SOME RECENT DEVELOPMENTS IN DIGITAL CONTROL SYSTEMS

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Introduction

The modern electronic computer is but a dozen years old. Yet this adolescent is recognized as one of the most powerful tools man has ever had at his disposal. The first digital computers were designed for scientific computations where the need for tremendous computing power was very evident. The results of their use can be seen in the developments of our modern technology - jet engines, nuclear power plants, and missiles for defense - these would not be possible without our giant-sized electronic brains.

Some six or seven years ago the idea of using electronic machines for business was new. The need was present, for paper work had grown to amazing size and complexity. Yet, business and industry shied away - considering computers a risk - too expensive and unreliable. It was government agencies that sponsored and used the first electronic computers for business data processing type applications. After a short period of use in which reliable operation and economic benefits were demonstrated, the computer manufacturers and business in general hopped on the band wagon. Management was quick to recognize the benefits of employing this new tool in business. Today there are over six hundred computers being used by business, and the number is growing rapidly.

The use of digital computers for process control is roughly in the same state that computers for business were five or six years ago. The need is present, for processing systems have likewise grown in size and complexity. System variables that are known to interact are controlled independently. The processing industries recognize the power of electronic computers and are certain that they will have broad application in the future (Ref. 1). There is much talk but few companies are willing to risk experimental trials, and again - too expensive and unreliable are the usual objections. We should note that for business applications, computers are far more expensive than any data processing equipment previously available. Their greatest value lies in doing things that could not have been done before. As an example, I can cite a recent business application of computers made by The Ramo-Wooldridge Corporation. Computer solution of inventory level as a function of expected sales and replenishment times leads to savings of $1, 000, 000 in lost sales by redistributing inventory with no change in total inventory, facilities, etc. This involved new techniques - a Monte Carlo analysis that could be carried out only with an electronic computer. In process control, likewise, the greatest benefits of computer control will come from new approaches to control that will improve quality, increase throughput, and reduce operating costs.

There are many cases of analog computers now being used for control applications in industry. For example, in controlling large rolling mills, economic power dispatching systems, complex simulators and trainers for submarine control, etc. (Ref. 2). In many cases this analog computer equipment has been built up without the complete knowledge of the behaviour characteristics of the system. In order to do this, specialists who are familiar with the industrial process in question must draw up equivalent circuits which can be handled by typical analog computer components. The analog computer man alone cannot solve these problems or develop the proper control functions. Hence, in the digital control field it is necessary for teams of digital computer personnel and technical people from the process industries to combine in a working team to properly develop the control conditions and equations which a digital computer can handle.

In my discussion today I would first like to define digital control systems, outline the types and their benefits, and, finally, give the results of recent work in the employment of computers for control.

Types of Digital Control Systems

A digital control system is a system in which the output of the digital system is converted into analog quantities that are used to control a process. The process may be a chemical plant, a steel rolling mill, a machine tool, or a guided missile.

Table I illustrates the possible modes of digital computer system operation with various combinations of digital and analog inputs and outputs.

Table I
Digital Systems

Type of System Input	Type of System Output	System Application	System Examples
1. Digital	Digital	Computing	Scientific and engineering computation, business data processing
2. Analog	Digital	Data reduction	Engineering tests, telemetered data, data logging
3. Digital	Analog	Digital control (director type)	Machine tool control
4. Analog	Analog	Digital control (feedback type)	Chemical process control, flight control

If we examine the inputs and outputs of various types of computer applications we see that scientific computing and business data processing have digital inputs and digital outputs. There is no automatic control, as such, involved.

The second type with analog input and digital output is data reduction. One variety is data logging.

A third application involves digital input but analog output. This is the case of numerically controlled machine tools. Data is fed into the system in digital form, computation is carried out, and digital data is converted into analog signals that control the drives of tables and tools of the machine. Finally, there are control systems in which the inputs are measurements of process parameters that are analog in nature. These are converted into digital numbers, computation is carried out, and digital signals are converted back into analog for control purposes. Hence, we see that one of the characteristics of systems for digital control is the employment of analog-to-digital and digital-to-analog converters.

A characteristic that distinguishes between the third and fourth types of process control is that in director type systems with digital input there is no feedback loop that modifies the input information as shown in Fig. 1. In the case of computers for process control, the computer usually forms part of the feedback loop and its control signals modify the inputs to the system as shown in Fig. 2, although this is not always the case. My remarks will be concerned with process control utilizing analog inputs and outputs. It should be noted that when a digital control system is used, it can also accomplish the functions of a data logger, since digital data is available that can be readily pointed out.

Benefits of Digital Control

The advantages of digital computers for process control may be outlined as follows:

1. Accuracy. Any desired accuracy can be built into a digital system and there is no deterioriation in information during computation. This will give impetus for development of better measuring instruments.

2. Data is in digital form and may be transmitted with ease. Many controllers are of the on-off type that can be actuated by digital signals. The trend toward the employment of digital data loggers lies in the ease of transmitting digital information and the ease of reporting this by print-out when required.

3. The high speed of computation means that computation time can be made very short compared with the time constants of most processes.

4. A high capacity storage is available as part of a computer which can be employed in many ways - for smoothing data, prediction, and self-checking.

5. The program is a stored instruction program in which the details of the computer program can be changed readily without changing equipment in the system. This provides great flexibility for system changes, programmed safety features, etc. Complex multi-variable problems can be solved easily.

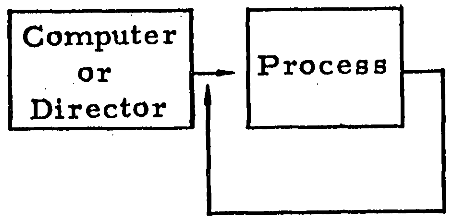


Fig. 1. Digital Control System - Director Type

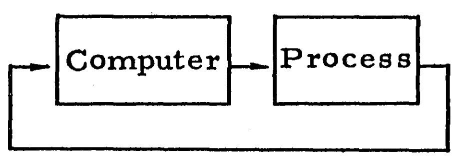


Fig. 2. Digital Control System - Feedback Type

6. A computer can make decisions which permit control for a great variety of modes of operation. The computer can analyze situations of far greater complexity than the human operator is able to cope with.

7. Multiple inputs and outputs can readily be handled by a digital computer at high speeds.

8. General-purpose machines can be applied to a great variety of operations. When necessary, special-purpose machines can be employed.

