Reprint

ISA Journal

INSTRUMENTATION • SYSTEMS • AUTOMATIC CONTROL

How To Plan Computer Control

by Dr. Montgomery Phister, Jr.,
(ISA Member)
Director of Engineering
The Thompson-Ramo-Wooldridge Products Company
A Division of Thompson Ramo Wooldridge Inc.
Los Angeles, California

Reprinted from the January 1959 issue of the ISA Journal

Here is a plan of action now being used by many large companies to evaluate, develop, and install closed-loop computer control systems on their major processes. This plan shows you how to overcome present limitations of process theory, process data, and instrumentation.

How To Plan Computer Control

by Dr. Montgomery Phister, Jr.,
(ISA Member)
Director of Engineering
The Thompson-Ramo-Wooldridge Products Company
A Division of Thompson Ramo Wooldridge Inc.
Los Angeles, California

COMPUTER CONTROL of continuous or batch chemical and petroleum processes promises substantial improvement in operation by continuous processing at optimum throughputs, yields, product qualities, and costs. This article introduces the reasons behind the move to on-line computer control, and presents a plan for developing and installing such a system.

ON-LINE COMPUTER

Figure 1 shows an on-line computer control system comprising a stored-program digital computer which takes information directly from the process and makes adjustments directly on the process.[1] Of course, no computer can do more than previously instructed to do by a set of commands stored in its memory. In obeying these commands, it reads instrument data, solves equations describing the process and, from these equations, improves process operation.

In systems now being planned and installed, the computer exercises control by adjusting the set-points of conventional pneumatic controllers—advantageous because the controllers compensate for very rapid changes or "noise" in process conditions, and because processes can be put under conventional automatic control when instruments or computer fail.

The cost of such a control system varies from $200,000 to $300,000, including instrument changes and engineering. One might reason that all or part of such an investment could be justified by the improved data collected with the computer and by possible elimination of manual calculation on process data. Even more expensive conventional data loggers have been justified and installed on such grounds. However, an on-line computer control system does much more than produce volumes of data for later analysis and consideration; its principal justification must come from *improved process operation.*

OFF-LINE COMPUTER

It is sometimes argued that an on-line computer (Figure 1) may have some slight advantage over an off-line computer (Figure 2), but, improvement in process operation is not worth the expense required to associate a

[1]Superior numbers indicate similarly numbered references at the end of this article.

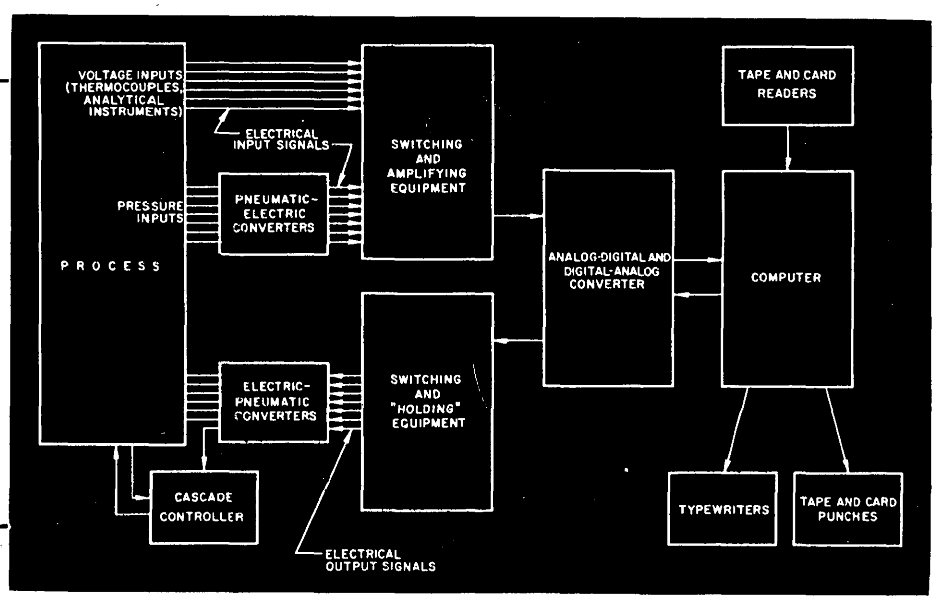

Figure 1. This is "on-line" computer process control. Its inputs come directly from process measuring instruments and it closes the control loop by directly adjusting the set-points of conventional process controllers.

