HANDBOOK OF INSTRUMENTATION AND CONTROLS

HOWARD P. KALLEN

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A PRACTICAL DESIGN AND APPLICATIONS MANUAL FOR THE MECHANICAL SERVICES COVERING STEAM PLANTS, POWER PLANTS, HEATING SYSTEMS, AIR-CONDITIONING SYSTEMS, VENTILATION SYSTEMS, DIESEL PLANTS, REFRIGERATION, AND WATER TREATMENT

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PREFACE

As the building and plant services—power, heating, air conditioning, refrigeration, prime movers, and others—have become more complex in the years since World War II, the engineer has become increasingly aware of the importance of well-designed instrumentation and control systems to ensure proper operation of these building and plant services. Yet, as a practical matter, few engineers other than instrumentation specialists have the opportunity in their day-to-day activity to fully explore the many applications of instrumentation and control systems to their engineering problems.

This handbook has been prepared with the "nonspecialist" engineer in mind, although the specializing instrumentation engineer will find much material in each section of practical value to him. The material is presented in sufficient detail to provide a sound basis for system design, application, selection, and operation. It is intended to be a practical tool for all who are concerned with the mechanical services in institutional, commercial, and industrial buildings.

Thus, this book will be useful to engineers who design and apply mechanical systems to buildings, plant engineers, architects, consulting engineers, maintenance and operating engineers, power and utility engineers, and others in allied fields.

In its general arrangement the handbook gives emphasis to fundamentals as well as practical application. In this way it is felt that the material will be equally useful to the nonspecialist and specialist alike.

After a study of fundamentals in the second section, the reader is provided with both qualitative and quantitative data on pressure, temperature, flow liquid level, pH, and conductivity—the variables most frequently measured and controlled in mechanical services for buildings. These are then tied together in a detailed discussion of systems for boiler and power plants, heating plants, mechanical drives, air-conditioning ventilation, and refrigeration, with considerable space devoted to actual cases.

It is hoped that this handbook will contribute not only to a better understanding of the instruments and controls themselves, but to a fuller appreciation of what they can and cannot be expected to do when integrated with mechanical-service systems. In this way the hazard of misapplication may be avoided. It is quite true that no mechanical-service system can be better than the controls which cause it to function.

A handbook, by its very nature, is a compilation of the knowledge of many people, organizations, and companies. And, while individual credits are acknowledged throughout this handbook, I wish to express special appreciation to such individuals as A. C. Wenzel of Republic Flow Meters Co., R. E. Sprenkle of Bailey Meter Co., J. E. Haines of Minneapolis-Honeywell Regulator Co., and D. M. Considine of Hughes Aircraft Corp., and particularly to the Instrument Society of America and the American Society of Mechanical Engineers.

Finally, I wish to acknowledge the invaluable help of Mrs. Katherine Mangione and of my wife Claire in the preparation and proofreading of the manuscript and index.

Howard P. Kallen

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Section 1

INTRODUCTION

Today's advanced control techniques owe much to their early development in the mechanical services field. Closed-loop control systems were pioneered almost 40 years ago. Since that time, the mechanical services have been a proving ground for an almost endless number of developments that have pushed the controls art to new heights.

But this has been a two-way street; in the same period, controls had much to do with boosting electric generating efficiency from roughly 3½ lb of coal per kwhr to ¾ lb. And other services—air conditioning with its zone controls, electrical distribution's load-frequency control systems—have reaped the full measure from a dynamic controls technology. Yet, the ultimate in controls is nowhere in sight. We will witness many new and fundamental developments in the years ahead. And, no doubt, engineers will some day look upon today's control methods as relatively crude ancestors of "truly modern" control.

Primary Measurements. Pressure—force per unit area—is one of the most important of controlled variables. For the mechanical services, pressures range from less than an inch of mercury to several thousand pounds per square inch. And they must be measured accurately. Because of the broad range, numerous pressure-measuring elements have been developed. They vary from direct means such as spiral and bourdon gages for high pressures to inferential methods such as thermal (hot-wire) gages for high vacuums.

