule-based model, which is based on the available expert knowledge and measured data.

Gain, Closed Loop The ratio of a change in output to a change in input of a closed loop system at a specified frequency.

Gain, Derivative (Rate Gain) The ratio of the maximum gain that results from the proportional plus derivative actions in a controller to the gain due to the proportional mode alone.

Gain, Dynamic For a sinusoidal signal, it is the magnitude ratio of the steady-state amplitude of the output signal from a device to the amplitude of the input signal to that device.

Gain, Loop At a specified frequency, it is the ratio of the magnitude of the change in the feedback signal to the change in its corresponding error signal.

Gain (Magnitude Ratio) For a linear system, it is the ratio of the amplitude of a steady-state sinusoidal output and the amplitude of the input that caused it.

Gain, Proportional The ratio of the change in the output of a controller with proportional action to the change in the input of the controller.

Galvanic Probe A probe in which no external voltage is applied across its electrodes and the current flows as the cell is depolarized when diffusion of the analyte occurs. Electrodes are consumed during this operation and require periodic replacement.

General Recipe A type of recipe that expresses equipment- and site-independent processing requirements. It is the highest level of recipe.

Gray Body An object with a constant emittance of less than unity. This emittance is constant at all wavelengths (over that part of the spectrum where the measurement takes place). This means that gray-body radiation curves are identical to those of a blackbody, except that they are dropped down on the radiated power density scale.

Gross Calorific Value The heat value of energy per unit volume at standard conditions, expressed in terms of British thermal unit per standard cubic feet (BTU/SCF) or as kilocalorie per cubic Newton meters (Kcal/N · m^3) or other equivalent units.

Ground A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth, or to some conducting body that serves in place of earth. (See NFPA 70-100.)

Ground Fault Protector Device used to open ungrounded conductors when high currents, especially those due to line-to-ground fault currents, are encountered.

Guard The "electronic guard" (called a "shield" in some RF level literature) consists of a concentric metallic element with an applied voltage that is identical to the voltage on the conductor that it is "guarding." This negates the capacitance between the guarded conductor and the outside world.

Guided Wave Radar (GWR) A contact radar technology where Time Domain Reflectometry (TDR) has been developed into an industrial-level measurement system where a probe immersed in the medium acts as the waveguide.

Hagen–Poiseuille Law Defines the behavior of viscous liquid flow through a capillary.

HART Is an open, smart field instrumentation protocol that is a de facto fieldbus. It imposes a 1200-bit-per-second digital signal on a twisted pair of wires carrying a 4- to 20-mA input.

Home Run Wiring Wire between the cabinet where the Fieldbus host or centralized control system resides and the first field junction box or device.

Hub (Shared) Multi-port repeater joining segments into a network.

Hunting An undesirable oscillation of some appreciable magnitude, prolonged even after the external stimuli that caused it disappear.

Hygrometer An apparatus that measures humidity.

Hygroscopic Material A material with great affinity for moisture.

Hysteresis That property of an element or system that shows the dependence of its output for a given excursion of the input on the history of prior excursions and on the direction of the current traverse. Hysteresis in a damper or valve is caused mostly by friction. Hysteresis in a process transmitter is the maximum difference between readings taken at the same measurand with upscale and downscale approaches to the readings. It is due to inelastic qualities of the sensing element, friction, and backlash.

Impedance Maximum voltage divided by maximum current in an alternating current circuit. Impedance is composed of resistive, inductive, and capacitive components. Like direct current circuits, the quantity of voltage divided by current is expressed in ohms.

Inaccuracy The degree of conformity of a measured or indicated value to a recognized standard value. It is usually expressed in terms of measured variable, percent of span, percent of upper-range value, or percent of actual reading.

Inaccuracy Rating The quantity that defines the limit that errors will not exceed while the device is operating under specified conditions. Can be expressed in terms of the measured variable (for example ±0.5°F), in terms of percent span, in percent upper-range value, in percent of scale length, or in percent of actual output reading.

Infrared That portion of the spectrum whose wavelength is longer than that of red light. Only the portion between 0.7 and 20 microns gives usable energy for radiation detectors.

Insulation Resistance The resistance measured across the insulation at reference operating conditions when a specified direct current voltage is applied. The goal of the measurement is to determine whether the expected leakage current will or will not be excessive.

Integral Action Rate (Reset Rate) For PI or PID controllers, it is the ratio of the initial rate of output change caused by the integral action to the change in steady-state output caused by the proportional action. Reset rate is often expressed as the number of repeats per minute because it equals the number of times the proportional correction is repeated by the integral action every minute.

Integral Controller See **Controller, Integral**.

Interface (1) Shared boundary. For example, the physical connection between two systems or two devices. (2) Generally, the point of interconnection of two components and the means by which they must exchange signals according to some hardware or software protocol.

Interoperability A marketing term with a blurred meaning. One possible definition is the ability for like devices from different manufacturers to work together in a system and be substituted one for another without loss of functionality at the host level (HART).

Intrinsic Safety When under all conditions, the available energy is limited to levels that are too low to ignite the hazardous atmosphere. This method is useful only for low-power equipment such as instrumentation, communication, and remote-control circuits.

Kinematic Viscosity (υ) Dynamic viscosity/density = $\upsilon = \mu/\rho$.

Lambda The desired closed loop time constant, often set to equal the loop lag time.

Latency Latency measures the worst-case maximum time between the start of a transaction and the completion of that transaction.

Lift The rise of the disc in a pressure relief valve.

Line Driver Inexpensive amplifier and signal converter that conditions digital signals to ensure reliable transmissions over extended distances without the use of modems.

Linearity, Independent The maximum deviation of a calibration curve from a straight line that is so positioned as to minimize that maximum deviation.

Linearity, Terminal-Based The maximum deviation of a calibration curve from a straight line, if the line is so positioned that they coincide at the upper and lower range values.

Linearity, Zero-Based The maximum deviation of a calibration curve from a straight line, if the line is so positioned that they coincide at the lower range value and to minimize the maximum deviation.

Linear Programming A mathematical technique for solving a set of linear equations and inequalities in order to maximize or minimize an additional function called an objective function.

Loop Gain Characteristics For a closed loop, it is the characteristic curve of the ratio of the change in the return signal to the change in the corresponding error signal.

Loop Transfer Function This value of a closed control loop is obtained by taking the ratio of the Laplace transform of the return signal to the Laplace transform of the corresponding error signal.

Lot Products produced by a set of similar batches, usually using the same master recipe. A collection of batches prepared using the same recipe. Typically, all batches of a lot are prepared from the same homogeneous source of raw material.

Louvers Assemblies installed on the air inlet faces of a tower to eliminate water splash-out.

Lower Explosive Limit (LEL) The lowest concentration of gas or vapor in air where, once ignition occurs, the gas or vapor will continue to burn after the source of ignition has been removed.

Lower Range-Limit See **Range-Limit, Lower**.

Low-Pass Filters Filters that are used to remove high-frequency interference or noise from low-frequency signals.

Makeup In cooling towers it is water added to replace loss by evaporation, drift, blowdown, and leakage. (Unit: percentage of circulation rate.)

Manchaster A digital signaling technique that contains a signal transition at the center of every bit cell.

Manipulated Variable The variable that is manipulated in order to reduce the controller's error and thereby to bring the controlled variable closer to set point.

Manufacturing Range A range around the specified burst pressure within which the marked or rated burst pressure must fall. Manufacturing range is not used in ISO standards.

Master Recipe A recipe for producing a batch of products using a particular set of process equipment.

Maximum Allowable Operating Pressure (MAOP) The maximum pressure expected during normal operation.

Maximum Allowable Working Pressure (MAWP) This is the maximum pressure allowed for continuous operation. As defined in the construction codes (ASME B31.3) for unfired pressure vessels, it equals the design pressure for the same design temperature. The maximum allowable working pressure depends on the type of material, its thickness, and the service conditions set as the basis for design. The vessel may not be operated above this pressure or its equivalent at any metal temperature other than that used in its design; consequently for that metal temperature, it is the highest pressure at which the primary pressure relief valve can be set to open.

Measurand The physical parameter to be measured.

Mechanical Draft Cooling Tower A tower through which air movement is effected by one or more fans. There are two general types of such towers: those that use forced draft with fans located at the air inlet and those that use induced draft with fans located at the air exhaust.

Mechanical Emissivity Enhancement Mechanically increasing the emissivity of a surface to near-blackbody conditions (using multiple reflection).

Micron Equivalent to 0.001 millimeters or 10,000 Ångstrom units. A unit used to measure wavelengths of radiant energy.

Model-Based Control (MBC) In model-based control (MBC), a process model is used to make control decisions. The controller uses this model of the process to calculate a value for the manipulated variable, which should make the controlled variable behave in the desired way. The "inverse" nomenclature arises from how the model is used. In a normal modeling approach, one specifies the process input, and the model predicts the process output response. In contrast, MBC determines the process input (manipulated variable) that will cause a desired process output response (controlled variable value) to occur. This is the model inverse.

Model Predictive Control (MPC) A model-based control technique that uses process output prediction and calculates consecutive controller moves in order to satisfy control objectives.

Modem Modulator–demodulator. Device that converts digital and analog signals. At the source, a modem converts digital signals to a form suitable for transmission over analog communication facilities. At the destination, the analog signals are returned to their digital form. Modems allow data to be transmitted over voice-grade telephone lines.

Modulation The result of a process whereby a characteristic of one wave is varied in accordance with some characteristics of another wave.

Morphology The shape and size of the particles making up the object; a direct relation exists between these structures and materials properties (ductility, strength, reactivity, etc.)

Multiple-Effect Evaporation Multiple-effect evaporations use the vapor generated in one effect as the energy source to an adjacent effect. Double- and triple-effect evaporators are the most common; however, six-effect evaporation can be found in the paper industry, where kraft liquor is concentrated, and as many as 20 effects can be found in desalinization plants.

Multiplexing A method that allows multiple logical signals to be transmitted simultaneously across a single physical channel. Compare with **Demultiplexing**.

Narrow-Band Pyrometer A radiation pyrometer that is sensitive to only a narrow segment of wavelengths within the total radiation spectrum. Optical pyrometers are one of the devices in this category.

Natural Draft Cooling Tower A cooling tower in which air movement is essentially dependent upon the difference in density between the entering air and internal air. As the heat of the water is transferred to the air passing through the tower, the warmed air tends to rise and draw in fresh air at the base of the tower.

Net Calorific Value The measurement of the actual available energy per unit volume at standard conditions, which is always less than the gross calorific value by an amount equal to the latent heat of vaporization of the water formed during combustion.

Network All of the media, connectors, and associated communication elements by which a communication system operates.

Neurons A brain cell that passes information by receiving and transmitting electrical impulses. Nodes in neural networks serve similar functions.

Neutral Zone See **Zone, Neutral**.

Newton The internationally accepted unit of force, defined as the force required to accelerate one kilogram by one m/sec^2. It equals 0.2248 pound-force or about 4 ounces.

Nodes Processing elements in neural networks.

Nominal Tonnage (Cooling) In cooling towers, one nominal ton corresponds to the transfer of 15,000 BTU/hr (4.4 kW) when water is cooled from 95 to 85°F (35 to 29.4°C) by ambient air having a wet-bulb temperature of 78°F (25.6°C) and when the water circulation rate is 3 GPM (11.3 lpm) per ton.

Nonfragmenting Disc A rupture disc design that, when burst, does not eject fragments that could interfere with the operation of downstream equipment (i.e., relief valves).

Nonincendive Equipment Equipment that in normal operations does not constitute a source of ignition. Therefore, its surface temperature shall not exceed ignition temperature of the specified gas to which it may be exposed, and there are no sliding or make-and-break contacts operating at energy levels capable of causing ignition. Used for all types of equipment in Division 2 locations. Relies on the improbability of an ignition-capable fault condition occurring simultaneously with an escape of hazardous gas.

Nonlinearity Nonlinearity is expressed as a percent of full range output (%FRO) and is determined from the maximum difference between a datum on the output vs. measurand plot and a best straight line (BSL) drawn through the data.

Normal Mode Rejection The ability of a circuit to discriminate against normal mode voltage. It can be expressed as a dimensionless ratio, as a scalar ratio, or in decibels (20 times the $\log_{10}$ of that ratio).

Normal Mode Voltage A voltage across the input terminals of a device.

Offset When in a controller the set point is fixed and in the steady state there is a deviation, it is called offset. The change in offset that results from a no-load to a full-load condition is often called “droop.”

Oil Immersion Equipment is submerged in oil to a depth sufficient to quench any sparks that may be produced. This technique is commonly used for switch-gears, but it is not utilized in connection with instruments.

On-Off Controller See **Controller, On-Off**.

Open Loop Gain The steady-state gain of a control loop when the other control loop(s) is(are) in manual. (Their control valve opening is constant.)

Operating Pressure The operating pressure of a vessel is the pressure, in pounds per square inch gauge, to which the vessel is usually subjected in service. A processing vessel is usually designed for a maximum allowable working pressure, in pounds per square inch gauge, that will provide a suitable margin above the operating pressure in order to prevent any undesirable operation of the relief device. It is suggested that this margin be approximately 10%, or 25 PSI (173 kPa), whichever is greater. Such a margin will be adequate to prevent the undesirable opening and operation of the pressure relief valve caused by minor fluctuations in the operating pressure.

Operating Pressure Margin The margin between the maximum operating pressure and the set pressure of the PRV.

Operating Pressure Ratio The ratio of the maximum operating pressure to the set pressure of the PRV.