9. The reliability of present day computers is far higher than that of the human operator. Programming can also be carried out which will provide self-correcting routines so that if the computer occasionally makes a mistake it will correct itself quickly.

10. Experience in digital control systems has shown very clearly that many new techniques can be developed utilizing the above features that cannot be evolved by armchair reasoning. They are the results of operational experience in using a computer for a given application.

I have made little mention of analog computers in this discussion. It is quite certain that analog computers can handle many of the control problems of process industries and, indeed, in many cases it will be more economical and expedient to use analog systems. Combined analog-digital systems also hold promise. One analog computer manufacturer now advertises digital input for setting up problems.

Recent Developments in Digital Process Control Systems

I would like to briefly describe some of the recent results of experience in the employment of computers for process control which point very significantly to the value of digital control systems. This will cover (1) brief status report on military computers, (2) work done during the last two years at the Case Institute, (3) some recent experiments carried on jointly by Burroughs and DuPont, and (4) a preliminary description of a new digital control system under development at The Ramo-Wooldridge Corporation.

1. Military Experience. In the military field, digital computers are being widely used for control of systems - one might say they are essential to modern weapon systems. In principle, the application and characteristics are very similar to those likely to be encountered in many process control industries. They have multiple inputs and outputs, complex relations between the variables, and many modes of control. Contrary to the usual belief that cost is not important in military systems - one reason for the development of digital control in weapon systems is the conviction that in the long run digital systems will be cheaper to produce than analog systems, in addition to having the above listed advantages. Much of the operational experience using digital computers is classified. However, one complete system has been declassified and described in literature. This is the Digitac Control System which employed an airborne

digital computer to control the flight of an aircraft (Ref. 3). A block diagram is shown in Fig. 3. A number of companies have described the details of computers built for military control applications. The most recent of these are transistorized.

The Ramo-Wooldridge Corporation has recently completed an airborne computer designed for military applications. Fig. 4 shows the arithmetic and control unit of the digital computer. The circuitry employs silicon transistors and diodes. Fig. 5 shows several of the plug-in units which compose the arithmetic and control section. Silicon semiconductor devices have great temperature stability, and this equipment is designed to work from minus 50 degrees centigrade to the boiling point of water. Fig. 6 shows the magnetic drum that can be sealed to keep dust out. The total power dissipation of this unit is about 325 watts. The magnetic drum drive takes about half of this power. The heat dissipation is low so that no cooling is required in operating this computer.

Table II lists some of the details of the computer, the number of transistors used, and compares it with a large million-dollar computer, the UNIVAC Scientific. We see that the airborne computer is as fast as the scientific computer, despite the large differences in size and weight. Actually, the large computer was employed to design its smaller brother.

	Airborne Computer	1103 UNIVAC Scientific
Weight (lbs.)	150	40,000
Volume (cu. ft.)	3.5	2300
Power (watts)	325	41,500
Multiplication Speed (μsec)	250	250
Tubes	8	4500
Transistors (no.)	1000	0
Diodes (no.)	5000	6000

Table II. Comparison Between Large UNIVAC Scientific Computer and Airborne Computer

2. Process Automation Project at Case Institute. A project to study employment of computers in process control has recently been completed at Case Institute of Technology (Refs. 4, 5, 6). This project was jointly sponsored by Case Institute, Clevite Corp., Republic Steel Corp., Thompson Products, Inc., and Westinghouse Electric. A team consisting of members of the chemistry, chemical engineering, electrical engineering, and mechanical engineering departments carried out the program.

