The Design, Construction, and Performance of a Large-Scale General-Purpose Digital Computer

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THE PRINCIPLES OF operation of the computer to be discussed in this paper have been described in the paper by Dr. T. Kilburn. The basic techniques required for the design and construction of a satisfactory computer were developed by Professor F. C. Williams and his group at the University of Manchester, and the Computer Section of Ferranti Ltd. have therefore made use of these proven techniques in their engineering approach to the problem of constructing a reliable computer. This paper describes the engineering techniques used and evaluates the performance of the computer to date, with a brief reference to the types of problems being handled on the computer. The first computer of the type described (Figure 1) now has been installed at the University of Manchester, and the construction and testing of further similar machines is proceeding.

Construction of Computer

In the development of digital computers, the point now has been reached where it is possible to produce a logical design for a computer, which will fulfill the requirements of the mathematical specification, and which can be constructed, in terms of circuits and components, with a reasonably certain expectation of success. The usefulness of a computer must therefore be entirely judged by its reliability in operation and the ease of maintenance. Consequently great importance must be attached to the mechanical design. This design must provide a very rigid base for the mounting of valve circuits with their associated components and for the interconnection of these circuits. Furthermore, the design must allow all components and valves to be readily cooled and also must allow easy access to any valve or component for testing and maintenance. It is believed that the construction of the Ferranti Computer fulfills all these requirements.

For most of the circuits a standard chassis has been used which takes a maximum of eight pentode-type valves, 27 diode valves, 66 components, a filament transformer, and 28 outlets, 14 at each end. The components are mounted on turret tags, the design of the tag strips being such that the leakage path from any tag is to earth, rather than to the adjacent tag. These chassis are mounted in doors, a typical door containing six chassis, Figure 2. The outlets on the hinge side of the door are connected via special Plessey connector strips, to flexible leads which terminate adjacent to the horizontal pulse lead ducts. The outlets on the handle side of the door are used for high-tension leads and for interconnections between chassis. The wedge shape of the chassis allows easy access to the valve bases and the inner ends of the components without increasing overmuch the size of the chassis. As the chassis are mounted in a vertical plane, there is effectively a metal sheet between the valves and the components, and hence the cooling problem is simplified. Further, the open type of chassis construction ensures that no hot spots can develop inside the chassis. When the circuit doors and the cover doors are closed the valves and the components are each enclosed in a separate chimney, so that there is a certain amount of convection cooling, which would, in fact, suffice for reliable operation. A forced ventilation system has been installed, and there is only a 10-degree centigrade rise in the temperature of the air extracted from the computer.

The swinging door type of construction gives very good accessibility to all circuits without changing their conditions of operation. This problem is simplified by the fact that all signal pulses are of at least 30 volts amplitude, whereas gate and trigger levels are of the order of 5 volts, so that small variations in capacitance or cross talk have no effect upon the operation of the circuit, Figure 3. In a serial computer of this type there is very little opportunity for the standardization of circuits and there is therefore no provision for the replacement of faulty units. It is found in practice that the majority of the time spent in trouble shooting is devoted to the location of the circuit at fault. This time is much decreased by the use of test programs, which rapidly check the operation of the computing elements, and indicate the location of any fault that is present by means of a code character, which, used in conjunction with a reference table, localizes the fault, sometimes to an individual valve, and at worst to an 8-valve chassis. Replaceable chassis would have very little effect on the maintenance time, and would certainly introduce another source of possible failures in the plug-in connectors.

For rapid checking of basic waveforms and the provision of triggering pulses for the test monitors, plug points are fitted to each door, supplying the useful waveforms.

Pulses are led around the machine in air-spaced cable ducts, there being a total of 160 such leads available. Each cable run goes from the center of a bay to the center of the adjoining bay, all junctions and interconnections being made at the center of the bays, where leads from the circuit doors are terminated. With this form of construction it is possible to standardize the construction of the bays and cable ducts and to make the interconnections specific for each bay by point-to-point wiring on numbered terminals.

The power supplies to the bays are carried on heavy copper busses along the top of the bays, and are individually fused before going to each door. The current for the valve heaters is derived from a 115-volt 1,600 cycle-per-second motor generator set, whose output is electronically stabilized. Incorporated in the electronic stabilizer is a system for slowly switching on the heaters over a period of 1½ minutes, and closing down in a similar time. With this system the heater volts are stabilized to better than 1 per cent, while the provision of multiple output transformers on each chassis ensures that there is no undue heater cathode voltage difference.

There are three main high-tension busses each of 15 amperes, at 300, 200, and 150 volts, and four low current supplies, three similar to the above, but highly sta-

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Figure 1. General view of the computer installed at the University of Manchester, with part of the control desk in the foreground

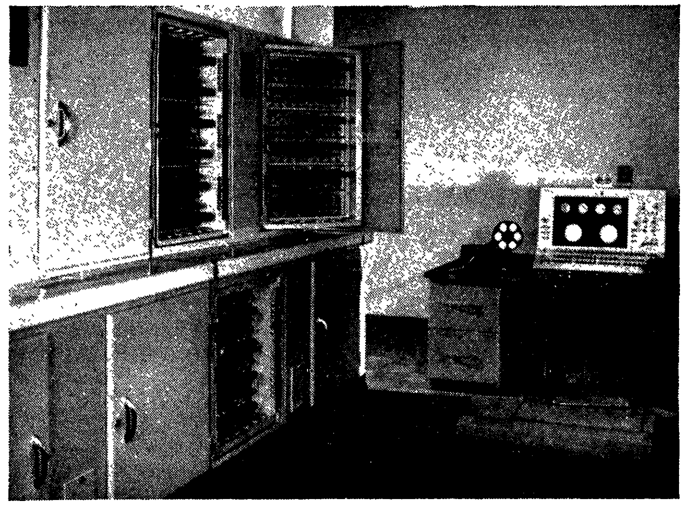


Figure 2. A view of the computer, showing circuit doors, with the control desk in the background