Operating Ratio of a Rupture Disc The ratio of the maximum operating pressure to the marked burst pressure expressed as a percentage (common U.S. definition). The ratio of the maximum operating pressure to the minimum of the performance tolerance expressed as a percentage (common ISO definition).

Operation A procedure that controls the execution of a number of phases in a batch. A major programmed processing action or set of related actions, normally consisting of one or more phases.

Optical Pyrometer Also called brightness pyrometer, it uses a narrow band of radiation within the visible range (0.4 to 0.7 microns) to measure temperature by color matching and other techniques.

Optimizing Control See **Control, Optimizing**.

Overpressure The pressure increase over the set pressure of the primary relief device. When the set pressure is the same as the maximum allowable operating pressure (MAOP), the accumulation is the same as the overpressure. Pressure increase over the set pressure of the primary relieving device is overpressure. *Note*: From this definition it will be observed that when the set pressure of the first (primary) safety or relief valve is less than the maximum allowable working pressure of the vessel, the overpressure may be greater than 10% of set pressure.

Overrange Limit The maximum input that can be applied to a device without causing damage or permanent change in its performance.

Partial Pressure In a mixture of gases, the partial pressure of one component is the pressure of that component if it alone occupied the entire volume at the temperature of the mixture.

Pascal-Seconds (Pas) Internationally accepted unit of absolute (dynamic) viscosity. Pas = Newton-sec/m^2 = 10 poise = 1000 centipoise.

PDVF, Polyvinylidene Fluoride This fluorocarbon has substantially lower temperature limits than the others (250°F or 120°C) and is less inert chemically. It is dissolved by the ketones (acetone, MEK, MIBK) and attacked by benzene and high concentrations of sulfuric acid. The most insidious enemy is caustic, which causes brittleness and cracking. It has much better toughness and abrasion resistance, than the other fluorocarbons, as well as unique electrical properties ($K = 8$).

PE (Polyethylene) A low temperature insulation that is compatible with a wide range of corrosives but is attacked by most petroleum products. Generally limited to situations where fluoro- and chlorocarbons are not allowed, such as the tobacco and nuclear power industries. Max. allowable temperature is in the 180°F (80°C) area.

PEEK (Polyether Etherketone) A high-temperature, injection-molded polymer that is chemically quite inert. This material has wide chemical application. Temperature capability is high at 450 to 500°F (225 to 260°C). Avoid any liquids with "phenol" in their name. Adhesive bonding to the molded parts would be difficult.

Perceptron A transfer function used in some neural networks.

PFA (Per-Fluoro-Alkoxy) A fluorocarbon that is quite inert chemically, melts at a fairly high temperature, and is easily plastic welded. It can be used up to 550°F (290°C), but as a probe insulation it is generally limited to 350°F (175°C) due to bonding limitations with the metal rod.

Phase A set of logic steps that completes a major processing function, such as charge, mix, heat, and reaction. A batch is usually in a stable state at the end of a phase. It is the lowest level of procedural control to accomplish a process-oriented task. Phases may be further subdivided into equipment-oriented steps and transitions for executing its defined task, as described in European standard IEC 60848 (1988) for specification of sequential function charts. Normally, the phase boundaries represent points of process transition, hold, or activity. The boundaries define major milestones and possible points of safe intervention. Phases may exist either as part of a recipe procedure (recipe phase) or independently for equipment control (equipment phase); however, any constituent steps are always part of the equipment phase.

Phase Difference Sensor (PDS) A contact radar technology; unlike TDR-based systems, which measure using sub-nanosecond time intervals, PDS derives level information from the changes in phase angle.

Phase Shift Of a signal, it is a change of phase angle with transmission. Of a transfer function, it is a change of phase angle with test frequency.

Phoneme The sound of a human voice.

Photodetector Measures thermal radiation by producing an output through release of electrical changes within its body. Photodetectors are small flakes of crystalline materials, such as CdS or InSb, which respond to different portions of the spectrum, consequently showing great selectivity in the wavelengths at which they operate.

Pixel ("Picture Element") Square dot, used in machine vision and camera technology.

Plenum Air distribution ducting, chamber, or compartment.

Poise (μ) Unit of dynamic or absolute viscosity (dyne-sec/cm^2).

Poiseuille (pi) Suggested name for the new international standard unit of viscosity, the Pascal-second.

Polarography Process for monitoring the diffusion current flow between working and auxiliary electrodes as a function of applied voltage as it is systematically varied. Concentration of analyte allows for flow of the diffusion current, which is linearly dependent on the analyte concentration. Polarography can be applied using direct current, pulsed direct current, or alternating current voltage excitation wave forms. Dissolved oxygen determination is an example of an application for which polarography is used.

Potentiometry When no current is passing between electrodes. Examples: ORP, pH, selective-ion electrodes. The potential difference (at zero current) is monitored between the measuring and reference electrodes.

Potting Potting compound completely surrounding all live parts and thereby excluding the hazardous atmosphere has been proposed as a method of protection. There is no known usage except in combination with other means.

Power Factor The ratio of total true power (watts) to the apparent power total rms (root-mean-square) volt-amperes.

PP (Polypropylene) Similar to PE. Used for low cost, and where fluoro- and Chlorocarbons are excluded. Max. temperature is in the area of 200°F.

Pressure, Design The pressure that is used in the design of a device for the purpose of determining the required minimum wall thickness and other characteristics for a given maximum working pressure (MWP) at a given temperature.

Pressure, Maximum Working (MWP) The very maximum pressure that is permissible in a device under any circumstances during operation, at a specified temperature.

Pressure Relieving Device The broadest category in the area of pressure relief devices, includes rupture discs and pressure relief valves of both the simple spring-loaded type and certain pilot-operated types.

Pressure Relief Valve (PRV) A generic term that might refer to relief valves, safety valves, and pilot-operated valves. The purpose of a PRV is to automatically open and to relieve the excess system pressure by sending the process gases or fluids to a safe location when its pressure setting is reached.

Pressure, Surge It is the sum of the operating pressure plus a pressure increment that develops for a very short time while pumps are starting or valves are closing.

Primary Standard A measuring instrument calibrated at a national standard laboratory such as NIST and used to calibrate other sensors.

Procedural Control Control that sequentially directs subordinate procedural elements or basic controls to execute the steps required by its defined process-oriented task.

Procedure A user-defined set of instructions that define the strategy for making a single batch of a particular type or grade of product.

Process Cell A set of equipment required for production of one or more batches. It usually consists of one or more units. It is a grouping of equipment that comprises one or more complete trains and defines the immediate local domain for production scheduling (analogous to a work cell in discrete manufacturing).

Process Inputs Identity and quantity of raw materials and other resources required to make a batch. Other resources include energy and manpower requirements.

Process Outputs Identity and quantity of products and/or energy produced at the end of a batch.

Process Parameters Variables, such as temperature, pressure, and time, that are set points and comparison values needed for the production of a batch.

Proof A specific gravity unit used in the alcohol industry.

Proportional Band In a proportional-only controller, it is the change required in the input signal to result in a full range change in the controller's output.

Proportional Controller See **Controller, Proportional**.

Protocol Formal description of a set of rules and conventions that govern how devices on a network exchange information. In communications it is a set of conventions or rules that must be adhered to by both communicating parties to ensure that information being exchanged between two parties is received and interpreted correctly.

Prosodic Characteristics The pitch of voice; the duration and intensity of speech.

Prosody Accent and voice modulation.

Psychrometer An instrument used primarily to measure the wet-bulb temperature.

(P)TFE (Tetra-Fluoro-Ethylene) In the abbreviation, the "P" stands for "polymerized." It is the oldest, highest temperature, and most inert fluorocarbon probe insulation. Extremely difficult to adhesive bond, it is usable up to 550°F (290°C), but on probes, its temperature limit is determined by the type of bonding to the probe rod (300, 450, or 550°F). This is the most common probe insulation in the industry. Since it never melts (it disintegrates producing HF at 600 +°F), it is difficult to fabricate, is impossible to plastic-weld, and exhibits a high degree of microporosity. Can be destroyed by butadiene and styrene monomer.

Purging, Pressurization, Ventilation These processes depend upon the maintenance of a slight positive pressure of air or inert gas within an enclosure so that the hazardous atmosphere cannot enter. Relatively recent in general application, it is applicable to any size or type of equipment.

Quevenne Degrees A specific gravity unit used in the expressing the fat content of milk.

Raceway A general term for enclosed channels, conduit, and tubing designed for holding wires and cables.

Radar (Radio Detection and Ranging) A system using beamed and reflected radio-frequency energy for detecting and locating objects, measuring distance or altitude, navigating, homing, bombing, and other purposes; in detecting and ranging, the time interval between transmission of the energy and reception of the reflected energy establishes the range of an object in the beam's path.

Radio Frequency A frequency that is higher than sonic but less than infrared. The low end of the RF range is 20 kHz, and its high end is around 100,000 MHz.

Radio Frequency Interference (RFI) A phenomenon where electromagnetic waves from one source interfere with the performance of another electrical device.

Range The region in which a quantity is measured, received, or transmitted. The limits of this region are the lower and upper range-values.

Range, Cooling For a cooling tower, it is the difference between the temperatures of water inlet and outlet. For a system operating in a steady state, the range is the same as the water temperature rise through the load heat exchanger. Accordingly, the range is determined by the heat load and water flow rate, not by the size or capability of the cooling tower.

Range, Elevated Zero A range in which the zero value of the measured variable is greater than the lower range-value. Sometimes the term "suppressed range" is also used, but "elevated zero" is preferred.

Range, Suppressed-Zero A range in which the zero value of the measured variable is less than the lower range value. Sometimes the term "elevated range" is also used, but "suppressed zero range" is preferred.

Range-Value, Lower The lowest value of the measured variable less that the particular device is adjusted to measure.

Range-Value, Upper The highest value of the measured variable that the device is adjusted to measure.

Rate Control Action See **Control Action, Derivative**.

Rated Relieving Capacity It is the maximum relieving capacity of the PRV. These data are normally provided on the nameplate of the PRV. The rated relieving capacity of the PRV exceeds the required relieving capacity and is the basis for sizing the vent header system.

Ratio Controller See **Controller, Ratio**.

Ratio Pyrometer See **Two-Color Pyrometer**.

Reactance (*X*) That part of the impedance of a circuit that is caused by either capacitance or inductance or both. (Units: ohms.)

Rear Mount A technique for making long inactive sections, by mounting the probe on the end of a pipe, with its coax cable running through the pipe to the top of the tank. The coax must survive the process temperature, so it is often of high-temperature construction.

Recipe A set of procedures and formula variables that specify the production of a batch. There are four types of recipes: general, site, master, and control. A recipe is the complete set of data and operations that define the control requirements for a particular type or grade of final or intermediate product. Specifically, each recipe comprises a header, formula, procedure, and equipment requirements.

Reference Junction The thermocouple junction that is at a known or reference temperature. It is that point at which the thermocouple extension wires are connected to the lead wires or to an instrument.

Reference Junction Compensation The means by which the effect of temperature variations at the reference junction is corrected for.

Reflectance or Reflectivity (*R*) The percentage of the total radiation falling on a body that is directly reflected without entry. Reflectance is zero for a blackbody, and nearly 100% for a highly polished surface. ($R = 1 - A - T$, where A is the absorbance and T is the transmissivity.)

Regulator See **Controller, Self-Operated**.

Relative Gain (RG) The ratio of the steady-state gain of the loop with other loops in manual, divided by the steady-state gain of the loop when the other loops are in automatic.

Relative Gain Array A matrix of dimensionless gain ratios giving one RG value for each pairing of manipulated and controlled variables.

Relative Humidity The ratio of the mole fraction of moisture in a gas mixture to the mole fraction of moisture in a saturated mixture at the same temperature and pressure. Or, the ratio of the amount of moisture in a gas mixture to the amount of moisture in a saturated mixture at equal volume, temperature, and pressure.

Relative Viscosity Ratio of absolute viscosity of a fluid at any temperature to that of water at 20°C (68°F). Since water at this temperature has a μ of 1.002 cp, the relative viscosity of a fluid equals approximately its absolute viscosity in cp. Since density of water is 1, kinematic viscosity of water equals 1.002 cSt at 20°C.

Relief Valve An automatic pressure relieving device actuated by the static pressure upstream of the valve, which opens in proportion to the increase in pressure over the operating pressure. It is used primarily for liquid service.

Relieving Pressure The sum of opening pressure plus overpressure. It is the pressure, measured at the valve's inlet, at which the relieving capacity is determined.

Reopening Pressure The opening pressure when the pressure is raised as soon as practicable after the valve has reseated or closed from a previous discharge.

Repeatability For full range traverses of a number of consecutive measurements, approaching from the same direction, it is the closeness of agreement among the outputs of the sensor when measuring the same value under the same operating conditions. It is usually expressed in percent of span. A more accurate term for it would be nonrepeatability.

Reproducibility For a number of consecutive measurements, approaching from both directions, it is the closeness of agreement among the outputs of the sensor when measuring the same value under the same operating conditions over a period of time. It is usually expressed in percent of span. A more accurate term for it would be nonreproducibility.

Reset Control Action See **Control Action, Integral**.

Resistive Component AC current can be separated into two components; the portion that is in phase with the excitation voltage is the resistive component.

Resistivity (*ρ*) It is the property of a conductive material that determines how much resistance a unit cube will produce. (Units: ohm-centimeters.)

Resolution The least interval between two adjacent discrete details that can be distinguished one from the other.

Resonance A condition evidenced by large oscillatory amplitude, which results from a small amplitude periodic input, when the frequency of that input is approaching one of the natural frequencies of the system.

