PROJECT WHIRLWIND
(Device 24-x-3)

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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FOREWORD

Project Whirlwind

Project Whirlwind at the Massachusetts Institute of Technology Servomechanisms Laboratory is sponsored by the Office of Naval Research under contract N5ori60. The objectives of the Project are the design and development of an electronic digital computer of large capacity and very high speed, and its application to problems in mathematics, science, engineering, simulation, and control. At the present time nearly all project resources are devoted to the design, construction, and testing of the computer.

The Whirlwind Computers

The Whirlwind computer will be of the high-speed electronic digital type, in which quantities are represented as discrete numbers, and complex problems are solved by the repeated use of fundamental arithmetic and logical (i.e., control or selection) operations. Computations are executed by fractional-microsecond pulses in electronic circuits, of which the principal ones are (1) the flip-flop, a circuit containing two vacuum tubes so connected that one tube or the other is conducting, but not both; (2) the gate or coincidence circuit; (3) the electrostatic storage tube, which uses an electron beam for storing digits as positive or negative charges on a storage surface.

Whirlwind I (WWI), now being built, may be regarded as a prototype from which other computers will be evolved. It will be useful both for a study of circuit techniques and for the study of digital computer applications and problems.

Whirlwind I uses numbers of 16 binary digits (equivalent to about 5 decimal digits). This length was selected to limit the machine to a practical size, but it will permit the computation of many simulation problems. Calculations requiring greater number length will be handled by the use of multiple-length numbers. Rapid-access electrostatic storage will have a capacity of 32,000 binary digits, sufficient for large classes of actual problems and for preliminary investigations in most fields of interest. The goal of 20,000 multiplications per second is higher than general scientific computation demands at the present state of the art, but is needed for control and simulation studies.

Reports

Quarterly reports are issued to maintain a supply of up-to-date information on the status of the Project. Detailed information on technical aspects of the Whirlwind program may be found in the R-, E-, and M-series reports and memorandums that are issued to cover the work as it progresses. Of these, the R-series are the most formal, the M-series the least. A list of the publications issued during the period covered by this Summary, together with instructions for obtaining copies of them, appears at the end as an appendix.

1. QUARTERLY REVIEW

Progress toward securing reliable operation of the computer with all of central control and test storage during July, August, and September, the period of this report, has been quite satisfactory. The time schedule presents a summary of the various activities of the Project and shows most of them on schedule. Marginal checking facilities are not as complete as we had hoped because of delays in the design and construction of equipment for automatic selection and variation of circuits. The manual system has proved itself very valuable. We have still found it impractical to devote enough manpower to the storage tube reliability tester to make it as useful for that purpose as we had initially planned, but we have changed the emphasis on its use and secured valuable performance data. The first Eastman Kodak reader-recorder was delivered in September and is now undergoing initial tests.

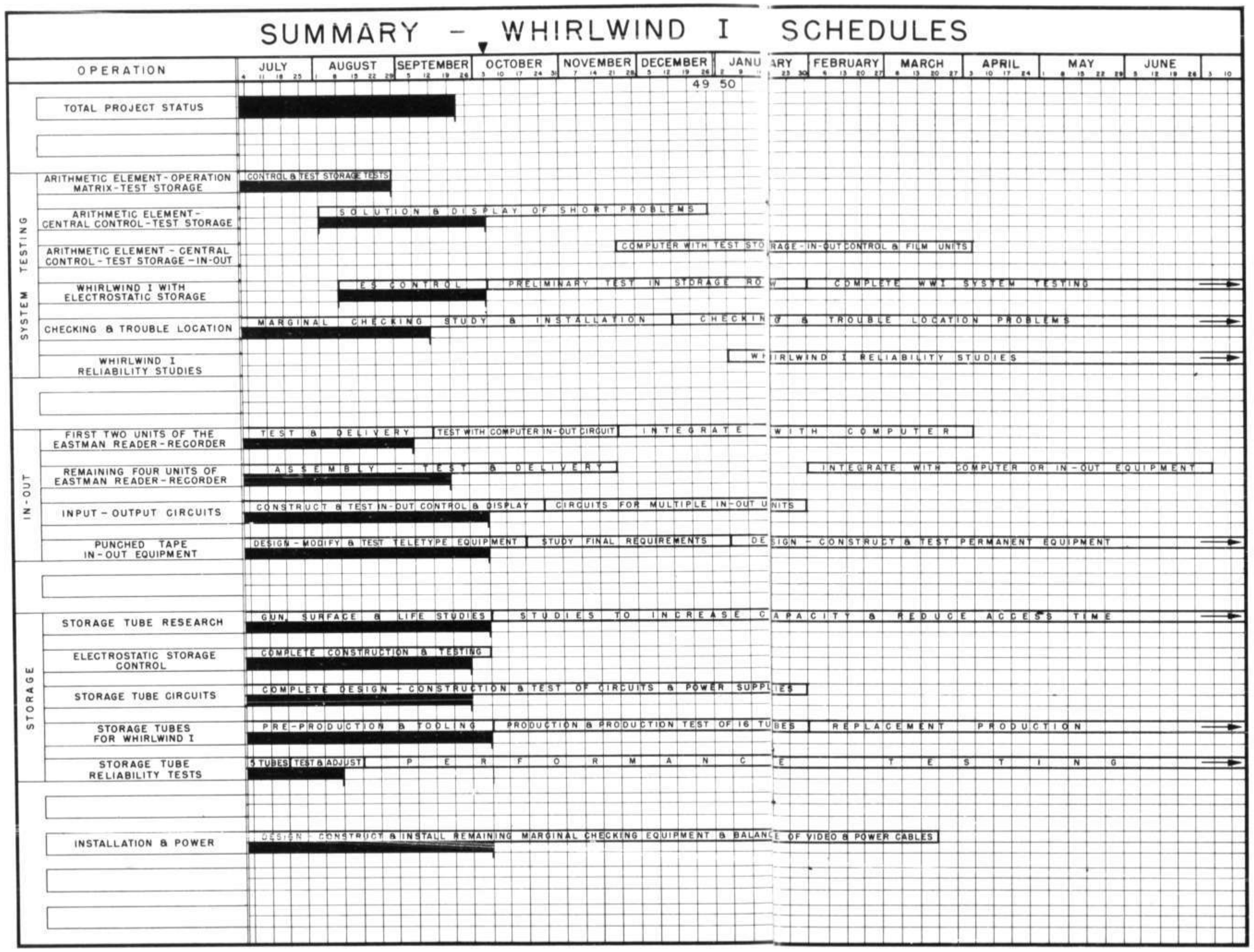
Test storage and all of central control have been incorporated into the system with the arithmetic element. The substitute central control, which was made up of test equipment, has been eliminated. The equipment remaining in test control is primarily an aid to trouble location; it performs functions such as introducing variable delays so that pulses occurring during any portion of a long computer program may be viewed on a synchroscope. Using the 19 orders now connected in central control and the 32-word test storage, we have been able to operate the computer on programs of some length. Some of these programs were designed primarily for testing the operation of the computer; others for obtaining the solutions of equations and displaying the solution on an oscilloscope as a series of computed points making up a curve. By means of these test programs, and particularly with the aid of marginal checking, we have isolated many small design weaknesses. Design changes are being incorporated as the need develops and, although we are not yet ready for extended reliability runs, all of these programs have run for periods of about an hour at a time without error. We feel that these refinements will be essentially completed by the time we are ready to incorporate electrostatic storage.

Failures of components other than tubes and crystals have been negligible. A total of 8 failures which occurred were probably the result of mechanical damage. We have replaced 56 crystals out of 10,000, and 40 vacuum tubes out of 3,300. Most of these were early failures, and we are encouraged by the small number of tube failures occurring between 500 and 1,800 hours, the maximum time now on a group of 1,200 tubes put in service in December 1948. The improved reliability of the five-digit multiplier has been gratifying. It was shut down for overhaul for the first two weeks of July. In the succeeding 10 weeks a total of 9 errors occurred, an improvement by a factor of 3 over the preceding quarter.

Storage tube construction has achieved considerable success. In May, as reported previously, a satisfactory 16 × 16 tube was built. In June we started a pre-production run of tubes in an effort to reproduce this satisfactory tube. Of 20 tubes constructed, 13 passed standard tests and 7 did not. Of these 7 failures, 5 occurred among the first 8 tubes built. We had expected to start a production run of tubes for initial use in Whirlwind I on October first, but a number of tubes already built appear to be satisfactory. There will be no substantial design changes between these scheduled runs, so that either pre-production or production tubes can be used interchangeably for development tests or operation in the computer. We are continuing our efforts on cathode and gun design to improve reliability, capacity, access time, and life.

Storage tube circuit design has been basically frozen, although minor changes may be made as a result of further tests. Electrostatic storage control is operating satisfactorily in its final location in the computer, as are the deflection-voltage generators and amplifiers. A prototype digit column of electrostatic storage is under test in the computer room. The repetitive elements of the electrostatic storage row are all under construction in our shops. These consist of signal-plate drivers, gun drivers, storage tube mounts, and storage output panels. We expect to complete these during January 1950 and to have them installed and ready for tests of the storage row during the first quarter of 1950. This row will receive complete tests to insure its reliability before integration with the rest of the computer.

Detailed descriptions of the foregoing are given in the body of this report. In addition, we are including in Section 6 discussions of multiple-register programming, coding of test problems, and questions involving the number of registers in Whirlwind I and the optimum numbering system for these registers. Also included is an abstract of a thesis on the application of a digital computer to a study of non-linear servomechanisms.



LEGEND

JULY

Period of one month, comprising the total number of days in the month.

PROTOTYPE

Operation to be performed, and the estimated time allotted for its completion. Estimates made in January 1949.

Indicates extension of the work into next period.

Work done. The ratio of the length of the solid bar to the length of the open bar above it shows percentage of completion at the end of the month.

▼

Date of the latest posting.

Summary line. Shows the overall status of the project.

2. SYSTEM ENGINEERING

2.1 INSTALLATION AND TESTING OF WWI

2.11 Equipment & Wiring Installed

As described in Summary Report 19, power wiring was complete and equipment was installed by July 1 for all of the computer except electrostatic storage and input-output equipment. The past 3 months have witnessed substantial progress in the installation of electrostatic storage; and the special display equipment, an element of the computer output, has been installed and put into operation (see Section 2.22).

All electrostatic-storage control and deflection panels have been installed in their final locations, and power wiring for these panels is complete as far as the racks are concerned. Final connection to the power distribution system must await completion of additional distribution panels and racks, which will be finished during October. This control and deflection equipment, filling 6 racks, is now being tested with power supplied from a temporary circuit-breaker panel, and no marginal checking is available for it at present.

Electrostatic-storage proper and its special power supplies remain to be installed, a total of 19 racks of equipment. No input-output equipment except special display has been installed.

The transmission line used for distributing deflection voltages to the storage tubes was installed in the 16 electrostatic-storage digit racks, as were power distribution strips, filament transformers, and other miscellaneous rack hardware.

During this 3-month period approximately 50 new WWI panels were completed, and 10 existing spare panels were modified for use in electrostatic-storage control and input-output control. In addition, power cables for most of these panels and nearly all video cables for them were completed.

2.12 Revision of Test Control

The Whirlwind test control has evolved into very nearly its final form. Test control at the present time contains the necessary controls for starting and stopping the computer and introducing initial conditions, as well as trouble-location aids. Ultimately these controls will be located at the operator's console, which is not yet built. However, the main purpose of test control, both in its final form and at present, is to provide at one central point all the information and control needed for trouble location and testing.

The original arrangement of test control was described in Summary Reports 13 and 15 and Report R-161. Test control provided a substitute for the central control of the computer; it consisted of an array of Whirlwind test equipment. This permitted complete testing of the arithmetic element and other flip-flop registers independent of central control. Thus it was possible to have a reliable arithmetic element when the Whirlwind system with test storage was tied together for the first time in early August. At that point both the arithmetic element and central control were reasonably dependable units. As a result there was little lost motion when the two were tied together, and the system was soon operating on simple programs using test storage.

About August 15 it became evident that the substitute central control would no longer be needed even as stand-by equipment. It was then removed from test control. At the same time other parts of test control were rearranged to provide greater flexibility. Facilities for introducing a variable delay element in series with synchroscope sweep triggers were provided. This allows viewing of pulses on a fast sweep of a synchroscope at any portion of a long computer program.

Also test control was arranged to use 6 digits of the program counter (only 5 program-counter digits are needed with test storage, leaving 6 normally unused digits) for periodic (cyclic) operation. The advantages of periodic testing were pointed out in Section 2.233 of Summary Report 19. The extension of this type of testing for Whirlwind operating with central control requires that a wait period be applied just after any arbitrary time pulse or step of an arithmetic operation within any order of a long program. This is accomplished, as stated in E-252, by use of 6 program-counter digits. To apply a wait period after time pulse m of order n: Time pulse m (from a push-button selector) is applied to the first of the 6 program-counter digits and the counter reset to 64 - n. The overflow of the counter is then used to halt operation. The computer is then cleared and the initial values reintroduced, and the program is restarted after a wait period determined by a master frequency divider.

In summary, the main parts of test control are:

1. Neon indicator lights for all flip-flops.
2. Push-button controls for starting and stopping computation.
3. Controls for setting flip-flop storage and certain other registers.
4. Automatic and manual voltage-variation controls.
5. Power switches and remote fuse indicators.
6. Circuits for the synchronization and delay of synchroscope sweeps.
7. Controls and associated equipment for periodic operation.
8. Error alarm indicators for built-in checking facilities.

2.13 Test Results

2.131 Marginal Checking

In their present state, marginal checking facilities consist only of manual selection and manual variation, the automatic functions not having been connected. However, the present marginal checking installation has proved extremely valuable in two functions: the testing of flip-flop balance and the improvement of circuit design.

The balance of all flip-flops is being periodically checked by means of screen-voltage variation. This has resulted in the replacement of several flip-flop tubes and crystal rectifiers before they became bad enough to cause steady errors.

Another important use of marginal checking in system tests has been the variation of certain voltages affecting signal amplitude in a given channel for the purpose of picking up weak links in the channel. For example, the +90-volt gate-tube screen voltage in the pulse generator and frequency divider was found in early system tests to have an operating range of 70 to 98 volts. The indicated design change now permits a variation from 60 to 120 volts without operation failure.

The automatic selection and variation equipment, now nearing completion, is expected to be even more valuable.

2.132 D-C Coupling of Control Matrix Outputs

Operation of the control matrix is now satisfactory. In its initial tests the output of gate circuits was found to vary considerably depending upon which line was selected (i.e., which order was being decoded). This variation, caused by vacuum-tube differences, was accentuated by the coupling between the gate tubes and the last amplifier stage. A change in the coupling circuits from a-c coupling to d-c coupling has greatly stabilized the gate-tube outputs. In addition, degeneration in the form of unbypassed screen-grid dropping resistors in matrix drivers has further stabilized gate-tube outputs.

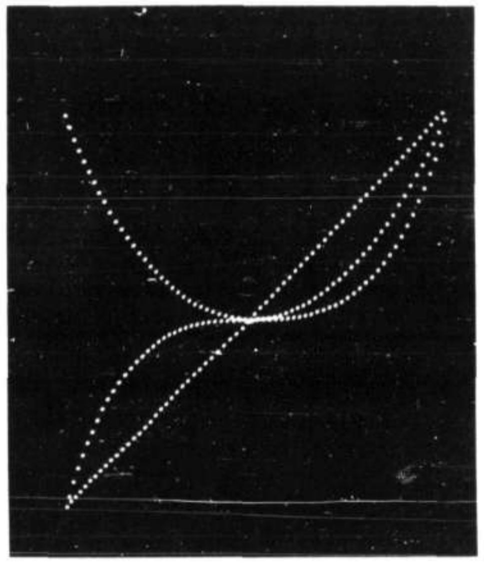
2.133 Test Storage Difficulties

The test storage output has given difficulties similar to those of the control matrix. The output of the storage registers has been found to vary according to the contents of the register. Also the output amplitude has been critically dependent upon the condition of the 2C51 driver stages.

The changes made in the control matrix were not directly applicable here. The test storage originally had not nearly so great a design margin as the control matrix, because its space allotment as a test item was not so great. Thus the power available does not permit the same stabilization as used in the control matrix. Several changes such as the addition of peaking inductors have been made. However, the problem has not yet been solved, and is still under study.

2.2 WHIRLWIND I OPERATION WITH CENTRAL CONTROL AND TEST STORAGE

After nearly two years of research, design, construction, and tests, the computing section of WWI has just passed a most significant milestone: solving an equation and displaying its solution. The accompanying photograph shows an oscilloscope display in which a family of curves, representing the powers of x, is plotted as a series of discrete points calculated by the machine.



Oscilloscope display of the solution of x, x^2, and x^3 for varying values of x.

Lest the simplicity of the problem belie its importance, the reader should be reminded that previous test problems given to the computer required merely single-point solutions, and that a progressive display, no matter how simple, can result only when all the basic parts of the computer act in harmony. Until recently, when all components of central control and test storage were tied into the system, it was not possible to carry out a program of the latter type.

