PROJECT WHIRLWIND

(Device 24-x-3)

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SERVOMECHANISMS LABORATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Project DIC 6345

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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 and the Air Materiel Command under Navy contract N5ori60. The objectives of the Project are the 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 Project resources are about equally divided between (1) operation of the computer and improvement of its reliability; (2) applications of the computer to engineering and scientific problems; (3) storage-tube research and development; and (4) design of additional terminal facilities.

The Whirlwind Computers

The Whirlwind computer is 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) may be regarded as a prototype from which other computers will be evolved. It is being used 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 permits the computation of many simulation problems. Calculations requiring greater number length are handled by the use of multiple-length numbers. Rapid-access electrostatic storage now has a capacity of 4096 binary digits, sufficient for some actual problems and for preliminary investigations in most fields of interest. Present speed of the computer is 20,000 single-address operations per second, equivalent to about 6000 multiplications per second. This speed, which is expected to be doubled by improvements now under way, 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 in the Appendix.

I. QUARTERLY REVIEW (AND ABSTRACT)

The computer has continued to operate successfully during the second quarter. Total operating time has been increased to about 80 hours a week, with about 35 hours a week scheduled applications time. As during the preceding quarter, about 90 per cent of the scheduled applications time has yielded useful work. This actually represents an improvement in reliability, because the computer has been used to solve increasingly difficult problems which have brought to light some previously obscure troubles. Improved marginal-checking programs read into electrostatic storage by the photoelectric tape reader have contributed to the reliability of the system.

The sixteen 300-series storage tubes now in the computer have been operating successfully for an average of 1200 hours (640 to 1730). Four tubes were replaced after an average of 800 hours because of dark areas on their targets caused by a focusing of ion current. Modifications of the tube processing techniques and changes in electrode voltages have eliminated this problem. The number of available electrostatic-storage registers has been increased from 256 to 304 by using the small segments of target area above and below the normal square. Research on higher-density storage continues, along with studies aimed at improving the high-velocity electron guns and the storage surfaces.

An in-out control has been designed; it will be built up primarily from existing general-purpose register panels. The Flexowriter input-output equipment has been operating quite reliably, but the photoelectric tape reader has not been satisfactorily reliable, probably because the present tapes are not sufficiently opaque. A new 16-inch display scope has materially improved output display. The Raytheon magnetic-tape drive units have been received but not yet operated in the computer. The problem of blemishes on the magnetic tape is being further studied.

A program has been started to repackage some of the Whirlwind basic units in more compact form. Plug-in models of a flip-flop, a gate unit, and a switch unit have been built for the new display decoders; it is planned to use them widely in future construction.

The applications group have been continuing to develop a collection of useful coded subroutines and to gain experience in the solution of representative engineering and scientific problems. Among the problems attacked have been: extra-precision and floating-point arithmetic; a study of economic systems that involves non-linear differential equations; a study of tape-wound magnetic cores that involves non-linear partial differential equations; a study of the optical constants of thin metal deposits that requires the solution of a pair of simultaneous transcendental functions; a study of the allocation of UHF television channels; and the design of a two-tower antenna system.

2. SYSTEM ENGINEERING

2.1 COMPUTER RELIABILITY

During the second quarter the computer has operated with about 90 per cent of the scheduled applications time yielding useful work. The operating time has been increased by Saturday work to approximately 80 hours a week, with about 35 hours a week of application time. The percentage of useful work obtained during applications periods has remained practically constant during the past quarter, but we feel that reliability has increased during this period, particularly during the last few weeks. The fact that the computer has been used during the last quarter on a large number of difficult programs probably accounts for some of the troubles which have recently appeared. Many of the remaining computer errors are now resulting from small isolated failures such as tube shorts or other component failures.

We are continuing to develop better marginal-checking programs and trouble-shooting techniques in order to increase reliability. A new method of measuring flip-flop margins, in which the restorer frequency in Whirlwind is varied over a wide range, replaces about 16 hours of complement test time with about half an hour of restorer-frequency checking. Rapid reading of check tapes into electrostatic storage by the photoelectric tape reader has improved the marginal-checking program. Thus it is finally feasible to use check tapes with a check program that is very comprehensive compared to the simple programs which could be stored in the 32 registers of test storage.

As the various design weaknesses in Whirlwind are corrected, the amount of trouble encountered due to tap shorts in the tubes and other types of sudden mechanical failures assumes greater importance. Unfortunately, these difficulties are not immediately found by marginal-checking procedures and usually cannot in any way be predicted. We are considering plans for increasing system reliability by special tube testing using panel vibration to expose poorly soldered joints and tap shorts in tubes. Plans for even more extensive marginal-checking programs are expected to further increase reliability of the computer during the second half of 1951.

2.2 ELECTROSTATIC STORAGE SYSTEM

Four storage tubes of the total complement of 16 in Whirlwind have been replaced during the past quarter, with an average life of 800 hours. The storage tubes now in Whirlwind have been operating for an average time of approximately 1200 hours, with a spread of 640 to 1730 hours. Most of these tubes were installed toward the end of the first quarter of 1951; therefore life expectancy of storage tubes was not predicted in the previous summary reports. The experience during this quarter shows that the life of storage tubes should be substantially above 1000 hours. As yet the operation of the storage tubes gives no indication that 1000 hours is near the maximum expected life of the tubes; the outlook is quite bright.

The four tubes which were replaced at about 800 hours showed a dark area near the center of the target when viewed by the television test method. This dark area was obviously an area of low secondary emission ratio, which resulted in poor positive-spot size. The dark spots were found to be caused by a focusing of ion current due to a change in electrode voltages which was made near the beginning of this quarter. Modifications of the storage-tube processing techniques and changes in tube electrode voltages have resulted in a reduction of ion current to a point that eliminates this problem.

The maintenance time required to keep the electrostatic-storage system in good running order has been sharply reduced during the last quarter. The small number of tubes which had to be changed has helped materially. In addition, different methods of tube adjustment and the speed-up resulting from experience has shortened operations substantially.

Time devoted to installation of new equipment has been increased from four to seven hours a week, so that modifications can be made in preparation for installation of the second bank of storage tubes this fall. Many modifications in the storage control have already been made, and more are planned, to allow storage control to operate with two banks of storage tubes as soon as the associated circuitry has been installed.

A 17th digit is being added to the storage system to keep track of whether a number stored in the other 16 digits has an odd or even number of ones in it (called the "parity" of the stored number). A parity register, with associated control circuits, will determine the parity of any 16-digit number to be stored and will store a one in the same address of the 17th digit if it is odd, thus making the parity of the 17-digit number always even. When this 17-digit number is later removed from storage, the parity register will determine the parity of all 17 digits and will stop the computer with an alarm if the parity is odd. Thus the computer stops immediately if any one, or any odd number of, storage tubes reads out incorrectly. This system will give a check on storage operation and expedite testing of the second bank. It should also permit use of test programs which are easier to operate, and will definitely tie down trouble to one section of the computer.

The number of electrostatic-storage registers now available in Whirlwind has been increased from 256 to 304 by using the small segments of target area above and below the normal square area. Modification of the deflection generators to make these registers available was very simple, and a switch on the test control allows immediate change between systems. In addition to these extra 48 registers, the storage tubes have been operated with a higher density of spots for some programs. In particular, one program (see Section 6.5) uses 348 registers, but the computer has not been able to operate at these higher densities except at the expense of reliability. This higher density has, however, been good enough to allow useful work to be accomplished. The system engineering group has emphasized an increase of the number of storage registers by the addition of a second bank of storage tubes rather than by increased density of the present bank. Some modifications of the tube electrode voltages should result in the operation of the tubes at more than 304 registers per bank.

By the end of 1951 there should be available nearly 1000 registers of high-speed electrostatic storage.

2.3 INPUT-OUTPUT SYSTEM

The Flexowriter tape equipment used for filling electrostatic storage and printing out tables of results has been operating quite reliably. Counters and timers have been added to the Flexowriter equipment so that the maintenance group can keep accurate track of the frequency with which maintenance is required. It is expected that improved Flexowriter equipment will be obtained and installed in Whirlwind in the near future.

The 16-inch display scope was installed in Whirlwind about two months ago. This scope has very much improved the output display but has shown that the present breadboard decoders are inadequate. New decoder designs are now in progress (see Section 3.5), and it is expected that the old decoders will be replaced during the month of October. A decimal display-light panel has been designed to operate with one of the flip-flop registers. This panel automatically decodes binary-coded decimal quantities and displays them in decimal as a set of illuminated numbers.

The photoelectric tape reader has been quite a help during the past quarter, but it has not been entirely trouble-free. As described in Section 5.2, much of the trouble seems to be caused by light transmitted through the yellow tape to the photocell at a spot where no hole has been punched. If black paper tape is procurable, it should overcome this difficulty.

Test control has again been modified to make it easier for the operators to use and particularly to avoid trouble with incorrectly thrown switches. In the past, the large number of switches available in test control has been very confusing to new computer operators. The modified test control now has a panel of lights which indicates the normal and test positions for all control switches. Thus the operator can tell at a glance if a switch is in the correct position.