Response Time The time it takes for the output of a device, resulting from the application of a specified input under specified operating conditions to move from its initial value to within some specified percentage of its final steady-state value.

Reverse Acting Controller See **Controller, Reverse Acting**.

Richter Degrees A specific gravity unit used in the alcohol industry.

Riser In case of a cooling tower, it is the piping that connects the circulating water supply line from the level of the base of the tower or the supply header to the tower inlet connection.

RMS Value See **Value, RMS**.

Roentgen A unit for expressing the strength of a radiation field. In a 1-Roentgen radiation field, 2.08 billion pairs of ions are produced in a cubic centimeter of air.

Roentgen Equivalent Man (rem) A unit of allowable radiation dosage, corresponding to the amount of radiation received when exposed to 1 roentgen over any period of time.

Root Valve The first valve off the process.

Rupture Tolerance For a rupture disc it is the tolerance range on either side of the marked or rated burst pressure within which the rupture disc is expected to burst. Rupture tolerance may also be represented as a minimum–maximum pressure range. Also referred to as performance tolerance in ISO standards.

Safety Relief Valve An automatic pressure-actuated relieving device suitable for use as either a safety or relief valve.

Safety Valve An automatic pressure-relieving device actuated by the static pressure upstream of the valve and characterized by rapid and full opening or pop action. It is used for steam, gas, or vapor service.

Sand Filling All potential sources of ignition are buried in a granular solid, such as sand. The sand acts, in part, to keep the hazardous atmosphere away from the sources of ignition and, in part, as an arc quencher and flame arrester. It is used in Europe for heavy equipment. It is not used in instruments.

Saturated Solution A solution that has reached the limit of solubility.

Saturation A condition where RF current from a probe-to-ground is determined solely by the impedance of the probe insulation. Increased conductivity in the saturating medium, even to infinity, will not cause a noticeable change in that current or in the transmitter output.

Saturation Pressure The pressure of a fluid when condensation (or vaporization) takes place at a given temperature. (The temperature is the saturation temperature.)

Saybolt Furol Seconds (SFS) Time units referring to the Saybolt viscometer with a Furol capillary, which is larger than a universal capillary.

Saybolt Universal Seconds (SUS) Time units referring to the Saybolt viscometer.

Scale Factor The value of the scale divisions on an instrument. To compute the value of the measured variable, the number of scale divisions is multiplied by this scale factor.

Scaling The conversion from engineering units to fractions or percentages.

Sealing The atmosphere is excluded from potential sources of ignition by sealing them in airtight containers. This method is used for components such as relays, not for complete instruments.

Seal-Off Pressure The pressure, measured at the valve inlet after closing, at which no further liquid, steam, or gas is detected at the downstream side of the seat.

Segment The section of a network that is terminated in its characteristic impedance. Segments are linked by repeaters to form a complete network.

Self-Regulation The property of a system, which permits attainment of equilibrium after a disturbance without the intervention of a controller.

Sensitivity The ratio of the change in output to the change of the input that causes it after a steady state been reached.

Sensor An input device that provides a usable output in response to the input measurand. (A sensor is also commonly called a sensing element, primary sensor, or primary detector. The measurand is the physical parameter to be measured.)

Service Term used by NFPA-70 (NEC) to demarcate the point at which utility electrical codes published by IEEE (NESC) take over. Includes conductors and equipment that deliver electricity from utilities.

Servomechanism An automatic feedback control device in which the controlled variable is a mechanical position or some derivative of that position.

Set Point An input variable of a controller that sets the desired value of the variable that is being controlled.

Set Pressure (Opening Pressure) The pressure at which the relief valve is set to open. It is the pressure measured at the valve inlet of the PRV, at which there is a measurable lift, or at which discharge becomes continuous as determined by seeing, feeling, or hearing. In the pop-type safety valve, it is the pressure at which the valve moves more in the opening direction compared to corresponding movements at higher or lower pressures. A safety valve or a safety relief valve is not considered to be open when it is simmering at a pressure just below the popping point, even though the simmering may be audible.

Shear Viscometer Viscometer that measures viscosity of a non-Newtonian fluid at several different shear rates. Viscosity is extrapolated to zero shear rate by connecting the measured points and extending the curve to zero shear rate.

Signal, Analog A signal representing a continuously observed variable.

Signal, Digital Information represented by a set of discrete values in accordance with a prescribed law.

Signal-to-Noise Ratio The ratio of the amplitude of a signal to the amplitude of the noise. The amplitude can be a peak or an rms value, as specified.

Signum A transfer function used in some back-propagation neural networks.

Sikes Degree A specific gravity unit used in the alcohol industry.

Simmer (Warn) The condition just prior to opening at which a spring-loaded relief valve is at the point of having zero or negative forces holding the valve closed. Under these conditions, as soon as the valve disc attempts to rise, the spring constant develops enough force to close the valve again.

Single-Effect Evaporation Single-effect evaporation occurs when a dilute solution is contacted only once with a heat source to produce a concentrated solution and an essentially pure water vapor discharge.

Site Recipe A recipe that includes site-specific information, such as local language and locally available raw materials.

Slab A set of nodes.

Smart Field Device A microprocessor-based process transmitter or actuator that supports two-way communications with a host; digitizes the transducer signals; and digitally corrects its process variable values to improve system performance. The value of a smart field device lies in the quality of data it provides.

Span The difference between the upper and lower range-values.

Specific Humidity The ratio of the mass of water vapor to the mass of dry gas in a given volume.

Specific Viscosity Ratio of absolute viscosity of a fluid to that of a standard fluid, usually water, both at the same temperature.

Spectral Emissivity The ratio of emittance at a specific wavelength or very narrow band to that of a blackbody at the same temperature.

Split Ranging A configuration in which, from a single input signal, two or more signals are generated or two or more final control elements are actuated, each responding consecutively, with or without overlap, to the magnitude of the input signal.

Standard Air Dry air having a density of 0.075 lb/cu. ft. at 70°F and 29.92 in. Hg.

Start-to-Leak Pressure For a safety relief valve it is the pressure at the valve inlet at which the relieved fluid is first detected on the downstream side of the seat before normal relieving action takes place.

Steady State A variable is at steady-state condition when it is exhibiting negligible change over a long period of time.

Stiction (Static Friction) The resistance to the starting of motion. When stroking a control valve, it is the combination of sticking and slipping.

Stiffness In the case of a spring element, it is the ratio of the change in force or torque to the resulting change in deflection.

Stoke Unit of kinematic viscosity υ (cm^2/sec).

Stress Force/Area (F/A).

Subchannel In broadband terminology, a frequency-based subdivision creating a separate communications channel.

Subsidence Ratio The ratio of the peak amplitudes of two successive oscillations of the same sign, measured in reference to an ultimate steady-state value.

Superimposed Backpressure Backpressure that is present in the discharge header before the pressure relief valve starts to open. It can be constant or variable, depending on the status of the other PRVs in the system.

Suppression See **Range, Elevated-Zero**.

Suppression, Zero See **Zero Suppression**.

Surge Pressure See **Pressure, Surge**.

Switched Hub Multiport bridge joining networks into a larger network.

Systematic Error See **Error, Systematic**.

System, Linear A system is linear if its time response to several simultaneous inputs is the sum of their individual (independent) time responses.

Tapping See **Dither**.

Teflon, TFE, FEP, and PFA Most people interchange the name Teflon with TFE. This is completely incorrect, but understandable. TFE was the first fluorocarbon polymer to carry the trade name "Teflon" at E.I. DuPont. DuPont chose to use the "Teflon" trade name for a whole family of fluorocarbon resins, so FEP and PFA made by DuPont are also Teflon. To complicate the matter, other companies now manufacture TFE, FEP, and PFA, which legally cannot be called Teflon, since that name applies only to DuPont-made polymers.

Thermopile Measures thermal radiation by absorption to become hotter than its surroundings. It is a number of small thermocouples arranged like the spokes of a wheel, with the hot junction at the hub. The thermocouples are connected in series and the output is based on the difference between the hot and cold junctions.

Throughput The maximum number of transactions per second that can be communicated by the system.

Time Constant (*T*) If a first-order system is responding to a step or an impulse, T is the time required to complete 63.2% of the total rise or decay. In higher-order systems, there is a time constant for each of the first-order components of the process.

Time, Dead The time interval between the initiation of an output change or stimulus and the start of the resulting observable response.

Time Domain Reflectometry (TDR) A TDR instrument measures the electrical characteristics of wideband transmission systems, subassemblies, components, and lines by feeding in a voltage step and displaying the superimposed reflected signals on an oscilloscope equipped with a suitable time-base sweep.

Timeout Event that occurs when one network device expects to hear from another network device within a specified period of time, but does not. The resulting timeout usually results in a retransmission of information or the dissolving of the session between the two devices.

Time, Ramp Response The time interval by which an output lags an input, when both are varying at a constant rate.

Time, Settling After a stimulus to a system, the time required for the output of the system to enter and remain within a specified narrow band centered on its steady-state value. If the stimulus is a step or impulse, the band is often specified as ±2%.

Topology Physical arrangement of network nodes and media within an enterprise networking structure or the surface features of an object or "how it looks," its texture; there is a direct relation between these features and materials properties (hardness, reflectivity, etc.).

Total Emissivity The ratio of the integrated value of all spectral emittances to that of a blackbody.

Train A grouping within one process cell of units and associated lower-level equipment that is capable of making a batch of material. A train may define a single equipment path for a batch or multiple possibilities, of which one will be selected based on availability during execution of the control recipe. Multiple batches can be processed simultaneously in the same train (but different units).

Tralles Degrees A specific gravity unit used in the alcohol industry.

Transducer A device that receives information in the form of one quantity and converts it to information in the form of the same or another quantity. This general definition also applies to primary elements or transmitters. An input transducer produces an electrical output, which is representative of the input measurand. Its output is conditioned and ready for use by the receiving electronics. (The terms "input transducer" and "transducer" can be used interchangeably.)

Transfer Function A statement of influence of an element or system, in a mathematical, tabular, or graphical form. This influence can be that of an element or system on a signal or action, which is compared at input and output terminals.

Transient The behavior of a variable during transition between two steady states.

Transient Overshoot It is the maximum overshoot beyond the final steady-state value of an output, which results from a change in an input.

Transistor Three-terminal, solid state electronic device made of silicone, gallium-arsenide or germanium and used for amplification and switching in integrated circuits.

Transmittance or Transmissivity (*T*) The percentage of the total radiant energy falling on a body that passes directly through it without being absorbed. Transmittance is zero for a blackbody and nearly 100 percent for a material like glass in the visible spectrum region. ($T = 1 - A - R$, where A is the absorbance and R is the reflectance.)

Transmitter A transducer that responds to a measured variable generated by a sensor and converts it to a standardized transmission signal. This signal is a function of only the measured variable. The term "transmitter," as commonly used with industrial process control instrumentation, has a narrower definition than those of a sensor or transducer: A transmitter is a transducer that responds to a measured variable by means of a sensing element and converts it to a standardized transmission signal that is a function only of the measured variable.

Twaddell Degree A specific gravity unit used in the sugar, tanning, and acid industries.

Two-Color Pyrometer Measures temperature as a function of the radiation ratio emitted around two narrow wavelength bands. Also called ratio pyrometer.

Unit A major piece of process equipment with its associated equipment modules. Mixers, storage tanks, and reactors are examples of units. The associated equipment modules include pumps, valves, heat exchangers, and agitators that are closely associated with the major process equipment. Units operate relatively independently of one another. They are equipment that contains and performs some major processing activity or activities (e.g., react, crystallize, make solution) on one batch at a time. A unit normally comprises a major piece of equipment and directly associated control modules and/or equipment modules that are not shared with other units.

Unit Procedure A major programmed processing action or set of related actions, normally consisting of one or more operations. Unit procedures are naturally related to a distinct regime of production: for example, all processing carried out in one batch unit of a multiunit production line.

Unit Recipe A part of a recipe that defines a part of batch production requirements within a unit. It usually includes a number of operations and phases.

Upper Explosive Limit (UEL) The highest concentration of gas or vapor in air in which a flame will continue to burn after the source of ignition has been removed.

Upper Range-Limit The upper limit of the value of the measured variable that a particular instrument is capable of measuring.

Varactor Voltage-sensitive capacitor.

Variable Backpressure Backpressure that varies due to changes in operation of one or more pressure relief valves connected into a common discharge header.

Variable, Controlled See **Controlled Variable**.

Variable, Manipulated See **Manipulated Variable**.

Velocity Gradient (Shear) Rate of change of liquid velocity across the stream—V/L for linear velocity profile, dV/dL for nonlinear velocity profile. Units are $V - L$ = ft/sec/ft = sec^{-1}.

Velocity Head The velocity head is calculated as $v^2/2g$, where v is the flowing velocity and g is the gravitational acceleration (9.819 m/s^2 or 32.215 ft/s^2 at 60 degrees latitude).

Velocity Limit The limit that the rate of change of a particular variable may not exceed.

Virtual Field Device (VFD) It is used to remotely view local device data described in an object dictionary. A typical device will have at least two VFDs.

Voltage, Common Mode See **Common Mode Voltage**.

Voltage, Normal Mode See **Normal Mode Voltage**.

Water Loading In case of cooling towers it is the water flow divided by effective horizontal wetted area of the tower. (Unit: GPM/ft^2 or m^3/hr m^2.)

Wave-Guide A device that constrains or guides the propagation of electromagnetic waves along a path defined by the physical construction of the wave-guide; includes ducts, a pair of parallel wires, and a coaxial cable.