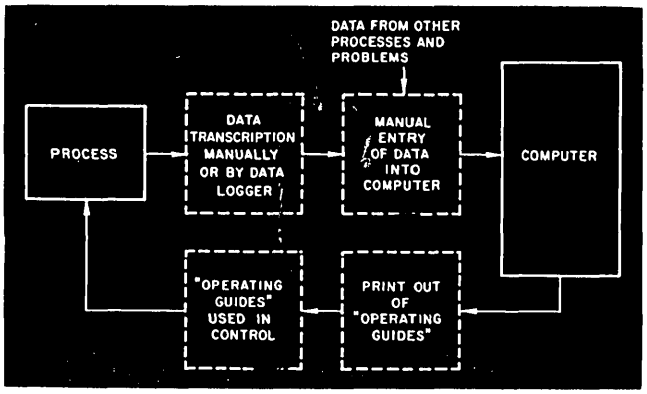

Figure 2. This is "off-line" computer process control, showing functional arrangement of independent operations to produce "operating guides" for the human operators.

computer *directly* with the process. However, in many, if not most, processes, information transfer between computer and process would be difficult were not the computer *directly* connected. An expensive data logger might be necessary which does no more than digitize instrument information and punch it into paper tape for later reading into the computer. Were this not done, information would have to be periodically gathered from recording charts and operators' logs, manually punched in tape or cards, and then entered into the computer. Time delays and possible errors make such a method unattractive.

But the argument—on-line vs. off-line computers—really hinges on the frequency and variety of process "upsets," caused by changes in such "external" or uncontrollable variables as raw material characteristics and availability, ambient conditions, process equipment coefficients and breakdowns, and market factors. Such changes alter the *state* of the process. Then, the best operating points for various process variables and therefore the best set-point adjustments for various controllers, vary as often as these changes occur. Generally, only a few uncontrollable variables are important in any process. Often, however, these few change at least several times a day, and sometimes every hour or minute. These changes can be so large that, if the process is left in one state for a relatively long period (corresponding to the time since the last computation by an off-line computer), significant losses in operating profit can result. Conversely, if the off-line computer were to try to print out a set of "operating guides" telling the operator what to do under a wide range of changes in uncontrollable variables, the resulting table usually would be too cumbersome to be practical. So, an off-line computer generally is unsatisfactory for complicated control problems.

PLAN OF ACTION

Many process companies have adopted the plan outlined below for the orderly investigation of on-line computer control possibilities. In the last four years, several companies have joined with ours in joint programs for this purpose.

The plan involves four steps: 1st, preliminary survey of plant operation and economics to choose the process most likely to benefit from computer control; 2nd, detailed study of the chosen process, to plan its control system; 3rd, engineering and installation of the computer control system; 4th, evaluation of the installed system to determine whether predicted benefits actually are being realized.

First Step: Preliminary Survey

The object of the preliminary survey is to choose a process likely to benefit from computer control. With systems costing from $200,000 to $300,000, choice of processes is narrowed to those producing large amounts of relatively valuable products. A good rule of thumb: value added to the raw materials times the highest percent of expected improvement must equal at least half the cost of the system (to provide payout in two years or less). Important features of processes meeting this criterion are examined in detail below:

1. Uncontrollable variables affecting process. What is frequency of change; effect on yield, throughput, cost, quality?

2. Maximum *theoretical* and *present* yield and throughput. Would compensation for uncontrollable variables be worth enough to pay for computer control?

3. Process adjustment. What controller set-points can be adjusted automatically? How much will it cost to make them so? Are there enough adjustments to permit control to react to external factors for "best" operation?

