PROJECT WHIRLWIND

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FOREWORD

Project Whirlwind

Project Whirlwind at the Massachusetts Institute of Technology Digital Computer Laboratory is sponsored by the Office of Naval Research under Contract N5ori60 and the United States Air Force under Contract AF19(122)-458. 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 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 initially had a capacity of 4096 binary digits, sufficient for some actual problems and for preliminary investigations in most fields of interest. This capacity is being gradually increased toward the design figure of 32, 768 digits. Present speed of the computer is 20, 000 single-address operations per second, equivalent to about 6000 multiplications per second. This speed 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.

1. QUARTERLY REVIEW (AND ABSTRACT)

A second bank of storage tubes -- which operate at a density of 32 x 32 spots -- was installed and tested during the fourth quarter of 1951, bringing the computer essentially to its original design specifications. Work on the second bank restricted the applications time to about 15-20 hours per week during much of the quarter, but during these hours the computer was about 90% reliable. With completion of the installation and testing of Bank B, the computer now becomes available for more extensive use by the applications group.

The new bank of storage tubes adds 1024 registers of high-speed storage to the 256 registers previously available, and opens up new fields of applications for the computer. A system of "programmed arithmetic," using a number of interpretive subroutines, is being developed to permit the computer to solve problems that involve numbers or precision outside its built-in limits. An example of one extra-precision floating-point subroutine is given in Section 6. Also described in Section 6 are four of the more important problems being attacked by the applications group:

1. Non-linear parabolic partial differential equations (a study of magnetic flux density)
2. Transcendental equations (optical constants of thin metal deposits)
3. Boolean matrix multiplications (group intercommunication experiments)
4. Approximation of curves by a sequence of unit differences (instructions for a digitally controlled milling machine).

A thesis study of the application of digital computers to the task of high-speed information searching indicates that a special-purpose machine would probably be more suitable than a general-purpose machine such as Whirlwind I.

A series of seminars on computing-machine methods is being held. Members of the MIT faculty and other outsiders are invited to attend.

The interim magnetic-tape input-output equipment has been used and tested successfully with the computer, but it is not yet available for general use.

A summary of vacuum-tube failures for the year shows that only 22 of them interrupted operation of the computer. Thus the preventive-maintenance program is proving highly effective. Installation of programmed marginal checking, now under way, will improve it even further. Failure rates for vacuum tubes were below those for 1950.

The annual summary of crystal failures indicates that the 1950 rate of 1 percent per thousand hours has been halved in 1951. Replacement of miscellaneous components remained at the 1950 figure of 0.02 percent per thousand hours.

The three-dimensional magnetic-core memory has been proved practicable by successful operation of a 16 x 16 array of metallic cores. Information has been written, read, and rewritten in the array at a 40-kc rate, and cycled through the array at a lower rate. The array has operated without error for several hours at a time.

A 16 x 16 array of ferrite cores has been constructed, and circuits for controlling it are being developed. A 2 x 4 section of the array has been in operation with access times of about a microsecond.

Ferroelectric materials so far tested for their suitability in storage arrays appear to be on the borderline.

In a study of the application of transistors to computer circuits, a blocking oscillator incorporating transistors operated successfully at repetition rates of 0.8 megacycle per second with 0.4-microsecond pulses. Indications are that transistors have many advantages for use in computer circuits, and that with further improvement they will become important components in computer design.

The 300-series storage tubes in Bank A of the computer have operated reliably although 9 tubes were replaced during the quarter at an average life of 1640 hours. Of the 17 tubes now in this bank, the average service is 1275 hours, with a maximum of 3590 hours.

The 400-series tubes operating at 1024 spots in Bank B have performed successfully, although their margins are lower than those of the tubes operating at 256 spots. At the end of the period the bank was being used for about 80% of the applications programs, and the 16 tubes had been in use an average of 735 hours.

Two magnetic-drum storage systems are being constructed by Engineering Research Associates for use with the computer. One of these will be used as a large-capacity storage system to supplement the high-speed electrostatic storage in the computer. Its 24, 576 16-digit registers will store both numerical data and computer subprograms. The other, known as the buffer-storage drum, will be used for temporary storage of data which is being communicated between the computer and certain special types of terminal equipment. Present schedules call for shipment of the drums late in 1952.

2. SYSTEM ENGINEERING

With the second bank of storage tubes completely installed and tested, the Whirlwind I computer has about fulfilled its original specifications. The addition of the second bank of tubes, operating reliably at a 32 x 32 density, has quintupled the former high-speed storage capacity of the computer. This achievement has opened up the field of computer applications considerably, with the current availability of 1280 registers of high-speed electrostatic storage (Bank A at 16 x 16 and Bank B at 32 x 32) and the prospective availability of 2048 registers (both banks at 32 x 32). More hours of computer time will be available to application groups during the next quarter.

2.1 RELIABILITY AND CHECKING

The computer has been about 90% reliable during the relatively few hours a week (15 to 20) recently assigned to applications time. With the present excellent reliability of electrostatic storage, programmed marginal checking is being integrated into the computer marginal-checking system. With its program stored in electrostatic storage, the checking system will be much more convenient than it is at present. It will be capable of checking many control and operation lines with a variety of programs.

A new automatic control for the marginal-checking system is planned to improve its reliability. The ball-disk integrator will be replaced with a one-shot clutch of the type used in the Flexowriter unit.

The possibility of writing programs to have the computer locate its own troubles has been assayed. On the basis of results with a few trouble-location programs, further investigations will be made of this technique.

2.2 INSTALLATION OF BANK B STORAGE

The installation of the second bank of storage tubes (Bank B), the evolution of new testing methods for it, and the maintenance of the first bank of tubes (Bank A) required approximately forty hours a week during the past quarter. Installation of Bank B was carried out smoothly and according to schedule; no major difficulties were encountered. Currently, programs written for no more than 320 registers can be run in either bank interchangeably.

New tests and lineup procedures were devised in the process of realizing the 32 x 32 operating density of the 400-series storage tubes in Bank B. A program was written which fits into test storage and provides several modes of testing. Marginal-checking techniques were then adapted for optimizing the operating settings of storage-tube gate amplitudes. Exhaustive tests with Bank B led to more rigorous test specifications for Bank A (which had already, of course, been operating reliably at 16 x 20 density for some months).

Work has just been resumed on the ES parity-check system for detecting electrostatic-storage information errors (see Sec. 2.2 of Summary Report 26). All cabling and equipment have been installed for Bank A; only the storage tube is lacking in Bank B. Timing and pulse amplitudes are now being checked prior to putting the parity-check system into operation.

2.3 INPUT-OUTPUT

The interim magnetic-tape equipment has been used and tested successfully with the computer on numerous occasions. However, it is not yet available for general use by the applications group.

With the exception of the in-out delay counter, which already has been operating with the special display orders, the rest of the input-output system is getting under way. The d-c coupled special display decoders with plug-in flip-flop units are being installed. The in-out switch, the d-c in-out register, and the overall in-out control are in the process of construction, and the design of the final relay system for tying in the Flexowriter equipment has been begun.

2.4 POWER SUPPLIES

Two new voltages are being planned for the WWI power system. A projected change in the program register and check register will involve the use of d-c coupled flip-flops. To drive the plates of these flip-flops, +50 volts at 5 amperes is being installed. For the new Burroughs test equipment, +300 volts at 5 amperes will be supplied.

3. CIRCUITS AND COMPONENTS

3.1 VACUUM-TUBE LIFE

3.11 WWI Computer

The maintenance records on the WWI Computer for the past year have been reviewed to obtain a picture of the effects of tube failures on system reliability. The failures were analyzed as to type; in addition, they were separated into two groups -- those that interrupted useful operation of the computer and those that were found as a result of routine preventive maintenance.

Failures that occur while the computer is being used in application studies are of the greatest concern, since they directly affect the reliability of the computer. Failures found by preventive maintenance also are of interest, since a large number of such failures might require increased scheduled maintenance and would imply a greater number of potential interrupting failures.

The data obtained are summarized in Figs. 3-1, 3-2, and 3-3. Those for types 7AD7 and 7AK7 are listed separately in Figs. 3-1 and 3-2, while those for all other types including tubes in the power supplies are combined in Fig. 3-3. The data show that only a very small proportion of the failures caused interruption of computer operation. Of the 22 such failures listed in the three charts, 16 were from shorts or opens, defects which would not manifest themselves so that they could have been found before the failure occurred. This signifies that the maintenance schedules in use are effective in minimizing the number of shutdowns resulting from tube failures.

TYPE FAILURE		INTERRUPTING	NON-INTERRUPTING		TOTAL
			MARG CHECK	OTHER CHECK	
LOW PLATE CURRENT		2	78	48	128
CHANGE IN CUTOFF				2	2
SHORTS	COMPLETE	3	53	13	69
	TAP	5	37	25	67
GAS OR LEAKS			6	3	9
ACCIDENTAL DAMAGE				20	20
TOTALS		10	174	111	295

NUMBER OF 7AD7'S IN USE 2175

CLOCK READING
JAN 1, 1951 5529.4 FIL HOURS
DEC 31, 1951 9500.9 FIL HOURS

Fig. 3-1. 7AD7 Tube Failures in WWI During 1951

TYPE FAILURE		INTERRUPTING	NON-INTERRUPTING		TOTAL
			MARG CHECK	OTHER CHECK	
CHANGE IN CUTOFF				2	2
SHORTS	COMPLETE	1	1	6	8
	TAP	1	1	5	7
OPEN					
GAS OR LEAKS			1		1
ACCIDENTAL DAMAGE				3	3
TOTALS		2	3	16	21

NUMBER OF 7AK7'S IN USE 1720

CLOCK READING
JAN 1, 1951 5529.4 FIL HOURS
DEC 31, 1951 9500.9 FIL HOURS

Fig. 3-2. 7AK7 Tube Failures in WWI During 1951

TYPE FAILURE		INTERRUPTING	NON-INTERRUPTING		TOTAL
			MARG CHECK	OTHER CHECK	
CHANGE IN CHAR	LOW PLATE CURRENT	3	8	77	88
	OTHER	1		17	18
SHORTS	COMPLETE	1	1	7	9
	TAP	2		24	26
OPEN		3		9	12
GAS OR LEAKS				11	11
ACCIDENTAL DAMAGE				15	15
TOTALS		10	9	160	179

NUMBER OF TUBES IN USE 2155

CLOCK READING
JAN 1, 1951 5529.4 FIL HOURS
DEC 31, 1951 9500.9 FIL HOURS

Fig. 3-3. Miscellaneous Type Tube Failures in WWI During 1951

The number of defective tubes found by marginal checking as compared to the number of those found by other checking methods should not be taken as a measure of the effectiveness of the marginal-checking facilities, particularly in the case of miscellaneous types, which include many tubes to which marginal checking is not applied.