Wet-Bulb Temperature (WBT) If a thermometer bulb is covered by a wet, water-absorbing substance and is exposed to air, evaporation will cool the bulb to the wet-bulb temperature of the surrounding air. This is the temperature read by a psychrometer. If the air is saturated with water, the wet-bulb, dry-bulb, and dew-point temperatures will all be the same. Otherwise, the wet-bulb temperature is higher than the dew-point temperature but lower than the dry-bulb temperature.

White Box Modeling This type of modeling is feasible if a good understanding of the process exists. In such cases, the dynamic models are derived based on mass, energy, and momentum balances of the process.

Wide Band (Total) Pyrometer A radiation thermometer that measures the total power density emitted by the material of interest over a wide range of wavelengths.

Wobbe Index AGA 4A defines the Wobbe Index as a numerical value, which is calculated by dividing the square root of the relative density (a key flow orifice parameter) into the heat content (or BTU per std. cubic foot) of the gas. Mathematically, the Wobbe Index is defined by the equation below:

$$\text{Wobbe Index} = \frac{\text{calorific value}}{\sqrt{\text{specific gravity}}}$$

(E)Xtensible Markup Language (XML) A computer authoring language for publishing documents through the World Wide Web on the Internet. For use in automation, it is better and more flexible than hypertext markup language (HTML).

Zero Elevation When the zero of a range is elevated, the amount of its elevation is the quantity by which the zero of the measured variable exceeds the lower range-value.

Zero Suppression When the zero of a range is suppressed, the amount of the suppression is the quantity by which the zero of the measured variable is below the lower range-value.

Zone, Dead A range of input through which the output remains unchanged. This holds true if the input signal is rising or dropping.

Zone, Neutral For two-position controllers (switches), the neutral intermediate zone is the range of input values in which the previously existing output value is maintained. If the output is *A* at low inputs and *B* at high ones, on a rising input, *A* is maintained until the input reaches the value corresponding to the set point of switch *A* plus this zone, while, when the input is dropping, the switch will change its output from *B* to *A* when the input has passed through the dead zone and reached the set point of switch *A*.

SOCIETIES AND ORGANIZATIONS

AATCC	American Association of Textile Chemists and Colorists
ACC	American Chemistry Council
ACGIH	American Conference of Governmental Industrial Hygenists
ACS	American Chemical Society
AGA	American Gas Association
AIA	Automatic Imaging Association
AIChE	American Institute of Chemical Engineers
AMTEX	American Textile Partnership
ANSI	American National Standards Institute
AOCS	American Oil Chemists' Society
APHA	American Public Health Association
API	American Petroleum Institute
ARI	Air Conditioning and Refrigeration Institute
ASA	American Standards Association
ASCE	American Society of Civil Engineers
ASM	Abnormal Situation Management Consortium
ASME	American Society of Mechanical Engineers
ASRE	American Society of Refrigeration Engineers
ASTM	American Society for Testing and Materials or ASTM International
Awwa	American Water Works Association
BSI	British Standards Institution
CARB	California Air Resources Board
CCITT	Consultative Committee for International Telegraphy and Telephony
CCSDS	Consultative Committee for Space Data Systems
CDC	Centers for Disease Control (United States)
CENELEC	European Committee for Electrotechnical Standardization
CIE	Commission International del'Eclairage
CII	Construction Industry Institute
CIL	Canadian Industries Limited
CNI	ControlNet International
CPAC	Center for Process Analytical Chemistry
CSA	Canadian Standards Association
DARPA	Defense Advanced Research Projects Agency
DIERS	Design Institute for Emergency Relief Systems
DIN	Deutsche Institut für Normung (German Standards Institute)
DOD	Department of Defense (United States)
DOE	Department of Energy
DOT	Department of Transportation
EBF	European Batch Forum
ECMA	European Computer Manufacturers Association
EEMUA	Engineering Equipment and Materials Users Association
EIA	Electronic Industries Association
EIA/TIA	Electrical Industries Alliance/Telecommunications Industries Alliance
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EXERA	The Instrument Users' Association in France
FCC	Federal Communications Commission
FCI	Fluid Control Institute
FDA	Food and Drug Administration
FF	Fieldbus Foundation
FIA	Fire Insurance Association
FM	Factory Mutual
FMRC	Factory Mutual Research Corporation
FPA	Fire Protection Association
FSEC	Florida Solar Energy Center
GERG	Groupe Européen de Rechérches Gaziéres (European Gas Research Group)
GRI	Gas Research Institute
HCF	HART Communication Foundation

IAEI	International Association of Electrical Inspectors
IBEW	International Brotherhood of Electrical Workers
ICE	Institute of Civil Engineers
ICEA	Insulated Cable Engineers Association
ICTS	International Consortium of Telemetry Spectrum
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IGT	Institute of Gas Technology
INPO	Institute for Nuclear Power Operation
IPTS	International Practical Temperature Scale
IrDA or IRDA	Infrared Data Association
ISA	Instrumentation, Systems, and Automation Society
ISO	International Standards Organization
ISSEP	International Soros Science Education Program
ISTM	International Society for Testing Materials
ITA	Instrumentation Testing Association
JBF	Japanese Batch Forum
JPL	Jet Propulsion Laboratory
KEPRI	Korean Electric Power Research Institute
LCIE	Laboratoire Central des Industries Electriques
LPGA	National LP-Gas Association
MCA	Manufacturing Chemists Association
NAMUR	German standardization association for process control (Normen-Arbeitsgemeinschaft für Meß- und Regeltechnik in der Chemischen Industrie)
NASA	National Aeronautics and Space Administration
NBFU	National Board of Fire Underwriters
NBS	National Bureau of Standards
NEMA	National Electrical (Equipment) Manufacturers Association
NEPSI	National Supervision and Inspection Center for Explosion Protection and Safety Instrumentation
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute of Standards and Technology
NSC	National Safety Council
NSPA	National Spa and Pool Association
NSPE	National Society of Professional Engineers
NRC	Nuclear Regulatory Commission
ODVA	Open DeviceNet Vendor Association
OSHA	Occupational Safety and Health Administration
OTS	Office of Technical Services
PCT	Patent Cooperation Treaty
PNO	Profibus User Organization
SAE	Society of Automotive Engineers
SAMA	Scientific Apparatus Manufacturers Association
SIREP	The Instrument Users' Association in the United Kingdom
TAPPI	Technical Association of the Pulp and Paper Industry
TIA	Telecommunications Industries Alliance
TUV	Technischer überwachungs Verein (Technical Inspection Association)
UA	United Association of Journeyman and Apprentices of the Plumbing and Pipe Fitting Industry of the United States and Canada
UL	Underwriters Laboratories, Inc.
USASI	USA Standard Institute
USNRC	U.S. Nuclear Regulatory Commission
VDMA	Verband Deutscher Maschinen und Anlagenbau e.V.
WBF	World Batch Forum
WEF	Water Environment Federation
WIB	The International Instrument Users' Association
WIDO	World Intellectual Property Office

ABBREVIATIONS, NOMENCLATURE, ACRONYMS, AND SYMBOLS

NOTES

1. Whenever the abbreviated form of a unit might lead to confusion, it should not be used and the name should be written out in full.
2. The values of SI equivalents were rounded to three decimal places.
3. The words meter and liter are used in their accepted English spelling form instead of those in the standards, namely, metre and litre, respectively.

1oo1	one out of one
1oo2	one out of two
1oo2D	one out of two with diagnostics
2oo2	two out of two
2oo3	two out of three
2oo3d	two out of three with diagnostics
2D	two-dimensional
3D	three-dimensional

A

a	acceleration
A	1) area; 2) ampere, symbol for basic SI unit of electric current; also admittance
Å	Ångstrom (= 10^{-10} m)
AA	atomic absorption
AAS	atomic absorption spectrometer
abs	absolute (e.g., value)
ABS	acrylonitrile-butadiene-styrene
AC, ac, a-c	alternating current
A/C	air to close
ACFM	volumetric flow at actual conditions in cubic feet per minute (= 28.32 alpm)
ACL	asynchronous connection-less
ACM	automatic control mode
ACMH	actual cubic meter per hour
ACMM	actual cubic meter per minute
ACS	analyzer control system
ACSL	advanced continuous simulation language
A/D	analog-to-digital, also analog-to-digital converter
AD	actuation depth
ADC	analog-to-digital converter
ADIS	approved for draft international standard circulation
ADPCM	adaptive differential pulse-code modulation
AE	analyzer element
A&E	alarm and event
AES	atomic emission spectrometer
AF or a-f	audio frequency
AFC	alkaline fuel cell
AFD	adjustable frequency drive
AGA3	American Gas Association Report No. 3
AGC	automatic generation control or automatic gap control
ai	adobe illustrator
AI	analog input or artificial intelligence
AI-AT	analog input–air temperature
AI-RT	analog input–return temperature
a(k)	white noise
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
AliS	alternate lighting of surfaces
ALP	low pressure air
Alpm	actual liters per minute
ALSW	admissible load supply well
alt	altitude
AM	amplitude modulation or actual measurement or alarm management
AMC	annual maintenance contract or adaptive model controller or auto-manual cascade
AMLCD	active matrix LCD
amp	ampere; also A, *q.v.*
AMPS	advanced mobile phone system
AMS	asset management solutions or analyzer maintenance solutions
a/n	alpha numeric
ANN	artificial neural network
ANS	adaptive neural swarming

AO	analog output
A/O	air to open
AOTF	acousto-optical tunable filters
AP	access point
APC	automatic process control or advanced process control
APDU	application (layer) protocol data unit
API	application programming interface or absolute performance index
°API	API degrees of liquid density
APM	application pulse modulation
APSL	air pressure switch, low
AR	auto regressive
ARA	alarm response analysis
ARIMA	auto regressive integrated moving average
ARP	address resolution protocol
ARX	auto regressive with external inputs (model)
ARW	antireset windup
AS	adjustable speed
ASCI	autosequentially commutated current-fed inverter
ASCII	American Standard Code for Information Interchange
AS-I	actuator sensor interface
ASIC	application-specific integrated chips
ASK	amplitude shift keying
ASU	air separation unit
asym	asymmetrical; not symmetrical
AT	air temperature or analyzer transmitter
ATG	automatic tank gauging
atm	atmosphere (= 14.7 psi)
ATP	adenosine triphosphate
ATR	attenuated total reflectance
AUI	attachment unit interface
AUTRAN	automatic utility translator
aux	auxiliary
AV	auxiliary (constraint) variable
AVC	air velocity controller
AVR	automatic voltage regulator
AWG	American wire gauge

B

B	bottom product flow rate
B2B	business-to-business
°Ba	Balling degrees of liquid density
BAC	biologically activated carbon
bar	1) barometer; 2) unit of atmospheric pressure measurement (= 100 kPa)
bara	bar absolute
barg	bar gauge
bbl	barrels (= 0.1589 m^3)
BCD	binary coded decimal
BCM	backup communication module
BCS	batch control system
BD	blow down
°Bé	Baumé degrees of liquid density
BEP	best efficiency point
BFO	beat frequency oscillator
BFW	boiler feed water
Bhp, BHP	brak horsepower (= 746 W)
BIBO	bounded input, bounded output
°Bk	Barkometer degrees of liquid density
blk	black (wiring code color for AC “hot” conductor)
BMS	burner management system or boiler management system
BO	basic operation
BOD	biochemical oxygen demand
bp or b.p.	boiling point
BPCS	basic process control system
BPS or bps	bits per second
BPSK	binary phase shift keying
Bq	becquerel, symbol for derived SI unit of radioactivity, joules per kilogram, J/kg
°Br	Brix degrees of liquid density
BSL	best straight line
BSTR	batch stirred tank reactor
BTR	block transfer read
BTU	British thermal unit (= 1054 J)
BWD	backwash drain
BWG	Birmingham wire gauge
BWR	backwash return
BWS	backwash supply

C

c	1) velocity of light in vacuum (3×10^8 m/s); 2) centi, prefix meaning 0.01
C	coulombs or symbol for discharge coefficient, also capacitance
°C	Celsius degrees of temperature
ca.	*circa*: about, approximately
CAC	channel access code
CAD	computer-aided design
Cal	calorie (gram, = 4.184 J); also g-cal
CAMAC	control advance moving average
CAN	control area network or control and automation network
CAPEX	CAPital EXpenditure
CARI	combustion air requirement index
CAS	cascade
CATV	community antenna television (cable)
CBM	condition-based maintenance
CBT	computer-based timing
cc	cubic centimeter (= 10^{-6} m^3)
CC	cooling coil
CCD	charge-coupled device
CCF	common cause failure or combination capacity factor
ccm	cubic centimeter per minute
CCR	central control room
Ccs	constant current source