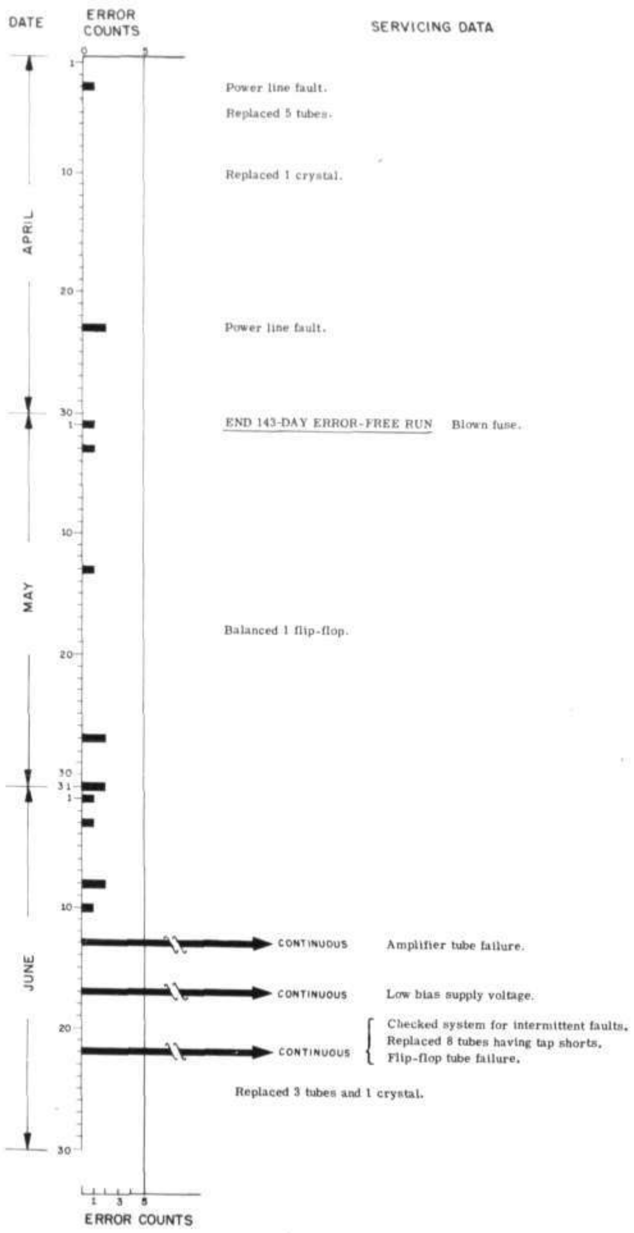


Fig. 3-1. Five-Digit Multiplier Performance

3. CIRCUITS AND COMPONENTS

3.1 FIVE-DIGIT MULTIPLIER

The five-digit multiplier (a prototype of the Whirlwind arithmetic element) has completed 26 months of operation in its extended reliability test. During this time it has been performing repeated multiplications of two five-binary-digit numbers and checking for a correct result at the end of each multiplication. Shortly after the test was started, it was found that elimination of random unexplainable errors was the greatest problem in obtaining higher system reliability. From time to time intermittent faults have been found such as poor electrical contacts and tubes showing internal shorts when tapped. Following correction of such a fault, a reduction in the frequency of errors has occurred. During the past quarter, interruption of the longest error-free run occurred when a power-supply fuse burned out for an unknown reason. This run had extended for 143 days, or nearly five months.

A summary of the multiplier performance during the past quarter is given on the chart of Fig. 3-1. Several errors have occurred in May and June, giving a relatively poor reliability record for these two months. Two factors are apparent which could at least partially explain these errors. First, several tubes were found to have intermittent faults when lightly tapped. Such faults seem to develop as the tubes age, possibly as a result of flaking of the cathode coating. Second, overall margins are somewhat lower than at the start of the run. Since the lowered margins are not the result of deterioration in a single component, their improvement will entail a relatively large amount of maintenance work. Manpower to do this has not been available during the last month.

3.2 VACUUM-TUBE LIFE

Extensive analyses of vacuum-tube life data have not been undertaken during the past quarter for two reasons: (1) the additional data obtained, which might be used to extend the curves already published in Summary Report 25, are not sufficient to bring out any significant changes in these curves, and (2) plans are under way to transcribe our tube records onto punched cards so that sorting and analysis can be accomplished more easily.

Special pulse testing equipment has been constructed for the tube shop so that routine testing for interface is now practical on all tubes returned for retest. An analysis of interface resistances in 7AD7 tubes retired from the computer since April 1, 1951, is included in the following section.

The chart of Fig. 3-2 shows a summary of type 7AD7 tube failures that occurred in the computer during the past quarter. These failures are grouped according to thousand-hour intervals of life.

Hours	Reason for Failure			Measured Interface Resistance (R_i) in Failed Tubes (ohms)				No. of Low-I_b Failures Having R_i >10 ohms
	Tap Shorts & Shorts	Low I_b	Other causes	<10	10 - 20	20 - 40	>40	
0 - 1000	3	3	0	6	0	0	0	0
1000 - 2000	3	3	1	4	2	1	0	1
2000 - 3000	13	2	1	12	1	1	2	1
3000 - 4000	4	4	0	5	0	1	2	1
4000 - 5000	6	4	1	6	2	2	1	1
5000 - 6000	9	8	2	15	2	0	1	1
6000 - 7000	8	8	0	11	2	2	1	2
7000 - 8000	12	5	0	14	2	0	1	0

Fig. 3-2. 7AD7 Failures in WWI April 1 - June 30, 1951
(Total in service: 1700)

Type	Total in Service	Hours at Failure	Reason for Failure; Number failed: Changes in Characteristics	Mechanical	Burn-out	Gassy
7AK7	1450	4492		2		
		6552			1	
		6825		1		
		7000-8000		2		
6Y6G	308	5696				1
5U4G	24	1164	3			
OD3-VR150	28	1085	1			
6SH7	3	1085		1		
6L6G	83	1085	1			
63J	18	6469	1			
		7156		1		
EL3C	2	1455	1			
5Y3GT	5	6320				1
6AL5	180	2879		1		
6SN7	400	3774	1			
		4184	1			
		5000-6000	1	1		
		6114	1			
		7060		2		
6AS7G	79	3734		1		
C16J	12	3266		1		
		7148		1		
3E29	140	4925	1			
		6456		1		

Fig. 3-3. Tube Failures in WWI (7AD7 omitted)
April 1 - June 30, 1951

In each interval two types of breakdown are given, one showing reason for retirement (tap shorts and shorts, low plate current, and other causes), and a second showing the magnitudes of the interface resistances found in these tubes. The minimum interface resistance that can be measured with the equipment used is about 10 ohms, so that the tubes listed as having less than 10 ohms have negligible interface. Since an interface resistance causes a reduced plate-current reading on a static test, the tubes that were retired because of low plate current and which were also found to have an interface resistance are listed in the last column on the chart.

There appears to be little correlation between the low-plate-current failures and the existence of interface. Thus other factors are apparently more serious than interface in producing plate-current deterioration in these tubes. That interface deterioration may not be a serious problem in these

Component	Type	Total in Service	No. of Failures	Hours of Operation	Comments
Capacitor	0.01 mfd	12,000	1	3173	Shorted
	20 x 20 mfd 450 V Plug-in	42	1	3277	Blew out
Choke	50 µh	1675	1	4939	Open
Crystal Rectifier	D-357	7700	28	1000-2000	2 grid: low back resistance
				2000-3000	1 grid: low back resistance
				3000-4000	7 grid: low back resistance 1 plate: low back resistance
				4000-5000	2 grid: excessive drift and low back resistance
				5000-6000	9 grid: low back resistance 1 mixing: low back resistance
				6000-7000	5 grid: low back resistance
	D-358	3000	80	0	2 clamp: low back resistance
				1000-2000	2 clamp: low back resistance
				2000-3000	2 clamp: low back resistance 1 clamp: excessive drift
				3000-4000	9 clamp: low back resistance
				4000-5000	16 clamp: low back resistance 2 clamp: excessive drift
				5000-6000	39 clamp: low back resistance
				6000-7000	7 clamp: low back resistance
Pulse Transformer	1:1	603	1	5	Open secondary: failure due to shelf-aging

Fig. 3-4. Failures of Components in WWI
April 1- June 30, 1951

tubes is further pointed out by the fact that the number of tubes showing interface does not increase for longer periods of service. However, since interface growth in a tube is known to be a function of time, and since the data analyzed here represent only a sample of the tubes in the computer, there is no assurance that interface deterioration will not become a predominant cause of low-plate-current failure after the tubes have had several more thousands of hours of service.

Failures among tubes other than type 7AD7 during the second quarter of 1951 are listed in Fig. 3-3. These include tubes used in the WWI power supplies as well as those used in computer circuits.

3.3 COMPONENT REPLACEMENTS IN WWI

Figure 3-4 lists the replacements of components other than tubes during the second quarter of 1951.

Of the 108 crystal failures all but five were replaced because of low back resistance. It is believed that the new crystals now being used, 1N34a's in place of D-357's, 1N38a's in place of D-358's, will eventually eliminate the wholesale replacement of crystals because of low back resistance. So far, the 1N34a and 1N38a crystals have been superior to the D-357 and D-358 crystals because they have consistently higher back resistance and more stable characteristics.

3.4 FERROMAGNETIC AND FERROELECTRIC CORES

A scheme for storing digital information in a three-dimensional array of magnetic cores, the results of research work on the individual cores, and the start of operation of a 4-core memory array were discussed in Summary Reports 24 and 25.

Developments since then include some encouraging tests on the array, an extension of the coincident-current selection scheme which promises to improve results significantly, tests on some new low-energy cores, and a start on research work with ferroelectrics.

3.41 The 4-Core Two-Dimensional Array

Operation of the 4-core array has been stable and with good margins. Deterioration of information occurs only in the first few cycles of disturbing activity, and it has a limit; disturbed-signal ratios average about 7 on an area basis, and are very large when measured on an amplitude basis about 10 microseconds after the start of the pulse.

A marginal check demonstrated that all coordinate (selecting) currents could be varied above and below an optimum setting by over 20 per cent before information patterns became unstable.

Design work on a much larger two-dimensional array is beginning.

3.42 3:1 and 5:1 Current Ratios

In the coincident-current selecting scheme used until recently, an individual core is asked to discriminate between two possible H amplitudes which bear a 2:1 ratio to each other. It is possible to devise selecting schemes in which the core has to discriminate between two H amplitudes which bear a greater ratio to each other. The resultant advantages are increases in signal ratios and in operating speeds; the cost is an additional increase in the surrounding electronic circuitry of the system for each increase in the H ratio.

In the 3:1 scheme illustrated in Fig. 3-5, each selecting winding carries a fraction of the full magnetizing current I equal to $\pm\frac{2}{3}$, $\pm\frac{1}{3}$, or 0; but the resultant magnetizing forces add algebraically in each individual core so that it "sees" only amplitudes of H which are proportional to I or $\frac{1}{3}$ I. With

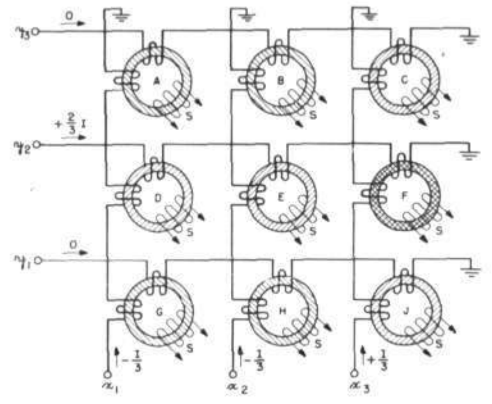


Fig. 3-5. A Two-Coordinate Array Using 3:1 Selection

the applied currents as shown, the selected y coordinate (y_2) carries $+\frac{2}{3}$ I while the rest carry no currents, and the selected x coordinate (x_3) carries $+\frac{1}{3}$ I while the rest carry $-\frac{1}{3}$ I. As a result, Core F has the full switching force of H applied, while amplitudes only one-third that amount (plus or minus) are impressed on the other eight cores. (If the polarities shown are for the read operation, then the opposite polarities would represent a write-ONE operation.) Since driving pulses of both polarities are used in the two-coordinate array, three-coordinate selection as described in Summary Report 24, Section 3.43, is no longer possible.