It is significant to compare the data for the 7AD7's and 7AK7's with similar summaries for the year 1950 which were published in Summary Report 25. During 1951 both the number of tubes in use and the length of time equipment was in operation increased about 30 percent over the 1950 figures. The number of failures increased only about 20 percent for 7AD7's and 15 percent for the 7AK7's. This implies lower failure rates for 1951, but the analysis is not sufficiently complete to be conclusive.

The number of failures during 1951 among the miscellaneous types is about double that for 1950. However, the number of tubes reported on is also about doubled, so that no significant changes in performance of these tubes can be deduced.

For all three groups of tubes, the ratios of interrupting failures to non-interrupting failures are smaller for 1951 than for 1950. This is a very desirable trend which it is hoped will continue and become an established fact as more data are obtained.

A chart of the tube failures which occurred during the past quarter is given in Fig. 3-4.

Type	Total in Service	Hours at Failure	Reason for Failure; Number failed			
			Change in Characteristics	Mechanical	Burn-out	Gassy
7AD7	2100	0-1000	8	3		1
		1000-2000		1		
		2000-3000	2	1		
		3000-4000	4	3		
		4000-5000	4	2		
		5000-6000	2			
		6000-7000	4	3		
		7000-8000	9	3		
		8000-9000	4	3		1
		9000-10000	1			
7AK7	1700	1000-2000		1		
		2000-3000		1		
		5000-6000		1		
		6000-7000	1	1		
		7000-8000		1		
		8000-9000	1			
6AK5	200	0-1000				1
		1000-2000		2		
		4000-5000	3	2		
6AS7	80	0-1000	12			
6SN7	400	5000-6000	1	1		
		6000-7000	3			
		7000-8000	2			
		8000-9000	1			
6L6	80	0-1000	1			
		1000-2000	2			
		2000-3000		1		
		6000-7000	1			
6J5	9	3000-4000		1		
6AL5	180	2000-3000	1			
		3000-4000	2	1		
		4000-5000	2			
6AG7	120	4000-5000	1			
6X4	9	0-1000		1		
6AN5	20	6000-7000	1			
		7000-8000		1		
6V6	50	8000-9000	1			
2C51	20	8000-9000			1	
0A2	4	8000-9000	1			
715B	20	5000-6000				1
3E29	160	0-1000	2			2
		3000-4000	1			
		6000-7000	1			
		7000-8000	1			
		8000-9000	4			
3D21A	3	4000-5000	1			
2C53/M1060	1	4000-5000	1			
5U4G	24	0-1000	2			
ELC16J	12	4000-5000	1			

Fig. 3-4. Tube Failures in WWI
October 1 - December 31, 1951

3.12 Life Tests

Only two life-test studies of vacuum tubes have been active in the past quarter, both of them primarily concerned with the resistance of cathode interface layers formed in some vacuum tubes. The properties of interface resistance and the troubles it may cause are described in Reports R-139 and R-179.

A life-test study of the SR1407, which is a video power pentode designed to replace the 7AD7 in computer service, has now run some 4000 hours. This test has demonstrated that the SR1407 will not develop troublesome interface resistance in normal operation. Although some interface resistance can be measured at low heater voltages (10 ohms, 4.5 volts E_f), the interface resistance is below measurable levels at rated heater voltage (less then 2 ohms, 6.3 volts E_f).

Another life-test study has been made using 6AG7 tubes to investigate rate of change of interface resistance with time. Tubes of two manufacturers were used; they were operated with no cathode current for a period of 1000 hours at normal heater voltage (E_f = 6.3 volts). Interface resistance was read at 50, 100, 200, 500, and 1000 hours, at heater voltages of 3.5, 4.5, and 6.3 volts. The tubes of only one manufacturer developed interface resistance. At 1000 hours, the average interface resistances of those tubes developing interface resistance was 84 ohms, when read at a heater voltage of 6.3 volts. It was found that interface resistance increased initially about as the square of the time. However, from 500 to 1000 hours the increase was approximately linear with time.

In addition to these life-test studies, two lots of tubes were tested for manufacturers to assist them in their research programs. Fifteen 6SN7GT tubes were tested for Sylvania Electric Products, Inc., to assist in setting up test equipment to read interface resistance. Forty-six standard diodes were tested for the Raytheon Manufacturing Company, where a study of materials used in oxide cathodes is being made.

A new and improved method for determining cathode interface resistance has been devised. A "complementary" network is inserted in the cathode lead of the tube under test while it is being operated in a transconductance bridge. When the transconductance bridge is excited with a square wave, it is possible to minimize the error waveform as observed on an oscilloscope by adjusting the network and bridge simultaneously. When a null is reached, the network is the exact complement (in a network theory sense) of the interface impedance. This material will be issued in an R-series report during the next quarter and will be presented before the IRE convention in New York on March 6, 1952.

3.2 COMPONENT REPLACEMENTS IN WWI

3.21 Crystal Rectifiers

Experience with crystal rectifiers in Whirlwind I during the past year has been very good. Fig. 3-5 is intended to give general information; it should not be used critically to analyze crystal performance. The total of 11,400 crystals is a conservative estimate; the 220 failures, however, are exact and represent a failure rate of about 0.5 percent of all crystals in use per thousand hours of operation. A comparison of total failures during 1951 with those of 1950 shows a decrease of 124, or 0.5 percent per thousand hours. This decrease is noteworthy, as the 1950 failure rate was only 1 percent per thousand hours.

TYPE CRYSTAL	NUMBER IN USE	FAILURES		FAILURES LOCATED BY	
		NUMBER	% OF NUMBER IN USE	MARGINAL CHECKING	OTHER CHECKING
D-357 (1N34A)	7500	66	0.9	53	13
D-358 (1N38A)	3500	154	4.4	115	39
D-359 (1N56A)	400	0			
TOTAL	11,400	220	1.9	168	52

CLOCK READING
JAN 1, 1951 5186.4 HOURS
DEC 31, 1951 9024.1 HOURS

Fig. 3-5. Failures of Crystal Rectifiers in WWI During 1951

During both years, most of the crystals which failed were D-358's. This type is used in flip-flop clamp circuits, where a back resistance of at least 0.5 megohm is essential. The 154 failures of these crystals for 1951 represents a decrease of 124 from the 1950 figure. Two reasons can be given for this decrease: (1) improved, glass-envelope crystals, 1N38A's, are being used as replacements; (2) rigorous tests for detecting drift are now given to all crystals prior to installation.

An improvement in the performance of clamp crystals can be expected for 1952, since more D-358's will be replaced by 1N38A's. The good job being done by marginal checking and other preventive-maintenance procedures in spotting poor crystals also assures that interruptions due to crystal failures will be unlikely.

3.22 Other Components

The total number of component replacements during 1951, other than vacuum-tube and crystal replacements, was 47. Figure 3-6 summarizes the number of failures for different types of components. (It should be noted that the total number at the bottom of the first column represents not the total number of components in WWI, but only those types of components in which some failures occurred.) The percentage of failures per thousand hours for these miscellaneous components is approximately 0.02, the same figure as for 1950.

COMPONENT	NUMBER IN USE	NO. OF FAILURES
CAPACITORS	21,107	11
CHOKES	3,989	2
RESISTORS	26,210	19
PULSE TRANSFORMERS	3,425	11
DELAY LINES	143	1
TOGGLE SWITCHES	544	3
TOTAL	55,418	47

CLOCK READING
JAN 1, 1951 5186.4 HOURS
DEC 31, 1951 9024.1 HOURS

Fig. 3-6. Failures of Other Components in WWI During 1951

A chart of component replacements during the past quarter is given in Fig. 3-7.

3.3 FERROMAGNETIC AND FERROELECTRIC CORES

Summary Reports 24 through 27 contained discussions of (1) a scheme for storing digital information in a three-dimensional array of magnetic cores, (2) the results of research work on the individual cores, (3) experimental operation of a 4-core array, (4) an extension of the original scheme which results in improved speeds and signal ratios, (5) design and construction of two 256-core memory arrays, (6) a magnetic-core matrix switch for selecting/driving one of the arrays, and (7) some work on ferroelectric-slab storage and on Harvard-type stepping registers.

The following paragraphs discuss activity during the last quarter, including (1) experimental operation of the 256-core metallic array, (2) partial results of the work on the ceramic array and matrix switch, (3) early experimental results on ferroelectric-slab storage, and (4) new materials, testing, and measurement.

3.31 16 x 16 Metallic Array

A fair demonstration of the practicability of the three-dimensional magnetic-core memory scheme has been given by recent successful operation of the 16 x 16 metallic array. (Fig. 3-8 is a photograph of the array proper.)

An arbitrary information pattern has been put into the array. The information in each successive core has been read and rewritten at a 40-kc rate, giving an array-scanning frequency of about 160 cps. The switching time of each core was about 10 microseconds using a selecting-current ratio of 2:1. The worst ONE-ZERO ratio (taken on an amplitude basis at the sensing-time point) was about 4:1. A test of current-variation margins indicated that any one coordinate current could be varied by more than 10% without interrupting operation. Partial operation of the array using 3:1 selecting-current ratios has also been accomplished; it resulted in a reduction of core switching time to roughly 5 microseconds.

