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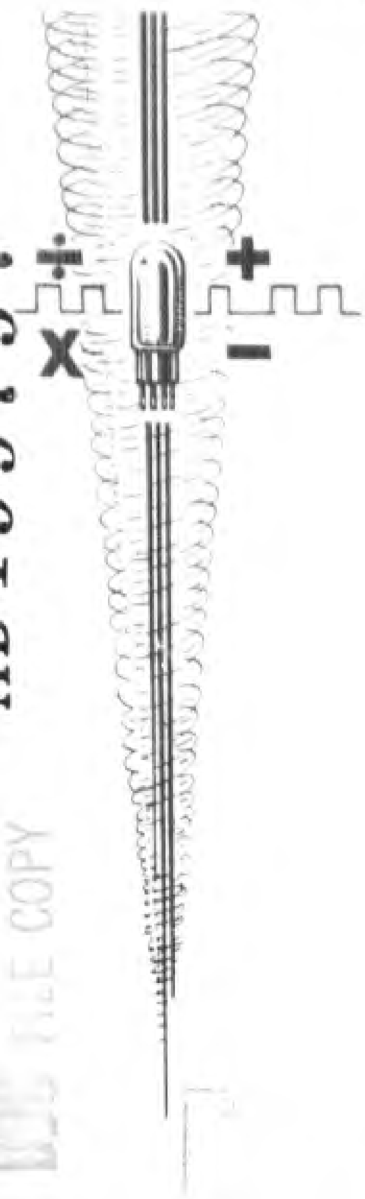
PROJECT WHIRLWIND

Contract N5ori60



SUMMARY REPORT NO. 2

VOLUME 1

THE WHIRLWIND PROGRAM
(PART I)

SERVOMECHANISMS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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1 of 15

PROJECT WHIRLWIND
Summary Report No. 2
November 1947

THE WHIRLWIND PROGRAM, PART I.

Volume 1, of 22 Volumes

Contract N5ori60

Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

R-155

Summary Report No. 2

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Foreword

Summary Report No. 2

Volumes 1 and 2 of this report review project status, objectives, technical development, applications, and facilities. Volume 3 and Volumes 5 through 22 correspond to technical appendices.

The material, in its presentation, presumes a general understanding of digital computers. A glossary is included in this volume. The reader who is unfamiliar with computers may find the introductory material of Volume 4 helpful.

A brief summary of the project is given in Section 1.0, a discussion of the Whirlwind program in 2.0, and a description of the Whirlwind I computer in 3.0.

Volumes 1 and 2 and parts of other volumes are new material not previously available. Many volumes contain technical material from the files. Some discontinuity will be apparent because new text, editing, reproduction, and binding of all 22 volumes have been completed in two and a half weeks to make available information requested on about November first by the Bureau of Standards.

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Glossary

Term	Meaning
Access time	The time required to transfer numbers to or from the storage.
Accumulator	The adding unit of the arithmetic element.
Analogue computer	A computer in which numbers are represented by physical magnitudes such as rotation of a shaft or quantity of charge in a condenser.
Arithmetic element	The part of the computer that performs the actual arithmetic operations.
A-Register	The register in the arithmetic element used to hold numbers coming into the arithmetic element from the bus.
Binary digit	A digit of a binary number. The binary system uses only the digits 0 and 1. Binary numbers contain an average of 2-1/3 times as many digits as corresponding decimal numbers.
Binary number system	A system in which the digits of a number are the coefficients of powers of the base 2; just as in the decimal system, the digits are coefficients of powers of the base 10.
Block diagram	A functional schematic; a drawing or study which is concerned only with the functions of its elements and not with their physical details.
B-Register	The register in the arithmetic element used for holding the multiplier, etc., during arithmetic operations.
Bus	A group of conductors used for transmitting a complete number or order.

Glossary, Continued

Term	Meaning
Carry	A possible overflow in a single digit column following an addition. The carry must be added from one digit column to the next.
Check register	The special register provided for the transfer check.
Control	That part of the computer which controls the operation of the storage and the arithmetic element.
Digital computer	A computer in which quantities are represented numerically.
Electrostatic storage tube	A special cathode ray tube in which binary digits are stored as positive or negative charges on a dielectric plate.
Flip-flop	A two-tube electronic device of which either one tube or the other is conducting but not both. According to which of the tubes is conducting, the flip-flop is said to be storing a 0 or a 1.
Gate tube	A multigrid tube which will conduct only if positive voltages are supplied to all grids. Only two-grid tubes are considered in this report.
High-speed carry	A system in which all carries in all digit columns are executed simultaneously.
Input	The equipment used for supplying information to the computer.
Master clock	The primary source of the pulses which are used to operate the computer.
Matrix switch	A switch for decoding binary numbers which operates by mixing, in a set of diodes or resistors, the outputs of flip-flops holding the binary number.

Glossary, Continued

Term	Meaning
Multiple-length number	A number that occupies more than one register, used for higher accuracy or for alphabetic information.
Multiple-address code	Orders in general consist of an instructional operation code plus the positions or addresses of one or more of the words in the storage. Orders are called single or multiple-address orders depending on whether there are one or more references to storage for each operation.
Operation control	The part of the complete control which directs the arithmetic part of each operation.
Operation matrix	The array of connections which gates the control gate tubes according to the selected position of the operation control switch.
Operation timing matrix	The array of connections which supplies the selected control gate tubes with the proper time pulses.
Order	A coded instruction inserted by the operator and used by the machine in carrying out its arithmetic operations.
Output	The equipment used for extracting information from the computer.
Parallel transmission	The system of data transmission in which the digits of a number are transmitted simultaneously over separate lines, as contrasted to serial transmission.
Program control	The part of the control which sets up each operation prior to its arithmetic execution.

Glossary, Continued

Term	Meaning
Program counter	The part of the computer that selects the next order to be performed.
Program register	The part of the computer used for holding orders after they are extracted from storage but before they are carried out.
Pulse repetition frequency	Number of pulses generated per second.
Register	A group of elements used in the machine to store a single number or order
Scale factor	The multiplier associated with each number in the machine used to force these numbers to occupy the limited range of a machine register.
Serial programming	Execution of complete arithmetic operations one at a time. Coding is simpler and easier to organize where simultaneous arithmetic operations are avoided. Serial programming is possible with either parallel or serial digit transmission. The alternate or multiple programming is sometimes used to increase computer speed.
Serial transmission	The system of data transmission in which the digits of a number are transmitted in sequence over a single line as contrasted to parallel digit transmission.
Shift	Movement of a number in a register one or more places to right or left; equivalent to multiplying or dividing the number by a power of 2.
Sign digit	A single digit of a machine number used to designate algebraic sign.

Glossary, Continued

Term	Meaning
Simulation	The representation of physical systems by a computer. For further information see Section 1.1.
Single-address code	Orders in general consist of an instructional operation code plus the positions or addresses of one or more of the words in the storage. Orders are called single- or multiple-address orders depending on whether there are one or more references to storage for each operation.
Step counter	The binary counter used in the arithmetic element to count the steps in multiplication, division, and shift operations.
Storage	That part of the computer that holds the numbers and orders used by the computer. It is made up of a number of storage registers.
Subprogram	A subsidiary sequence of orders which may be inserted in the main sequence of orders whenever desired.
Three-address code	See multiple-address code.
Time pulse distributor; Time pulse	A device for distributing clock pulses on to a set of lines in some fixed sequence; the resulting pulses.
Toggle-switch storage	The 27 toggle-switch registers making up part of the test storage.
Transfer	The transmission of a number from one register to another.
Trigger	A sharp pulse used for initiating a switching operation.
Word	The several digits making up a number or order.

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R Series Memorandums

1.0 Summary

Project Whirlwind at the Massachusetts Institute of Technology Servomechanisms Laboratory is sponsored by the Special Devices Center of the Office of Naval Research. The Project is engaged in the study and design of simulation and control systems involving high-speed electronic digital computers. The greater part of the Project effort is at present directed toward the design of such computers.

The original objective of the Project when started in December 1944 was the construction of a simulator to predict the flight characteristics of large aircraft. Electrical analogue computing equipment similar to that used in some fire-control computers was first proposed but was discarded as unsuited to a problem as complicated as the aircraft simulator. It was realized that the required capacity and sensitivity could only be obtained by the use of numerical computation methods. Equipment and techniques originally developed for radar made possible the necessary high computing speeds.

The electronic digital computers under investigation are so universal and flexible in their applications that the scope of the Project has been extended to the study of other problems. These other applications include air traffic control, Army and Navy War College combat simulators, guided missile data reduction, Census Bureau problems, and logistics computations. These new problems require digital computers and associated data conversion equipment which are no different from the equipment being developed for the aircraft simulator. The computers will also be entirely suitable for scientific and engineering calculations including statistical research.

The most important element of these simulation and control systems is a properly designed electronic computer. Designs contemplated include provision of storage capacities of as much as 16,000, 10-digit decimal numbers and computing rates as high as 25,000 multiplications per second. Design and construction is now proceeding on a prototype computer called Whirlwind I. This computer will have a storage capacity of 2,000, 5-digit decimal numbers and a computing rate of 20,000 multiplications per second. All computers contemplated can be set up for new problems in a matter of minutes, using previously prepared photographic input films.

Technically Whirlwind I is of the parallel-digit-transmission type, uses electrostatic storage tubes for storing numbers and orders, and operates in the binary instead of the decimal number system. Automatic conversion equipment is being provided at film preparation units so that the human operator need handle only decimal numbers.

An aircraft cockpit and control equipment is being built to study the aircraft control problem. Full scale solution of aircraft stability must await a larger computer than Whirlwind I. It is planned that Whirlwind I and at least part of the associated simulation equipment will be operating by January 1949.

Sections of a Whirlwind type computing element have been built and are satisfactorily passing tests. The electrostatic storage tube, which is being developed at M.I.T., is progressing on the desired time schedule. Its status is now between the research and development phases. Small tubes have been built and have proved successful. Work is proceeding on larger tubes with faster operation. Special electronic circuits have been developed and are operating satisfactorily.

Automatic checking of computer operation, and inspection methods for detecting marginal operation are being incorporated.

Mathematical research into problems of most urgent interest is part of the Project work. Training in digital computers and their applications is included in the Project and the M.I.T. academic activities.

1.1 The Simulation Problem

The primary objective of Project Whirlwind is to develop simulation and control systems based on digital computers. The immediate objective is to provide a computer for simulating in detail the flight of aircraft on a real time scale.

As the term is used here, simulation is the substitution of a computational process for some real physical process. In flight simulation, a computational process that solves equations describing the flight of an airplane is substituted for the real flight of the airplane.

Simulation constitutes a means for setting up in the laboratory a working model of a complex process. This working model is a means for studying the behavior of the process, developing equipment for controlling the process, and training human operators to control the process.

Two phases exist in nearly all simulation problems -- the study of human reactions, and the representation of a physical system. In aircraft simulation for example, primary stress is on the physical aircraft representation but evaluation is based on the human pilot reactions. In simulators used for personnel training, on the other hand, primary stress is on the human element although here again the proper physical environment is provided by the simulator.

Drawing A-31203 shows the elements of any simulator system. Captions illustrate the aircraft control and stability simulator. A flexible computer with complete generality of internal organization is programmed to execute the control and computation operations required for the problem. Input mechanisms receive the data and control code to describe the problem. In operation, inputs are continuously received through physical-to-numerical converters from the specialized simulation setup. These inputs provide the human variable of the problem. Outputs are sent to display units for the human operators and are also recorded for study and reference.

The computer with its input, output, and conversion equipment is the heart of the simulation system. It is non-specialized and can serve without alteration in many different simulation systems. The display and actuation equipment is designed for the particular simulation problem. See Section 6.0.

The computer part of the simulator is identical with that required in control systems.

1.2 The Control Problem

Control corresponds in many ways to simulation. The computer can be identical and other physical equipment may be similar. In control, the computer is not substituting for a missing part of the system but is an active and necessary part of the system operation. The digital computer as a control device will correlate available information on the process being controlled, will predict according to prescribed rules, and will actuate the desired controls and displays. See Section 3.0 and 6.0 for discussion of control and its application to air traffic, industrial processes, power plants, and accounting.

The great computing capacity of an electronic digital machine can be utilized to control processes whose complication is beyond the scope of present day analogue controllers. These processes include those where the amount of calculation required for the correlation of information is large or where the sensitivity of control must be very great. A digital computer is also capable of providing accurate compensation for non-linear closed loop systems and can execute any logical operations which are specified.

Where the number of controlled quantities is large a digital computer will be less expensive, smaller, and lighter in weight, than equivalent analogue controllers, even when these latter can do the work. The generality and flexibility of the digital computer permits ready change from job to job as circumstances require. The obsolescence rate on digital computers for control should be low since the basic computer is independent of obsolescence of the processes and equipment controlled.

2.0 The Whirlwind Program

Present project work is devoted to design and construction of the Whirlwind I computer, its associated equipment, and its application to problems of principal interest. The Whirlwind I equipment is being designed as a prototype of the system selected for use in simulation and control. However it will have capacity for many actual problems of interest and for preliminary study of more complex problems. Particular attention is given to engineering design, packaging, servicing ease, checking, and trouble location New designs following Whirlwind I will increase machine capacity and reduce physical size.

The most important mathematical problems are being formulated and coded. Block diagrams of the Whirlwind I computer are nearly completed. Electrostatic storage tubes will be constructed at the Servomechanisms Laboratory. An aircraft cockpit complete with indicating instruments and control force loading servos is being designed.

Sylvania Electric Products, Inc., is designing parts of Whirlwind I and will construct most of the system.

Photographic input and output equipment will come from the Eastman Kodak Company.

Over 40 staff members are engaged in Project Whirlwind work at M.I.T. To house this activity, M.I.T. has recently purchased the Barta Building on Massachusetts Avenue to permit expansion of the Servomechanisms Laboratory facilities. Section 10.0 treats personnel and facilities in detail.

Training of new personnel in the design and use of computers is an essential part of the program. Training and academic work are discussed in Section 8.0

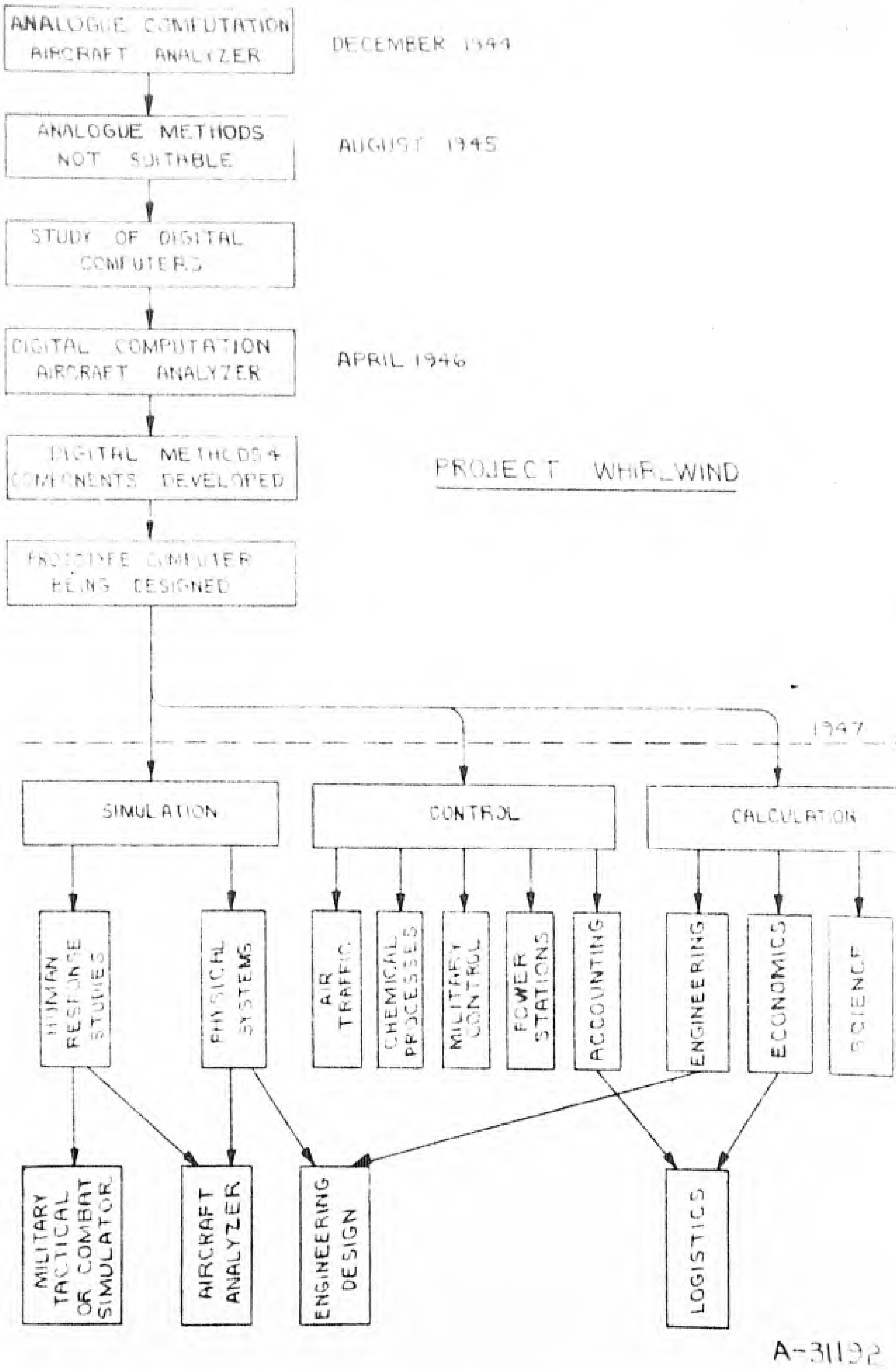
A long-range viewpoint has been adopted, and stress has been laid on obtaining the proper components for a computing machine of high performance and maximum reliability. A parallel-digit transmission system rather than a serial system has been adopted as most satisfactory for the Whirlwind requirements. Likewise, the system is being designed around electrostatic storage tubes of new design rather than the less suitable storage components already in existence.

Magnetic intermediate storage as an erasable medium may be required in certain future applications of the Whirlwind system. Magnetic studies are being conducted as part of the program, and equipment developed at other computer research centers can be utilized in future applications.

The Whirlwind I computer will be followed by Whirlwind II, plans for which are not fully established. The Whirlwind II computer has been tentatively referred to as having a register length of 40 binary digits and a storage capacity of 640,000 binary digits. These tentative specifications will be revised to fit the problems of greatest interest before final design is undertaken. The more pressing problems in simulation and control indicate a machine with a shorter register length than originally planned. The next design following Whirlwind I is expected to have a register length longer than 16 digits of Whirlwind I, and equivalent or higher computing speed. In physical form it will be much more compact and may be semi-mobile.

2.1 Review of Preliminary Investigations

The evolution of the Whirlwind Program is illustrated in Drawing A-31192. The contract was undertaken in December 1944 for the development of an aircraft stability and control analyzer based on analogue computing equipment. This work is reviewed in


ANALOGUE COMPUTATION AIRCRAFT ANALYZER
DECEMBER 1944
ANALOGUE METHODS NOT SUITABLE
AUGUST 1945
STUDY OF DIGITAL COMPUTERS
DIGITAL COMPUTATION AIRCRAFT ANALYZER
APRIL 1946
DIGITAL METHODS & COMPONENTS DEVELOPED
PROJECT WHIRLWIND
PROTOTYPE COMPUTER BEING DESIGNED
1947
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CONTROL
CALCULATION
HUMAN RESPONSE STUDIES
PHYSICAL SYSTEMS
AIR TRAFFIC
CHEMICAL PROCESSES
MILITARY CONTROL
POWER STATIONS
ACCOUNTING
ENGINEERING
ECONOMICS
SCIENCE
MILITARY TACTICAL OR COMBAT SIMULATOR
AIRCRAFT ANALYZER
ENGINEERING DESIGN
LOGISTICS

A-31192

Volume 3, Summary Report No. 1. Approximately nine months of study demonstrated that analogue computation was unsuited to the aircraft simulation problem. Sufficient analogue computing equipment for solution of the aircraft equations could not be assembled into one working unit. The required non-linear functions of several variables proved especially difficult to organize on an analogue computing basis.

In the fall of 1945 digital computation was recognized as the only probable solution to large-scale simulation problems. Discussion with Dr. H. H. Goldstine, then with Army Ordnance, and with Dr. John von Neumann of the Institute for Advanced Study were especially helpful at this period of Project Whirlwind development. By April 1946 it was concluded that the aircraft stability and control analyzer could be handled by digital computation.

During the course of the digital computer studies the aircraft simulation problem was investigated by members of the Servomechanisms Laboratory, the Aeronautical Engineering Department, and the Mathematics Department of M.I.T.

The numerical ranges of variables in the aircraft problem were investigated and are reported in Volume 14, R-49. The results of this work formed the basis of a scale factor study in reducing the aircraft simulation to digital computing machine terms. An actual airplane model was tested in the Wright Brothers Wind Tunnel to obtain the data necessary for complete aircraft simulation. The wind tunnel data required is much more extensive than normally taken in engineering studies of aircraft models. The results of these wind tunnel studies for the particular model under test are given in Volume 14, R-98. The equations of motion selected to represent an airplane are given in the appendix to Volume 3 and in Volume 14. The equations include many functions of several variables to be measured by wind tunnel tests.

The complete set of flight equations for aircraft simulation were coded in the terms required for a serial type digital computer. This coding is summarized in Volume 14, C-15, and formed the basis for establishing required storage capacity and computing speed in a digital machine. It was found that a multiplication time of 50 microseconds or less, including transfers, would be required. To permit sufficiently rapid access to stored data, the function tables for presenting the aircraft must be stored in the high-speed internal memory. A storage capacity of at least 10,000 numbers of about 30 binary digits each is required to contain both the initial data and the controlling program.