The 5:1 scheme is an extension of the same type of reasoning and requires an additional set of windings on the cores.

Tests made on the single-core tester indicate that in the 3:1 scheme the signal ratios or response times of the cores are improved by a factor of about 2 over the original 2:1 scheme. This moves the signal ratios of the Ferramic A core away from the marginal region and reduces the response time of the 1-mil Selectron core to under 10 microseconds. A similar additional improvement occurs for the 5:1 scheme.

3.43 New Cores

Tests on sample fractional-mil tape-wound cores supplied by the Armco Steel Corp. gave promising results for a specially annealed $\frac{1}{4}$-mil Mo-Permalloy core. Very small cores of this type with inside diameters of $\frac{1}{4}$ inch were obtained from Magnetics, Inc., for further testing. They have very good signal ratios and a response time of about 8 microseconds in the 2:1 scheme and 4 microseconds in the 3:1 scheme. They have much smaller

hysteresis loops than previously successful cores, because they have lower coercivity and lower maximum flux density; they require, therefore, lower driving power and single-turn driving currents low enough to be supplied directly from receiving-type vacuum tubes.

3.44 Ferroelectric Storage

Dielectric materials have been developed in this country recently which have hysteresis loops in the D-E plane analogous to the hysteresis loops of magnetic materials in the B-H plane. These so-called ferroelectric materials have possibilities as storage media in arrangements which are similar to, and which in some cases may be the duals of, the ferromagnetic storage schemes. An investigation into these possibilities is being started.

3.5 PLUG-IN UNITS

Now that Whirlwind circuits are well understood, it is no longer necessary to use the open breadboard type of construction. A program of repackaging certain basic units has been started in order to conserve space and to investigate problems which may arise when compact construction is used.

Three basic units are being built for the new display decoders — a flip-flop, a gate unit, and a switch unit. The first two of these are common computer circuits, and it is planned to use them widely in future construction. The decoders consist of 22 identical stages, each containing six tubes. The 132 tubes will be built in 66 plug-in units and will be mounted in a space of seven square feet, compared to about 46 square feet required for the old type of construction. Because of the plug-in feature, this saving in space will not be at the expense of accessibility for maintenance.

The plug-in units are built on commercially available molded plugs which, although inexpensive, are accurately and sturdily made (see Fig. 3-6). Each unit is held in place by a long knurled screw which passes through the center of the unit and screws into the chassis. The chassis is made of aluminum bars $\frac{1}{2}$ inch square which form a rugged open mounting for the sockets. A terminal strip is mounted behind each socket to carry filament

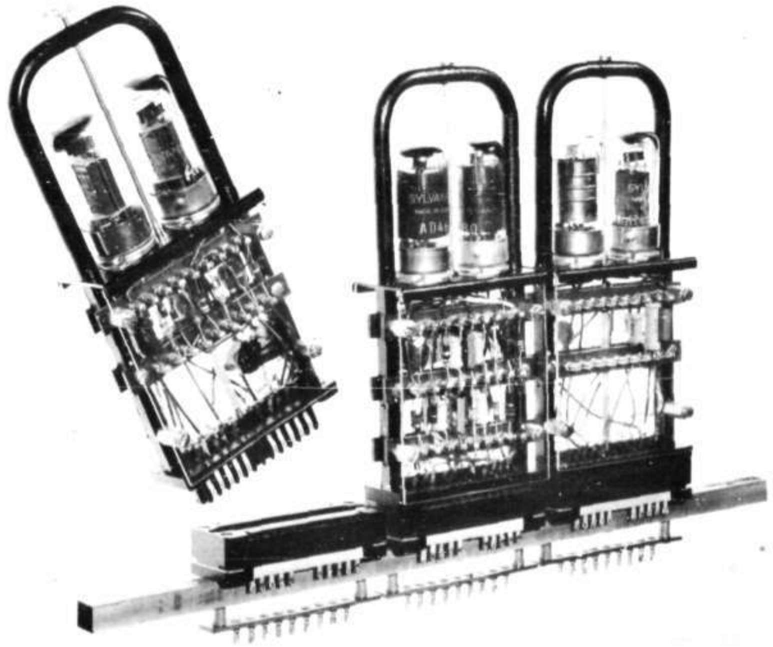


Fig. 3-6. Plug-In Units. Left to right: gate unit, flip-flop, switch unit.

busses and video wiring. The frames of the units are grounded separately from the circuits to eliminate shock hazard. Plastic covers have been placed on the units to protect the parts and wiring.

With the exception of large mica condensers, which will be replaced by ceramic discs, space has been provided for standard parts, pulse transformers, and tubes. This plan should result in a design giving the same performance attained with the previous type of construction and in addition make a real saving in space.

An important by-product of reducing the space requirements is the saving in coaxial cable and the reduction of the transmission-line problems. This type of construction when extrapolated to an overall system will allow the use of short open-wire transmission paths for many of the channels now using coaxial cable with impedance-matching transformers. The resultant savings in components will be appreciable.

4. ELECTROSTATIC STORAGE

4.1 TUBE PROGRAM

The first bank of 300-series storage tubes has been giving excellent computer operation throughout this period. Although four tubes of the original 16 have had to be replaced because of the progressive formation of "dark spot" areas of low secondary-emission ratio, it is felt that the factors responsible for these dark areas have been uncovered and that further formation can be prevented.

With 16 tubes now operating in the computer and adequate replacements being built up, the opportunity for building research tubes for the study of higher density is being utilized. Simultaneously, a program to improve cathode life and simplify the tube construction is under way.

4.11 Tube Experience in Whirlwind I

As described in Summary Report 25, the reliability of electrostatic storage improved markedly after the installation of 16 of the 300-series all-dagged storage tubes which have a conducting coating over the entire inside walls. These tubes are free from the random fluctuations in potential on the bare glass windows of the 100-series tubes that were shifting the high-velocity reading beam away from previously written spots, with the consequent loss of stored information.

However, after roughly 750 hours of use in the computer, three of the 300-series tubes began giving marginal operation. Television read-out showed that these tubes all had dark circular areas approximately an inch in diameter near the center of their storage surfaces. With the type of read-out in use, these dark spots corresponded to areas having a lower secondary-emission ratio than the rest of the surface. After 800 hours of operation, a fourth tube had to be replaced because of "dark spot" formation.

Tubes having these localized areas of low secondary emission are unsatisfactory because the array of storage spots are no longer uniform in size. The secondary-emission ratio of the beryllium mosaic at 2000 volts is not a critical parameter of tubes so long as it remains above unity. However, it is highly desirable that this ratio be as uniform as possible over the entire surface to achieve uniformity in size of positive spots. Since the current-density distribution of the high-velocity beam is not ideally square, the size of positive spot produced by a given beam charge is directly related to the secondary-emission ratio of the surface. Conversely, the current density available for writing negative spots is unaffected by the secondary-emission ratio of the surface, so that the erasing requirements of non-uniform positive spots cannot be met by external adjustment of the write-minus charge.

4.12 Ion-Current Distribution

The appearance of the dark spots was such that the possibility of an ion blemish was immediately suggested. Continued ion bombardment could conceivably alter the secondary-emission properties of the storage surface, and a non-uniform ion density over the surface would give rise to the dark areas observed. However, quantitative measurements of the distribution of ion current had not been previously carried out.

As a result of a master's thesis research on the primary holding-beam distribution, a special research tube was available which could be easily used for measuring ion currents. This tube was described in Section 4.21 of Summary Report 25; it is similar to a 300-series storage tube except that the storage surface and signal plate are replaced by a plate containing 13 separate current-sampling apertures each backed by a Faraday cage. With the collector screen equal in potential to the holding-gun cathode, the positive ion current, which normally would strike the negative storage surface of the standard storage tube, can be determined.

The ion currents measured to seven of the cages along a diameter of the tube are shown in Fig. 4-1 for different third-anode voltages with the collector screen fixed at 100 volts. Standard operating voltages for 300-series tubes in the computer include 150 volts on A_3 and 100 volts on the collector. It can be seen that under these conditions the ion-current ratio between the center and the edge of the surface is nearly 10 to 1, with a very pronounced peak near the center. An excellent correlation exists between the shape of the ion-current distribution and the shading pattern in and around the dark spots observed in the rejected storage tubes. A rough calculation also tends to confirm the assumption that positive ions striking the storage surface are responsible for the formation of dark spots. From Fig. 4-1 it is apparent that the rate at which a dark spot will form, i. e., the ion-current density, is significantly related to the potential of the third anode. With A_3 above the collector potential, the field between those electrodes forms a convergent lens which effectively focuses the ion flow at the center of the surface.

During the course of these measurements it was also observed that the potential of A_3 affected the gas pressure within the tube, with definite indi-

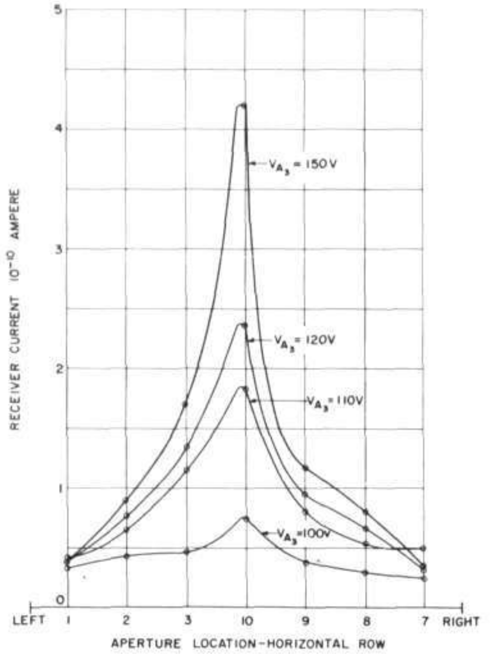


Fig. 4-1. Positive Ion Current Distribution at Aperture Plate of RT-197-1

cations that under bombardment with electrons having velocities greater than 30 electron volts, the third anode was releasing considerable gas. This gas was in turn ionized by the relatively efficient low-velocity holding beam; the resulting ions were focused by A_3, and finally impinged upon the storage surface. Thus, as A_3 is raised above the collector potential not only does the focusing action become stronger but in all probability more ions are produced from an increase in gas released by A_3. The amount of this gas was frequently great enough to contaminate the oxide cathodes to the point where only a fraction of the normal emission was obtained. Before the cathodes were permanently damaged by ion bombardment, this loss of emission was reversible, and continued operation was usually possible with an increased heater voltage.