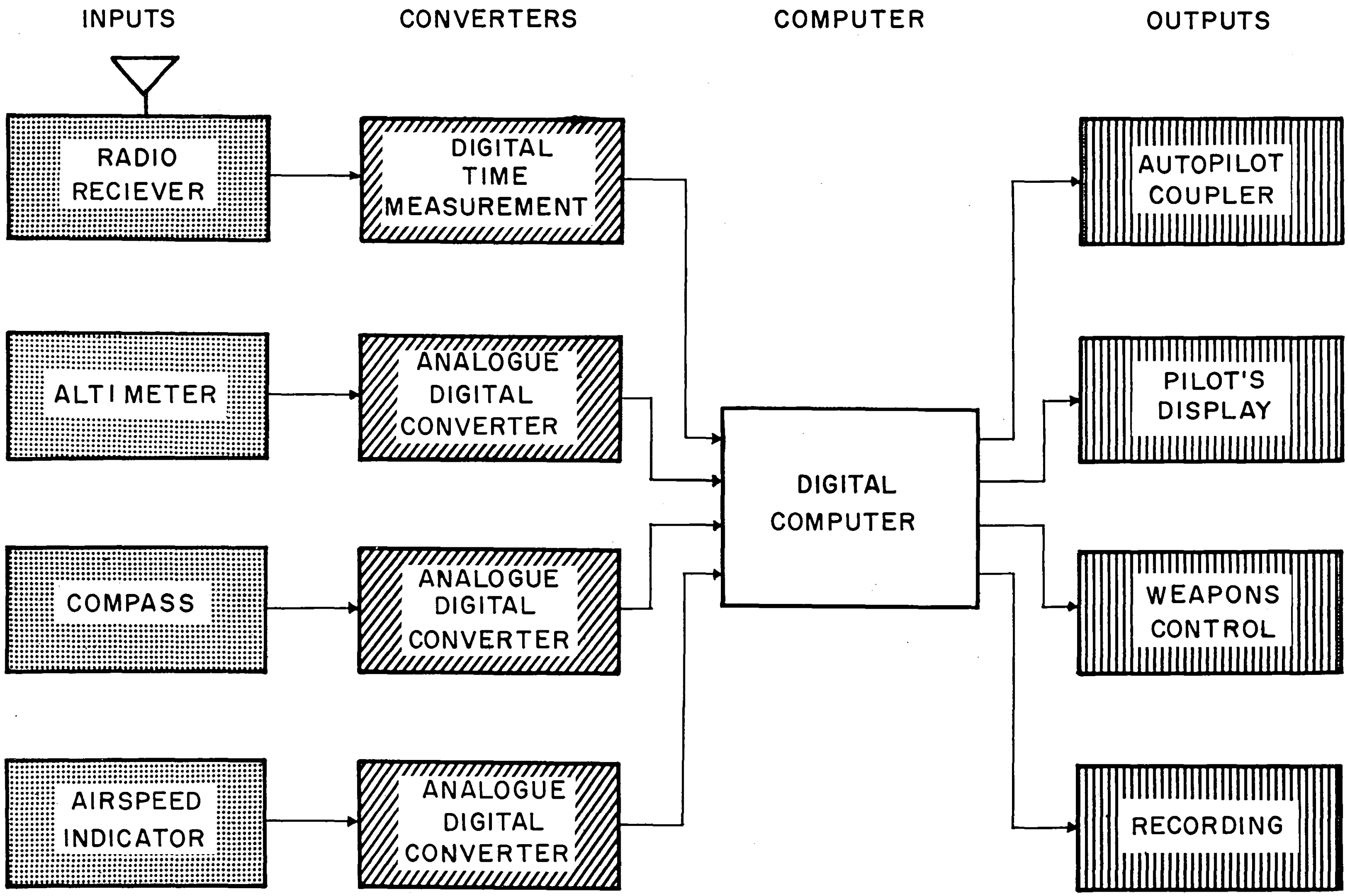


Fig. 3 Schematic Block Diagram of Digital Computer System for Performing Various Control Functions on Aircraft

