HANDBOOK OF APPLIED INSTRUMENTATION

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PREFACE

The following kinds of people will find this handbook of particular value:

1. The *manufacturing, process,* and *instrumentation engineer*—the person who analyzes the needs and benefits of instrumentation and control and who selects and in some cases designs the instrumental equipment best fitted for a given industrial process, scientific application, or military and aerospace use.
2. The *instrument and control user* who relies on measuring, controlling, and data-processing devices to provide greater efficiency, safety, and quality of the program or process with which he is concerned. The user may be a process engineer, a plant superintendent, a laboratory scientist, or an astronaut.
3. The *technically inclined or technically trained top-management man* who desires to comprehend instrumentation so that he may take full advantage of applied instrumentation in achieving greater profit yields and higher quality in a competitive market or in obtaining the utmost in accuracy and in the saving of time in research and development programs.
4. The *technical student* who may plan on specializing in instrumentation and control; and the *technical student* who may not plan on such specialization, but who realizes that, regardless of what technical field of endeavor he may pursue, he soon will encounter a need to know the fundamentals of applied instrumentation.
5. The *business student* who realizes that instrumentation and control represent one of the most certain means in today's tight profit squeeze of getting more from his investment in manpower and facilities.
6. The *educator,* particularly in technical schools and universities, who can base one or more complete instrumentation and control courses on the crisp and logically outlined format of this handbook.
7. The *self-starting type of instrument and controls craftsman* who knows that a broadened knowledge of how instruments and controls are applied, of what their economic end values are, of how they are used in industries and fields beyond his own, will place him in a good position for career advancement.

The authors and editors of this handbook have placed much stress on the objective of bringing about a greater interchange of applicational data from one field to the next—in other words, a merging of the disciplines of instrumentation. That is why this handbook includes detailed descriptions of instrumentation applications from nearly all of the major industries and scientific fields. The

editors carefully surveyed and screened the many areas of instrumentation in a process of selecting those fields which portray a representative cross section of the subject.

The user of this handbook is urged to canvass the descriptions of those fields which may be somewhat foreign to him for ideas which may spark an instrumental solution to his particular problem. The editors have found in their own instrumentation experience that such crossbreeding of applied technology can save hundreds and even thousands of man-hours and the accompanying costs for development facilities and materials. Careful use of this handbook may save you from reinventing a device or solution that already exists for your problem.

Much stress has been given in the development of this handbook on the "how to" or application engineering aspects of instrumentation. Although many of the early sections of this handbook provide concise descriptions of the "what" of instrumentation, this latter area is covered in more detail in the "Process Instruments and Controls Handbook" (McGraw-Hill). These two handbooks together form a complete compendium on the subject.

Following are thumbnail descriptions of selected subsections of this handbook:

Sec. 1-1—Definition and Classification of Variables

A complex subject is understood best when properly structured. Instrumentation and control are based upon the measurement of literally scores of variables. Some of these variables are thermal in nature; others involve radiation; some are concerned with mechanical forces; still others relate to numerical quantities and rates; some are geometric in character; some involve physical properties, or chemical properties, or electrical characteristics of matter. The classification of variables in this subsection represents a *first in the permanent literature* on the subject.

Sec. 1-2—Measurement Errors

No matter how well designed or how perfectly made, there always are exacting requirements for instruments and controls that go beyond the current state of the art. Hence it is extremely important to the designer and user of precise instruments to appreciate the meaning of errors, how to analyze them, how to predict them, how to compensate for them. This subject is thoroughly covered by an experienced National Bureau of Standards scientist and world authority on this subject.

Sec. 1-3—Factors in Selection of Measuring Methods

Few fields of technology rival instrumentation in the almost endless variety of methods and choices available. For example, there are at least ten basically different methods for measuring temperature, a dozen ways to measure pressure, over a score of ways to measure liquid level, and so on. But astute analysis usually points to the one best measurement for a given application. The big question always is—"How do you go about finding this one best way?" This handbook section is devoted to providing the answers to such complex and provocative questions.