The array has also been operated with a moving information pattern (the contents of one core shifted to the next in turn) at a reduced rate and with reduced margins.

Error-free operation for periods as long as several hours is highly encouraging in view of the very large variation of characteristics among the 256 cores and the incomplete state of development of the logical test equipment surrounding the array. It is believed that two major lines of future effort should be (1) to construct new arrays out of cores with greater uniformity of characteristics, and (2) to remodel or replace surrounding test equipment until the logical test setup performs with a high degree of reliability. A third line of effort is, of course, aimed at obtaining significant data from the test operation of the array for use in future design work and reliability estimates.

3.32 Ceramic Memory Array and Matrix Switch

A 16 x 16 planar array of small ferrite memory cores has been constructed. The electronics for selecting, sensing, and thoroughly testing the array have been assembled, and work is continuing on the magnetic-core matrix switch to drive the memory.

There are many as yet unsolved engineering problems in the switch and its coupling to the memory; however, portions of the memory up to 2 x 4 in size have been in operation driven by small experimental switches.

Component	Type	Total in Service	No. of Failures	Hours of Operation	Comments
Capacitors: Mica	0.001 mfd	3300	1	52	Mechanical
			1	7415	Open
Ceramic Trimmer	7-45 mmfd	200	1	4300	Intermittent
Bath Tub	0.01 mfd	75	1	8133	Oil leak
Crystals	D-357	7500	1	2000-3000	Mixing crystal: excessive drift
			6	5000-6000	Mixing crystals: 2 change in characteristics, 4 drift
			4	7000-8000	3 Mixing crystals: 2 change in characteristics, 1 drift 1 Grid crystal: drift
	D-358	3500	1	5000-6000	Clamping: drift
			1	8000-9000	Matrix: Change in characteristics
Resistors: Carbon	1.5 Megohms 1/2 watt	10	1	5319	Change in characteristics
	2200 ohms 1 watt	175	1	8448	Intermittent open
Resistors: Wire-Wound	3.3 ohms 2 watt	50	1	3665	Open
	3100 ohms 8 watt	50	1	676	Open
	5000 ohms 8 watt	700	1	4531	Open
Resistors: Variable (Carbon)	2500 ohms 2 watt	40	1	3564	Intermittent Open
Toggle Switch	SPST	500	1	7953	Intermittent
Pulse Transformers	1:1	600	1	544	Open
	3:1	2241	1	8043	Intermittent
	5:1 (193-8)	335	1 3	7494 8000-9000	Open Open
	5:1 (193-10)	5	1	8751	Intermittent

Fig. 3-7. Failures of Components in WWI
October 1 - December 31, 1951

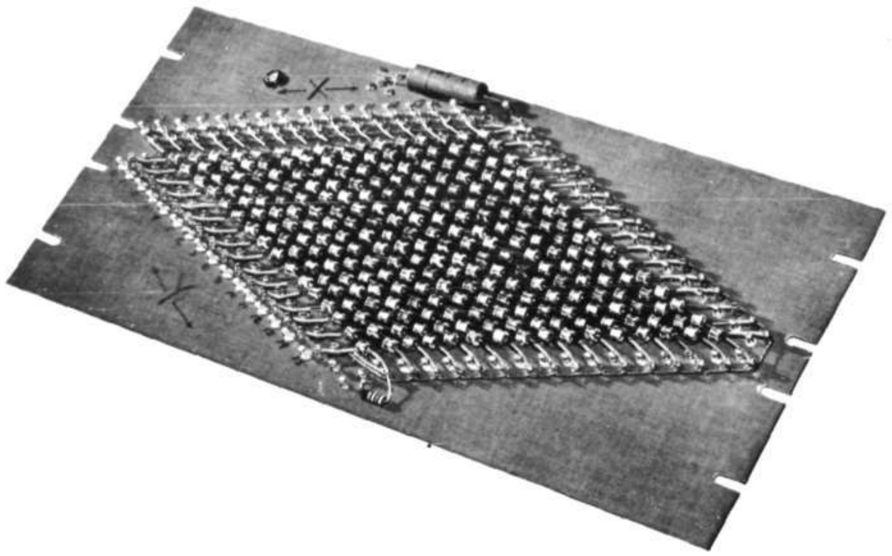

Fig. 3-8. 16 x 16 Metallic-Core Magnetic
Memory Array

Arbitrary patterns of ONE's and ZERO's have been cycled within these portions for several hours. Information was available one microsecond after it was requested; the total read-rewrite time was about three microseconds.

3.33 New Materials, Testing, and Measurement

Improved magnetic materials continue to arrive slowly, and a limited amount of measuring and evaluation goes on. A complete and organized measuring, testing, and record-keeping program is being designed.

Equipment is being constructed for acceptance and life testing. Liaison with other users and producers of these types of magnetic cores is good, particularly in the area of test techniques and standards.

3.34 Ferroelectric Storage

Equipment has been assembled to pulse-test single ferroelectric condensers in a way which closely approximates their operating conditions in a storage matrix (Summary Report 27). Voltage steps of two amplitudes (either polarity) can be applied to the condenser under test by the discharge of a thyratron. At a low frequency, the equipment cycles through a sequence of read, write, and half-amplitude disturb pulses, testing various materials which appear promising.

The materials currently being tested appear to be on the borderline of suitability for a matrix memory. Switching, however, is faster than anticipated. Some materials have been observed to switch in 0.4 microsecond. Improved characteristics were noted when the material was cooled below -5 C.

3.4 TRANSISTORS

The objective of the transistor group is to evaluate the transistor as a digital-computer element. This evaluation must be made in comparison with the vacuum tube and the magnetic core.

3.41 Preparation Period

The period from June 1951 to September 1951 was spent in a general study program. To provide the framework for this study, a Transistor Bibliography, E-421, was compiled. This bibliography contains 27 entries which cover the physics of the transistor and 70 entries which cover the applications.

Experimental work related to the various articles from the bibliography was carried on using four Bell Laboratory Type A transistors made in 1948. A cursory study of the following circuits was made:

(1) Class A Amplifiers
(2) Multivibrators
(3) Oscillators

Circuits were designed for plotting the four main static characteristics. The first of these consists of four d-c meters mounted on a panel (see F-1379 in Engineering Note E-435). Emitter and collector current and voltage can be read on a point-to-point basis. The time and labor involved in the process of taking static characteristics in this way became prohibitive; therefore a second system was devised. This system employed a half-wave rectifier with variable-amplitude sine-wave input, two or three small batteries, an oscilloscope, and a Land camera. With this setup the collector and backward transfer characteristics can be obtained in approximately 10 minutes.

In addition to the study and experimentation, the members of the group attended a weekly transistor symposium conducted by Prof. R. Adler of the Research Laboratory of Electronics.

3.42 Study of a Blocking Oscillator

When the Type 1698 transistors became available, the group decided to make a detailed study of some simple circuit in order to gain experience in the use of the ideas which had been studied during the summer. The blocking oscillator was used for this purpose, and a study was made which lasted from October 1 to November 15. The results of this study are reported in Engineering Note E-435. It was found that the large-scale equivalent circuit described in that report is quite satisfactory for qualitative analysis of transistor circuits. Operation at repetition rates of 0.8 megacycle per second with pulses of 0.4-microsecond duration were obtained. It was found that when high peak emitter currents are used, the characteristics shift during the cycle of operation, so that the static characteristics must be modified for design purposes in such a way as to allow for this shift. A permanent change in the characteristics of the transistor under test was observed to take place during the course of the investigation. This change was mainly a reduction in the back resistance of the collector diode.

3.43 Preliminary Evaluation of a Transistor as a Computer Component

After the experience with the blocking oscillator, it was decided that a preliminary evaluation of the transistor should be made in order that we might have some idea of its advantages and disadvantages. This study, which is described in Memorandum M-1353, pointed up the fact that the transistor has many advantages as a computer component and that its main disadvantages will partially or wholly be eliminated as transistors become available and manufacturing techniques improve. The advantages of the transistors are:

(1) Small size (1/1000 cubic inch for beaded units)
(2) Short switching time (less than 0.2 microsecond)
(3) Low power requirements (1/10 watt or less total)
(4) Long life (70,000 hours to 63% failures)
(5) Inherent negative resistance characteristic (results in simpler switching circuitry)
(6) Low capacitances.

Its disadvantages are:

(1) Temperature sensitivity
(2) High noise figure
(3) Variation of parameters among different units
(4) Low power output.

There is some evidence that the variation of parameters can be reduced with better manufacturing techniques. The effects of temperature sensitivity and low power output can be eliminated in many cases with proper circuitry. The high noise figure is a great disadvantage for small-signal work. Its effects can be easily reduced in large-signal circuitry.

One flip-flop counter stage is being studied. This counter employs a circuit due to Dr. R.H. Rediker of MIT modified by the transistor group after a study of the negative-resistance curve had been made.

3.44 Definition and Measurements of Parameters

A preliminary definition of the transistor parameters which seem to be most important to us has been made, and a standardized measuring procedure has been adopted. The purpose of this work is (1) to determine how these parameters vary from the manufacturer's data and (2) to write a meaningful life history of each of the units we use. The results of this work are discussed in Engineering Note E-441. The measurement of parameters will be an aid to the designer, who must know and allow for these variations. To provide data for the life histories, a log will be kept which will show significant parameter changes with time and different applications.

3.45 Counter Circuit

Plans have been made to build a transistor counter (see Memorandum M-1353). This counter will be based on the evaluation of memory and gate circuits which will precede its design. It is expected that this counter will utilize the advantages and minimize the disadvantages of the transistor and that the resultant design can be used in the evaluation of the transistor as a computer element.