A relative newcomer to the field is the pressure transducer. It is based on electrical interpretation of pressure. A common design uses the strain-gage principle. The strain gage itself consists of a wire grid bonded to the surface of a small piece of Bakelite-impregnated paper. When the gage is cemented to the surface subjected to load, the wire grid stretches, changing its electrical resistance. By measuring resistance changes (with a potentiometer), we indirectly measure pressure. Transducers are compatible with the highest pressures the mechanical services field will be required to measure for years to come.

Temperatures that concern mechanical engineers are in the range of −200 to well over 1000°F. To meet the requirements of this wide spectrum, researchers constantly seek new principles of measurement, improving on existing methods.

Over certain temperature ranges, we have a wide selection of measuring elements. But range is only one of several key factors. Sensitivity, accuracy, response speed, cost, expected useful life, corrosion resistance—all need to be considered.

Briefly, present measuring practice breaks down like this: filled-system (vapor, gas, mercury) thermometers from −150 to 1000°F; resistance thermometers from −100 to 600°F; thermocouples from −300 to 2700°F; radiation (optical) pyrometers from 200 to 7000°F. We shall see more of radiation techniques for extremely high temperatures or in situations where it is impractical to contact the area being measured.

Liquid-, vapor-, and gas-flow measurement—of key importance to the mechanical services—has been the subject of several recent developments. But differential-pressure (orifice plate, flow nozzle, venturi tube) methods still are most frequently used. They are simple, easy to use, and readily adaptable to electric or pneumatic transmissions.

Area-type flow meters fit directly in the flow line and require no orifice plates or other primary elements. Pressure drop across the meter body is constant while flow area varies. For viscous fluids at least (oils, black liquor, etc.), we can expect stepped-up use of these meters.

Newest flow-sensing elements depend on electrical and magnetic techniques. One design employs a bucket-wheel rotor that spins freely between supports in the flow line. A powerful magnet inside the rotor produces an a-c signal with a frequency directly proportional to flow rate. These units can measure accurately continuous or intermittent flow of chemicals, liquefied gases, and solutions containing suspended particles at temperatures up to 1000°F. Range is from 0.08 to 5,200 gpm.

Recently developed methods of liquid-level measurement make use of radioactive materials. The gamma-ray system is based on the change in the number of gamma rays that can penetrate a layer of liquids. As layer thickness increases, the number decreases. Gamma-ray source is a minute quantity of radioactive material such as radium salts.

Controllers. A distinguishing mark of modern controls is their inability to tolerate time lags. Lacking "flywheel effect," they require faster, more accurate control response. To meet this need, more controllers will lean toward sophisticated control modes—combinations of proportional, automatic reset, and rate action.

On the question of pneumatic versus electrical and electronic controllers, we are likely to witness increasing use of all three types. This is largely because no one design will cover the full range of what is certain to be a fast-growing list of jobs.

Remote Transmission. Remote transmission of measurements—sending instrument signals over relatively long distances—has many advantages: safety, economy, convenience. Where high-pressure high-temperature fluids are present, remote transmission eliminates hazards by permitting control from a safe location. Thus, we shall see a strong trend continuing in this direction. Recent findings of an Edison Electric Institute questionnaire covering direct versus transmitted pressure for oil, hydrogen, high-pressure steam and water systems back up this thinking. Of 46 answering utility companies using some form of remote transmission (either electric or air or both), 63 per cent were on steam systems, 50 per cent on water systems, and 79 per cent on oil systems.

Telemetering, extension of the in-plant transmission idea, fills an important need in the far-flung power, pipeline, and water-supply systems of today. As these systems continue to grow, telemetering will take on even greater importance. Carrier current is the most common transmission medium on power systems, with private lines, leased lines, and microwave following in that order.

Systems Engineering. In the strict sense of the word, there is nothing new about *systems engineering* in the controls field. Instrument men have been engineering control systems for years.

Today, however, the term appears to be taking on an added meaning—complete *integration* of control-system design with the system it serves. The controls expert is called in and works closely with the equipment engineer from the early stages of design. The net result is a better control system, and equipment that is easier to control.

Scope. The scope of material covered in this handbook is intended to be of direct interest to the mechanical engineer engaged in the design, application, and operation of systems for mechanical services: steam plants, power plants, heating plants and heating systems, air-conditioning systems, diesel plants, and refrigeration systems. And, although the instrumentation and controls discussed have a broad application in other fields, notably the process industries, they are viewed here mainly as they apply to the mechanical services.