Sec. 2-1—Temperature

What is the basic, physical nature of temperature? What significance do temperature measurements have in the industrial plant? In the laboratory? In nuclear work? In aerospace research? How are temperature standards established? How are they used in the daily calibration of detectors? These basic considerations, often overlooked in the permanent literature, are covered in this subsection.

Sec. 2-2—Calorific Value

The ability of substances to produce heat is an important variable to industry and research. But, to date, the descriptions of this topic have been confined to very

specialized books and journals. This subsection is another first in the permanent literature of instrumentation.

Sec. 3-1—Radiation Fundamentals

Principally within the past decade or so, radiation has become important as a tool of instrumentation. Much material on radiation instrumentation has appeared in the literature, but very little of a summary nature on the fundamentals of radiation as interpreted for the instrument designer and user. This subsection, prepared by an outstanding radiation physicist, meets this objective.

Sec. 3-2—Nuclear-radiation Detectors

Radiation detectors no longer are confined to nuclear-reactor research but are required in such fields as medicine, biological research, aerospace exploration, and food processing. This subsection provides a comprehensive review of radiation detectors written to be understood by the men of many fields who may be called upon to use them. The authors have pioneered their design, development, and application for many years.

Sec. 3-3—Radioisotopes in Instrumentation

Not so many years ago the use of radioisotopes for tracing the flow of complex substances in complex systems was new and novel. Today this practice is commonplace. But, again, the literature has lagged behind the art. This subsection, representing a comprehensive review of the subject, is another first in the permanent literature on instrumentation.

Sec. 3-4—Photometric Variables

A few years ago the human eye was the primary instrument for assessing such properties of materials as gloss, sheen, brightness, and close gradations of color. This subsection, prepared by a world authority on the subject, reviews a new generation of photometric instruments.

Sec. 3-5—Acoustic Measurements

The effects of noise on office and factory efficiency and the many applications of ultrasonics in industry and medicine have required the development of a new line of measuring instruments. Two of the nation's pioneers in this field describe what instruments are available, how they can be used, and what instruments still are needed.

Sec. 4-1—Force Measurement

With the tremendous forces encountered in aerospace, nuclear, chemical, and other technologies today and with the invention of numerous new methods for the measurement of such forces, this subsection is of much importance.

Sec. 4-2—Pressure and Vacuum Measurement

This subsection provides a comprehensive tabular and pictorial summary of mechanical, electrical, pneumatic, and other methods for the measurement of pressure and vacuum.

Sec. 5-1—Flow

In addition to supplying a comprehensive but concise review of available flow-measurement devices, this subsection analyzes the importance of flow as a variable and reviews the basic physical and hydraulic theories which underlie the design and application of flow-measuring-and-controlling devices. The author has been associated with the flow-measurement field for nearly thirty years.

Sec. 5-2—Acceleration Measurement

Acceleration measurement has taken on increasing importance in industry and particularly in the fields of missile technology and aerospace exploration. In this

subsection the characteristics of accelerometers and their application engineering are described.

Sec. 5-3—Speed Measurement

With the trend toward greater and greater automation of industrial and other physical processes, the engineer is called upon more frequently to specify the most suitable speed-measurement method. These factors are covered in detail in this subsection.

Sec. 5-4—Weight and Weight Rate of Flow

Sophisticated instrumental methods for application to bulk solids came much later than in the case of the fluid systems. But progress in recent years has been rapid. This progress, together with a summary description of available hardware and weight control systems for both bulk and discrete solids, is detailed in this subsection. The author has devoted over twenty years in this area of technology and is responsible for numerous scientific advancements.

Sec. 5-5—Liquid Level

Probably no variable represents so many instrumental methods and possibilities for its measurement. Over thirty years of experience in this field have enabled the author of this subsection to pass along detailed recommendations concerning the best liquid-level measurement system for a given application.

Sec. 5-6—Solids Level

This is another variable involved in the instrumentation and automation of bulk-solid handling systems. Very slow in its initial development, numerous schemes of measurement have become available recently. These are described by an author of many years of experience and are passed along to the user of this handbook in an effort to assist the designer and user in selecting the best measurement method for his application.