The discussion which follows will trace briefly the system testing during the last quarterly period which culminated in this first actual computation, examine the display problem itself, and present the method and test problems which were used in transferring the arithmetic element from test control to central control.

2.21 System Testing

At the time Summary Report 19 was compiled, the history of WWI system operation contained only the records of a series of intensive tests on computer components and subassemblies, taken with test equipment acting as a temporary test control and test storage (Summary Report 19, Section 2.2).

During July, temporary test storage consisting of only 2 registers was replaced by a permanent test storage of 27 toggle-switch and 5 flip-flop registers. This installation permitted thorough testing during August of the control switch, control matrix, and test-storage switch, the last units of central control to be tested.

Nineteen of the orders listed in Summary Report 19, Section 2.4, are now in use in the WWI system. Any one of these may be selected for execution by the control switch. A given setting of this switch selects a line in the operation matrix which in turn selects a particular group of control-pulse output units used in the order selected. The time-pulse distributor, which sends the 8 basic time pulses to these output units at 1-microsecond intervals, provides the system with the pulses needed to carry out this order.

System operation presupposes that each of these orders with its full complement of pulses is functioning with proper timing and amplitude in each channel. To assure this, a pulse-by-pulse, order-by-order study was made to check the timing and amplitudes.

The 32-word test storage in use with the present system can be manually set to contain any of the above 19 orders and the numbers which are to be used in conjunction with each. For system operation the computer must be able to select and to read out the information from this storage.

With all of central control in operation during September, the computer for the first time could act as a unit and produce computed results. Although the test problems it solved were relatively simple, all parts of the computing section were used, thereby verifying the logical design of the machine. Future programs, more complex in nature, will be drawn up during October, and the extent of their complexity will be limited only by the 32-word capacity of test storage.

2.22 Display

The special display equipment described in Section 5.2 makes possible the observation of simple curves such as the ones shown in the oscillogram. The computer program which produces this display is very simple in nature; it is given in Section 6.25.

The display itself (see Section 2.2) is produced as follows:

1. During the programming of the problem a special-display order is inserted immediately following that order in the program where the calculation of a particular point has been finished.
2. This display order inserts a binary number into a decoder unit which produces a voltage level proportional to the number inserted.
3. This voltage is then amplified to deflect a normally blanked oscilloscope, which is intensified at the proper time.

The start of the sweep circuit of the oscilloscope initiates the problem, and the sweep and problem solution progress simultaneously. Whenever a point has been calculated it is displayed, so the time between points on the curve represents the actual time between calculations.

The significance of the display device may already be apparent. In curve plotting, for example, constants can be varied at will and the new curves displayed instantly. In equations dealing with real-time problems, the points on the oscilloscope screen could, for example, indicate the position of aircraft in an air corridor.

2.23 Test Problems

In addition to the display problem described above, several test problems have been run during the last few weeks. They are given in more detail in Section 6.2. These problems have no significance as mathematical solutions, but serve as a very useful tool in establishing the operating limits of certain portions of the machine. The first of these simply transmits a series of 1's and 0's throughout the system and assures that all flip-flop registers in the computer have the ability to retain both of these digits for specified periods of time. As each channel contains the same digit at the same time, this problem has simplified the location of incipient trouble when marginal checking studies are made.

A second, more complex problem causes each of the orders in the computer, 19 at present, to be used in a self-checking sequence. This problem is

useful in assuring that the computer has the ability to use all its orders and may later become one of the important check sequences.

In a modified program called "switch check" (see Section 6.21), each storage register contains the address of an adjacent register. The numbers in storage when read out can be checked in the check register against the program counter, as they are arranged to follow the same sequence. This program checks considerable equipment and indicates immediately the location of a failure by digit column and register number. This system was used to assure adequate operation of the storage switch, program counter, program register, and check register before complete computer programs were begun.

The most significant problem yet run is that discussed in Section 6.24 below. It is a sequence for converting all possible binary numbers to their equivalent binary-coded decimal numbers and reconversion of the decimal back to the binary form. This program will be used later when decimal data are being used in the input, and will avoid, in some cases, the necessity for external conversion equipment.

Although no extended reliability runs have been made, all of these test problems have been run for periods of about an hour at a time without error.

It is interesting to note that in the performance of these various test sequences the computer finds no more difficulty in solving the more complex programs than the simpler types. While this should be true of an automatic computing machine, it is none the less quite reassuring to find that it really is so.

3. CIRCUITS AND COMPONENTS

3.1 FIVE-DIGIT MULTIPLIER

The reliability test on the 5-digit multiplier (see Summary Report 19) was resumed on July 15 after a two-week shutdown. During the shutdown period all tubes were tested, and some work was done on the system to eliminate potential sources of errors. This work included: (1) installing new adapters for all type 7AD7 tubes used in circuits originally designed for octal-base tubes, (2) modifying some of the control equipment to give greater discrimination against noise in those circuits, (3) examining all test equipment used in the system for poorly made connections, (4) performing preventive maintenance on the power-supply motor-generator sets, and (5) installing limit switches on the filament-voltage regulator to prevent its jamming as a result of power-line transients which force it to the limits of its travel. Forty-nine tubes were replaced on the basis of the static-plate-current measurements that were made. Most of these tubes had been in use for several thousand hours and showed excessive deterioration.

Before the shutdown the multiplier had been on a three-month life run, the results of which were given in Summary Report 19. During that period a reduction in the incidence of errors was obtained, but at its close errors were still occurring at a rate of one about every two days.

A summary of the life run from July 15 to September 30, given in the accompanying chart, shows that considerable improvement in reliability was obtained during this quarter. A total of 9 errors occurred. Two of these were caused by a city power failure and a local thunderstorm respectively. Of the remaining 7 errors, 6 were of a transient nature and one was continuous. The chart also shows that considerably less work was done in servicing the equipment than during the previous quarter: component replacements total only 6 crystal rectifiers and 5 tubes.

The principal attention given to the system was a routine marginal-checking procedure carried out each day. About 45 hours were spent in checking and servicing during the 1800-hour period, or an average of about 35 minutes a day. Gradual deterioration of some components within the system is evident from the marginal checking data. The rate of deterioration is sufficiently slow that the faulty components can be located and replaced at leisure.

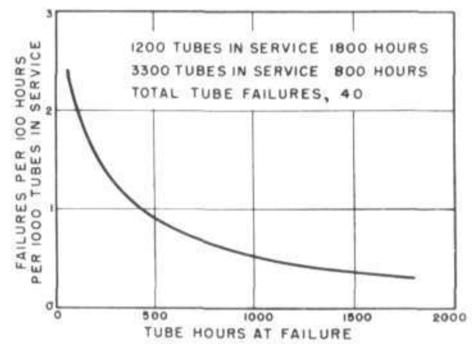
The available evidence seems to indicate that the isolated errors which occur are caused by factors other than marginal circuit operation. Poor solder connections, loose screw terminals, and transient noise generated by arcing within a tube are among the likely sources of these errors.

3.2 VACUUM TUBE LIFE

3.21 Failures in WWI

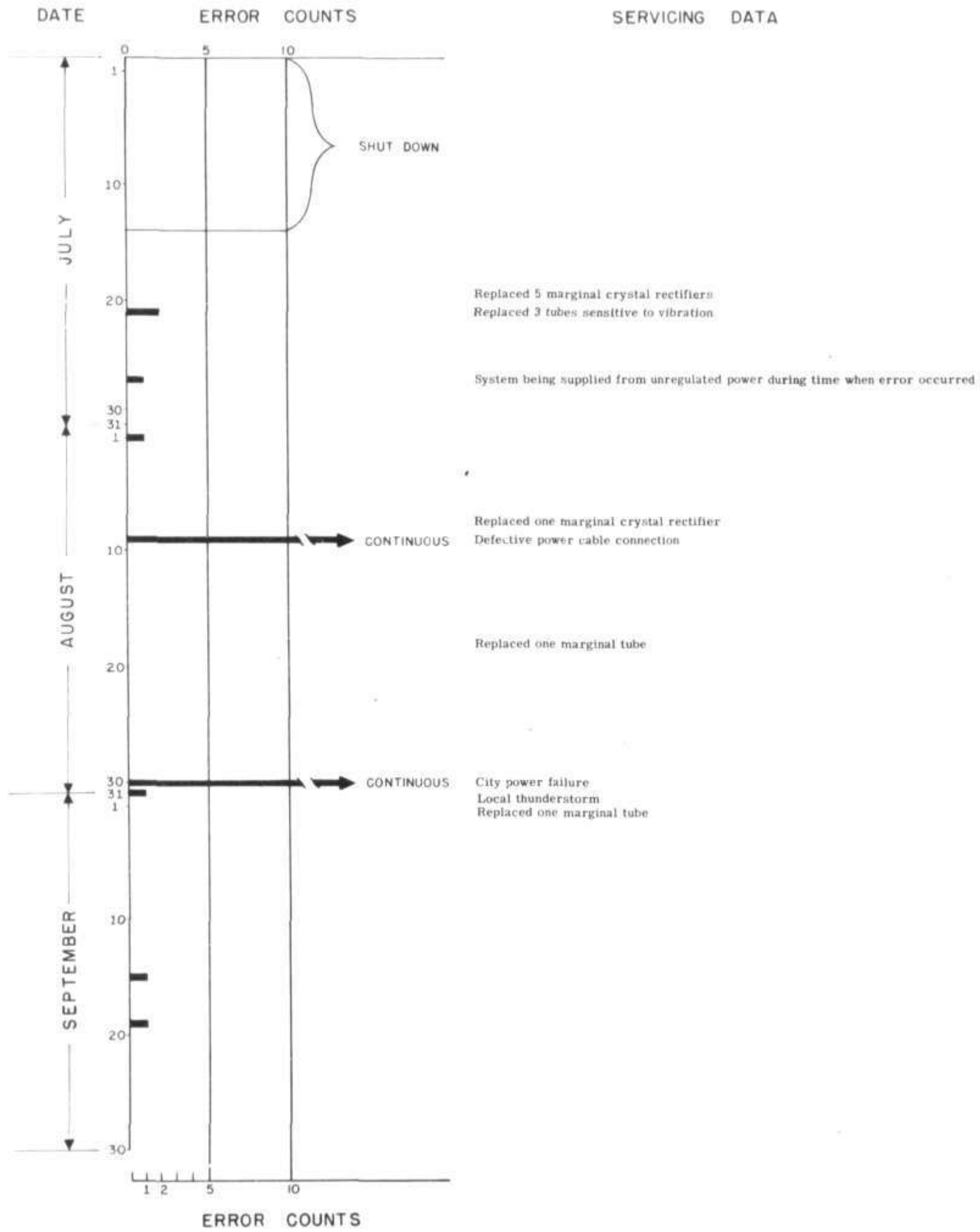
All vacuum tube failures in WWI since its initial operation in December are classified in the accompanying table and graph. Summary Report 19 listed 8 failures during the first 1,000 hours of operation of 1,200 tubes. An additional 2,100 tubes were installed during May, June, and July. The total time on the initial installation of 1,200 tubes is now 1,800 hours. The cumulative total number of failures among the 3,300 tubes now in the system is 40. The table breaks these down into tube types, quantities of each now in operation, hours at failure, and reasons for failure.

There are far more tubes in the system which have had, say, 500 hours of operation than those which have had 1,800. The graph takes account of this by plotting failures per 100 hours per 1,000 tubes against tube hours at failure.



TUBE FAILURES IN WWI

The small number of failures justify only limited general conclusions, but certain trends become evident. The shape of the failure curve in the 1,000 - 2,000 hour range shows clearly that general tube replacement should not be contemplated until the tubes have a period of use indeterminately greater than the present 1,800 hours. The large



TUBE FAILURES IN WWI

Type	Total in Service	Hours at Failure	Reason for Failure; Number Failed: Change in Characteristics	Mechanical	Burn-Out	Gassy
7AK7	1240	0-100		2		
		100-500	4	1		
		500-1000		3		
		1000-2000		1		
7AD7	1372	0-100	2		1	1
		100-500	4			
		500-1000	3	3		
		1000-2000	2			
3E29	92	0-100				1
		100-500		1		1
		500-1000				
		1000-2000				
6SN7	371	0-100		1		
		100-500	1	1		
		500-1000		1		
		1000-2000				
2C51	44	0-100				
		100-500	1			
		500-1000	1	1		
		1000-2000				
6L6	37	0-100				
		100-500	1			
		500-1000				
		1000-2000				
6Y6	204	0-100				
		100-500		2		
		500-1000				
		1000-2000				

number of failures below 500 hours, together with the fact that nearly half of all the failures are mechanical, indicates that our initial tests should be improved. With few exceptions, all tubes have been tested both before and after preburning for 100 hours. Rejects are not included in this tabulation. Of the 17 mechanical failures, 2 were intermittent open circuits; 15 were internal shorts. A new short tester is now being used for initial testing. This is sensitive to very short-time tap shorts which can cause random errors and are difficult to locate in a computer.

The fact that there has been only one heater failure seems to justify our procedure of turning off heaters when the computer is not in operation. This is usually done 5 or 6 times a week; heaters are gradually raised to operating temperature and similarly cooled off during 5-minute periods.

Two failures of 2C51 tubes among 44 should not be held against the type. The circuits in which they are used were underdesigned and a slight tube deterioration makes them inoperative. The circuits are being redesigned.

There remain 20 tubes replaced for gas or other changes in characteristics. Many of these changes were indicated by marginal checking; most of them could have been. When marginal checking facilities are complete, we will be able to anticipate the need for most of such replacements and make them at our leisure during checking before the tubes have deteriorated to the point of causing computer errors.

3.22 Vacuum Tube Life Tests

Some results have been obtained from tests on the special RCA 6AG7 and Raytheon 6AN5 tubes which were reported in Summary Report 19 as having been on test for 1000 hours. They have been tested for cathode interface resistance at 2200 and 2000 hours respectively.

The 6AG7 tubes with cathode sleeves of high-silicon-content, "active" alloy (RCA N34A or Driver-Harris 799) have shown definite cathode deterioration of the cathode-interface resistance type when operated both normally-on and normally-off. The deterioration is greater in those operated normally-off. The 6AG7 tubes with cathode sleeves of "normal" alloy (RCA N109 or International Nickel 220) and tubes with cathode sleeves of "passive" alloy (RCA N81) have shown no definite changes at 2200 hours. Tests made by RCA on other tubes of the same lots have corroborated these results.

Of 20 Raytheon 6AN5 tubes with cathode sleeves of "passive" alloy which have been tested at 2000 hours, 19 have changed very little, and one, which operates with a very hot screen under JAN test conditions, has changed somewhat. Twelve similar 6AN5 tubes have operated satisfactorily in a flip-flop life test for 2000 hours.

Life tests on three groups of special 7AD7 tubes, reported on at 2500 hours in Summary Report 19, have been continued. At 4500 hours measurements under pulse-test conditions for formation of cathode interface resistance give the same results as at 2500 hours. Of 10 tubes made with cathode sleeves of 599 "active" alloy, 8 show some formation. Of 10 tubes with cathode sleeves of high-purity 499 "passive" alloy, two show some formation. Thirty special tubes made with cathode sleeves of Sommers "A" alloy show essentially no formation of cathode interface resistance.

A group of 7AD7 tubes was reported in Summary Report 19 to have been operated at 5 volts heater potential for 1500 hours with no development of cathode interface resistance; these tubes have now been in operation for 3500 hours and still show no change. A group of 6AG7 tubes operated with a heater potential of 7.5 volts shows an acceleration in the development of cathode interface resistance in susceptible tubes, as was the case with 7AD7 tubes operated at 8 volts.

During April four 7AD7 tubes were given to Dr. A. S. Eisenstein of the University of Missouri for examination and analysis. Two of these tubes had developed considerable apparent cathode interface resistance; two were new tubes. Using X-ray techniques, Dr. Eisenstein determined that the two tubes with apparent cathode interface resistance had interfaces of barium orthosilicate less than 5×10^{-4} cm thick. No interface was found in the new tubes. Eight additional tubes have been sent to Dr. Eisenstein for analysis.

Most of the tubes now under life tests have changed relatively little. Whereas the 6AG7 tubes in which cathode interface was first suspected had changed considerably at 1500 hours, the lots of 6AG7 and 7AD7 tubes now under test seem to be considerably better in this respect. It will therefore be some time before more definite conclusions can be reached on the tubes now under test. Efforts are being made to determine any significant manufacturing changes between the initial and present lots of tubes.

3.3 FAILURES OF COMPONENTS IN WWI

The table on the next page lists failures of electrical components (exclusive of tubes) since operation of the computer started last December. Tube failures are treated under Section 3.2.

Five pulse transformers have developed open circuits. Most of these failures resulted from the winding becoming separated from the terminal lug, usually caused by the attachment of test leads. Any future redesign of these transformers should make them more rugged at this point.

No comment need be made on other component failures with the exception of crystals. A total of 56 crystals have been replaced. No particular significance should be attached to the hours of operation at which the replacements were made. Although a few crystals had to be replaced to make the circuits initially operative, the majority of questionable crystals were located during routine marginal checking.

