

8563796

*Robert A. Mollenkamp*

---

*Introduction to*  
**AUTOMATIC  
PROCESS  
CONTROL**

**IRP**

*Instructional Resource Package*

**STUDENT TEXT**

TP273  
M6

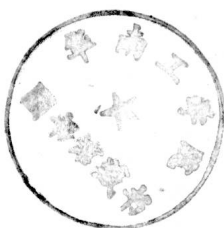
8563796

***Robert A. Mollenkamp***

***Introduction to***  
**AUTOMATIC**  
**PROCESS**  
**CONTROL**



E8563796



INSTRUMENT SOCIETY OF AMERICA



## **INTRODUCTION TO AUTOMATIC PROCESS CONTROL**

Copyright © by Instrument Society of America 1984

All rights reserved.

Printed in the United States of America.

No part of this publication may be reproduced,  
stored in a retrieval system,  
or transmitted, in any form or by any means,  
electronic, mechanical, photocopying, recording or otherwise,  
without the prior written permission of the publisher:

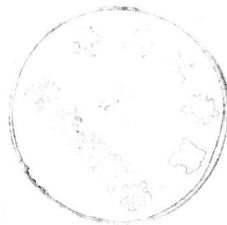
*The Instrument Society of America  
67 Alexander Drive, P.O. Box 12277  
Research Triangle Park, NC 27709*

**ISBN 0-87664-748-4**

The Instrument Society of America wishes to acknowledge the cooperation of those manufacturers, suppliers, and publishers who granted permission to reproduce material herein. The Society regrets any omission of credit that may have occurred and will make such corrections in future editions.

*First printing March 1984*

*Introduction to*  
**AUTOMATIC  
PROCESS  
CONTROL**





2878022

TP273  
M6

8563796

Introduction to automatic  
process control.

IRP

ckage

# **STUDENT TEXT**

*Developed by*  
**THE EDUCATION DEPARTMENT**  
Instrument Society of America

# **PREFACE**

I hope that this study will be only a small part of your training and experience in process control, a rapidly changing field due to recent advances in computer technology. Our current bottleneck in performing many worthwhile and profitable industrial projects is simply a lack of trained people at all levels. I hope that your studies provide you with the same challenges and enjoyment that I continue to find in each day of my work.

I would welcome any questions or comments that you might have about this textbook and your experiences in applying the ideas you have studied. I encourage you to write to me at:

Process Technology Corporation  
P.O. Box 937  
Rolla, Missouri 65401

Bob Mollenkamp  
Rolla, Missouri  
June 9, 1983

# CONTENTS

Preface	v
---------	---

Figures and Table	ix
-------------------	----

## **Section 1 INTRODUCTION TO THE STUDENT**

1-1 Course Contents	1
1-2 Course Objectives and Audience	2

## **Section 2 THE PROCESS CONTROL SYSTEM**

2-1 Process Control Objectives	3
2-2 The Feedback Concept	6
Questions	11

## **Section 3 PROCESS DYNAMICS**

3-1 The Importance of Process Dynamics	13
3-2 The Steady-State Gain (How Much)	14
3-3 The Time Constant (How Fast)	20
3-4 Dead Time	25
3-5 The Integrating Process	28
3-6 The Runaway Process	30
3-7 Nonlinear Effects	31
3-8 Dynamic Elements in Series	36
3-9 Distributed Processes	40
Questions	42

## **Section 4 PROCESS DYNAMICS FROM PLANT TESTS**

4-1 Approximating the Process Dynamics	45
4-2 Step Testing the Process	46
4-3 Using Simple Graphical Methods for Analysis	47
4-4 Using Simple Computational Methods for Analysis	49
4-5 The Fundamentals of Frequency Response Testing	52
4-6 Process Models from Frequency Response Data	59
4-7 Practical Considerations in Plant Testing	62
Questions	65

## **Section 5 CONTROL SYSTEM COMPONENTS**

5-1 The Feedback Loop	69
5-2 Measurement and Signal Transmission	69
5-3 The Control Valve	73
5-4 The Three-Mode Feedback Controller	77
5-5 The Plant Operator	85
Questions	86

**Section 6**  
**APPLYING FEEDBACK CONTROL**

6-1	Preliminary Considerations for Feedback Control	87
6-2	Selecting the Proper Controller	88
6-3	Controller Tuning Techniques	93
6-4	Stability from a Practical Viewpoint	102
	Questions	107