A serial type digital computer was first considered and was discarded in favor of a parallel machine. A comparison of parallel and serial machines will be found in the following section.

Selection of digital computation for the aircraft simulation problem opened up vast new fields of application for the equipment under development. These might be divided into:

A. Simulation

B. Control

C. Calculation

The applications to simulation and to control are of principal interest to Project Whirlwind. However, a natural by-product of the equipment necessary in these two fields is the computing equipment required for calculation in engineering, science, and economics.

Simulation is distinguished from other applications of computers primarily by the presence of human beings in the process being studied, and by the necessity for a real-time scale of the solution. These two overlapping aspects of simulation can be divided into (1) human response studies and (2) studies on physical systems. Simulation embodies both the human and physical elements in varying degrees. A military tactical or combat simulator might be primarily concerned with command functions and the training and evaluation of persons responsible for decisions. The original problem of aircraft simulation must on the other hand stress the behavior and reality of the aircraft as physical equipment.

The field of control is a broad one, including such diverse applications as air traffic, chemical processes, military equipment, power stations, and fiscal control or accounting. As indicated in the figure, most practical problems involve a combination of several of these divisions.

The greatest long-range contribution of computing equipment may be in the field of calculation relating to engineering and to the physical and social sciences. The greatest amount of equipment will, however, find its way into the simulation and control functions.

A prototype is considered necessary for initial design and application studies of a parallel type computer. As with most digital computers, a small machine is impractical to build. Once a satisfactory control system has been established, at least half of the equipment necessary for a useful computer is in existence. The Whirlwind I system has been designed as a compromise between a small computer for study purposes and a large machine for handling problems of immediate interest. A small machine of the parallel type means a short number register length. The register length of Whirlwind I was selected to give a satisfactory order length for controlling the desired amount of storage and for providing a satisfactory number of control operations. The number or word length is 16 binary digits, making possible the control of 2,048 storage registers of 16 binary digits each and making available 32 control orders. Whirlwind I will incorporate more internal storage than any existing computer. Its storage capacity and speed are satisfactory for initial studies in most simulation and control problems. For the use of Whirlwind I in the study of aircraft simulation see Volume 14, M-148 and M-65. For the relationship of Whirlwind I to air traffic control, see Section 6.1 in this volume. Studies to date indicate that a high-speed computer of the Whirlwind type with somewhat greater storage capacity and register length than Whirlwind I will probably be best suited to most simulation and control problems. Because these machines can be operated with multiple-length numbers for high precision, they will likewise meet most computation requirements.

2.2 Parallel versus Serial Computer

An extensive study of serial computing systems was made before selecting a parallel system for Project Whirlwind. Some of the results of this serial study are outlined in Volume 7, E-24. The serial machine considered used a three-address code in order to obtain higher operating speed. Multiple-address codes are less inefficient than a single address code and are considered undesirable. To obtain the required computing speeds for the Whirlwind problems, the machine on a serial basis became much too complicated.

A heavy computing load exists in nearly all simulation and control problems being considered. Where a computing load sufficient to occupy the time of a high-speed parallel machine exists, it can be shown that the parallel computer uses its circuit components more efficiently than the serial system.

In any practical machine, the parallel computer is larger in physical size than the serial. However, as shown below, the computing capacity per unit of circuit components is much higher in the parallel than in the serial machine. Although larger, the parallel machine is actually no more complex in organization and arrangement than the serial machine, since both must have a control capable of carrying out the same types of operations. The serial machine tends to be composed of many different types of electronic circuits whereas the additional size of the parallel machine requires only duplicating circuits, especially in the arithmetic element.

Efficiency in the serial machine is low because circuit components can be used only a small fraction of the time. During much of the operating time, circuit components in a serial machine using delay type storage are inactive while waiting for stored quantities to become available at the output of the delay units. Efficiency is further reduced in the serial machine because the rather complex control equipment capable of carrying out high-speed operations is inherently limited in its speed by the associated storage and arithmetic units.

The following tabulation is set up for a computer typical of those which may follow Whirlwind I for many simulation and control problems. Two thousand storage registers of 20 binary digits each have been selected for discussion. Estimates for tubes in the parallel system are obtained from the figures in Volume 16, M-132. Twenty-five percent has been added to those tube used in parts of the system which would be increased from 16 to 20 units. The vacuum-tube flip-flop and toggle-switch storage inserted in Whirlwind I for test purposes have been omitted. Neither the parallel nor serial estimate includes input and output equipment, since type and number might be special to the particular application and would be used at comparable efficiencies in the two machines. In some classes of problems, the parallel computer can control and effectively use a larger number of input and output units than can the serial computer. Estimates for the serial system are based on the best available information, and are approximately correct.

	Parallel	Serial (Estimates)
Tubes in Control including Storage Switching	1100	500
Tubes in Arithmetic Element	1300	300
Tubes in Storage System	500	400
Total Tubes not including Input and Output	2900	1200
Multiplications per second	20,000	1200
Multiplication per second per Tube	6.9	1.0

$$\text{Efficiency Ratio} = \frac{\text{Parallel}}{\text{Serial}} = \frac{6.9}{1}$$

It will be seen from these figures that where a sufficient computing load exists, the parallel system shows approximately a 7 to 1 advantage over a serial system in capacity per vacuum tube. Since the types of circuits are similar in either case, the number of tubes can be taken as a reasonable basis for comparing total cost.

Other secondary advantages accrue to the parallel machine. The design can be readily extended to more digits per word because timing and control does not depend on word length as in supersonic and magnetic drum storage of the delay type. The register length can be increased by simply adding equipment for the extra digit columns. High speed is obtained while still maintaining the serial or step-by-step programming sequence. This, along with the single-address code, simplifies problem setup and coding. The simultaneous availability of the setup and coding. The simultaneous availability of the sign digit and the entire numerical value of a number is advantageous in reducing computing time for certain operations. For trouble-location purposes, the parallel computer can be more readily operated on a pulse-by-pulse basis from a push button control. Operation of the computer below a certain maximum speed is independent of repetition rate, and close temperature control is not necessary as with mercury delay lines.

3.0 Whirlwind I

Whirlwind I is a prototype computer being constructed to test the engineering principles of the Whirlwind System and for research into computer applications. In Whirlwind I will be tested the results of the research and engineering design reported in Volumes 3 through 19. A general description of Whirlwind I follows in the next section. Block diagrams for the arithmetic and control units are complete in Volumes 5 and 6. Detailed block diagrams on input and output and on storage are not included in Volumes 5 and 6 but are outlined in Volume 7.

Functions in Whirlwind I have been so divided that research and development of the arithmetic and control units can be entirely independent of the high-speed storage. More rapid progress is possible where the groups working on these two divisions can operate without continuous and detailed coordination.

Sylvania Electric Products, Inc., in Boston is contributing to the final engineering and the construction of Whirlwind I to the maximum of its ability. The Eastman Kodak Company is developing the photographic input and output devices which will be used.

Drawing B-31202 is an approximate time schedule for the Whirlwind I system. It does not include general activities such as mathematical and coding studies, or research which is not a necessary part of Whirlwind I. Electronic assemblies are expected by the summer of 1948, storage tubes and circuits by fall, and complete system operation by about January 1949. See Section 4.1 for experience to date with a 5-digit arithmetic element.

3.1 Description of Whirlwind I

Whirlwind I is an electronic computer using parallel binary digit transmission. To make problem coding easy, operations are performed one at a time in serial order. For simplicity and storage economy, a single-address code is used. In general the code describes in its two sections the storage register location and the control operation to be performed. An exception is made in shifting, where the register section of the order indicates the number of positions to be shifted.

A register length is 16 binary digits, and the computer will have a storage capacity of 2,048 registers.

Operating time for the different control orders does not vary greatly. It is primarily set by the storage extraction time, the necessary transfers, and the transfer check sequence. A complete multiplication including all transfers will require about 50 microseconds. Future designs should require less time even though register lengths will be longer. Whirlwind I does not compute while electrostatic storage is being set up; this overlapping may be incorporated in future designs.

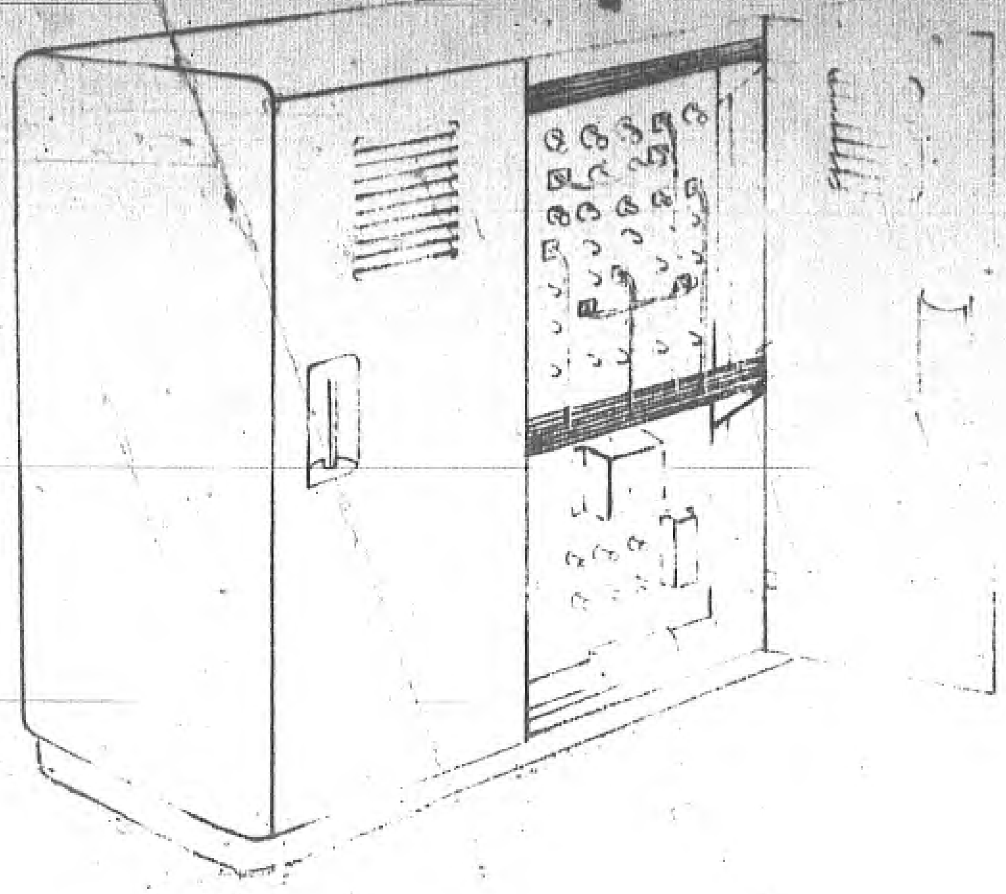
The 16-digit length is satisfactory for many simulation and control problems. Three special orders are provided for convenience in the use of multiple-length numbers. These special orders are described briefly in Volume 7, M-137. The sequence of operations to be executed by any one of these orders is optional and can be selected by the operator for each individual problem. They can for example be used for double or triple length operations of addition, subtraction, and multiplication. On the other hand, they might be used for extraction of roots, carrying out interpolation sequences, integration, or performing matrix operations. They are essentially special program orders requiring less than the usual number of steps by the operator.

Numerical input and output will be from 35-mm photographic film. Graphical output plotted both as functions against real time and as one variable plotted against another will be provided. Families of curves can be traced and photographically recorded. Important in simulation problems is the ability to accept inputs from physical measurements and to control special output indicators and servomechanisms. Conversion equipment will be provided for converting shaft positions and electrical signals to binary numbers. On the output, binary quantities will be converted to instrument indications, cathode ray tube deflections, and control voltages.

Thirty-two control orders are available. Many of these are discussed in detail in the Block Diagrams, Volumes 5 and 6. Additional ones are discussed in Volume 7, M-137. The remaining orders are available for assignment in the future as required. The system is so designed that special orders can be readily added as needed.

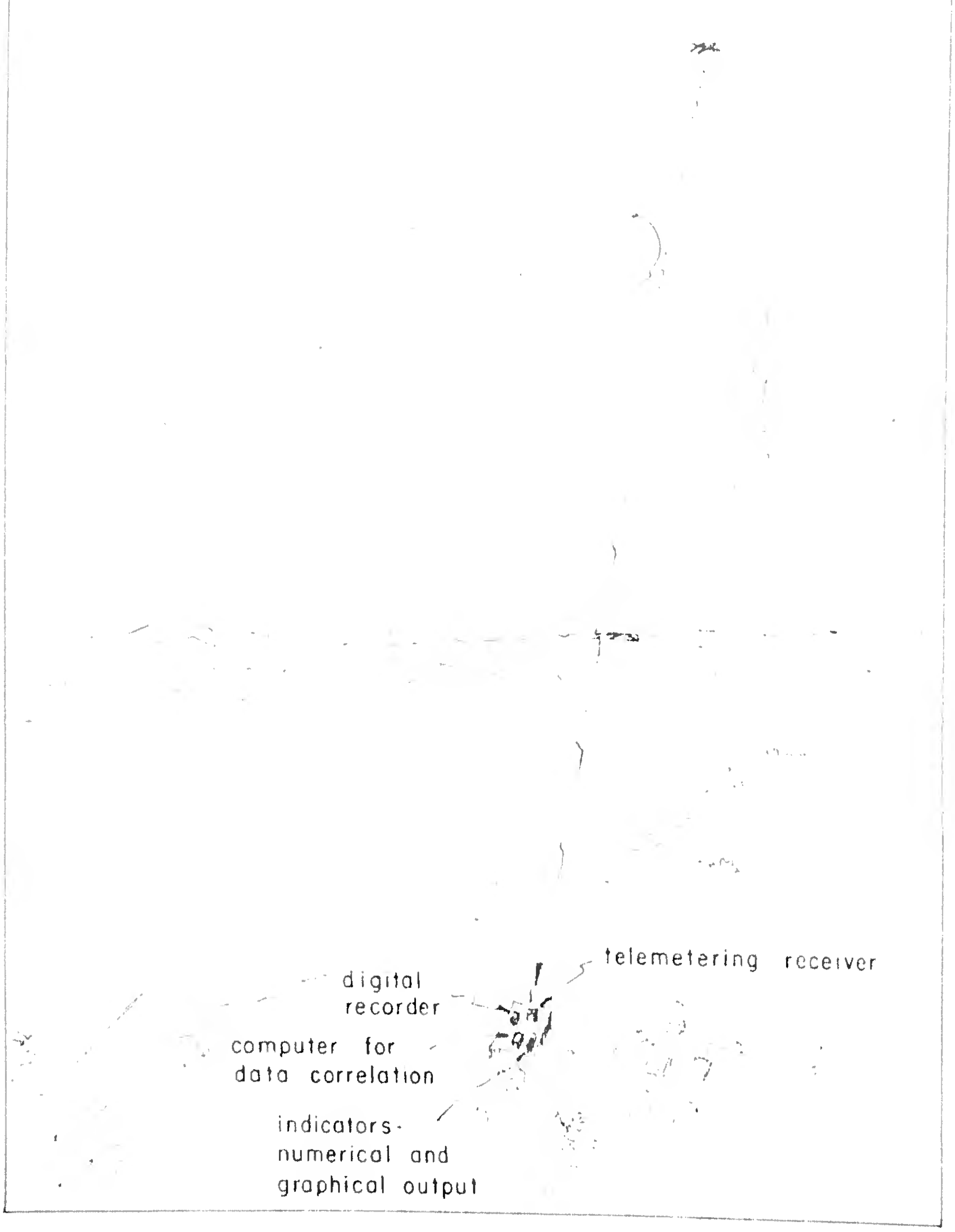
Design of the computing circuits stresses reliability and the widest operating margins consistent with the required performance. Even though operation is possible down to zero pulse-repetition rate, direct-current coupling between vacuum tube stages has been virtually eliminated. Wider component tolerances and better reliability result from the a-c coupled stages. This idea, referred to as restorer-pulse operation, is a most important advance in computing circuit design. It is discussed in Section 4.34 and Volume 15.

Whirlwind I is being designed for maximum access to electronic circuits. As discussed in Volume 13, M-147, components are laid out and assembled on flat panels. The panels are similar to those of the 5-digit multiplier, photograph FB-265, Section 4.0, Units will be housed in cabinets as shown in the illustration. Cabinets will be arranged as shown in the Drawing B-31016, which is further discussed



WHIRLWIND I

GUIDED MISSILE DATA EVALUATION



A-31191

A-31191

6.5 The Census Problem

It is only very recently that information has been received about the census problem. Consequently, very little study has been given to the census problem in relation to Whirlwind I. The following comments have been prepared on this short notice.

The peculiar properties of the census problem seem to be as follows:

a. Very large quantities of external data must be handled.

b. The bulk of the work lies in sorting and tabulating this external data.

c. It will be necessary to transfer, sort and tabulate alphabetical data using the machine.

The gains expected from the use of digital computers are:

a. Greater speed and economy.

b. More efficient storage of external data.

There are then two considerations in the machine:

a. Its internal organization, computing speed, and setup procedure must be such as to efficiently carry out limited manipulations with large quantities of data.

b. The input and output equipments must be arranged to supply and receive the large quantities of data handled by the machine and to do so rapidly and efficiently. An efficient balance must be maintained between the operating speeds of the computer and its input

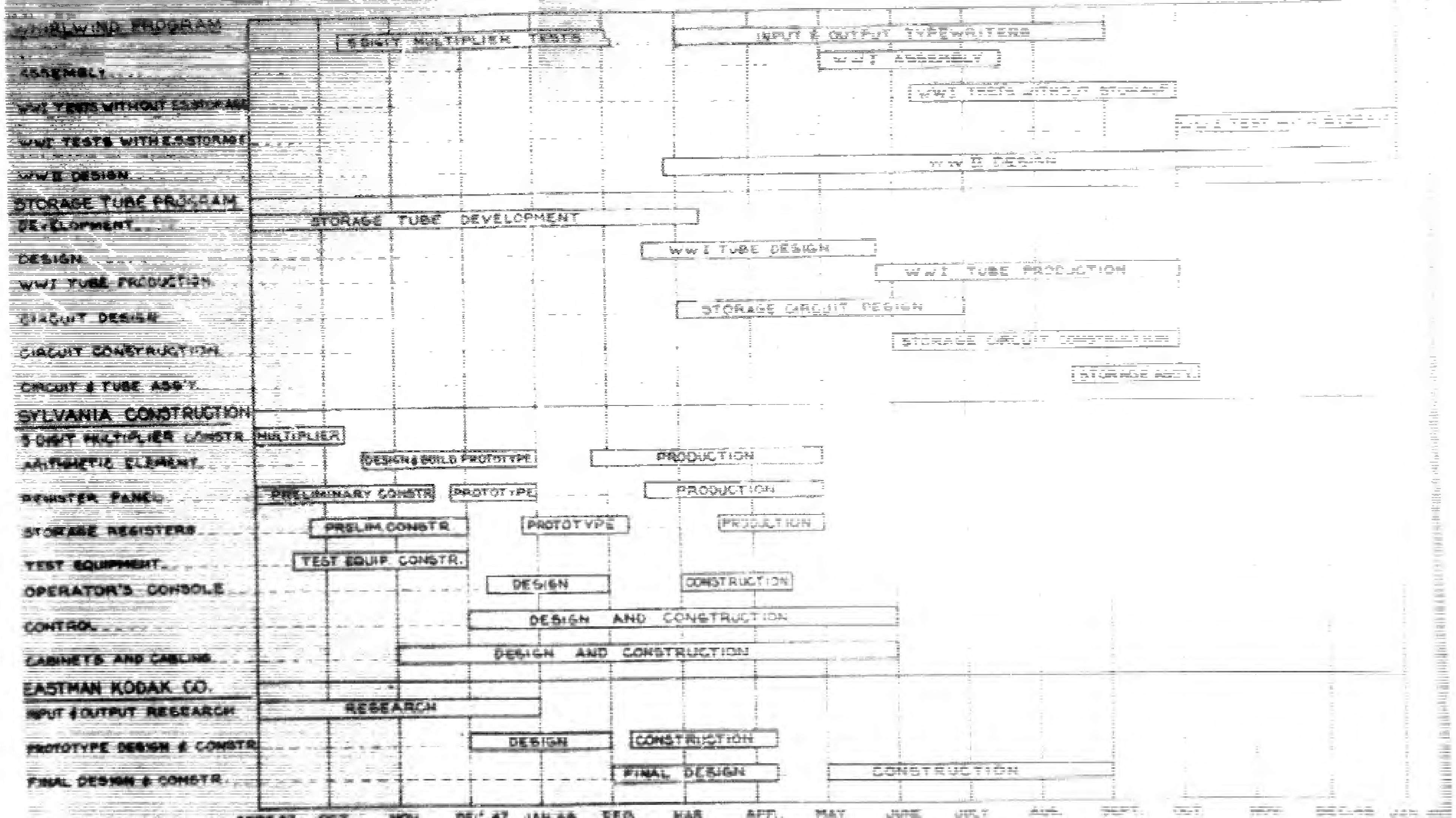
Blurred Pg

and output equipment. The ratio of the number of computer operations performed to the amount of input data received from tapes is much less than exists in simulation, control and scientific calculation problems.