There appears to be some evidence that the back resistance of crystals has deteriorated on the shelf as well as in the computer. The back resistance of some crystals, which is initially satisfactory for a few seconds, drifts downward after 15 to 30 seconds. Any crystals which show this tendency should be suspected, and we are now using an initial testing procedure which will reject such drifting crystals. Considerable work remains to be done on the explanation and elimination of this drift, and these remarks are presented in a very tentative form as a suggestion to others who may encounter the same difficulties.

FAILURES OF COMPONENTS IN WWI

Component	Type	Total in Service	No. of Failures	Hours of Operation	Comments
Choke	50μh	1300	1	0-100	Open circuited.
			1	100-500	Open due to mechanical damage. Found by marginal checking.
Crystal Rectifier	D-357	5800	4	0-100	Mixing crystals; low back resistance.
			10	500-1000	2 mixing crystals; 1 high forward resistance, 1 low back resistance.
					5 gating crystals; excessive drift.
					3 clamping crystals; 2 low back resistance, 1 excessive drift.
	D-358	3100	5	0-100	Clamping crystals; low back resistance.
			4	100-500	3 clamping crystals; 2 excessive drift, 1 low back resistance.
					1 input crystal; low back resistance.
			33	500-1000	Clamping crystals; 6 low back resistance, 27 excessive drift.
Power Plug	D-122	250	1	100-500	Loose pin.
Pulse Transformer	1:1	500	1	100-500	Open secondary.
			1	1000-2000	
	3:1	2000	1	1000-2000	Open primary.
	5:1	250	2	1000-2000	Open primary.

4. ELECTROSTATIC STORAGE

4.1 TUBE PROGRAM

Most of the effort of the storage-tube development group during this last quarter has been applied to the preproduction run of storage tubes of the ST 96 model. This run was started in June, as described in Summary Report 19, and has achieved considerable success.

The next quarter will be used to construct the first set of tubes for WWI. At the same time every effort will be made in the studies of electron guns and target geometry to improve access time, storage density, and life.

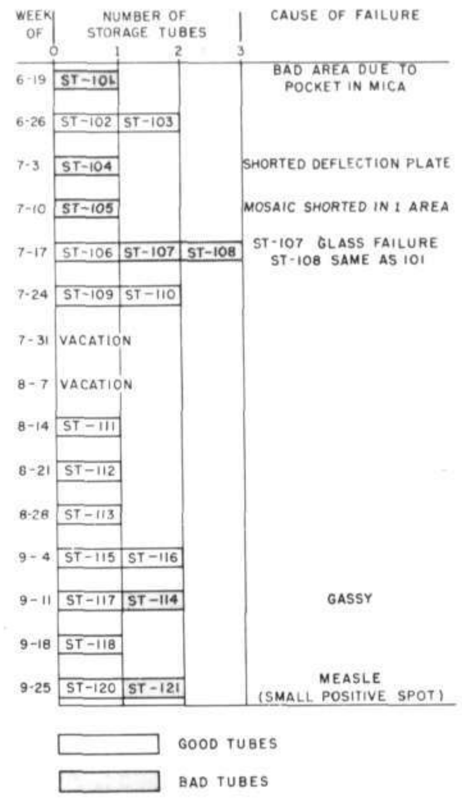
4.11 The Preproduction Run of Storage Tubes

Storage Tube 96, constructed in May of this year, met our preliminary performance specifications. It was capable of storing arrays of 16 × 16 spots with an access time of about 20 microseconds. The surface was uniform and with low leakage, and the gun currents adequate. Brief specifications of this tube are as follows:

Surface Diameter	3-3/4 inches
Dielectric	Mica, 0.0065 inch thick
Mosaic	Beryllium, 40 mesh, 0.002-inch spacing
Signal Plate	Silver paint on back of mica
Collector	Stainless steel, 120 mesh, 0.0025-inch wire
Collector-to-Surface Spacing	0.015 inch
High-Velocity Gun	RCA 5UP
Holding Gun	MIT Dwg SD-34616
Getters	2 on high-velocity gun

Except for the signal plate, which is now applied by evaporation instead of painting, and minor variations in dielectric thickness and collector-to-surface spacing, these are also the specifications for all the tubes of the preproduction run.

A total of 20 storage tubes have been made in this run up to October 1. Of these, 13 passed standard tests and 7 did not. Of the failures, 5 occurred among the first 8 tubes built, and represent a sort of starting transient. There have been 2 failures in the last 12 tubes, a shrinkage of 17 per cent. In the 7 weeks between the end of the construction crew's vacation on August 15 and the end of the quarter, 8 satisfactory tubes were built, a record slightly better than the predicted average of one good tube per week. The details of the preproduction run are shown in the accompanying figure.



STORAGE TUBE PREPRODUCTION RUN

The major source of failures during the run was traced to the silver paint at first used as a signal plate on the back of the mica. Considerable evidence had pointed to the silver paint used in other parts of the tubes as one source of the high surface leakage that plagued us during the spring, an effect probably due to migration of the binder. The painted signal plate, however, was adequately baked, and the front surface of the mica was cleaned before the beryllium mosaic was evaporated. The silver signal plate was therefore still employed for the first part of the run, while the use of silver paint for other purposes in the tubes was stopped; no further leakage occurred.

However, the silver paint still caused other bad effects which resulted in the loss of 3 of the preproduction tubes. ST 101 exhibited an area about 1 inch in diameter that had entirely different storage characteristics from the rest of the surface. Measurements showed the difference to be not in the surface characteristics, but in the surface-to-signal-plate capacitance. When the tube was dissected, a pocket was found in the mica under the silver back. Apparently a section of mica still adhering to the silver had lifted away from the rest of the sheet. Although the separation was small, the low dielectric constant of the vacuum (compared to mica) produced a large change in surface-to-signal-plate capacitance. The same trouble was found in ST 108.

Another difficulty resulted from buckling of the thin mica sheet due to the baked layer of silver paint. Apparently the shrinkage of the paint during baking makes the thin sheet convex on the mosaic side, which in turn reduces the spacing between the surface and the collector in the center of the area. This spacing is not particularly critical, but is kept small to control the distribution of secondary electrons. The spring-loaded collector is very flat, but buckling of the mica can reduce the spacing to dangerous limits. The target assemblies are inspected, but the heating cycles during final processing can cause additional buckling. In ST 105 this buckling was severe enough to cause actual contact between collector and mosaic in one area, shorting out the surface.

These troubles led us to abandon silver paint for the signal plate. Tubes made in the last six weeks have evaporated-silver backing plates. The evaporation is at present carried out in a sealed-off evaporation tube under high vacuum, one mica sheet being processed at a time. Although the construction and processing of these tubes is not as complicated as that of the beryllium mosaic evaporation tubes, the change has added to the effort involved in storage-tube construction. The high uniformity of tubes built since this change attests to its value. As soon as techniques are worked out, the silver evaporation will be carried out in a bell jar on the vacuum firing system.

ST 107 suffered a glass failure during processing, and has not been rebuilt. The gassy ST 114 will be reprocessed. ST 121 exhibits the first measle (small positive spot — see page 12, Summary Report 18) that has troubled us during the run. Since this tube came off the pumps on the last day of the quarter, there has as yet been no time to remove the measle, or failing that, to dissect the tube for study. Since this tube was assembled under non-standard conditions, we do not expect any recurrence of the trouble.

4.12 Future Production

Production of storage tubes was scheduled to begin October 1 at a rate sufficient to supply 16 satisfactory tubes by January 1, 1950. Since production and preproduction tubes are identical, this schedule date is largely academic. The preproduction tubes have been diverted into performance, prototype, and life tests. In all likelihood some of the "production" tubes will meet the same fate. We shall step up our tube construction rate somewhat, attempting to average 2 tubes a week before shrinkage. As the storage-tube mounts come from production (starting in late December), they will be filled with the best of the available tubes. There is no expectation that substantial changes in the tube design will be made this fall. We shall not hesitate, however, to make changes if the advantages obtained are considerable and our ability to make the changes is well proved by experimental tubes. There is no necessity for all the tubes in WWI to by physically identical; it is necessary that all tubes be able to work under the same conditions.

4.13 Research

During the last quarter the storage-tube production group built 8 research tubes in addition to the storage tubes described above. Most of the effort went into tubes for the study of cathodes and electron guns. A substantial part of the tube shop's capacity goes into research tubes, and it is hoped that this situation can be maintained in the effort to improve the life, capacity, and speed of the tubes. The research-tube capacity forms, however, a safety factor that can be diverted, if necessary, to storage-tube production in order to maintain schedules.

4.131 Cathode and Gun Studies

The preproduction run has shown that consistently uniform surfaces and target assemblies can be built using present techniques. Attention has therefore shifted to the electron guns. These guns, in particular the high-velocity guns, are now one of the major limitations on the performance of the storage tube:

Reliability — Variations in beam current, not only from tube to tube, but short-time variations in the beam current of a single tube, constitute the greatest present threat to the operating safety factors that mean reliable operation.

Capacity — The limitation on storage capacity at the moment is beam diameter. To be exact, capacity and speed are interdependent, since it is difficult to obtain small beam diameter and high current density at the same time.

Speed — The limitation on writing speed at the moment is current density in the high-velocity beam. The available current in the holding beam also affects the necessity for rewriting after reading, a major item in the present access time.

Life — Cathode deterioration is the present limitation on tube life.

A serious effort is being made to improve the cathodes. At present we are using RCA cathodes of considerable age (as much as a year). We are setting up facilities to prepare our own cathodes, with the expectation of obtaining more uniform as well as fresher cathodes.

Experiments have shown a loss in beam current from guns operated with heaters on but grid cut off for a period of a few hours. These guns recover in a matter of minutes to hours. The effect is slight in new guns, becoming more pronounced with age. This effect, rather than the reduction in maximum beam current with age, may be the determining factor in gun life. The effect can be minimized by changing the operating cycle of tubes, by better cathodes, by gun modifications to draw continuous cathode current with the beam cut off, or by replacing aging guns. A quantitative report on this work will appear in a later summary report.

We are also preparing to build some experimental electron guns. It is hoped to obtain improved current density, spot size, and uniformity by careful alignment of machined, instead of stamped, parts. At the same time the ability to construct special guns will enable us to change the geometry and therefore the electron-optical characteristics of the guns.

By far the greatest part of the work in building a storage tube goes into the target end, with its numerous mechanical parts; its construction requires the fabrication of two evaporation tubes, as well as extensive washing and inspection. A second major item is the glass work involved in the gun necks and the main body seal. It would be very wasteful to discard all this work because of a gun failure. Since the storage surface is not damaged by reasonable exposure to air, the guns can be cut out and replaced and the tube reprocessed, thus saving the target assembly and most of the glass.

During reprocessing, the large exhaust tubulation on the target end of the tube used for the initial processing will be left intact, and a smaller tubulation in the holding-gun stem will be used. This small tubulation will be satisfactory, since the large metal masses in the target end are still thoroughly clean and gas-free. The reprocessing cycle, for this same reason, can be much less time-consuming than the initial processing. It is estimated that salvaging a tube by gun replacement, once the technique is well established, will require less than one-fourth the effort involved in the construction of a new tube.

4.132 Target Studies

Studies are in progress to increase tube capacity and speed by modifications of the target structure as well as by gun improvement. These studies fall into two parts:

1. Mosaic size. A finer mosaic than the present 40 mesh will probably be needed to reach the goal of 32×32 spot arrays no matter what the electron-beam diameter may be. The effect of mosaic size on spot stability is the subject of a master's thesis now in progress. This study will also include the effects of collector mesh and spacing.
2. Dielectric thickness. An alternative to increasing beam-current density, in the effort to obtain greater writing speed, is to reduce the spot-to-signal-plate capacitance, thus decreasing the needed charge. A study of the effects of increasing the thickness of the mica dielectric is now in progress.

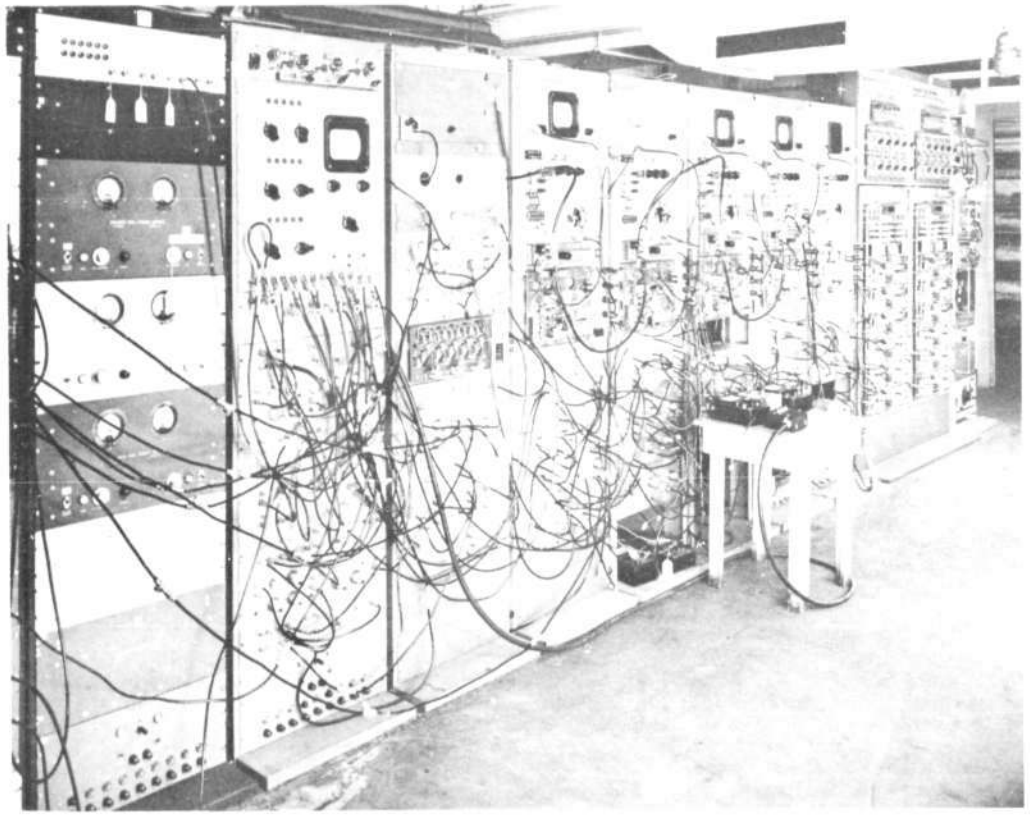
4.2 RELIABILITY TESTER

During this quarter the installation of 5 complete tube positions in the reliability tester was completed. The accompanying photograph shows the assembled equipment.

As described in the previous Summary Report, No. 19, the emphasis in the use of this equipment has been changed from reliability to performance. Some reliability runs have been made, but none with more than three tubes. It was only in the latter part of the quarter that more than three new tubes became available to this equipment. The equipment has also been under-staffed because of vacations and the thesis commitments of the engineer in immediate charge. Successful cycling tests with 16×16 arrays in three tube stations have been made. The remaining two stations have not been completely debugged, the time having been spent instead on performance testing of the new tubes.

Preliminary testing for surface uniformity, gun currents, and gross errors in the production tubes will be carried out in the television setup in the test laboratory. Before a tube is pronounced satisfactory for WWI, however, it will be put through dynamic tests in the reliability tester. These tests are being designed not only to operate each tube under computer conditions but also to determine the ranges of operating conditions or safety factors for each tube.

A detailed series of tests is being performed on a representative sample of the preproduction run of tubes. These tests will be completed early in the next quarter. The recent assignment of a new engineer to the equipment should help in obtaining a greater quantity of useful results in the future.



STORAGE TUBE RELIABILITY TESTER

From left to right the first rack contains power supplies; the second and third, control and timing circuits; the next 5, storage tubes; the last 3, deflection circuits and test equipment.

4.3 DEVELOPMENT OF STORAGE-TUBE CIRCUITS

In order to have circuits designed, tested, and constructed for operation of electrostatic storage tubes in WWI by February 1950, it was necessary to begin circuit work while the tube development was far from complete, in January 1949. Since many of the final operating characteristics were unknown, circuit development was based on the best available estimates, and the circuit design was modified as additional information on storage tubes was obtained. Safety factors were chosen to minimize circuit modifications. Because many circuits required by storage tubes are so different from the other Whirlwind computer circuits and are closely integrated with continuing tube development, the circuit design was undertaken by the storage-tube group.

4.31 General Circuit Considerations

4.311 Required Characteristics

The decision was made to design the circuits so that the storage tube would run with greatest reliability, at the expense of operating speed. The following aids to greater reliability were adopted:

1. A waiting period before each use of the storage tube is allowed so that the holding gun has extra time in bringing all parts of the storage surface to a stable potential.
2. After each reading operation, a spot is rewritten to insure that no loss of information occurs. Of course, the holding gun, if allowed enough time, will restore a spot to its stable potential, but rewriting is included to counteract discharging of a spot by continuous reading. Increased holding-beam current density may come with later tube designs, making rewriting unnecessary.
3. The signal plate is switched during the reading operation to insure reliable output signals. This requires more time, but greatly increases the signal-to-noise ratio.
4. Provision is made so that rewrite times can be different from write times. Also, gates of different lengths are available depending on whether a 1 or 0 is being written.