Sec. 6-1—Parts Dimension Measurement and Control

Dimension measurement is one of the cornerstones of automation in all industries which handle discrete units, such as the metalworking, mechanical fabrication, and assembly industries. The authors of this subsection are recognized world authorities in this field.

Sec. 6-2—Thickness Measurement of Sheet and Web Materials

The advent of plastic kinds of materials gave much impetus to the production of materials in sheet and web form and also gave cause for the modernization of the earlier metallic films and foils. Improvements in X-ray and other radiation measurement principles greatly aided the development of new thickness gages. The authors of this subsection describe an entire cafeteria of thickness-measurement devices and provide detailed application guidance.

Sec. 6-3—Position Measurement and Control

Position is another key measurand in many automation systems. Unfortunately, the past literature on this subject has been spotty and incomplete. The authors of this subsection targeted on compiling the first really comprehensive review of an applicational nature to be found in the permanent literature.

Sec. 7-1—Fluid-density and Specific-gravity Measurement

The summary presented in this subsection is designed to assist the instrumentation engineer in his selection of the right system for a given application. This is another subject that heretofore has not been covered adequately in the permanent literature.

Sec. 7-2—Humidity and Dew Point

These important variables are encountered in almost all industrial processes and scientific research. What are the instrumental methods for their measurement? What are the basic mathematics and theory concerning them? How can you go about selecting the best measurement method for your need? The author of this subsection proceeds to answer these questions in a logical fashion.

Sec. 7-3—Moisture Content of Materials

For those handbook users who have attempted heretofore to find descriptions of moisture-measurement methodology in one reference, the work of the author of this subsection will be deeply appreciated. Another first in the permanent literature.

Sec. 7-4—Viscosity and Consistency

Few variables are more difficult to comprehend. The author of this subsection carefully explains the basics of rheology, after which he documents the units and scales of viscosity. This is followed by a tabular and pictorial "how to select" guide.

Sec. 8-1—Analysis Instruments

This subsection provides an insight to the selection and application of analytical instrumentation, especially for on-line measurements. As more and more computers enter the process-control loop, analytical instrumentation for measuring the chemical composition of raw materials, of intermediate and sidestream materials, and of final products will become mandatory. The author describes numerous analytical methods and provides an excellent structuring of this extremely complex subject.

Sec. 9-1—Electrical Variables

The basic instrumentation for measurement of current, emf, and other electrical characteristics is described in terse, application engineering style.

Sec. 10-1—Fundamentals of Automatic Control Engineering

Scores of books and hundreds of articles have appeared on this subject, but the author of this subsection faced the challenge of organizing his material in such form that it would be meaningful not only to the student who may be learning of automatic control theory for the first time but also to the technical manager, plant superintendent, scientist, and aerospace engineer who may not desire to become completely expert in the field, but who does require a day-to-day working knowledge of the subject. Because of years of experience as a systems engineer in applying instruments and controls, the author is eminently well qualified to appreciate the many viewpoints of users of this handbook.

Sec. 10-2—Application of Photoelectric Controllers

The author of this subsection, in describing available photoelectric controls and citing numerous examples of their practical application, provokes the imagination and creativity of the instrumentation and processing or manufacturing engineer. Often the ingenious application of photoelectric controls can greatly simplify and reduce the cost of applications that might initially appear to require a rather exotic control system.

Sec. 10-3—Controller Types and Final Control Elements

This subsection provides a terse, tabular, and pictorial summary of electric, pneumatic, mechanical, and hydraulic types of controllers and final control elements, including valves and dampers. The stress is on "how to select"; the design details of the hardware will be found in the "Process Instruments and Controls Handbook" (McGraw-Hill).

Sec. 11-1—Applications of Analog Computers

The practical considerations of applying analog computers to the supervision and control of manufacturing and processing are the objectives of this subsection. Unlike

the run-of-mill coverage of this relatively complex subject in the periodical literature, where too often the material is highly mathematical in content or too nebulous in reducing the subject to a practical application science, this subsection will assist the handbook user in determining where analog computers can be used and where some other solution to the problem may be best.