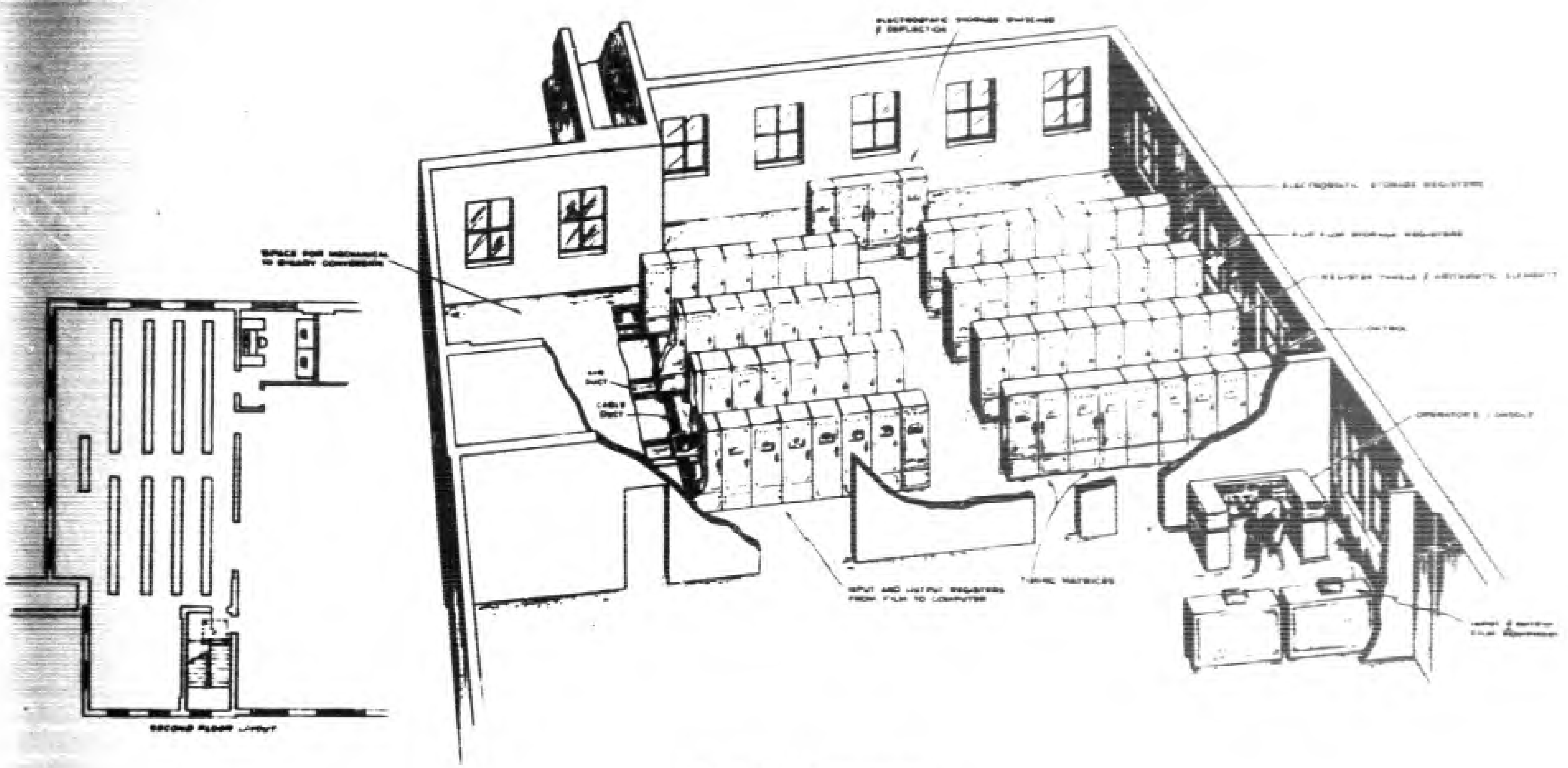
It is difficult without a detailed study to discuss the suitability of the film input and output of Whirlwind I to the census problems. It may well be that an erasable medium such as magnetic tape may be sufficiently less expensive and even sufficiently more flexible to warrant its use instead of photographic film. It is also difficult to estimate the efficiency of balance between Whirlwind I and its proposed input and output devices for census problems. It is always possible, however, to use multiple input and output equipment with a single computer. Comment will be limited here to discussion of the internal organization of the computer itself.

First, the Whirlwind I order code has been designed to be completely general and flexible. The only departures have been a few additions to facilitate computation on the problems of principal interest. Corresponding modifications for handling census information could be incorporated. However, no such modifications seem warranted.

The census problem reduces to a series of inspections on externally supplied digital information. These inspections determine either equality or magnitude of the numbers involved. The character of the number determines its disposition or the disposition of accompanying data. The desired operations may include tabulation in selected registers, the restorage of the entire block of data on an output tape, or even modification of the data itself.



TIME SCHEDULE FOR SUMMARY REPORT NO. 2



PROPOSED ARRANGEMENT
WHIRLWIND I INSTALLATION

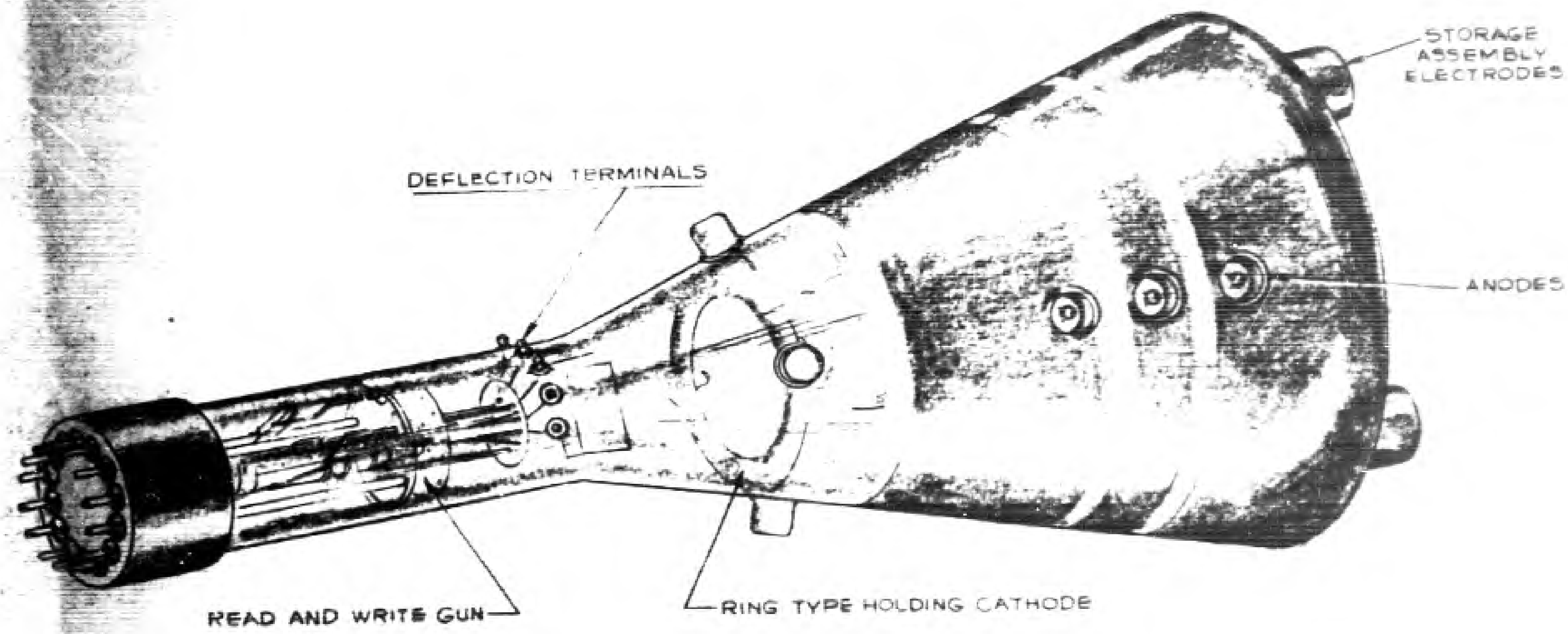


FIGURE 7

POSSIBLE FINAL STORAGE TUBE DESIGN

A—30688

performed one at a time in serial order. For simplicity and storage economy, a single-address code is used. In general the code describes in its two sections the storage register location and the control operation to be performed. An exception is made in shifting, where the register section of the order indicates the number of positions to be shifted.

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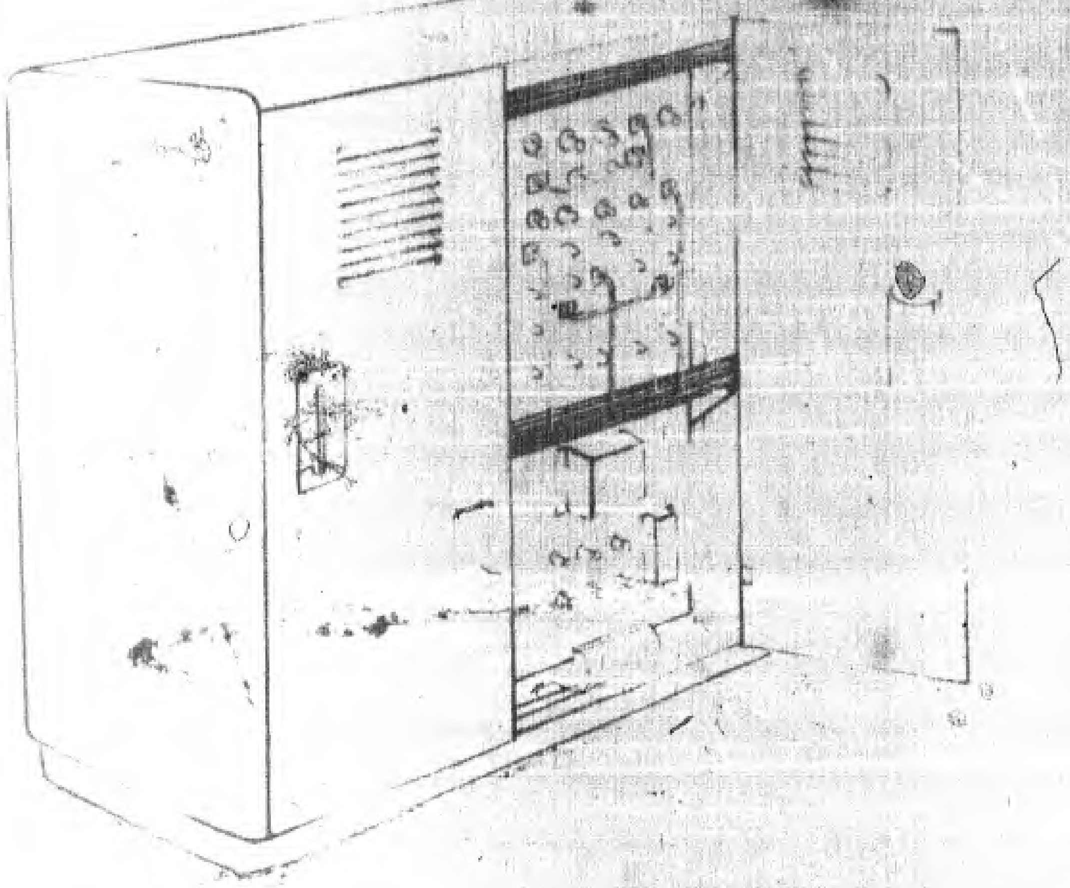


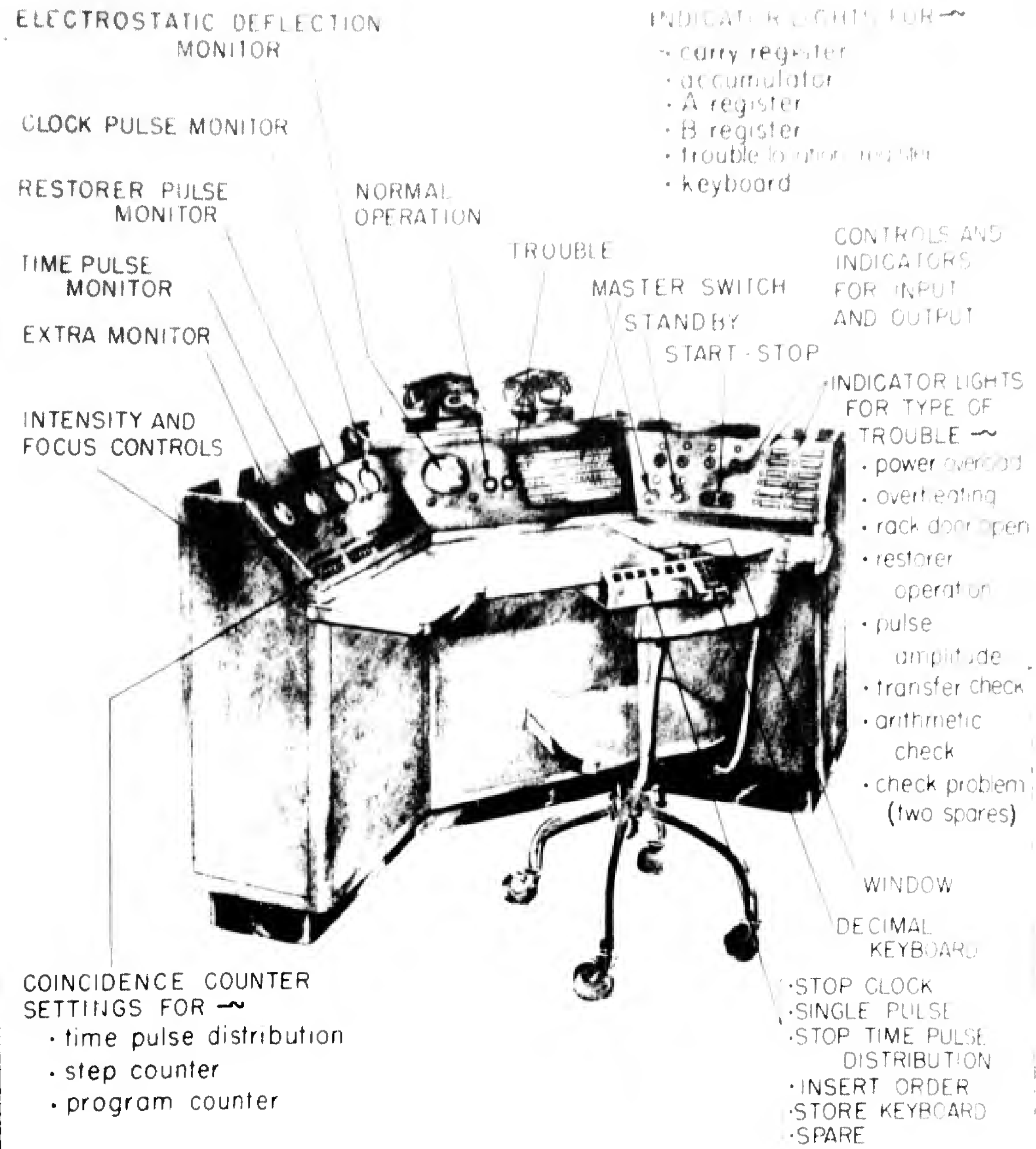
WHIRLWIND I

in Volume 13, M-68. The computer is so arranged that all circuits are available for testing while in operation. About 1,600 square feet of floor space will be occupied by Whirlwind I. The same components arranged into the design being proposed for Whirlwind II would be less accessible but would occupy much less space. Both areas are exclusive of power supplies and cooling equipment.

About 3,500 vacuum tubes will be used in Whirlwind I. Volume 16, M-132, tabulates these by function. About 900 tubes are used in test storage to facilitate the design and installation of Whirlwind I. Test storage would probably not be used in future machines. The control desk for Whirlwind I is illustrated in Drawing A-31083. Detailed design is not yet done. Most of the switches and indicators are for checking and trouble location, which will be discussed in Section 5.0. A ten-key decimal-input keyboard is illustrated as part of the operator's console, and a close-up is shown in Drawing A-31188. Some applications may require a keyboard of typewriter or teletype style through which coded alphabetical information can be handled. Both numbers and orders will be inserted through the same keyboard. An order button is used to indicate that the succeeding decimal digits must be coded into two groups, one for the register location and one for the operation order. Identification symbols for orders will be changed from the present alphabetic notation to decimal notation, or the alphabetic code for orders will be selected so that it can be put on the keyboard along with the decimal digits.

3.2 Description of Arithmetic Element

Whirlwind I uses a high-speed parallel-digit pulse-type arithmetic element. A complete discussion of this arithmetic



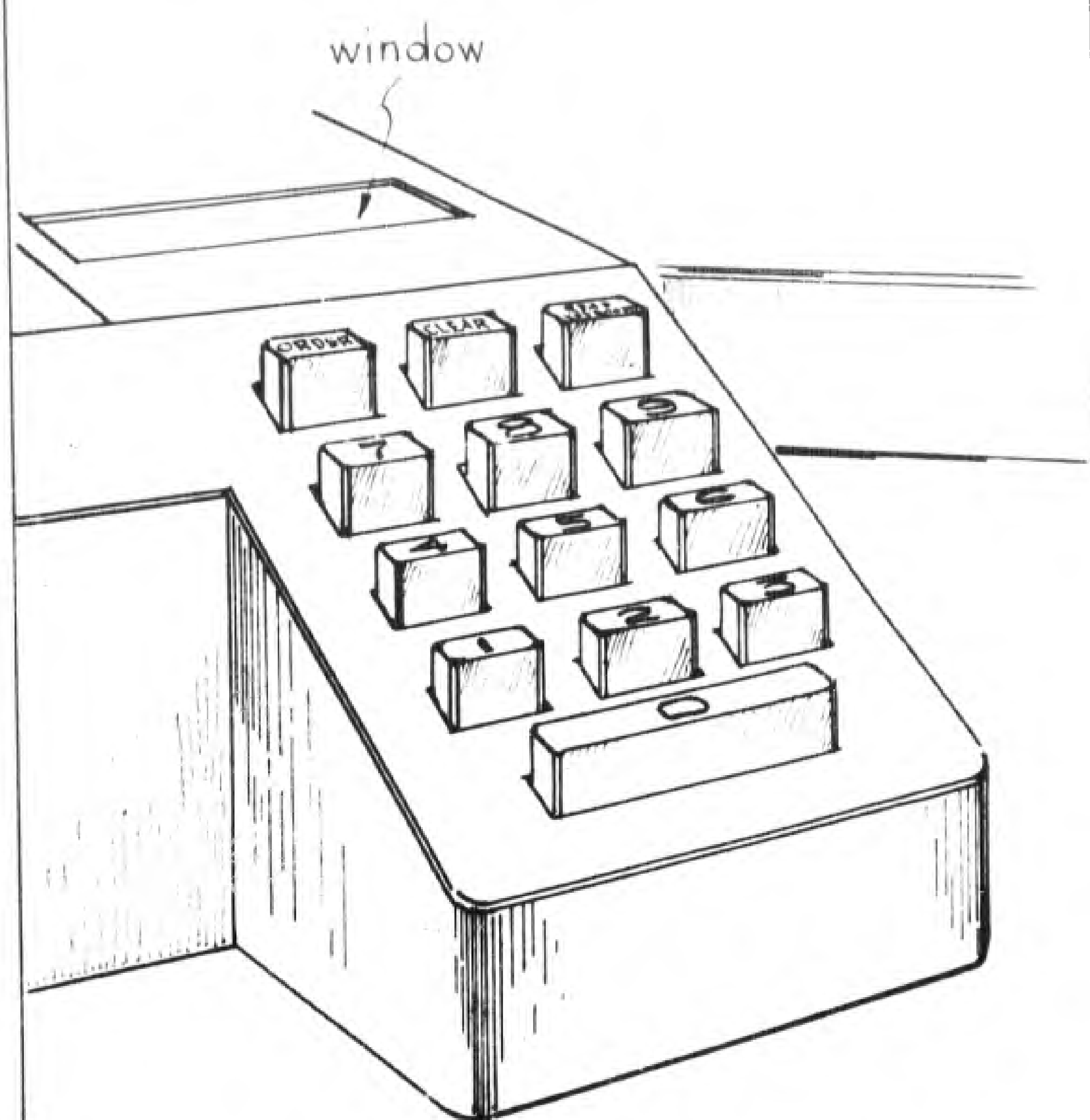
OPERATOR'S CONSOLE - WW I

SERVOMECHANISMS LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE 39 MASSACHUSETTS

A-31083

A-31083

DETAIL OF DECIMAL KEYBOARD
OPERATOR'S CONSOLE-WWI



A-31188

A-31188

element can be found in the Block Diagram Report, R-127, Volumes 5 and 6.

The arithmetic element consists basically of an accumulator capable of adding binary numbers. Associated with this accumulator are two additional registers used for the temporary storage and manipulation of numbers involved in other arithmetic operations. A counter, control gate tubes, and control flip-flops are also part of the arithmetic element.

Each stage of the accumulator consists of two flip-flops, one acting as a binary counter for forming the addition and the second acting as a temporary storage position for the carry. The accumulator works in a step-by-step fashion. If a binary number originally resides in the accumulator and a second number, held in one of the other registers of the arithmetic element, is added into the accumulator, the sum will be formed by the adder flip-flops. The carries, if any, will be stored in the carry flip-flops. This action is paralleled in all digit columns and is accomplished by a single control pulse from the main control of the computer. A second step is required to perform the carry before the final sum appears in the accumulator. A high-speed carry system is provided in the accumulator for performing the entire carry in one step.

The accumulator is also used for performing the other arithmetic operations. Subtraction is performed by the use of complements, multiplication by successive additions, and division by successive subtractions. The multiplication operation consists of the repetition of three successive steps. The first step adds the multiplicand to the partial product according to the selected digit of the multiplier. The second step shifts the partial product in order to align it properly with the multiplicand. The third step performs a carry on the partial product. To speed up the multiplication operation in Whirlwind I, these last two steps are combined. A small matrix switch in each digit column performs both the shift and the carry in one step. Details of this method will be found in Volume 5. Time is saved by omitting the addition operation if the multiplier digit is zero. A further speed increase is obtained by supplying the arithmetic element with clock pulses at a higher repetition rate than to the remainder of the computer. The use of high-speed carry in addition, and the use of higher repetition frequencies and combined operations in multiplication, result in arithmetic element operation times which are comparable to access times of the electrostatic storage being developed for Whirlwind I.