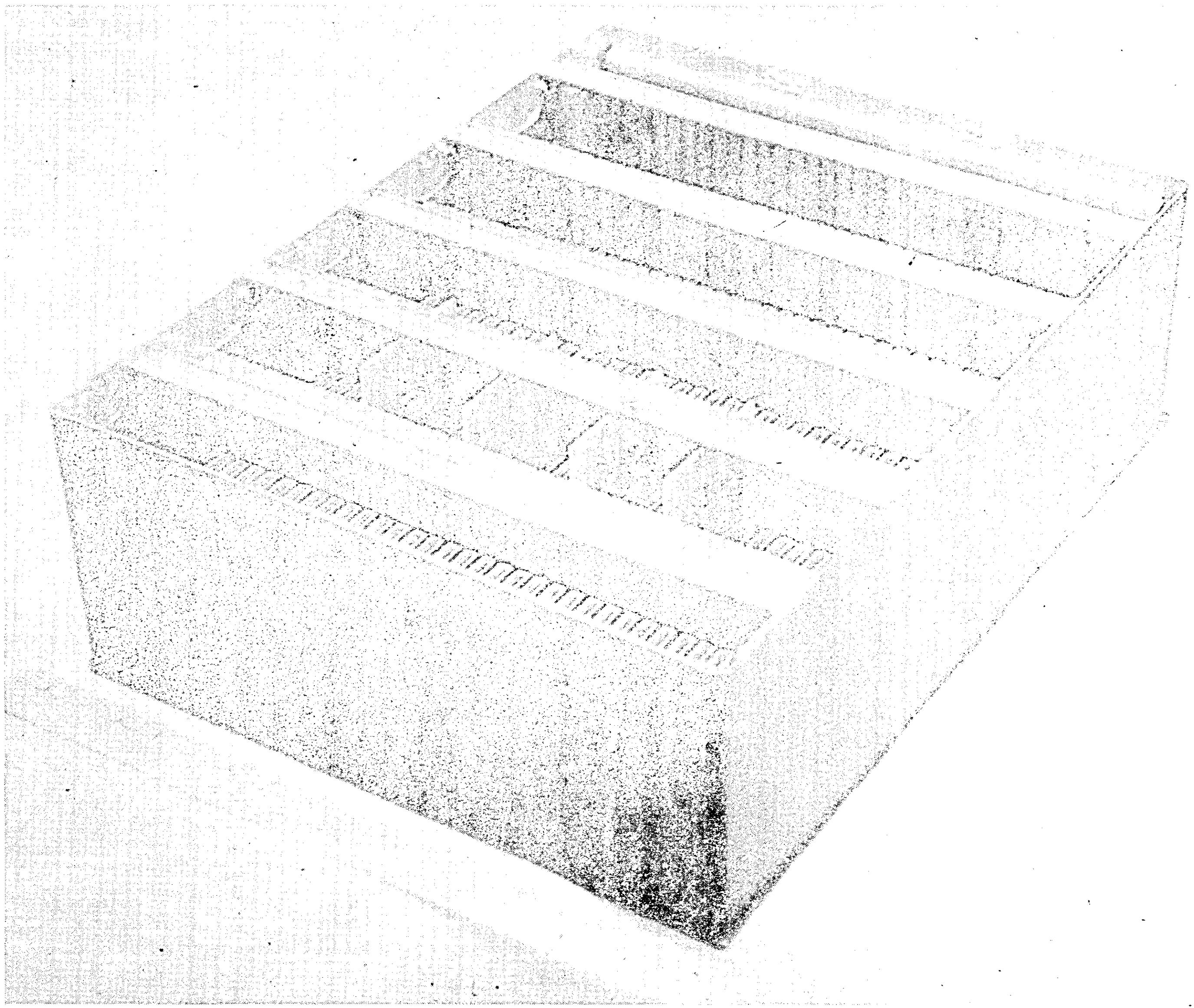


Fig. 4 Arithmetic and Control Unit

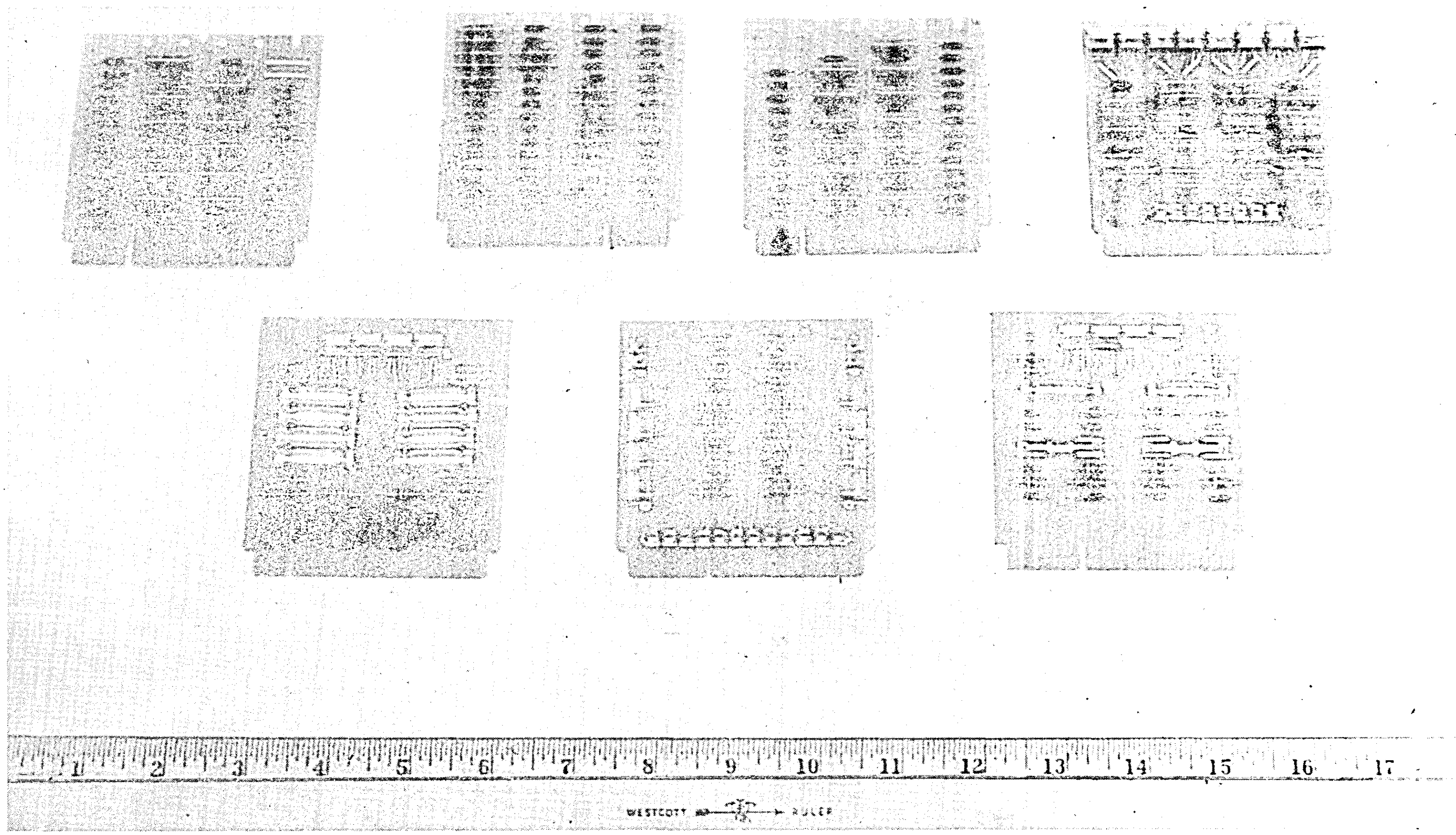


Fig. 5 Typical Printed Circuits

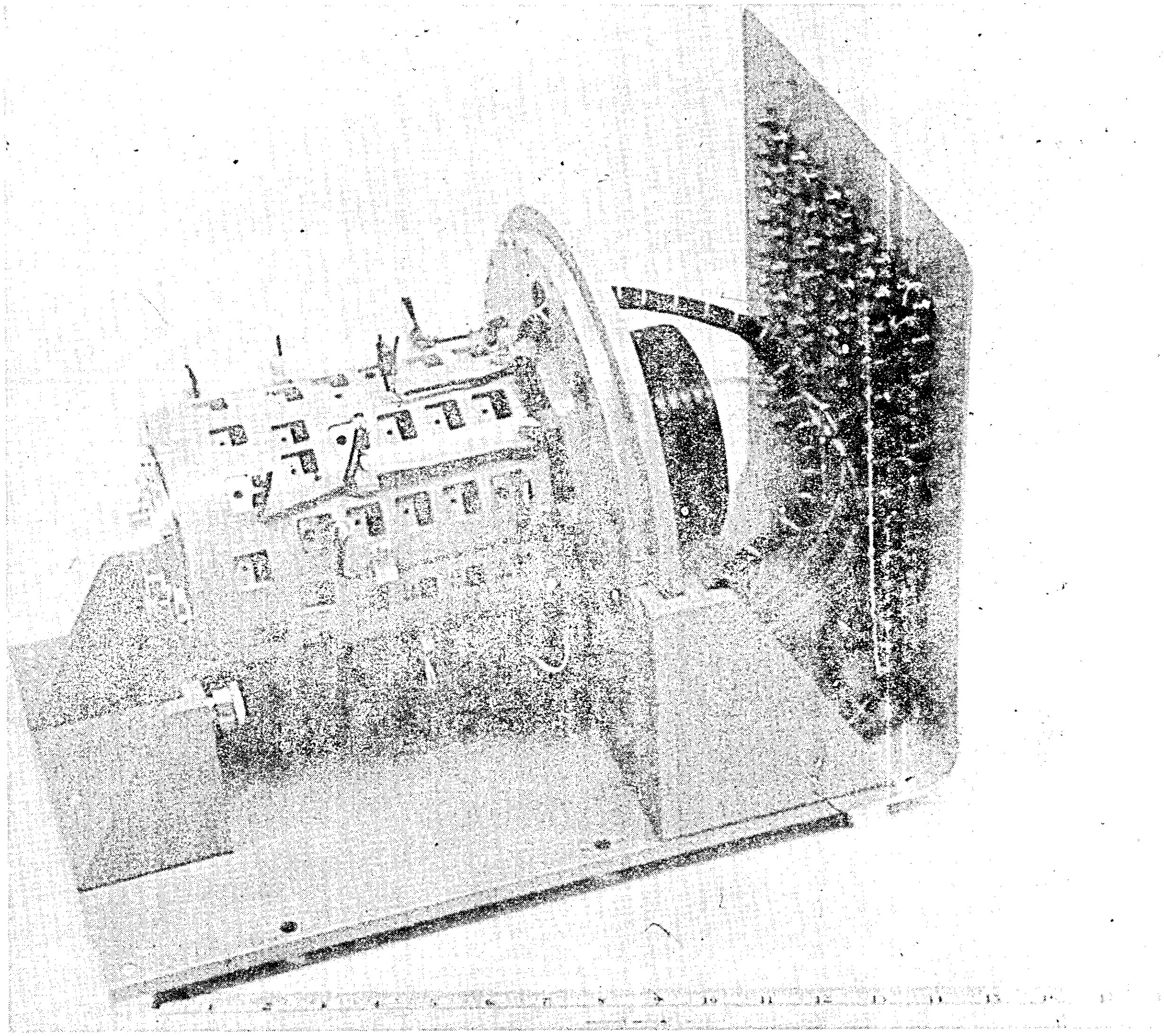


Fig. 6 Magnetic Drum Storage

The objective of the project was to use a computer control system to optimize a batch process. The process chosen was the hydrogenization of cottonseed oil to form oleomargarine. The usual batch process control is shown in Fig. 7. The criterion for optimization is that which would have been normally chosen by management - to complete the process in a minimum length of time, i.e. at the lowest cost. Both analog and digital computers were considered, but an analog computer was chosen for this experiment on the basis of cost and availability several years ago.