Two obvious solutions were possible in order to remove the ion-current peak and reduce the gas pressure: the reduction of A_3 to approximately 100 volts or the use of a material for A_3 which does not release gas under electron bombardment. On a short-term basis the first alternative has been followed; however, research work on other conducting coatings is in progress. Some improvement is also obtained by operating with the holding gun biased a few volts negative. This reduces the number of primary electrons striking the third anode and consequently the amount of gas released.

Another possibility which is being investigated is the addition of an auxiliary screen in front of the present collector. The potential of A_3 had previously been set to 150 volts to reduce spot interaction during negative writing. Thus, the auxiliary screen may be used instead of A_3 to control spot interaction, while A_3 can be permanently kept at 100 volts.

4.13 WW Acceptance Tests

As a result of the thesis work on the distribution of holding-beam and ion-current densities, a test was devised which gives a measure of the ion-current variations over the surface of a standard storage tube. It is felt that this test may be carried out rapidly enough to be used in the acceptance testing of all storage tubes. The essential feature of the test is that the ion current is allowed to charge the storage surface in a positive direction during a time in which the target is more negative than the holding-gun cathode, so that the surface receives no electron current. Starting initially with the surface at holding-gun cathode potential, a 50-volt negative gate, variable in time between roughly 0.05 and 5 seconds, is applied to the signal plate. During this gate, the holding beam is left on continuously, and A_3 and the collector are at their normal potentials, so that the surface charges positively at a rate determined by the ion-current density under standard operating conditions. When the signal-plate gate has ended, the surface is examined by a television read-out. Those areas of the surface which have been charged through a voltage equal to first crossover for the beryllium mosaic will then appear positive, while any area whose potential has shifted by an amount less than first crossover will be restabilized negative by the holding-beam electrons. A plot of the positive spot size produced versus the reciprocal time of the signal-plate gate appears much the same as the curves of Fig. 4-1.

4.14 Tube Production

The main objective of the tube construction program was first to produce adequate replacements for the bank of 16 storage tubes already operating in Whirlwind and second to stockpile tubes for a second bank of 16 storage tubes. At the same time, we tried to build research tubes which would aid in the development of a tube capable of increased density and longer cathode life.

During the three months from 1 April 1951 to 30 June 1951, 23 300-series storage tubes were constructed for the computer (see Fig. 4-2). Five of the tubes failed to pass the acceptance test. Three of the tubes had poor secondary-emission characteristics below 100 volts. In an attempt to speed up the processing of the beryllium mosaics, the beryllium was evaporated at a temperature higher than the usual practice. This resulted in mosaics with poor secondary-emission characteristics below 100 volts. When this was discovered, the mosaics were again prepared at a lower temperature; the mosaics were satisfactory. One tube had poor cathode emission and another tube imploded on the shelf. Besides the five failures, two tubes were declared marginal because of the poor secondary-emission characteristics of the mosaic below 100 volts and poor cathode emission.

Nine research tubes were constructed. Three of the tubes were prototypes of the 400-series storage tubes described in Section 4.21. Two of the tubes had an auxiliary screen in front of the collector screen. One tube was used to determine the restoring current and crossover voltage of plain mica. One tube was a 300-series storage tube to test a new technique for preparing and processing a conductive coating of the envelope. The distribution of holding-gun current density was studied in a modified 300-series storage tube with a signal plate consisting of four concentric rings. Two tubes were used to test our technique for mounting and processing Philips type "L" cathodes in structures that could be used in electron guns.

Six experimental tubes were made to find a conductive coating which would release less gas under electron bombardment than our present dag coating. It was found that a special silver paint coating was better than dag, but a tin oxide coating produced by vapors from stannous chloride was most favorable. These studies of conductive coatings were temporarily shelved for the summer.

4.2 STORAGE-TUBE DEVELOPMENT

4.21 Tests on 400-Series Prototype Tubes

During this period several research tubes have been constructed with the known parameters chosen so as to give the best performance at an increased storage density. Several of these parameters were as follows:

1. A reduction in the mica dielectric thickness from 10 to 3 mils.
2. A reduction of the high-velocity beam throw by approximately 1 inch and operation of the high-velocity gun with 2500 volts overall acceleration voltage.
3. A 5-mil spacing between storage surface and collector, obtained by removing the inscribed square from a circular piece of mica. This open square then outlines the storage surface.
4. A 70-mesh-per-inch mosaic in place of the previous 40-mesh.
5. A lengthening of the holding-gun throw by $\frac{1}{2}$ inch and operation with the second anode of the holding gun at 100 volts.

Rather exhaustive tests have been completed on one tube of this series. These tests have included single-shot operation and measurements of spot size, cycling tests, and spot-interaction tests.

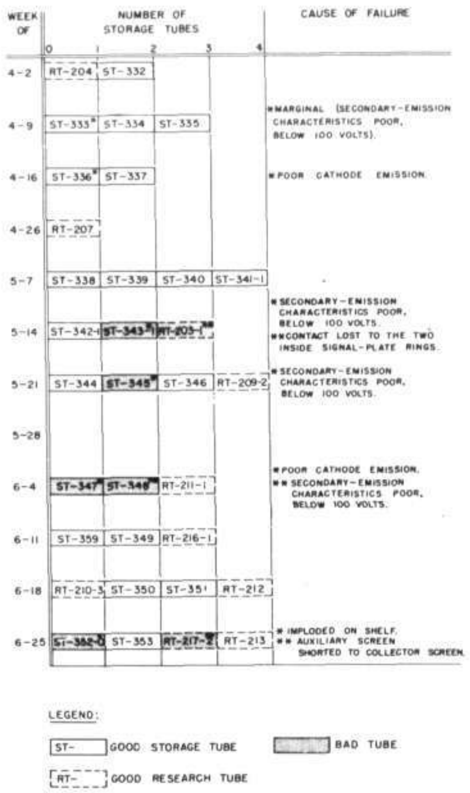


Fig. 4-2. Storage-Tube Production Record

The spot-interaction test makes use of a 9-spot array in which the center spot is written positive. Alternate positive and negative writing then takes place for an arbitrary number of cycles around the eight outside spots, after which the center spot is again read out and checked. It is intended that the spot-interaction test will simulate the severest possible operation of the storage tubes in computer use and that the single-shot tests represent the easiest possible operation. However, neither of these tests results in the completely random operation which a tube finds in computer use.

These tests have shown that the beam-current margins on writing positive and negative must be different from those previously used with 300-series tubes. The most prominent change is the reduction of the amount of write-positive charge. Present 300-series tubes allow a factor of safety of 4 in the writing of positive spots. At 32 x 32 operation, this factor of safety requires a write-minus charge which results in a prohibitive amount of spot interaction. The tests have also indicated that the setting of the focus electrode voltage will be somewhat more critical than at 16 x 16 operation. Whereas a range of more than 100 volts was possible, this voltage will now have to be maintained within ±25 volts.

Although the 400-series prototype tubes would cycle any arbitrary pattern for as long as five hours, no further attempt has been made to investigate the maximum length of cycling or the margins of voltage and gate amplitude during cycling. Instead, it is felt that the satisfactory operation in both single-shot tests and spot-interaction tests gives conditions under which the tubes will operate most reliably. Tubes set up so as to pass both of these tests have cycled all available patterns for extended periods of time.

A tentative conclusion from the higher-density tests is that the mica thickness may have been reduced too far: the capacitance per unit area is now so great that, in order to get a satisfactory size of spot within a reasonable writing time, it is necessary to use currents in which space-charge spreading of the electron beam begins to come into play, and the minimum obtainable beam size occurs ahead of the target surface. Accordingly, the mica thickness in future research tubes for high-density studies will be made somewhat greater than 3 mils.

A research tube is also available which is similar to the 400-series prototype but with an auxiliary collector screen mounted approximately 100 mils in front of the normal collector screen. Initial observations on this tube indicate that spot interaction during negative writing may be reduced by correctly setting the potential of this screen, but its effects on other aspects of operation must be more fully investigated.

In the near future one of the 400-series prototype tubes is to be placed in the computer instead of one of the 16 300-series tubes now operating. It will have separate power supplies, so that higher-density operation can be achieved only in this tube with normal conditions on the 15 remaining tubes.

4.22 Gun Research

Considerable time has been spent during this period in determining the fringe-current distribution of the high-velocity beam. While it is well established that the central region of the current-density distribution is of a Gaussian shape, it has been observed that the positive-spot size produced by long writing gates — or normal writing gates and a very short holding-gun time between successive writes — cannot be accounted for on the basis of a Gaussian distribution. The positive spot size under the conditions above can be predicted if a second term is added to the current-density distribution which decays in an exponential manner from the center of the beam. It remains for further experiment to determine whether the beam shape has an exponential component or whether some other process is responsible for the large positive spots observed. Whichever is true, it is convenient to express the current-density distribution as

$$j = j_o \left[c e^{-ar^2} + (1 - c)\, e^{-br} \right] ,$$

with j being the current density at a radius r from the center of the beam where its value is j_0, and c a constant which determines the contributions of the Gaussian and exponential terms in conjunction with their decay constants a and b respectively.

Ideally, c would be unity and a would be as large as possible, giving a Gaussian beam with a high value of j_0/i, where i is the total beam current. Experimentally, however, c appears to be less than one, giving rise to what might be regarded as an interference term, in which the beam-current decay is exponential with increasing radius. For the least interference, b should be as large as possible. The present testing is to find what factors determine the value of b. Preliminary results indicate that the high-velocity-beam throw is one of the more significant parameters, with both focus and overall acceleration voltages playing a very minor part.

During this period several cathode-study research tubes have been made and tested using Philips type "L" cathodes. The results have been quite encouraging. It may be possible to obtain the required emission density at a cathode temperature considerably below the rated value of

1270 C. In this event, a stable emission may be realized with good heater life and negligible evaporation of barium onto the storage surface.

4.23 Surface Studies

One of the problems associated with storage-tube operation for some time has been the marked discrepancy between the first-crossover voltage and the collector voltage at which a positive spot is no longer held positive but drops down to the potential of the holding-gun cathode. As measured by several methods, including both capacitive and direct connections to a storage surface, the first-crossover voltage is in the vicinity of 20 volts. Nevertheless, positive spots can seldom be maintained for a collector voltage below 50 volts.

This problem has been circumvented in the past by simply operating with a collector voltage of 100 volts. It became significantly more important recently because of an upward trend in the minimum collector voltage required for stability of positive spots, with some tubes needing as much as 80 volts on the collector to hold positive spots. A correlation between tube processing schedules and the resultant "lower switching voltage" revealed that the poor tubes with the high switching voltages generally had heavier coatings of beryllium than tubes which would hold positive spots down to the normal value of 50 volts. This value is now being maintained by taking particular care during the evaporation process to deposit a light coating of beryllium very slowly.