The characteristics of the arithmetic element may be summarized as follows:

1. parallel-digit type
2. pulse-type accumulator
3. high-speed carry
4. combined shift and carry for multiplication
5. higher repetition frequency for the multiplication operation

The step-by-step or pulse-type accumulator has been selected rather than the balancing or current-adding type of accumulator. The pulse type is considered more reliable, faster, and more amenable to trouble location because operations occur one at a time in response to controllable impulses.

3.3 Description of Storage

Electrostatic tubes have been chosen for the Whirlwind computer high-speed internal storage. They will give immediate access to stored numbers, are suitable for a parallel type computer, and can be developed on a time schedule abreast of the other computer components.

Tubes are the deflection type using the high-velocity beam of a single cathode ray gun for reading and writing. Both plus and minus signals are read out of the tube, corresponding to the digits 0 and 1. Better reliability is thus obtained than from a storage system using the presence and absence of signals as an indicator.

A brief explanation of the tube is reproduced here from Volume 9, M-130. An elementary electrode arrangement without holding gun is illustrated in Drawing A-30893. For simplicity the explanation is made in terms of input switching on the signal grid. Actually, changing the potential of this grid will affect the deflection sensitivity of the tube and in practice the grid in front of the surface is grounded and switching as well as output signals are taken through the signal plate. Deflection plates position the electron beam, prior to its being turned on, to the point on the dielectric surface at which writing or reading is to take place.

The digits 1 and 0 are written as positively and negatively charged areas on the dielectric surface at the point of beam impact. The dielectric surface must have a secondary emission ratio greater than unity. (A ratio of two or more is desired.) To write the digit 1, the signal grid is made positive to collect secondary electrons from the dielectric, resulting in a positive surface. This positive charging is accomplished by collecting the excess secondary electrons above the number in the high-velocity beam. To write the digit 0, the signal grid is made negative, no electrons are collected, and the surface charges negatively at the rate permitted by current flow in the primary beam. Secondary emission is not a necessary factor in negative charging.

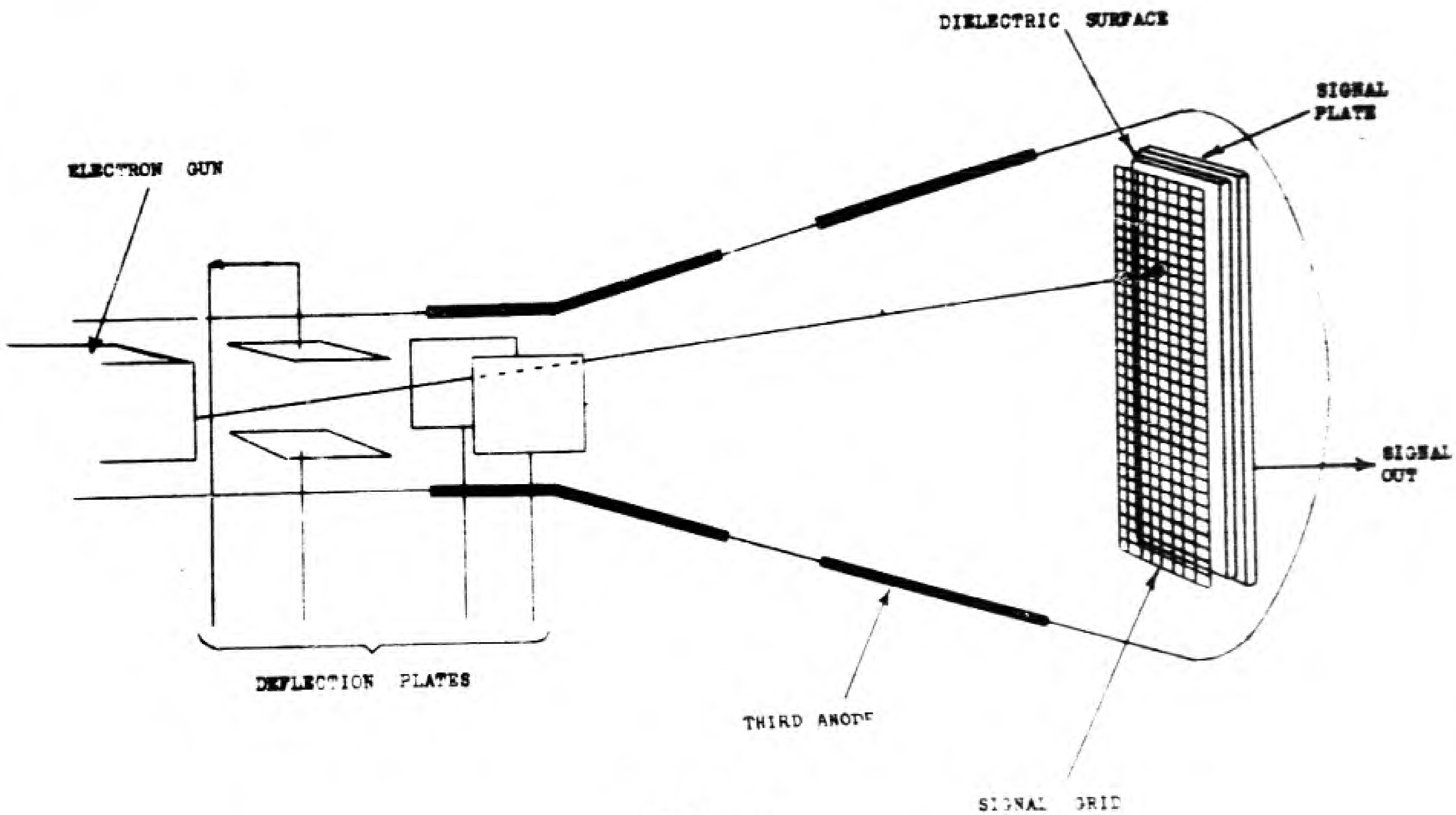


FIG. 1

ELECTROSTATIC STORAGE TUBE

Reading of signals is accomplished by positioning the signal grid voltage midway between the two writing voltages and discharging the dielectric positively or negatively toward this voltage. The output signal appears at the signal plate by capacitive coupling through the dielectric. Rewriting will probably be incorporated as part of the reading operation, to re-establish the stored signal at full magnitude.

Permanence of the stored signal is insured by the regenerative action of a flood of low-energy electrons operating on a principle which was used in the R.C.A. Selectron tube, some German tubes, and the N.R.L. radar storage tube. Drawing A-30685 shows how the self-sustaining effect is obtained from the holding gun. A positive area and a negative area are shown on the dielectric. The holding gun is at about the same potential as the negative areas and the signal grid is at about the potential of the positive areas. Consider the positive area: secondary electrons are emitted and a number just equal to those in the primary beam are collected by the signal grid. The other secondary electrons return to the dielectric surface. If the surface should tend to become more positive, additional secondaries are pulled back to reduce the positive charge, while if the surface should tend to become less positive, more secondaries will be repelled to the signal grid to return the dielectric to its original point of stability. Consider the negative area: the area is approximately at holding-gun potential, and primary electrons, if they strike at all, will have low velocities and will emit few secondary electrons. If the surface becomes more negative, all primary electrons will be reflected and ohmic leakage will reduce the charge to the balance point, while if the surface becomes less negative, electrons from the primary beam will be collected to return the surface to the stable negative potential.

A-30885 USED IN 63 5 MEMO M-102

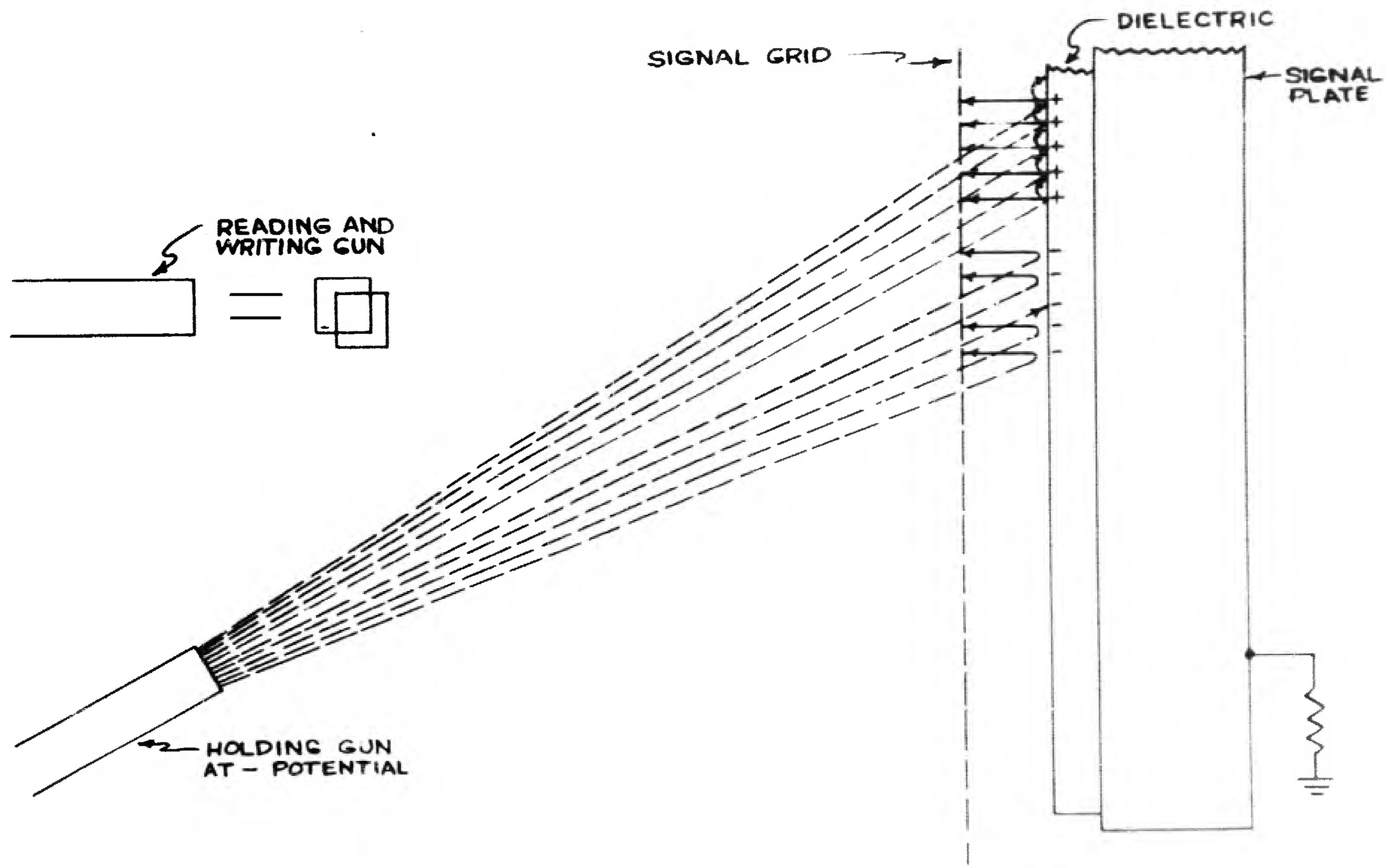


FIGURE 2

A–30885

Figure B-30888 illustrates a possible physical form of the final tube combining the high-velocity and holding electron sources. See Volume 9, M-130, for additional discussion.

The present storage tube status is intermediate between the research and the development phases. Operating principles have been satisfactorily demonstrated in the research laboratory. Results to date indicate that the storage tube will meet the following requirements which were outlined at the Harvard Computing Symposium in January 1947. (Volume 9, R-110):

1. High transfer speeds of 6 to 8 microseconds between transmission of a control order and the storage or reading of a signal.

2. Unique storage of both zeros and ones as output signals of opposite polarity to provide greater reliability.

3. The inherent ability to read out a checking signal during storage of a number to indicate proper operation.

4. A high signal-to-noise ratio.

5. A high density of stored signals to permit a 32-by-32 mosaic of stored numbers.

6. A simple mechanical design which can be readily produced in quantity.

In addition to the high-speed electrostatic storage, Whirlwind I will be equipped with a bank of test storage. While expensive of vacuum tubes, this test storage will facilitate the installation and testing of the first Whirlwind computer. After Whirlwind I is operating satisfactorily, this test storage will be used for the storage of check problems. Future Whirlwind computers will probably not include the equivalent of test storage. The test storage made up of vacuum tubes and toggle switches is discussed in the Block Diagram Report, Volumes 5 and 6.

3.4 Description of Central Control

A complete description of the Whirlwind I control will be found in the Block Diagram Report, R-127, in Volumes 5 and 6 of this report.

Since Whirlwind I attains its high operation speeds through the use of parallel channels, its operating sequence has been kept extremely simple, resulting in a relatively simple control. A single-address code has been adopted, and the control has been designed to be as flexible as possible. The control is capable of extension and ready modification both in changing existing orders and in adding new ones.

The control consists of the following elements:

1. Master clock
   The computer can be run non-synchronously but for computing efficiency is run at its highest practicable rate in synchronism with a crystal-controlled clock-pulse generator. The master clock also generates high frequency clock pulses synchronized with the normal frequency for use in the high-speed parts of the arithmetic element.

2. Eight-way time-pulse distributor
   This distributor produces time pulses in time sequence on eight different lines. These time pulses are distributed through connection matrices to the elements of the computer.

3. Operation switch
   This switch is set by the operation code

section of the order to select the operation to be performed. The outputs of this switch are sent to a crystal matrix which controls the distribution of the time pulses to the elements of the computer.

4. Program counter

   The computer uses a single-address code and takes orders in numerical sequence from the storage unless directed to do otherwise. The program counter keeps track of the position in storage of the next order to be performed.

5. Program register

   The program register is used for the temporary storage of orders after their extraction from storage and before they are sent to the control switches.

Enough spare equipment is being provided in the connection matrices associated with the time-pulse distributor and operation switch to allow the addition of new orders at a later time if desired.

3.5 Description of Input and Output Devices

The Whirlwind I computer will use photographic film as its input and output medium for coded data. Other inputs are from direct conversion of physical quantities to digital values.

The Eastman Kodak Company is developing readers and recorders for the storage and use of binary data on 35-mm film. This work is being carried on in close collaboration with M.I.T., although under a separate contract with the Special Devices Center. The Eastman Kodak Company is also developing automatic film developers for processing the 35-mm film. A report of this work will be found in the Eastman Kodak Progress Report No. 1 in Volume 11 of this report.

Eastman is developing a single design for multiple purpose application. It will be used for manual transcription, film copying and editing, computer input, computer output, transcription to typewriter, and external data recording as for guided missile test ranges.

The information is stored on the film in the form of opaque and transparent spots. There are 50 channels across the width of the film with about 100 lines per inch of film length. Both numbers and their complements are stored as a checking procedure. A cathode ray tube is used for scanning the film in both reading and recording. In reading, the beam is swept across the lines in sequence, a photocell behind the film picking up the information. In recording, the beam is swept behind a mask with deflection voltages applied to deflect the beam to either the number or the complement line depending upon whether the number stored is a one or a zero. Digits are supplied to the recorder and received from the reader at approximately a 500 kilocycle rate during the writing sweep. The equipment can be arranged to store either 50-digit information requiring two lines for both number and complement or 25-digit information requiring but one line for both number and complement. The actual operation of writing or reading requires about 100 microseconds in the first case and 50 microseconds in the second. The film drive is clutch controlled. The film may be read or exposed at as slow a linear speed as desired, but the system is being designed for a maximum speed of about 1,000 numbers per second. Designed film capacity is 400 feet, although space is being provided for 1,000-foot magazines. A 400-foot roll of 35-mm film will store 12,000,000 binary digits of information.

The M.I.T. Servomechanisms Laboratory is developing the keyboards and decimal-to-binary converters to be used for film preparation, and also the registers and control equipment needed to connect the Eastman reader-recorders to the Whirlwind computer. It will not be necessary for the machine operators to use other than decimal notation. Conversions will be performed automatically at the keyboards in the case of data to be entered into the machine and either in the computer itself or at the output printer for numerical information extracted from the machine.

In simulation applications it is necessary that analogue information such as shaft positions or electrical magnitudes be converted to numerical quantities for use by the machine. Numerical outputs of the computer must be converted back to analogue quantities. These devices are being developed. Some are described in Volumes 11 and 12 and in Section 4.4, Volume 1.

3.6 Aircraft Cockpit Simulation

The cockpit is that part of the aircraft simulator which (1) converts the pilot's reactions to electrical signals which are transmitted to the computer, (2) receives information from the computer and conveys it to the pilot as simulated aircraft behavior, and (3) produces an environment which will convey to the pilot the illusion that he is air-borne.

The simulator will include a cockpit which is equipped with all controls, instruments, and other devices which would normally be found in the aircraft. Configuration of these devices and general interior appearance will be faithfully reproduced, since psychological as well as mechanical stimuli are necessary in obtaining normal reactions and valid evaluation from the pilot. See Volume 14, R-94, by Dr. Holder formerly of the Massachusetts General Hospital.

While the cockpit being designed at present is not intended to be the final one for use in the Whirlwind II system, it is necessary to achieve simulation adequate for testing the Whirlwind I system and studying the effectiveness of simulation techniques. All pilot controls will be active. The positions and rates of travel of the rudder, elevators, and ailerons will be measured and transmitted to the computer. Values of the forces on the controls will be received from the computer and will actuate hydraulic servomechanisms which apply the proper forces to simulate the "feel" of the aircraft. Similar signals will be transmitted to aircraft instruments to indicate the aircraft's behavior.

The cockpit of the Whirlwind I simulator will be mounted on springs so that it may be vibrated to increase the illusion of flight. Noise will also be generated in the cockpit. Both noise and vibration will be controlled by flight conditions to add reality.

The equipment, servos, and power units developed in this work can be applied to many other simulation problems.

4.0 Research and Development

This section treats the general procedure and steps in developing Whirlwind components. The work and status of specific system elements follow in the next sections. The material of this section is included to stress the large amount of engineering and laboratory research necessary to convert block diagrams or design studies into a functioning system. An element finally arriving in the Whirlwind system will have passed through the following ten steps:

1. Systems planning and block diagram studies
2. Circuit research
3. Circuit development
4. Circuit design
5. Panel assembly
6. Prototype design
7. Systems test
8. Final design
9. Final model testing
10. Final assembly and use

The following series of photographs illustrate steps 2 through 7, using the arithmetic unit as an example.

Step 1, the systems planning and block diagram research, is illustrated by Volumes 5, 6, and 7.

Step 2, on circuit research, is illustrated in FB-263. Basic research is done on breadboard circuits involving a few vacuum tubes and associated components. The circuit is evaluated for potential usefulness and a study is made of component tolerances and circuit behavior under laboratory test conditions.

Step 3 is shown in FB-245. Here is an early version of the arithmetic element showing the high-speed shift-and-carry matrix laid out in a physical form similar to that used for matrix switches.

interconnection problems are studied. The loading of vacuum tubes due to succeeding non-linear grid input impedances is investigated. Tests are made on varying pulse repetition rates and information is obtained on the operating tolerances of circuits.

Step 4 is a first engineering design illustrated in FB-264. Here is the component sub-assembly for a high-speed flip-flop complete with input trigger circuit, output buffer amplifiers, and neon indicator lights with associated driving triodes. This unit is the result of many drafting room and engineering layouts to arrange circuit components for easy accessibility and short lead wires. Primary attention must be given to reducing capacitances and the lengths of video circuit wires. Components are installed on terminal boards for easy production and so that they may be individually removed for repair.

Step 5 is the assembly of several of the previous circuit stages into the panel assembly unit of FB-262. Here is illustrated the first approximation to a final design. Although a system might be assembled with elements at this stage of development, reliability and ease of manufacture and maintenance usually indicate that additional redesigns should be made. This panel assembly of the arithmetic element was tested for high-speed operation including the operation of input gates and output buffer amplifiers. The high-speed shift-and-carry matrix of FB-245 has now taken the form of the double square in the upper central portion. Further studies are conducted on circuit component tolerances and the problems which have arisen due to the rearrangement of components in the preceding design step.

Step 6 corrects the troublesome features of the panel assembly. This prototype design shown in FB-267 was built in multiple for small-scale systems tests.

Step 7, the small-scale systems testing, is shown as the complete 5-stage arithmetic unit of FB-265. Five stages of the arithmetic unit and a manual control for multiplication are illustrated. Here problems in cabling with associated attenuation and pulse reflections can be studied. Bus drivers for coaxial line can be systems tested for the first time, and the use of coaxial line with multiple driving and receiving points can be studied. Upper limits of operation set by tube capacitances and circuit wiring can be determined. The computing elements are driven by actual signal sources, not by the laboratory test equipment previously used. The circuits are tested over variable and intermittent pulse repetition frequencies from push-button control to several megacycles. Trouble location methods for the final computer can be formulated. Small-scale systems operation is valuable in the training of personnel. Both the Servomechanisms Laboratory staff and Sylvania engineers have worked on the 5-stage multiplier to learn systems problems and testing techniques. The value of the preceding design steps is demonstrated by the short time to put such a new system into operation. (See following section.)

Step 8, the final design, will incorporate changes found necessary in the small-scale systems tests. For example, the components of the arithmetic element will be rearranged so that the A-register, the B-register, and the accumulator can be constructed separately. This will make video cabling more orderly and will make installation and maintenance of the equipment easier. Circuits will be altered to use the new higher powered Sylvania gate tube in place of 6AS6's.

Systems tests have demonstrated that rectifier, type power supplies are unsatisfactory for computing machine use. Transient power line disturbances can feed through these supplies and trigger computing circuit elements. Whirlwind I will be fed from motor-generator sets.