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4. ELECTROSTATIC STORAGE

4.1 TUBE PROGRAM

Installation of a second bank (Bank B) of storage tubes with 1024 spots per tube (400-series) has been completed during this quarter. These tubes are operating at the same access time as the first bank (Bank A) of 256-spot tubes.

The percentage of good 1024-spot tubes runs somewhat lower than that of the previous production of 300-series tubes. Research effort is being directed toward improving this condition and extending the life and performance of the 32 x 32 tubes.

4.11 Tube Experience in Whirlwind I

Operation of the 300-series tubes in Bank A has been consistently good, although a total of 9 tubes have been replaced during this quarter. Of the tubes replaced, 2 suffered a loss of high-velocity gun current caused by an arc-over within the gun structure. This took place when the operating acceleration voltage was changed on all tubes from 2000 to 2500 volts. In a third tube, the holding-gun current deteriorated below a usable value, and in another tube an intermittent heater-cathode short developed after 2000 hours of use. The other 5 tubes were replaced because of non-uniform spot size and low operating margins. These tubes were in varying stages of ion-spot formation, and several had small isolated blemishes or non-uniform collector-to-surface spacings. These five tubes were not rejected because of complete failure while in service, but because of relatively low margins during operation with a new and more severe test program developed in the course of the installation of the 1024-spot tubes in Bank B.

The average life of the tubes removed was 1640 hours, ranging between 160 and 2880 hours. Five of the tubes had also been used for more than 2000 hours. For the 17 tubes in Bank A (the seventeenth is a parity-check digit that has been added), the average service is 1275 hours, with a minimum of 320 and a maximum of 3590 hours. Four of the tubes have more than 2500 hours of use, while 7 have been in for 550 hours or less. The tube with nearly 3600 hours of operation, incidentally, is the first 300-series tube made, ST305-2, and was installed during December 1950.

During this quarter 16 of the 400-series prototype tubes have been installed in the computer. These tubes are being operated at 1024 spots per tube in the second (Bank B) storage position. The operation margins on the various gate amplitudes and electrode voltages are somewhat less than those for tubes operating at 256 spots. However, the feasibility of 32 x 32 operation has definitely been demonstrated, and at the end of this period Bank B storage was being used for approximately 80% of the applications programs.

The 16 tubes in Bank B (the parity-check digit has not yet been installed) have been operating an average of 735 hours, with values between 180 and 910 hours. None of the tubes has shown any evidence of dark-spot formation. During the course of the installation and alignment, however, 8 tubes were replaced in Bank B. Since there was a constant demand for tubes at that time, they were not all given shelf life before installation in the computer. Four of the tubes suffered a loss of emission in one or both guns, and one developed an intermittent grid-to-cathode short. The other three tubes were removed because of low operating margins and non-uniform spot size, caused in one case by a loose collector screen. The average life of the tubes removed was 170 hours.

4.12 Tube Production

During the three months ending on December 31, 1951, a total of 50 new tubes and one reprocessed tube were constructed. Ten of these tubes were not complete storage tubes but consisted only of a high-velocity gun with a Philips Type "L" cathode mounted in a 2-inch glass cylinder approximately 8 inches long. Three tubes were used in research studies at 32 x 32 density, while 38 tubes, designated as research tubes (RT) because of minor differences in tube geometry or target structure, were actually 400-series prototype tubes intended for use in the computer. In Fig. 4-1 it will be noted that several tubes of this latter group have been designated as "marginal tubes for 32 x 32 operation." Because the writing requirements over the surface are not uniform, these tubes have operating ranges which are considered too narrow for use in Bank B. However, the tubes are satisfactory at a 16 x 16 density and are being used as Bank A replacements. Of the 38 tubes made for use in the computer, a total of 8, or 21%, were of this marginal type. Four of these are known to have failed at 32 x 32 operation because of an interference pattern between the collector and auxiliary-collector screens. This pattern occurred when an attempt was made to use the same size of wire mesh for both screens. The other four tubes had uneven collector-to-surface spacings or isolated failure points which were too small to interfere seriously with 16 x 16 operation.

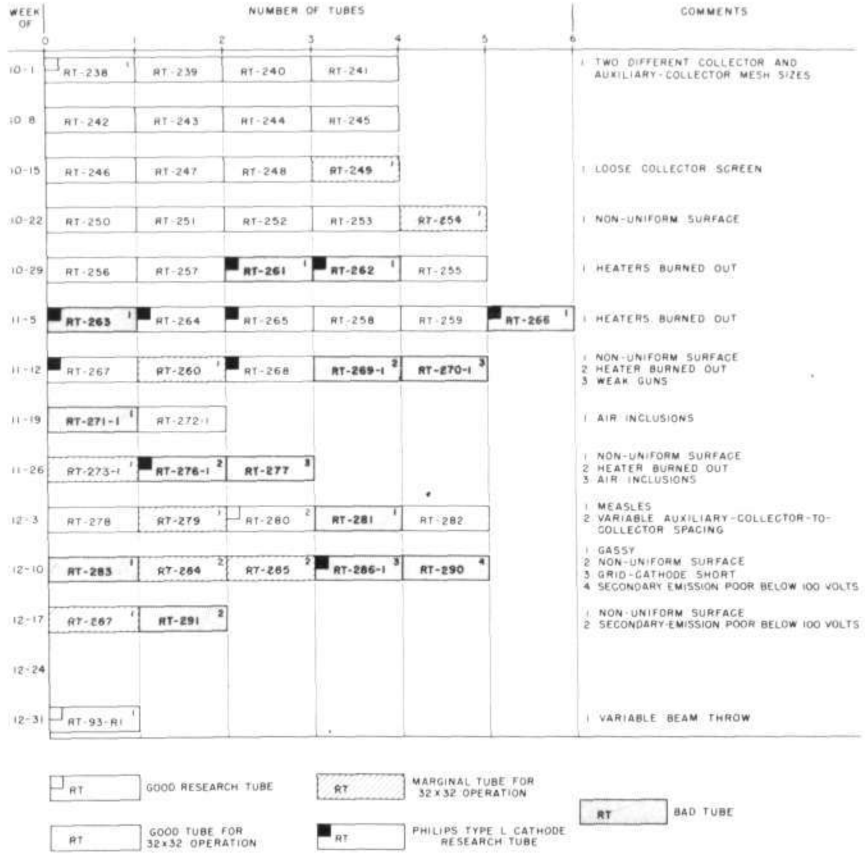


Fig. 4-1. Storage-tube Production Record

The figure of 58% good tubes for 32 x 32 operation is lower than that previously obtained on 300-series production. This is not felt to be particularly serious or indicative that tubes storing 1024 spots are appreciably more difficult to make than those storing 256 spots. Since the causes of failure are known, it is felt that corrective measures can be taken which will improve the acceptance figure. The 40% value for successfully processed research tubes with Philips "L" cathodes is not encouraging. Of the 6 which failed, one had a grid-cathode short and the remaining 5 had their heaters burned out during processing.

4.13 Research

As mentioned in Summary Report 27, two research tubes were made to investigate the effect of the size of the auxiliary-collector mesh on tube performance. A slight improvement in spot interaction was obtained in the quadrants having a 70-mesh auxiliary collector instead of the 40-mesh which had previously been used. In all other respects the 70-mesh quadrant appeared to be normal. However, when tubes were made having both

70-mesh collector and auxiliary-collector screens, an interference pattern was produced which was severe enough to give a nonuniform array of spots. The distribution of spot size over the surface was not sufficiently well defined to suggest a moiré effect, and the interference lines did not show up on a television-type display unless the holding-gun was turned off and a relatively intense scanning beam was used. As a result, this condition did not become apparent until the low operating margins for several of these tubes were noted. Of the 12 tubes of this type made during this quarter, 3 were satisfactory for 32 x 32 use in the computer, 5 were rejected for other reasons, and the other 4 have been assigned as replacements for Bank A. Future tubes will use 40-mesh auxiliary-collector screens of a different orientation between screens to avoid any interference.

During this period two tubes were made using a conductive coating of stannic oxide in place of the aquadag. Although the pressures observed during processing and subsequent tests were less by a factor of 10 than those of previous tubes, two things took place which may be serious enough to discourage further use of the new coating. First, there was difficulty in getting normal emission from both electron guns; second, the secondary-emission characteristics of the surfaces were very poor below 100 volts primary velocity. It seems probable that some contaminant is being released by the stannic oxide coating which must be more completely expelled before the tube is processed with the storage surface and electron guns in place.

The four tubes with Philips "L" cathodes which have been satisfactorily processed have shown promising results on life tests. They are being aged at 5-8 watts heater power input, this being sufficient to give 50 to 100 microamperes beam current from a standard 5UP gun structure. The two most striking characteristics of these cathodes compared to the oxide-coated type is their constant level of emission as a function of duty cycle and their complete freedom from loss of emission when the grid is pulsed positive with respect to the cathode by as much as 50 volts. The average age of the four tubes is 1423 hours, with RT264 having 1679 hours and RT268 1204 hours.

Because of the high incidence of heater burn-outs during processing, no Type "L" cathodes have yet been placed in storage tubes. The research will be continued, however, as improvements in the heater structure and processing techniques are expected.

Life testing of the first 400-series prototype tube has now extended to 3500 hours with no trace of dark-spot formation. It is safe to assume that this factor will not place an upper limit upon the life of storage tubes.

5. INPUT-OUTPUT

5.1 MAGNETIC TAPE

The temporary magnetic-tape setup mentioned in Summary Report 27 has been found to operate quite satisfactorily. The temporary system is still connected with the computer. It is being tested with various modes of operation, and it is sometimes used with the computer on application problems. In this way the system can be employed for useful computation, and at the same time provide performance data and serve to acquaint operators with the programming problems.