The electrostatic-storage control is designed so that as improvements are made in storage tubes, the above features can be omitted or the times modified by simple changes in connections or by changing counter reset lines.

The storage-tube mount, shown in the two photographs on page 22, consists of two mu-metal magnetic shields and coupling circuits between external panels and the storage tubes. These coupling circuits can be adjusted to compensate for different characteristics in different tubes. The mount has been designed to take the largest expected tube. Provision is made so that the gun neck and target sizes can change over a substantial range. Major changes in tube design will require redesign of the mounting castings and internal shield, but the external box and circuit arrangement will be unaffected.

4.312 Use of Spare WWI Panels in Control

The requirement of great flexibility results in an extensive storage control system requiring many circuits to route the control pulses correctly. To reduce the design and construction time, it was decided to use spare WWI panels where possible. The electrostatic-storage control described in Section 4.321 uses spare standard WWI panels for all functions except a few pulse-standardizing circuits.

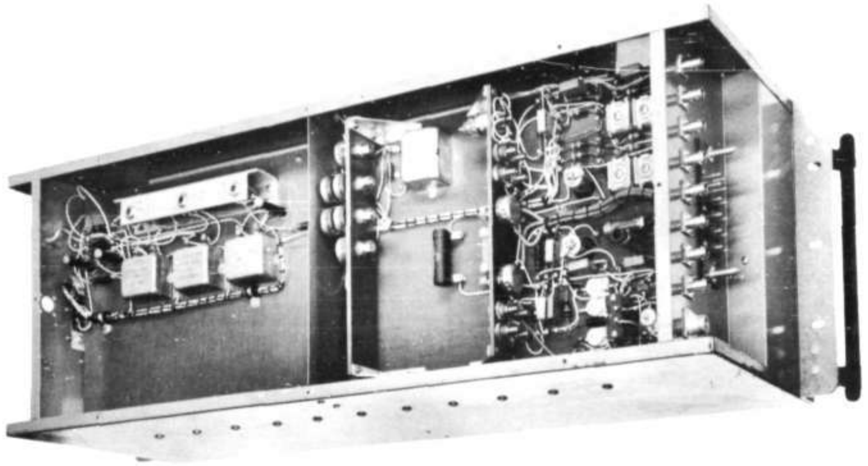
4.313 Other Storage-Tube Circuits

The major portion of WWI circuits are binary in nature; that is, they operate on the presence or absence of pulses and are quite insensitive to amplitude changes. Four types of circuits are used with storage tubes, however, which have no counterpart in the rest of the computer:

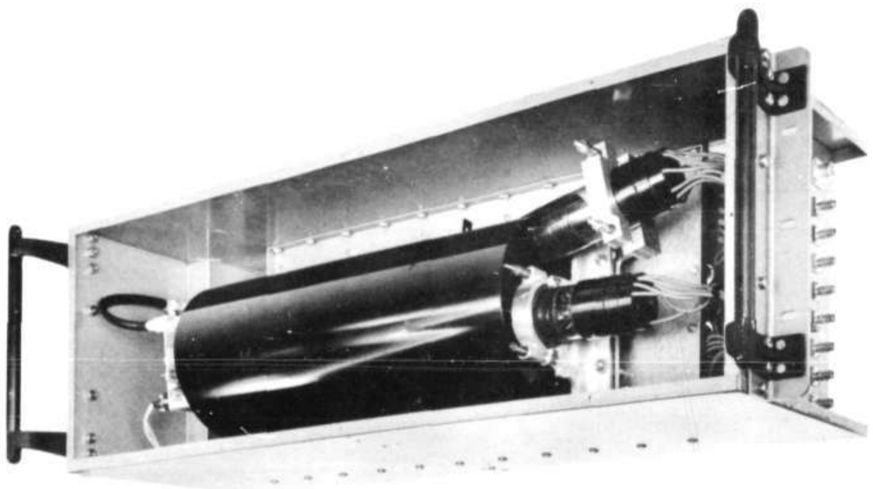
1. The electrostatic-storage deflection circuits are binary-to-analog converters. They take 10 digits of the address code and convert them to 2 deflection-plate voltages which determine the horizontal and vertical positions of the storage-tube beams. The question of voltage drift with time and temperature is extremely important in this application. This circuit is a critical part of the storage system, and has therefore been studied very carefully.
2. The gun-driver and signal-plate-driver circuits require close control of gate amplitudes. For example, a 5-percent decrease in the gate amplitude on the high-velocity gun results in about 20-percent decrease in gun current. The d-c level of the top of the gate is the important factor; it must not shift with variations in repetition rates.
3. The r-f readout system uses signals of about 500 microvolts at the signal plate, which must be amplified without interference from r-f pulses of 100 volts applied to the grid of the high-velocity gun.
4. Because of the general requirements specified above for the tube drive circuits, the electrode power supplies must be well regulated. This is particularly true of the cathode supply for the high-velocity gun, since variations in this voltage directly affect the deflection sensitivity.

4.314 Marginal Checking

The circuits discussed above are sufficiently different from the rest of the WWI circuits that some of the marginal-checking concepts must be modified. Many of these circuits have several cascaded stages of linear gain. This means that changes in gain in any of the stages would be equally effective in changing the final output. There is a continuous deterioration of signal until some range of operation is reached that is essentially binary. Thus, a change in bias of the high-velocity gun or in screen voltage in one of the r-f pulser stages is equally effective in reducing storage-tube output signals. The voltage at which the suppressor drive from the r-f amplifier fails to allow a pulse to pass the output gate tube is a measure of circuit perform-



The storage tube mount contains centering, focus, bias, and other adjustable controls in a compartment behind the storage tube.



Storage tube mount with tube in place. The high-velocity and holding guns are at the bottom; the signal plate coupling circuits at the top.

ance. However, only one control in the linear system is necessary, and other trouble-shooting techniques must be used to determine the remaining margins within the linear system (see E-290).

4.32 Operation of Electrostatic Storage

The preceding discussion has shown how the storage-tube circuit requirements differ from those in the rest of WWI. The methods used in developing the electrostatic-storage system and the resulting characteristics will now be discussed.

4.321 Electrostatic-Storage Control

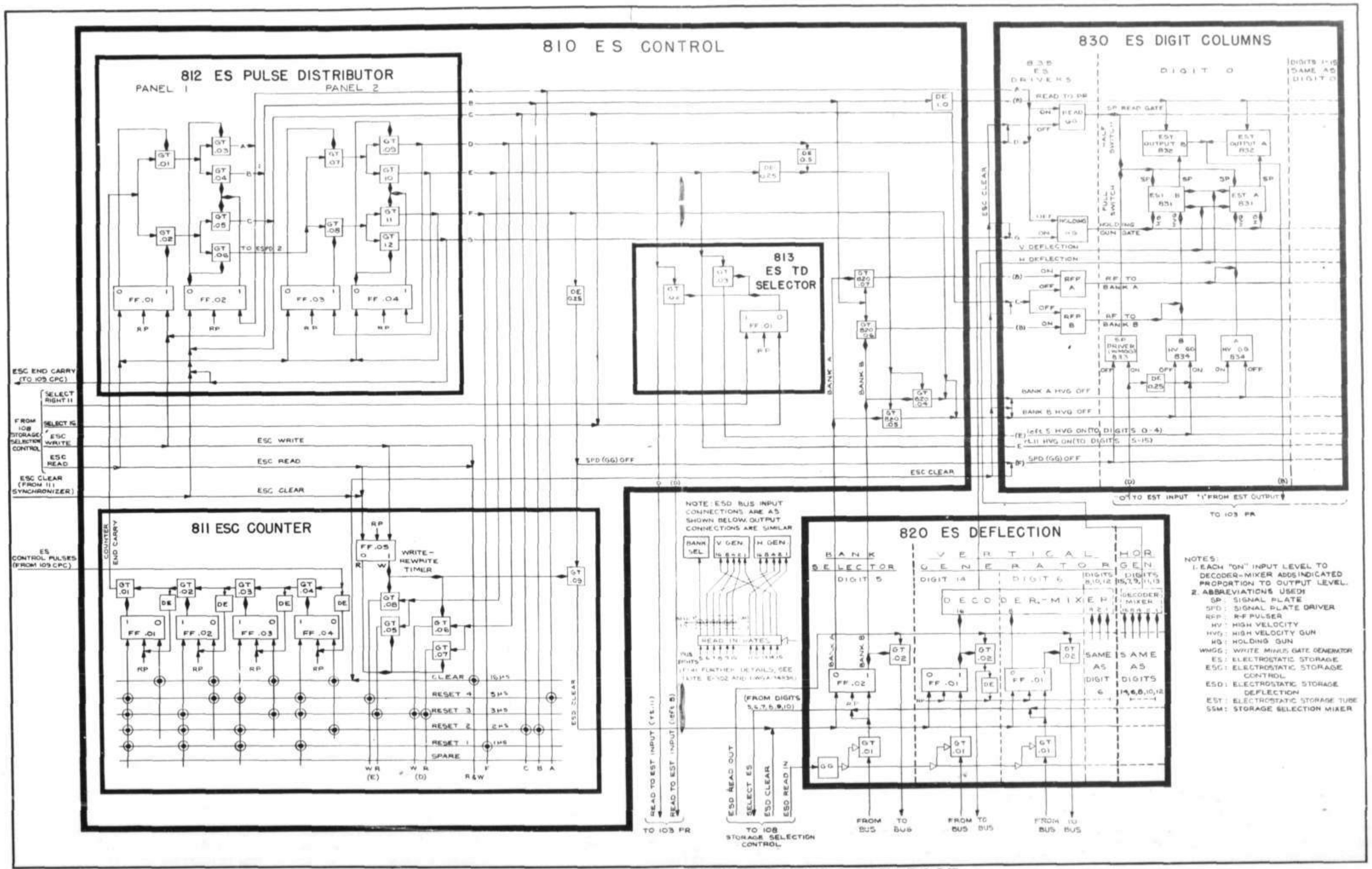
Since the electrostatic-storage (ES) control circuits are made from modified spare WWI panels, the method of operation was largely determined by the type of panels available. The storage system is shown in the accompanying block diagram. Pulses from the central control set up the write or read operations, bank selector, transfer digit selector, and deflection. Operation is then turned over to ES control until the storage operation is complete.

As soon as ES control begins operation, restorer pulses are removed from all of WWI. The ESC counter (consisting of 4 program-counter panels) receives pulses from clock-pulse control and counts a predetermined number of pulses before sending an end-carry pulse to the pulse distributor. The pulse distributor (2 modified accumulator panels) resets the counter after each pulse, and the write-rewrite timer part of the ESC counter controls the reset times depending upon the operation. Thus the ESC counter reset determines the delay between time pulses A through G. This is a very flexible system since the time between any 2 pulses can be varied independently from 1 to 16 microseconds by simply changing the reset line.

Time pulses A through G are used to perform the functions outlined in the following table:

Time Pulse	Function
A	Cut off holding-gun current in both banks of tubes.
	Switch signal plates of both banks for reading.
B	Turn on r-f pulses in one bank only to give a modulated reading beam from the high-velocity gun.
B + 1 μs	Gate a standard pulse through the output gate tube. This reads contents of storage tube to the program register.
C	Turn off r-f pulser. This completes the reading cycle. Time pulses D through G will now rewrite.
D	Remove signal-plate reading gate.
	Cut off holding-gun current. (It is already off if read operation is used, but during a write operation, time pulses A, B, and C are omitted.)
	Switch signal plates of both banks for writing a negative-potential spot in the digit where the program register shows a 0 should be written. (Only digits 5 through 15 affected for td operation.)
D + 1/4 μs	Turn on the high-velocity gun to give a writing beam for tubes in which a 0 should be written. Both banks are turned on at this point. (Only digits 5 through 15 affected for td operation.)
D + 1/2 μs	Turn off high-velocity guns in unselected bank. Because of gate rise times, beam of unselected bank has not caused appreciable changing of storage surface.
E	Turn on high-velocity guns of both banks. Thus the beam is also turned on for tubes in which a 1 is being written. This means that the beam is on longer for writing 0 than 1. (Only digits 5 through 15 affected for td operation.)
E + 1/4 μs	Turn off high-velocity guns in unselected bank.
F	Turn off all high-velocity guns.
F + 1/4 μs	Return all signal plates to their neutral potential.
G	Turn on all holding-gun beams.
	Return operation to main control.

The completed control has been assembled from the modified spares; testing is complete, and operation is satisfactory.



BLOCK DIAGRAM ELECTROSTATIC STORAGE

4.322 ES Digit Column

Each digit column of electrostatic storage consists of two storage-tube mounts, a gun driver, an output panel, and a signal-plate driver in one rack. These repetitive units are new designs.

The storage-tube mount is the removable storage element. The initial installation will be made with one tube per digit column; the second tube will be added later. Replacement tubes will be inserted in spare mount boxes, and bench adjustments will be made of parameters such as deflection sensitivity and centering, focus, bias, and A_3 and collector-screen voltages. The mount performs two major functions. First it supports one storage tube and shields it against stray magnetic and electrostatic fields; the photographs on page 22 show the mechanical arrangement. Second, the mount contains the circuits required for coupling the video and r-f circuits to the tube as well as the circuits for the adjustments to standardize operating characteristics as described above. Provision has been made for local as well as remote indication of some of the more important electrode voltages and currents in each mount.

The circuits required to drive the guns are located immediately below the mounts on the gun-driver panel. The two gate generators on this panel consist of standard WWI flip-flops with associated output amplifiers. These circuits are coupled to the mounts, where they drive the high-velocity gun grids during writing operations. The ES control supplies "initiate" and "terminate" pulses to the gate generators to control writing times. A buffer amplifier on each gun-driver panel inverts a remotely generated gate and couples it to the grids of the two holding guns to cut off the holding beam during tube operation.

The video gate from the gun driver is mixed in the mount with a remotely generated r-f pulse. The r-f pulse is used during the read operation to intensity-modulate the high-velocity gun beam. This reading-beam current flows through the signal-plate coupling network in the mount and then drives the input of the r-f amplifier. The r-f read-out system has been used to separate the small signal caused by the reading beam from the large-amplitude signal-plate gates. (See article in Summary Report 15.) The separation is accomplished by (a) frequency discrimination due to r-f amplifier band-pass characteristics and (b) time discrimination by using the r-f amplifier output to gate a read-out pulse through a WWI gate circuit. This system gives an estimated signal-to-noise voltage ratio of about 20:1, depending somewhat on the tube and other operating characteristics.

The signal-plate driver switches the signal plates of both banks for write-minus or read operations. The gate generator which supplies the write-minus gate is located on the signal-plate driver panel and is actuated by a pulse from the program register, thus causing a negative spot to be written when the corresponding program-register digit holds a 0. The read gate is generated at a remote point and transmitted at a 25-volt level to all signal-plate drivers. The signal-plate driver mixes and amplifies the write-minus and read gates. Separate control of the amplitude of these gates is available.

4.323 ES Deflection

There are two deflection systems, one for horizontal and one for vertical drive. The 3 basic units of the deflection system are the decoder, output amplifier, and transmission line. A decoder consists of 5 binary-weighted current sources with provision for switching these so that they sum at the output amplifier. Each of the 5 sections consists of a flip-flop which is set by an address-digit pulse via a read-in gate tube and which controls a crystal gate circuit. The smallest current source is approximately 1 milliampere and the largest 16. This gives 32 steps of 1 milliampere each when the sources are summed.

The currents are summed in the low-input impedance of a feedback amplifier. This amplifier is designed to give a maximum output voltage swing of 200 volts plate-to-plate, and is stabilized with negative feedback to reduce effects of circuit component drift and voltage changes and also to give the correct input and output impedances. The gain of the amplifier is constant, and the output voltage swing is controlled by varying the amplitude of the decoder current sources.

The deflection voltage obtained from the amplifier is distributed to the storage-tube mounts through a specially designed transmission line. A terminated line was chosen to insure stability of the output amplifier, and a special line was constructed to obtain an amplifier load of higher impedance with low attenuation characteristics.

The deflection system described above is used to pick the register in storage which is to be used. A method of switching at high speed between electrostatic storage and test storage is being provided. This method substitutes the 32 registers of test storage for the first 32 registers of electrostatic storage by mixing the decoder inputs from digits 5 through 10 inclusive and using an output from this mixer to indicate that electrostatic storage is required.

Monitoring means are being provided in the form of a remote-display scope in the WWI test control. This display scope has its deflection plates driven by the storage-tube deflection system and has a continuous beam current, thus indicating the position of the beam at all times. An alarm means is under consideration which would use a cathode-ray tube as above with a blank spot in the phosphor at the cleared deflection spot. Each time the deflection units were cleared, the beam would be intensified and an alarm sounded by a photocell if clearing were not correct.

4.324 Power Supplies

The storage tube and its associated circuits require different voltages and different regulation from the rest of Whirlwind I. Six electronically regulated supplies with the required characteristics will be located in the computer room; power will be distributed through a high-voltage distribution system.

4.33 Present Status

The electrostatic storage system will not be connected to the rest of the computer until it has been demonstrated that trouble-free operation can be expected. Until this integration is made, a simple test-equipment setup will be used to supply the required pulses.