4. Planning difficulties. Will available measuring devices provide accurate process data? What is known about the effect of changing conditions and about the theory of process operation?

When several processes in a plant have been scrutinized, at least one good prospect can be selected. After this preliminary survey, lasting from two weeks to a month, you can only roughly estimate possible economic benefits of computer control for these selected processes. Not until after the next step—a detailed application study lasting four to eight months—can the potential of a digital computer control system be estimated with reasonable precision.

Second Step: Detailed Process Study and System Planning

Next, the detailed application study must be carried out. This study, which our company makes available free to its customers, usually takes the full time of two to six engineers with backgrounds in the process concerned, instrumentation, control systems theory, and computers. In analyzing the process, the study team (including engineers from the customer's operations) develops equations describing the process, investigates instrumentation required for computer control, examines the effect of process dynamics and carries out a preliminary evaluation of the probable payout which might result from computer control.

Development of Process Equations. Computer control improves process operation only by solving a set of equations which describe the process and enable quantitative predictions of process reactions to varying conditions to be made. In our approach to equation derivation, we look at the process from an *economic* viewpoint. The first equation written expresses the operating "profit" as a function of the manner of process operation. Its usual form: "profit" equals value of products minus cost of raw materials minus operating costs. Note that the only operating costs important to control are those which *vary* with process operation. Fixed costs—depreciation, insurance, etc.—do not affect process operation, so the "profit" this equation represents is *not* true profit in the usual meaning of the word.

With this first equation derived, we next investigate limitations on process operation. Example: construction of a reactor may be such that it cannot be operated above 500 psi. A complete set of such constraints is very important, for it defines precisely what the control system can and cannot do.

Finally, we derive equations relating product characteristics to all variables which effect them: these are the hardest equations to derive.

Theoretical Approach. Derivation of these equations usually proceeds simultaneously along two lines. One is a theoretical approach requiring that process kinetics be described by a set of differential equations, and that these equations be solved for the particular configuration of equipment—equations often so complicated that they can't be solved analytically, but must be numerically integrated.

Unfortunately, the kinetic equations usually provide only an *approximate* knowledge of what is really going on in the process. Often, many side reactions occur, sometimes in minor components not supposed to be present or to enter into the reaction at all; these side reactions can very markedly affect the progress of the principal reaction. Or, so *many* components take part in the reactions that it is impossible to solve the very large number of equations involved. At best, the theoretical approach usually provides only a *rough* quantitative idea of the effect of raw material compositions and flow rates on process operation.

Statistical Approach. The other—"statistical"—approach, requires that suitable process operating data be collected and subjected to some kind of regression analysis. These data may be collected from pilot plant operation, from hourly log sheets if the process has operated for some time, or from published literature. Regression analysis, or "curvefitting," involves choice of an arbitrary equation and fitting it to the data as closely as possible. Here, success depends on the reliability and completeness of the data used.

Unfortunately, typical process data is incomplete and imprecise, in that many important process parameters are hard to measure, and are only infrequently measured. Sometimes, factors which actually have important effects on process operation, but which are not known to have any effect at all, are, therefore, not measured. Changes in these factors cause changes in process operation which cannot be understood until this new variation is measured. Process data also is imprecise because of inaccuracy in measuring instruments or in methods used to transcribe data.

Nevertheless, it usually is possible to derive suitable equations.[2 to 10] Remember that the equations do not have to describe the process *exactly;* even *approximate* equations, used full-time to compensate for disturbances, will result in better control than is obtained through conventional automatic control, where an operator makes adjustments based on his limited, qualitative understanding of process operation.

The computer solution involves all the equations mentioned here. The computer control system must measure the uncontrollable variables, must substitute them into the equations, and must solve for values of the controller set-points that will maximize process operation, yet satisfy all constraints. Of course, computation can be very simple or very complicated depending on the character of the equations.