Using the results obtained in the testing of the temporary setup, the design of the equipment for the final system is being carried out. The final magnetic-tape system will work with the in-out control described in Summary Report 26. The decision to group the magnetic-tape heads in pairs to reduce difficulties with tape blemish will be applied to the final system, and this has necessitated a few superficial changes in the design of in-out control.

The computer, by setting up the in-out switch, will be able to select one of four tape units and to drive it either forward or reverse and to select the mode of operation. The three possible modes of operation are read, record, and re-record. The re-record mode is one in which a portion of the information in a previously recorded tape is replaced. This mode involves both reading and recording -- reading to locate the desired position, and recording to insert the new information.

The information is put on the tape in blocks of a length determined by the computer, with the spaces between blocks long enough to allow the tape to stop -- about 0.2 inch. The blocks are made up of lines of information across the tape. These lines are spaced at a maximum density of 100 per inch. Because of the grouping of the 6 heads into 3 pairs, there are effectively only 3 channels across the tape. Two of these channels are used to record data received from the computer, and the third is used as an index channel in which a pulse is recorded whenever there is information in the other two channels. Thus 8 lines along the tape are needed to record one 16-binary-digit computer word. The words are split up during recording and assembled during reading by in-out control, so that the programmer does not have to arrange for these operations. The programmer does have to make sure that reading is done with the tape moving in the same direction as when it was recorded, so that the words will be assembled correctly.

During a recording operation, a special character -- called a block mark -- is automatically recorded as the first line in each block. This block mark is used in reading to determine the beginning of a block of information, and the control is arranged to detect a block mark and activate the reading circuits. This feature along with others allows the computer to keep track of the location of information on the tape by reading only one line in a block and counting it, without having to spend time reading all of the information in each block. The block mark is also used during the re-record operation to trigger the circuits from the reading to the recording mode at the proper time. The fact that a block mark must be detected in order to activate the reading circuits makes it possible to start the tape in the middle of a block of information without getting into trouble.

5.2 MAGNETIC DRUMS

Two magnetic-drum systems are being constructed by Engineering Research Associates of St. Paul for use with the Whirlwind computer. These have been designated as the auxiliary-storage drum system and the buffer-storage drum system. A brief description of this equipment was given in Summary Report 26.

The auxiliary-storage drum is to be used as a large-capacity storage to supplement the high-speed electrostatic storage in the computer. This drum is designed to have 2048 registers around its circumference and to have 12 groups of 16 heads. This arrangement provides a total capacity of 24,576 16-digit registers. It will be used for storage both of numerical data and of computer subprograms. The system will be connected so that transfers of information can take place only between the drum and electrostatic storage. These transfers will take place by way of the in-out register and will involve use of the in-out switch and the in-out control. This method of integration was chosen because it permits the most straightforward design. However, the addition of more elaborate control features at a later date is not precluded.

Several modes of operation for this equipment are being planned. These are described in some detail in Memorandum M-1358. Basically, they provide a programmer with a choice of either single-word or block transfers and of various methods for specifying the drum registers to be referred to. For single-word transfers an average wait-time of 8 milliseconds will be necessary in order to locate the desired drum address. For block transfers a similar wait time will be necessary to locate the address of the first word in the block, but succeeding words will be handled at intervals of 64 microseconds, which is nearly the maximum operating speed of electrostatic storage.

The buffer-storage drum is to be used for temporary storage of data which is being communicated between the computer and certain special types of terminal equipment. Principally, it is to be utilized where input data is arriving in a random and asynchronous manner from many sources. In order to handle data of this type without the use of some such buffer storage, it would be necessary for the computer to be ready at all times to receive each piece of data and store it in electrostatic storage. The buffer drum will accumulate data of this sort so that it will be necessary only for the computer to remove the information at relatively infrequent intervals and at points in the computer program where such data transfer is convenient. Special dual heads on the buffer drum will be used to control the recording processes and insure that new data is not recorded in registers containing information which has not been extracted by the computer. Transfers between the buffer drum and the computer may be done either in blocks of words or a single word at a time in manners similar to those used with the auxiliary-storage drum.

The use of dual heads on the buffer drum offers additional possibilities in communicating information between the computer and various slow-speed terminal-equipment devices such as typewriters and punched-tape equipment. The information may be transferred between the computer and the drum at the high speed of electrostatic storage and between the drum and the terminal equipment at the necessary low speeds.

The two magnetic-drum systems will be constructed in separate units and will utilize the type of plug-in construction which is standard for ERA design. Filament power for the equipment will be supplied from the WWI computer buses and therefore will be cycled on and off slowly along with the rest of the computer. The necessary d-c voltages will be obtained from special motor-generator sets and voltage-regulator circuits furnished with the equipment. However, the wiring for distribution of this d-c power is being planned so that the marginal-checking facilities of the computer can be applied to the drum systems.

Present schedules call for shipment of the drum systems during the last quarter of 1952. Installation of power wiring, video cables, and control circuits for tying the systems to the computer is being planned so that integration with the computer can be accomplished without delay after the units arrive.

6. MATHEMATICS, CODING, AND APPLICATIONS

6.1 PROGRAMMING OF EXTRA-PRECISION AND FLOATING-POINT OPERATIONS

For a large proportion of scientific and engineering computation, the short-length fixed-point number system with which the Whirlwind I computer is designed to operate is a limitation which must be overcome by programming. The sixteen binary digits (one of which is a sign digit) which make up a normal number in the computer are equivalent to four and a half decimal digits with sign. Thus an arbitrary number may have to be increased or decreased by as much as 1 part in 65,536 when it is rounded off to fit into the standard register length. The fixed-point logic requires that care be taken in planning the computation to insure that all numbers be less than unity in magnitude. Therefore (1) the upper bounds of the magnitudes of all variables must be known at least approximately, and (2) quantities which would normally be greater than one must be premultiplied by some number, usually a negative power of two, to make them smaller than one. Further difficulties are encountered when variables grow small, and particularly when they pass through zero, during the computation, because in this event the number of significant digits may diminish far below the number of actual digits being carried unless further care is exercised.

These difficulties inherent in the use of a short-length fixed-point number system were recognized long ago, and the design of the Whirlwind I computer was undertaken with full cognizance of the apparent limitations. There were numerous reasons for this decision, the most important of which are the following:

(1) No real limitation is imposed, because more precision (i. e. more digits) and/or a floating point (i. e. no restriction on magnitude and no unavoidable loss of significant digits) can both be provided by proper programming, using subroutines, with no greater difficulty than if the computer had been designed to handle longer, floating-point numbers.

(2) Use of short, fixed-point registers together with a single-address instruction code permits by far the most efficient use of total storage capacity and the greatest simplicity of design and construction in a machine intended in part for control applications. This is true because high speed and low precision are characteristic of the needs of most control problems. The high speed necessitates a parallel machine, so that extra digits in a number mean extra equipment.

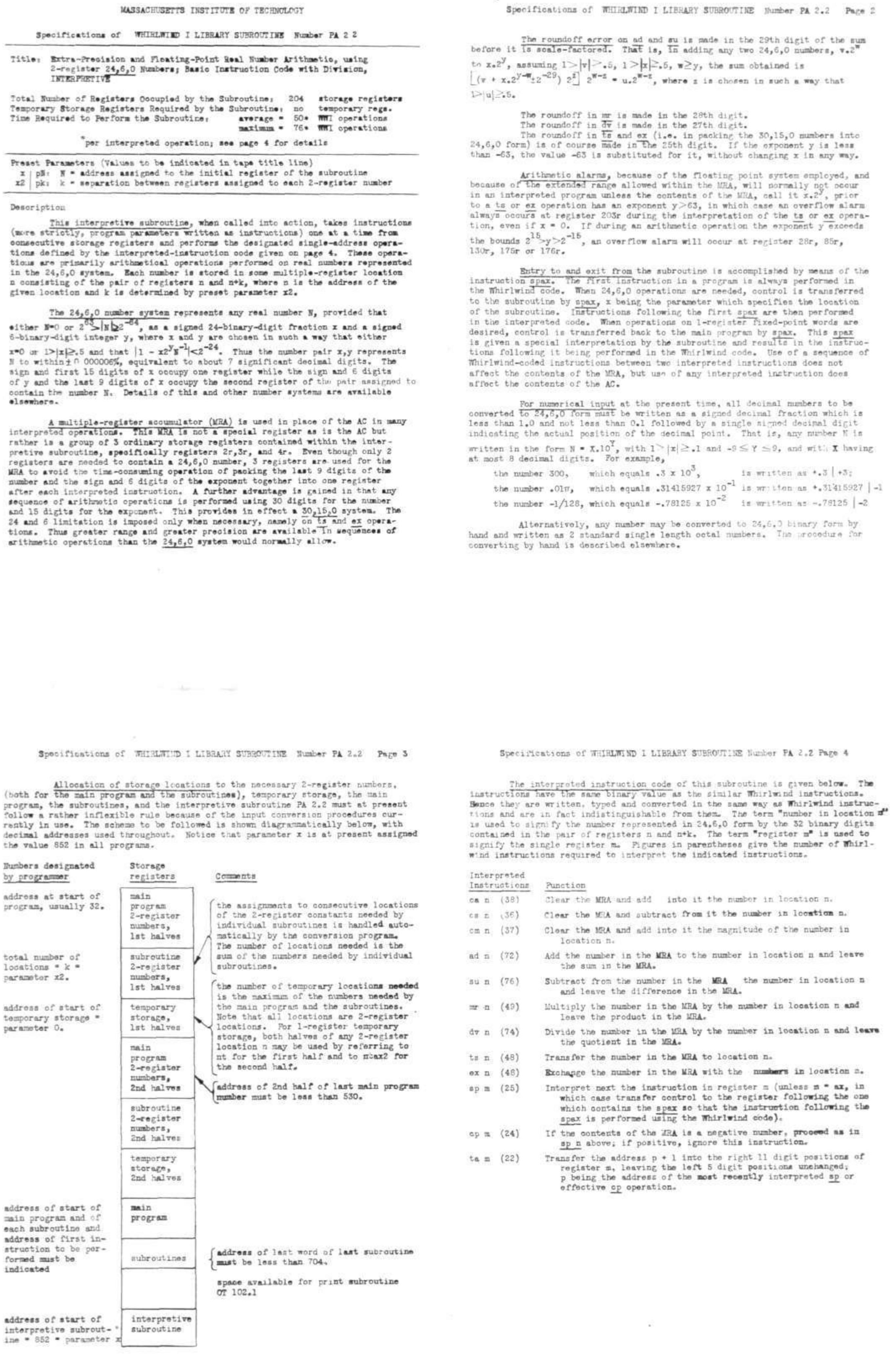
(3) Fixed-point arithmetic is virtually a necessity in any problems in which extensive logical operations are performed or in which the instructions of the program are modified arithmetically. A strictly floating point would be somewhat more complicated designwise and considerably less convenient in practise, because it is more difficult to fix a floating point than to float a fixed point by programming.