Sec. 11-2—Application of Digital Computers

Unless one follows this rapidly progressing subject on a day-to-day basis, he will find it difficult to amass information quickly that will enable him to make a determination of the practical applicability of digital computers to his problems. The author of this subsection has structured the subject for quick and convenient comprehension and presents applicational details in a realistic fashion.

Sec. 11-3—Instrumentation Data Processing

This subsection presents a practical, immediately usable review of available data-processing equipments with just enough discussion of principles and theory to assist the handbook user in selecting the right equipment for his job. The author, a veteran data-processing scientist, brings to the permanent instrumentation literature for the first time, in the editors' opinions, a well-organized evaluation and assessment of this subject. Suddenly what appeared to be an extremely complex subject takes on an air of simplicity.

Sec. 11-4—Counters and Digital Indicating Devices

This provides a terse review of these workhorses of instrumentation that are found in practically every systems engineering and electronics laboratory—with growing application for process and machine control.

Sec. 12-1—Steel Production Instrumentation

This subsection represents the most thorough review of this kind attempted to date in the permanent instrumentation literature. The author brings to this section over forty years of concentrated attention to the instrumentation needs of this industry. Handbook users in other industries where temperature measurements and control and where complex, interlocked fuel-firing controls are encountered will find much to consider for their own needs. The steel industry not only has brought earlier instrumentation applications to a high degree of refinement but has also developed many new instrumental methods for controlling new processes. These are covered in this subsection.

Sec. 12-2—Glass and Ceramics Industries Instrumentation

The most thorough review of this kind attempted to date in the permanent instrumentation literature. Many concepts for instrument applications in other high-temperature industries can be found in this subsection. For the executive of a glass or ceramics plant, this subsection sets a high standard against which to measure his own application of instruments and controls for the upping of product quality simultaneously with profit.

Sec. 13-1—Instrumentation Practices in the Process Industries

In this subsection one of the newer generation instrumentation and systems-engineering executives and recent President of the Instrument Society of America reviews the subject of instrumentation from the standpoint of technical management. This subsection brings out the way a company should organize for the engineering and maintenance of instruments and controls and provides numerous ideas on how to sell instrumentation upstairs to top management.

Secs. 13-2 through 13-7—Instrumentation of Heat Exchangers, Filters, Crystallizers, Distillation Columns, Dryers, and Evaporators

The following observations apply to all of these subsections. About thirty years ago, the chemical engineer came up with a conceptual, technological breakthrough

by recognizing that various operations, such as those mentioned above, appear in repeated fashion in numerous processes. By zeroing in on the study of these so-called unit operations, rather than in attempting to study each process entirely on its own, the chemical engineer literally saved years in advancing the science of chemical processing.

Surprisingly, and difficult to explain, the literature has included to date only spotty references to the instrumentation and control of these well-defined unit operations. Possibly the most important *first* in this handbook is this series of comprehensive analyses of the needs for and the "how to" of instrumenting the chemical unit operations. It is fully expected that this pioneering editorial attack will be copied many times over in the years to come. The eminence of the authors of each of these subsections in their field is beyond question.

Sec. 13-8—Pulp and Paper Production Instrumentation

This is an industry which has had to face the profit squeeze for many years. Striving for efficiency through automation is not a new concept in this industry. Consequently, users of this handbook from other fields can gain much by way of ideas from the manner in which the advantages of instrumentation have been squeezed out and refined for pulp and paper production. The author is one of the nation's leading authorities on this subject.

Sec. 13-9—Food-industry Instrumentation

Revolution is a rather mild word when applied to the progress and changes which have taken place in the food industry over the past few years. For example, the sanitary requirements have placed a hardship on instrumentation engineers for years, but these problems largely have been licked by new instrument designs which afford "in process" cleaning on an automatic cycle. Older applications, such as pasteurization, have been modernized to include electronic instrumental approaches. All of these applications, the conventional and the new, are described in this subsection by an engineer who has specialized in the instrumentation for this particular industry for a number of years. To the technical managers of food plants, this section should provide considerable "food for thought."