CCS computer control system or constant current source
CCTV closed circuit television
CCW counterclockwise
cd candela, symbol for basic SI unit of luminous intensity
CD compact disk, collision detector, compel data or dangerous coverage factor, cold deck
CDDP cellular digital packet data
CDF cumulative distribution function
CDMA code division multiple access
CDPD cellular digital packet data
CDT color detection tube
CDTP cold differential test pressure
CE Conformité Europeéne (European Conformity) applicable to electrical safety
CEHED chlorination–caustic extraction–hypochlorite bleaching–caustic extraction–chlorine dioxide
CEMS continuous emissions monitoring system
CENP combustion engineering nuclear power
CF cleanliness factor or cubic foot
CFA continuous flow analyzer
CFE cartridge filter effluent
CEM cause and effect matrix
CFM or cfm cubic foot per minute (28.32 lpm)
CFR Code of Federal Regulations
CF/Yr cubic foot per year
CHP combined heat and power
CHS chemical sludge
CHWP chilled water pump
CHWR chilled water return
CHWS chilled water supply
Ci curie (= 3.7×10^{10} Bq)
CI cast iron or corrosion inhibitor
CIM computer-integrated manufacturing
CIO channel input–output
CIP 1) computer-aided production; 2) control and information protocol (an application layer protocol supported by DeviceNet, ControlNet, and Ethernet/IP); or 3) clean in place
CJ cold junction
CL clamp on
CL1 electrically hazardous, Class 1, Division 1, Groups C or D
CLD chemiluminescence detector
CLOS common Lisp object system
CLP closed-loop potential factor
cm centimeter (= 0.01 m) or cubic meter
CM condition monitoring or communication (interface) module or control module
CMF Coriolis mass flowmeter
CMMS computerized maintenance management system
CMOS complementary metal oxide semiconductor
CMPC constrained multivariable predictive control
cmph cubic meter per hour
CMR common mode rejection
CMRR common mode rejection ratio
CMS carbon molecular sieve
CMV common-mode voltage
CNC computerized numerical control
CNI ControlNet International
Co cobalt
CO controller output or carbon monoxide or contact output
CO_2 carbon dioxide
CO_2D carbon dioxide demand
COD chemical oxygen demand
COF coefficient of haze
COM component (or compiled) object model
COND conductivity
COP coefficient of performance
cos cosine, trigonometric function
COT coil outlet temperature
COTS commercial off-the-shelf
COV coil outlet velocity
cp or c.p. 1) candle power; 2) circular pitch; 3) center of pressure (cp and ctp may also be used for centipoises)
cpm cycles per minute; counts per minute
cps 1) cycles per second (= Hz); 2) counts per second; 3) centipoises (= 0.001 Pa.S)
CPS computerized procedure system
CPU central processing unit
CPVC chlorinated polyvinyl chloride
CR corrosion rate
CRC cyclical redundancy check or cyclic redundancy code (an error detection coding technique based upon modulo-2 division; sometimes misused to refer to a block check sequence type of error detection coding)
CRDS cavity ring-down spectroscopy
CRH cold reheat
CRLF carriage return-line feed
CRT cathode ray tube
Cs cesium
CS 1) carbon steel; 2) constant speed; 3) chlorine solution
CSD crystal size distribution
CSH constant speed held
CSL car seal lock
CSMA/CD carrier sense, multiple (medium) access with collision detection
CSO car seal open
CSS central supervisory station
CSSD compatible single side band
cSt centi stoke
CSTR continuous-stirred tank reactor
CT cooling tower or the product of *C* for disinfectant concentration and *T* for time of contact in minutes

CTDMA	concurrent time domain multiple access
CTMP	chemi-thermo-mechanical pulp
CTWP	cooling tower water pump
CV	controlled variable or control valve
CVAAS	cold vapor atomic absorption spectroscopy
CVF	circular variable filters
cvs	comma-separated variables
CW	clockwise
CWA	Clean Water Act
CWR	cooling water return
CWS	cooling water supply
CWT	centralized waste treatment

D

d	1) derivative; 2) differential, as in dx/dt; 3) deci, prefix meaning 0.1; 4) depth; 5) day
D	diameter; also dia and ϕ or derivative time of a controller or distillate flow rate
DA	data access or direct action or difference in aeration
D/A	digital-to-analog
DAC	device access code or digital-to-analog converter
DACU	data acquisition and control unit
DAE	differential algebraic equation
DAMPS	digital advanced mobile phone system
DAS	data acquisition system
DB or dB	decibels
dBa	decibels with "*A*" weighing to approximate the human ear
DBB	double-block and bleed
DBPSK	differential binary phase shift keying
DC or dc	direct current
DC	diagnostic coverage
DCAC	direct contact after cooler
DCE	data communications equipment
DCOM	distributed COM
DCS	distributed control system
DD	data definition or device description
D/DBP	disinfectants/disinfection byproducts
DDC	direct digital control
DDE	dynamic data exchange
DDL	device description language (an object-oriented data modeling language currently supported by PROFIBUS, FF, and HART)
DEDED	chlorine dioxide treatment–caustic extraction–chlorine dioxide treatment–caustic extraction–chlorine dioxide treatment
deg	degree; also ° (π/180 rad)
DEMUX	demultiplexer
Deoxo	deoxidation unit
DES	data encryption standard
DF	direction of flow
DFIR	diffused infrared
DFR	digital fiber-optic refractometer
DFT	digital (or discrete) Fourier transforms
DG	directed graph
DH	data highway
DH+	data highway plus (high-speed peer-to-peer link)
DHCP	dynamic host configuration protocol
DI	discrete (digital) input
dia	diameter; also *D* and ϕ
DIAC	dedicated inquiry access code
DIR	diffused infrared
DIS	draft international standard
DIX	Digital-Intel-Xerox (DIX is the original specification that created the de facto Ethernet standard; IEEE 802.3 came later, after Ethernet was established)
d(k)	unmeasured disturbance
D(k)	measured disturbance
DLE	data link escape
DLL	dynamic link library
DLPD	digital light processor display
Dm or dm	decimeter
DM	delta modulation
DMA	dynamic mechanical analyzer or direct memory access
DMC	dynamic matrix control(ler)
DMFC	direct methanol conversion fuel cell
DMM	digital multi-meter
DN	diameter nominal, the internal diameter of a pipe in rounded millimeters
DO	dissolved oxygen or discrete (digital) output
DOAS	differential optical absorption spectroscopy
d/p cell	differential pressure transmitter (a Foxboro trademark)
DP	decentralized peripheral
DPC	damper position controller
DPCM	differential pulse code modulation
DPD	*N*,*N*-Diethyl-*p*-phenylenediamine
DPDT	double pole double throw (switch)
dpi	dots per inch
DPS	differential pressure switch
DQPSK	differential quadrature phase shift keying
DR	decay ratio
DSB	double side band
DSL	digital subscriber line
DSN	distributed sensor network
DSP	digital signal processing
DSR	direct screen reference
DSSS	direct sequence spread spectrum
DST	dirty service trim
DSTM	dual-scan twisted nematic
DT or dt	dead time (second or minutes) or delay time
DTB	draft tube baffle
DTC	digital temperature compensation or dead time compensator
DTD	document type definition
DTE	data terminal equipment
DTGS	deuterated tryglycine sulfate

DTL	diode-transistor logic
DTM	device type manager (an active-X component for configuring an industrial network component; a DTM "plugs into" an FDT)
DU	dangerous component failure occurred in leg but is undetected
DV	disturbance variable
DVC	digital valve control or discrete valve coupler
DVM	digital voltmeter
DWS	dewatered sludge

E

e	1) error; 2) base of natural (Naperian) logarithm; 3) exponential function; also exp (–*x*) as in e^{-x}
E	1) electric potential in volts; 2) scientific notation as in $1.5E-03 = 1.5 \times 10^{-3}$; 3) tray efficiency in distillation
E{.}	expected value operator
E&I	electrical and instrumentation
EA	evolutionary algorithm or exhaust air
EAD	exhaust air damper
EAF	exhaust air fan
EAI	enterprise application integration
EAM	enterprise asset management
EAPROM	erasable alterable programmable read-only memory
EBCDIC	extended binary code for information interchange
EBR	electronic batch records
ECD	electron capture detector
ECG	electrocardiogram
ECKO	eddy-current killed oscillator
ECLiPS	English control language programming software
ECN	effective carbon number
ECTFE	ethylene chloro-tetra-fluoro-ethylene (Halar)
ED	explosive decompression
EDD	electronic device description
EDS	electronic data sheet (DeviceNet)
EDTA	ethylenediaminetetraacetic acid
EDXRF	energy dispersive x-ray fluorescence
E/E/PE	electrical/electronic/programmable electronic
E/E/PES	electrical/electronic/programmable electronic system
EEPROM	electrically erasable programmable read only memory
EFB	external feedback
EFD	engineering flow diagram
EFRVD	expected flow rate value through dryer
e.g.	*exempli gratia*: for example
EHC	electro-hydraulic control or extended horizon adaptive controller
EHM	equipment health management
e(k)	feedback error
E.L.	elastic limit or enthalpy logic
ELD	electroluminescent display
Em	minimum error
EM	equipment module
Emf or EMF	1) electromotive force (volts); 2) electromotive potential (volts)
EMI	electro-magnetic interference
EMI/RFI	electromagnetic and radio frequency interference
em(k)	process/model error
EN	European standard
ENB	Ethernet card
EP	evolutionary programming or equipment phase
EPA	enhanced performance architecture
EPC	engineering-procurement-construction (firm or industry)
EPCM	engineering, procurement, and construction management (companies)
EPDM	ethylene propylene diene terpolymer
EPROM	erasable programmable read only memory
EPS	electronic pressure scanner, encapsulated postscript file, emergency power supply, or expanded polystyrene
EPSAC	extended prediction self-adaptive controller
EQ or eq	equation
ER	external reset
ERM	enterprise resource manufacturing
ERP	enterprise resource planning or effective radiated power
ERW	electric-resistance-welded
ES	evolutionary strategy
ESD	emergency shutdown (system)
ESN	electronic serial number
ESP	environmental simulation program
ETFE	ethylene-tetrafluoroethylene copolymer (Tefzel)
ETM	elapsed time meter
ETMI	expected total mass input
ETMP	expected total mass produced
ETS	equivalent time sampling
EU	engineering unit
EVOP	evolutionary operation or evolutionary optimum
EWMA	exponentially weighed moving average
Exp	exponential function as in exp (– at) = e^{-at}; also *e*

F

F	frequency; also freq or filter, also farad, symbol for derived SI unit of capacitance, ampere · second per volt, A · s/V, also feed flow rate
°F	Fahrenheit degrees [t°C = (t°F – 32)/1.8]
FAH	flow alarm, high

FAL	flow alarm, low
FAN	fuzzy, analytical intelligence, neural network
FARM	frame acceptance and reporting mechanism
FAT	factory acceptance testing
FB	friction bound
FBAP	function block application process (FF)
FBD	function block diagram
FBG	fiber bragg grating
FBT	fire box temperature
FC	1) flow controller; 2) fail closed; 3) forced circulation; 4) fire command panel
FCC	fluid catalytic cracking unit
FCCU	fluidized catalytic cracking unit
FCOR	filtering and correlation (method)
FCS	frame check sequence or field control system
FCV	flow control valve
FD	forced draft
FDE	fault disconnection electronics
FDL	fieldbus data link
FDM	frequency division multiplexing
FDMA	frequency division multiple access
FDS	flame detection system or fines density sensor
FDT	field device tool (a MS Windows-based framework for engineering and for configuration tools)
FE	1) final element; 2) flow element; 3) filter effluent
FED	field emission display
FEED	front end engineering and design
FEGT	furnace exit gas temperature
FEP	fluorinated ethylene propylene
FES	fixed end system
FF	1) Foundation Fieldbus; 2) feedforward
FF-HSE	Foundation Fieldbus, high-speed Ethernet
FFIC	flow ratio controller
FFT	fast Fourier transform
FGB	fiber bragg grating
FGD	flue gas desulfurization
FGR	flue gas recirculation
FH	frequency hopping
Fhp	fractional horsepower (e.g., $^1/_4$ HP motor)
FHSS	frequency hopped spread spectrum
FI	1) flow indicator; 2) fail intermediate; 3) filter influent
FIA	flow injection analyzer
FIC	flow indicator controller
FID	flame ionization detector
FIE	flame ionization element
FIFO	first-in, first-out
Fig. or FIG.	figure
FIR	finite impulse response (model)
FISCO	Fieldbus Intrinsic Safety COncept
fl.	fluid
FL	fail last (position)
fl. oz.	fluid ounces (= 29.57 cc)
FM	frequency modulated or Factory Mutual
FMAX	maximum feed availability
FMCW	frequency-modulated carrier wave
FMEA	failure mode and effects analysis
FMEDA	failure modes, effects, and diagnostic analysis
FMS	1) fieldbus message specification; 2) fieldbus messaging services/system
FNC	function byte
FO	1) fiber optic; 2) fail open
FOP	fiber optic probe
FOPDT	first order plus dead time
FOSS	first order system series
FOV	field of view
fp or f.p.	freezing point
FPC	fine particle content
FPD	flame photometric detector
FPGA	field programmable gate arrays
FPM or fpm	feet per minute (= 0.3048 m/m)
fps or ft/s	feet per second (= 0.3048 m/s)
FRC	flow recording controller
FRM	frequency response method
FRO	full range output
FS or fs	full scale or flow switch or full stroke
FSA	fault state active
FSC	fail safe controller
FSH	flow switch, high
FSHL	flow switch, high-low
FSK	frequency shift keying
FSL	flow switch, low
FSNL	full speed no load
FSPF	first stage permeate flow
FST	full stroke testing
FT	Fourier transfer or flow transmitter
FTA	fault tree analysis
FTC	fail to close
FTIR	Fourier transform infrared
FTL	fuzzy technology language
FTNIR	Fourier near infrared
FTO	fail to open
FTP	file transfer protocol
FTS	fault tolerant system
FTU	formazin turbidity unit
FW	finished water