ES control has been installed in Whirlwind I since the middle of August, and operation is now satisfactory. No tests will be made using marginal checking techniques until voltage-variation facilities are available in November.

The deflection system has been installed, with a slight modification to permit automatic counting. Tests of the decoder, amplifier, and transmission line indicate that adequate margins of safety are available.

A prototype digit column consisting of prototypes of the mount, gun driver, signal-plate driver, and output panel has been in operation with a storage tube for a couple of weeks. The final r-f pulser and temporary power supplies are being used. A digit column will be set up using production units as they become available.

The various portions of the storage row receive pulses from the test-equipment system. A television monitoring system has been installed (see Summary Report 11). Tests will be run to determine maximum speeds, dependence of system operation on repetition rates, and reliability. The test-equipment system is flexibly designed, with two major modes of operation:

1. As a flexible system. This design allows testing of the various portions of the storage system under widely different operating conditions, to determine operating limits.
2. As a simple system. Most of the test equipment can be removed and operation as a reliability tester obtained. This simple system uses small quantities of only the most reliable test equipment and thus endeavors to limit failures to either the storage tubes or the associated Whirlwind circuits.

Reliability runs of the complete storage row are not expected until February 1950.

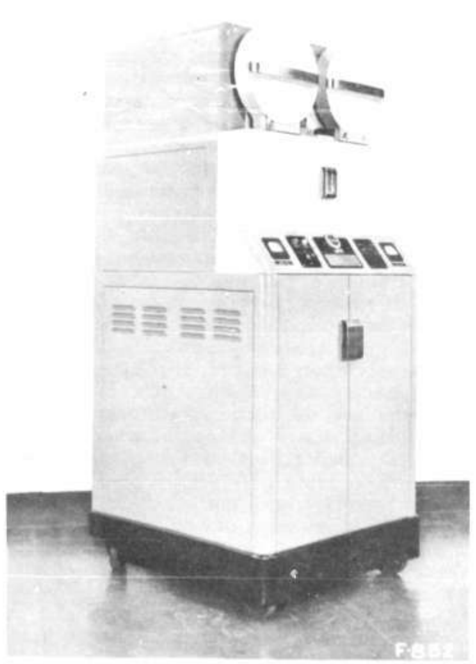
5. INPUT - OUTPUT

5.1 READER-RECORDER

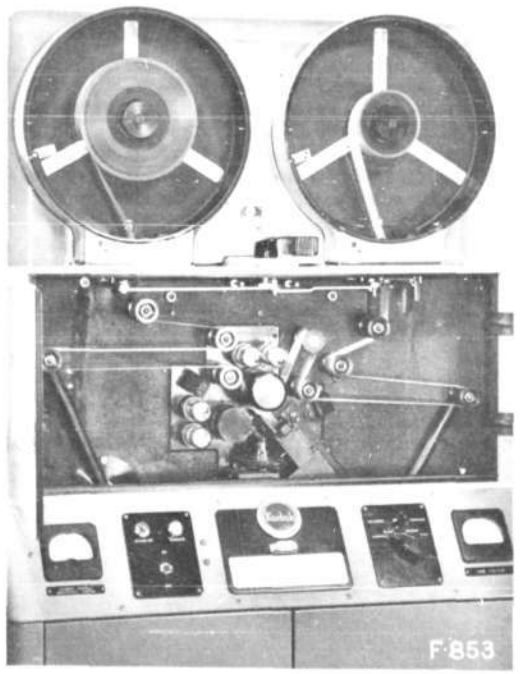
The first of 6 reader-recorder units which are to be a part of the input-output equipment of WWI was delivered by the Eastman Kodak Company on September 13. As described in Summary Report 13, these units are designed (a) to record binary numbers on photographic film by suitable exposure to light from the face of a cathode-ray tube, and (b) to read such recorded data by scanning of the processed film with a cathode-ray tube. This equipment is shown in the accompanying photographs.

The unit received has been under test at the Eastman Kodak Company for about 3 months, but since normal operation of the equipment requires *the use of external registers for holding the word* to be recorded or receiving the word to be read, and for checking the transfers, adequate tests of reliability were not possible.

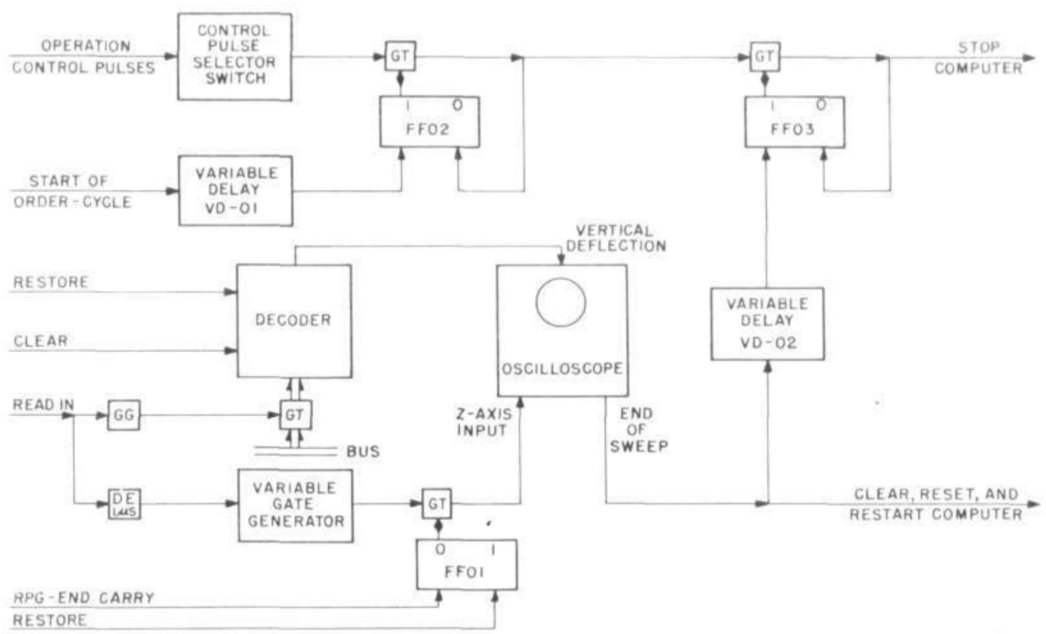
After arrival of the reader-recorder, tests were made by the designers (Eastman) to check circuit adjustments and alignment of the optical system to insure that no damage had occurred during shipment. A familiarization program is now being carried out to acquaint some of the engineers on the Project with the design and operation of the unit. Plans have been made to follow this with a study of the reliability of the equipment. The input-output element of WWI will be used to provide the necessary checking features, and a standard-test-equipment setup will allow simulation of storage and control in order to carry out the study without interfering with other testing being done on the rest of the WWI system.



Film reader-recorder unit.



Close-up of reader-recorder unit showing film magazines, optical system and phototubes, and control panel.



BLOCK DIAGRAM OF DISPLAY EQUIPMENT

5.2 DESIGN OF DISPLAY EQUIPMENT

The display equipment now in use with WWI is intended primarily for demonstration purposes. It gives a qualitative picture of solutions to problems set up in test storage, and it illustrates a type of output device that can be used when data are desired in graphical rather than numerical form. It provides a visual plot on a cathode-ray tube of one or more computed functions for a certain range of the independent variable. The existing interim system displays computed functions against time; two-axis systems to be installed later will make it possible to plot the results of many engineering computations.

One value for each of the functions to be plotted is obtained by a single cycle through a program set up in test storage, and successive points on these curves are derived from repeated cycles through the same program with the independent variable increased by a fixed increment for each cycle. Since these successive points occur equally spaced in time (except for small variations in multiplication and division times as the values of the multipliers or dividends change), the linear horizontal sweep of an oscilloscope is used to provide deflection along the axis of the independent variable. The length of the sweep is adjusted to correspond to the time required to compute the desired number of points on a curve. The same functions with the same range of the independent variable are recomputed for each sweep of the oscilloscope, a steady pattern being produced on the face of the cathode-ray tube; see the oscillogram reproduced in Section 2.22. Actually, the displayed curves are made up of a series of closely spaced spots, because all of the curves are generated simultaneously, so that the beam of the cathode-ray tube must be blanked while it is being deflected from one curve to another.

The arrangement of the display system is shown in the accompanying block diagram. It consists essentially of an oscilloscope having a linear horizontal sweep, a decoder for converting binary numbers into analogous voltages which provide vertical deflections for the cathode-ray beam, gate generating circuits to produce the unblanking pulses, and control circuits to accomplish periodic repetition of the computations.

The decoder design was copied from the *deflection-voltage generator to be used with electrostatic storage*. It contains high-speed flip-flops into which the binary number to be decoded is read in parallel. Each flip-flop controls a diode gating circuit which in turn controls the switching of a binary-weighted current source, either into a load resistance or not, depending on whether the flip-flop holds a 1 or a 0 respectively. At least 8 binary digits were required to obtain smooth curves on the 5-inch cathode-ray tube that was used. The sign digit has to be included in the number read into the decoder, so allowance had to be made for the fact that in WWI, 0 may be represented by either a binary number containing all 0's or all 1's (including the sign digit). This ambiguity was taken care of by giving a weight of 127 to the 0 position of the sign-digit flip-flop and weights of 64, 32, 16, 8, 4, 2, and 1 to the 1 positions of the other flip-flops. A 0 in the sign digit column then will produce the same deflection voltage as will all 1's in the remaining 7 digit spaces combined.

A Dumont type 241 oscilloscope was chosen as being the most suitable of those available in the laboratory. Consideration was given mainly to the gain, linearity, and bandwidth of the vertical-deflection amplifier, the linearity of the horizontal sweep, and the provision made for applying unblanking signals to the Z-axis of the cathode-ray tube. The oscilloscope was modified so that it produces an output pulse at the end of each sweep. This pulse is used to reset all variables to their initial values and to restart computation.

Provision is made for stopping the computation at any step in the whole problem and allowing at least a few hundred microseconds before the end-of-sweep pulse. This waiting period between the stopping and restarting of the calculations is to allow sufficient time for flip-flop indicator lights to come on and show the contents of all registers at the last step of the problem. Such a procedure has proved valuable in other testing in locating the cause of faulty operation. The control-pulse selector switch and variable delays VD-01 and VD-02 permit selection of the particular step at which computation is to be halted. Flip-flops FF02 and FF03 with their associated gate tubes ensure that the stop pulse obtained is synchronized with the selected control pulse.

A variable-length-gate generator which is triggered 1 microsecond after a number has been read into the decoder is used to produce the unblanking signal. The delay introduced takes account of the finite rise times of the decoder and scope amplifier and ensures that the cathode-ray beam is fully deflected before it is intensified. The length of the unblanking gate is adjustable to allow some variation of the brilliance as well as elongation of the displayed spots between problems requiring different sweep speeds. The requirements for the unblanking pulse generator were complicated by the fact that the flip-flops in the decoder are capacitively coupled to their diode switching circuits, so that d-c restoration must be provided. This is accomplished by periodically switching all flip-flops to their complementary positions for 1 microsecond. Since restoration may occur during the variable-gate-generator pulse, the cathode-ray beam must be blanked until it has completed its excursion to its complementary position and back. Flip-flop FF01 provides blanking during the restoration period. This blanking pulse is mixed with the gate-generator pulse to produce the required input signal to the Z-axis of the cathode-ray tube.

The initial tests of the display system disclosed limitations in the circuits of the oscilloscope. Since a greater number of points give the appearance of more nearly continuous curves, especially when several functions are displayed at once, it is desirable to operate the oscilloscope at its slowest sweep speed. Under these conditions, non-linearity in the sweep and inadequate low-frequency response in the vertical amplifier become apparent. By compromising on the number of spots shown, however, quite satisfactory displays can be obtained with the present equipment.

5.3 DESIGN AND MODIFICATION OF TELETYPE

The input-output element of WWI, comprising the in-out register, the comparison register, and in-out control, is adaptable to a variety of terminal equipment. Preliminary consideration has been given to the use of teletype equipment as a means of transcribing orders and numbers later to be stored on film or inserted into WWI storage.

For the initial work on this problem, equipment has been designed and constructed for reading information punched on teletype tape either onto film or into WWI storage. This information must be manually converted into binary form, and the punching is done so that the holes in the tape are true representations of the binary words involved. Both the word and the complement are recorded; therefore 32 hole positions are required to represent a 16-digit word. An example of one such word is shown in Figure 1. Since one row of hole positions contains 2 digits, 8 rows are needed for the 16 digits and a ninth row to signify the end of the word. A tape of this sort may be prepared from the keyboard of a standard teletype page-printer. This method will be used initially, but of course is highly inadequate for large quantities of data.

A block schematic of the teletype-tape reader is shown in Figure 2. Its principal components are: (1) a modified teletype transmitter-distributor for scanning the tape and initiating pulses which insert the information into the input-output element of the computer, (2) gate tubes used in sensing the holes punched in the tape, and (3) circuits for controlling the movement of the tape and providing control pulses for checking the reading operations and initiating transfer of the number onto film or into WWI storage.

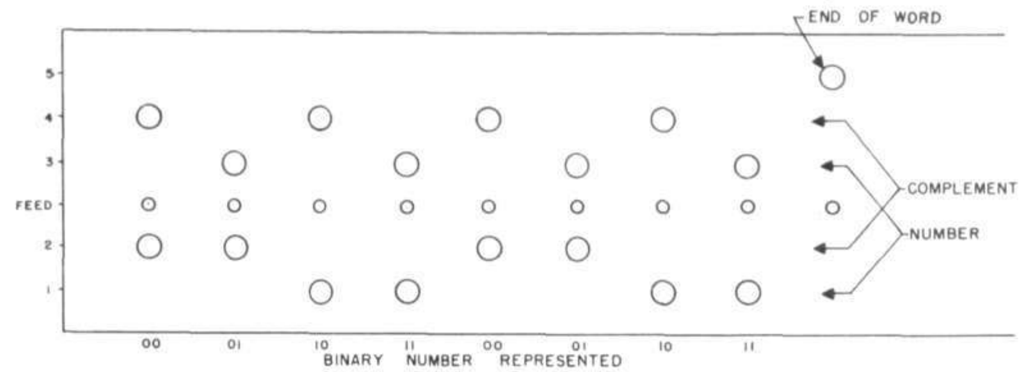


FIG. 1. TYPICAL PUNCHED TAPE.

A transmitter-distributor is a unit of teletype equipment used for transmitting teletype signals to a line from a punched tape. It is mechanically geared so that the tape-sensing pins are raised at the beginning of a revolution of the distributor brush and lowered at the end of the revolution. The tape is advanced at the end of the revolution. Energizing the release magnet permits the distributor brush to rotate, and when this magnet is de-energized the brush comes to rest on the "stop" segment of the commutator.

As has been described previously, 4 hole positions of a row are used to represent digits of a word. The contacts associated with the tape pins corresponding to these 4 holes are connected to one control grid of the gate tubes in such a way that a given gate tube will pass pulses only if its associated pin finds a hole in the tape.

The sequence of operations involved in reading a number from tape into the input-output element is as follows. A start pulse fires the gas tube, causing the auxiliary relay to pull in. This in turn

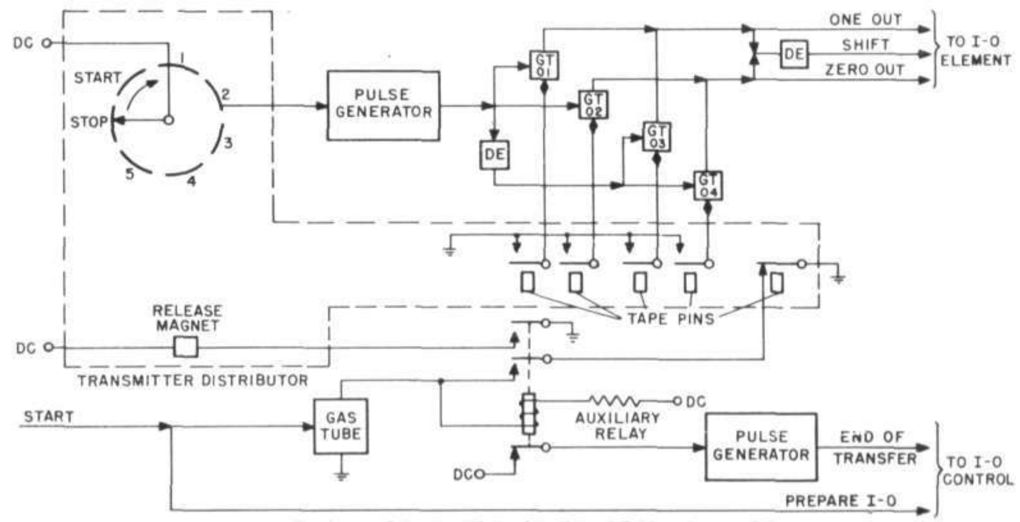


FIG. 2. BLOCK SCHEMATIC OF TELETYPE READER.

energizes the release magnet to start rotation of the distributor brush. The start pulse also prepares the input-output element for receipt of a word. As the brush contacts segment 2 of the commutator, a pulse is generated and applied to gate tubes GT01 and GT02. The hole positions sensed by these gates correspond to a digit and its complement, so that only one gate should be open, and either a 0 or a 1 is shifted into the input-output element. After a short delay, a pulse is applied to GT03 and GT04 and a second digit is shifted into the input-output element in the same manner.