Instrumentation Requirements. Proper instrumentation is a major problem in planning any computer control system. As equations are developed, one learns which process variables are important and must be fed into the computer. Many such variables can be measured with sufficient accuracy and speed using currently-available instruments, or even already-connected instruments. The really difficult measuring problem usually involves physical or chemical characteristics of materials. Here, we investigate on-stream analyzers like chromatographs, mass spectrometers, etc.

In cases where *direct* measurement of some variables is impossible, investigate alternative means. Example: the dielectric constant of some refinery streams may give a good measure of octane number. As a last resort, try hourly, once-per-shift, or daily laboratory analyses, inserted via punched card or tape into the computer. Between such readings, the computer can use values extrapolated from the last few process measurements.

Process Dynamics. A computer control system periodically samples process data. Then, it computes what corrections should be made, and executes them by adjusting the set-points of conventional controllers. The frequency of sampling and the manner of adjustment are specified by proper commands stored in the computer's memory. Sample intervals might vary from two minutes to an hour; process adjustments can be sudden major changes to controller set-points, or very-slowly changing adjustments, as desired.

The sample-data rate and the manner of adjustment by the computer depend on the dynamics of the process and its controlling instruments, and cannot be set without knowledge of these dynamics. Where a complicated process with material and/or energy feedback tends to be unstable, a detailed process-dynamics analysis may be required in planning the control system. Here, it may be necessary to measure process dynamic characteristics, to extensively analyze these and other measurements and even to simulate the process and proposed sampled-data system on a computer. Remember, however, that *exact* knowledge, while desirable, is *not* necessary. An approximate representation of the response to sudden changes of the most important process parts may be enough.

Preliminary Evaluation. When the equations have been derived, suitable instruments found, and process dynamics considered, the proposed computer control system is fairly well defined, and its potential effect on process operation can be roughly evaluated. This evaluation usually is based on "typical" data describing process operation over a data period a week to a month long. Equations developed in the study are tested by substituting measurements taken during the typical data period into the equations, and computing the resulting yield, product qualities, etc. Results are compared with those actually obtained, and the effectiveness of the equations as representations of the process is evaluated.

Next, the effectiveness and value of the equations used in *control* can be estimated. Here, the study team must substitute measurements from the typical data period into the equations, and then solve the equations to learn how the computer control system would have controlled the process. Then, the yield and qualities which *would* have resulted from computer control can be compared with what *actually* happened, and a dollar improvement per week, month, or year calculated. This estimate must be compared with estimates of the value of other, less expensive methods for improving process operation. If its payout is greater than other possibilities, and is sufficient to return the investment in the required time, the computer control system is justified.

Third Step: Installation Engineering

The installation engineering phase of our plan takes the framework established during the detailed study stage, and from it builds a working system. So, installation engineers must complete computer functions specifications: 1. to insure proper fit of the process instrumentation into the computer input-output system; 2. to help work out the process operator's functions; 3. to write out and check out the computer program; and 4. to participate in installation and shakedown.

Computer Functions. The most important function of the computer control system is, of course, *control.* However, several additional functions can be performed if desired, including all those possible with conventional data-logging or data processing systems: printing out data about the state of the process; checking for troubles or process and instrument failures; printing out instrument readings once per hour, or on operator demand; computing and printing out for future reference yield, conversion, efficiencies, catalyst activities, heat-exchanger coefficients or operating guides; printing out hourly or daily averages or totals; collecting and recording data on process operating costs; printing out results or punching them into cards for later accounting department use; checking that variables fall within prescribed limits; checking on *its own operations,* printing out warnings and actuating alarms when it finds trouble.

Instrumentation Problems. The detailed study and final decisions on computer functions determine just what instruments are to be connected to the computer. Each instrument characteristic must be carefully examined: signal level, expected noise, and required accuracy.