Instrumentation for certain mechanical services, because of its highly specialized nature, has been omitted. In this category is nuclear-reactor instrumentation. For an excellent treatment of this subject, the reader is referred to "Control of Nuclear Reactors and Power Plants" by M. A. Schultz, McGraw-Hill Book Company, Inc., 1955.

Credits. As editor of this handbook, I have received the most generous assistance and cooperation from a great number of U.S. instrumentation manufacturers, the Instrument Society of America, ASME, consulting engineering firms, and many users of mechanical-service instrumentation. While specific credits are made throughout the book, I wish to take this opportunity to express my deep appreciation to the many individuals and companies without whose cooperation preparation of this handbook would have been impossible.

Section 2

INSTRUMENTATION AND CONTROL FUNDAMENTALS

SYMBOLS AND NOTATIONS

In order to convey his ideas and information effectively and concisely, the controls engineer makes use of a system of symbols. They are, in effect, his "shorthand" and should be understood by the engineer who is responsible for design, selection, operation, or maintenance of control systems for the mechanical and electrical services.

A system of symbols has been standardized by the Instrument Society of America[1] and is given here in condensed form.

General. Instruments and instrumentation items are identified and represented by a system of letters and numbers, together with a number of simple basic pictorial symbols for illustrating the items on flow plans and other drawings.

Identifications. The identification shall consist of a combination of letters used to establish the *general identity* of the item with its purpose and functions. For some requirements this will be sufficient and complete; but usually it will be followed by a number that will serve to establish the *specific identity* of the item. The identifications shall be used for the complete designation of the item in written work, and in combination with the pictorial symbol for representation on flow plans or other drawings.

General Identifications. The general identifications shall consist of letters as listed in Table 2-1 used in combinations as shown in Table 2-2.

Table 2-1 covers the letters that may be employed, the definition or significance of each, and the permissible position or positions in which each may be used when combining.

Table 2-2 covers the permissible combinations of letters of identification and shows the significance of each such complete general identification.

In the use of the letters, or their combinations, the following rules and instructions apply:

1. All identifying letters shall in all cases be written in upper case. The

[1] *Tentative Recommended Practice, Instrumentation Flow Plan Symbols, ISA RP5.1*, Instrument Society of America.

only exceptions are the *optional* use of "d" and "r," and the use of "p" in the combined first letter "pH"; as per footnotes of Tables 2-1 and 2-2.

2. The *maximum* number of identifying letters in any combination shall be *three* (3). The only exception is in the use of "pH," or chemical symbols such as CO_2 where the self-defining pair is treated as a single letter.

Table 2-1. Letters of Identification

Upper-case letter	Definition, and permissible positions in any combination		
	First letter—process variable or actuation	Second letter—type reading or other function	Third letter—additional function
A	—	Alarm	Alarm
C	Conductivity	Control	Control
D	Density	—	—
E	—	Element (primary)	—
F	Flow	—	—
G	—	Glass (no measurement)	—
H	Hand (actuated)	—	—
I	—	Indicating	—
L	Level	—	—
M	Moisture	—	—
P	Pressure	—	—
R	—	Recording (recorder)	—
S	Speed	Safety	—
T	Temperature	—	—
V	Viscosity	—	Valve
W	Weight	Well	—

Note 1: When required the following may be used optionally as a first letter for other process variables:
(1) "A" may be used to cover all types of analyzing instruments.
(2) Readily recognized self-defining chemical symbols such as CO_2, O_2, etc., may be used for these specific analysis instruments.
(3) The self-defining symbol "pH" may be used for hydrogen-ion concentration.

Note 2: Although not a preferred procedure, when considered necessary it is permissible to insert a lower-case "r" after "F" to distinguish flow ratio. Likewise, lower-case "d" may be inserted after "T" or "P" to distinguish temperature difference or pressure difference.

3. A letter shall have only one definition or significance in its use as a "first" letter in any combination, to define the process variable.
4. A letter shall have only one definition or significance when used as *either* the "second" or the "third" letter in a combination, to define the type of device.
5. *It is* particularly important in writing the combinations of letters to adhere to the sequence of arrangement shown by Table 2-2.
6. No hyphens shall be used between letters or combinations of letters.