(4) Many scientific and engineering problems, as well as most control problems, require high precision only at certain critical stages if at all; and almost all problems involve some logical functions (if only to keep track of the arithmetic steps) in which long numbers are not needed. For efficient use of storage, numbers which require only a few digits should be stored in as short a register as possible. Since control applications require high-speed operations on short numbers, it is more sensible to combine two short registers by programming when necessary than to halve a long one. The alternative, namely the optional short-or-long system used by Wilkes, is difficult to mechanize in a parallel computer but appears to have advantages.

The recent availability of 1024 registers of electrostatic storage has, for the first time, made feasible the undertaking of extensive calculations which require either extra precision (above the 16 binary digits normally used) or floating point or both.

In the Whirlwind I Subroutine Library there are already in use several interpretive routines for performing programmed arithmetic. The name programmed arithmetic has been applied to all types of arithmetic different from the real-number, fixed-point, 15-binary-digit, less-than-one-in-magnitude system built into the Whirlwind I computer. The specifications, as given in the Subroutine Library, of the most popular of the extra-precision floating-point subroutines is reproduced in Fig. 6-1. Using this subroutine, one can program a 7-decimal-digit floating-point computation just as easily, and in fact in almost exactly the same way, as one can program the 4-1/2-decimal-digit fixed-point computations ordinarily performed on WWI. The average floating-point extra-precision program is likely to take about 25 times as long to perform as its fixed-point counterpart and requires ordinarily somewhat less than twice the number of storage registers.

A detailed analysis of the advantages of



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Specifications of WHIRLWIND I LIBRARY SUBROUTINE Number PA 2 2

Title: Extra-Precision and Floating-Point Real Number Arithmetic, using 2-register 24,6,0 Numbers; Basic Instruction Code with Division, INTERPRETIVE

Total Number of Registers Occupied by the Subroutine:	204	storage registers
Temporary Storage Registers Required by the Subroutine:	no	temporary regs.
Time Required to Perform the Subroutine: average =	50*	WWI operations
maximum =	76*	WWI operations

*per interpreted operation; see page 4 for details

Preset Parameters (Values to be indicated in tape title line)
x | pN: N = address assigned to the initial register of the subroutine
x2 | pk: k = separation between registers assigned to each 2-register number

Description

This interpretive subroutine, when called into action, takes instructions (more strictly, program parameters written as instructions) one at a time from consecutive storage registers and performs the designated single-address operations defined by the interpreted-instruction code given on page 4. These operations are primarily arithmetical operations performed on real numbers represented in the 24,6,0 system. Each number is stored in some multiple-register location n consisting of the pair of registers n and n+k, where n is the address of the given location and k is determined by preset parameter x2.

The 24,6,0 number system represents any real number N, provided that either N=0 or $2^{63} > |N| \geq 2^{-64}$, as a signed 24-binary-digit fraction x and a signed 6-binary-digit integer y, where x and y are chosen in such a way that either x=0 or $1 > |x| \geq .5$ and that $|1 - x2^{y}N^{-1}| < 2^{-24}$. Thus the number pair x,y represents N to within ± 0.000006%, equivalent to about 7 significant decimal digits. The sign and first 15 digits of x occupy one register while the sign and 6 digits of y and the last 9 digits of x occupy the second register of the pair assigned to contain the number N. Details of this and other number systems are available elsewhere.

A multiple-register accumulator (MRA) is used in place of the AC in many interpreted operations. This MRA is not a special register as is the AC but rather is a group of 3 ordinary storage registers contained within the interpretive subroutine, specifically registers 2r,3r, and 4r. Even though only 2 registers are needed to contain a 24,6,0 number, 3 registers are used for the MRA to avoid the time-consuming operation of packing the last 9 digits of the number and the sign and 6 digits of the exponent together into one register after each interpreted instruction. A further advantage is gained in that any sequence of arithmetic operations is performed using 30 digits for the number and 15 digits for the exponent. This provides in effect a 30,15,0 system. The 24 and 6 limitation is imposed only when necessary, namely on ts and ex operations. Thus greater range and greater precision are available in sequences of arithmetic operations than the 24,6,0 system would normally allow.

Specifications of WHIRLWIND I LIBRARY SUBROUTINE Number PA 2.2 Page 2

The roundoff error on ad and su is made in the 29th digit of the sum before it is scale-factored. That is, in adding any two 24,6,0 numbers, $v.2^{w}$ to $x.2^{y}$, assuming $1 > |v| \geq .5$, $1 > |x| \geq .5$, $w \geq y$, the sum obtained is $\left[(v + x.2^{y-w} \pm 2^{-29})\, 2^{z}\right] 2^{w-z} = u.2^{w-z}$, where z is chosen in such a way that $1 > |u| \geq .5$.

The roundoff in mr is made in the 28th digit.
The roundoff in dv is made in the 27th digit.
The roundoff in ts and ex (i.e. in packing the 30,15,0 numbers into 24,6,0 form) is of course made in the 25th digit. If the exponent y is less than -63, the value -63 is substituted for it, without changing x in any way.

Arithmetic alarms, because of the floating point system employed, and because of the extended range allowed within the MRA, will normally not occur in an interpreted program unless the contents of the MRA, call it $x.2^{y}$, prior to a ts or ex operation has an exponent $y > 63$, in which case an overflow alarm always occurs at register 203r during the interpretation of the ts or ex operation, even if x = 0. If during an arithmetic operation the exponent y exceeds the bounds $2^{15} > y > 2^{-15}$, an overflow alarm will occur at register 28r, 85r, 130r, 175r or 176r.

Entry to and exit from the subroutine is accomplished by means of the instruction spax. The first instruction in a program is always performed in the Whirlwind code. When 24,6,0 operations are needed, control is transferred to the subroutine by spax, x being the parameter which specifies the location of the subroutine. Instructions following the first spax are then performed in the interpreted code. When operations on 1-register fixed-point words are desired, control is transferred back to the main program by spax. This spax is given a special interpretation by the subroutine and results in the instructions following it being performed in the Whirlwind code. Use of a sequence of Whirlwind-coded instructions between two interpreted instructions does not affect the contents of the MRA, but use of any interpreted instruction does affect the contents of the AC.

For numerical input at the present time, all decimal numbers to be converted to 24,6,0 form must be written as a signed decimal fraction which is less than 1.0 and not less than 0.1 followed by a single signed decimal digit indicating the actual position of the decimal point. That is, any number N is written in the form $N = X.10^{Y}$, with $1 > |x| \geq .1$ and $-9 \leq Y \leq 9$, and with X having at most 8 decimal digits. For example,

the number 300,	which equals $.3 \times 10^{3}$,	is written as +.3 | +3;
the number .01π,	which equals $.31415927 \times 10^{-1}$	is written as +.31415927 | -1
the number -1/128,	which equals $-.78125 \times 10^{-2}$	is written as -.78125 | -2

Alternatively, any number may be converted to 24,6,0 binary form by hand and written as 2 standard single length octal numbers. The procedure for converting by hand is described elsewhere.

Specifications of WHIRLWIND I LIBRARY SUBROUTINE Number PA 2.2 Page 3

Allocation of storage locations to the necessary 2-register numbers, (both for the main program and the subroutines), temporary storage, the main program, the subroutines, and the interpretive subroutine PA 2.2 must at present follow a rather inflexible rule because of the input conversion procedures currently in use. The scheme to be followed is shown diagrammatically below, with decimal addresses used throughout. Notice that parameter x is at present assigned the value 852 in all programs.

Numbers designated by programmer	Storage registers	Comments
address at start of program, usually 32.	main program 2-register numbers, 1st halves	the assignments to consecutive locations of the 2-register constants needed by individual subroutines is handled automatically by the conversion program. The number of locations needed is the sum of the numbers needed by individual subroutines.
total number of locations = k = parameter x2.	subroutine 2-register numbers, 1st halves	
address of start of temporary storage = parameter 0.	temporary storage, 1st halves	the number of temporary locations needed is the maximum of the numbers needed by the main program and the subroutines. Note that all locations are 2-register locations. For 1-register temporary storage, both halves of any 2-register location n may be used by referring to n+ for the first half and to n+ax2 for the second half.
	main program 2-register numbers, 2nd halves	address of 2nd half of last main program number must be less than 530.
	subroutine 2-register numbers, 2nd halves	
	temporary storage, 2nd halves	
address of start of main program and of each subroutine and address of first instruction to be performed must be indicated	main program	
	subroutines	address of last word of last subroutine must be less than 704.
		space available for print subroutine OT 102.1
address of start of interpretive subroutine = 852 = parameter x	interpretive subroutine	

Specifications of WHIRLWIND I LIBRARY SUBROUTINE Number PA 2.2 Page 4

The interpreted instruction code of this subroutine is given below. The instructions have the same binary value as the similar Whirlwind instructions. Hence they are written, typed and converted in the same way as Whirlwind instructions and are in fact indistinguishable from them. The term "number in location n" is used to signify the number represented in 24,6,0 form by the 32 binary digits contained in the pair of registers n and n+k. The term "register m" is used to signify the single register m. Figures in parentheses give the number of Whirlwind instructions required to interpret the indicated instructions.