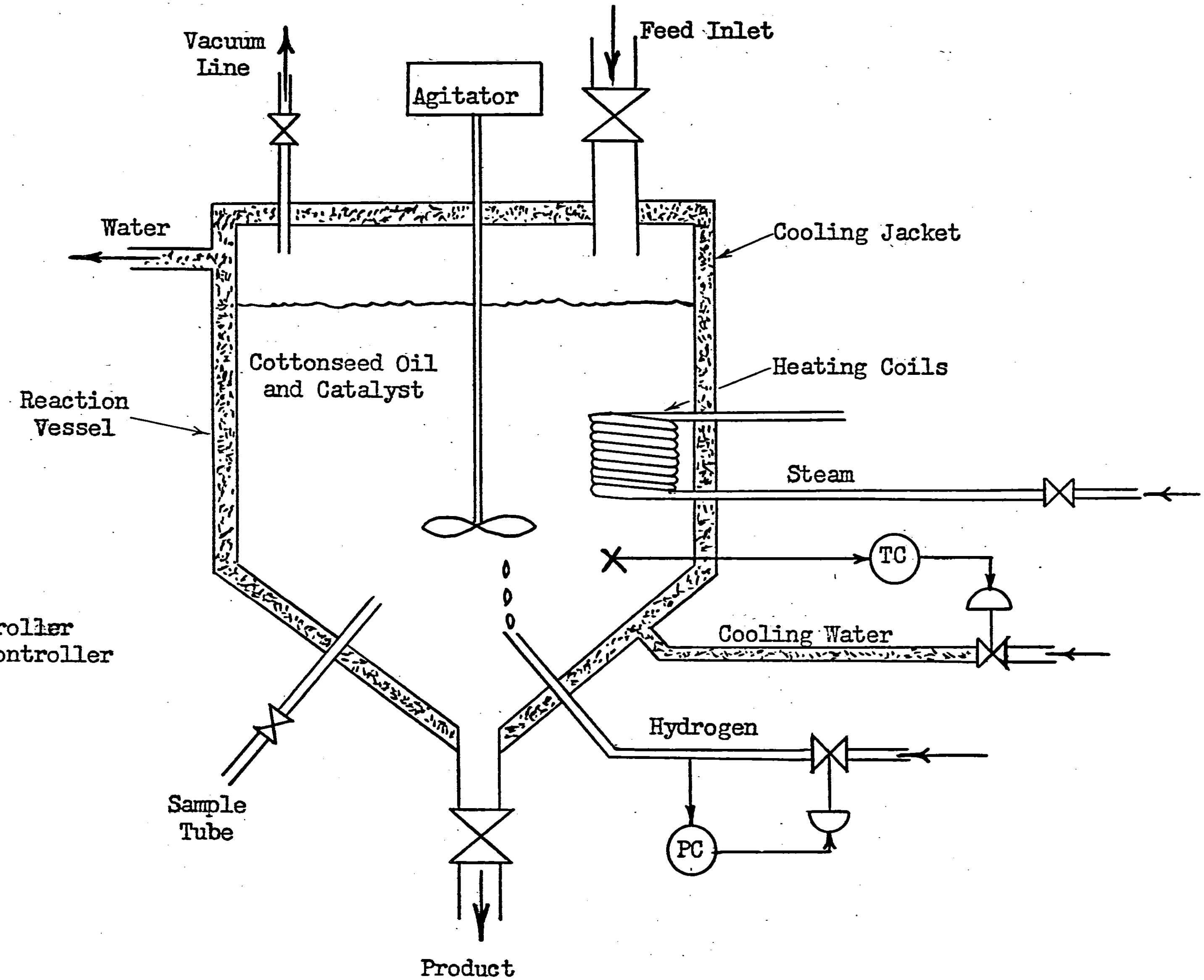
While the process chosen was relatively simple compared with many industrial processes, yet the details of the process kinetics and response characteristics are not known. The variables that express process behaviour were difficult to measure, and statistical fluctuations in the process made it difficult to measure the exact state of process at any one time. Measurements of product composition were made by refractive index and by infrared spectography to compute control of temperature and pressure, as shown in Fig. 8.

The procedure consists basically of setting up the initial conditions and the desired final conditions in the computer. The equation for the process is known only approximately, and the path was derived using calculus of variations. Fig. 9 shows the computed path. The computer was used to control the process along the desired path. If, however, deviations between the two paths occur, the computer recomputes an optimum path by a self-checking computer and guides the system along a new path to the end point.

We can see here similarity between this and experience in the military control field. When an aircraft is being controlled to fly toward a given target and if it deviates from this path or if the wind changes, it does not attempt to go back to the old path but flies a new course which gives the minimum time of approach. Fig. 10 shows a plot of the actual path in test runs. This shows that the experimental points compared with the predicted curve are in good agreement. The workers conclude that the experimental results demonstrate that optimizing for computer control is feasible with existing equipment. In particular, the batch process could be controlled so that a product of desired specification was produced and this was done in a minimum processing time following a path which always provided the optimum path from the point of the process. In concluding, the authors pointed out that total control of the plant would require more automatic instrumentation, a more complex computer, a magnetic drum storage, and provisions for programming start-up and shutdown operations. It is evident from these conclusions that a digital computer would have been a much more flexible tool for a control application of this type.