G

g	acceleration due to gravity (= 9.806 m/s^2) or conductivity
G	giga, prefix meaning 10^9 or process gain or conductance
GA	genetic algorithm
gal.	gallon (= 3.785 liters)
GB	gigabyte, 1,000,000,000 bytes
GbE	gigabit Ethernet
Gbps or GBPS	gigabits per second
G_c	feedback controller transfer function
GC	gas chromatograph

g-cal	gramcalorie, *q.v.*; also cal
GD	group of dryers
G_d	unmeasured disturbance transfer function
G_D	measured disturbance transfer function
G_{D}	approximate feedforward transfer function model
GEOS	geosynchronous Earth orbit satellites
GFC	gas filter correlation
G_{ff}	feedforward controller transfer function
GHz	giga-Hertz
GI	galvanized iron
GIAC	general inquiry access code
GLR	gas-to-liquid ratio
G-M	Geiger–Mueller tube, for radiation monitoring
G_m	model transfer function
GMC	generic model control
GMR	giant magneto resistive
GMV	generalized minimum variance
GOSUB	go to subroutine
GOX	gaseous oxygen
GP	genetic programming
G_p	process transfer function or process gain
GPa	giga-Pascal (10^9 Pa)
GPC	generalized predictive control
GPCP	general process control programming
GPH or gph	gallons per hour (= 3.785 lph)
GPC	generalized predictive controller
GPM or gpm	gallons per minute (= 3.785 lpm)
GPS	global positioning satellite
gr	gram
grn	green (wiring code color for grounded conductor)
GSC	gas-solid chromatography
GSD	Profibus version of an electronic data sheet
GT	gas turbine
GTG	gas turbine generator
GTO	gate-turn-off thyristor
GUI	graphical user interface
GWR	guided wave radar
Gy	gray, symbol for derived SI unit of absorbed dose, joules per kilogram, J/kg

H

h	1) height; 2) hour; 3) suffix indicating heavy key component; 4) hour
H	1) humidity expressed as pounds of moisture per pound of dry air; 2) henry, symbol of derived SI unit of inductance, volt · second per ampere, V · s/A; 3) high; 4) humidifier
H1	field-level fieldbus, also refers to the 31.25 Kbps instrinsically safe SP-50, IEC61158-2 physical layer
HAD	holographic autostereoscopic display or historical data access
HART	highway addressable remote transducer
HAZOP	HAZard and OPerability studies
HC	horizontal cross-connect or heating coil
HCN	hydrogen cyanide
HD	hot deck
HEC	header error check
HF	hydrogen fluoride or hydrofluoric acid
HFE	human factors engineering
HFT	hardware fault tolerance
HGBP	hot gas bypass
HGC	hydraulic gap control
hh	suffix indicating heavier key component
HH	high-high
hhv	higher heating value
HIC	hand indicating controller
HIPPS	high-integrity pressure protection system
HIPS	high-integrity protection systems
HIS	human interface station
HIST	host interface system test
HK	heavy key
HLL	high-level logic
HLLS	high-low limit switch
HMI	human–machine interface
HMP	hexametaphosphate
HMSD	hexamethyldisiloxane
hor.	horizontal
HP or hp	horsepower (U.S. equivalent is 746 W) or high pressure
HPBF	high performance butterfly valves
HPD	hybrid passive display
HPLC	high pressure (or precision) liquid chromatography
hr	hour
H&RA	hazard & risk analysis
HRH	hot reheat
HRL	hysteresis, repeatability and linearity
HRSG	heat recovery steam generator
HS	hand switch or hot standby
HSE	high-speed Ethernet (host-level fieldbus)
HSF	hydrofluosilic acid
his	human system interface
HTG	hydrostatic tank gauging
HTML	hyper text markup language
HTTP	hyper text transfer protocol
HV	high voltage
HVAC	heating, ventilation, and air conditioning
H/W	hardware
HWD	height, width, depth
HWP	hot water pump
HWS	hot water supply
Hz	Hertz, symbol for derived SI unit of frequency, one per second (l/s)

I

I	integral time of a controller in units of time/repeat
IA	instrument air or impedance amplifier

IAC	inquiry access code
IAE	integral of absolute error
IAQ	indoor air quality
ibid	in the same place
IC	integrated circuitry, intermediate cross-connect, initial condition, or inorganic carbon
I&C	instrumentation and control or information and control
ICA	independent computing architecture
ICCMS	inadequate core cooling monitoring system
ICMP	Internet control message protocol
ICP	inductively coupled plazma
ID	inside diameter or induced draft
IDCOM	identification command
i.e.	*id est*: that is
IE	integral error
I&E	instrument and electrical
IEC	interactive evolutionary computation
IEH	Instrument Engineers' Handbook
IETF	Internet engineering task force
IF	intermediate frequency
IFS	initiate fault state
IGBT	insulated gate bipolar transistor
IGV	inlet guide vane
IIS	Internet information server
IL	instruction list
ILD	instrument loop diagrams
IMC	internal model control or injection cycle
iMEMS	integrated micro-electro-mechanical system
IN	insertion
in.	inch (= 25.4 mm)
IrGaAs	iridium gallium arsenide
in-lb	inch-pound (= 0.113 N × m)
I/O	input/output
IP	Internet protocol or ionization potential or intermediate pressure
I-P	current-to-pressure conversion
IPA	isopropyl alcohol
IPL	independent protection layer
IPS	in-plane switching
IPTS	international practical temperature scale
IR	infrared
IRQ	interrupt request queue
IS	intermediate system or intrinsic safety
ISAB	ionic strength adjustment buffer
ISE	integral of squared error or ion selective electrode
ISFET	ion-selective field effect transistor
ISM	industrial, scientific, medical
ISP	Internet service provider or interoperable system provider
IT	information technology (as in IT manager or IT department) or current transmitter
ITAE	integral of absolute error multiplied by time
ITD	indium tin oxide
ITSE	integral of squared error multiplied by time
ITT	intelligent temperature transmitters
IWF	initial weighing factor
IXC	intereXchange carrier

J

J	joule, symbol for derived SI unit of energy, heat or work, newton-meter, N · m
JB	junction box
JIT	just-in-time manufacturing
JSR	jump to subroutine
JT	Joule Thomson
JTU	Jackson turbidity unit

K

k	kilo, prefix meaning 1000
K	coefficient, also dielectric constant or process gain
°K or K	degrees Kelvin, symbol for SI unit of temperature or process gain (dimensionless)
Kbs, Kbps	kilo bits per second
KBs	kilo bytes per second
k-cal	kilogram-calories (= 4184 J)
kg	kilogram, symbol for basic SI unit of mass
kg-m	kilogram-meter (torque, = 7.233 foot-pounds)
KHP	potassium acid phthalate
kip	thousand pounds (= 453.6 kg)
kJ	kiloJoule
km	kilometer
KOH	potassium hydroxide
K_p	proportional gain of a PID controller
kPa	kilo-Pascals
K_u	ultimate controller gain
kVA	kilovolt-amperes
KVSP	Kalrez valve stem packing
kW	kilowatts
KWD	kilowatt demand
kWh	kilowatt-hours (= 3.6×10^6 J)
KWIC	Kilowatt indicating controller

L

l	suffix indicating light key component
L	1) liter (= 0.001 m^3 = 0.2642 gallon), 2) length; 3) inductance, expressed in henrys; 4) low; 5) reflux flow rate
L2F	laser two-focus anemometer
Lab	CIE functions for lightness, red/green, blue/yellow
LACM	local automatic control mode
LAG	liquid argon
LAN	local area network
LAS	link active scheduler (FF)
Lat	latitude

Lb or lb	pound (= 0.4535 kg)
lbf	pound force
lbm	pound mass
LC	level controller or liquid chromatography
LCD	liquid crystal display
Lch	CIE functions for lightness, chroma, hue
LCI	load commutated inverter
LCM	life cycle management
LCSR	loop current step response
LCV	level control valve
LD	ladder diaphragm or load
LDA	laser Doppler anemometer
LDAD	load distribution algorithm (dryers)
LDAW	load distribution algorithm (wells)
LDP	large display panel
LEC	local exchange carrier or lower explosive limit
LED	light emitting diode
LEL	lower explosive limit
LEO	low Earth orbit satellites
LEPD	light emitting polymer display
LF	linear feet
L/F	reflux-to-feed ratio
LFL	lower flammable limit
LGR	liquid-to-gas ratio
LI	level indicator
LIC	level indicator controller
LIDAR	laser induced doppler absorption radar or light detection and ranging
LIFO	last-in first-out
lim. or lim	limit
lin.	linear
LIN	liquid nitrogen
liq.	liquid
LK	light key
ll	suffix indicating lighter key component
L/L	lead-lag
LL	leased lines or low-low
LLC	logical link control
LLK	lighter than light key
LLOI	low-level operator interface
lm	lumen, symbol for derived SI unit of luminous flux, candela.steradian, cd.sr
ln	Naperian (natural) logarithm to base e
LNG	liquified natural gas
LO	lock open or local override
LOC	limiting oxygen concentration
log or $\log_{10}$	logarithm to base 10; common logarithm
LOI	local operation interface
long.	longitude
LOPA	layers of protection analysis
LOR	local-off-remote
LOS	line of sight
LOX	liquid oxygen
LP	1) liquified petroleum; 2) linear programming; 3) low pressure
LPC	1) large particle content; 2) line predictive coding
LPG	1) liquified petroleum gas; 2) liquified propane gas
lph	liters per hour (0.2642 gph)
lpm	liters per minute (0.2642 gpm)
LPR	linear polarization resistance
LPV	linear parameter varying
LQG	linear quadratic Gaussian
LRC	1) longitudinal redundancy check; 2) level recording controller
LRL	lower range limit
LRV	lower range value
LS	1) level switch; 2) lime slurry
LSB	least significant bit
LSI	large-scale integrator
LSL	lower specification limit
LTI	linear time-invariant
LV	low voltage
LVDT	linear variable differential transformer
LVN	limiting viscosity number
lx	lux, symbol for derived SI unit of illumination, lumen per square meter, lm/m^2

M

m	1) meter, symbol for basic SI unit of length; 2) milli, prefix meaning 10^{-3}; 3) minute (temporal); also min
M	1) thousand (in commerce only); Mach number; 2) molecular weight; 3) mole; 4) mega, prefix meaning 10^6
mA or ma	milliamperes (= 0.001 A)
MAC	medium access control or model algorithm control or main air compressor
MACID	medium access control identifier
MAE	minimum absolute error
MAOP	maximum allowable operating pressure
MAP	manufacturing automation (access) protocol
MAU	media access unit
MAWP	maximum allowable working pressure
Max	maximum
MB	megabyte, 1,000,000 bytes or megabits
MBC	model-based control
MBPC	model-based predictive control
MBPS, mbps, Mbps, Mbs, MBs	megabits per second
MC	main cross-connect
MCFC	molten carbonate fuel cell
mCi or mC	millicuries (= 0.001 Ci)
m.c.p.	mean candle power
MCP	main control panel or manual control mode
MCR	master control relay
MCT	mercury cadmium telluride or minimum cycle time

MDBS	mobile data base station
MDIS	mobile data intermediate system
MDPH	maximum pressure difference (header towell)
m/e	mass-to-energy ratio
med.	medium or median
MEDS	medium Earth orbit satellites
MEMS	micro electro mechanical structures
m.e.p.	mean effective pressure
MES	manufacturing execution system, management execution system, or mobile end station
MeV	mega-electron volt
MF	micro filtration
MFAC	model free adaptive control
MFC	model free control or microbiological fuel cell
MFD	mechanical flow diagram
MFE	magnetic flux exclusion
mfg	manufacturer or manufacturing
MFI	melt flow index or melt factor index
MFR	manual flow rate
mg	milligrams (= 0.001 gr)
MGD	million gallons per day
mg/l	milligrams per liter
mho	outdated unit of conductance, replaced by Siemens (*S*), *q.v.*
MHz	megahertz
mi	miles (= 1.609 km)
MI	melt index
MIB	management information base
micro	prefix = 10^{-9}; also μ (mu) or µm and sometimes u, as in ug or µg, both meaning microgram (= 10^{-9} kg)
micron	micrometer (= 10^{-6} m)
MIE	minimum ignition energy
MIMO	multiple-input multiple-output
MIMOSA	machinery information management open system alliance
min	1) minutes (temporal); also m; 2) minimum, 3) mobile identification number
MIR	multiple internal reflection
MIS	management information system
ml	milliliters (= 0.001 l = 1 cc)
MLR	multiple linear regression
mm	millimeters (= 0.001 m) or millimicron (= 10^{-9} m)
MMAC	multiple model adaptive control
mmf	magnetomotive force in amperes
MMI	man–machine interface
mmpy	millimeters per year
MMS	machine monitoring system or manufacturing message specification
MMSCFD	million standard cubic feet per day
MMV	manually manipulated variable
MOC	management of change
MODBUS	a control network
MODEM	modulator/demodulator
MOEA	multiobjective evolutionary algorithm
MOGA	multiobjective genetic algorithm
MOGP	multiobjective genetic programming
mol	mole, symbol for basic SI unit for amount of substance
mol.	molecules
MOON	M out of N voting system
MON	motor octane number
MOS	metal oxide semiconductor
MOSFET	metallic oxide semiconductor field-effect transistor
MOV	metal oxide varistor or motor-operated valve or most open valve
MOVC	most open valve control
mp or m.p.	melting point
MP	medium pressure
MPa	mega Pascal (10^6 Pa)
MPC	model predictive control
MPEC	mathematical problem with equilibrium constraints
MPFM	multiphase flowmeter
mph or MPH	miles per hour (1.609 km/h)
MPHC	model predictive heuristic controller
MPM or mpm	meters per minute
mps or m/s	meters per second
MPS	manufacturing periodic/aperiodic services
Mpy	mills per year
mR or mr	milliroentgens (= 0.001 R)
MRAC	model reference adaptive control
mrd	millirads (= 0.001 rd)
mrem	milliroentgen-equivalent-man
MRP	material requirement planning or manufacturing resource planning or material/product planning
ms	milliseconds (= 0.001 s)
MS	mass spectrometer or Microsoft
MSA	metropolitan statistical areas
MSB	most significant bit
MSC	monitoring and sequential control
MSD	most significant digit
MSDS	material safety data sheet
MT	measurement test
MTBE	methyl tertiary butyl ether
MTBF	mean time between failures
MTSO	mobile telephone switching offices
MTTF	mean time to fail
MTTFD	mean time to fail dangerously
MTTFS	mean time to spurious failure
MTTR	mean time to repair
MTU	master terminal unit
MUX	multiplexer
MV	minimum variance or manipulated variable
MVA	multiple-domain vertical alignment
MVC	minimum variance controller or multivariable control