The contact associated with the fifth tape pin is used to form a holding circuit for the auxiliary relay. As long as no hole appears in the fifth hole position this relay remains energized and the tape continues to advance and shift digits into the input-output element. On the ninth tape advance, tape-pin contact 5 opens to release the relay and stop the distributor. This action generates a pulse which instructs the input-output control that the transfer has been completed and is ready to be checked. Both the word and its complement are read into the input-output element in order that the transfer can be checked before the word is recorded on film or placed in the computer storage.

Succeeding numbers are read from the tape by repetition of the sequence described above. If the information is being put into storage, the start pulses are ordered by the computer control. If it is being recorded on film, a continue-operation pulse from input-output control following the recording process orders the next word to be read.

Many problems still exist in the design of a final system of teletype input and output devices. Most of these problems arise from the fact that present commercial equipment for tape punching and reading is not designed for applications where complete checking of all operations is required. As a result, redesign or modification of available units is necessary to obtain the accuracy demanded by the computer.

6. MATHEMATICS, CODING, AND APPLICATIONS

6.1 MULTIPLE-REGISTER PROGRAMMING

In programming a problem for solution by the Whirlwind computer, one may encounter two difficulties inherent in the computer, entirely aside from the difficulty likely to be encountered in planning the logical sequence of operations to be followed by the computer in reaching a solution. These difficulties, precision and scale factor, are closely interrelated; they arise from the fact that the Whirlwind computer is a fixed-point machine with a short register length.

The scale-factor problem consists in writing a program in such a way that the numbers resulting from arithmetic operations do not exceed the register length of the machine and do not lose any undue amount of precision through rounding off; more briefly, the problem is that of keeping numbers centered in the registers so that as many digits are carried as is possible without an overflow.

The precision problem arises whenever the data and the method of computation justify very precise results, whenever the number of arithmetic operations is large enough to cause appreciable round-off error, and whenever the scale factor is poorly handled so that the length of the registers is not efficiently used.

6.11 Scale Factor

There are three immediately evident ways of attacking the scale-factor problem. First, if the problem being programmed is of such a nature that the maximum value of each of the numbers involved is known and if the magnitudes of the numbers do not vary over too wide a range, the programmer can associate with each quantity a definite scale factor. That is, each quantity X can be stored as $X \cdot 2^n$ where n is an integer such that

$$\text{Max} \quad |X \cdot 2^n| < 1$$

and where preferably

$$\text{Max} \quad |X \cdot 2^n| \geqq \frac{1}{2}.$$

The number n, which may differ for each variable but will not differ for various values of X, is the scale factor associated with the quantity X. The use of predetermined scale factors, not subject to change by the computer during a computation, is amply illustrated in the program given for an Intact Stability Study appearing in R-156.

Second, in some cases there will be an intermediate or final result which can be used as a criterion for judging whether any readjustment of scale factor is needed. Thus, some quantity may act as a bound on all the other quantities in the computation, and as the computation proceeds, this quantity may gradually increase or decrease. This situation is quite possible, for example, in the point-by-point solution of a differential equation, as in a trajectory problem. In this case, the program can be written in such a way that the criterion quantity is periodically examined during the computation. If it grows too large or too small, the scale factors of all the quantities involved are adjusted by a subprogram in the computer to correspond to the change needed in the criterion quantity. This is then a periodic (automatic) readjustment of scale factor.

Third, a program can be written assuming that each quantity X is stored in two parts, with $X \cdot 2^n$ in one register and n in a second register. Then each arithmetic operation must be replaced by a combination to handle both the numbers and the scale factors. Generally it will be assumed that

$$1 > |X \cdot 2^n| \geq \frac{1}{2}.$$

This method of associating a scale factor with each quantity and continually varying the individual scale factors to keep the quantities centered in the register is the floating-point method (the binary point floats; it is not fixed at one point in the register).

6.12 Precision

The problem of obtaining sufficient precision may in some cases be solved by a better numerical method or by a better handling of scale factor. Otherwise, it becomes necessary to use double-length, or double-precision, numbers which are stored to 30 binary digits precision, 15 digits plus a sign digit in each of two registers (cf. Summary Report 6, page 15, and M-328).

This method of double-length numbers requires that each arithmetic operation be replaced by a combination of operations to effect the double-length operation. For example, to find the sum of the number stored in register 20 plus the number stored in register 30 and store the result in register 40, the sequence used is:

```
ca 20
ad 30
ts 40
```

To find the double-length sum, assuming that the two halves of the numbers are stored in consecutive registers, larger half first, the sequence used is:

```
ca 21
sa 31
ts 41
ca 20
ad 30
ts 40
```

The sa 31 operation stores any overflow digit from the addition of the smaller halves, and the ca 20 operation automatically adds in the carry, if any. Double-length multiplication requires from 19 to 35 orders, depending on the accuracy of round-off desired; double-length division, about 80 orders. These figures compare with 3 orders for ordinary single-length multiplication or division.

6.13 Subprogramming

The programs for a problem using double- or higher-precision and/or floating-point numbers (henceforth called multiple-register programs) will unavoidably require 2 to 10 times as much computing time as the ordinary programs for the same problem simply because there is more computing to be done; but multiple-register programming need not require either much extra program storage capacity or more work on the part of the coder than ordinary programming. For by the use of subprograms to carry out the multiple-register arithmetic, and by the use of one of several special techniques for entering such subprograms, the program can be written in much the same fashion as usual. Briefly, the several subprogramming techniques can be described in order of increasing complexity of the subprogram or in order of decreasing complexity of the translation from a single-register to a multiple-register program.

1. Three-address subprograms in which the addresses of 2 operands and the address in which the result is to be stored are supplied to a chosen subprogram which performs the arithmetic. Essentially this is the technique for which the automatic subprogram operations were intended, as described in M-328. Since the elimination of these as, ax, ay, az operations, the 3-address subprograms require the use of 4 orders in the main program, 3 to give the 3 addresses and one to choose the particular subprogram.
2. Single-address subprograms in which each order, with the possible exception of red-tape orders, is replaced by a pair of orders, one indicating the operation, the other the address. This is the 2-register method described in Summary Report 10, page 18, and in M-659.
3. Re-coding programs in which a regular single-register program written according to a few special rules is examined order by order by a master re-code program and each order is replaced by its multiple-register equivalent.

The first two procedures have been worked out in some detail as described in the references given.

The third procedure has not yet been thoroughly investigated. The first technique demands that the program be written with multiple-register performance in mind. The second technique provides a fairly straightforward method for translating manually a single-register program into a multiple-register program. The third technique will enable an ordinary single-register program to be inserted without modification into the computer, with the computation being carried out in multiple-register form. Each of the three techniques costs more in terms of computing time than the preceding one; the use of subprograms at all costs more in computing time than not using subprograms; and the multiple-register programs cost more than the single-register programs regardless of the technique used. For almost any problem requiring great precision, however, the computing time will not be the critical factor.

All of these techniques will be described in detail in a forthcoming report, together with other techniques and with descriptions of subprograms for such operations as square-rooting, trigonometric function evaluation, interpolation, etc., as well as for floating-point and double-precision operations. It is expected that this report will appear at the end of the next quarter under the title, "Subprogramming for Whirlwind I".

6.2 CODING OF TEST PROBLEMS

The successful performance of several different test programs by the Whirlwind computer is reported in Section 2.2 of this report. The need for such programs has of course long been realized, and the programs were for the most part written before the installation of test storage and other essential components of the Whirlwind I system. The principles used in coding several different problems, all of which have been successfully performed by the computer, are described below. A number of other programs have been written and tried; the programs treated below have been selected as being especially interesting and representative.

6.21 The Switch Check Program

The "switch check" program is only in a loose sense a program at all. Basically, switch check is a procedure which may be used under Whirlwind I control or under test control to perform a continuous check on the storage switch, on digits 11 to 15 of the program counter, and on some of digits 11 to 15 of toggle-switch storage. In operation, switch check proceeds by taking the content of toggle-switch register No. 0 and sending it to the storage switch (using the program register in its normal role as intermediate storage). The content of register No. 0 is at the same time compared with the content of the program counter, and an alarm is given if the two numbers differ. The toggle switches are set so that register No. M contains the quantity M + 1; i.e., so that register No. 0 contains 1, No. 1 contains 2, etc., and No. 31 contains 0. Thus, initially, the content of register No. 0, namely 1, is sent to the program register, thence to the storage switch (selecting register No. 1 for the next cycle), and thence to the check register. Meanwhile, the program counter has been indexed by 1, so that it now contains a 1, and its content has also been sent to the check register. A transfer check pulse then performs an identity check on the two numbers. The storage switch now selects storage register No. 1, which contains 2, and when the program counter is again indexed it also contains 2, thus again yielding a correct identity check. The process continues until all 32 positions of the storage switch are used, and the cycle automatically repeats indefinitely with a repetition rate of about 3125 times per second. The procedure is described in more detail in M-863.

6.22 Test Program No. I

One of the early test procedures for checking the operation of the many flip-flops in the computer was a cyclic complementing of all flip-flops by means of single pulses injected on the restorer line at an audio-frequency rate. The visual result of the procedure was that all the indicator lights, both red (1 side) and white (0 side), lit with equal intensity. If any flip-flop was sticking, only one of its pair of indicator lights would be on, and this fault would be immediately apparent to even a casual observer. This procedure seemed to be so fruitful that a program was written to mimic, as nearly as possible, this computer complementing cycle.

Test Program No. I uses some arithmetic gyrations to put 1's into all digits of the arithmetic element registers (AR, AC, AC carry, and BR) and to make sure that the 1's actually stay in those registers. Then 1's are stored in all digits of all flip-flop storage registers, and after 0.70 second, during which the computer is occupied with counting to 32768 by 1's in the accumulator, the content of each of the flip-flop registers is checked against all 1's stored in a toggle-switch register. The read-in, wait, and check process is then repeated with all 0's substituted for all 1's. The complete cycle is repeated indefinitely, each cycle lasting about 1.4 seconds. The cycles can be shortened to about 500 microseconds by not requiring the computer to count to 32768 by 1's.

The technique of delaying the computer between parts of a program by causing it to count a large number of small increments has been used frequently since this first application. Such a delaying procedure can be used to slow the computer down so that different sets of results may be observed visually.

There is an obvious advantage to the computer complement program over the straight audio-frequency complement pulse scheme: no visual check is necessary, and any error, even a single transient error, will be detected. Test Program No. I is described in detail in E-295.

6.23 Test Program No. II

The completion of the central control element was heralded by the performance of Test Program No. II, which provides a strenuous test of the 24 operations so far adopted for Whirlwind I with the exception of the 6 input-output operations (see Summary Report 19, pp. 24-25). Since repeated use must be made of the check operation qc (a temporary operation which checks the content of AC against the content of the indicated storage register; see E-250), the program must make frequent use of the numerical properties of the orders. That is, since there is not sufficient test storage available to permit storing a 28-order program and numerous constants, many of the orders are made to serve a second function as numbers. The program is a good example of this special technique intended to make the most of cramped storage. The program is given, together with an explanation, in E-296.

6.24 Binary-to-Decimal Conversion and Reconversion

Since it is intended that by means of a special subroutine the Whirlwind I computer will itself convert orders, data, and results from binary-coded decimal to binary and from binary to binary-coded decimal form, one of the first programs of a practical nature to have been tested on the computer is the conversion program. The program actually contains two separate programs, one for converting from binary to binary-coded decimal and one for binary-coded decimal to binary, both stored together in test storage. These two programs are each of interest as display programs. The insertion of a binary number in one register (the flip-flop registers are used since they have lights and switches in the control room) and the selection of the proper program yields as a result the decimal equivalent, one decimal digit appearing in binary-coded form in each of the 4 remaining flip-flop registers. The insertion of decimal numbers with the proper program yields the binary equivalent. One of the two programs is selected by setting the program counter reset switches to the register containing the first order of the desired program.

The computer actually performs the conversions repeatedly at a rate of about 5000 conversions per second.

For test purposes the two programs are combined so that a binary number is converted to coded decimal form and then the coded decimal result is reconverted to binary form and checked against the original binary number. The binary number is then increased by adding a 1 in the right-hand end, and the process is repeated. In this way the computer is made to perform and check all possible conversions from 1 to 16383, a feat requiring about 7 seconds (n.b., the computing times are given for the present system using test storage with its 1-microsecond access time; when electrostatic storage is used, the times will be at least doubled, since ultimate access time of at best 5 or 6 microseconds is anticipated). The details of the conversion program (known as Test Program No. V) appear in E-299.

6.25 Demonstration Programs Using Special Display

The recent installation of special display equipment (see Sections 2.22 and 5.2 of this report) provided an opportunity to try some programs intended for use with test storage and the display scope, such as the programs discussed in E-220. An important convenience factor had to be considered, namely that it is desirable to be able to alter the program slightly or even to change the program completely by using the switches on the test-control racks. By use of the switches which determine the numbers to which the flip-flop storage registers and the program counter are reset, a change can be introduced without any interruption while the computer is in operation, since the registers in question are actually reset only by a pulse from special display during the flyback time of the display scope. The switches of toggle-switch storage (since they, unlike the reset switches, actually pass video pulses) are in the computer room and hence, although readily accessible, are not "front panel" controls.

With these factors in mind, two quite elementary programs were written, each being quite short so that both can be stored simultaneously in toggle-switch storage, and either one selected at will by changing the program counter reset switches (the same scheme was used in the conversion program, Section 6.24 above).

The first of these programs simply plots the values of x, x^2, and x^3 for x between -1 and 1. In this powers-of-x program, the values are plotted for $-1 + 2^{-15} + nh$, where n simply increases until a value of x greater than 1 is reached and where the value of the increment h can be chosen at will, using the reset switches of a flip-flop register. Photographs of the resultant curves are shown in connection with Section 2.22 of this report. The program used proceeds as follows (see Summary Report 19 for explanation of code):

Register No.	Order	Description
1	ca 10	Puts the content of register No. 10, originally $-1 + 2^{-15}$, into AC
2	ad 11	Adds the desired increment to the x in AC
3	qd 10	Stores the new value of x in register No. 10 and displays x on the display scope
4	mh 10	Multiplies x in AC by x from register No. 10, forming x^2 in AC
5	qd 9	Stores x^2 in a dummy register and displays x^2 on the display scope
6	mh 10	Multiplies x^2 in AC by x from register No. 10, forming x^3 in AC
7	qd 9	Stores x^3 in a dummy register and displays x^3 on the display scope
8	sp 1	Returns to the order in Register No. 1, thus repeating the cycle for a new value of x
(FF register) 9		Temporary storage
(FF register) 10		Contains x, reset to 1.000000000000000 initially
(FF register) 11		Contains h equals approximately 2^{-7}

No provision is made to prevent the value of x from overflowing (becoming greater than 1). The arithmetic check pulse is suppressed by means of a front panel switch for this program so that no alarm occurs. The effect of an overflow is, therefore, to start over again at -1. The plot of values of x from -1 to 1 is therefore simply repeated until the display scope ends its sweep and starts the whole program over again; thus by adjustment of the display sweep frequency the cycle can be stopped before x exceeds 1 and the overflow prevented if so desired.

The second display program is designed to plot the pairs of curves $\pm Ax^2$ for $-1 < x < 1$ and for several values of A in the range $1 > A \geq 0$. The program used is as follows; the registers used are in practice chosen so that they will not conflict with the powers-of-x program (the actual program is given in E-300).

Register No.	Order	Description
(FF register) 1	ca 16	Puts a value of A (initially from register No. 16) into AC
2	mh 21	Multiplies by x (initially $-1 + 2^{-15}$) from register No. 21
3	mh 21	Multiplies again by x
4	qd 24	Displays Ax^2 and stores it in register No. 24
5	cs 24	Puts $-Ax^2$ into AC
6	qd 24	Displays $-Ax^2$ and stores it in register No. 24
7	ao 1	Increases the content of register No. 1 by 2^{-15} (initially changing from ca 16 to ca 17), thereby selecting a new value of A
8	su 23	Subtracts ca 15 + n from the quantity ca 16 + n in AC (where n is the number of pairs of curves desired)
9	cp 1	If the result is negative or 0, meaning that fewer than n pairs have been plotted, control is returned to register No. 1 to plot another pair
10	ca 21	All the curves having been plotted for one value of x, x is put into AC
11	ad 22	h is added to x, thereby giving a new value of x
12	ts 21	The sum is stored in register No. 21
13	ca 20	The order ca 16 comes to AC from register No. 20
14	ts 1	The order ca 16 is stored in register No. 1, thus preparing to repeat the whole cycle for the new value of x
15	sp 1	Control is returned to register No. 1 to repeat the whole cycle
16	$0.111111111111111 = 1 - 2^{-15}$	
17	0.100000000000000 = 1/2	
18	0.010000000000000 = 1/4	
19	0.000000000000000 = 0	
20	ca 16	
(FF register) 21		Contains x, reset to 1.000000000000000
(FF register) 22		Contains h, equal approximately to 2^{-7}
(FF register) 23		Reset to ca 15 + n, where n is the number of pairs of curves desired
(FF register) 24		Temporary or dummy storage

The comment made in the last paragraph concerning the overflow as x is increased past 1 is applicable here. The two programs appear to require 11 + 24 = 35 registers, but since registers 9, 10, and 11 in the first program serve the same purpose as registers 24, 21, and 22 in the second program, these registers can be common to both, and only 32 total registers are required. Note that by changing the reset switches of register 23 the number of pairs can be varied. The increment h and the initial value of x can be changed in both programs.