Interpreted Instructions	Function
ca n (38)	Clear the MRA and add into it the number in location n.
cs n (36)	Clear the MRA and subtract from it the number in location n.
cm n (37)	Clear the MRA and add into it the magnitude of the number in location n.
ad n (72)	Add the number in the MRA to the number in location n and leave the sum in the MRA.
su n (76)	Subtract from the number in the MRA the number in location n and leave the difference in the MRA.
mr n (49)	Multiply the number in the MRA by the number in location n and leave the product in the MRA.
dv n (74)	Divide the number in the MRA by the number in location n and leave the quotient in the MRA.
ts n (48)	Transfer the number in the MRA to location n.
ex n (48)	Exchange the number in the MRA with the numbers in location n.
sp m (25)	Interpret next the instruction in register m (unless m = ax, in which case transfer control to the register following the one which contains the spax so that the instruction following the spax is performed using the Whirlwind code).
cp m (24)	If the contents of the MRA is a negative number, proceed as in sp n above; if positive, ignore this instruction.
ta m (22)	Transfer the address p + 1 into the right 11 digit positions of register m, leaving the left 5 digit positions unchanged; p being the address of the most recently interpreted sp or effective cp operation.

Fig. 6-1. Specimen Subroutine Specifications

various real-number systems will be given in the next Summary Report. At that time a detailed explanation of the functions of an interpretive subroutine will be given, complete with examples of how they work and how they are used.

6.2 PROBLEMS OF GENERAL INTEREST

Outlines of four of the more important problems under study on the Whirlwind I computer are given in the succeeding sections. Only the first of these is being pursued entirely by Digital Computer Laboratory personnel. Work on the other three is being performed in large part by the originators of the problems.

6.21 Non-Linear Parabolic Partial Differential Equations (Study of Magnetic Flux Density)

Numerical solutions have been obtained for the non-linear partial differential equation

$$\frac{\partial^2 H}{\partial x^2} - 6\frac{\partial B}{\partial t} = 0$$

with boundary conditions

$$H(x_o, t) = H(-x_o, t) = 0 \text{ and } H(x, o) = 0,$$

as mentioned in Summary Reports 24 and 26. The method chosen was one that approximated the differential equation by a six-point difference equation.

The first set of results obtained approximated the f(H) curve by three straight lines. Calculations were carried out for three values of the time interval Δt; the space interval Δx was kept fixed. The values chosen for Δt were guided by the stability studies for the linear case, as described in Summary Report 26. The results at corresponding grid points of the x, t plane were found to differ by a very large amount, indicating that the numerical solution was not converging to the time solution as Δt was made smaller. However, very little is actually known about the uniqueness or even the existence of the solution of the differential equation with this choice of f(H), which has physically unrealistic discontinuities in its first derivative.

A second approximation was then introduced for the f(H) curve, keeping the first derivative $\frac{dB}{dH}$ continuous. Results were again obtained for three values of Δt keeping Δx fixed. This time the results at corresponding grid points showed some agreement, but trials at values of Δt small enough to avoid oscillations were limited by the fact that the corresponding changes in calculated values became too small for the number of digits being carried, so that the difference equation solution leveled off erroneously. The programs are now being revised to carry out the calculations with a double-length precision of 30 binary digits.

6.22 Transcendental Equations (Optical Constants of Thin Metal Deposits)

In connection with the study started some time ago by Dr. A.L. Loeb in the MIT Department of Chemistry (see Sections 6.4 of Summary Report 26 and 6.12 of Summary Report 24), several new programs have been written. In this problem the optical constants (that is, the index of refraction and the coefficient of absorption) to be calculated are transcendental functions of the measured reflection and transmission ratios.

As a preliminary step, the problem was originally programmed to calculate the reflection and transmission from assumed values for the optical constants. These assumed values were then changed manually until the calculated values of the reflection and transmission ratios, displayed on the oscilloscope, agreed with the measured ones.

This program is being revised to eliminate the manual interference by including the iteration necessary to obtain the desired results, which can then be printed directly. A further revision will take into account the reflection of radiation incident on the backing.

Another program has been written to compute the conductivity as a function of thickness, at various wave lengths, from a measured transmission value under the assumption that the dielectric constant of the metal examined is equal to that of air.

6.23 Boolean Matrix Multiplications (Group Intercommunication Experiments)

In the course of experimental work on a theory of basic communications among human beings, the Group Networks Laboratory of the Research Laboratory for Electronics at MIT is now attempting to develop a theory to explain the various experimental results which they have obtained.

Ordinary methods of analysis having thus far proved of little use in obtaining a finite prediction theory, the Group Networks Laboratory is now planning to use the Whirlwind computer in an attempt to find empirical solutions. The problem has been coded by Arnold Simmel and Dr. Luce of the Group Networks Laboratory, with the aid of J. W. Carr of the Whirlwind staff.

The problem may be stated as follows: experiments have been made on the communication behavior of five-man teams, who pass discrete pieces of information step-by-step within the team, until all information becomes common knowledge. The number of steps taken to arrive at the "common-knowledge" condition, with the same initial conditions, is recorded in each experiment. A first assumption to be tested on the computer is that the passage of information obeys simple laws of probability. This can be tested by having the computer play the part of all five men and make repeated experiments using purely random choice of communication paths. The results of the computer trials can then be compared with experimental results to see if the same distributions are obtained.

The passage of information in discrete steps is represented in Whirlwind by Boolean matrices, with elements of value only one and zero, whose multiplication under a peculiar Boolean condition represents a discrete time step during the communication experiment. The machine, with the aid of random numbers introduced from secondary storage (for the moment, perforated paper tape is being used), simulates the equi-probable choices of path for information passage required by the simplest theory. The number of matrix multiplications (discrete time steps) necessary for the common-knowledge condition to occur is tabulated internally by the computer, and after a preassigned number of machine "experiments" the total number of times that each specific number of steps has been required is printed out.

So far, the program for the problem has been written and is under test for various network configurations for which answers are known. After a thorough checking of such known solutions, actual performance of the problem with the random numbers will be attempted.

The present intention is next to expand the program from the present equi-probability condition to ones involving conditional probabilities, since the present theory of communication groups is based to a large extent on such relationships. If the problem can be carried to its conclusion, it is possible that a complete theory of the behavior of such communications groups will have been constructed for the first time.

6.24 Approximation of Curves by a Sequence of Unit Differences (Instructions for a Digitally Controlled Milling Machine)

A servomechanical device is being built by the MIT Servomechanisms Laboratory to control the motion of a milling machine. During one step of variable length in time, the cutting head is moved along each of the three axes of motion, the amount by which it is moved in each direction being determined by a group of specially coded characters on a standard perforated tape. By directing the milling machine through a suitable sequence of straight line cuts it is possible to make any desired straight or curved cut in the metal, accurate to within ±0.0005 inch.

All other automatically controlled milling machines work from a template, and simply reproduce the template. The digitally controlled milling machine will be able to produce special cams or templates directly from the specifications, thereby performing automatically what is now an expensive, time-consuming, and highly skilled manual operation.

The specifications of a given surface must be reduced to a sequence of straight lines to be traversed by the center of the cutting head, making allowance for the dimensions of the tool. These straight line cuts must then be expressed in the code required by the controlling servo. Since the inception of the digitally controlled milling machine project, it has been assumed that these calculations could be carried out most satisfactorily on a large digital computer. Recently a member of the staff of the Servomechanisms Laboratory, with the aid of Digital Computer Laboratory personnel, has undertaken the programming of the first phases of this problem. Successful programs have been obtained for the generation of straight and circular cutting instructions as well as for the routine task of translating control tapes prepared decimally by hand on Flexowriter equipment to the proper coded form used by the control device. More complicated two- and three-dimensional cuts will be programmed in the next few months.

6.3 HIGH-SPEED INFORMATION SEARCHING

As the body of scientific information has continued to expand, more and more time and energy must be expended to locate documents related to a certain topic or combination of topics. During recent years considerable success has been achieved in reducing information-searching operations to routines that can be performed with the aid of mechanical devices, such as punched-card sorters and microfilm scanners. It seems unlikely, however, that these devices will prove entirely satisfactory for large files of information. The development of electronic digital computing equipment has created new possibilities for high-speed performance of routine searching operations.

This article presents in highly condensed and simplified form the results of a Master's thesis entitled, "Electronic Digital Machines for High-Speed Information Searching," presented to the Department of Electrical Engineering of MIT in August 1951.

Before any machine can be used for information searching, the information must be analyzed and encoded in such a way that a search by machine for a given subject will direct attention to all pertinent documents while rejecting nearly all those documents which are not of immediate interest. It is desirable to be able to locate documents in a file by specifying a set of defining topics or index terms. It is further desirable to be permitted to express these criteria in a logical equation, so that, for example, a document related to topic A, as well as to either topic B or C, will be located. For collections of documents numbering less than about 300,000, this selection process can be accomplished by the use of punched cards and IBM's new electronic card sorter, or by ERA's microfilm Rapid Selector. For collections numbering in the millions, it is evident that very much higher-speed techniques must be employed.

With modern electronic digital computers, searching operations can be expressed in terms of a series of successive checks for identity supplemented by a systematic method of keeping a record of the intermediate results. A study of the applicability of the general-purpose digital computer made it evident, however, that certain modifications would make the computer more suitable for information searching.

The study revealed that for a search of average complexity, in which the machine is required to scan an encoded index of the form already mentioned (allowing about 900 binary digits to index a document completely), Whirlwind in its present form would take about 3 seconds to scan the index entries for a single document. By endowing the computing element of the machine with the ability to perform certain special orders, it might be possible to reduce the time for searching a single index block by a few tenths of a second -- but no more. At this rate, it would still take more than 800 hours to search the index to a million documents.