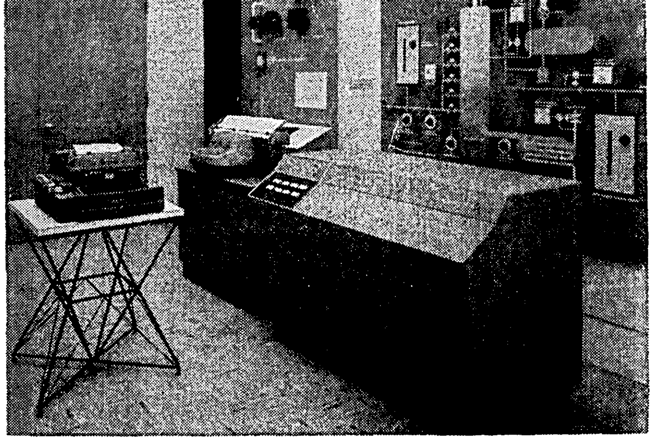

Figure 3. The Thompson Ramo Wooldridge RW-300 Digital Control Computer. Combined typewriter, paper tape punch, and tape reader (left); data-logging typewriter (center).

Of course, different instruments require different treatment. Thermocouple signals must be amplified, and 60-cycle and other noise rejected. For wide-range temperature measurement, it may be necessary to fit a curve, such as ax^2+bx+c, to the voltage-temperature characteristic, and the computer may have to use this curve in interpreting the incoming values. Incoming pneumatic signals must be converted to electrical. Flow signals may require pressure, temperature, or density compensation: these compensations can be carried out by the computer.

Analytical instruments introduce several special problems. Mass spectrometers or infrared analyzers usually provide signals containing several quantities measured simultaneously; the presence of one component may effect the measurement taken on another. In sorting these interactions, it usually is necessary to solve a set of algebraic equations; the computer can solve these easily in the course of exercising control. X-ray spectrometers or gas chromatographs provide *periodic* rather than continous signals. Here, the computer can provide a signal initiating an analysis, and the instrument may signal back to the computer when the analysis is complete, or when it is time for the computer to sample the instrument output.

Often, analytical instrument calibration is a problem because these instruments tend to drift slowly with time. This drift can be compensated by instructing the computer to periodically introduce a sample of known composition into the analyzer, and then to correct the coefficient used in interpreting data from that instrument.

After examining all details of this kind, the character and complexity of the computer's analog and digital input-output systems can be determined exactly, and the computer system assembled. For the Thompson Ramo Wooldridge RW-300 Digital Control Computer (Figure 3), any such input-output system can be built of standard, plug-in circuits merely by connecting them in different configurations. Thus, although each input-output system is different from any other, they all are similar in their use of common, standard components.

Operating Procedures. It is important for several reasons that one or more process operators always be available to supervise the computer control system. So, a set of carefully-defined procedures must be set up, during the installation engineering phase, describing the functions and responsibilities of the operators, and explaining how they are to comumnicate with the control system. The operators involved should help to draw up these procedures, and become familiar with them.

The most common operator intervention is when the operator or process engineer changes the control system. Examples: changes in the number and character of quantities logged, changes in alarm or scanning limits, changes in instrument coefficients. Also, major changes may come about as a result of further analysis of the process, or changes in market conditions, or of changes in the process itself, requiring major modification of the control equation solved by the computer. You must provide means for easily introducing these changes—at least minor ones—into the computer, preferably by use of standard prepunched cards or tape.

Also, it is extremely important to plan for computer and operator action during emergency conditions. Installation engineers must investigate potential instrument failures and evaluate their effects on the control system. They must survey all potential process instabilities and danger signals enunciated by the computer, and arrange that appropriate action be taken They must consider the effect of various computer failures, and arrange that, whether a complete failure occurs (as when the computer power supply fails) or whether some small, hard-to-detect fault appears (as when a single control-system resistor fails), no hazardous conditions can possibly result. The computer must be provided with auxiliary devices which automatically turn it off under specified abnormal conditions, and which hold its controller set-points at their current settings when the computer is suddenly disconnected, so that the least possible process upset occurs. Here, the operator must take over control of the process. Since this may happen infrequently—every couple of months or so—operators must be kept in training for the job of conventional automatic control.