6.3 NUMBER OF ELECTROSTATIC STORAGE REGISTERS IN WWI

6.31 The 2048-Register Specification

WWI is limited to 2048 registers of storage by the register length of 16 binary digits: 5 digits are assigned to operation selection and 11 digits to the address or storage-location selection. More than 2048 storage registers would require an address with more than 11 digits, which would in turn require an increased register length. Increasing the register length of WWI may be desirable for other reasons and may actually be accomplished in the future, but this problem is not under discussion here.

The original choice of 11 address digits for 2048 storage registers in WWI was made on the following basis: For convenience in selection, the linear array should be a power of 2, thus making the total array a power of 4. It was felt that 16 × 16 or 256 would be inadequate, 32 × 32 or 1024 attainable and reasonable, and 64 × 64 or 4096 of substantial difficulty in both tube design and deflection-circuit design. Therefore 32 × 32 was specified as the density. The selection of one spot in such a tube requires 10 binary digits, 5 to select the vertical deflection and 5 to select the horizontal deflection. A total of 11 digits was specified, to provide for 2 banks of tubes. In view of the original conception of WWI as a prototype for larger machines, a study of the operation of multiple banks is more important than the provision of twice as much storage.

6.32 Usefulness of Initial 256 Registers

The first bank of storage tubes to be installed in WWI will have a storage capacity of 16 × 16 spots. The efforts of the development group have been applied almost entirely to the problems of stability, reliability, and reproducibility, with relatively little consideration given to increasing the storage density or reducing the access time. Consequently the production run of tubes for WWI, which will begin in the next quarter, will be of the 16 × 16 design.

During the several months which will elapse between the initial operation of WWI with 16 × 16 tubes and the completion of replacement tubes of greater capacity, the machine will necessarily be restricted to limited classes of useful problems. These classes are by no means insignificant.

A storage capacity of 256 registers (or more descriptively, 4096 binary digits), while small compared to the needs of the large-scale electronic calculator, is substantial compared to the capacities of existing machines. There are many problems fitting this storage capacity that are not trivial. An example of such a problem is the solution of a non-linear differential equation with two-point boundary conditions, of order up to fifth or more depending on the complexity of the problem.

A capacity of 256 storage registers will handle segments of most problems of ultimate interest and will be adequate for many months during which the use of a machine like WWI is being studied. All basic code sequences can be tested, and methods of machine operation and the use of library programs can be developed. Many scientific problems which tax the commonly available computing facilities can be handled with limited storage working in cooperation with input-output tape equipment.

It is expected that additional storage capacity will be available before the possibilities of 256 registers have been fully explored.

6.4 OPTIMUM SPOT NUMBERING SYSTEM FOR INTERIM WWI STORAGE TUBES

The numbering of the stored spots in the storage tubes in WWI is by no means fixed by the nature of the tubes. The particular spot chosen by a particular address is of no importance as long as it is the same one every time. The numbering system is determined by the nature of the deflection decoders and by their connections to the main bus. Since there are no logical restrictions except that the numbering system be consecutive, it can be chosen on the basis of convenience or flexibility or both.

As described in Section 6.3 of this report, the density specified for WWI storage tubes is 32 × 32. In order to select any spot in this array, two 32-position (5-binary-digit) deflection decoders have been designed and built (see Section 4.323). These are of the binary-weighted current-adding type.

Many different connections of the decoders are possible, some of which are shown in the accompanying diagrams. The curves and table show that the connections of Figure 4 have great advantages in certain cases. Particularly with tubes capable of storing an array intermediate between 16 × 16 and 32 × 32, this arrangement gains both in the total number of available registers and in the number of consecutively numbered registers.

If the inputs to these decoders are connected to the main bus in the simple order shown in Figure 1, then spot numbering starts with 0 in one corner of the tubes of one bank (the upper left corner is shown for convenience, but the actual corner depends on how you look at the tube). The numbering proceeds along a row, then starts over on the next row, etc. Spot No. 1023 is in the lower right corner. When two banks of tubes are used bus digit 5 is connected to the bank-selection FF. Spot No. 1024 is in the upper left corner of the tubes in the second bank, with the numbering proceeding as in the first bank. This numbering system is simple and straightforward; it was originally selected as the numbering system for the 32 × 32 tubes.

But trouble arises when it becomes desirable to substitute tubes storing less than 32 × 32 digits. The first problem is the numbering for 16 × 16 tubes. The simplest approach physically is simply to disconnect the inputs to the 1's increments in both decoders. This will omit every other row and every other spot in the remaining rows. See Figure 1. A 16 × 16 array will remain, with centering and gain for the deflection generators unchanged. The difficulty is that the remaining registers are no longer consecutively numbered. Gaps in the sequence of numbers are at best a great nuisance to the programmer, and at worst render the machine completely useless.

This arrangement is one of the worst possible. WWI is a single-address machine and as such takes its orders consecutively unless interrupted by a subprogram order. There are no consecutively numbered registers in the above arrangement; consequently the only recourse for the machine is to make every order a subprogram order directing the machine to omit the succeeding nonexistent register. This is an extreme situation. Practically, non-consecutively numbered registers have a value provided they are accompanied by a sufficient group of consecutively numbered registers to hold the orders. The non-consecutively numbered registers can be used for constants and partial results or even for short subprograms if the registers come in groups. The ideal is for all usable registers to be consecutively numbered.

Many numbering systems will provide consecutive numbering for all 256 registers in 16 × 16 tubes, one of them being shown in Figure 2. The 1's digit in each decoder is left unconnected. The remaining sections are connected in order, with the right-hand 8 of the 11 bus lines assigned to the address. The numbering system is now the same as for the 32 × 32 tubes, but with half the number of rows and columns. This system was originally selected for the 16 × 16 tubes. It was planned to keep the 16 × 16 array until 32 × 32 tubes became available and then to change the cabling to that shown in Figure 1. If two banks

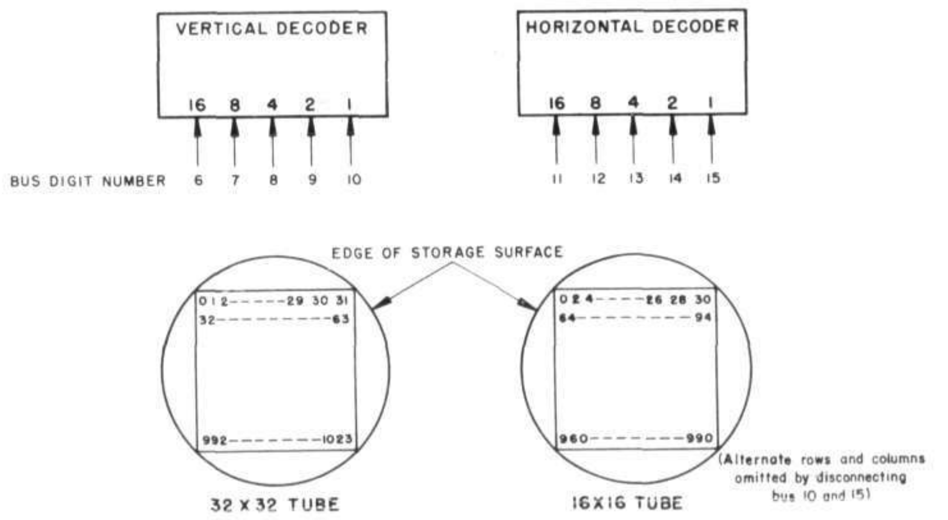


FIG. 1. OLD CONNECTIONS.

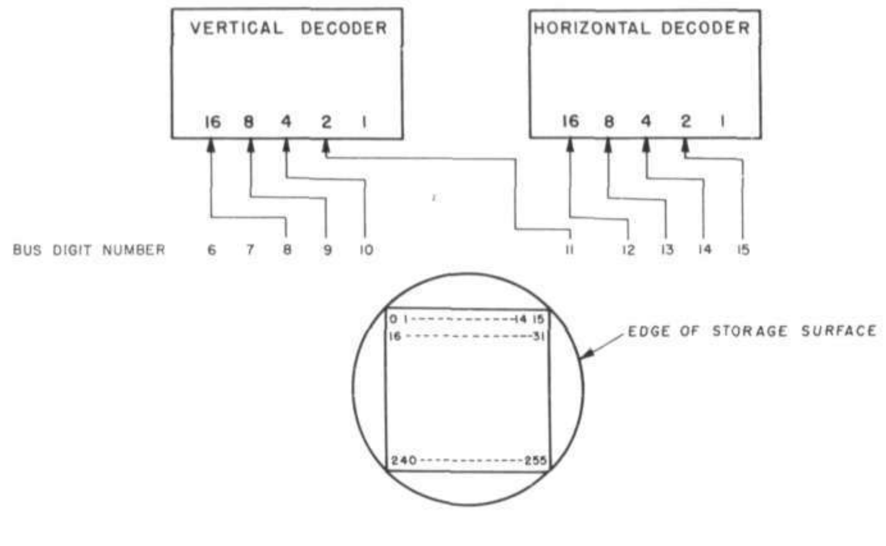


FIG. 2. CONNECTIONS FOR 16X16 TUBE.

of 16 × 16 were added before the changeover to 32 × 32, then the bank-selection FF could be connected to the ninth address digit, bus digit 7.

This proposal has recently come in for some reconsideration on two grounds:

1. It would be very valuable if intermediate stages in the storage tube development -- tubes capable of storing arrays greater than 16 × 16 but less than 32 × 32 -- could be efficiently used.
2. The square array thus far considered makes use of only about two-thirds of the storage surface, which is circular. If spots could be stored in the unused segments of the storage surface, an appreciable increase in storage capacity could be obtained without any physical change in the tubes themselves.

There is no clean-cut solution to either of these problems. With more than 16 spots in a row or column, all 5 sections of the decoders must be used. It is easy to vary the gain of the generators to provide the minimum allowable spacing between spots. The pattern would normally be centered on the surface, giving access to all available spots. Unfortunately the numbering would be badly broken up, with not more than 32 consecutively numbered registers in any group.

An early proposal for partially remedying this situation is shown in Figure 3 which gives the numbering for 32 × 32 and 25 × 25 tubes. The decoders are simply reconnected so that only 16 spots, half the spots in a row of 32, are numbered in order before starting over on the next row. When the left halves of all the rows have been numbered, the numbering starts over on the right halves. If the deflection centering circuits for each storage tube are adjusted to place the No. 0 spot at the upper left corner, then a partial solution to the problems (1) and (2) is obtained. A substantial block of consecutively numbered registers (to be exact, 16 × the linear array) is obtained. The other usable spots, including those in surface segments A and B, are non-consecutively numbered. The remaining segments C and D are unused. The numbering for 16 × 16 tubes would be the same as shown in Figure 2 except for the additional spots in the two usable segments shown for a 25 × 25 tube in Figure 3. This arrangement is about as good as can be obtained by simply reconnecting the decoders to the bus. It suffers from the necessity for providing large centering voltages as well as from the large number of non-consecutively numbered registers that result.

A much better solution can be obtained by a more desirable reconnection of the decoders, as

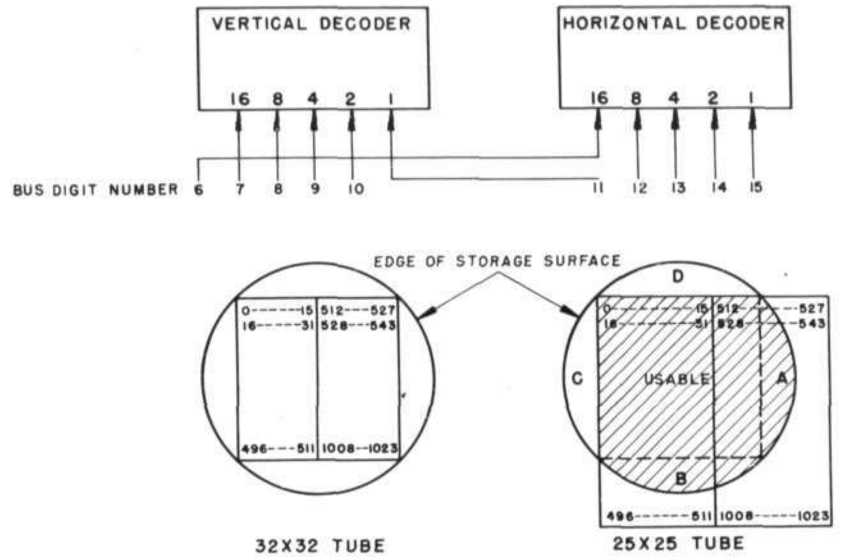


FIG. 3. REVISED CONNECTION.

shown in Figure 4. The numbering starts at the center of the tube and proceeds outward in all directions, in a strange though orderly arrangement. The figure shows one complete quadrant; the other quadrants are mirror images, those to the right of the center-line being greater by 1 for each spot and those below the center-line greater by 2.

The system of Figure 4 has many advantages:

1. It gives the largest block of consecutively numbered storage of any system tried.
2. It covers the entire storage surface and thus gives the maximum possible number of spots.
3. It requires no special centering.

The modifications required in the decoders are not difficult. Sufficient deflection voltage is obtainable to cover the extra surface segments. If two banks of storage with tubes less than 32 × 32 are provided, the number of consecutively numbered registers as well as the total number of registers can be doubled by connecting the first address digit (bus line 15) to the bank-selection flip-flop, all the decoder sections being moved over one digit on the bus to make room. This arrangement puts all even-numbered registers in one bank and all odd-numbered registers in the other.

The table and graph on page 43 give a summary of the total number of registers and the number of consecutively numbered registers available for the different systems for tubes capable of storing the given square arrays.

No improvement is obtainable over the simple linear connection for 32 × 32 tubes unless the decoders are modified to give 64 positions and the number of address digits in WWI is increased. Note that the new system permits an increase of nearly 50 percent in the total number of registers available with the present 16 × 16 tubes, and an increase of almost 10 percent in the consecutively numbered registers over the connections of Figure 2.

The system of Figure 4 is being built into WWI. Just how much use will be made of its capabilities will depend on the progress of storage-tube development. It has not been decided whether or not to reconnect the decoders for a simpler system when final specification 32 × 32 tubes are available.