Table 2-2. Complete General Identifications
(Combinations of letters)

	First letter—process variable or actuation	Second and third letters—type of device												
		Controlling devices				Safety (relief) valves	Measuring devices		Glass devices for observation only (no measurement)	Alarm devices			Primary element	Wells
		Separate controllers			Self-actuated (integral) regulating valves									
		Recording	Indicating	Blind			Recording	Indicating		Recording	Indicating	Blind		
		-RC	-IC	-C	-CV	-SV	-R	I-	-G	-RA	-IA	-A	-E	-W
Temperature	T-	TRC	TIC	TC	TCV	TSV	TR	TI	///	TRA	TIA	TA	TE	TW
Flow	F-	FRC	FIC				FR	FI	FG	FRA	FIA		FE	///
Level	L-	LRC	LIC	LC	LCV		LR	LI	LG	LRA	LIA	LA		///
Pressure	P-	PRC	PIC	PC	PCV	PSV	PR	PI	///	PRA	PIA	PA	PE	///
Density	D-	DRC	DIC	DC			DR	DI	///	DRA	DIA			///
Hand	H-		HIC	HC	HCV		///	///	///	///	///		///	///
Moisture	M-	MRC	MIC	MC			MR	MI	///	MRA	MIA	MA	ME	///
Conductivity	C-	CRC	CIC				CR	CI	///	CRA	CIA	CA	CE	///
Speed	S-	SRC	SIC	SC	SCV	SSV	SR	SI		SRA	SIA	SA		///
Viscosity	V-	VRC	VIC				VR	VI	VG	VRA	VIA			///
Weight	W-	WRC	WIC				WR	WI		WRA	WIA		WE	///

Note: The optional additional process variables given in footnotes of Table 2-1, when used, shall be combined with second and third letters as per above.

Shaded spaces (///) indicate impossible combinations. Blank spaces indicate improbable combinations.