With radical changes in the wiring of the computer, searching operation could be performed with a much smaller percentage of time consumed in transferring and storing intermediate results. If Whirlwind were rewired with the intention of using it for information searching, the time required to scan a block of index entires could be reduced to perhaps a hundredth of a second. This would enable the machine to scan the index to one million documents in about three hours.

Where the aim is to achieve the highest possible speed in identifying operations, the performance of all operations in sequence -- an inherent feature of the design of existing digital computers -- becomes the bottleneck. A special-purpose electronic digital machine could be built which would be simpler in design than a rewired general-purpose digital computer and would scan and select much more efficiently. All criteria used to define a search could be checked simultaneously against each index entry being scanned. The coded index information would be stored on some semi-permanent medium such as magnetic tape. The machine would scan the coded entries, and copy and print the serial number of the selected documents. It is estimated that such a machine could scan a magnetic-tape index to about 5 million documents an hour, the physical limitations on tape speed being the governing factor in the over-all searching rate.

Intuitively one feels that there must be a less cumbersome approach to the information-retrieval problem than that of scanning the entire index. An idea worthy of further study recently suggested by a member of this Laboratory is a scheme of successive binary selection, making successively one of two choices, guided by the successive binary digits in a binary number. The binary number in this case would be the number constructed by assembling in some manner the binary-coded forms of index terms defining the search. There presumably could be a multiplicity of different binary numbers which would lead to the location of the same document.

It is an important fact to remember that the availability of any machine for information searching cannot of itself solve the information-searching problem. A major investment would have to be made for encoding any large file of information before machine searching would be possible.

In addition to the detailed coverage of what has been summarized here, the thesis report (issued as report R-200) includes at the ends of the chapters what the author feels to be a fairly complete bibliography on the subject of information searching, excluding the detailed accounts of specific applications of indexing schemes involving punched cards and microfilm. (An exhaustive bibliography concerning punched cards is given in Casey, R.S., and Perry, J.W., Punched Cards, Their Application to Science and Industry.) Since the thesis report was prepared with the cooperation of several individuals experienced in the field of handling documentary information, most of the significant accomplishments in the field have probably at least been noted.

6.4 SEMINARS ON COMPUTING MACHINE METHODS

A series of seminars has been organized to discuss numerical methods. Approximating polynomials, methods of matrix inversion, and certain topics in the numerical solution of partial differential equations have been discussed. Among the topics planned for the near future are:

1. Convergence and stability studies for parabolic and hyperbolic partial differential equations
2. Study of the use of characteristics in solving hyperbolic partial differential equations
3. Study and comparison of iterative, relaxation, and kernal function procedures in the theory of elliptic partial differential equations.

Interested members of the MIT faculty and others outside the Digital Computer Laboratory have been invited and are attending and participating.

7. APPENDIX

7.1 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, Digital Computer Laboratory, 211 Massachusetts Avenue, Cambridge 39, Massachusetts.

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

No.	Title	No. of Pages	Date	Author
R-197	The Gate and Delay Unit (Test Equipment Booklet No. 9)	8	9-1-51	R.R. Rathbone R.L. Best
R-199	The Digital Computer Laboratory	4	9-10-51	
R-200	Electronic Digital Machines for High-Speed Information Searching. M.S. Thesis (Abstract in E-433)	133	11-1-51	P.R. Bagley
R-201	Applications and Procedures for the Whirlwind I Computer	16	11-1-51	C.W. Adams
E-403	Television Demonstration Unit, Part I	11	9-20-51	M.F. Mann
E-422	Rectangular-Loop Magnetic Core Materials	8	9-4-51	W.N. Papian
E-428	Proposed New Order dm (qm), Difference of Magnitudes	3	10-5-51	R.P. Mayer
E-429	Proposed New Order cl (qc), Cycle Left	4	10-8-51	R.P. Mayer
E-430	Order sf, Proposed Modification Involving AR	1	10-8-51	R.P. Mayer
E-431	500-Volt Power Supplies Used in the Whirlwind Computer	26	10-17-51	W.J. Nolan
E-432	A Study of the Holding Beam in the MIT Storage Tube (Abstract of R-198, a Master's Thesis)	2	10-24-51	J.O. Ely
E-434	Burroughs Test Equipment	7	10-31-51	R.L. Best
E-435	Study of a Transistor Blocking Oscillator	7	11-23-51	D.R. Brown J.F. Jacobs N.T. Jones
E-436	Bibliography on Components and Circuit Fabrication Techniques	23	12-19-51	B. Paine
E-437	Procedure for Fabricating Delay Lines from Bulk Cable	5	11-29-51	J.S. Hanson
E-438	Binary Counting with Magnetic Cores	18	12-21-51	D.A. Buck

No.	Title	No. of Pages	Date	Author
E-439	Location of Operations dm (qm) and cl (ql); Permanent Operation ex	2	12-20-51	C.W. Adams R.P. Mayer
M-1280	The Use of "Dag" for Interior Wall Coating	3	9-20-51	R.A. Maglio
M-1284	Method of Preparing Subroutines for the Subroutine Library	16	9-24-51	J.W. Carr J.T. Gilmore
M-1303	Possible Uses of a Magnetic Drum with the Library of Subroutines	3	10-22-51	J. W. Carr
M-1304	Progress on Subroutine Library	11	10-23-51	J. W. Carr
M-1311	Conversion of the WWI Flip-Flop to D-C Coupling	6	10-25-51	F. Irish
M-1316	Order-by-Order Print-Out	2	11-2-51	J.W. Carr
M-1317	Summary of WWI Component Failure Analysis During September, October, 1951	3	11-21-51	B. Paine
M-1323	Proposed Addition of a Parity Checking Arrangement to the Final Paper Tape Input Equipment	5	11-6-51	F.E. Heart
M-1328	Flexowriter Tape Comparer	2	11-16-51	J.W. Carr
M-1337	Use of the Interim Tape Equipment	12	11-27-51	F.E. Heart
M-1350	Operational Procedure on the Whirlwind Computer	7	12-10-51	J.T. Gilmore
M-1358	Operation of Magnetic Drums with WWI	15	12-27-51	E.S. Rich

7.2 PROFESSIONAL SOCIETY PAPERS

Three members of the Laboratory staff took part in the program of the Joint AIEE-IRE Conference held in Philadelphia December 10-12. Jay W. Forrester presented a paper entitled "Digital Computers - Present and Future Trends." R.R. Everett and N.H. Taylor spoke on "The Whirlwind I Computer."

W.K. Linvill's paper "Sampled-Data Control Systems Studied through Comparison of Sampling with Amplitude Modulation" was published in the AIEE Transactions, Vol. 70, 1951.

7.3 VISITORS

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

Dr. M.V. Wilkes of the University of Cambridge, England.

Mr. W.W. Davis, Mr. D.C. Friedman, Mr. J.H. Wright, Mr. A.W. Holt of the National Bureau of Standards.

Dr. V.D. Noe of Stanford Research Institute, who discussed transistors.

Mr. B.V. Bowden and Mr. J.M. Bennett of Ferranti Electric, Ltd., and Mr. T. Kilburn of Manchester University, England.

Mr. S.M. Rubens of Engineering Research Associates, Inc., who discussed magnetic-core storage and magnetic measuring.

Mr. J.K. Galt of Bell Telephone Laboratories.

Dr. E. Albers-Schönberg and Mr. C.L. Snyder of General Ceramics, who discussed development and procurement of rectangular-loop magnetic ferrites.

Mr. R.L. Sink and Mr. V.R. Bradburn of Consolidated Engineering Corporation.

Professor W.W. Soroka of the University of California, Berkely, California, who was interested in instruction in the design and use of computing machines.

Mr. Edgar Reich of Rand Corporation.

Dr. O. Whitby, Stanford Research Institute, who discussed magnetic-tape input and output.

Captain M.S. McDowell of the U.S.A.F. Research and Development Command.

Mr. Peter Prentky and Mr. Francis V. Alla of the Raytheon Computer Project, who discussed stabilization of filament voltage and cycling of filament voltage.

Mr. D.R. Young of International Business Machines Corporation.

Mr. E.J. Smith of Brooklyn Polytechnic Institute, who discussed magnetic amplifiers.

Mr. M.E. Spitz, Mr. W.E. Pickett, and Mr. H.N. Goldman of Sylvania.

Mr. H.T. Larson of Hughes Aircraft, who was interested in the progress of magnetic-core storage.

Professor Sanai Mito of Harvard, and Dr. Kenichi Owaki of the Kobe Kogyo Corporation.

Mr. L.S. Pelfrey and Mr. G.R. Spencer of Raytheon who discussed transistors and transistor characteristics for computer work.

Mr. T.H. Bonn and Mr. W.J. Bartik of Eckert-Mauchly Computer Corporation, who were interested in magnetic-core storage.

Mr. L.P. Tabor and Mr. E.S. Krendel of the Franklin Institute, who were interested in using Whirlwind I.

Mr. T.V. Moore of Standard Oil Development Company.

Mr. W.E. Buescher, Materials Control Engineer, and Mr. C.A. Peterson of Sylvania Electrical Products, Inc., who discussed methods of measuring cathode interface resistance.

Mr. W.E. Elliott of Elliott Brothers, England, and Mr. H.J. Crawley of National Research and Development Corporation, England.

Mr. R.G. Counihan of International Business Machines Corporation, who discussed magnetic cores and magnetic storage.

Mr. B.H. Geyer, Jr., Mr. C.D. Cockburn, and Mr. W.D. Novak of General Electric.

Mr. R.L. Sisson and Mr. H.H. Sarkissian, Director of Applied Research, Computer Research Corporation, who discussed magnetic tape units and magnetic drums.