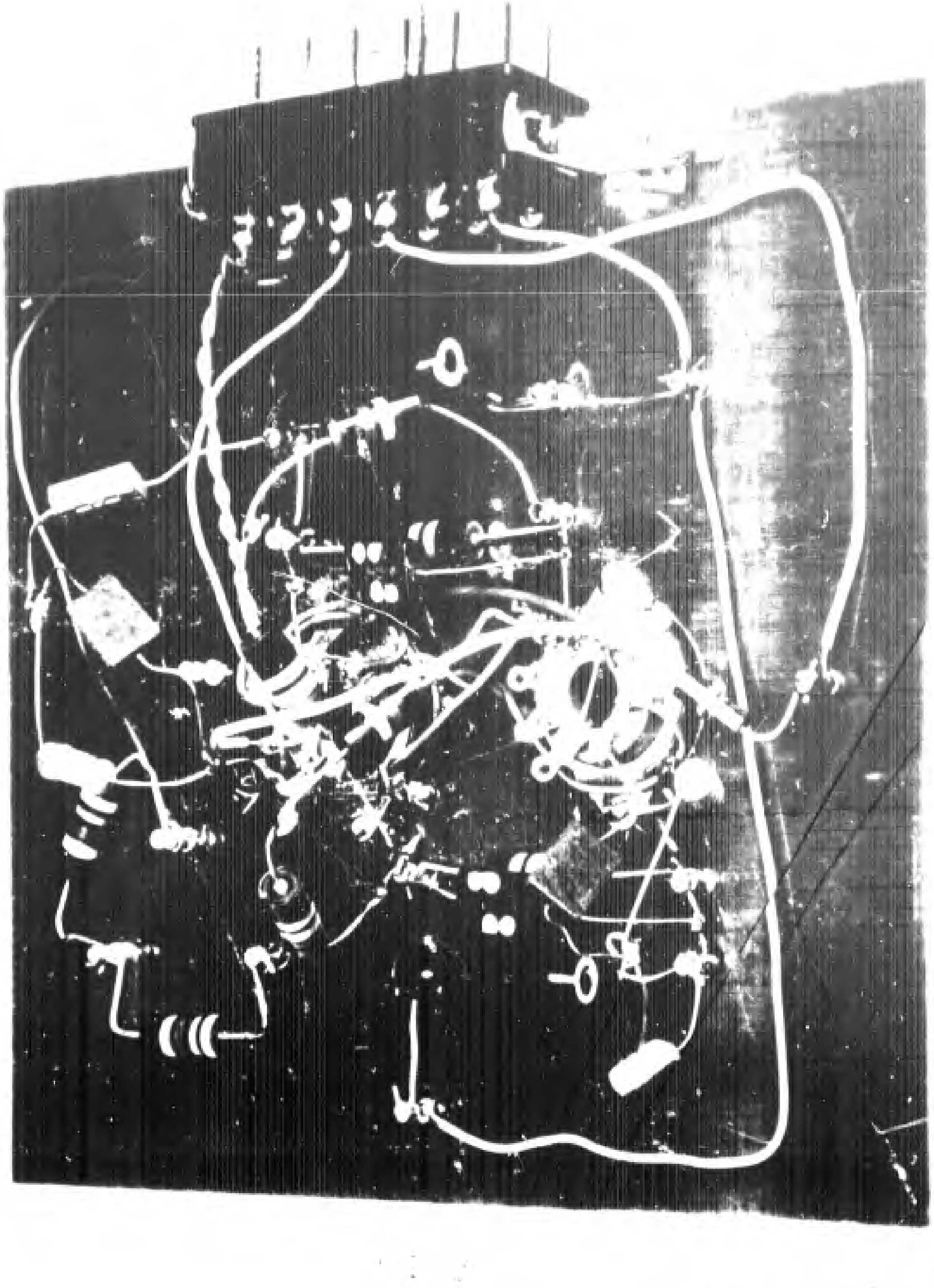
Models of the final design at step 9 can be tested in the small-scale systems setup of step 7.

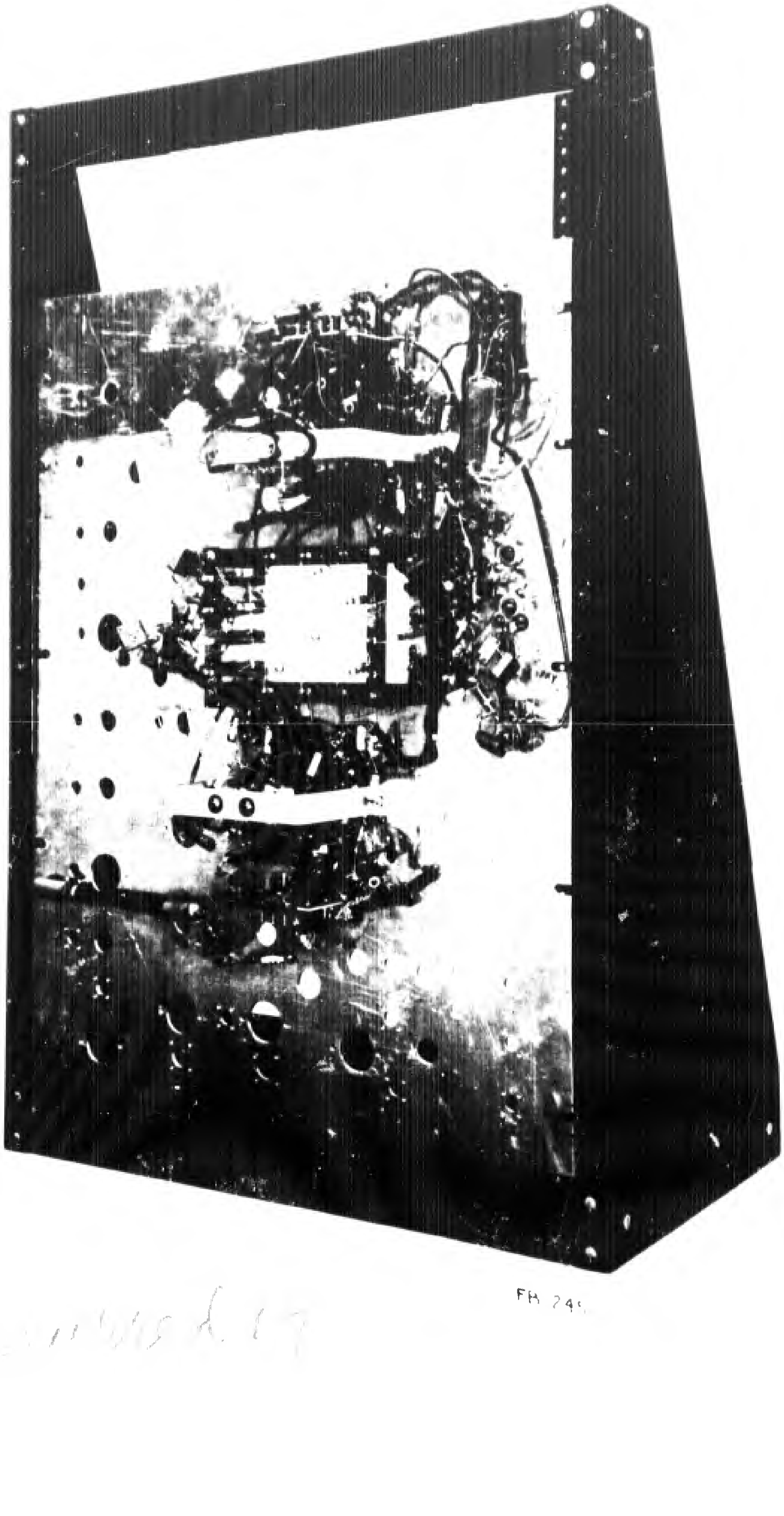
4.1 Arithmetic Element Development

Two factors were necessary before the first circuit schematic of the arithmetic element was drawn: one, the block diagram; two, the results of research and development of the basic components of the arithmetic element such as flip-flops and gate tubes. The circuit schematic was given careful consideration and during that time the a-c coupling scheme was introduced. The first laboratory work on the arithmetic element was done with a breadboard layout of a single digit of the accumulator. This included the four-position switch, and the laboratory work was conducted primarily to test the shift-and-carry operation and the a-c coupling.

Following the breadboard accumulator, a preliminary single-digit column of the arithmetic element was built. This design gave more consideration to the physical arrangement and quality of components than had been given in the past. The laboratory work done on this unit provided a basis for writing the test specifications for a 5-digit prototype arithmetic element which has been constructed by Sylvania.

This prototype has only 5 digit columns plus a simple control panel for performing multiplication. The 5-digit multiplier provides an opportunity to check the performance of a large assembly of smaller components. The smaller elements, such as flip-flops, gate circuits, etc., have been thoroughly tested as units to operate in a larger system, but many unforeseen difficulties and problems best solved by assembling a large number of elements can be studied by working with such a prototype.





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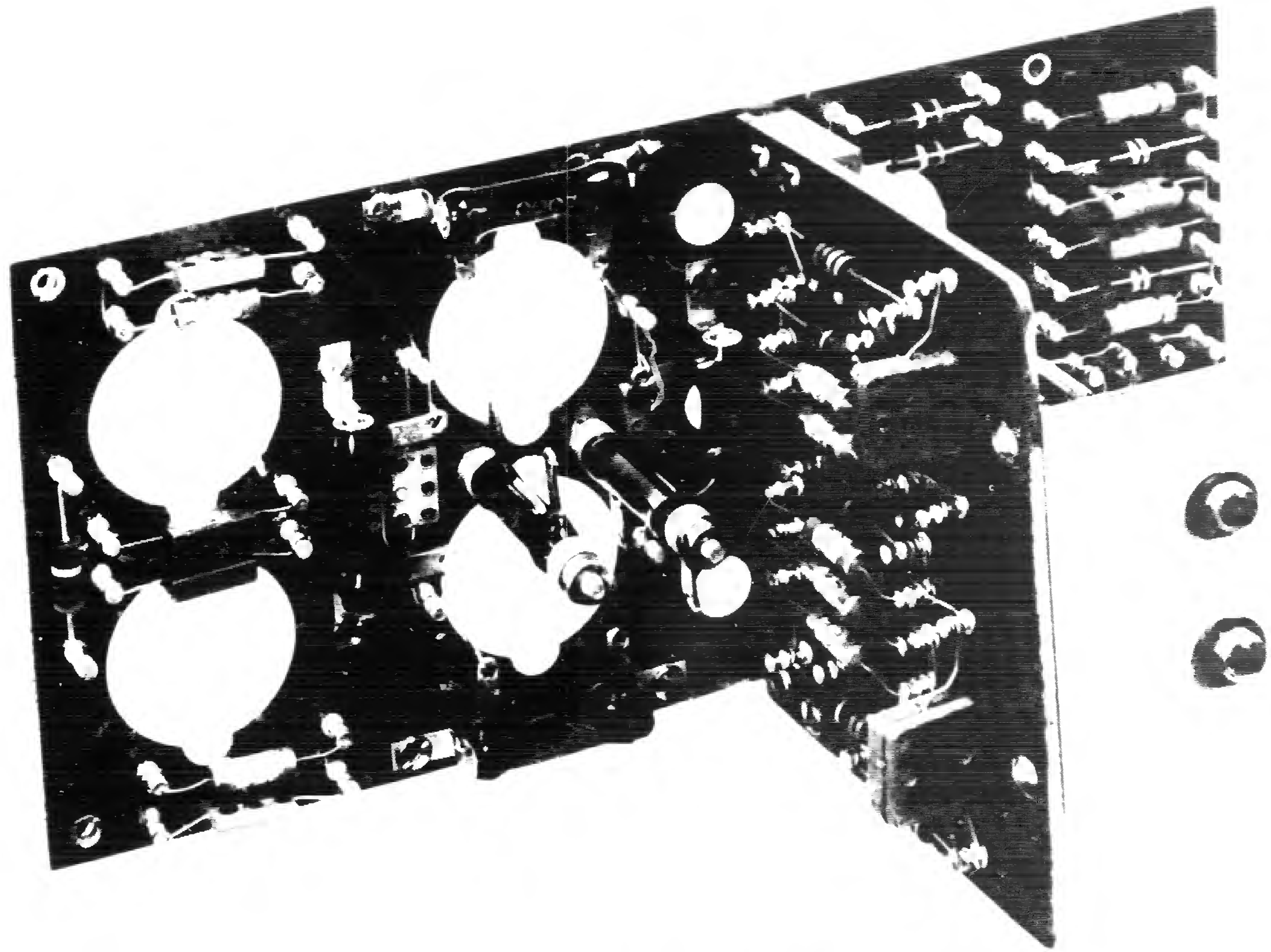

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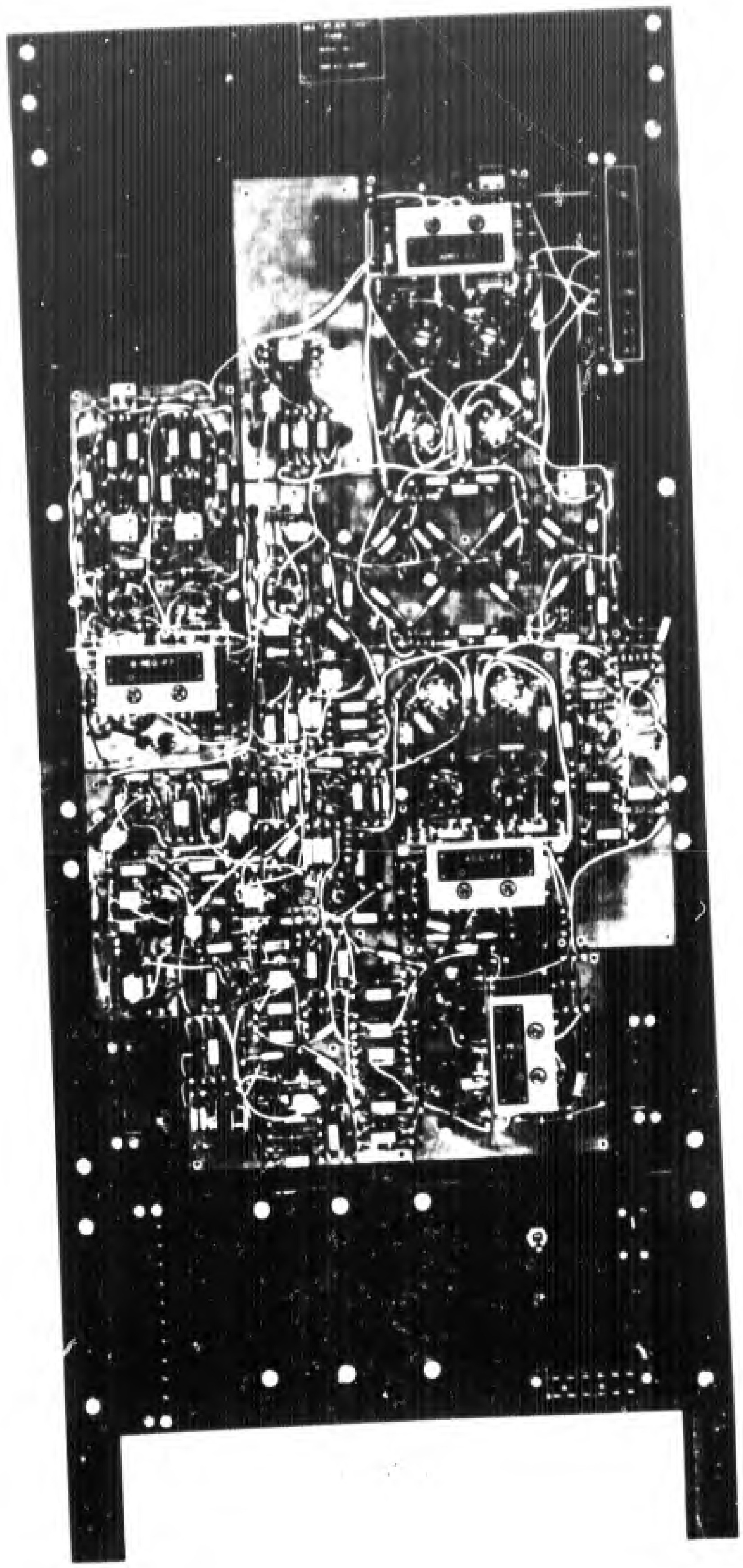