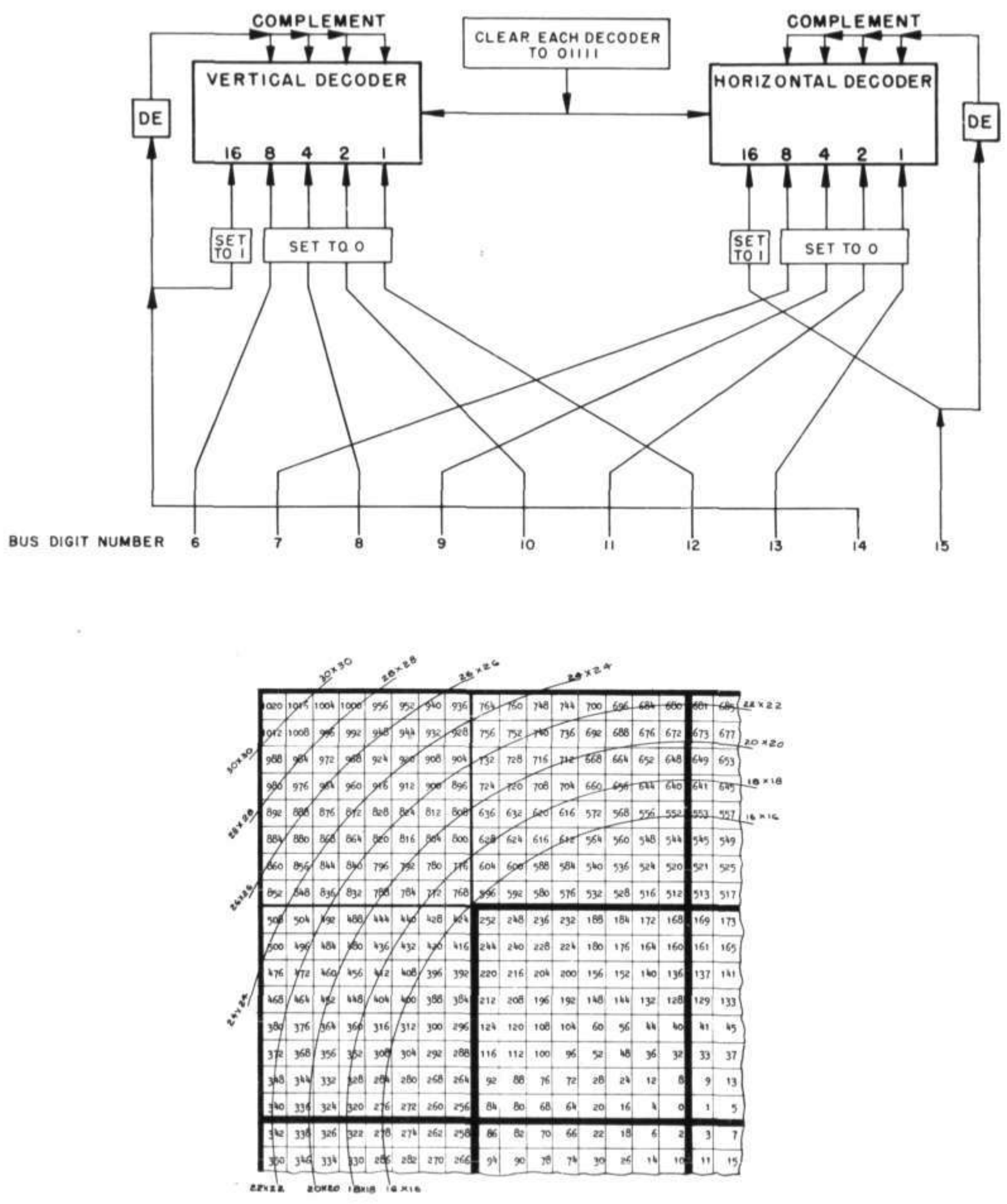
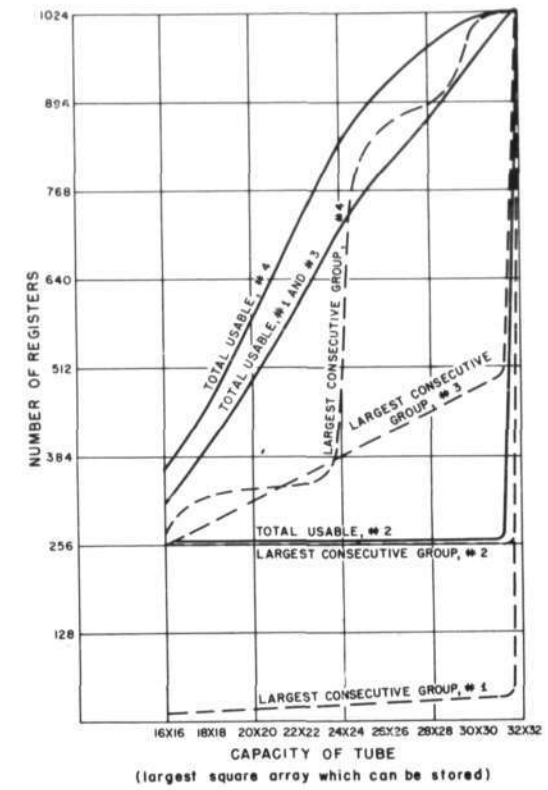


FIG. 4. FINAL CONNECTIONS.



	Connections of Figure 1		Connections of Figure 2		Connections of Figure 3		Connections of Figure 4	
Tube Capacity (Square Array)	Total Registers	Consecutive Registers	Total Registers	Consecutive Registers	Total Registers	Consecutive Registers	Total Registers	Consecutive Registers
16 × 16	308	16	256	256	308	256	360	276
18 × 18	392	18	256	256	392	288	460	324
20 × 20	488	20	256	256	488	320	576	336
22 × 22	596	22	256	256	596	352	708	340
24 × 24	708	24	256	256	708	384	840	500
26 × 26	796	26	256	256	796	416	916	860
28 × 28	880	28	256	256	880	448	976	892
30 × 30	956	30	256	256	956	480	1012	1012
32 × 32	1024	1024	1024	1024	1024	1024	1024	1024

6.5 STUDY OF NON-LINEAR SERVOMECHANISMS WITH THE AID OF AN AUTOMATIC DIGITAL COMPUTER

A method of using a high-speed digital computer to study the behavior of non-linear servomechanisms is presented in a recent MIT master's thesis that has been published as Project Whirlwind Report R-172. The method is useful for studying nominally linear servos with imperfections, such as coulomb friction, back-lash, or saturation, as well as studying inherently non-linear systems such as contactor or relay-amplifier servos. In addition, the use of the computer makes it feasible to study a system with complex input functions such as noise or random torque loads superposed on test inputs.

The method of applying the computer consists, briefly, in dividing the servo system into elements, and describing each element by equations suitable for iterative solution by the relaxation method. The computer can then be coded to solve the system equations. Each servo element may be represented by a subprogram in the computer, so that the behavior of individual elements can be observed as an aid to design. Since the relaxation method makes use of successive approximations, care must be taken to select computer constants which will ensure that the approximations converge to a solution. Also, the time interval chosen for numerical integrations must be short enough to describe the servo system accurately. Criteria for the choice of constants are developed and the analysis of a contactor servo is carried out as an illustration.

The solution of servo operation by conventional linear differential calculus requires the existence of, or assumption of, linearity. In many cases, this limitation leads to gross errors. The alternative is to take non-linearity into account by means of a point-by-point analysis, which is prohibitively laborious when ordinary methods of computation are used. A high-speed digital computer not only makes such solutions feasible, but permits study of system response to a variety of input functions with a variety of adjustments of the servo parameters. A complex system might require about 1000 orders in the computing cycle for each time interval and about 1000 time intervals to represent the servo response. It is estimated that, on the average, each order would be repeated 10 times per computing cycle, which would require 10,000,000 operations. Whirlwind I would be adequate to handle such a system, and working at an average of 80 microseconds per operation it would require about 14 minutes of computing time for a solution.

7. APPENDIX

7.1 VISITORS

During the past quarter the Laboratory has had among its visitors the following:

Capt. J. H. Pearson and Cmdr. R. G. Dosé of the Office of Naval Research, and Mr. L. B. Dowd and Mr. Urner Liddel of the Boston Branch, ONR.

Dr. L. W. Fink, Dr. H. Nyquist, Dr. G. W. Trichel, and Lt. Cmdr. D. M. Rubel, representing the Computer Panel of the RDB Committee on Physical Sciences.

Major Gen. R. C. Copeland, Director of Armament, Office of Deputy Chief of Staff for Air Materiel, Hq. USAF, with Col. John Whiteley and Lt. Col. D. M. Simpson of Hq. USAF and Mr. Walter McNeil and Mr. James Rone of Wright Field, who stopped at the Laboratory on a visit to M.I.T.

Prof. F. C. Williams of the University of Manchester to discuss storage tubes and digital computers.

Mr. James Moore of the Bureau of Aeronautics.

Dr. Eugene Ritter of the Aeronautical Research Center of the University of Michigan.

A group of officers of New England Naval Reserve units.

A group of students of a special government-sponsored class in computation held at M.I.T. in the early summer.

The week of the Second Symposium on Large-Scale Digital Calculating Machinery at Harvard in September brought many visitors to this Laboratory, among whom were the following:

Mr. A. E. Smith of the Computer Branch of ONR.

Cmdr. A. T. Magnell of ONR.

Mr. J. H. Kusner, Lt. Col. J. R. Dyer, and Cmdr. E. D. Stanley, Jr. of the Munitions Board, Office of the Secretary of Defense, interested in the possible application of digital techniques to logistics.

Mr. Marshall K. Wood and Mr. George B. Dantzig of the Air Comptroller's Office, also interested in logistics.

Lt. H. N. Laden, Mr. C. L. Stec, Mr. R. H. Jones, and Mr. L. D. Whitelock of the Bureau of Ships, and Mr. D. A. Wilkinson of General Electric.

Dr. Jan Rajchman of RCA.

Mr. Robert Serrell, representing computer work at RCA for Special Devices Center.

Mr. Arthur L. Samuel of IBM.

Dr. R. D. O'Neal, Mr. D. H. Wilson, and Mr. M. R. Holter of the University of Michigan's Aeronautical Research Center.

Mr. J. Weinstein, Mr. H. Stein, Mr. H. G. Lindner, and Mr. R. H. Noyes of the Computer Committee, Signal Corps Engineering Laboratories.

Mr. C. C. Gotlieb, Mr. V. G. Smith, Mr. B. A. Griffith, and Mr. A. C. Ratz of the University of Toronto's new computer project.

Dr. H. D. Huskey and some of his associates at the Institute for Numerical Analysis, National Bureau of Standards, University of California: Mr. D. F. Rutland, Mr. B. F. Ambrosio, Mr. E. Lacey, Mr. W. F. Gunning (Rand), Mr. H. Wright, Mr. H. D. Elbourn, Mr. C. H. Page, and Mr. A. S. Leiner.

Mr. Richard S. Burington of the Bureau of Ordnance.

Lt. J. W. Belyea, Naval Headquarters, Royal Canadian Navy.

Mr. C. S. Manning, Mr. A. Huntington, and Mr. E. E. McConn of U.S. Naval Electronics Laboratory.

Mr. J. W. Follin, Jr., Applied Physics Laboratory, Johns Hopkins University.

7.2 REPORTS AND PUBLICATIONS

Project Whirlwind technical reports and memorandums are routinely distributed to only a restricted group who are known to have a need for detailed information on the Project. Other authorized people who are interested in particular phases of the work may obtain copies of individual reports by making specific requests for them. Requests for classified material should in general be addressed to the Mathematics Branch, Office of Naval Research, Navy Department, Washington 25, D. C. Requests for unclassified material, or requests for classified material where approval has been previously arranged, should be addressed to John C. Proctor, Servomechanisms Laboratory, 211 Massachusetts Avenue, Cambridge 39, Massachusetts.

The following reports and memorandums were among those issued during the third quarter of 1949:

No.	Title	Classification	No. of Pages	Date	Author
SR-19	Summary Report No. 19, Second Quarter, 1949	Conf.	45	8- 5-49	
R-150	The Pulse Mixer	-	12	6-28-49	R.R. Rathbone
R-151	The Gate Panel	-	7	8-17-49	R.R. Rathbone
R-160	Performance of a 1024-Position Deflection-Voltage Generator (BS Thesis)	-	59	4-18-49	J. O. Ely
R-164	Video Amplifier and Cathode Follower Probe	-	20	6- 8-49	R.R. Rathbone
R-169	The Solution of Power-Network Problems on Large-Scale Digital Computers (SM Thesis, Abstract in E-253)	-	132	6-29-49	P. A. Fox
R-170	Analysis and Design of Sampled-Data Control Systems (DS Thesis, Abstract in E-254)	-	154	6-30-49	W.K. Linvill
R-171	The Register Panel (D-C Coupled)	-	15	7-25-49	R.R. Rathbone
E-255	Basing Procedure E 150	-	5	6-27-49	T. F. Clough, R. E. Byram
E-256	Washing Procedures - Series W	-	13	6-28-49	T. R. Parkins
E-257	Modification of ACO Panel	-	2	7- 5-49	J. M. Salzer
E-258	Function of the Program Counter End Carry	-	2	7- 6-49	C. W. Adams
E-260	Cases of Critical Timing	-	8	7-25-49	J. M. Salzer
E-261	The History of the Theories and Development of High-Vacuum Pumps and Some Methods of Measuring Very High Vacua	-	57	7-22-49	J.H. McCusker
E-262	Crystal Limiter	-	5	7-25-49	K. McVicar
E-263	Modification of 2:1 - 4:1 Binary Frequency Divider	-	2	7-25-49	H. Kenosian
E-264	The History of the Development of High-Vacuum, Hot-Cathode, Electrostatic Electron Guns	-	78	7-25-49	J.S. Rochefort
E-265	Control of Tube Components	-	2	8- 1-49	R. Shaw, T. F. Clough
E-266	Comments on the Testing and Dissection of ST101-1	-	2	7-25-49	C.L. Corderman
E-267	Time Saved by Simultaneous Operation of AE and ES	-	6	7-29-49	R. P. Mayer

No.	Title	Classification	No. of Pages	Date	Author
E-268	Storage Tube ST96: Construction, Processing and Initial Testing	-	3	8- 1-49	M.I. Florencourt
E-269	Storage Tube ST97: Construction, Processing and Initial Testing	-	2	8- 1-49	M.I. Florencourt
E-270	Storage Tube ST98: Construction, Processing and Initial Testing	-	4	8- 1-49	M.I. Florencourt
E-271	Storage Tube ST101: Construction, Processing and Initial Testing	-	3	8- 9-49	M.I. Florencourt
E-272	Storage Tube ST102: Construction, Processing and Initial Testing	-	3	8- 9-49	M.I. Florencourt
E-273	Storage Tube ST105: Construction, Processing and Initial Testing	-	3	8- 9-49	M.I. Florencourt
E-274	Storage Tube ST106: Construction, Processing and Initial Testing	-	3	8-10-49	M.I. Florencourt
E-275	Storage Tube ST107: Construction, Processing and Initial Testing	-	2	8-10-49	M.I. Florencourt
E-276	Storage Tube ST108: Construction, Processing and Initial Testing	-	3	8-10-49	M.I. Florencourt
E-277	Storage Tubes ST109 and 110: Construction, Processing and Initial Testing	-	4	8-11-49	M.I. Florencourt
E-278	Equipment for Special Display	-	3	8-11-49	E. S. Rich
E-279	Storage Tube Life Testing	-	5	7-28-49	C. Corderman
E-280	ST103: Construction, Processing and Initial Testing	-	3	8-19-49	M.I. Florencourt
E-281	Multivibrator Frequency Divider	-	4	8-22-49	R. L. Best
E-282	ST111: Construction, Processing and Initial Testing	-	3	8-29-49	M.I. Florencourt
E-283	ST112: Construction, Processing and Initial Testing	-	2	8-26-49	M.I. Florencourt
E-284	High Velocity Electron Gun - Assembly A-160	-	4	8-30-49	G. W. Kaplan
E-285	Electron Holding Gun HG3-2 - Assembly A-150	-	5	8-29-49	G. W. Kaplan
E-286	Investigation of the Stabilizing Curve of the Storage Tube With the High-Speed, Write-Read Unit	-	19	8-29-49	J.S. Rochefort, N.S. Zimbel
E-287	Methods of Cutting Mica	-	3	8-31-49	I. Paulsen
E-288	Signal Plate Driver	-	7	9- 2-49	G. G. Hoberg
E-291	Storage Registers for WWI	-	4	9-14-49	R.R. Everett, S.H. Dodd
E-292	Storage Tubes 113 and 115: Construction, Processing and Initial Testing	-	4	9-12-49	M.I. Florencourt
E-293	Standard Test Equipment: Evaluation	-	8	9-22-49	H. Kenosian
E-294	Read-Gate Generator & Holding-Gate Generator	-	2	9- 2-49	G.G. Hoberg
M-788-1	Suggestions for Mental or Manual Binary Conversion	-	3	7- 1-49	C. W. Adams
M-866	Summary of Register Driver Type I Test Results	-	1	6-22-49	G. C. Sumner

No.	Title	Classi-fication	No. of Pages	Date	Author
M-869	Bi-Weekly Report, 6-24-49	Restr.	25	6-24-49	
M-872	Changes in Report R-145, The Register Panel	-	1	7-27-49	R.R. Rathbone
M-874	Comments on E-256	-	1	7- 7-49	M.I. Florencourt
M-875	Bi-Weekly Report, 7-8-49	Restr.	32	7- 8-49	
M-877	Proposed Method for Automatic Test Checking of Arithmetic Control Flip-Flops	-	10	7-25-49	G. Cooper
M-879	Design of a New Target Assembly for the M.I.T. Computer Storage Tubes	-	2	7-21-49	H. Klemperer
M-880	Electrostatic Storage Tube Mount	-	3	7-22-49	W. J. Nolan
M-881	Bi-Weekly Report, 7-22-49	Restr.	31	7-22-49	
M-883	Vacuum Tube Failures During July, 1949	-	4	8- 1-49	H. B. Frost
M-884	Checking of the Time Pulse Distributor	-	2	7- 8-49	C. W. Adams J. M. Salzer
M-887	Bi-Weekly Report, 8-5-49	Restr.	29	8- 5-49	
M-888	Proposed Test Program for Reader-Recorders	-	8	7- 9-49	E. S. Rich
M-889	Bi-Weekly Report, 8-19-49	Restr.	26	8-19-49	
M-890	MS Thesis Proposal: Conversion Devices for a Digital Computer	-	26	8-26-49	A. K. Susskind R. L. Sisson
M-891	Low-Speed Binary Counter	-	2	8-24-49	R. R. Everett
M-892	MS Thesis Proposal: A Method of Test Checking an Electronic Digital Computer	-	9	8-26-49	G. Cooper
M-893	Proposal for Control of ES Power Supplies	-	4	8-29-49	C. W. Watt
M-895	New Snubbers to Mount on Holding Guns	-	3	8-31-49	F. H. Caswell
M-897	Bi-Weekly Report, 9-2-49	Restr.	28	9- 2-49	
M-899	Bi-Weekly Report, 9-16-49	Restr.	18	9-16-49	
M-903	Bi-Weekly Report, 9-30-49	Restr.	31	9-30-49	