bilized, and a +50-volt stabilizer supply. The three main supplies are obtained from motor generator sets, with electronic voltage stabilization, and smoothed by an electronic filter network consisting of a choke with an a-c connected shunt-type stabilizer on the output. With this system the over-all stability is considerably better than 1 per cent and the peak-to-peak ripple, under machine computing conditions, is less than 0.25 volt. All power supplies, and every valve in the stabilizing system, can be metered, and the stabilizers, which are of identical construction, can be rapidly changed. The whole system is interlocked, so that the high-tension voltage cannot be switched on before the heaters, and all the high-tension voltages must be available before power can be supplied to the computer.

The Electronic Design of the Computer

The computer is fundamentally a low-speed machine, as the basic digit frequency is only 100 kc per second. High computing speeds are obtained, however, by virtue of the rapid access time of the Williams type storage system. A further advantage of this type of storage system is that the period allowed for the computing circuits to operate, sometimes known as the 'meditation' time, is accurately defined. Information is received from the store not later than 1 microsecond after the beginning of the digit period, and information must be returned to the store not later than 3 microseconds after the beginning of the digit period. Hence there is a meditation time of 2 microseconds during which the computing circuits must settle to their final configuration. As the meditation period has a mark space ratio of 1 to 4, it is possible to be quite sure of the independence of successive digits. An average 1,000 arithmetic operations per second are performed.

Because of this low basic pulse rate, it is possible to make use of the accurate bottoming characteristic of a pentode such as the *EF50*, the approximate American equivalent of which is the *6AC7*. A 'bottomed' *EF50* has an output impedance of 2,000 ohms, and it is found that all *EF50* valves bottom in the range +12 to +18 volts for an anode load of 47,000 ohms. As negative going pulses are used throughout the computer, the negative excursion is defined by the values of the level changing resistor network, whilst the positive excursion is held at ground level by a catching diode on the output of the resistor network. As a result of this simple definition of voltage levels the machine may be connected in a completely d-c manner, thereby overcoming all doubts about the dependence of machine operation upon variation of digit patterns.

When the circuit design was started it was intended to assume a 30 per cent variation in valve slope, ±20 per cent change in component value, and ±10 per cent change in high-tension voltage. It was found that although the first two requirements could be fairly easily met, it was difficult to satisfy all three requirements simultaneously. Hence, in view of the stability of the power supplies provided, designs were based on the first two requirements only. As a final safeguard 10 per cent components were used throughout the machine.

In the circuit design no attempt has been made to minimize the number of valves, or to make use of waveforms which were just good enough. In spite of this, the over-all number of valves is very small when compared with the number of facilities available in the computer. Throughout the machine all the trigger and counter circuits make use of the same basic circuit, in which the triggering and retriggering pulses are applied to the grids of the valves, and the crossover switching networks are connected to the suppressors. The suppressor waveforms are fed into cathode followers, the outputs of which are used as the output waveforms from the circuit.

Gating circuits normally use an appropriate assembly of diodes, although multi-electrode valve circuits are used in cases where fast operation is required.

In arranging the decoding of the function numbers to set up the required routes through the machine for a specific operation, there are two alternative schemes. One is to have a central decoding station, with as many outputs as there are functions, using each output to operate the required gates and circuits by means of multiple 'OR' gates. The alternative scheme is to decode at each functional gate or circuit. As many such gates or circuits have to be operated for more than one function, it is possible to save on decoders by decoding on only part of the function number, that is, the decoder may be made operative for 1, 2, 4, 8 . . . function numbers. With this system care has to be taken in the allocation of function numbers to the various functions, but that the system is economical compared with the central decoding station system will be seen from the following:

Number of functions	52
Number of function gates and circuits	53
Total number of operations for function gates and circuits, for all functions	184
Number of decoding units in central decoding station	52
Number of decoders in system used	53

It has not been found that the latter system, which is used in the computer, has introduced any difficulty into the maintenance and testing of the machine. Although one extra decoder is required for the system adopted, the 53 decoders perform the 184 operations without any additional encoding. The more conventional decoder and encoder would have used approximately three times as much equipment.

It should be noted that no special valves or components have been used in any part of the equipment. Of the four main valve types used, the *EF50* is employed in most circuits, the *EF55*, of which the American equivalent is the *6AG7*, is a high power valve used chiefly for cathode followers, the *EA50* (*1/26AL5*) as the switching diode, and the *EF91* (*6AK5*) as the amplifier valve in the cathode-ray tube and magnetic drum storage systems. The resistors and condensers used are all standard commercially available components, the resistors being ordinary carbon 10 percent tolerance items, except in a few cases where either 2 per cent high stability cracked carbon resistors, or high wattage wire-wound resistors have been used. All components are chosen so that the mean power dissipated in them is only 50 per cent of their nominal rating This under-rating of components, combined with the low ambient temperature, has led to very reliable operation, as will be seen from the later discussion of machine reliability. The following shows the approximate number of valves and components used in the computer:

Valves EF50	950
Valves EF55	350
Valves EA50	2,350
Valves EF91	300
Other types	50
Resistors	12,000
Condensers	2,500

The Cathode-Ray Tube Store

The principles of operation of the Williams Storage System have been widely described, and we will only remark that the present computer uses a mixture of two types of operation—the "defocus-focus" and the "dot-dash" systems. It was found that although the defocus-focus system was to be preferred as it showed a reduction in the number of troublesome 'phonies', an increased amplitude of signal, and a reduced sensitivity to time base voltage fluctuations, it was not possible to obtain satisfactory single shot writing with the available 'digging' time of 1.8 microseconds, although the system was quite satisfactory at 5 microseconds. The addition of a very small amount of dot-dash type deflection, in which the focused dash was drawn to the edge of the area defined by the defocused dot, overcame this problem, and this method of operation has been found to be very reliable in practice.