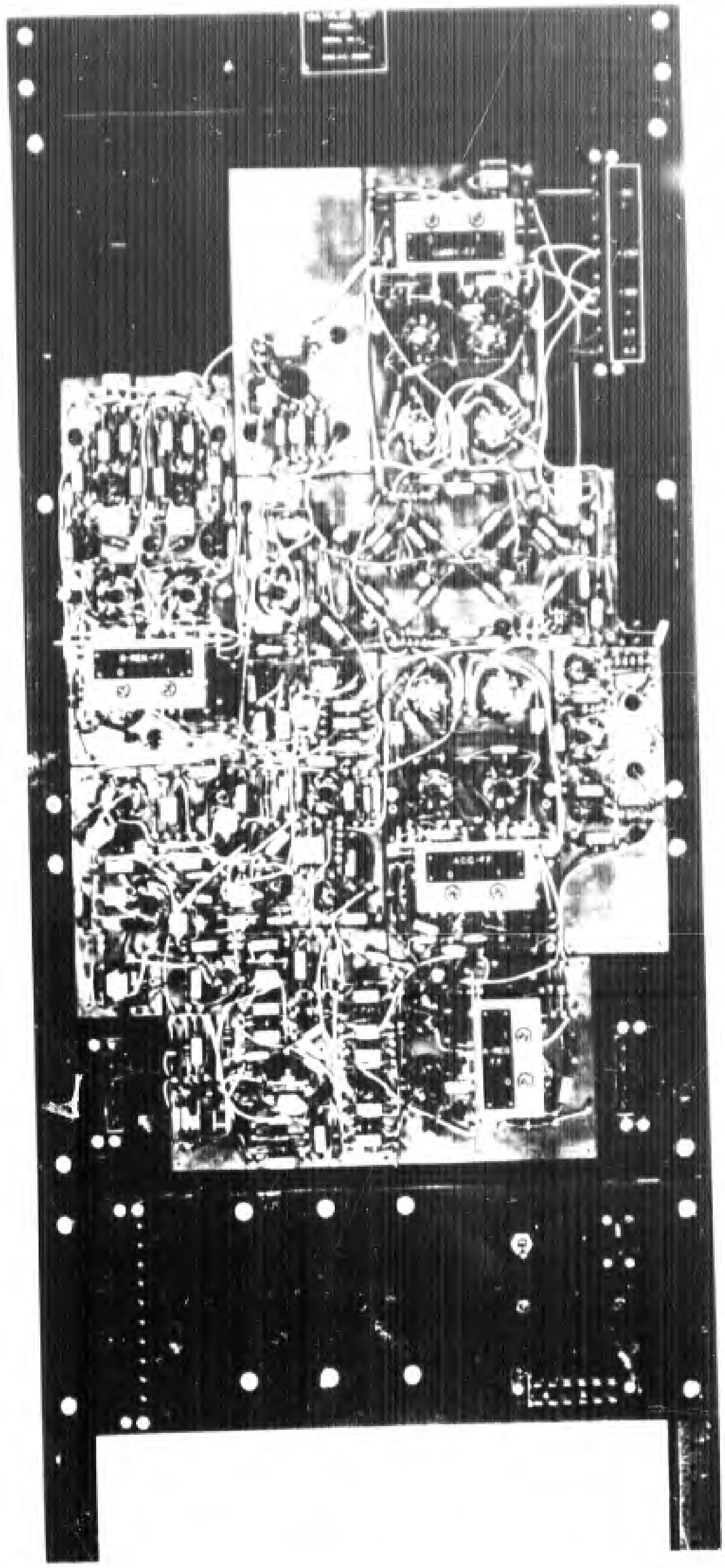

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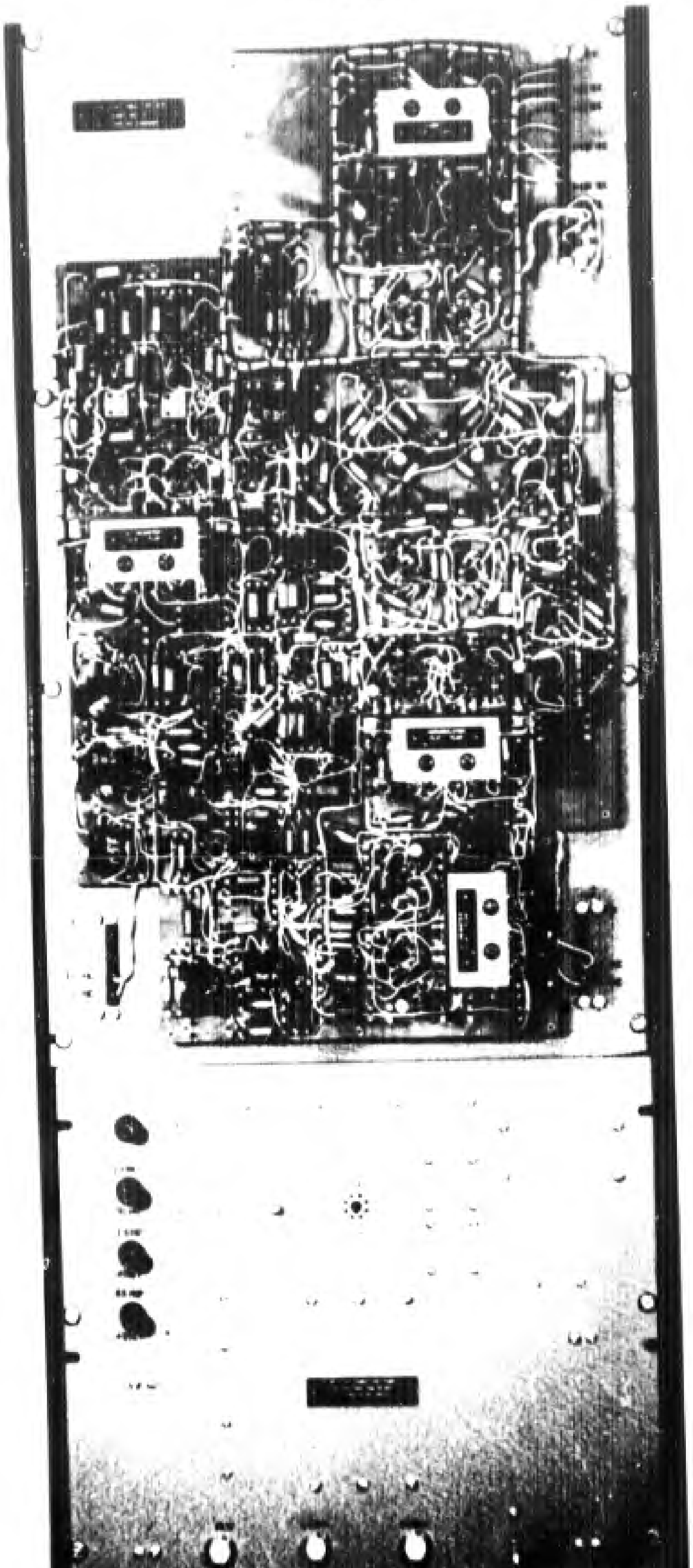
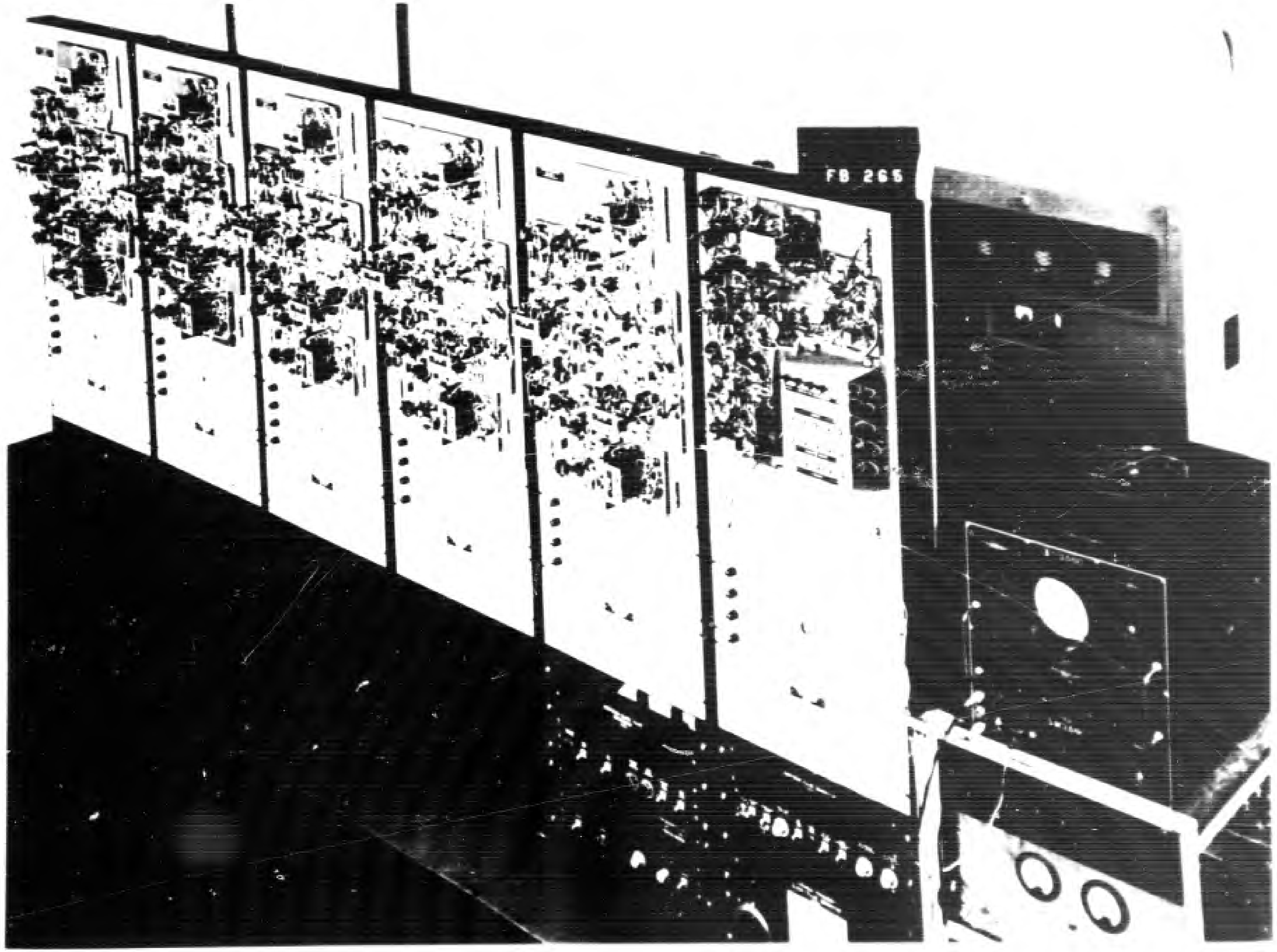
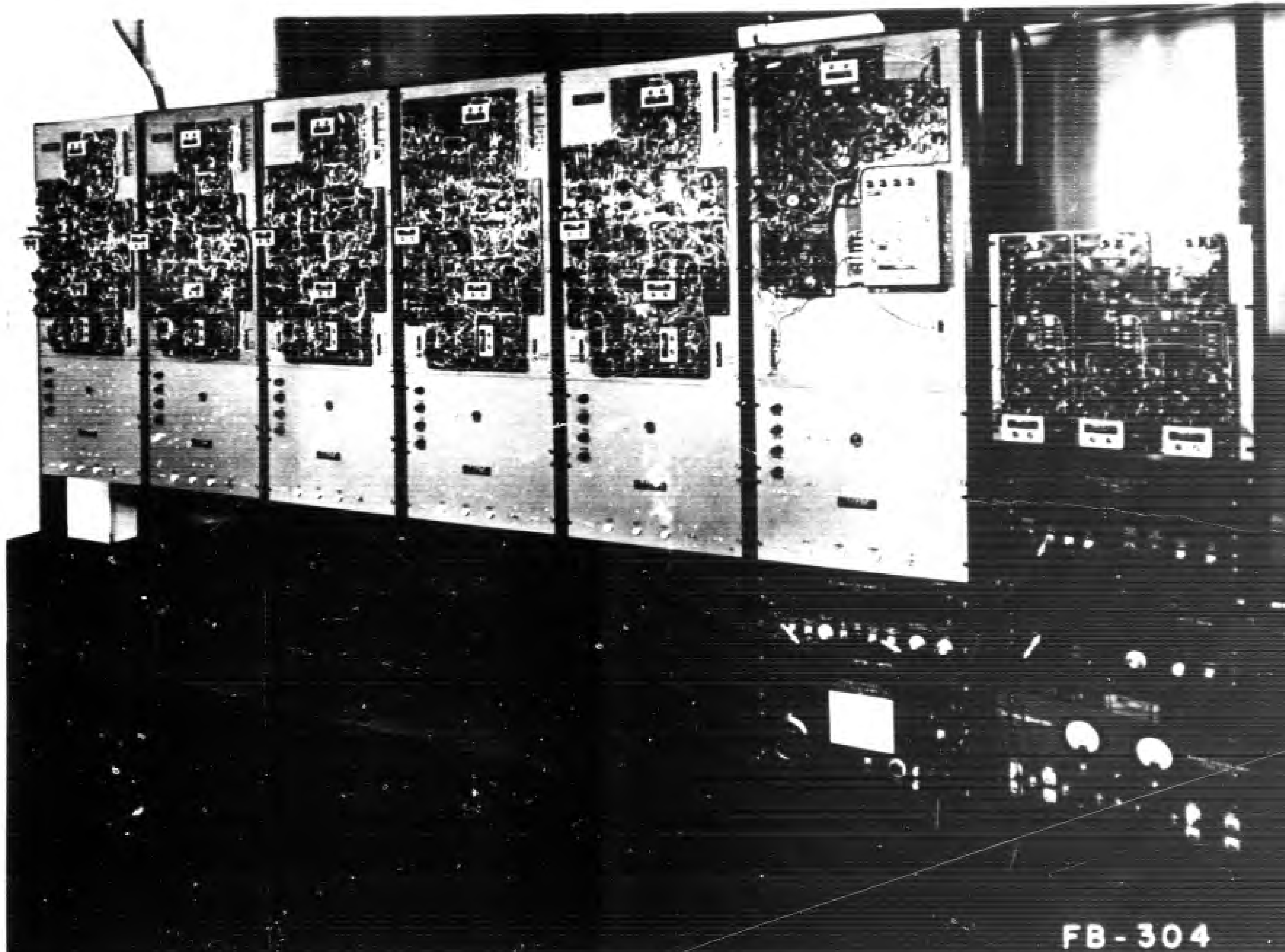



FB 265


FB-304

The 5-digit multiplier is being used to study the pulse shape and pulse delay when a pulse passes through a number of tubes in series or when a single tube must drive the grids of a number of tubes connected in parallel. Because of the non-linear nature of the circuits and the variable pulse-repetition frequency, a careful investigation of all coupling circuits is necessary. Another problem which can be studied with the 5-digit multiplier is trouble location. Trouble-location techniques and suitable test equipment which will be valuable for Whirlwind I are being developed as work progresses on the 5-digit multiplier. The multiplier is also useful for educating new personnel, stimulating thinking in terms of system problems, and as a demonstrator. When circuit studies are complete, the multiplier will be operated as a life test unit.

The 5-digit multiplier is shown in photograph FB-304 complete with step counter and restorer-clock pulse distributor on the first rack; and manual control, restorer pulse generator, and master clock on the second rack. The digit columns include all the circuits required in the Whirlwind I arithmetic element, but a simple control for performing only multiplication is provided. Since multiplication is the most complicated operation required in the arithmetic element, and since all the arithmetic-element circuits are included in each column, all the problems anticipated in the Whirlwind I arithmetic element may be studied in the 5-digit multiplier. The control includes two 5-digit toggle-switch registers into which can be set the numbers to be read into the A and B registers. These toggle switches are directly coupled to the read-in gates of these registers. After the A and B registers have been cleared by a clear push button, a read-in push button causes the read-in gates of the two registers to be pulsed, and the numbers are transferred to the registers. Multiplication can then be carried out either step-by-step or automatically.

After the multiplication has been completed, a 3-stage step counter automatically closes the gate tube which sends pulses to the B-register. This counter is reset each time the clear push button is depressed. The step-counter end-carry pulse is also delayed and used to initiate the high-speed carry.

A number of problems have been uncovered by the work with the multiplier to date. Satisfactory step-by-step multiplication has been achieved as well as automatic multiplication at pulse-repetition frequencies up to 2 megacycles.

The time schedule for assembly and test of the 5-stage multiplier is interesting and proves the value of careful engineering design.

First multiplier chassis
arrived from Sylvania-----------September 25, 1947

Final assemblies
delivered-----------------------October 14, 1947

Push button operation
functioning---------------------October 20, 1947

Operation at 100 kc
repetition rate-----------------October 28, 1947

Operation at 1 megacycle--------November 13, 1947

Operation at 2 megacycles-------November 14, 1947

Further tests will be made to determine the upper limit of operating frequency.

4.2 Storage Tube Development

Work on electrostatic storage tubes is summarized in Volume 9, M-159 and M-130. The latter discusses the amount of time devoted to basic research and to development of vacuum tube test equipment and construction and laboratory techniques. (See Volume 9, M-46, M-56, R-130, and Volume 10, R-131, R-128, and R-132). Because of stress on basic research and on the fundamental behavior of the tube components, only a few tubes have been constructed and tested. Most of those in which all components of the storage tube have been included are of recent origin. The laboratory facilities at M.I.T. permit completion of a new tube within a few days after design is completed. Most tube tests are made with video test equipment under pulsed conditions comparable to the final tube application. Dependence is not placed on steady-state testing methods. For convenience in construction, storage tubes have thus far been made with small storage surfaces 3/4 inch in diameter. There is no reason to believe that other than normal mechanical difficulties will be encountered in increasing the tube size. The available equipment discussed in Volumes 2, 9, 10, and 19 will enable the Servomechanisms Laboratory to construct the required tubes for Whirlwind I. Servomechanisms Laboratory staff members are accepting responsibility for converting the laboratory results to construction practice and for operating the tubes in a working computer. A conservative program is therefore planned in which basic research information forms a firm foundation for development and construction.

Results of some earlier tests are reported in Volume 9, M-130. Improved results have since been obtained on other tubes. Good output signals of 0.1 volt without output preamplifier have been obtained. Signal-to-noise ratio is excellent. The 0.1 volt output has been obtained in a reading time of 3 microseconds. Writing time is longer than desired in a final tube. Writing time at present is in the range of 20 to 60 microseconds, but no attempt has yet been made to shorten the writing time. The writing time is predictable on the basis of physical and geometrical properties and can be improved by obtaining higher beam current, using a thicker dielectric layer on the storage assembly, and selecting a secondary emitting surface with a lower first cross-over voltage than has thus far been used. Many of the test results to date have been obtained on willemite phosphor surfaces. Willemite was most readily available but is notoriously poor for the purpose. The 3/4 inch diameter storage surface has been used for storing 12 digits. This density is within a factor of two of final objectives. Independence of adjacent stored areas has been demonstrated over long periods of time, but in some tubes has not been as reliable as finally desired. Some tubes have been built with excellent independence of adjacent stored areas, and others with writing times of 20 to 40 microseconds. No tube has yet been constructed to combine these features.

Apparent solutions to the existing storage tube problems are known. Considerable effort must yet be expended before a satisfactory tube is expected; however, the storage tube development program appears to be meeting the time schedule of the remaining Whirlwind I components. Since the Whirlwind I system is independent of the exact storage tube characteristics, any tubes which exhibit satisfactory reliability can be used. Final tubes meeting all of the goals set forth in Section 3.3 are not necessary to begin work with Whirlwind I. Future storage tube development will include selection or design of a better high-velocity gun to give greater beam current, the investigation of other secondary emitting surfaces, life tests on secondary emitting surfaces, continued investigation of mosaic versus continuous dielectric storage surfaces, the development of a larger size tube, and improved mechanical design. Coincidentally an effort will be made to reduce the physical size of the tube from the presently planned 5-inch diameter to a 3-inch diameter.

Deflection circuits for the storage tubes are considered satisfactorily demonstrated on a research basis. Only engineering design remains to be done and no work is at present being devoted to this phase of the program. A demonstration system will be set up to show high-speed rapid selection by the deflection circuits, and will be used in conjunction with improved storage tubes now being planned. A resume of the deflection circuit studies is given in Volume 10, E-32, E-31, and R-120.

4.3 Electronic-Circuit Development

4.31 Flip-flops

The two basic elements of the block diagrams are the flip-flop and the gate circuit. Flip-flops are used as binary counters, storage elements, and gate generators. For the Whirlwind computers, flip-flops must have a switching time of approximately 0.1 microsecond. Development of a reliable, high-speed flip-flop has been a task of prime importance in the electronics group and will continue. The present flip-flop employs two 6AG7 pentodes and a common cathode-bias resistor. It may be set to a desired state by applying a pulse to the proper control grid, or it may be triggered by applying a pulse to the cathodes. Recent work has included a study of the factors that influence reliability, and minor changes in flip-flop design are being investigated by means of a flip-flop life-test rack containing ten flip-flops. Ten flip-flops were switching 2×10^5 times per second. The first run of 500 hours had a counter on one flip-flop to count errors. For the remaining 9 flip-flops, an odd but not an even number of errors could be detected. Up to 237 hours there were no errors. Between 237 and 253 hours there were at least 5 errors, probably due to power supply failure. Between 253 and 429 hours there were no failures. Between 429 and 493 hours there was one error. From 493 to 500 there were none.

At 500 hours, counters for the detection of errors were put on all flip-flops, and the method of triggering was changed. A further run of 302 hours produced no errors. This corresponds to 2×10^{12} operations without failure from any cause. (See Volume 15, E-54 and M-138). A master's thesis is now in progress to investigate a different type of flip-flop which may eliminate the need for precision components. Flip-flops are discussed in Volume 15.

4.32 Gate Circuits

The other basic element of the block diagram, the gate circuit, has also experienced considerable development. An evaluation of gating methods was made early in the program (see Volume 19, R-109). A tube having two sharp-cutoff grids is most desirable for the Whirlwind computers; the Western Electric 6AS6 pentode is such a tube. However, since the 6AS6 is a low-current miniature tube, it has proved inadequate for working into the low-impedance loads necessitated by very short pulses. Sylvania has developed a new gate tube for the Whirlwind computers, Sylvania type SR-1030. This has a lock-in base and provides 40 milliamperes of plate current with the control grid and the suppressor grid at cathode potential. The tube eliminates the necessity of driving grids positive and makes a more reliable design possible. It will be available in production quantities about January 1, 1948, and will have an RMA type number. Circuits for the new tube are being investigated at present at M.I.T. with pre-production samples. A more detailed treatment of gate tubes may be found in Volume 16.

4.33 High-speed Switches

High-speed multi-position switches are called for by the block diagrams, for the time-pulse distributor and for the operation switch in the control, for selection of a desired register in storage, and for the shift-and-carry operation in the arithmetic element. An evaluation of switching methods was made very early by the project and a master's thesis was written on the most promising switch, the crystal-matrix switch. The problem was to develop a switch which would have a switching time of a fraction of a microsecond. The thesis (see Volume 17) describes an 8-position switch having a switching time of approximately 0.5 microsecond. A preliminary design of a 32-position switch has been completed. The switch has been constructed and tested. An improvement on the original design has been found which reduces the switching time of the 32-position switch to 0.2 microsecond (see Volume 17, R-123).

4.34 A-C Coupling

In order to avoid the cascading of power supplies, the amplification of power-supply-voltage drift, filament transformer isolation, and other difficulties accompanying direct coupling, a scheme of a-c coupling has been devised which preserves the functional advantages of direct coupling. This scheme requires that each flip-flop in the computer be triggered twice by two pulses one microsecond apart (so that the flip-flop returns to its original state) during a time in the cycle when the flip-flop is not otherwise active. This is done frequently enough so that the coupling capacitors do not have time to discharge; the desired d-c level is obtained by use of clamping diodes. A-C coupling is an important factor in the Whirlwind computers which makes operation more reliable by permitting wider tolerances on power-supply voltages and pulse amplitudes. It is discussed in greater detail in Volume 15.

4.35 Crystal Rectifiers

Crystal rectifiers are used in Whirlwind I for clamping (d-c restoration), for isolation in coupling trigger sources to flip-flops, for mixing signals in a common load, in high-speed multi-position switches, and in pulse generating circuits. In addition, Sylvania is developing special high-conductivity crystals for coupling to the digit transfer bus and for use in the deflection circuits. Crystal rectifiers possess many advantages over vacuum-tube diodes, but they possess the disadvantage of having a back conductance which frequently cannot be neglected and which increases with temperature. Measurements have been made to determine the characteristics of crystals, particularly at overload and at high ambient temperatures. Close contact is being maintained with the crystal group at Sylvania, where life tests, including life tests under pulsed conditions at high ambient temperatures, are being conducted. Crystal rectifiers are discussed in Volume 15.

4.36 Pulse Transformers

Pulse transformers are important components of the Whirlwind computers. Their use as impedance transformers and for pulse inversion greatly reduces the number of tubes required and simplifies circuit design. Commercial pulse transformers suitable for the pulse shape and power levels used have not been obtainable. A study of pulse transformers was undertaken and a report prepared which thoroughly discusses transformer analysis and design (see Volume 18, R-122). Transformers for Whirlwind I have been designed and a study of applications has been made. At present, two transformer types are adequate for all applications. One type is a one-to-one inverter transformer and the other is a three-to-one impedance transformer intended primarily for coupling vacuum tubes to low-impedance cables. An investigation of voltage step-up transformers is now being carried out (see Volume 19, E-60). Pulse transformers are discussed in Volume 18.

4.37 Miscellaneous Tubes

Of a total of 3,500 tubes for Whirlwind I, 1,1150 are used in gate circuits, 700 are used in flip-flops, and 870 are used as buffer amplifiers (see Volume 16, M-132).

The tube used in flip-flop circuits and for most buffer amplifiers is the 6AG7 pentode. Pulse characteristics of the tube have been obtained and tube life is being investigated. A group of 100 6AG7's are undergoing life test at the present time. The tubes are being overdriven by a 60-cycle voltage on the control grid; the filament voltage is left on 24 hours a day. After 2,200 hours, no tube failures have been observed. Final conclusions should not be drawn from this statement, however, because the life test rack was operating improperly during the first 1,650 hours of operation (see Volume 16, M-119). Also, a group of 10 flip-flops using 6AG7's is being life tested. After 500 hours of operation, no tube failures have been observed (see Volume 15, B-64). An investigation of the so-called "black-out" effect has been conducted to find out if this will cause trouble in the Whirlwind computers. Black-out was observed in the 6AS6 gate tube, but only when the pulse driving the control grid positive was 10 microseconds or greater in length. No trouble due to black-out effect is expected in the Whirlwind computers and the effect has been observed only in the 6AS6 gate tube. Miscellaneous vacuum tubes are discussed in Volume 16.

4.38 Miscellaneous Circuits

A number of computer circuits in addition to those already mentioned have been investigated. These include: buffer amplifiers to drive the digit transfer bus, and buffer amplifiers to simultaneously drive a number of tubes in different racks. The project has also designed and constructed a 3-stage step counter, a preliminary time-pulse distributor, and has designed the register panel and the flip-flop storage for Whirlwind I. Final designs of the last two items, register panel and flip-flop storage, are being prepared by Sylvania. These miscellaneous circuits are discussed in Volume 19.