Concurrently, however, a master's thesis research into the lower switching phenomenon has been in progress. From this work it is becoming evident that the secondary emission and leakage properties of the background dielectric material determine to a large extent the collector voltage at which positive-to-negative switching takes place. Thus the conclusion is reached that it was not the thickness of the beryllium coating as such which was adversely affecting the lower switching voltage, but rather some difference in mica treatment accompanying the different evaporation schedules required to produce the thick and thin coatings.

Within the next period the first of the glass sintered surfaces should be available for testing so that their utility as storage-tube dielectrics may be evaluated.

5. INPUT - OUTPUT

5.1 IN-OUT CONTROL

A block diagram of an in-out control (IOC), which harmonizes the operation of the computer program with the partially independent actions of the external units, is shown in Fig. 5-1. With the exception of the delay counter (404), which will be constructed by converting the comparison register (404) to a d-c-coupled counter, IOC will consist of six of the general-purpose d-c register panels identical with those being constructed for the in-out register and described on page 24, Summary Report 25.

The IOC accomplishes the following:

a. Synchronizes internal and external pulse signals.

b. Stops the computer if it attempts to get ahead of an external unit.

c. Gives an alarm if an external unit gets ahead of the computer program.

d. Allows certain external units to operate through several cycles or in-out processes in response to a single computer order.

e. Counts delays needed between steps in the in-out operation.

Each of these five functions can be generally assigned to the appropriate one of the following five components found in IOC:

Synchronizer (415)
Interlock (413)
Alarm Control (414)
IOC Counter (411)
IO Delay Counter (404)

The sixth component of IOC is reset control (412). This unit receives information from the setting of the in-out switch (IOS) and controls the setting of the other components in IOC so that they will operate in the manner desired for the particular external unit selected by IOS.

Each read (rd) or record (rc) order will transfer one word between the computer and the in-out register (IOR). In reading, the first recorded word which is reached is placed in IOR by the readers; in recording, the word in IOR is recorded in the first space reached.

While magnetic-tape units handle information in words of four digits, IOC was designed so that each rc and rd order will transfer a 16-digit word between the computer and IOR; and the IOC counter will control the buildup or breakdown from one 16-digit word to four 4-digit words. This method saves the very substantial amount of internal storage and computing time that would be needed if the computer were to perform the buildup or breakdown within itself by the use of subprograms.

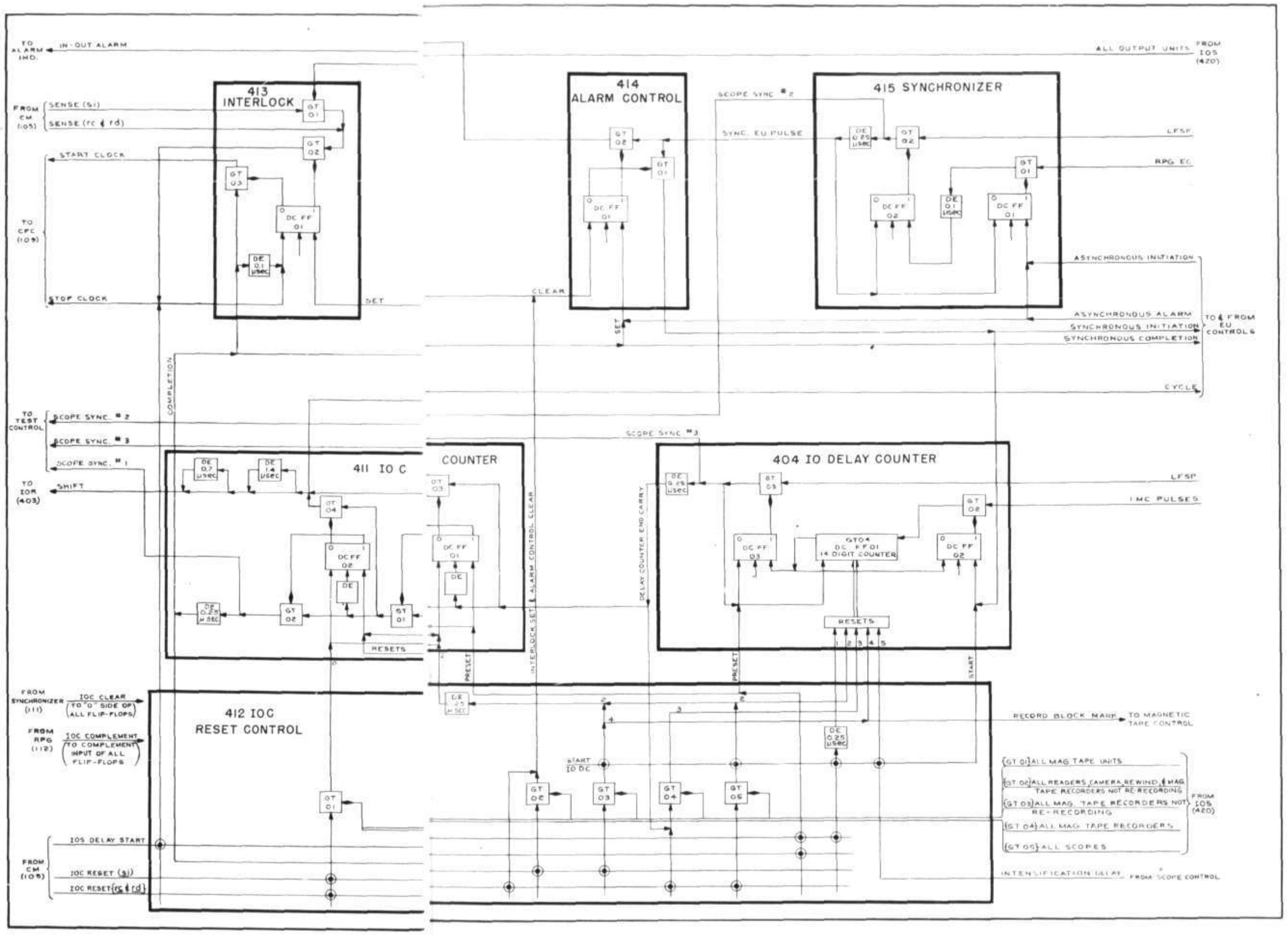


Fig. 5-1. In-Out Control

Paper-tape units will be arranged to transfer either 4-digit words or 6-digit Flexowriter code groups.

Magnetic-tape units have six channels for information: one contains previously recorded index marks which indicate lines where recording may take place; another is used for block marks which indicate the beginning of a block of information; and the other four are used for information transferred between the units and the computer. The index marks appear necessary because of blemishes on the tapes which prohibit recording in some places. Block marks are used primarily to simplify the computer's task of locating the beginning of a block of information.

The magnetic-tape units will have three modes of operation, read, record, and rerecord, and will not begin transferring information immediately. In recording, a delay is counted to form the space necessary between blocks; then a block mark is recorded automatically, and then the data recording begins. In rerecording, which is used to replace a single block on a tape with another block of new information, the tape runs until a block marker is reached; then recording begins. Reading is similar to rerecording in that the tape moves until a block mark is reached before the reading process is allowed to start. Thus the operator is assured of always starting to read or rerecord at the beginning of a block.

A discussion of the actual operation of in-out control with the various external units is given in M-1235, Operation of In-Out Control.

5.2 PHOTOELECTRIC TAPE READER

Since the writing of Summary Report 25, the photoelectric tape reader, which was described in Section 5.4 of that report, has been installed into the computer system on a test basis. The purpose of this temporary installation, which is shown in the block diagram of Fig. 5-2, is to find out whether

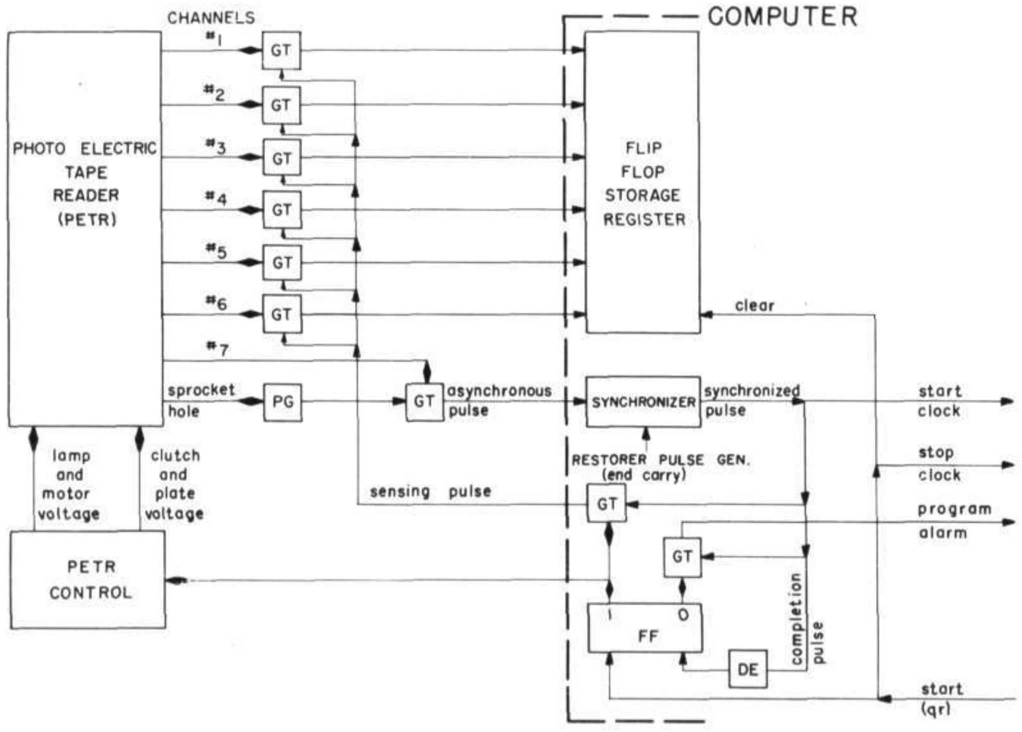


Fig. 5-2. Photoelectric Tape Reader

the reader and its associated circuits are sufficiently reliable.

The photoelectric tape reader is designed to scan standard 7-hole tape such as is prepared by Flexowriter punching equipment. The unit contains pickup phototubes for each of the seven information holes, as well as one for the sprocket-feed hole. The phototube signals are individually amplified, so that the output from the unit consists of parallel pulses appearing on eight lines.