**Section 7**  
**CASCADE, RATIO, AND FEEDFORWARD**

7-1	Feedback Improvement Techniques	109
7-2	Cascade Control	109
7-3	Ratio Control	120
7-4	Feedforward Control	125
	Questions	137

**Section 8**  
**WORKING WITH MULTIPLE CONTROL LOOPS**

8-1	Control Loop Interactions	139
8-2	The Relative Gain	140
8-3	Pairing the Manipulated and Controlled Variables	144
8-4	Relative Gains for Industrial Processes	146
8-5	Dynamic Effects on Control System Interactions	154
8-6	Changing the Control Strategy	156
	Questions	159

<b>REFERENCES</b>	161
-------------------	-----

<b>ANSWERS TO QUESTIONS</b>	163
-----------------------------	-----



# FIGURES AND TABLE

## Table

4-1. Equations for Finding a Second-Order Plus Dead Time Model	51
--	----

## Figures

2-1. Superheated Steam Boiler	6
2-2. Control of Home Temperature	8
2-3. Temperature Variation in Home Control	8
2-4. Level Control in a Surge Tank	9
2-5. Set Point Response of Liquid Level	10
2-6. Load Change Response of Liquid Level	10
3-1. Level Control in a Surge Tank	14
3-2. Open-Loop Liquid Level Process	15
3-3. Level Step Response	15
3-4. Level Step Response	16
3-5. Typical Open-Loop Process	17
3-6. Heating Tank	18
3-7. Response of Heating Tank	19
3-8. Vapor-Filled Tank	22
3-9. Pressure Response	22
3-10. Mixing Tank	24
3-11. Response of Process with Dead Time	26
3-12. Fluid Mixing Process	26
3-13. Step Responses	27
3-14. Surge Tank	29
3-15. Level Response	29

3-16. Exothermic Chemical Reactor	30
3-17. Reactor Heat Effects	31
3-18. Flow Control Loop	32
3-19. Square Root Unit	33
3-20. Gain of Square Root Unit	34
3-21. Temperature Process Gain	35
3-22. Two Tanks in Series	36
3-23. Two-Tank Process Response	38
3-24. More Tanks in Series	39
3-25. Multiple Tank Responses	39
3-26. Approximate Model Response	40
3-27. Heat Exchanger Tube	41
3-28. Equivalent Model of Heat Exchanger Tube	41
4-1. Step Response of Multiple Time Constant Process	48
4-2. Step Response of Multiple Time Constant Process	49
4-3. Sinusoidal Variation of Process Input and Output	53
4-4. First-Order Process Amplitude Ratio	55
4-5. Second-Order Process Amplitude Ratio (Equal Time Constants)	56
4-6. Second-Order Process Amplitude Ratio (Unequal Time Constants)	56
4-7. Phase Difference between Input and Output Signals	57
4-8. First-Order Process Phase Angle	58