Special cathode ray tubes are used which have several unusual features. The electron gun assembly, which is of the pentode type, is specially designed to give a finely focused beam at low accelerating voltages. At 1 kv on the final anode, the focused spot size is 0.3 millimeter. The alignment of the gun, and the assembly of the deflector plates is carefully controlled, the specification allowing 5 millimeters variation in the position of the undeflected spot from the center of the tube, with an X sensitivity of

$$\frac{660 \pm 80 \mathrm{mm/V}}{V_{a3}}$$

and Y sensitivity of

$$\frac{1{,}100 \pm 120 \mathrm{mm/V}}{V_{a3}}$$

These relatively close tolerances allow the tubes to be operated in parallel from the same time base systems, without reducing unduly the usable screen area, which measures 10 centimeters × 10 centimeters on a 6-inch cathode-ray tube. On this area are stored 1,300 digits on 65 20-digit lines, although on test 2,560 digits have been stored on the same area. The phosphor of these tubes consists of a thick layer of carefully purified Wille-

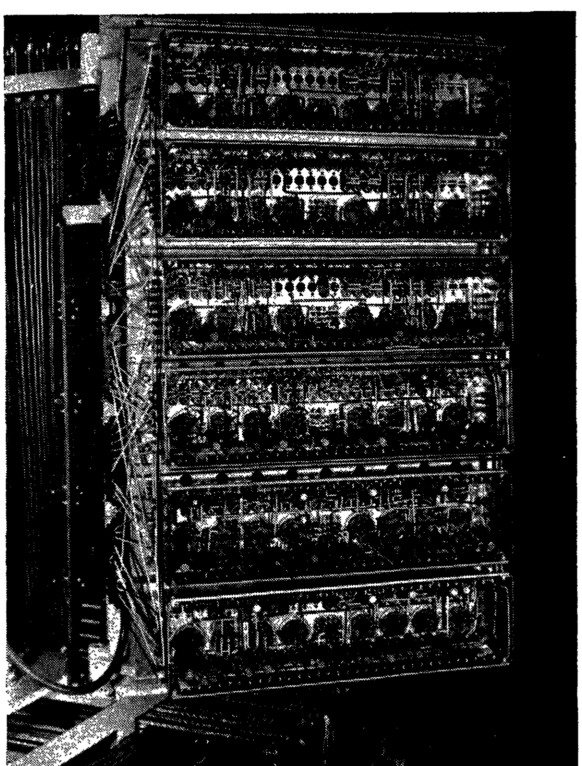


Figure 3 (left). One of the chassis doors, showing typical circuits and interconnections

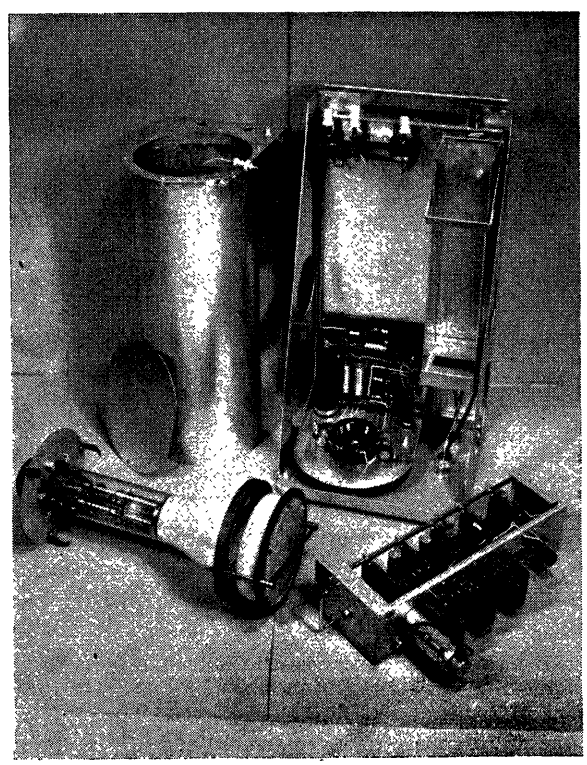


Figure 4 (right). The component parts of the cathode-ray tube storage unit

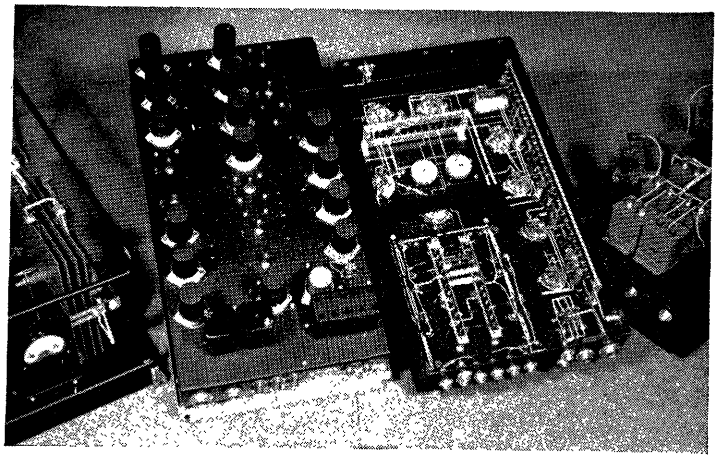


Figure 5. The timebase and stabilizer units

mite. The layer is made thick to overcome pin hole problems, and careful purification reduces the number of 'phonies', that is, points where the phosphor has an abnormally low secondary emission characteristic. The use of a silver coating as an inner conductive deposit instead of the more normal aquadag also helps to reduce the number of phonies.