The seventh hole position is punched in the tape to indicate the presence of a character punched in the other positions on the tape. It distinguishes between unused sections of tape and tape left purposely blank to indicate all zeros. The photoelectric tape reader makes use of the seventh-hole pulse to control a gate tube being sensed by a 0.1-microsecond pulse generated from the sprocket-feed-hole pulse. The output pulse of this gate tube, which is asynchronous with respect to the 62.5-kc restoration pulses, is synchronized; it is used to sense the gate tubes controlled by the six information pulses. The output from these six gate tubes, then, accomplishes the actual parallel transfer into the flip-flop register.

The read cycle of the unit is initiated by a qr order. A time pulse of this order sets a flip-flop which in turn starts the operation of a relay control circuit. This control circuit applies the drive motor and exciter lamp voltages within a few milliseconds, but a delay of 4 to 5 seconds follows before the amplifier plate voltage is applied and before the clutch is energized to start accelerating the tape. This delay allows the exciter lamp to reach operating temperature before it is used.

The flip-flop mentioned above also controls the distribution of the synchronized pulses resulting from a combination of seventh hole and sprocket-feed hole. Normally this synchronized pulse passes the gate tube controlled by the one side of the flip-flop and senses the gate tubes controlled by the six information pulses. Following a short delay, this synchronized pulse also sets the flip-flop back to the zero side, and the read cycle is over. If for some reason another character is read before the occurrence of the next qr order, meaning that the computer is not prepared for another word, the resulting synchronized pulse passes the gate tube on the zero side of the flip-flop and causes a program alarm which stops the computer.

When the flip-flop is set to zero, the relay that operates the clutch and controls the plate voltage starts to release, but in normal operation the qr orders occur at a fast enough rate to keep the control relays energized all the time. At the end of a reading period when the clutch relay does release, the lamp and motor voltages remain on for another 30 seconds. This delay prevents the lamp from being turned on and off unnecessarily when the reader is being used continuously. During this 30-second period the reader is in a standby state of readiness. At the end of this period a complete cycle of the reader's controls has occurred.

During the period of this temporary installation, the reader has been used continuously, but it has not been satisfactorily reliable. Because the tape is too translucent and of varying density, the noise level is very high, with occasional peaks that have sufficient amplitude to allow sensing pulses to pass the gate tubes and to be interpreted as information pulses.

At present a more opaque tape is being sought. Such a tape would increase the contrast between the tape and the hole, and would also reduce the noise level. A change in the circuit design of the reader itself may also be necessary, but the work on that has just begun and as yet nothing definite has been decided.

5.3 MAGNETIC TAPE

The five magnetic-tape drive units ordered from Raytheon Manufacturing Company have all been received along with some spare heads. Although none of the units have been operated in the computer, they seem to perform quite well as tape-handling mechanisms. It may be necessary to increase the wrap angle of the tape around the head to make for more positive contact between the head and the tape.

The work on magnetic tape is at present aimed at getting one working unit into the computer. This program has been divided into three parts: (1) electronic selection and switching of the heads, (2) elimination of noise and errors due to dust, (3) study of the problem of tape blemishes and development of a system for detecting bad spots on tape and recording index marks on the tape to indicate usable portions of the tape.

During the past quarter the problem of electronic control and selection of the read-record heads was worked on as a thesis topic. A circuit which will perform the desired functions requires a switching time of 2 milliseconds. This time is the time required for decay of the transients acting on the reading amplifier. The same transient-decay time would be required in a relay system; therefore the electronic control results in a net saving of the time required for operation of the relay, or about 10 milliseconds. Preparations are now being made for a temporary installation of one magnetic-tape unit in the computer to obtain additional data on the performance of the control and switching circuits and the tape drive unit.

The work on elimination of dust has just started. The intention is to brush and blow the dust off the tape before it passes under the head. Since the dust is attracted to the tape by static electricity, a small amount of radioactive material will be used near the head to ionize the air and allow the tape to discharge so that the dust can be removed.

The problem of blemishes on the magnetic tape is being studied by detecting the modulation, due to blemishes, of a 35-kilocycle signal recorded on the tape. Present indications are that the problems of dust and blemishes could very easily cause considerable difficulty; however, our data is by no means complete, since we have not yet tested or received some of the better tape now being manufactured, nor are our present tests refined to the point where troubles due to dust and blemishes can be distinguished from one another.

5.4 MAGNETIC DRUMS

Two proposals for magnetic-drum storage systems to be used with the Whirlwind computer have been received from the Engineering Research Associates of St. Paul, Minnesota. These proposals result from engineering discussions and plans which have been going on for the last few months to extend the usefulness of the Whirlwind system by enlarging the terminal facilities.

One drum, called the auxiliary storage drum, will be used to increase the memory of the computer. The computer will control the transfer of blocks of information between drum and electrostatic storage. These blocks will be of arbitrary length with arbitrary drum and electrostatic-storage addresses. The average block access time will be of the order of 8 milliseconds, which is half a drum revolution period. The drum capacity is about 24,000 Whirlwind registers. This system should aid materially in removing the restriction of limited storage in Whirlwind as it now stands, and should allow the solution of many more problems than are now possible.

A second drum, called the buffer storage drum, is being planned for the temporary storage of information which arrives from outside the computer at random times.

As soon as an engineering evaluation of circuits can be made, we expect to order either all or parts of these systems. It will take about a year to procure the drum storage and incorporate it into the Whirlwind system.

5.5 DISPLAY SCOPE (16-INCH)

The display system up until the second quarter has consisted of four 5-inch oscilloscopes (Dumont 304-H's). The horizontal and vertical deflection inputs are the outputs of 8-digit decoders which produce voltages proportional to the binary numbers fed in. A detailed description of the display system is given in Summary Report 20, Section 5.2, and photographs of various display programs are shown in Summary Report 21, Section 6.12, and Summary Report 22, Section 6.24.

Use of the 5-inch display oscilloscope showed the desirability of a larger display surface. Therefore, a K1048P7M magnetically-deflected tube was acquired. This tube is similar to the 16AP4 television tube with a long-persistence phosphor.

Special direct-coupled deflection amplifiers were developed for the 16-inch tube. The principles of these amplifiers are covered in a master's thesis of the MIT Electrical Engineering Department entitled A Direct-Coupled Amplifier for Magnetically Deflecting an Oscilloscope Tube submitted in January 1951 by R. L. Best.

Because the ratio of spot diameter to tube-face diameter is considerably smaller with the 16-inch magnetic tube than with the 5-inch electrostatic tube, the 16-inch tube has greater resolution of detail in the display. The smallest "step" furnished by the 8-digit decoders is larger than the possible resolution of the 16-inch tube, so that the new decoders now under construction will have 11 digits.

The 5-inch oscilloscopes must be intensified for about 50 microseconds in order that the spot may be visible for about a minute in a darkened room. Attempts to reduce the intesification time by increasing the beam current of the cathode-ray tube resulted in serious "blooming" or de-focusing of the spot. The 16-inch magnetically-deflected tube provides the same persistence with only 5 microseconds of intensification. The display may therefore be made considerably more rapid.

Three 16-inch display units are under construction in addition to the one now in use. Two will be mounted with power supplies and deflection amplifiers in wheeled cabinets which may easily be moved to any location. One tube will be mounted in an elevated position for convenient display to groups of people, and the fourth unit will be mounted in a rack with a camera semipermanently attached. The computer will control the camera shutter and the indexing of the film. A timed brightening of the edge-lighted plastic grid covering the face of the tube will also be automatically provided when desired.

6. MATHEMATICS, CODING, AND APPLICATIONS

The group working on scientific and engineering applications of the Whirlwind computer have three principal goals: (1) Development of a simple, effective organization making use of standard procedures and coded subroutines to facilitate preparation and execution of coded programs. (2) Training and assisting interested and qualified people (those who have problems to solve on the computer and those MIT students who want to learn about computing machines) to set up their own coded programs. (3) Solution of certain problems, each of which is typical of some class of problems and is therefore valuable not only in its own right but also in broadening the experience of the programmers in the group.

The procedures being used in preparing punched tapes and operating the computer were described in Section 6, especially Section 6.3, of Summary Report 25. Some of the work which is being done on development of coded subroutines, on training, and on solution of problems is described in the following paragraphs.

6.1 EXTRA-PRECISION AND FLOATING-POINT ARITHMETIC (INTERPRETIVE SUBROUTINES)

For those computations in which great precision is unnecessary and in which there are no extensive calculations that will build up roundoff errors, a short register length and a fixed-point arithmetic element are entirely satisfactory. In these cases, a short-register, fixed-point machine is much more efficient than a long-register and/or floating-point machine. But problems inevitably arise which demand more precision and a wider range of values than can be handled directly in such a machine. It then becomes imperative to have a simple method for increasing register length and for floating the radix point. In principle, it is easy to increase register length by writing a coded program in which the computer is instructed to deal with numbers which are stored in two or more parts in two or more registers. To make such programs simple to write in practice, one needs some method of using subroutines to carry out the multiple-register equivalents of the basic machine operations, as was briefly discussed in Section 6.1 of Summary Report 20.

The most promising method of those mentioned in Summary Report 20 is the one in which a subroutine is constructed in such a way that it examines and performs in multiple-register fashion a list (or program) of instructions which are written as if they were ordinary single-register instructions (subject only to a few special rules). Such a subroutine has been independently conceived and called by various names by various people. A very satisfactory name has been provided by Dr. Wilkes and his associates at Cambridge University, who have defined the term "interpretive subroutine" so as to include the subroutines in question (see page 34, Wilkes, Wheeler, and Gill, Programs for an Electronic Digital Computer, Addison Wesley Press, June, 1951).

Interpretive subroutines capable of interpreting a fairly general code of instructions, resembling quite strongly the ordinary Whirlwind I order code, have been written for performing several different forms of multiple-length arithmetic. The most promising of these, perhaps, is a double-length form in which numbers are represented in the from $x \cdot 2^y$ with x being a signed 24-binary-digit number and y a signed 6-binary-digit integer, which provides better than the equivalent of a signed 7-decimal-digit number with a floating decimal point in the range 10^{-18} to 10^{18}. These programs are being extensively tested and polished before being added to the library of subroutines now being accumulated.