x

## Figures and Table

4-9.	Second-Order Process Phase Angle	58	6-9.	Tuning Parameter Correlation for PI Controller	101
4-10.	First-Order Plus Dead Time Process Phase Angle	59	6-10.	Tuning Parameter Correlation for PID Controller, for 5% Overshoot	102
4-11.	Magnitude and Phase Characteristics of Dynamic Elements	60	6-11.	Mixing Tank Temperature Control System	104
4-12.	Pulse Test Results	61	6-12.	Maximum Proportional Gain for Changes in Transmitter Gain	105
4-13.	Approximate Amplitude Characteristics	61	6-13.	Maximum Proportional Gain for Changes in the Process Time Constant	105
4-14.	Process Block Diagram	62	6-14.	Maximum Proportional Gains for Changes in Dead Time	106
4-15.	Noise Test Data	62	7-1.	Surge Tank Level Control	110
4-16.	Step Test Data	63	7-2.	Level-Flow Cascade Control	111
4-17.	Step Test with Other Upsets	63	7-3.	The Multiple Loops of Cascade Control	112
5-1.	Variation of Process and Measurement Signals	72	7-4.	Self-Regulated Process Response	113
5-2.	A Typical Control Valve	73	7-5.	Integrating Process Response	113
5-3.	Control Valve Trim	74	7-6.	Continuous Stirred-Tank Reactor	115
5-4.	Inherent Control Valve Characteristics	75	7-7.	Feedback Temperature Control of a Reactor	115
5-5.	Pressure Drop in Process Equipment	76	7-8.	Temperature-Flow Cascade Control of Reactor Temperature	116
5-6.	Installed Valve Characteristic	76	7-9.	Temperature-Jacket Temperature Cascade Control of Reactor Temperature	116
5-7.	Liquid Level Control of a Surge Tank	78	7-10.	Three-Level Cascade Control of Reactor Temperature	117
5-8.	Alternate Level Control System	79	7-11.	Feedback Control of Heat Exchanger Outlet Temperature	117
5-9.	Calibration Results for a Proportional Controller	80	7-12.	Temperature-Flow Cascade Control of Heat Exchanger Temperature	119
5-10.	Calibration Results for a Proportional-Integral Controller	81	7-13.	Temperature-Pressure Cascade Control of Heat Exchanger Temperature	119
5-11.	Heat Exchanger Temperature Control	82	7-14.	Flow Control of Feed to a Blending Process	121
5-12.	The Consequences of Reset Windup	83	7-15.	Ratio Control of a Blending Process	121
5-13.	Calibration Results for a Proportional-Derivative Controller	84	7-16.	Temperature Mixing Process	123
6-1.	Surge Tank Level Control	89	7-17.	Ratio Control of a Mixing Process	124
6-2.	Liquid Level Response with Proportional Control	89	7-18.	Combined Feedback-Ratio of a Mixing Process	126
6-3.	Variation in Discharge Flow Rate with Valve Position	91			
6-4.	Properties of Common Control Loops	94			
6-5.	The Decay Ratio	95			
6-6.	Overshoot Definition	95			
6-7.	The Integrated Absolute Value of the Error	96			
6-8.	Tuning Parameter Correlation for PI Controller	101			

7-19.	The Feedback Concept	126	8-2.	Block Diagram of a Summer	141
7-20.	The Feedforward Concept	127	8-3.	Block Diagram of a Transfer Function	141
7-21.	The Cancelling Effect of Feedforward	127	8-4.	Open-Loop Multivariable Process	142
7-22.	Feedforward Temperature Control of a Mixing Process	129	8-5.	Multivariable Process with Open-Loop Gains	142
7-23.	An Alternate Feedforward Control System for a Mixing Process	130	8-6.	Multivariable Process with One Feedback Loop	143
7-24.	Combined Feedback-Feedforward Control of the Mixing Process Temperature	131	8-7.	The Form of the Relative Gain Matrix	145
7-25.	Open-Loop Responses	133	8-8.	An Example Relative Gain Matrix	145
7-26.	Dynamic Characteristics of a Lead/Lag Element for a Unit Step Input	134	8-9.	The Best Relative Gain Matrix	145
7-27.	Response for a Change in Hot Feed Flow	134	8-10.	An Example with Negative Relative Gains	146
7-28.	Response for a Change in Cold Feed Flow	135	8-11.	The Mixing Process	148
7-29.	Response for Changes in Hot Feed Temperature	135	8-12.	Open-Loop Gains of the Mixing Process	151
7-30.	Feedforward with Dynamic Compensation	136	8-13.	Mixing Process Relative Gains	151
8-1.	Multivariable Control System	140	8-14.	Relative Gains from the Process Equations	153
			8-15.	The Mixing Process with a Tank Added	155
			8-16.	A Modified Feedback Control Strategy	156
			8-17.	Relative Gains for the Modified Strategy	158

# SECTION 1 INTRODUCTION TO THE STUDENT

## 1-1 COURSE CONTENTS

The purpose of this course is to demonstrate the fundamental engineering methods of designing and improving process control systems at the first level of control. The method used is to avoid as much as possible the highly mathematical approach used in most formal textbooks. The emphasis is on a rather practical, application-oriented approach, although some would argue that any course that doesn't use a screwdriver, an ohmmeter, or a wrench is too theoretical.

The subject coverage of the text includes a wide range of topics including:

- The objectives of process control
- Process dynamics
- The feedback controller
- Cascade, ratio, and feedforward control
- Interacting control systems

Little time is spent on the extremely important subjects of measurement techniques, control valve characteristics and selection, or the electronic or pneumatic hardware for signal transmission and calculation in the control system. These topics are covered in detail by other *Instructional Resource Packages*.