The cathode-ray tube storage unit, Figure 4, comprising the cathode-ray tube assembly and amplifier, is enclosed in a shielded box. The cathode-ray tube has a shield fitted to its base, which also is an aid to the fitting of the tube into its socket. The pick-up plate is clamped against the face of the tube by means of a sponge-rubber-covered ring around the flare of the tube. This assembly fits into a double screening tube the inner cylinder of which is mumetal, and the outer mild steel. After the tube is in position a front panel is fitted to the shielding tube. The cathode-ray tube shield is grounded at one end only, to prevent circulating currents, and the amplifier is placed immediately alongside with a very short lead from the pick-up plate to the first stage grid. This amplifier, which has a pass band of 5 to 750 kc per second, is of fairly conventional design except for two features. It has been found that many so-called low-noise amplifier valves produce sporadic pulses of the order of 1-2 millivolts more frequently than would be expected from ordinary noise theory. Two valves which show an improvement in this respect are the *EF37A* and the *M.E. 1400*, the latter being used for the first stage. The other feature of this amplifier is the introduction of a delay line into the cathode of the penultimate stage. As the time constant of the first grid circuit is long compared with the digit period, asymmetric waveforms are produced in normal regenerative operation, with consequent dangers of shift of zero level, and movement of the grid base. The introduction of the open circuited delay line makes the normal regeneration signals symmetrical and reduces the asymmetry of the waveforms produced when writing is taking place.

The extra-high-tension unit, the time bases, and the time base high-tension stabilizers are special units, Figure 5. The X and Y time bases, in the center, are antivibration mounted, and are supplied with carefully smoothed high-tension derived from a stabilizer, part of which is shown on the right. The extra-high-tension unit is not regulated, but is derived from the stabilized 115-volt 1,600 cycle-per-second supply. Part of this unit is shown on the left of Figure 5. The high-tension stabilizers are of an a-c type, as variations in voltage at frequencies less than 5 cycles per second are unimportant. The amount of ripple permissible on the time bases is 20 millivolts, and the peak-to-peak ripple on the output from the stabilizers is less than 10 millivolts.

On test, storage patterns have been stored for periods of up to 40 hours without error, and the cathode-ray tube life appears to be at least 12,000 hours,

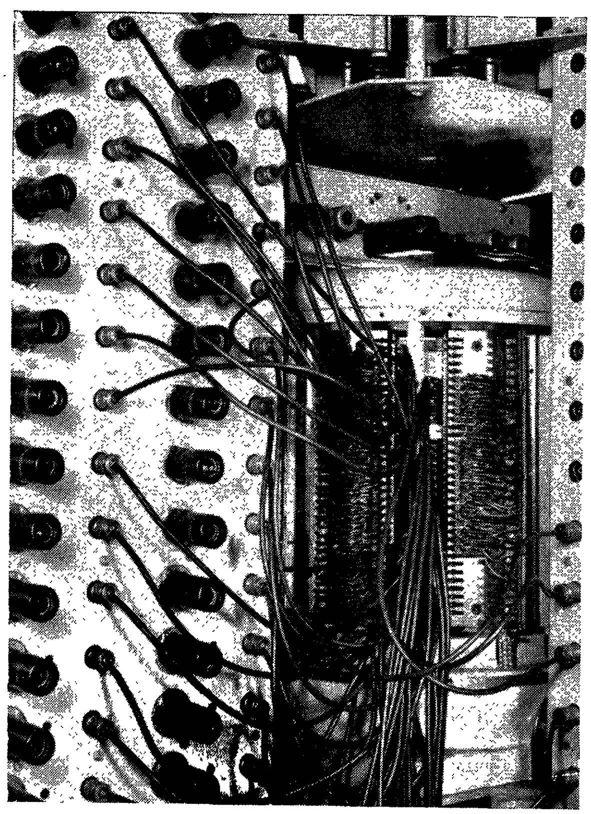


Figure 6 (left). The magnetic storage drum and associated equipment installed in the computer

Figure 7(below). A detailed view of the construction of the magnetic storage drum