Sec. 14-1—Automatic Combustion Control Systems for Boilers

Despite strides in other energy processes, the boiler plant will remain on the industrial and commercial scene for many years. The instrumentation and control of boilers, from the small portable type to the largest installations, has gone through years of refinement. The handbook user will find in this section an account of instrumental means which reflect the mingling of new concepts with well-established methods.

Sec. 14-2—Steam Power Plant Instrumentation

Any handbook user with a steam power plant, large or small, will find described in this subsection the "how to" of selecting and applying instruments and controls.

Sec. 14-3—Electric Power Generation and Distribution Control

This subsection puts together in one place a summary of instrumental and control methodology and thus represents a breakthrough in the permanent instrumentation literature. Before this, the person interested in the subject had to pore through scores of periodicals and actually depend heavily on manufacturers' literature. All of the authors of this subsection are recognized authorities in their field. One of the first industries to demonstrate realizable economic savings through the application of digital control computers.

Sec. 14-4—Nuclear Reactor Instrumentation

As the most recent energy process, nuclear fission instrumentation coverage in the literature has been skimpy and scattered. The eminent author of this subsection

has carefully organized and structured this complex subject and, for the first time, has brought it into focus in one place in the permanent instrumentation literature.

Sec. 15-1—Process Laboratory Instrumentation

Instrumentation in the process laboratory differs quite drastically from the needs of the large-scale production process. Usually the laboratory scientist does not have the funds available and often does not have the knowledge to apply instruments and controls that literally are larger than his laboratory apparatus. Often he does not have the room or the time. Fortunately, specialized instruments have been made available commercially for such use and these are described in this subsection. But, more important, the author describes scores of ingenious homemade devices that the laboratory scientist can put together in a relatively short time—methods that are adaptable to the measurement of variables in a very small space or of very minute quantities. This subsection represents the collection of these ideas by an expert in the field over a period of years.

Sec. 15-2—Pilot-plant Instrumentation

Steadily the concept of piloting instrumentation techniques in the pilot plant is taking hold as well as the piloting of chemical and physical principles and of processing equipment. A part of this slow recognition of applying adequate instrumentation to pilot plants stems from the sad lack of literature on this subject. A thorough literature search may uncover a few articles. The author of this subsection not only describes available hardware for these applications but also develops justification for instrumentation expenditures in pilot plants and a philosophy for guiding these applications.

Sec. 15-3—Environmental Test Instrumentation

Greatly accelerated by the developmental needs of defense and military products, the means to test these products under severe conditions prior to use now comprises the relatively new field of environmental test instrumentation. The author of this subsection, a national expert in this area of specialized instrumentation, describes basic types of vibration-measuring instruments. Shock and acceleration testing, measurements of simulated altitudes, temperature and humidity measurement problems peculiar to environmental simulation, testing of components and products in acoustical environments, and explosion testing are among the many subjects covered. This subsection will be of particular value to those handbook users in the aerospace and associated industries and to all other users who have a growing concern for the pretesting of components, materials, subsystems, and entire systems prior to their actual intended use.

Sec. 15-4—Electronic Laboratory and Research Instrumentation

Surprisingly little attention has been given in the professional literature to the assemblage of data on the many kinds of instruments used in the typical electronics-type laboratory. In this subsection an outstanding staff of engineers has developed this "big picture" for the first time—with emphasis on a review of the kinds of instruments available, their characteristics, and guidance toward selection for specific laboratory applications.

Sec. 16-1—Aircraft and Aerospace Vehicle Instrumentation

A comprehensive review of flight and attitude instruments, navigational instruments, engine and motive power instrumentation as applied to modern air and spacecraft. The author of this subsection is a pioneer and outstanding authority in his field.

Sec. 16-2—Aircraft Flight Simulation Instrumentation

As air and spacecraft become more and more complex and sophisticated in design and use, the need to simulate flight conditions for crew training has grown. The