MW	megawatts (= 10^6 W)
MWC	municipal waste combustors
MWD	molecular weight distribution

N

n	1) nano, prefix meaning 10^6; 2) refractive index; 3) number of trays
N	newton, symbol for derived SI unit of force, kilogram-meter per second squared, $kg \cdot m/s^2$
N_0	Avogadro's number (= 6.023×10^{23} mol^{-1})
N-16	nitrogen-16
NA	numeric aperture
NAAQS	National Ambient Air Quality Standards
NAP	network access port/point
NARMAX	nonlinear autoregressive w/exogenous moving average input nodes
NARX	nonlinear autoregressive w/exogenous input nodes
NAT	network address translation
NB	nominal bore, internal diameter of a pipe in inches
NBJ	nonlinear Box-Jenkins
NC or N/C	normally closed (switch contact)
NC	numeric controller
NCAP	networking capable application processors
NDIR	nondispersive infrared
NDM	normal disconnect mode
NDT	nondestructive testing
NEC	National Electrical Code
NESC	National Electrical Safety Code
NEXT	near end cross-talk
nF	nano filtration
NFI	near field imaging
NFIR	nonlinear finite impulse response
NIC	network interface card
NIP	normal incident pyrheliometer
NIR	near infrared
Nm or nm	nanometer (10^{-9} meter)
NMR	nuclear magnetic resonance
NMV	normal mode voltage
NO or N/O	normally open (switch contact)
NOE	nonlinear output error
NPN	transistor with base of p-type and emitter and collector of n-type material
NPS	nominal pipe size, the internal diameter of a pipe in inches
NPSH	net positive discharge head
NPSHA	net positive discharge head available
NPSHR	net positive discharge head required
NPT	network time protocol
NR	narrow range
NRM	normal response mode
NRZ	nonreturn to zero (NZR refers to a digital signaling technique)
NS	nominal pipe size, the internal diameter of a pipe in inches
NTC	negative temperature coefficient
NTP	network time protocol or normal temperature and pressure, corresponding to 1 atm. absolute (14.7 psia) and 0°C (32°F)
NTSC	national television standards code
NTU	nephalometric turbidity unit
NUT	network update time

O

OA	operational amplifier or outside air
OAC	operator automatic control
OAD	outside air damper
OCD	orifice-capillary detector
OD	outside diameter or oxygen demand
ODBC	open database connectivity or communication
OEM	original equipment manufacturer
OES	optical emission spectrometer
oft or OFT	optical fiber thermometry
ohm	unit of electrical resistance; also Ω (omega)
OI	operator interface
OI-F	operator interface for filtering
OI-P	plant operator interface
OIU	operator interface unit
OJT	on-the-job training
OL	overload
OLE	object linking and embedding
OLED	organic LED
OLE_DB	object linking and embedding data base
OMAC	open modular architecture controls
OMMS	optical micrometer for micro-machine
ON	octane number
OP	output or operating point
OPAM	online plant asset management
OPC	object link embedding (OLE) for process control
OPEX	OPerational EXpenditure
OP-FRIR	open path Fourier-transform infrared
OP-HC	open path hydrocarbon
OP-TDLAS	open path tunable diode-laser absorption spectroscopy
OP-UV	open path ultraviolet
Or	orange (typical wiring code color)
OREDA	Offshore Reliability Data Handbook
ORP	oxidation-reduction potential
OS	operator station or operating system
OSFP	open shortest path first
OSI	open system interconnection (model)
OSI/RM	open system interconnect/reference model
OT	operator terminal or open tubular
OTDR	optical time domain reflectometer
OTSG	once-through steam generator
oz	ounce (= 0.0283 kg)
OZ	ozone

OZA ozonated air
OZW ozonated water

P

p 1) pressure; 2) pico, prefix meaning 10^{-12}, also resistivity
P&ID piping and instrumentation diagram
Pa pascal, symbol for derived SI unit of stress and pressure, newtons per square meter, N/m^2
PA plant air, phase angle, or pole assignment
PAC path average concentration or process automation controllers
PAFC phosphoric acid fuel cell
PAH pressure alarm, high
PAL phase alternating line or pressure alarm, low
PAM pulse amplitude modulation
PAN personal area network
Pas Pascal-second, a viscosity unit
PAS process automation system (successor to DCS) or project application specification
PB proportional band of a controller in % (100%/controller gain) or push button
PC personal computer (MS-Windows based) or pressure controller
PCA principal component analysis
PCB printed circuit board
PCC pressure correction control
PCCH pressure correction control mode
PCCS personal computer control system
PCDD polychlorinated dibenzo-*p*-dioxin
PCDF polychlorinated dibenzo furans
PCL peer communication link
PCM pulse code modulation
PCR principal component regression
PCS process control system or personal communication services
pct percent; also %
PCT Patent Cooperation Treaty
PCTFE polychlorotrifluoroethylene
PCV pressure control valve
PD positive displacement or proportional and derivative or percentage detected or position detector
PDA personal digital assistant or photodiode array
PDD pulsed discharge detector
PDF probability density function, probability of failure or portable document file
PDIC pressure differential indicating controller
PDLCP partial differential linear complementary problem
PdM predictive maintenance
PDM pulse duration modulation
PDP plasma display panel
PDS phase difference sensor
PDU protocol data unit
PDVF polyvinylidene fluoride
PE polyethylene or penalty on error or pressure element
PED pressure equipment directive
PEEK poly ether ether ketone
PEL permissible exposure level
PEMFC proton exchange membrane fuel cell or polymer electrolyte membrane fuel cell
PES programmable electronic system
Pf picofarad (= 10^{-12} F)
PF or p.f. power factor
PFA per-fluoro-alkoxy copolymer (a form of Teflon)
PFC procedure functional chart or procedure function chart
PFD process flow diagram or probability of failure on demand
PFDavg average probability of failure on demand
PFPD pulsed flame photometric detector
PGC process gas chromatograph
PGNAA prompt gamma neutron activation analysis
pH acidity or alkalinity index (logarithm of hydrogen ion concentration)
PHA process hazard analysis
pi or pl Poiseuille, a viscosity unit
PI proportional and integral or pressure indicator
P/I pneumatic-to-current (conversion)
P&I piping and instrument (diagram)
PIC pressure indicating controller or path integrated concentration
PID proportional, integral, and derivative (control modes in a classic controller) or photoionization detector
P&ID piping (process) and instrumentation diagram (drawing)
PI-MDC path integrated minimum detectable concentration
PIMS process information management system
PIO program input–output
PIP process industry practices
PIR precision infrared radiometer
PL preload
PLC programmable logic controller
PLD programmable logic devices
PLED polymeric LED
PLL phase locked loop
PLS physical layer signaling or partial least squares
PM photo multiplier or penalty on moves or phase modulation
PMA physical medium attachment
PMBC process model based control
PMD photomultiplier detector
PMF probability mass function

PMLCD	passive matrix LCD
PMMC	permanent magnet moving coil
PMS	plant monitoring system
PMT	photo-multiplier tube or photometer tube
PN	pressure, nominal
PNP	transistor with base of n-type and emitter and collector of p-type material
PO	polymer
POF	positive opening feature
POL	problem oriented language
POPRV	pilot operated pressure relief valve
POTW	publicly owned treatment works
PP	polypropylene or pole placement
ppb or PPB	parts per billion
PPC	process procedure chart
PPD	pounds per day
ppm or PPM	parts per million or pulse position modulation
ppmV	volumetric parts per million
PPP	point-to-point protocol
ppt	parts per trillion
PRBS	pseudo random binary sequence
PRC	pressure recording controller or production cycle
PRD	pressure relief device
Precip	precipitate or precipitated
PRV	pressure relief valve or pressure reducing valve
PS	power supply (module) or pressure switch or partial stroke
PSA	pressure swing adsorption
PSAT	pre-startup acceptance test
PSD	power spectral density or photosensitive device
PSE	pressure scale effect
PSG	phosphosilicate glass
PSH	pressure switch, high
PSI	pre-startup inspection
psi or PSI	pounds per square inch (= 6.894 kPa)
PSIA or psia	absolute pressure in pounds per square inch
PSID or psid	differential pressure in pounds per square inch
PSIG or psig	above atmospheric (gauge) pressure in pounds per square inch
PSK	phase shift keying
PSL	pressure switch, low
PSM	process safety management
PSS	programmable safety system
PSSR	pre-startup safety review
PST	partial stroke testing
PSTN	public switched telephone network
PSU	post-startup
PSV	pressure safety valve
pt	point or part or pint (= 0.4732 liter)
PT	pressure transmitter
PTB	Physikalisch-Technische Bundesanstalt
PTC	positive temperature coefficient or programmable telemetry controller
PTFE	polytetrafluoroethylene (conventional Teflon)
PU	per unit
PUVF	pulsed ultraviolet fluorescence
PV	process variable (measurement) or the HART primary variable
PVC	polyvinyl chloride
PVDF	polyvinylidene fluoride
PVHI	process variable high (reading or measurement)
PVLO	process variable low (reading or measurement)
PW	private wire
PWM	pulse width modulation
PWR	pressurized water reactor
PZT	lead-zirconate-titanate ceramic

Q

q	1) rate of flow; 2) electric charge in coulombs, C
q^{-1}	backward shift operator
Q	quantity of heat in joules, J or electric charge
°Q	Quevenne degrees of liquid density
QA	quality assurance
QAM	quadrature amplitude modulation
QBET	quench boiler exit temperature
QCM	quartz crystal microbalance
QEV	quick exhaust valve
QMS	quality management system
QoS	quality of service
QPSK	quadrature phase shift keying
qt	quart (0.9463 liter)
q.v.	*quod vide*: which see
QV	quaternary variable

R

r	radius; also rad
R	1) resistance, electrical, ohms; 2) resistance, thermal, meter-kelvin per watt, m · K/W; 3) gas constant ($= 8.317 \times 10^7$ erg · mol^{-1},$°C^{-1}$); 4) roentgen, symbol for accepted unit of exposure to *x* and gamma radiation, ($= 2.58 \times 10^{-4}$ C/kg)
r^2	multiple regression coefficient
Ra	radium
RA	return air or reaction (failure) alarm or reverse action
RACM	remote automatic control mode
Rad	1) radius; also r; 2) radian, symbol for SI unit of plane angle measurement or symbol for accepted SI unit of absorbed radiation dose, (= 0.01 Gy)
RAD	return air damper
RADAR	radio detection and ranging

RAID	redundant array of inexpensive disks
RAM	random access memory
RASCI	responsible for, approves, supports, consults, informed
RAT	return air temperature
RBC	remote base communication module
RCF	rotational centrifugal force
RCU	remote control unit
R&D	research and development
RD	rupture disk
RDP	remote desktop protocol
Re	Reynolds number
REC	roll eccentricity compensation
ReD	Reynolds number corresponding to a particular pipe diameter
redox	oxidation–reduction
rem	measure of absorbed radiation dose by living tissue (*r*oentgen *e*quivalent *m*an)
rev	revolution, cycle
RF or rf	radio frequency or return fan
RFC	request for comment (an Internet protocol specification) or rotational centrifugal force or rising film concentrator
RFF	remote fiber fluorimetry
RFI	radio frequency interference
RFQ	request for quote
RG	relative gain
RGA	residual gas analyzer or relative gain array or relative gain analysis
RGB	red, green, and blue
RGM	reactive gaseous mercury
RH	relative humidity or reheated or reheater
RHA	relative humidity alarm
RHC	receding horizon adaptive controller or reheat coil
RHCV	relative humidity control valve
RHE	relative humidity element
RHPZ	right half plane zero
RI	refractive index
RIO	remote operator interface
RIP	routing information protocol
RJT	ring joint type
r(k)	set point
RLL	relay ladder logic
RMS or rms	root mean square (square root of the mean of the square) or rotary mirror sleeves
RNG	ring number
RO	reverse osmosis
ROI	return on investment
ROM	read-only memory
RON	research octane number
RPC	remote procedure call (RFC1831)
RPG	remote password generator
RPM or rpm	revolutions per minute
rps	revolutions per second
R_r	reaction rate, slope
RRF	risk reduction factor
RRT	relative response time (the time required to remove the disturbance)
RS	recommended standard
RSA	rural service areas
RSS	root sum squared
RSSI	received signal strength indicator
RTD	resistance temperature detector
RTL	resistance-transistor logic
RTO	real time optimization or operation
RTOS	real time operating system
RTR	remote transmission request
RTS	ready (or request) to send
RTS/CTS	request to send/clear to send
RTU	remote terminal unit
RUDS	reflectance units of dirt shade
RV	relief valve
RVDT	rotary variable differential transformer
RVP	Reid vapor pressure
RW	raw water
RWF	raw water flow
RWS	remote work station