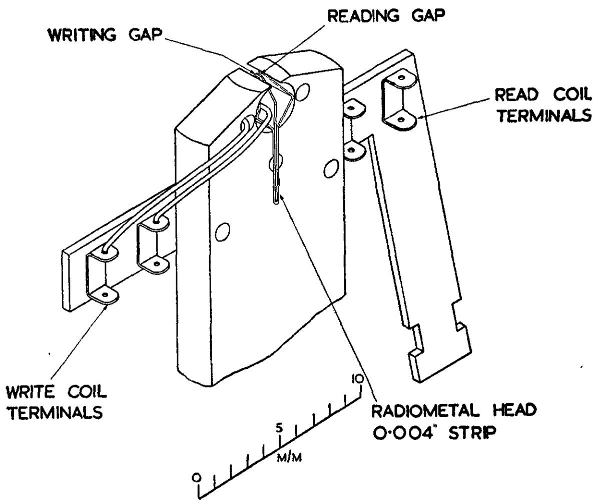


Figure 8. Schematic view of the magnetic recording head

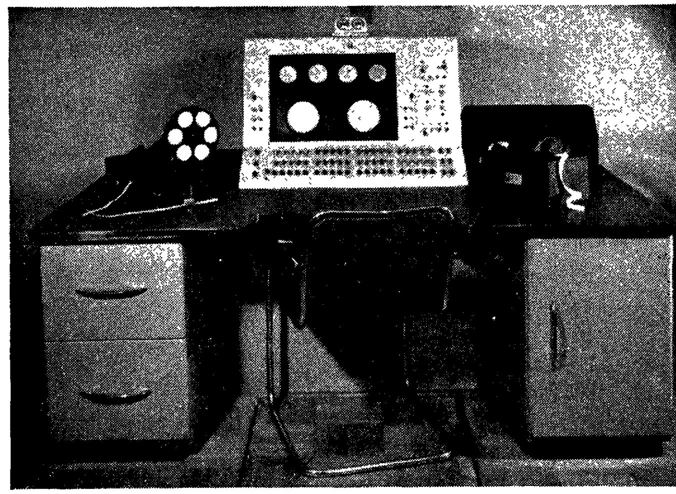


Figure 9. The control desk, with console and input-output equipment

as no tubes have failed since the computer was brought into operation. Furthermore, the stability of operation appears to be very good, as minor adjustments only have had to be made to three of the 12 stores in operation during the last three months.

The Magnetic Drum Storage System

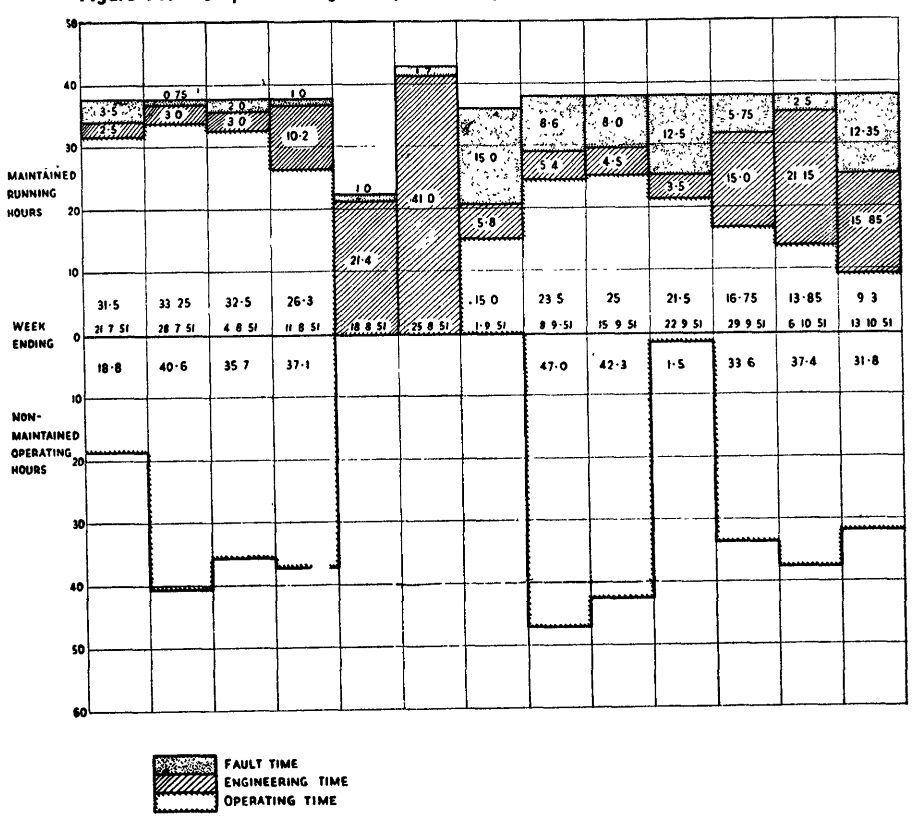
The outstanding feature of the computer is the very large backing up magnetic drum store, which may be truly considered as the main storage system. This has an ultimate capacity of 655,360 digits, or approximately 16,000 long numbers. So far a capacity of 4,000 long numbers has been installed, Figure 6.

The basic drum, Figure 7, consists of a cylinder 8½ inches long and 6 inches in diameter, driven internally by a squirrel-cage induction motor. Its normal running speed is 1,950 rpm and it has an eccentricity of less than 0.0003 inch. The drum is plated with a thin film of nickel, and precautions even more stringent than those taken in gramophone record processing have to be taken, as any impurities or pin holes in the nickel film would lead to unreliable operation. Each recording head is 0.012 inch wide, and there are approximately 170 digits recorded per peripheral inch, or 2,088 digits per track.

The drum is run in synchronism with the basic clock waveform generator of the computer, and the positional synchronising accuracy is 1/100 degree or approximately 0.0005 inch at the circumference. This accuracy of synchronization is obtained with a circuit similar to those used for "balanced strobes" in radar systems, a series of pulses recorded on the drum being balanced against a clock waveform. The total linear range of the servo is $\pm 1/30$ degree, so that the desired accuracy is readily achieved if there is no external disturbing force. Any such force would necessarily come from the drum bearings, which are of extra precision finish, and the drum had therefore been designed with a very high inertia friction ratio to offset any irregularities in running. If a disturbing force equal to twice the normal running friction is assumed to be dangerous, then it may be shown that an inertia-friction ratio leading to a run down time to standstill of 23 minutes is necessary. The drum in use has a run down time of over 30 minutes, so that there is a considerable margin of safety. The braking force is applied to the drum by means of an eddy current brake, mounted on an assembly similar to the driving motor.