6.2 NON-LINEAR DIFFERENCE EQUATIONS (STUDY OF ECONOMIC SYSTEMS)

A member of the staff of the Harvard University Department of Economics, Dr. Alan Manne, has attempted an investigation of models of several extremely simple economic systems by having Whirlwind determine the solution of the set of equations specifying each system. A typical system consisted of two industries, the output of each of which was related to the output of the other and to the capacities, or inventories, of both by the following set of recursive equations:

$$x_1(t) = \begin{cases} c_1[K_1(t) - k_1(t)] + b_1 & \text{if } K_1(t) > k_1(t) \\ b_1 & \text{if } K_1(t) \leqslant k_1(t) \end{cases}$$

$$K_1(t) = a\sum_{i=1}^{4} w_i \; x_2(t - ih)$$

$$k_1(t) = \ell\, k_1(t - h) + x_1(t - h) - b_1$$

and similarly for x_2, K_2 and k_2. The outputs x take on one of two values as determined by the relative values of the "idealized" capacities K, which depend only upon the past output of the other industry, and the ordinary capacities k. This "switching rule" is of primary importance in giving a physical interpretation to the system, for it allows the introduction of decisions based upon relative productions and inventories. For each of a number of sets of values for the parameters a, ℓ, b_i, c_i, and w_i a solution for 80 values of t was plotted on a display scope and photographed. A preliminary analysis by Dr. Manne of about a hundred such photos indicates that stable, slowly oscillating solutions do exist and can be located by the methods used. A discussion of these results and of the theory involved will be published shortly in a paper by Dr. Manne.

6.3 NON-LINEAR PARTIAL DIFFERENTIAL EQUATIONS (STUDY OF TAPE-WOUND MAGNETIC CORES)

A study of the non-linear partial differential equation

$$\frac{\partial^2 H}{\partial x^2} - \sigma \frac{\partial B}{\partial t} = 0$$

$$B = f(H)$$

with boundary conditions $H(x_0, t) = H(-x_0, t) = H_0$. $H(x,0) = 0$ (mentioned in Summary Report 24) has led to a consideration of the problem of the stability of numerical solutions. By approximating the differential equation by a 6-point difference equation, one can obtain a numerical solution that is stable but exhibits damped oscillations about the non-oscillatory true solution if the ratio $r = \Delta t/(\Delta x^2)$ is not sufficiently small. Here Δt denotes the time interval and Δx the space interval used in the numerical analysis. Since all the interest is in the transient response, these oscillations make the numerical solution of comparatively little value.

When the value of r is made small, the oscillations are eliminated, but for the practical purposes of reducing computation time and roundoff errors, r should be fairly large. In an attempt to establish criteria for choosing r, the linear case resulting when $B = \mu H$, where μ is constant, was thoroughly investigated. For this case one can determine theoretically the largest value of r that can be used and still avoid oscillations. In the linear case, explicit solutions can be obtained for both the differential equation and the corresponding 6-point difference equation; and the two solutions were tabulated for various values of r on Whirlwind and compared to check the accuracy of the theoretical criteria. The solution of the difference equation was also obtained by a direct numerical procedure using a Gauss-Seidel type iteration and checked against the direct evaluation of the explicit expression for the solution. These criteria are now being applied to the non-linear case.

6.4 TRANSCENDENTAL EQUATIONS (OPTICAL CONSTANTS OF THIN METAL DEPOSITS)

Several programs have been written and are being tried out in connection with the study commenced some time ago (see Section 6.12 of Summary Report 24) by Dr. A. L. Loeb in the MIT Department of Chemistry on an ONR contract. In this problem, the reflection and transmission ratios of thin metal deposits have been determined empirically as a function of wave length, especially in the infra-red region. The optical constants (that is, the index of refraction and the coefficient of absorption) are to be calculated from these. Since the reflection and transmission ratios are transcendental functions of the optical constants, the problem requires repeated evaluation of the transcendental functions for various sets of assumed values of the optical constants until the calculated values of reflection and transmission ratios agree with the measured ones.

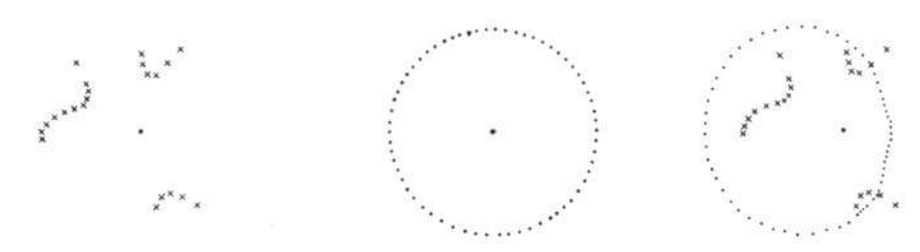
6.5 COMBINATORICS (UHF TV CHANNEL ALLOCATION)

A combinatorial problem of some importance has been suggested by members of the Research Division of the Allen B. Du Mont Laboratories. The problem consists in establishing the optimum assignment of the soon-to-be-opened UHF television channels (numbers 14 through 65) to the various cities in the country. The problem from the computational point of view comes from the interferences between various channels; it can be condensed into the following statement.

Given the coordinates of N proposed transmitter sites, the problem is to assign one channel to each of them, obeying the rule that a given channel number, n, cannot be assigned to a given site unless the distances from that site to any sites at which channels n, $n \pm 1$, $n \pm 7$, $n \pm 8$, $n \pm 14$, and $n \pm 15$ are already assigned are greater than 155, 65, 60, 20, 60, and 75 miles respectively. A direct procedure of trying all possible combinations in a certain order was programmed and tried for the New England area alone, but was abandoned (as expected) after $2\frac{1}{2}$ hours of computation (5 million trials) gave little success. In a slightly subtler approach, if no channel can be assigned to a certain site but if only one conflict (a so-called "tilt") prevents the assignment of channel n to that site, the assignment of n is made and the assignment that caused the tilt is changed by the same procedure. This program has worked for small regions but must wait for more storage to be available before it can be given a real test on a large region.

6.6 TRIGONOMETRY (TWO-TOWER-ANTENNA RADIATION PATTERN)

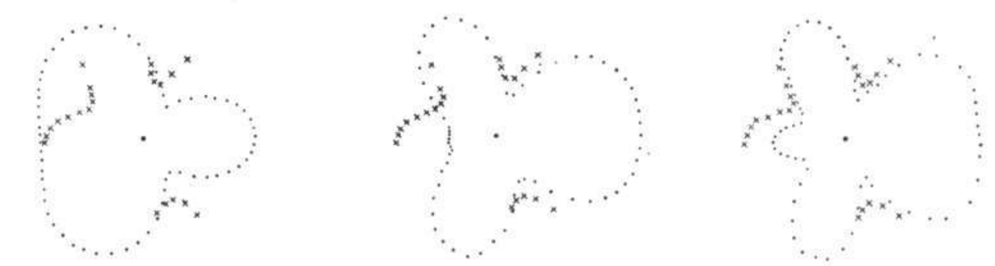
In connection with a new subject, Practice in the Use of Digital Computers, given in the Electrical Engineering Department in the Spring Term, 1951, students each worked out an original program and performed it on the Whirlwind Computer. An undergraduate in the Physics Department, who had been an antenna designer, programmed the computer to calculate the radiation pattern from a two-tower antenna for given values of the physical separation of the two towers, the relative phase of the signals at the two towers, and the relative amplitude of the signals of the two towers. He furthermore arranged his program to vary one or more of these parameters, while keeping the radiated power constant, in order to meet specifications of maximum and minimum radiation in certain directions. In this way the computer was programmed to design a two-tower antenna meeting any reasonable set of requirements. (These requirements arise in practice in building a new transmitter either because it is necessary not to radiate much power towards another transmitter operating on the same or an adjacent frequency or because it is undesirable to radiate power toward an unpopulated region.) As the field strength in each direction was calculated by the computer, its value was plotted on a display oscilloscope along with the conditions to be met, so that the results for each set of parameters could be watched as they converged to the desired solution. The results, as calculated and plotted by the computer for a few values of the parameters, are shown in Fig. 6-1. The method can of course be generalized to



a) The Restrictions: Field strength in the indicated directions is not to exceed the indicated amounts, unrestricted where unmarked.

b) The Unrestricted Radiation Pattern: With relative amplitudes and phases equal, amplitude chosen to radiate specified power, and with tower spacing equal to zero.

c) With spacing increased to 100 yards, some restrictions have been met.



d) With spacing of 200 yards.

e) With spacing of 300 yards.

f) With spacing of 348.9 yards, the required solution is obtained.

Fig. 6-1. Design of a Two-Tower Antenna.
(Sketched from photographs of results calculated and plotted by WWI.)

more than two towers, but in that case the number of parameters becomes quite large and the design problem is a more delicate one.

6.7 OTHER PROBLEMS SOLVED BY MIT STUDENTS

Other students in the Practice in the Use of Digital Computers have prepared and successfully operated additional interesting programs. For example, a Mathematics undergraduate, whose SB thesis involved a study of roundoff errors in numerical computation, programmed the solution of a simple differential equation ($y'' + y = 0$) using a randomized roundoff procedure, and compared results with those obtained by using the normal, built-in roundoff procedure (in the built-in procedure, roundoff is performed by adding $\frac{1}{2}$ to the last place, while in the random procedure, a "random" number between 0 and 1 is added instead). His results confirm previous results obtained elsewhere that ordinary roundoff is not always random and that a truly random procedure, even though it has a larger variance, is frequently better (see D. G. Aronson, An Analysis, of the Accumulation of Errors in Numerical Quadrature and Integration, SB thesis in Math., MIT, 1951).

An Electrical Engineering graduate student has been working on an SM thesis concerned with prediction by Wiener-Lee Theory of the angle of pitch of an aircraft acted upon by atmospheric turbulence. To test the theory, the autocorrelation function of some actual empirical data was obtained, and the predicted results checked against the actual data by means of a program written for the Whirlwind computer (see L. S. Bensky, The Prediction of Atmospheric Turbulence, SM Thesis in EE, MIT, 1951.)

Another EE graduate student has carried out an integration of the equation $y'' + y = 0$ by a 9-point formula which he had derived for an SB thesis. The results were calculated with double precision (i. e., to nine decimal places) and were checked against tabulated values of sine x. The agreement was good.

6.8 NUMERICAL QUADRATURE (INTACT STABILITY STUDY)

The various integrations of volumes and moments of volumes required in routine intact stability studies as performed by the Bureau of Ships were programmed for the Whirlwind computer as an SM thesis in 1949, before the computer was in operation (see page 20 of Summary Report 16 and the thesis report itself, R-156). This program is being revised and corrected preparatory to actually performing it on the computer in the near future.