S

S or s	1) second, symbol for basic SI unit of time; 2) Laplace variable; 3) Siemens (Siemens/cm), symbol for unit of conductance, amperes per volt, A/V; 4) separation
SA	supply air
SAN	surface acoustic wave
SAP	service access point
SASFC	single automatic stage flow control
sat.	saturated
SAT	site acceptance test or supervisory audio tone or supply air temperature
SAW	surface acoustic wave
S.B.	set-point bandwidth
SC	system codes or speed controller
SCADA	supervisory (system) control and data acquisition
SCCM	standard cubic centimeter per minute
SCD	streaming current detector or sulfur chemilumenesce detector
SCE	saturated calomel electrode
SCFH	standard cubic feet per hour
SCFM	standard cubic feet per minute (air flow at 1.0 atm and 70°F)
SCM	station class mark
SCMM	standard cubic meter per minute
SCO	synchronous connection oriented
SCOT	support coated open tubular (column)
SCR	silicone-controlled rectifier or selective catalytic reduction
SCS	sample control system

SD — component in leg has failed safe and failure has been detected
S/D — shut down (valve)
SDIU — Scanivalve digital interface unit
SDN — send data with no acknowledgement
SDS — smart distributed system
SEA — spokesman election algorithm or slurry density sensor
Sec or sec — seconds; also s
SEI — system efficiency index
SELV — source: extra low voltage
SER — sequence of event recorder
SF — supply fan
S/F — smoke and fire (detector)
SFC — sequential function chart or system function configuration or static frequency converter
SFD — system flow diagram or start of frame delimiter
SFF — safe failure fraction
SFI — sight flow indicator
SFR — spurious failure rate
SG or SpG — specific gravity; also sp. gr.
S/H or S&H — sample and hold
SH — superheated or superheater
SHE — standard hydrogen electrode
SHS — sample handling system
SI — system international
SIC — speed indicating controller
SID — system identification digit (number)
SIF — safety instrumented function
SIG — special interest group
SIL — safety integrity level
sin — sine, trigonometric function
SIS — safety instrumented system
SISO — single-input single output
SKU — stock keeping units
SLAMS — state and local air monitoring stations
SLC — safety life cycle or single loop controller
slph — standard liters per hour
slpm — standard liters per minute
SMC — sliding mode control
SMCr — sliding mode controller
SMR — specialized mobile radio
SMTP — simple mail transfer (management) protocol
S/N — signal-noise (ratio)
SNCR — selective non-catalytic reduction
SNG — synthetic natural gas
SNMP — simple network management protocol
SNR — signal-to-noise ratio
SNTP — simple network time protocol
SOA — safe operation area
SOAP — simple object access protocol (an Internet protocol that provides a reliable stream-oriented connection for data transfer)
SOE — sequence of events
SOER — sequence of events recorder
SOFA — secondary over fire air
SOFC — solid oxide fuel cell
SONAR — sound navigation ranging
SOP — standard operating procedure
SP — set point or Smith predictor
SPC — statistical process control
SPDT — single pole double pole throw (switch)
Sp. G or sp. gr. — specific gravity; also SG
Sph — starts per hour
SPI — serial peripheral interface
SPL — 1) sound pressure level or 2) sound power level
SPR — set-point rate
SPRT — standard platinum resistance thermometer
SPST — single pole single throw (switch)
Sq — square
SQC — statistical quality control
SQL — structured (or standard, or sequential) query language
Sr — steradian, symbol for SI unit of solid angle measurement
SRD — send and request data with reply
SRS — safety requirements specification
SRV — safety relief valve
SS — stainless steel or selector switch
SSB — single side band
SSC — solid state contactor
SSE — size scale effect
SSF — Saybolt seconds furol
SSL — secure socket layers
SSR — solid state relay
SSU — Saybolt seconds universal
ST — structured text or steam turbine
STC — self-tuning controller
std. — standard
STEL — short term exposure limit
STEP — standard for the exchange of product model data
STG — steam turbine generator
STIG — steam injection gas turbine
Stm. — steam
STP — shielded twisted pair or standard temperature and pressure, corresponding to 70°F (21.1°C) and 14.7 psia (1 atm. Abs.)
STR — spurious trip rates or self-tuning regulator
SU — security unit or component in leg has failed safe and failure has not been detected
SUS — Seybold universal seconds or stochastic uniform selection
SV — secondary variable or safety valve or solenoid valve
S/W or SW — software
SWIR — short wave infrared
s^2_y — sample variance of output *y*

T

t — 1) ton (metric, = 1000 kg); 2) time; 3) thickness
T — 1) temperature; 2) tera, prefix meaning 10^{12}; 3) period (= 1/Hz, in seconds); 4) tesla, symbol for derived SI unit of magnetic flux density, webers per square meter, Wb/m2
$T^1/_2$ — half life
TAH — temperature alarm, high
TAL — temperature alarm, low
Tan — tangent, trigonometric function
Tanh — hyperbolic tangent
TAS — thallium-arsenic-selenide
Tau — process time constant (seconds)
TBM — tertiary butyl mercaptan
TBP — true boiling point
t/c — thermal coefficient of linear expansion
TC — thermocouple, temperature controller or total carbon
TCAM — timer/counter access modules
TCD — thermal conductivity detector
TCI — track command in
TCO — track command out
TCP — transmission control protocol
TCP/IP — transmission control protocol/Internet protocol
TCV — temperature control valve
t_d — process dead time (seconds)
T_d — derivative time (in seconds) of a PID controller
TD — time delay
TDLAS — tunable diode laser absorption spectroscopy
TDM — time division multiplexing
TDMA — time division multiple access
TDP — dew point temperature
TDR — time domain reflectometry
TE — temperature element
T/E — thermoelectric
TEM — transmission electron microscope
TFELD — thin film electroluminescent display
TFT — thin film transistor
TG — thermogravimetry
TGQ — total gas supply
TH — upper limit of comfort zone
THC — total hydrocarbon
THR — total heat release
Ti — integral time (in seconds) of a PID controller
TI — test interval (time interval between tests) or temperature indicator
TIC — temperature indicating controller or total inorganic carbon
TIFF — tagged image file format
TISAB — total ionic strength adjustment buffer
TL — lower limit of comfort zone
TLV — threshold limit value
TMP — 1) thermo-mechanical pulp; 2) transmembrane pressure
TMR — triple modular redundancy
TMT — tube metal temperature
TN — total nitrogen or twisted nematic
t_o (t_d) — process dead time (seconds)
TOC — total organic carbon
TOD — total oxygen demand
TOF — time of flight
TOP — technical and office protocol
TP — turbine protection
TPD — tons per day
TQM — total quality management
TR — temperature recorder or time delay relay
T/R — transmit/receive
TRC — temperature recording controller
TRI — track reference in
TRO — track reference out
T.S. — tensile strength
TSA — temperature swing adsorption
TSH — temperature switch, high
TSL — temperature switch, low
TSM — thermal stress monitoring
TSR — terminate and stay resident
TT — temperature transmitter or transit time
TTC — tungstram titanium carbide or time to close
TT&C — telemetry, tracking and command
TTFM — transit time flow measurement
TTL — transistor-transistor logic or time to live
TTO — time to open
TTP — through the probe
t_u — ultimate period
TV — tertiary variable
°Tw — Twadell degrees of liquid density
TWA — time weighed average
TWB — wet bulb temperature
TWM — technical working method
TY — temperature relay
τ (Tau) — process time constant (seconds)
τF — PV filter time constant F

U

u — prefix = 10^{-6} when the Greek letter μ is not available
UART — universal asynchronous receiver transmitter
UBET — unbiased estimation
UCMM — unconnected message manager
UDP — user/universal data/datagram protocol
UEL — upper explosive limit
UF — ultra filtration
$u_{fb}(k)$ — feedback controller output
UFD — utility flow diagram
$u_{ff}(k)$ — feedforward controller output
UFL — upper flammable limit
UGS — underground gas storage
UHF — ultra high frequency
UHSDS — ultra high speed deluge system
u(k) — controller output

UML	universal modeling language
UPS	uninterruptable power supply
UPV	unfired pressure vessel
URL	upper range limit
URV	upper range value
USART	universal synchronous/asynchronous receiver transmitter
USB	universal serial bus
USL	upper specification limit
USV	unloading solenoid valve
UTP	unshielded twisted pair
UTS	ultimate tensile stress
UUP	unshielded untwisted pair
UV	ultraviolet
UVS	uninterruptible voltage supply
UV-VIS-NIR	ultraviolet-visible-near infrared

V

v	velocity
v or V	volt, symbol for derived SI unit of voltage, electric potential difference and electromotive force, watts per ampere, W/A
VA	vertical alignment
Vac	a.c. voltage
VAV	variable air volume
VBA	visual basis for applications
VCO	voltage controlled oscillator
VCR	virtual communication relationship
VDC	volts DC
VDF	vacuum fluorescent display
VDT	video display tube
VDU	video display unit or visual display unit
vert.	vertical
VF	vacuum fluorescent
VFD	variable frequency drive or vacuum fluorescent display or virtual field device
VFIR	very fast infrared
VHF	very high frequency
VIS	visible
V-L	vapor–liquid (ratio)
V/M	voltmeter
VME	Virsa Module Europe (IEEE 1014-1987)
VMS	vibration monitoring system
VOC	volatile organic compounds or volatile organic carbon
VP	valve position
VPA	valve position alarm
VPC	valve position controller
VPN	virtual private network
VPS	valve position switch
VR	virtual reality
VRL	very low frequencies
VRML	virtual reality modeling language
vs.	versus
VSA	vacuum swing absorption
VSD	variable speed drive
V&V	verification & validation
VVVF	variable voltage variable frequency drive

W

w	1) width; 2) mass flow rate
W	1) watt, symbol for derived SI unit of power, joules per second, J/s; 2) weight; also wt water; 3) water
WAN	wide area network
Wb	weber, symbol for derived SI unit of magnetic flux, volt · seconds, V · s
WCOT	wall coated open tubular (column)
WDXRF	wavelength dispersion x-ray fluorescence
WF	weighing factor
WFS	water flow switch
WG	standard (British) wire gauge
Wh	white (wiring code color for AC neutral conductor)
WI	Wobble Index
WLAN	wireless local area network
WPAN	wireless personal area network
WS	work station
wt	weight; also W

X

x	molar fraction of light component in bottom product
X	reactance in ohms
XLS	limit switch
XML	eXtensible markup language
XP	blade pitch position
x-ray	electromagnetic radiation
XRF	x-ray fluorescence
XSCV	superheat control valve
XSET	start-up setting
XYZ	tri-stimulus functions

Y

Y	expansion factor, or molar fraction of light component in distillate
y(k)	process output
yd	yard (= 0.914 m)
yr	year

Z

z	molar fraction of light component in feed
Z	1) atomic number (proton number); 2) electrical impedance (complex) expressed in ohms
ZAFC	zinc air fuel cells
ZC	position controller
ZEB	zero energy band
ZIC	position indicating controller
ZOH	zero order hold
ZSC	limit switch – closed

ZSCO	limit switch – closed/open
ZSO	limit switch – open
ZSRG	zero signal reference grid
ZT	position transmitter or zone temperature
∂	partial derivative

MISCELLANEOUS LETTER SYMBOLS

α (alpha)	1) geometric angle; 2) radiation particle (helium atom); 3) linear expansion coefficient; 4) average relative volatility between the key components across the column
β (beta)	radiation particle (electron)
γ (gamma)	1) electromagnetic radiation; 2) surface tension; also σ (sigma)
Δ (delta)	difference, change or deviation from a steady-state condition
ε (epsilon)	1) emmissivity; 2) linear strain, relative elongation $\varepsilon \times \Delta 1/1°$
η (eta)	1) efficiency; 2) viscosity (absolute); also μ
θ (theta)	thermal resistance
λ (lambda)	1) thermal conductivity; 2) wavelength; 3) relative gain
Λ (lambda)	relative gain array
μ (mu)	1) viscosity (absolute); also η; 2) linear attenuation coefficient; 3) prefix, micro = 10^{-6}; also u; 4) mμ: millimicron (10^{-9} m)
μm	micron (10^{-6} m)
ν (nu)	viscosity, kinematic
π (pi)	1) surface pressure; 2) constant = 3.1416…
ρ (rho)	1) density; 2) resistivity
σ (sigma)	1) surface tension; also γ; 2) conductivity; 3) normal stress; 4) nuclear capture cross section
Σ (sigma)	summation
τ (tau)	1) time delay; 2) shear stress; 3) time constant
ω (omega)	angular velocity expressed in radians per second
Ω (omega)	ohm
ϕ	diameter, also dia and D
~	alternating current
′	minute, angular or temporal
″	second, angular
$\perp$	perpendicular to, normal to
$\parallel$	parallel
%	percent; also pct

GREEK ALPHABET

Α, α	alpha
Β, β	beta
Γ, γ	gamma
Δ, δ	delta
Ε, ε	epsilon
Ζ, ζ	zeta
Η, η	eta
Θ, θ	theta
Ι, ι	iota
Κ, κ	kappa
Λ, λ	lambda
Μ, μ	mu
Ν, ν	nu
Ξ, ξ	xi
Ο, o	omicron
Π, π	pi
Ρ, ρ	rho
Σ, σ	sigma
Τ, τ	tau
Υ, υ	upsilon
Φ, ϕ	phi
Χ, χ	chi
Ψ, ψ	psi
Ω, ω	omega