The recording system used is one of phase modulation in which a square wave recording current is used, the waveforms being positive or negative at the strobing time dependent upon whether a 1 or a 0 is to be written. The advantage of this system is that the waveform is balanced about zero, and hence no d-c component need be considered in the design of the transformers associated

Figure 10. Graph showing the operational performance of the machine to date



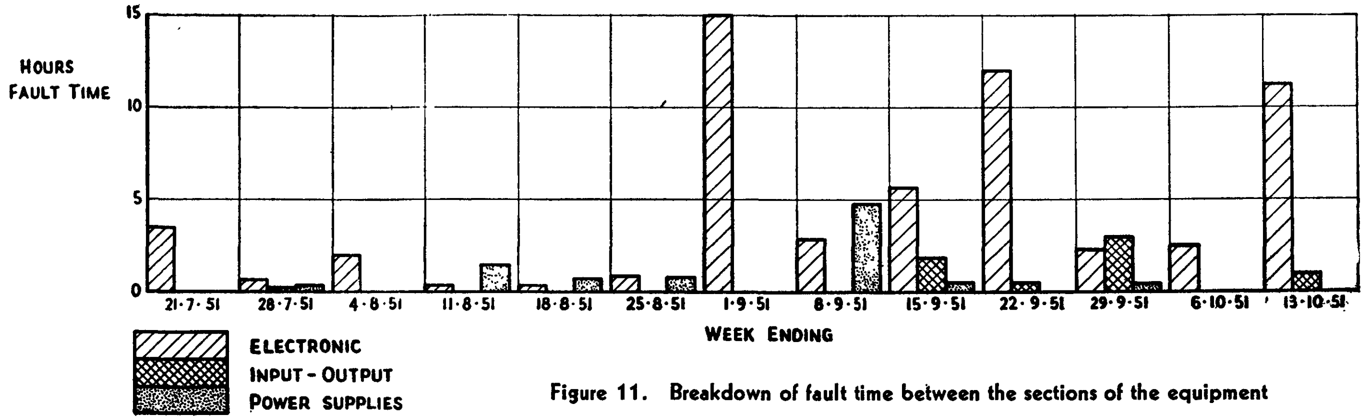


Figure 11. Breakdown of fault time between the sections of the equipment

with the reading and writing system. Since the recording is at the basic digit frequency of the machine, it is necessary to provide two heads per track, one for reading and one for writing, spaced apart by rather less than one digit length. The strobe examining the input digit waveform is placed one third of the way along the digit, so that the recording waveform is 1/3 of a digit late on the input. As the peak amplitude of the output waveform is examined there is a further 1/4 of a digit delay, giving a total of 7/12-digit delay. There also is a slight delay in the reading amplifiers, so that a total delay of approximately 5/6 of a digit is introduced. Hence to restore the correct timing the reading head must be placed in advance of the writing head by approximately 0.005 inch. The method of achieving this is shown in Figure 8 which shows the construction of an individual read-write head.

There are 256 tracks on the drum, obtained by interleaving eight blocks of heads. Each head is selected for writing by means of a relay tree, and each head has a final transformer of 20:1 step down to provide the head writing current of 4 amperes. The selection of a track for reading is by means of a switched amplifier tree.

The Input Output Equipment

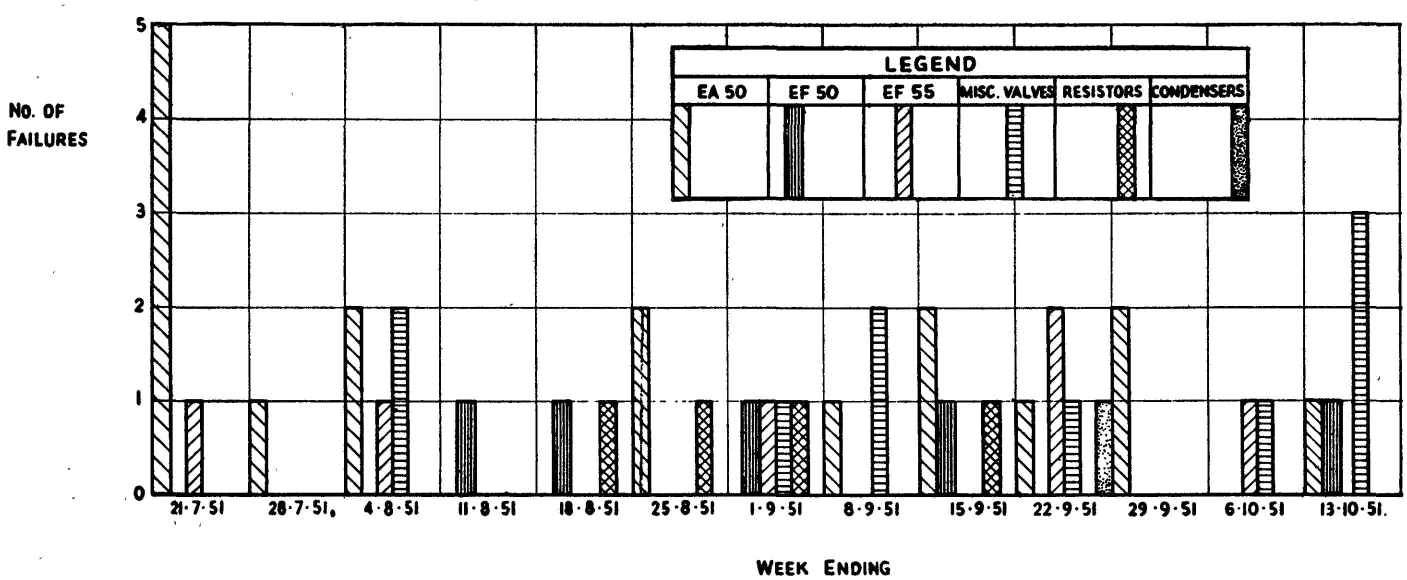
There are four units grouped on the control desk, Figure 9. In the center is the control console, with store displays, and switches for controlling the operation of the machine. On the left is the output tape perforator. In the right background is the teleprinter output, and in the right foreground the tape input unit.