Special rules and procedures should be specified for startup and shutdown of the process. The computer can take part in these operations, either directly by carrying out some routine procedures, or indirectly by printing out pertinent data for operator use during startup and shutdown. When these computer, controller, and operator functions together are worked out in detail, they enable much smoother, quicker startup and shutdown than possible with conventional automatic control.

Computer Programing. When all computer functions are carefully defined, instrumentation is decided on, and computer-operator procedures are established, it is possible to write the set of commands to be stored in the computer's memory.

In planning the program, installation engineers must work closely with computer programers and mathematical analysts. All computational steps must be carefully reviewed and defined (with special attention paid to scaling the data so that all numbers lie in a range the computer can handle), and broken down into independent and relatively simple operations that can be planned and tried one at a time.

Some problems in programing a computer for process control are new and challenging. One difference between process control and scientific, engineering, or business applications, is that the computer's principal function is to operate the process *24 hours a day, 7 days a week*. Such continuing operation on a single set of calculations means that computer functions change slowly. So there need be little emphasis on programing for rapid and frequent insertion of new programs into the computer. A second difference is that the computer, which basically does one thing at a time, very rapidly, is here required to do a great many things in varied sequences depending on the process, on the time of day, and on the operator's needs. To schedule these functions properly, programers must provide the computer with an executive routine which enables it to choose its own sequence of operations.

When all parts of the program are written and checked out *individually*, they must be checked out *together*. This must be done in a manner that simulates typical process conditions. Such check-out must occur before the system is delivered, for there usually will be enough unexpected difficulties during installation without complicating them with an unchecked program.

Installation. The installation engineers must plan the control system installation and start-up very carefully, anticipating all difficulties which might occur. During the first weeks, the process instruments will be connected to the computer inputs, and a special computer program used to check out these connections and log specified instrument readings. Thus, incorrect instrument or computer wiring and any special electrical problems will be caught and corrected. Then, a modified control program will be used to perform exactly the functions the computer control system is to do, except that it *prints out* operating guides rather than making adjustments *directly* on the process. This mode of operation may continue for days or weeks while the operators examine the guides and make adjustments needed. Also, special emergency conditions can be simulated by manipulating computer inputs, and response to these conditions checked for correspondence with those planned.

When the operators and engineers are confident that the computer is operating correctly and reliably, the computer outputs will be connected to the controllers. These connections are made one at a time, enabling operators to observe the results and be sure that everything is going smoothly. This whole procedure must be carefully planned, for you can expect unusual circumstances and conditions that have not been anticipated.

Fourth Step: Operational Evaluation

When the computer is in closed-loop operation, evaluation and revision should begin. Collect and analyze data about process operation to learn whether *actual* benefits are more or less than predicted during planning. Such benefits may be hard to measure because the improvements are small, percentage-wise, and because it is difficut to compare the results obtained *with* the new control system, to those which would have occurred *without* it. But, various periods during the first year under the new controls may be precisely comparable to similar periods during previous years. In any case, the advantages of consistent operation shift by shift, week in and week out, should be apparent.

During evaluation, you should continually try to improve computer control and keep it up to date as changes are made in the process and instrumentation. Computer functions should be periodically reviewed, and new functions substituted as new ideas are generated. Control equations should be studied and improved as you get information on process operation. Such efforts require attention from one completely familiar with the control computer program: only such a person successfully can make the necessary changes.

FUTURE OF COMPUTER CONTROL

If computer control lives up to its promise, many process industries will seek to apply it. It seems that, in ten years or so, a *modern* refinery or chemical plant will contain a computer connected to *every* process unit. Some of these computers may be larger, and more powerful than those available now; others may be smaller and less flexible, depending on the complexity of the process concerned. Supplying data to this group of on-line computers may be a "super-computer" which handles "strategy" rather than "tactics" of the plant. It will determine objectives of each of the process units, using as input-data information on cost and quality of raw materials, product values, inventories, orders, and anticipated market demands, and communicating operating data to the various subsidiary process-control computers.