3. Continuous Process Control. A team of engineers from DuPont and Burroughs has recently carried out an on-line digital computer analysis of a chemical process to investigate requirements for computer, instrumentation, and output (Refs. 6 and 7). The controlled process was a chemical reaction between liquid and gaseous ingredients at the Electrochemical Department of the DuPont Niagara Falls plant, shown in Fig. 11. Eleven measurements

Fig. 7 CONVENTIONAL CONTROL OF HYDROGENATION PROCESS



Code:

PC - Pressure Controller
TC - Temperature Controller

Fig. 8

AUTOMATION OF HYDROGENATION PROCESS (COMPUTER CONTROL)

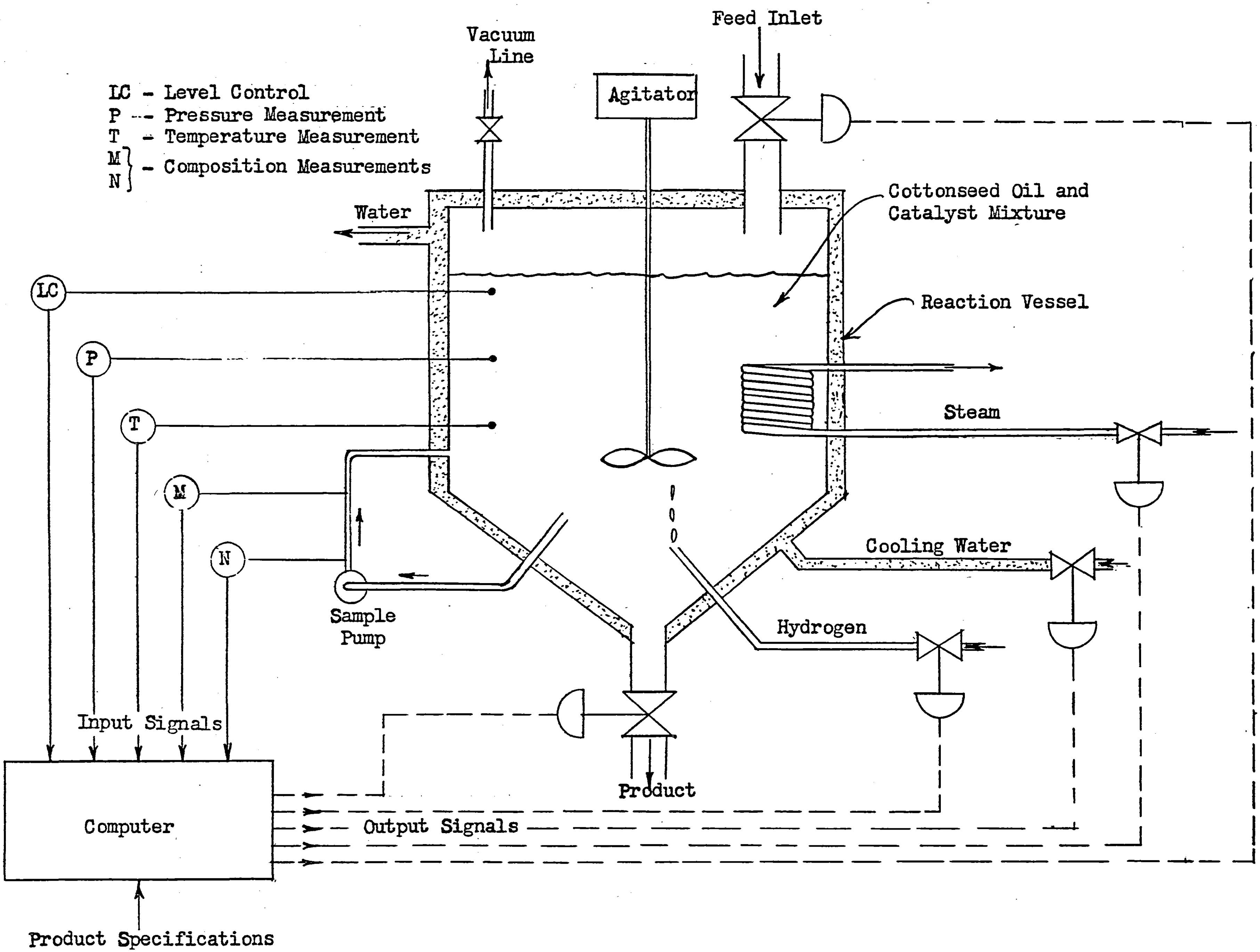


Fig. 9

CALCULATED OPTIMUM PATH FOR 3C - 4R SYSTEM