The three main rows of switches along the bottom of the console are, at the top, a group whose setting may be used in the course of computation, by the use of the appropriate function number in the programme. In the middle is a group which simulates the ordinary instruction, and which is of great value in testing the machine without using a program, whilst the bottom row enables single digits in the main store to be changed. A prepulse switch initiates computations, which may proceed at 1,000 operations per second or at a reduced speed of 50 operations per second. Alternatively only one operation may be carried out for each movement of the key.

The right-hand panel has controls for the input-output equipment, high-tension "on" "off," and indicators showing the sign of the accumulator, multiplier, er cetera.

The cathode-ray tube display has along the top the contents of the four subsidiary stores, from right to left, the B-tube, control, accumulator, and multiplier tube. Underneath are the two main displays, each of which may be made to show the contents of any of the eight main stores. The input equipment consists of a specially developed photoelectric type of reader which can accept information at very high speed. As soon as the computer has called for a character from the input, the reader moves the tape on to the next character, and stops there until another input operation is called for. If the tape is stationary on a character, then the next character is available for reading in 5 milliseconds, giving a mean speed of 200

Figure 12. Details of valve and component failures



characters/second, whilst if the tape is not brought to rest, a maximum speed of 250 characters/second is possible. On test this equipment has read 500,000 characters at a time without error, and a loop of tape has been passed through the reader 10,000 times without any sign of wear. From experience to date this part of the equipment would appear to require maintenance at about three monthly intervals.

The output equipment is basically standard teleprinter apparatus, operating at normal teleprinter speeds. The most important addition to this equipment is a check system. Contacts are fitted to the interposers (for the punch) and combination combs (for the teleprinter) and the output operation is only released when these contacts have the same configuration as the electronic equipment operating the output system. Faulty operation of the contacts due to dirt et cetera, will result in a failure to check and computation will be stopped. Manual resets are provided to release the output equipment.

Present development work on the output equipment includes the provision of a tape punch operating at a speed of 50 characters per second, and a parallel type printer operating at 160 characters per second.

Applications of the Computer

The programmer will find that there are two points about this machine which differentiate it from most others—the presence of a large and readily available backing store, and the B tube. Of these two, the first is certainly the most important, as anyone who has coded for a machine with a restricted store will realize.

The provision of a magnetic storage drum has two effects from the point of view of the machine user. The first, of course, is that it widens considerably the class of problem which can be handled: for example, network analysis problems involving the inversion of symmetric matrices containing up to 80 × 80 complex elements are being tackled, and this task is still well within the capacity of the machine.

The other effect is perhaps not so obvious, but is even more important in the long run. The devices which a programmer must use in order to conserve space when he is operating with only a small store have perhaps only one thing to be said in their favor and that is that they give their inventors the feeling of satisfaction which usually arises from the solution of mathematical puzzles. Apart from this, such devices are usually error-provoking and they render programs containing them difficult to explain to the neophyte.

Once, then, the confining effect of a small store is removed, the justification for using 'tricks' becomes very much less, and a substantial saving in programming time results. This point can be best appreciated by those who have programmed for both a machine with small storage and one with which, for most problems, space virtually ceases be a consideration.

One other point about the use of a storage drum is that it becomes possible to keep many basic subroutines and machine testing routines permanently in the machine—a convenience which helps both the user and the maintenance engineer. In fact, the importance of some subroutines is such that the writing head associated with the track in which they occur is disconnected. They cannot then be written over by mischance.

The convenience of the B tube is greatest in routines which have a large number of varying addresses in the inner loop, matrix operations being typical—in such cases, program times may be more than halved. The B tube also is useful as a set of short-line accumulators for simple operations.

Subroutines

A fair basis of comparison between computing machines is the time taken to do various standard subroutines; a selection of these times follows. The times stated are the maximum times, and they include the time taken to transfer the subroutine from the storage drum to the cathode-ray tube store (0.03 seconds).

Square Roots and Reciprocal Square Roots

These are for convenience produced by one subroutine, the results being presented in standardized form. Time: 0.105 second.

Cosine

This forms the cosine of an angle between $-\pi$ and $+\pi$, and it is accurate to 11 decimal digits. Time: 0.08 second.

Natural Logarithm

This extracts the natural logarithm of a number lying between 2^{40} and 2^{-40}. Time: 0.08 second.

Reciprocal

The result is presented in standardized form. Time: 0.095 second.

Inverse Trigonometrical Routine

Given the sine and cosine of an angle, this finds the angle (lying between $+\pi$ and $-\pi$). Time: 0.10 second.

Reciprocal of a Matrix

Because of the organization of the transfer of information from the magnetic drum, matrix operations are most conveniently carried out by using 4 by 4 submatrices as the unit of operation. A reciprocating subroutine which standardizes each submatrix after operating on it is being developed, and it is expected that the approximate time taken to invert an $n \times n$ matrix will be 0.04 n^3 second.

Longer Calculations

Among the industrial computations which have been and are being carried out may be mentioned the following:

1. Investigation of the behavior of a cotton thread in a ring spinning device. This investigation now is complete and occupied in all ten hours of machine time (most of which was for actual computation). Taking into account centrifugal force and air resistance the problem involved the solution of a set of four linear simultaneous differential equations and was used as a test case for the general routine for solving such equations. The method used is one of the Runge-Kutta type giving 4th order accuracy in the length of the interval.

2. Computation of Laguerre functions. It is expected that about 30 hours of actual computing time will be taken up with the tabulation of the required functions, most of which will be printing time.