## 1-2 COURSE OBJECTIVES AND AUDIENCE

The primary objectives in this text are to examine the characteristics of various industrial processes and to see how these characteristics influence or determine the choice of the control strategy. Although some of the material does require some mathematics that is normally in the realm of the engineer, others (technicians, sales personnel, managers, etc.) may find that perhaps eighty percent of the material is not only understandable but also informative and useful. However, the text is designed primarily for use by those engineers and technicians actively engaged in design or operation of process control systems.

The style of this text is at best informal, but it is the author's sincere belief that technical education does not have to be a dreary experience. Those who feel that true education at higher levels must include some suffering may wish to skip many of the parenthetical comments throughout the text.

# SECTION 2

# THE PROCESS CONTROL SYSTEM

## 2-1 PROCESS CONTROL OBJECTIVES

What is the meaning of “process control”? Among the several explanations are:

- Keeping industrial processes at their most efficient operating points
- Preventing runaway conditions in the process that might endanger people or equipment
- Displaying information for plant operators so they can keep the process running safely and efficiently.

Process control is all of these things and more. One could go on and on trying to come up with one short definition of process control but would probably not be very successful. The reason is that process control is concerned with many aspects of plant design and operation. Control specialists are concerned with the instrumentation or hardware for measurement and control, design techniques for control systems, basic strategies of control, digital data communications, digital computations, computer programming, maintenance of control systems, and so on.

## 4

## The Process Control System

The overall objectives of process control systems depend on one's position in a company. The plant manager is most interested in "the bottom line", i.e., profit and cost, as well as more intangible items such as company image. The production superintendent is most concerned with meeting production schedules and maintaining a competent work force. The head of the engineering design group wants to efficiently produce process designs that are cost effective and require a minimum of field modification. The process engineer would like to find ways to improve the productivity of the process equipment. The plant operator likes a process that is understandable and "stable as a rock". The instrument mechanic would like instrumentation that is reliable and easy to service. All of these objectives are dependent upon process control systems.

The organization in most companies resembles a pyramid with many levels — each with its own responsibilities and concerns. A pyramid of process control objectives could be developed that would be quite similar to the company organization chart. In fact, this is one of the objectives of some rather advanced distributed control concepts.

At each level the process control concerns can be classified into four different categories of control:

- Feedback regulation
- Feedback improvement or stabilization
- Control of events
- Optimization of operations

The first of these categories deals with the control of some variable, either measured or calculated, at a set point. The second is designed to improve the operation of basic feedback control using techniques such as feedforward, cascade, ratio, multivariable decoupling, and adaptive control. The third type of control includes the handling of emergency situations, startup, shutdown, and batch process sequencing. Optimization calculates the plant operating conditions that will result in the highest profit, lowest cost, or minimum energy consumption, as just a few examples, and takes into account the limitations and operating constraints for the plant.

Of these four categories of control the primary interest here is in the first two — feedback regulation and feedback improvement. While these topics are of importance at all levels of the company pyramid, their design, application, and operation occur at the first level of process control. Therefore, examples will be presented of control of temperatures, pressures, flow rates, chemical composition, and so on.

At the first level of control there are many variables that might require control. Although it is not possible to list all the variables used in the thousands of industrial processes, the controlled variables can be classified into five categories (Ref. 1):

- (1) Production rate
- (2) Product quality
- (3) Inventory
- (4) Processing environment
- (5) Economics

The meanings of these terms are best explained by an example from Reference 1.