COMPARISON OF IBM 650 SOLUTION
WITH PHILBRICK COMPUTER SOLUTION

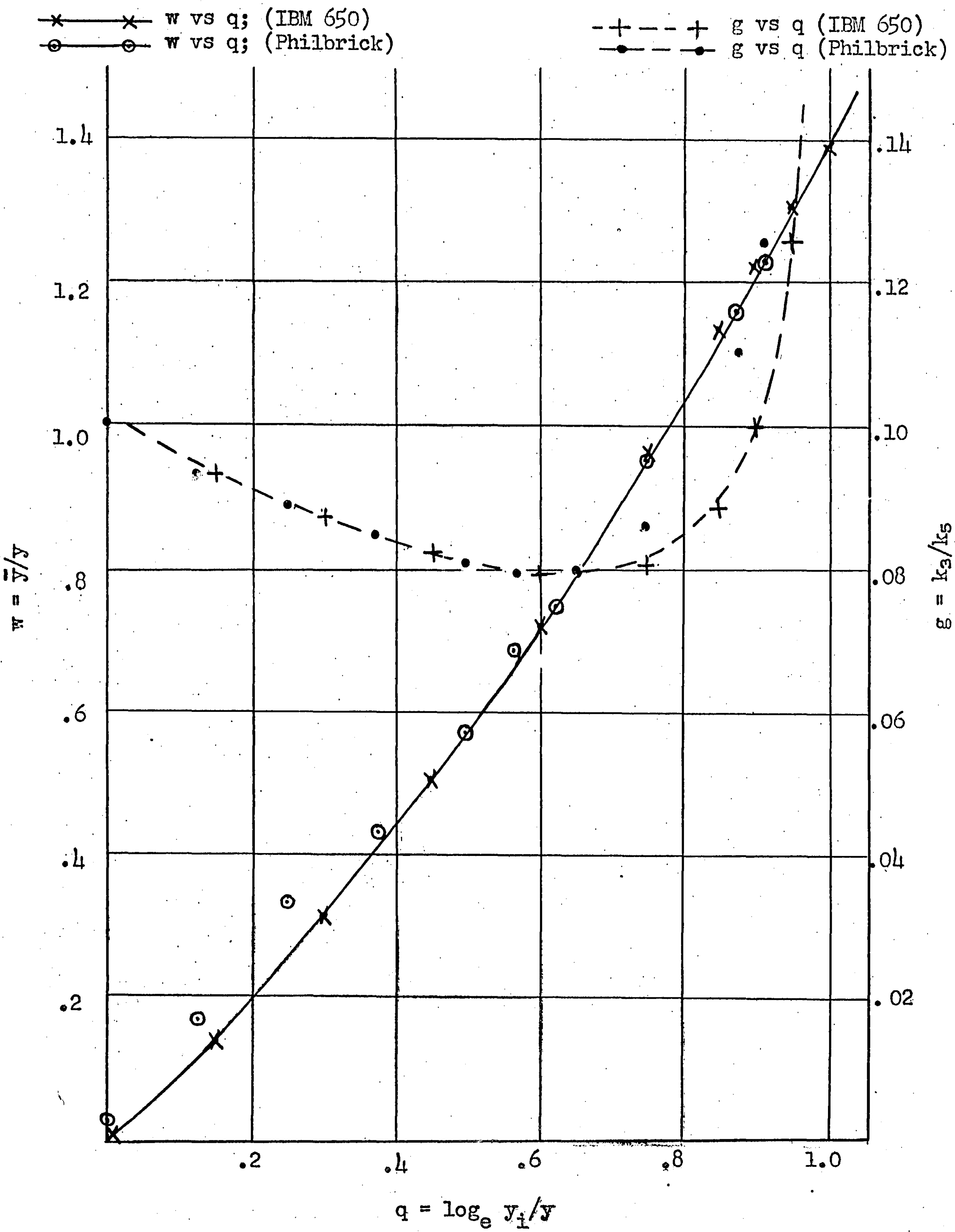
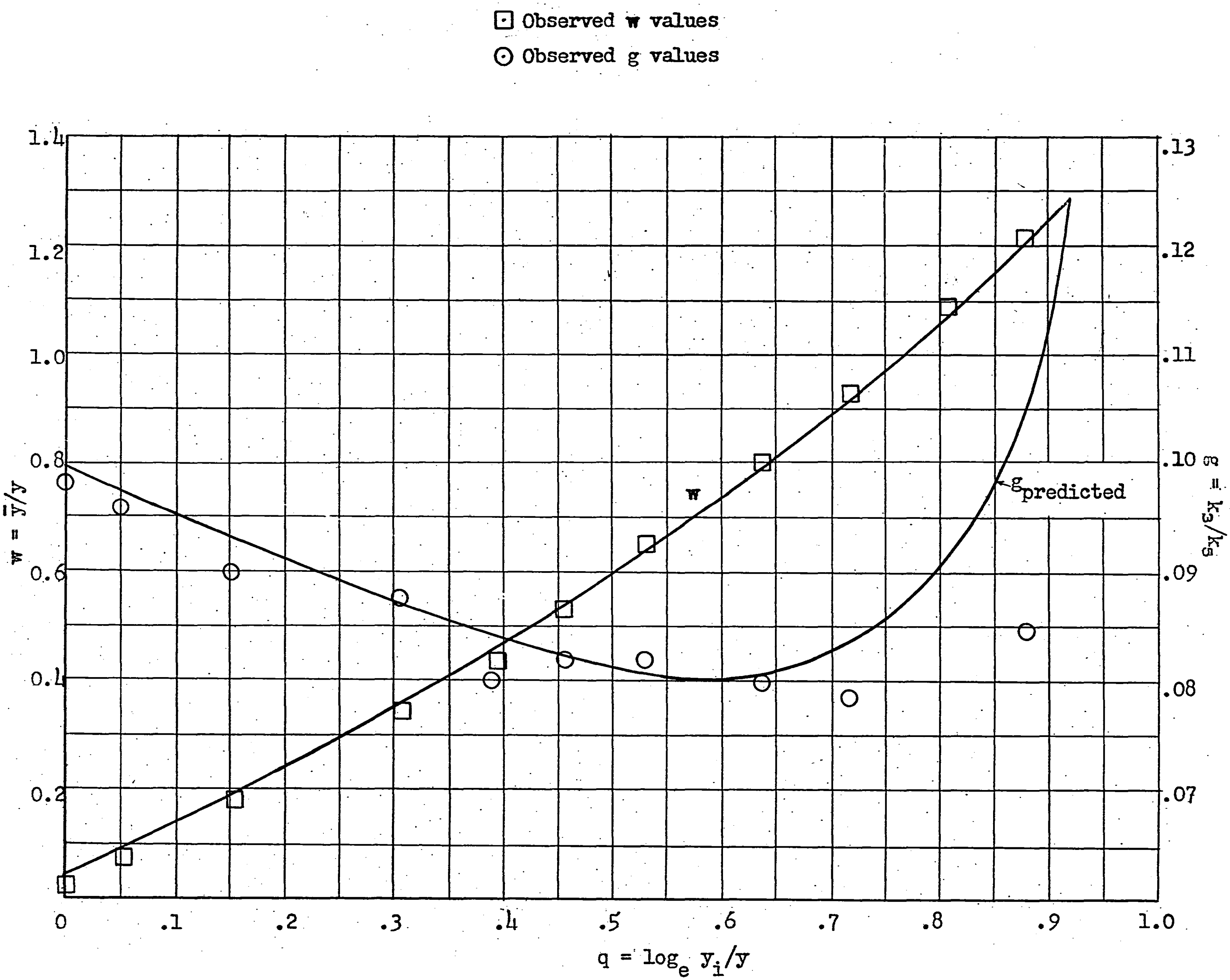


Fig. 10 COMPUTED PATHS FOR PILOT PLANT OPTIMUM PATH RUN



were selected to define the instantaneous state of the process. These were ten liquid levels and one chemical composition of reactor output. These data were transmitted to the Burroughs' general-purpose computer UDEC11 in Philadelphia where flow rates and other calculations were made (see Fig. 12). The results were then transmitted to Wilmington, Delaware and displayed. The results gave continuous data on total production, production rates, raw material used, yield, material balance, and losses.