Operators will still be necessary, and will play an important part in plant operation. Probably the control computers for several process units will be located in a common control room and their functions monitored by a team of operators constantly on the lookout for trouble, and ever ready to take over control from one or more of the processes. Such operators will have to be familiar with computer control system functions, and will have to be regularly drilled in assuming control of the process when the computer is disconnected. Such operators need not be either computer maintenance men or computer programers. But any computer knowledge they possess will be of value to them and their company.

Process engineers will continue to analyze processes to improve their operation, study process economics, and plan plant changes and expansions. Changes in the process will require corresponding changes in the program for the computer which operates it. Thus, control systems will always be up to date and reflect the latest information about the processes they control. Also, when a computer control program has been set up, the process engineer will *know* he can return even several months later to find the process operating exactly as he had planned. The computer control system may have modified some numerical coefficients of the equations to keep them up to date in the face of slight changes in the process. But the computer will not have discarded hard-won knowledge for superficial reasons.

The plan of action outlined in this article for the development and installation of a computer control system involves a number of complicated and difficult steps. But, we believe, the potential benefits awaiting those who solve these problems will repay their efforts many times over.

References

1. "System Characteristics of a Computer-Controller for Use in the Process Industries," W. E. Frady and M. Phister, Jr., *Proceedings of Eastern Joint Computer Conference*, 12/9-13/57, Washington.
2. "Fitting the Computer into a System," M. Phister, Jr., and E. M. Grabbe, *Control Engineering,* Vol. 4, No. 6, 6/57, pp. 129-136.
3. "Digital Computers for Process Control," T. M. Stout and C. G. Laspe, *Industrial and Engineering Chemistry,* Vol. 49, 7/57, pp. 38A-42A.
4. "How to Establish the Control Problem for an On-Line Computer," E. W. James and A. S. Baksenborn, *Control Engineering,* Vol. 4, No. 9, 9/57, pp. 148-159.
5. "Digital Computers in Refinery Process Control," C. G. Laspe, *The Petroleum Engineer,* Vol. 29, No. 10, 9/57, pp. C-30-C-38.
6. "The Digital Computer as a Process Controller," J. W. Tierney, et al, *Control Engineering,* Vol. 4, No. 9, 9/57, pp. 166-175.
7. "Optimizing Control of a Chemical Process," D. P. Eckman and I. Lefkowitz, *Control Engineering,* Vol. 4, No. 9, 9/57, pp. 197-204.
8. "System Considerations in Computer Control of a Semicontinuous Chemical Process," T. M. Stout, *AIEE Conference on Computers in Control,* Atlantic City, 10/57.
9. "Application of Digital Systems to Process Control," M. Phister, Jr., *ISA Meeting, Chemical Petroleum Division,* Wilmington, 2/58.
10. "Mathematical Relationships for Computer Control Systems," T. M. Stout, *ASME Semi-Annual Meeting,* Detroit, 6/58.
11. "Plant and Process Dynamic Characteristics," *Proceedings of a Conference at Cambridge,* 4/4-6/56, by the Society of Instrument Technology, Academic Press, New York, 1957.
12. "A Survey of Techniques for the Analysis of Sampled-Data Control Systems," *IRE Transactions on Automatic Control,* PGAC-2, 2/57, pp. 79-90.
13. "Dynamic Analysis of Heat Exchanger Control," B. D. Hainsworth, et al, *ISA Journal,* Vol. 4, No. 6, 6/57, 230-235.
14. "Frequency-Response Analysis and Controllability of a Chemical Plant," A. R. Aikman, *Transactions, ASME,* 11/54, pp. 1313-1323.
15. "Frequency Response Analysis of a Fractionating Column," A. R. Aikman, *ISA Journal,* Vol. 3, No. 10, 10/56, pp. 412-416.
16. "Programming a Digital Process Control Computer for System Reliability," W. S. Aiken, *Conference on Automation and Computers,* 6/3/58, College of Engineering, University of Texas, Austin.
17. "Reliability Aspects of Digital Computer Process Control Systems," W. S. Aiken, presented at the *Twin Cities PGEC Chapter of the IRE,* 2/26/58.