4.39 Test Equipment

Basic test equipment for research in computer circuits must include a synchroscope and a pulse generator. Because of the high pulse-repetition frequency and short pulse length used in the Whirlwind computers, a synchroscope with very fast sweep is necessary. The Model 5 synchroscope has proved adequate for most work. The TS-239/UP is superior for certain purposes. The most widely used test equipment designed by Project Whirlwind has included a gas-tube pulse generator for generation of short pulses at low pulse-repetition frequencies and a high-frequency clock-pulse generator (1 to 6 megacycles). The high-frequency clock-pulse generator is very similar to the master clock that will be used in Whirlwind I (see Volume 19, E-48). In order to use the a-c coupling scheme, a source of pairs of pulses spaced approximately 10 microseconds apart is necessary. This restorer-pulse generator has been used with many test arrangements, including the 5-digit multiplier (see Volume 19, E-52). A similar generator will be used in Whirlwind I. A general-purposed gate-and-delayed-trigger generator has been designed and many are in use. A tube tester has been designed and built in this laboratory for obtaining static and pulse characteristics of vacuum tubes. A crystal tester has also been designed and constructed for testing forward and back resistance of germanium-crystal rectifiers (see Volume 15, E-37). Test equipment is described in Volume 19.

4.4 Input and Output Equipment Development

The photographic film reader-recorders to be used for numerical inputs and outputs with the Whirlwind I computer are being developed at the Eastman Kodak Company. The stage of this development is reported in their Progress Report No. 1 in Volume 11. The equipment is essentially in breadboard stage with experimental setups of cathode ray tubes, optical systems, electronic equipment, and film drives. At the moment these breadboards are in the form of separate components, although it is hoped that by the first of 1948 a complete working breadboard system will be available. Development time is being reduced by the design of a single unit which can be made into a reader or recorder by suitable changes in its optical system. The housings, film drives, mechanical systems, and much of the electronics will be identical for both units. The automatic film-processing equipment will be an adaptation from already existing designs with somewhat different specifications. A revision of plans since the Eastman Kodak report permits use of a recording mask with only two rows of openings.

One experimental model of a decimal-to-binary converter has been built at M.I.T. and is described in a thesis by D. J. Crawford in Volume 12. This unit has operated satisfactorily but must be redesigned before inclusion in final keyboard equipment.

One of the project engineers has been studying magnetic recording for use as an erasable intermediate-speed memory device. His preliminary findings are reported in R-124 in Volume 11. This work is still in a preliminary stage but further experiments are being carried on as discussed in M-106, Volume 11.

Volumes 11 and 12 also report the project work on devices for conversion between numerical and analogue quantities. The first of these devices was built in 1946 and used a 2-way counter to count pulses generated as a graduated disc moved in front of a pair of photocells. This device operated satisfactorily but has since been discarded as being too complicated and expensive. If many quantities are to be converted, a complete counter converter is needed at each shaft. Work was again begun on this problem in June of 1947 with emphasis on the design of conversion methods requiring but a single complicated converter for many quantities, the additional equipment required at each conversion point being very small. Some experimental work has been done on a frequency-modulation system in which the motion of a condenser connected to a shaft varies the frequency of an oscillator, the resulting frequency being measured by binary counters. This method is basically suited only to conversion from mechanical position to numerical code. However, all these methods are reversible either through the use of feedback systems within the converter or through the use of external servomechanisms. Another method now being studied is the use of pulse-time coding. Boot-strap sweep circuits are used for converting from electrical magnitude to a time difference between a pair of pulses. This time difference is then converted to a numerical quantity by means of a binary counter and a fixed-frequency supply of clock-pulses. This system is also reversible.

It is not expected that any one of these conversion devices will suffice for all problems because of the great difference in specifications for the accuracy, precision, and sensitivity of the various quantities being converted. If the sensitivity requirements are small, then direct binary-weighted conversion systems such as are discussed in the deflection circuit studies in Volume 10 could be used. In some cases where the sensitivity must be one part in ten thousand or better, multi-speed systems should be used. A part of this problem is the design of servomechanisms which will operate satisfactorily on intermittent data received from digital computers. In some cases the computer itself can be left in the servo-loop, thus allowing the use of the great computational capacity and flexibility of the computer in servo compensation. In other cases it may be desirable to close the servo-loop outside of the computer, the servo receiving only positional data. One of the staff members of the Electrical Engineering Department at M.I.T. is at present studying these problems in preparation for a doctorate thesis.

4.5 Aircraft Cockpit Development

While the cockpit now being designed is intended for Whirlwind I and is not the more extensive system planned for Whirlwind II, it is considered important that the cockpit be adequate to permit study of the aircraft analyzer as a whole as well as study of simulation techniques.

The early work on the simulation program was devoted to study of the effects necessary for adequate flight simulation and suitable devices for obtaining realistic pilot reaction. The effects considered necessary are: (1) control-force loading, (2) presentation of aircraft behavior by means of a simulated instrument panel, (3) noise and vibration, and (4) reproduction of the interior appointments and appearance of an actual cockpit. In addition to these factors, motion of the cockpit was considered. (See Volume 14, R-125.)

Motion of the cockpit to simulate accelerations felt by the pilot during maneuvers presents a difficult problem. The simulation can at best be only approximate. It is not feasible to mount the cockpit in such a manner that it may have the same degrees of freedom as the aircraft, since sustained accelerations would required prohibitively large displacements. A compromise considered was to suspend the cockpit as a pendulum free to swing about two axes (pitch and roll) and thus to control the direction of the gravity vector so that horizontal components of acceleration on the pilot could be produced by tilting. (See Volume 14, R-100, M-74.) This system would require the development of large hydraulic servomechanisms suitable for moving the mass of the entire cockpit structure. Since this program presented serious difficulties, and since the value of such a system could not be definitely established, this phase of the work has been discontinued as a part of the immediate Whirlwind program. However, the cockpit will be supported by springs so that it may be vibrated.

The control-force loading servos are force-producing servos which compare the actual forces indicated by strain gages with the required forces dictated by the computer. The difference, or error, is amplified electronically to actuate a small torque motor. The output movement of the torque motor is amplified by a hydraulic booster to operate a differential pressure regulator valve. This regulator controls the hydraulic pressure on a piston connected to the controls. The demands of high speed of response and high precision have necessitated a good deal of study and experiment to develop suitable components, particularly the hydraulic amplifier and the pressure regulator.

A test model of the system described above has been built and tested. While the system worked well, it still requires further development to be completely satisfactory. A faster hydraulic amplifier is being developed, and work is under way to design a more satisfactory regulating valve.

The control-force loading equipment must also insert calibrated amounts of elastance, backlash, and coulomb friction to simulate these imperfections in actual aircraft controls. This problem has been approached in two ways. Mechanical devices have been designed to insert these quantities in the control linkages, and a study is being made to determine the merits of calculating these effects in the computer and simulating them by means of the hydraulic servos.

Data on aircraft instrument characteristics have been gathered, and tentative layouts of the instruments started. The slower, less precise instruments (such as fuel gages) will probably be voltmeters energized from the computer. The more precise instruments will be small servomechanisms receiving input data from the computer. Space limitation and exacting precision requirements necessitate careful design to achieve accurate simulation of performance and appearance.

In connection with the studies of instrument servos and control-force loading servos, the nature of the input signal must receive careful attention. The signal received from the computer will be discontinuous since information will be read out of the computer periodically rather than continuously; hence changes in signal magnitude will be in discrete steps.

The effect of such operation is difficult to predict, and careful tests of the Whirlwind I system will be necessary to evaluate and perhaps modify the servos.

Techniques of generating realistic noise and vibration effects have already been accomplished by the Navy in the construction of Operational Flight Trainers.

5.0 System Design Studies

Block Diagrams showing the organization and control operations of the Whirlwind I computer will be found in Volumes 5 and 6. These block diagrams describe the control and the arithmetic element but are not complete in their description of input and output devices, the control desk, checking and trouble location, and the storage system. Work continues toward completing the Whirlwind I block diagrams. Block diagrams for Whirlwind II will be started, as well as a detailed consideration of probable Whirlwind II applications. The reader is referred to Volumes 5, 6, and 7 for accounts of the system block diagrams, detailed discussion of the computer codes, methods of handling alphabetical information, checking, trouble location, and special operations.

Checking and special control functions are reviewed in the following two sections.

5.1 Inspection, Checking, and Trouble Location

Two categories of computer application must be distinguished:

1. Those applications where high cost in life or property depend on the continuous and correct operation of the equipment. Most such applications fall in the control category, for example, handling of air traffic, chemical processes, and some military operations.

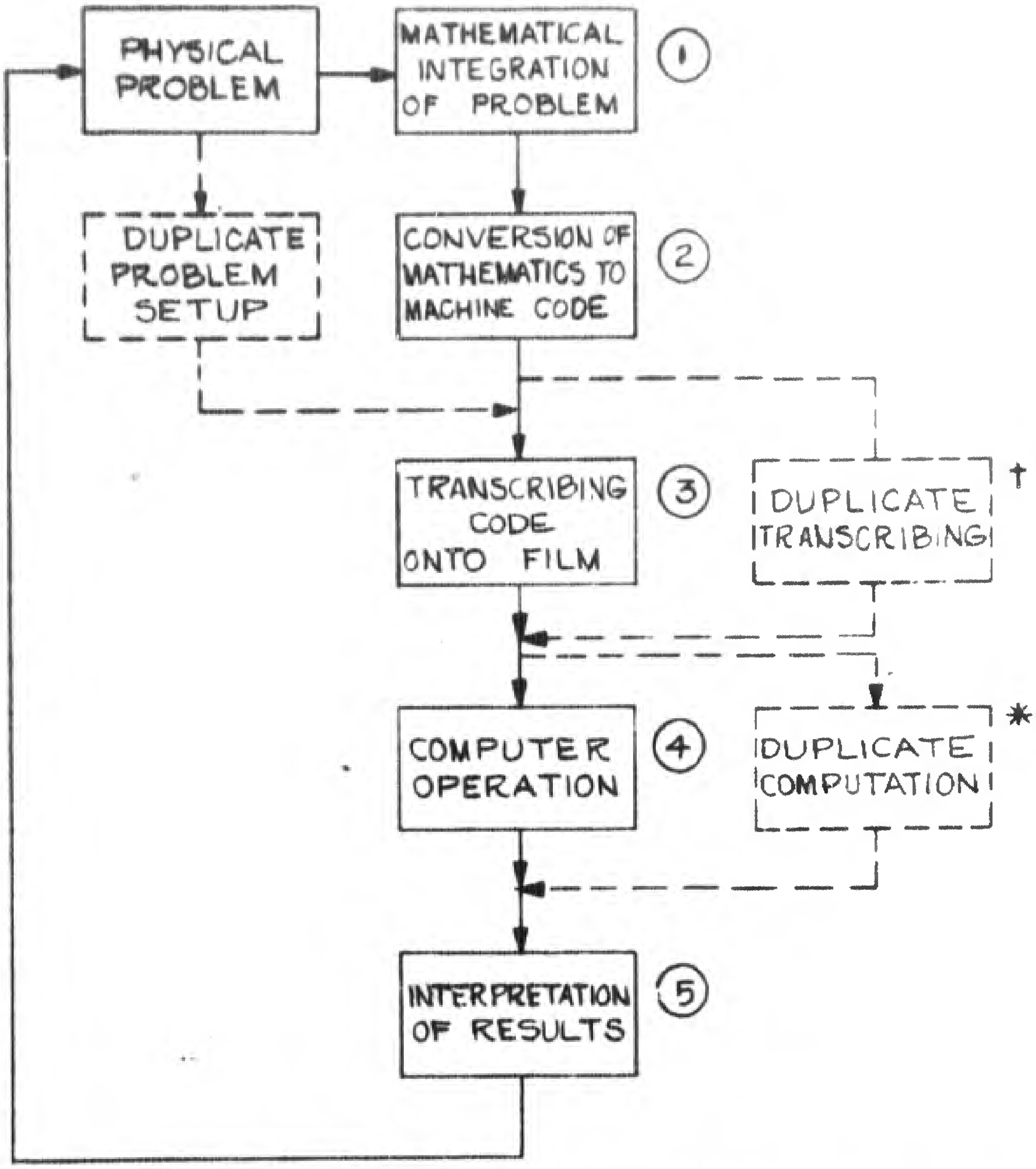
2. Those applications where continuity of operation is not of primary importance even though incorrect answers may be financially costly.

In Class 1 not only must faulty answers be rejected but correct answers must be simultaneously available. A minimum of three machines is required. In case of a failure, the two answers that agree can be taken as correct. A minimum of four machines is required if the check is to continue while one machine is being serviced. The number provided for each problem will depend on the economics of the situation. Checking using one pair of machines will in general be unsatisfactory since there is no quick way of determining which is providing correct answers when a discrepancy occurs.

Class 2 computations where continuity of computer operation is not essential are the ones more ordinarily discussed. The normal flow diagram for solving a problem by digital computation is shown in Drawing A-31200.

Checking of step 1, the mathematical interpretation of the physical problem, and step 2, the conversion of the mathematical formulation to machine code, can be done by having the problem independently formulated by two capable groups. The two independent formulations can then be run through the machine, a comparison of the answers giving a thorough check on the operation of the entire sequence since the two formulations will, in general, be quite different. It is also possible to check these steps by comparing the machine answers with certain known results obtained by other means. Well designed mathematical checks involving smoothness or identities should also help in this checking.

Depending upon the length and nature of the problem, transcription from written code to photographic film can be done by duplication and comparison or by proof reading. The operator inserts orders and numbers through a decimal keyboard as discussed in Section 3.1. With a more elaborate keyboard it would



† OFTEN DESIRABLE; IN MANY PROBLEMS WILL BE REPLACED BY PROOF READING. (SEE TEXT)

* INEFFICIENT IN MOST APPLICATIONS. (SEE TEXT)

PROBLEM SOLUTION SEQUENCE

A-31200

be possible to insert alphabetic information as well. The numbers are to be recorded on the film in binary notation, the conversion having been performed automatically by equipment at the keyboard. The sequence is as follows:

1. Decimal input on keyboard by operator.
2. Conversion to binary number.
3. Decoding the binary number back to decimal.
4. Printing the decimal number on a paper tape.
5. Inspection of decimal number by operator.

   The conversion equipment operates rapidly enough so that the printing is essentially coincident with the input. The binary number has not yet been recorded on the film; thus the operator can correct any errors.
6. Recording of binary number on film.
7. Checking of the recorded number with the original through photocell interlock. (See Volume 11, Eastman Kodak Report). Both the number and its complement are recorded and checked.

Two such films can be transcribed and compared if desired. Another possibility is to check the first film against a second operator as proposed for the Bureau of Standards magnetic wire input. However, checking is sufficiently complete in the writing process that proof reading of the paper tape against the original data should be satisfactory for most problems. Checking by duplicate tapes or duplicate operators is equivalent to proof reading but ties up equipment. Again the choice is an economic problem depending on the value of the solution. It is expected that many engineering solutions will be run for trial and inspection purposes in which extensive checking will not be justified.

Checking within the machine itself will use four different methods.

1. Continuous checking of some parts of the equipment at each step of an operation.

2. Intermittent checking of the remainder of the equipment by the use of check problems.

3. Checking of check circuits and for incipient failures due to marginal operation by the use of inspection problems.

4. Checking for true intermittent failures by mathematical checks.

Continuous checking of all parts of the computer either by elaborate internal checking or by the duplication of computers does not seem warranted. Such checking is no more successful for discovering steady-state errors than intermittent checks by check problems. Continuous checking will discover intermittent or transient failures but loses much of its value because it supplies inadequate information for the diagnosis and correction of the trouble. Mathematical checks are a much less expensive way of discovering transient failures. The time saved by immediate detection of a transient fault will not be important as long as such faults are relatively rare and care is taken to provide restarting points in the course of a lengthy calculation. Some continuous checking particularly in transfers between film and computer and transfers within the computer itself will be provided in Whirlwind I. These checks examine large sections of the machine but require relatively little equipment and no loss of time.

Check problems will be part of the main program within the machine and will be run automatically at frequent intervals, probably of the order of one second. The problems will be designed to test the operation of all elements of the computer with as few operations as possible. The time required for check problems is not expected to exceed 1 to 5 percent of total computing time. An error made by any part of the computer during the check problem will cause the computer to stop. Steady-state failures will thus be detected shortly after they have occurred as well as intermittent failures of high occurence frequency.

Inspection problems will also be performed at intervals at the discretion of the operator, for example, once a day or as practice proves necessary. Component life tests to date indicate that intervals of this length or greater are practical. (See Section 4.1 and 4.3). The inspection procedure will check all normal checking circuits for proper operation. Furthermore, it will be designed to detect marginal operation and incipient failures. For example, the inspection problems will be run in the computing machine as sufficient operating conditions are altered to demonstrate the operating margin of component circuits. Failure will be reduced from a marginal to continuous occurrence and will be picked up in the normal checking and comparison processes so that the source of error can be located and marginal operation eliminated. As examples, the following operating conditions can be changed:

1. Plate voltage raised and lowered to check flip-flop transfer rates, amplifier output signals, etc.

2. Grid bias voltage raised and lowered to check circuit tolerances to input trigger signals.

3. Clock repetition rate increased and decreased to check frequency independence of circuits.

4. Artificial loads added to critical circuits to check stability of signals.

Execution of this inspection sequence can be made entirely automatic and should take but a few minutes if equipment is properly designed.

It is expected that the majority of intermittent failures will be avoided by the marginal failure checks in the inspection problem. Thos intermittent failures which are not so avoided can best be discovered by the use of mathematical checks on results or partial results. Such checks might be for smoothness or identity or even in extreme cases by repetition using an entirely different computing method. Even if a simple mathematical check is not possible intermittent failures can be discovered by simply repeating the original problem. Steady-state errors which could cause both answers to be wrong and yet check will be discovered by the check problems. A true intermittent error will cause a discrepancy between the two runs.

Discovering the existence of an error is only one part of checking. Just as important is the location and repair of the faulty part. The Whirlwind computers will use three general methods for this purpose.

1. Indicators will be provided for blown fuses, open breakers, overtemperature and other physical troubles. Monitors will be provided for pulse shapes, amplitudes, and frequencies. These monitors will be automatic with indicators and will also present wave shapes on oscilloscopes at the operator's console.

2. The entire computer can be run step-by-step, the contents of all computer registers being available on neon indicators at the operator's console. In addition, it will be possible to run the machine at high speed and yet to determine the contents of any register at any time. Coincidence counters, illustrated in the control desk, Drawing A-31083 of Section 3.1, make it possible to select the contents of any of the computer registers at any time-pulse in any operation of a computing sequence. The advantages of this system are both that the computer functioning at high speed may be checked and that it will be much faster to reach a particular point in a computation by this means than by step-by-step operation. The coincidence counters can be set to stop the computer at the selected point in a problem or to simply extract the desired information and allow the computer to proceed. Provision will

be made for the automatic comparison of extracted numbers with others previously extracted or set in by the console keyboard.

3. Trouble-location problems are expected to be a most powerful aid in locating faults which occur continuously or at frequent intervals. The value of these processes has already been demonstrated in the 5-stage multiplier. The trouble-location problems may consist of many thousand orders but need be prepared only once for the computer. They will be stored on one of the input films and called into use only when needed. The sequence will start with elementary operations requiring a minimum amount of equipment and gradually incorporate the operation of other computing circuits. The computer will generate a distinctive number pattern for each different part which fails. Once the computer is built and running it can be used for generating these patterns itself although they can be generated more laboriously by manual means. The table of patterns against failures can either be consulted by the operator or stored on film and consulted by the machine. It is expected that the majority of machine failures can be located within a few minutes by this means.

5.2 Special Control Functions

The Whirlwind I computer is so designed that addition of special operations is relatively easy. Many of these special operations have not been included in the first design but can be added in later designs or even added to Whirlwind I at a later date. Some special operations require no changes in the physical equipment.

Alphabetical information and sorting by alphabetical classification can be readily handled in the Whirlwind Computer. Alphabetical problems have thus far not been ones of major interest, but are discussed in Volume 7, M-134, and in Section 6.5 of this Volume. Preliminary investigations indicate that the high computing speed and the large amount of internal storage which can be provided in Whirlwind computers can be effectively and efficiently used in correlation and sorting problems.

Accumulation of products is typical of the kind of operation which could be readily provided if the need arose. Accumulation of products might be highly desirable in matrix operations. One of the extra order positions available in Whirlwind I could be used for this special operation. Accumulation of products is discussed in Volume 7, M-136.

Extracting square roots while not included in Whirlwind I as a specific program order is not appreciably more difficult for the parallel type arithmetic element than the process of division. Automatic division has been included as more generally useful. In Whirlwind I square roots are extracted by programmed arithmetic steps. However, the automatic extraction of square roots would require little additional equipment and would be desirable for any machine frequently used for problems involving triangulation.

Special output controls are required in many of the simulation problems. The equipment will, therefore, be able to perform such functions as operating switches, controlling servomechanisms, and performing other logical operations of a physical nature which have been set up in the controlling program.

6.0 Applications

The Project Whirlwind goal is a complete simulation system including digital computer, input and output conversion of physical quantities to numerical inputs and the reverse, and any specialized components required for specific applications. Essential to this program is a soundly engineered computer which can be used as a tool in the work to be done. Operating speed has been set high not only to make possible the calculation of control and real-time simulation problems, but also to use efficiently the electrical and electronic components of the system. The Whirlwind system can accept information in many forms, including numbers on film and magnetic tape; binary, coded-decimal, and alphabetical symbols; electrical voltages; time-pulse modulation; and mechanical positions.

The computer can put out numerical and graphical results, and can control information and communication systems.

The Whirlwind computer can be arranged to provide control signals for mechanisms reading films, magnetic tape, paper tape, or punched cards, so that information in any original form including teletypes can be utilized.

Because of the control and computing flexibility, problems and information coded for other computing systems can likewise be interpreted, used directly, or converted to the proper Whirlwind system of notation. This would include the acceptance of data originally prepared in the coded decimal system, either ordinary or excess three, as well as alphabetical information coded in several forms. Additional comments on alphabetical work will be found in a section on the Census Bureau.