The computation required about 2, 150 storage locations (1, 800 instructions and 350 numbers), took 20 seconds of computing time, and was repeated every six minutes. Measurement and conversion required about three minutes, and a computation was performed every six minutes. Results were averaged over half-hour intervals. Fig. 13 shows reactor yield and Fig. 14, total production - typical computer outputs.

The results proved the feasibility of digital control of continuous processes and gave data on computer and output requirements. Improvements that could be made in plant instrumentation were also indicated.

4. A New Digital Control System. One great deterrent to the employment of computer control in the process industry has been the lack of availability of a process control computer designed specifically for this type of application. You will note that at Case Institute analog equipment was used because it was cheaper and available at the time. In the Burroughs-DuPont experiment a scientific computer was employed. In general, industries are not willing to pay for the development of special digital computers for process control systems. They consider it too much of a gamble at this stage. Again we might draw a parallel with business. Business did not trust electronics at first - now they embrace it to the point of ordering data processors without knowing what they will be used for. The equipment now in use, even though it may be three or four years old, is reliable. Self-checking is possible, and, in general, we might say that business is quite satisfied with performance.

We have under design in our company, based on our military computer experience, a digital control system designed specifically for industrial control - with high reliability. This digital control system will consist of a digital computer and associated conversion equipment to provide analog inputs and outputs. As such, it can be employed in a great variety of industrial control situations. It will be a serial magnetic drum computer with storage for 8, 000 words. The computer has general purpose stored program capability. A particular feature of its design for industrial process control is its ability to accept in analog form, signals from a large number of process measuring instruments and to furnish in analog form, signals to a large number of process control actuators. A large number of digital inputs and outputs may also be handled. All circuitry will use transistors and diodes. The computer is being developed by a group of computer engineers in cooperation with a team of engineers experienced in the various phases of chemical and industrial process instrumentation and control. We expect to have this system completed by next fall.

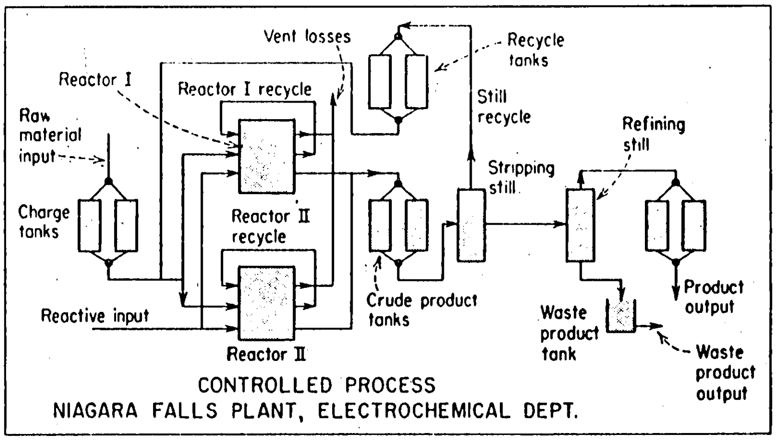


Fig. 11. Controlled Process

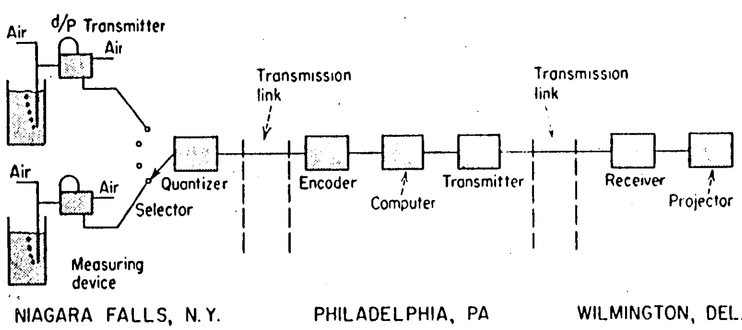


Fig. 12. Computer Control System

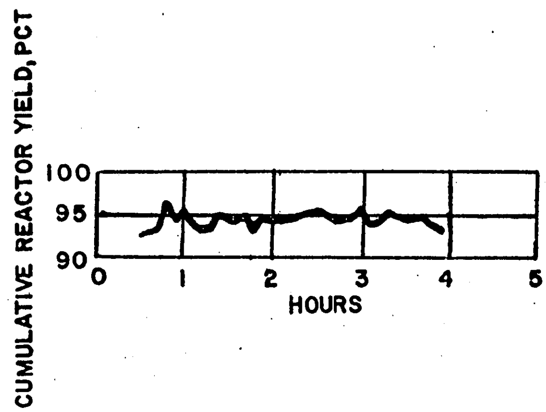


Fig. 13. Computed Cumulative Reactor Yield

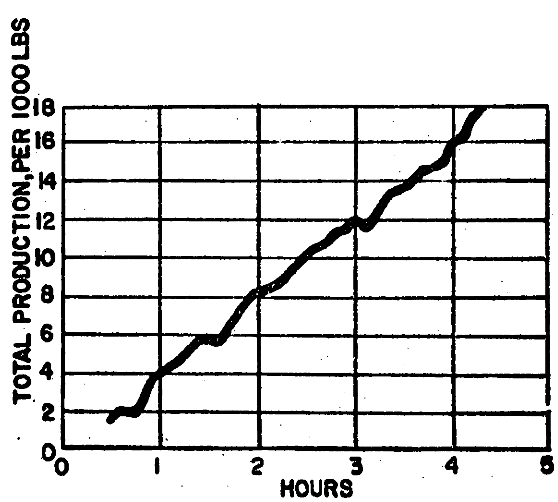


Fig. 14. Total Production During Run

Conclusion

Four developments in digital control that have come about in the last year or so, or that are now under way, have been outlined. These results demonstrate the value of digital control in complex systems. System performance may be optimized even though process dynamics are known only approximately and multi-variable measurements may be combined to compute production and yield rates. Finally, computers designed specifically for process control are under development.

In concluding, I would like to emphasize once more the need for operational experience in employing digital control systems. Our present situation reminds me of the old saying that the time to prune an apple tree is "when the saw is sharp." We have seen a steady sharpening of digital techniques, instrumentation, and knowledge of process dynamics - we are ready for more operational experience.

Note: Figures 11, 12, 13, and 14 are reproduced from
CONTROL ENGINEERING (Refs. 6, 7)
Figures 7, 8, 9, and 10 are taken from Ref. 4

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