6.9 20,000 MULTIPLICATIONS (AUTOCORRELATION COEFFICIENTS)

Ten correlation coefficients obtained from 2000 pieces of data were needed by members of the MIT Department of Meteorology. The calculation, using trapezoidal integration, involves the accumulation of 10 sums of 2000 products. Programming the problem required less than 45 minutes, preparing a punched tape with the 2000 pieces of data less than 60 minutes, preparing the program tape less than 10 minutes, reading the program and numbers into the machine less than 5 minutes (which could have been reduced by using the photoelectric tape reader), and performing the calculation less than 30 seconds (which could have been reduced by a more efficient program). The 2 hours from start to finish compares favorably with an estimated 8 hours on IBM equipment or about 35 hours by hand.

6.10 OTHER PROBLEMS BEING UNDERTAKEN

Prof. W. P. Allis of the MIT Physics Department has suggested a problem in ambipolar diffusion. The diffusion of electrons and ions in a plasma in the presence of space charge leads to two coupled second-order, second-degree differential equations. Compatible values of electron and ion concentrations are sought. The problem is being programmed for the Whirlwind computer by associates of Prof. Allis with the aid of a member of this Laboratory.

Mr. Claude Brenner, working in Aero-Elastic and Structures Research Laboratory at MIT on Bureau of Aeronautics contract NOas51-183-c, is planning to begin work on the solution of a pair of simultaneous integro-differential equations for each of a number of sets of values of parameters. He will also program the problem himself with the aid of a member of this Laboratory.

6.11 REVISIONS IN THE WHIRLWIND ORDER CODE

Summary Report 21 (Fourth Quarter, 1949) contained a tabulation of the Whirlwind I order code, and Summary Report 22 carried some additions to the order code. Revisions that have been made in the original code are presented in the following table.

REVISIONS IN THE WHIRLWIND I ORDER CODE

October, 1949 through May, 1951

Order	Operation Name	Code Dec.	Code Binary	Function
A. Permanent addition to the Code:				
ck x	check	11	01011	Stop the computer and ring an alarm if contents of register x is not identical with contents of AC; otherwise proceed to next order.
B. Minor changes not affecting previous functions of certain orders:				
sa x	special add	21	10101	Add contents of register x to contents of AC, storing result in AC and retaining any overflow for the next ca, cs, or cm. Only orders 1 through 15, 23, 30, and 31 may be used between sa and the ca, cs, or cm for which the sa is a preparation. Use of any other operation between sa and ca, cs, or cm will result in the overflow being lost completely, with no other effect on the normal function of the intervening operation.
sl*n	shift left without roundoff	27	11011	Multiply contents of AC and BR by 2^n, as in sl n, but do not roundoff nor clear BR.
sr*n	shift right without roundoff	28	11100	Multiply contents of AC and BR by 2^{-n}, as in sr n, but do not roundoff nor clear BR.
C. Temporary order likely to become permanent:				
qe x	exchange	13	01101	Exchange contents of AC with contents of register x (original contents of AC to register x, original contents of register x to AC).
D. Major changes in the order code:				
rs--	(remote unit) stop	1	00001	To be discontinued: at present it has the temporary function of stopping the computer.
rf k	run forward	2	00010	Discontinued. Replaced by operation si (described below).
rb k	run backward	3	00011	Discontinued. Replaced by operation si (described below).
E. Tentative new order (not yet completely defined):				
si k	select in-out unit			Select the particular piece of terminal equipment (with mode and direction of operation, if necessary) specified by the address.
F. Present temporary orders (to be discontinued when replaced by the more general si, rd and rc operations):				
qh x	h-axis set	6	00110	Transfer contents of AC to register x; set the horizontal position of all display scope beams to correspond to the numerical value of the contents of AC.
qd x	D-scopes display	7	00111	Transfer contents of AC to register x; set the vertical position of the beams of the display scopes to correspond to the numerical value of the contents of AC; display (by intensifying) a spot on the face of the D-display scopes.
qf x	F-scope display	23	10111	Same as operation qd, except display a spot on the face of the F-display scopes.
qr n	read/ shift right	30	11110	Perform two logically distinct functions: 1) Cause the photoelectric tape input reader to read the next character containing a hole in position 7 from tape into digits 0 through 5 of FF Register #3 (holes or no holes in tape positions 1 to 6 becoming ones or zeros in digit columns 0 to 5 respectively). 2) Shift the contents of AC and BR to the right n times. The sign digit is shifted like any other digit and zeros are introduced into the left end. (no roundoff, no BR clear, no sign control). Note: If more than 3 milliseconds (= about 60 orders) elapses between one qr and the next, the reader stops. This must not happen except where 3" of blank tape has been provided for the purpose.
qr*n				Same as qr n above, except the mechanical tape reader, rather than the photoelectric tape reader, is caused to read. The mechanical reader can read line-by-line (i.e. no blank tape is required at places where the reader is allowed to stop).
qp n	punch/ shift right	31	11111	Perform two logically distinct functions: 1) Cause the paper tape output equipment (punch or printer or both, depending on the settings of the switches) to record one character with holes or no holes in positions 1 to 6 on tape corresponding respectively to ones or zeros in digit columns 10 through 15 of AC, and with a hole in position 7. 2) Shift right as in operation qr.
qp*n				Same as qp n above, except no hole is put in position 7.
qs n	index camera	12	01100	Perform two logically distinct functions: 1) Move the next frame of film into place in the display scope camera and open the shutter if it is not already open. The shutter is closed manually when the film is removed for developing. 2) Shift right as in operation qr.

*The fact that the six largest binary digits of the address section of orders sl n, sr n, qr n and qp n are normally zero (and in any case are disregarded by the step counter which counts the shifts) is exploited to permit the addition of an extra variant, as described, to each of the orders mentioned. The star (*) in sl*n, sr*n, qr*n, and qp*n implies that digit 6 (the 2^9 = 512 digit of the address) will be a one, while in sl n, etc., with no star, digit 6 is to be a zero. This can be accomplished during preparation of tape by typing sl (800 + n) for sl*n.

7. ACADEMIC PROGRAM IN AUTOMATIC COMPUTATION AND NUMERICAL ANALYSIS

As described in Summary Reports 23, 24, and 25, the Electrical Engineering Department at MIT offered an integrated graduate-school program in Automatic Computation and Numerical Analysis during the 1950-51 academic year. The subjects that made up this program, as listed in the above Summary Reports and also in the MIT catalogue, were:

Subject	Number
Numerical Analysis	6.531
Seminar in Numerical Analysis	6.533
Introduction to Digital Computer Coding and Logic	6.535
Control Systems Employing Two-Valued Elements	6.567
Numerical Analysis	6.532
Laboratory in Numerical Analysis	6.534
Machine Computation	6.536
Electronic Computation Laboratory	6.538
Practice in Use of Digital Computer	6.68

Registration of students during 1950-51 indicated an active interest in these subjects. It is currently planned to offer essentially the same program in the 1951-52 academic year.

8. APPENDIX

8.1 REPORTS AND PUBLICATIONS

Project Whirlwind technical reports and memorandums are routinely distributed to only a restricted group who are known to have a particular interest in the Project. Other people who need information on specific phases of the work may obtain copies of individual reports by making requests to John C.Proctor, Servomechanisms Laboratory, 211 Massachusetts Avenue, Cambridge 39, Massachusetts.

The following reports and memorandums were among those issued during the second quarter of 1951.

No.	Title	No. of Pages	Date	Author
SR-24	Summary Report No. 24, Third Quarter, 1950	24		
SR-25	Summary Report No. 25, Fourth Quarter, 1950 and First Quarter, 1951	34		
R-195	Initial Testing of a Computer Electrostatic Storage System (M. S. Thesis Report. Abstract in E-405)	63	4-23-51	R. W. Read
R-196	Programming for Whirlwind I	61	6-11-51	H. Saxenian
E-394	Built-In Checking of Control Switch and Operation Matrix	6	12-22-50	H. L. Ziegler
E-402	Circuitry, Relay Timing, and Operation of WWI Tape Output Equipment	11	4-10-51	J. S. Hanson
E-404	Plan for the Second Bank of Storage	7	4- 4-51	R. W. Read
E-406	Preliminary Tests on the Four-Core Magnetic-Memory Array	11	6-18-51	W. N. Papian
M-1194	Equipment Proposal for Programmed Marginal Checking (PMC)	7	4- 4-51	C. W. Watt
M-1198	Preparation of Punched Tape for Conversion	3	4-17-51	P. A. Fox
M-1216	Procedures for Processing and Recording Punched Tape Computer Programs	10	5-17-51	D. E. Lenihan P. A. Fox
M-1217	Conversion Tables	11	6-11-51	J. Frankovich F. Helwig
M-1224	A Proposed Marginal Checking System	3	6- 6-51	R. E. Hunt
M-1226	Additions to Project Reports of Current Interest, Report R-173-1	3	6- 8-51	
M-1232	The Photoelectric Conversion Program	1+	6-22-51	J. T. Gilmore

8.2 VISITORS

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

Admiral G. F. Yoran, Captain Ernest L. Johnson, Mr. E. T. Cook, and Mr. R. M. Whittemore of the Bureau of Supplies and Accounts, and Mr. James Rutterberg and Mr. Charles E. Bishop of the U. S. Navy.

Mr. Roger W. Slinkman and Mr. Charles F. Douglass of Sylvania Electric Products, Inc., and Mr. Robert K. Lyons of Burroughs Adding Machine Company, who discussed the results of test on the newly developed SR1407 vacuum tube.

Dr. Jan Rajchman of RCA, discussing three-dimensional information storage using magnetic cores.

Dr. John von Neumann of the Institute for Advanced Study.

Dr. W. A. Bruce of Carter Oil Company.

Dr. A. Wang of the Computation Laboratory, Harvard University, who discussed static magnetic delay lines.

Mr. A. V. Haeff of Hughes Aircraft Company, who was interested in storage tubes.

Mr. J. L. Hill and Mr. J. P. Jones of Engineering Research Associates, who discussed the design and application of magnetic drums.

Mr. D. H. Clewell, Assistant Director, and Mr. Julius Aronofsky of Magnolin Petroleum Company, who were interested in setting up a problem on WWI.

Mr. R. P. Wakeman of Allen B. DuMont Labs, Inc., who investigated the use of WWI for the allocation of TV channels.

Dr. M. V. Juncosa and Mr. J. V. Holberton from Aberdeen Proving Grounds.

Mr. B. M. Beins and Mr. M. V. Long of Shell Development Company, who were interested in the use of a computer for process control and the solution of systems of simultaneous partial differential equations.

Mr. W. H. Reid of IBM, to discuss magnetic-core storage.

Dr. Harry H. Goode of the University of Michigan.

Dr. A. H. Taub, Mr. R. I. Hulsizer, Mr. Nelson Wax, and Mr. S. W. Sherwin, of the University of Illinois, interested in computer reliability and checking.