Many simulation and computing applications have been informally considered with various groups. Only a few of the studies have been reduced to final written form, because data on objectives and operating requirements of the problem have in general been too incomplete.

The following problems are typical of the types which have been considered and discussed. Most have been pursued far enough to make certain that Whirlwind equipment would meet the requirements of the application. Here again sufficient detail has usually been missing.

6.1 Air Traffic Control

Consider for a moment air traffic control. We can, for the purpose of example discuss traffic control as merely an information center without becoming involved in the problems of aircraft pilot psychology, the question of data presentation to the pilot, and the relative merits of the various automatic landing systems. The comments apply equally to control at airports or along the airways. Air traffic control and proper handling of the information may require among others the following functions:

A. Radar Information

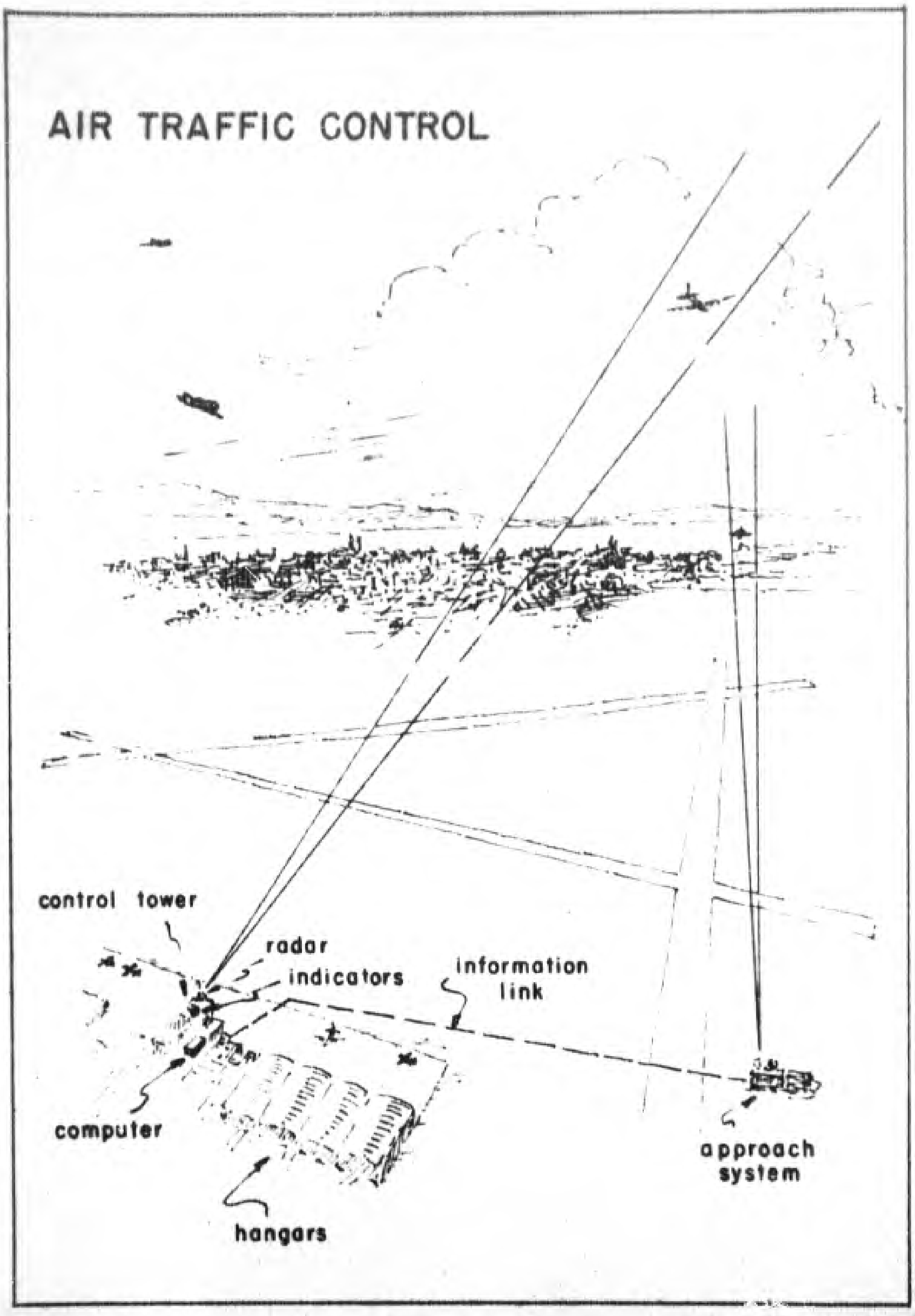
1. The computer should receive radar data indicating the range, bearing, and vertical angle of all aircraft in the vicinity.

2. This radar information as it arrives must be correlated with previous aircraft information.

3. The radar may often supply beacon signals to the computer for identification of most of the aircraft.

B. Evaluation of Information

1. Incoming information must be used to correct the calculated locations of planes in the vicinity.



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2. Based on available information, future courses should be extrapolated or predicted to check against collision or to detect aircraft out of assigned positions.

3. Store required information about each aircraft in the area. This information would include:

   a. X-coordinate of position
   b. Y-coordinate of position
   c. Altitude
   d. X-coordinate of speed
   e. Y-coordinate of speed
   f. Rate of climb
   g. Rate of turn
   h. Accuracy probabilities of the above positions and rates
   i. Destination
   j. Origin
   k. Identification
   l. Other information of interest

4. The computer acting as an information center should recognize new aircraft entering the area and likewise should recognize and remove from the computing system those aircraft which have left the area or have landed.

5. The computing system should use information from other detectors as it becomes available. For example, triangulation from other radar sets, visual sights, beacons, and radio can all be correlated to give a better overall picture.

C. Presentation of Information

Suitable displays and indicators should be available for presenting the required information, including:

1. Indication of new aircraft coming within the area.

2. Indication of aircraft out of position or flight pattern.

3. Warning of possible collision courses and perhaps indication of recommended course changes.

4. Display of the surrounding air activity, showing present position of craft, their predicated positions, and some indication showing altitude as well as X-Y position.

D. Automatic Control

So far as the information center and computing equipment are concerned, operation can be readily extended to include automatic control such as blind landing operations. This function would be dependent on suitable detecting apparatus for providing the required accuracy of aircraft position.

E. Safety

Safety and reliability in air traffic control would of course be of utmost importance. Computing equipment for handling the air traffic control problem must be engineered for the greatest possible reliability. In addition this type of application justifies the use of multiple computing units for reliability and checking purposes.

Consider now the problem of air traffic control outlined above. The capacity of a computing machine is specified by two quantities: its digit storage capacity and its computing speed. The air traffic control problem will be related here to the Whirlwind I system. This is not because the Whirlwind I system is ideally suited to traffic control, but rather because it serves as an example and a scale of reference. Approximate data for the Whirlwind I system follow:

Storage: 2,000 registers, 16 binary digits each

Speed: 20 microseconds, plus or minus, per basic operation

We must examine both the speed and the storage capacity in order to evaluate the usefulness of a given machine in a specified problem. The figures which follow are probably accurate within 30% and are based on detailed studies of similar problems. In Item B-3 above, we listed 13 quantities which might be required for each aircraft. Others not listed might bring the total to 20 storage registers for each airplane. In general, the 16-digit accuracy of a storage register in Whirlwind I will be sufficient for any of these quantities with the possible exception of X and Y positions and certain of the rates. Quantities requiring higher accuracy may be handled with 2 storage registers allocated to the quantity, providing 32 binary or approximately 10 decimal places of sensitivity. Assume for purposes of illustration that we wish to handle a maximum of 50 airplanes in the area at one time. Total storage required for aircraft data is then 50 times 20, or 1,000 storage registers.

Based on previous work, about 500 registers are required for storing the computing program. These control orders include those required for handling the radar correlation, the identification of new aircraft, the extraction of old aircraft from the computing system, and recognition of the various alternates and emergency situations which the information center is to handle. A preliminary mathematical treatment of radar correlation is given in Volume 8, M-124.

Fifteen hundred registers are therefore required for storing the computing program and the airplane data. The remaining 500 storage registers of Whirlwind I would be available for storing data regarding flight patterns, or might be used in connection with automatic landing procedures.

We must now examine computing speed requirements for the above problem. In general, only a part of the 500 orders will be required each time a particular aircraft in the air control system is considered, because many of the possible emergencies and contingencies need not be treated. Say for example 300 orders are required for disposing of a new piece of radar information relating to a particular airplane. The remaining 200 orders are used only occasionally to treat unusual circumstances. The computation, sorting, and control indicated by the 300 orders will require, at 20 microseconds each, approximately 6000 microseconds. To treat each of the 50 airplanes would then require 0.3 seconds, as indicated in the tabulation below.

Whirlwind I storage		2048 registers
Registers per plane	20	
Number of planes	50	
Registers for all planes		1000
Registers for program		500
Registers remaining		548
Computing time per order, average	20 microsec.	
Orders per aircraft, average	300	
Computing time per aircraft		.006 sec.
Computing time, 50 aircraft		0.3 sec.

It is probably not necessary to compute aircraft positions each one-third second, but the additional time might be devoted to landing or other operations. Extension of the storage capacity by addition of other digit columns would make possible the handling of larger numbers of aircraft or intricate details relating to flight patterns and control operations.

6.2 Air Forces Computer

Representatives of the Air Forces visited the Servomechanisms Laboratory in May, 1947, to discuss the application of Whirlwind computers to a large-scale bookkeeping and logistics problem. The problem was considered only in the detail permitted by a single conference. The result of the conference indicated that Whirlwind computers would serve usefully in the required application and that their high speed and large internal memory would be valuable in the sorting and collating operations required. The problem also required operations on matrices up to the order 100, the performance of which is greatly accelerated by extensive internal storage.

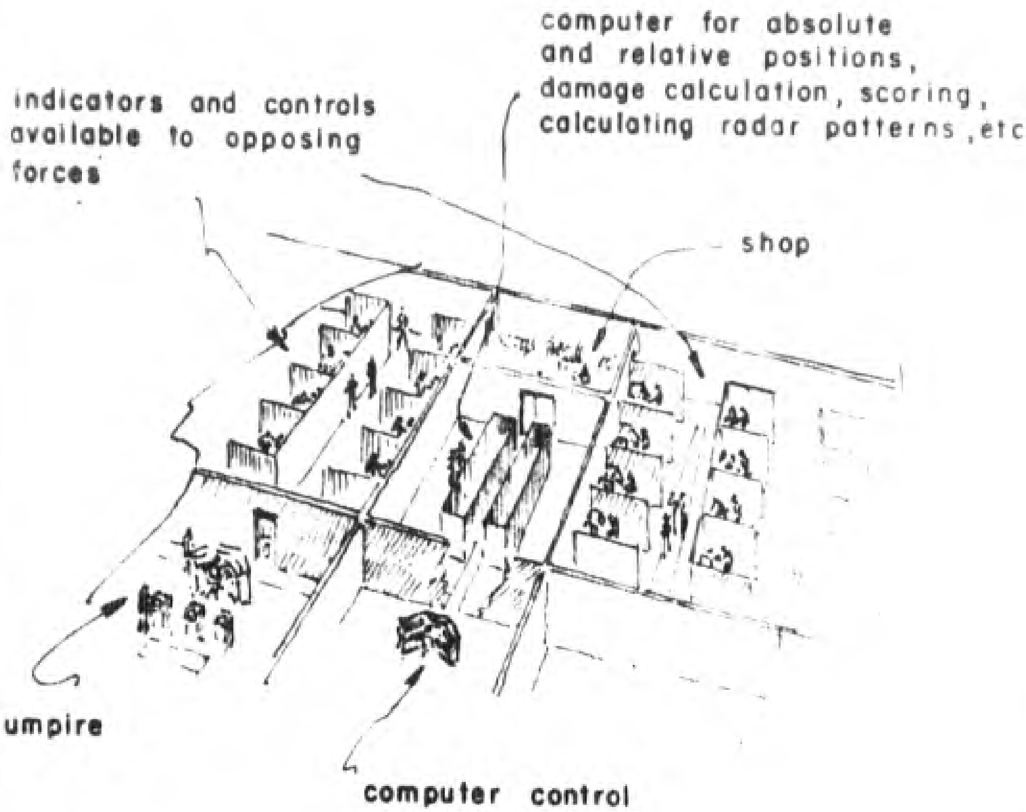
No work was undertaken in connection with the Air Force program because it was pointed out that Project Whirlwind was progressing as rapidly as possible and that additional funds at that time would not appreciably accelerate the availability of equipment to the Air Forces. It was further pointed out that Whirlwind equipment when developed would meet the requirements and that the Air Forces would be well advised to await the availability of the first Whirlwind system to try certain of the problems outlined.

Specifications as originally written for the Air Forces describe a computer some 10 times the capacity of Whirlwind I but smaller than Whirlwind II.

6.3 Army and Navy War College Simulator

Simulators for tactical training have been discussed on several occasions with members of both the Army and the Navy. A computer with characteristics of the Whirlwind system at a size intermediate between Whirlwind I and Whirlwind II seems most appropriate. In one application the simulator must generate the absolute and the relative motions of ships and task groups of the opposing forces being simulated. At each of the many command centers must be controls which set into the computer such factors at the discretion of the command group as course, speed, fire control, and defense. The computer must keep a running account of positions, damage, offensive and defensive capacity, and scoring.

WAR COLLEGE TACTICAL SIMULATOR



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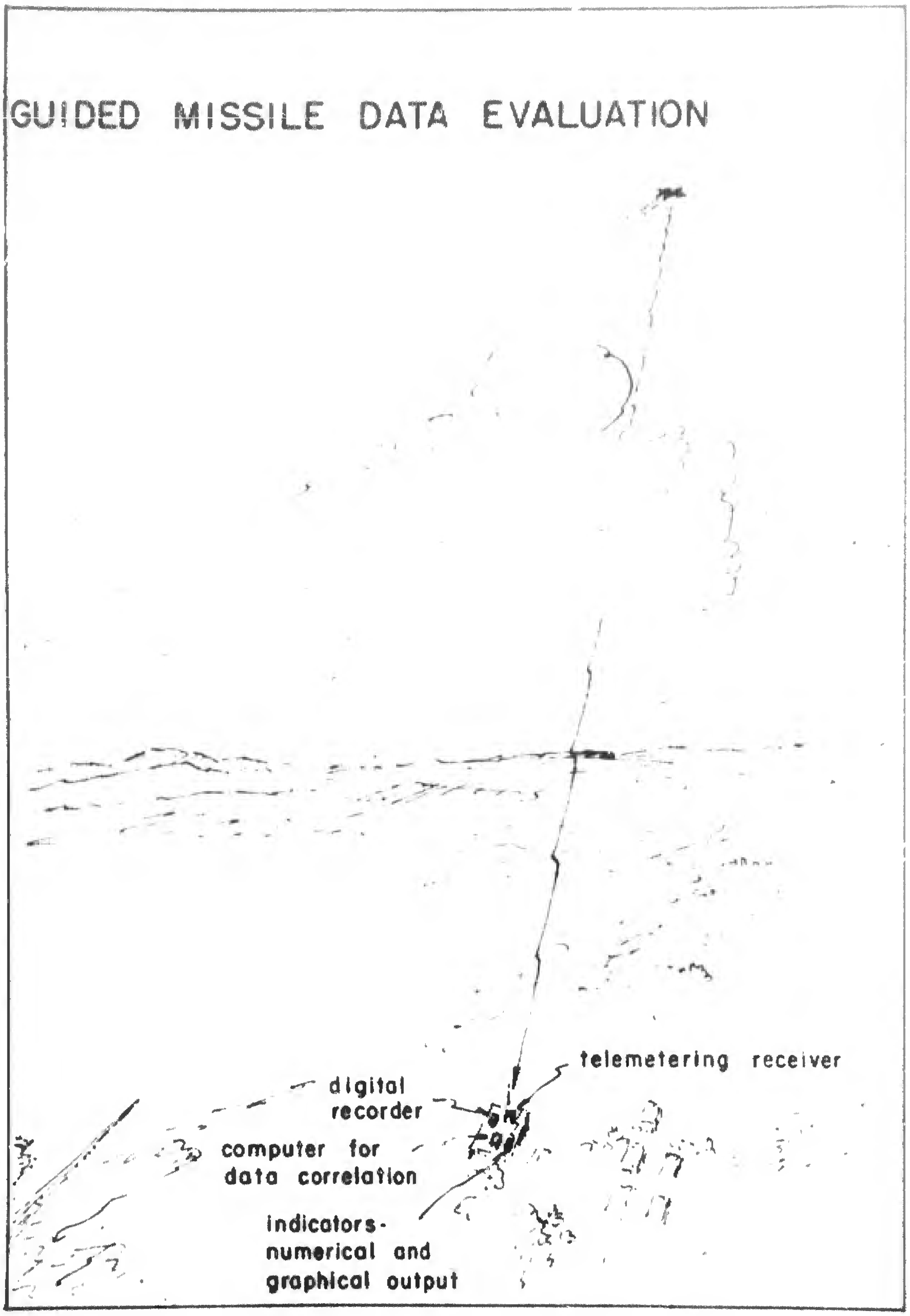
6.4 Guided Missile Data Reduction

Components of the Whirlwind system are suitable in practically the form now contemplated for application to the problem of guided missile data reduction. A computer of the Whirlwind I type might be used, but a redesigned and more compact version, equivalent in physical construction but of smaller capacity than Whirlwind II, would be more suitable. In such a guided missile data handling system, all telemetered information should be recorded in a form suitable for direct use by digital computation. Signals modulated by code, time pulse, frequency, or amplitude can be interpreted by reasonably simple circuits and recorded as binary numbers on photographic film. Since the data that are recorded will be subject to the usual experimental errors, including roughness in the numerical values and in many cases omission of signals due to telemetering and communication failure, it will be necessary that the computing system smooth and interpret the recorded data.

For example, the computing program can be so designed that missing information can be filled in by extrapolation of preceding and succeeding data. Such a computing program might be readily set up on the basis of trajectory continuity and smoothness. In most tests, data will be recorded at several receiving points, and these must be properly matched and evaluated in the data reduction process. Triangulation for trajectory becomes possible by measuring the time difference of signal reception at several receiving points or by triangulation using the measured radar range from several locations. Time would be recorded along with the data to permit correlation by the computer. Data on trajectories and the missile control system behavior should be reduced to the final form required for interpretation before the material leaves the numerical form in which it can be handled by the computing system.


GUIDED MISSILE DATA EVALUATION
telemetering receiver
digital recorder
computer for data correlation
indicators- numerical and graphical output

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6.5 The Census Problem

It is only very recently that information has been received about the census problem. Consequently, very little study has been given to the census problem in relation to Whirlwind I. The following comments have been prepared on this short notice.

The peculiar properties of the census problem seem to be as follows:

a. Very large quantities of external data must be handled.

b. The bulk of the work lies in sorting and tabulating this external data.

c. It will be necessary to transfer, sort and tabulate alphabetical data using the machine.

The gains expected from the use of digital computers are:

a. Greater speed and economy.

b. More efficient storage of external data.

There are then two considerations in the machine:

a. Its internal organization, computing speed, and setup procedure must be such as to efficiently carry out limited manipulations with large quantities of data.

b. The input and output equipments must be arranged to supply and receive the large quantities of data handled by the machine and to do so rapidly and efficiently. An efficient balance must be maintained between the operating speeds of the computer and its input

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b. The input and output equipments must be arranged to supply and receive the large quantities of data handled by the machine and to do so rapidly and efficiently. An efficient balance must be maintained between the operating speeds of the computer and its input and output equipment. The ratio of the number of computer operations performed to the amount of input data received from tapes is much less than exists in simulation, control and scientific calculation problems.

It is difficult without a detailed study to discuss the suitability of the film input and output of Whirlwind I to the census problems. It may well be that an erasable medium such as magnetic tape may be sufficiently less expensive and even sufficiently more flexible to warrant its use instead of photographic film. It is also difficult to estimate the efficiency of balance between Whirlwind I and its proposed input and output devices for census problems. It is always possible, however, to use multiple input and output equipment with a single computer. Comment will be limited here to discussion of the internal organization of the computer itself.

First, the Whirlwind I order code has been designed to be completely general and flexible. The only departures have been a few additions to facilitate computation on the problems of principal interest. Corresponding modifications for handling census information could be incorporated. However, no such modifications seem warranted.

The census problem reduces to a series of inspections on externally supplied digital information. These inspections determine either equality or magnitude of the numbers involved. The character of the number determines its disposition or the disposition of accompanying data. The desired operations may include tabulation in selected registers, the restorage of the entire block of data on an output tape, or even modification of the data itself.

The Whirlwind computer will perform these functions through the use of its addition, subtraction, shifting, and conditional subprogram orders. Programs may be readily written for examining numbers which occupy considerably less than a register length, as will be the case in most of the census applications, or for examining numbers which occupy several register lengths such as are likely to occur in alphabetical sorting. No trouble is presented by blocks of information requiring several registers in which each register contains several short numbers.

The high computing speed of Whirlwind I should result in short solution times in census problems as in others. If the computer handles information faster than the input and output devices can transfer it, then a number of such devices can be used with each computer. It may also be possible to use some of the high computing speed to perform more complicated sorting and tabulating processes within the computer, thus reducing the number of transfers between tapes. This advantage will become more apparent if a large amount of storage capacity is provided. At present Whirlwind I will allow tabulation in about 1000 to 2000 different categories depending upon the size of the tabulation and the amount of program required. If desired, this storage capacity can be increased.

Although no though was given to alphabetic data when the organization of Whirlwind I was planned, there seems no reason to suppose that the computer will be unable to handle it. The machine will handle such data, considering each alphabetic character as a binary coded number which does not occupy a full register length. The machine will require no facilities beyond those already available for sorting alphabetic data in

[redacted]

sequence, examining alphabetic information for equality, or manipulating arithmetic information with alphabetic markers. Further information on this subject will be found in Volume 7, M-134.