### **Example 2-1** Control of a Superheated Steam Boiler

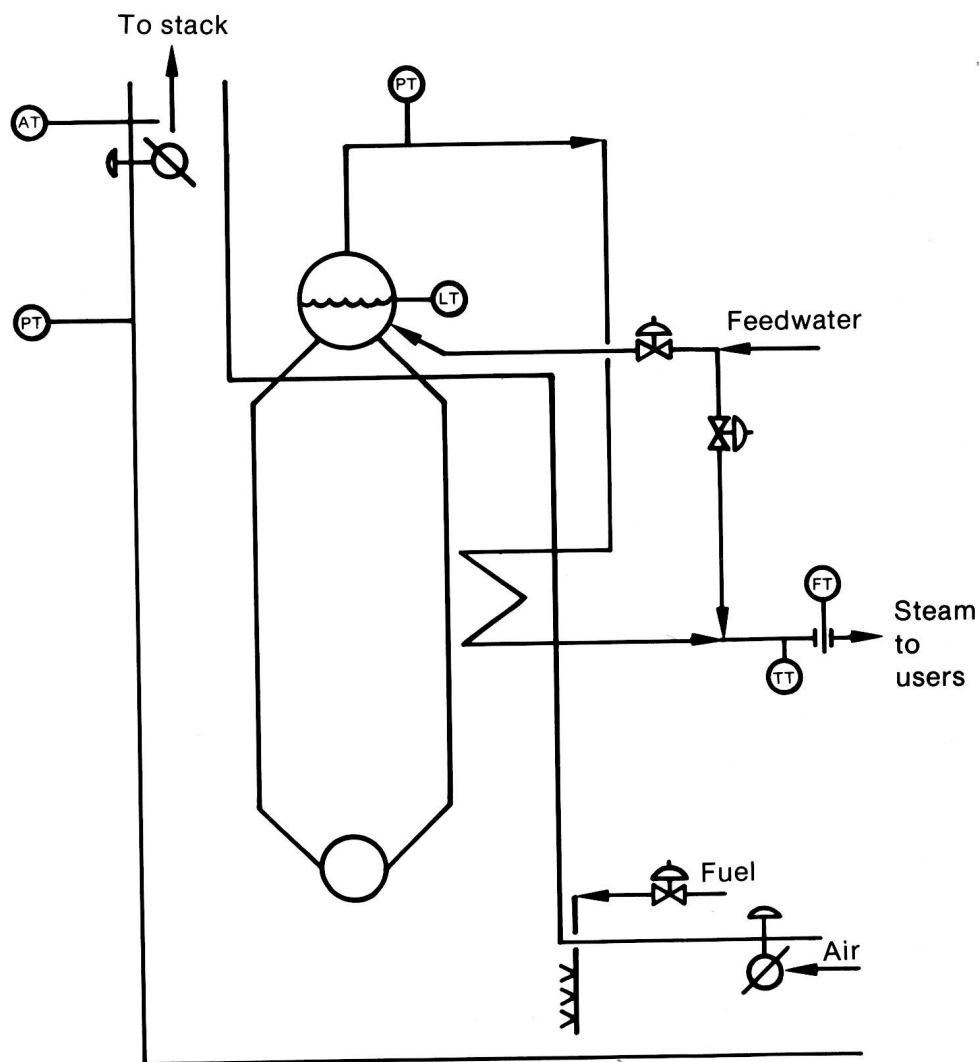
Classify the controlled variables represented by the transmitted signals from a boiler (Figure 2-1).

#### **Solution**

1. Production rate through the boiler is steam flow, usually set by downstream process demand.
2. Inventory is the accumulation of either mass or energy. In this process, liquid level in the drum is an inventory variable. Also, the steam pressure is an inventory variable because pressure is a measure of the mass in a gas system.
3. The processing environment includes those operating conditions that, while not really important in and of themselves, have an important effect on the process performance and product quality. In this example the furnace pressure or draft is an environmental variable.
4. Product quality is the chemical composition, purity, thickness, color, or whatever else determines the value of the product to customers. In this example the steam temperature is the product quality.
5. Economic variables are either directly or indirectly related to profits, or costs. In the boiler, the cost of processing is related to the composition of the flue gas.

Each type of variable has its own requirements and objectives. Inventory variables may require only loose control while product quality variables deserve very close, tight control. Economic variables are controlled in such a way as to maximize or minimize some profit or cost. Production rate constraints depend on the current market situation for the plant, i.e., production limited, market





**Figure 2-1. Superheated Steam Boiler (Ref. 1)**  
(Courtesy ISA)

limited, or resource limited. For any particular variable, one or more of the techniques described earlier may be applied to regulate, stabilize, control events, or optimize. The first of these techniques is feedback regulation.

## 2-2 THE FEEDBACK CONCEPT

How many types of control are there? ONLY TWO! What about feedback, feedforward, cascade, ratio, adaptive, supervisory, direct digital, distributed, learning, and decoupling control? Only the first two in the list are basic control strategies. The rest are modifications and variations of the basic strategies — *feedback* and *feedforward*. Of the two strategies, feedback control is the technique used in the vast majority of industrial applications at the first level of control. Because of the importance of the feedback concept the idea is introduced