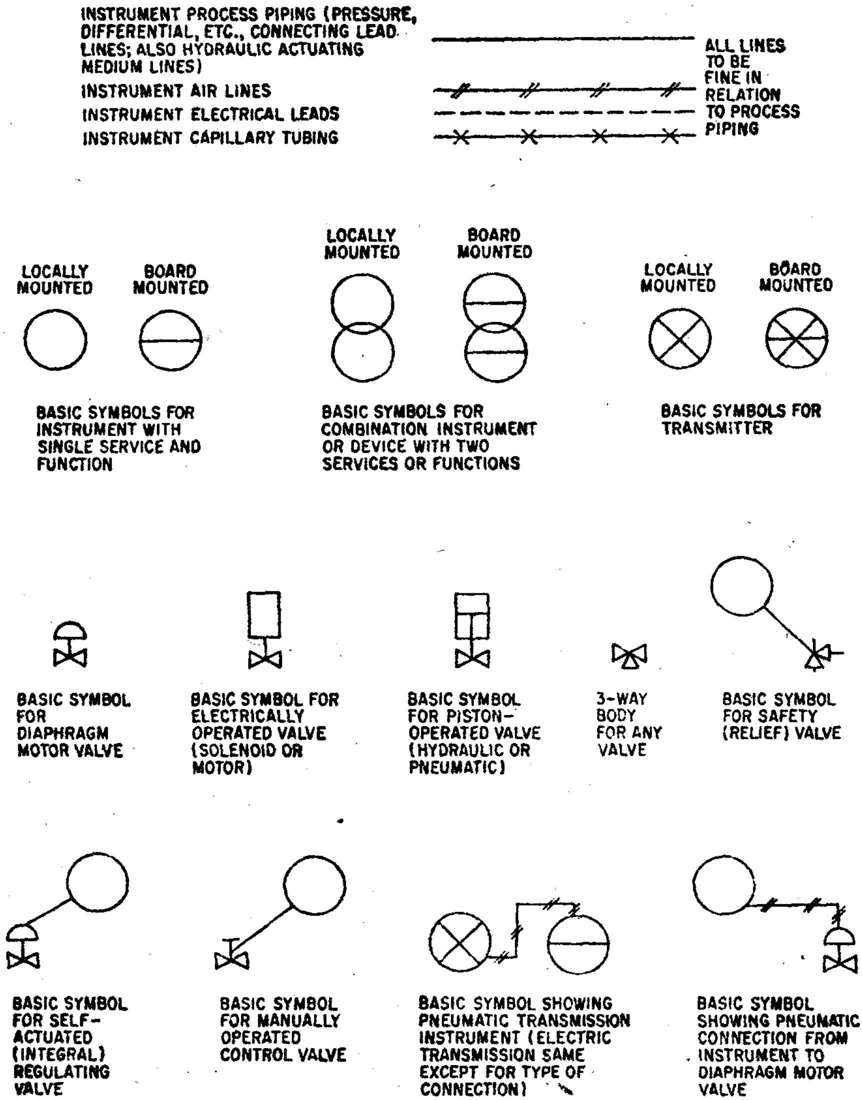

FIG. 2-1. Basic instrumentation symbols. (*From ISA RP5.1.*)

Specific Identifications. In most cases it will be necessary to supplement the general identification of an item by a numerical system, to establish its specific identity. Any system of item or serial numbers may be used, consistent with the requirements of the user. The numbers may pertain only to the same kind of item within one process unit; or may be a com-

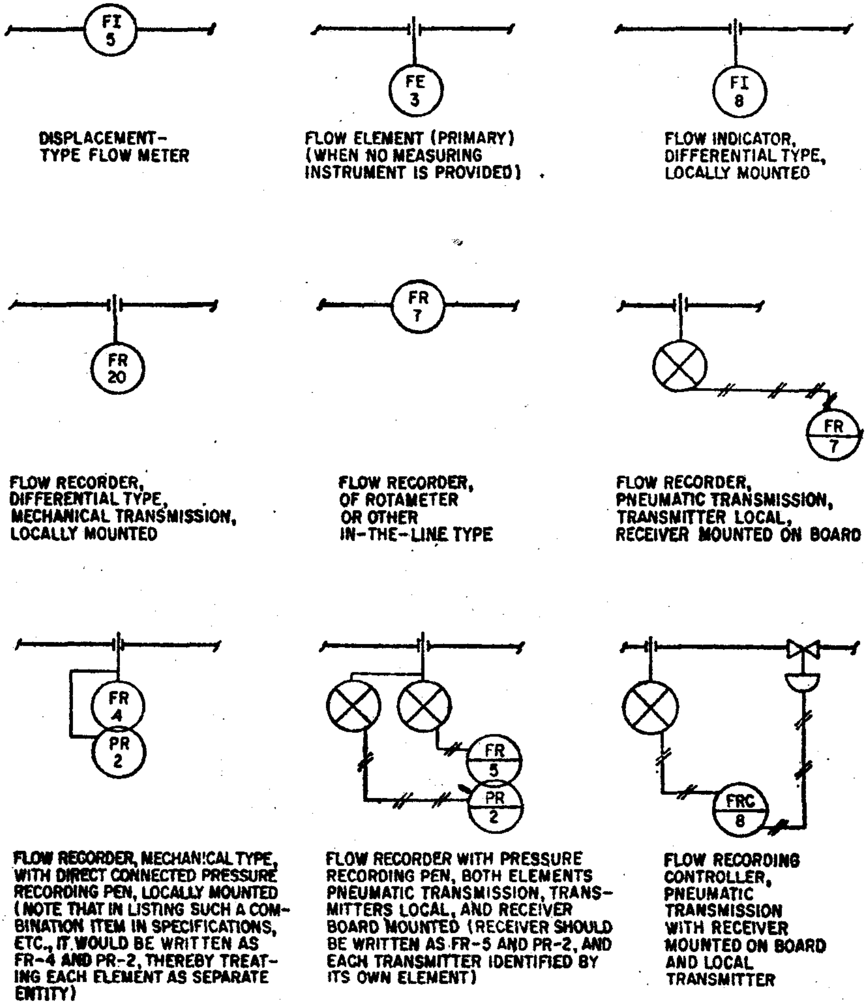

FIG. 2-2. Typical instrumentation symbols for flow. (*From ISA RP5.1.*)

plete serial-number system for a plant or an organization. In any case the series of consecutive numbers will be suitable for use with the general identifications.

When used in written work, the number shall be placed after the letters, and separated from them by a hyphen. For example, temperature-recording controller, item number one (1), is written as TRC-1.

Applying the Identifications. The identifications, wherever possible, shall be used to identify a complete instrumentation application with all its components, instead of independent identifications being assigned to