3. A study of power network problems requiring the computation of load flows and of machine swing curves. A program is being constructed which will have general application to any power network within the storage capacity of the machine.

Evaluation of Machine Performance to Date

For the purpose of this description the period July 14, 1951 to October 13, 1951 inclusive will be considered. The week beginning July 14, 1951 was the week following the formal handing over of the computer, and it has become apparent, even within these 13 weeks of operation, that several improvements can be made in the method of running a machine from an engineering view point.

When the system was first started, no formal maintenance period was allowed—the machine was switched on at 8:30 a.m. and handed over to the operators at 9 a.m. if working. Each operator was allocated a given number of hours per day, but if the machine became unserviceable during an operator's period, then that operator was not recompensed for the time lost in servicing. Hence there was a tendency not to report faults, but to continue to attempt to use the machine.

This tendency was particularly noticeable when the faults were of an intermittent nature. After the first four weeks of operation this system was changed to one in which the allocation of time for a week was based upon the previous week's record. It is interesting to note the very large increase in fault time starting at the seventh week when the holiday period was over. Operators now are willing to devote time to helping the maintenance engineer trace faults always on the understanding that this time is booked as fault time.

As the system is worked at present, there is a fixed maintenance time—8:30 to 10:00 a.m.—each day, and the maintenance engineer is in attendance until 5:30 p.m. If the machine is serviceable at 5:30 p.m., it is kept in operation and is used until either the operators have completed their schedule of work or a fault develops. This system tends to cause violent fluctuations in nonmaintained operating time, as even a very simple fault will cause the machine to be closed down until the following day.

Nevertheless the long hours logged during nonmaintained hours are very encouraging and it is therefore the intention, as soon as maintenance engineers are trained, to put the machine on to a 24-hour service, probably for five days per week.

The time devoted to engineering covers a number of activities. Any computer can always be improved, especially in the first few months of its use for computation, and this machine has proved to be no exception. Part of the time shown in Figure 10 has been devoted to the installation of magnetic storage—only a very limited storage was available at the dedication date—a random number generator has been installed, and a number of circuit modifications made. As a result of the experience gained, new circuits are being developed, and these will be incorporated in the machine as they become available.

A total of 834 hours has been logged since dedication, with 74½ hours fault time, that is, practically 90 per cent availability. It is confidently expected that these figures will show a considerable improvement with better fault finding techniques and experience and longer periods of available maintenance.

A more detailed analysis of fault time, as shown in Figure 11, indicates that, as is to be expected, of the three subdivisions, the electronic equipment was responsible for the majority of faults—approximately 80 per cent of the total fault time. Most of the fault time in both the electronic equipment and the power supply equipment was due to valve failures, whilst mechanical faults caused most of the failure time in input-output equipment, due chiefly to the use of prototype equipment which was not suitable for prolonged operation. New input-output equipment is now installed with a consequent reduction of failures.

In the computer there are 4,000 valves, 12,000 resistors, and 2,500 condensers, and the total number of failures for each of the main valve types, and the components, is shown in Figure 12. It will be observed that there has been a total of 39 valve failures in the past 834 hours. If we assume an exponential valve life expectancy, we obtain an average valve life of 85,600 hours. In the same time there have been failures in three resistors and one condenser, which on the same basis leads to lives of 3,336,000 and 2,085,000 hours respectively. In view of the fact that standard, commercially available valves and components have been used, it is considered that these figures are satisfactory for what is still a running-in period.

Joint Discussion*

B. Moffat: (Mellon Institute): Dr. Kilburn, what speeding up, quantitatively, do you get through the use of the Williams' tube? In other words, at what speed does the arithmetic unit progress with respect to the relatively slow synchronized reading in the Williams' tube?

T. Kilburn: As I understand your question you mean what speed would you get if you left out the Williams' tube and just used the magnetic drum.

B. Moffat: No—as differentiated from the magnetic drum.

T. Kilburn: The digit frequency is 10 microseconds and the digit frequency on both the cathode-ray tube and drum is the same. The difference in speed is simply in the access times.

B. Moffat: I did not see why, if the drum and tube are synchronized, the access is faster with the Williams' tube.

T. Kilburn: The required line of the raster is immediately available. In the parallel machine the required spot area is immediately available.

W. L. Martin: (University of California, Los Angeles): A question of Mr. Pollard. I would like to ask the size of the cathode-ray tube and the approximate cost, also any data on the cost of the whole computer.

B. W. Pollard: The size of the cathode-ray tube is approximately 6 inches in diameter, and the tube is 14 or 16 inches long. The tube is made by the General Electric Company of Wembley, England. I do not think I am competent to quote the price they would quote to you—but it would be something of the order of £30.

Your second question was the price of a complete computer of the type we have been describing. We are proceeding with the construction of further models and we have at the present time two under construction, due to be completed in the next few months. One of those may be available at around $400,000 to $450,000, which will include free maintenance for one year, and also installation.

A. H. Taub (University of Illinois): I would like to ask either of the speakers about the organization of the various memories. If one has a problem such as a partial differential equation where the program is of the order of 3/4 of one of the pages and the initial data is of the same size, so at each stage if the solution one has to refer to a page and a half, does this mean that the machine is stopped or is there any other "out"?

T. Kilburn: There are eight cathode-ray tubes and—did you imply the total amount of data was just a page and a half?

A. H. Taub: I meant to imply that each step of the inner race cycle was, since there are eight cathode-ray tubes, $8^1/_2$ pages.

T. Kilburn: I can assure you, on our machine that there are a lot of problems for which the cycle is less than eight cathode-ray tubes, because the choice of eight tubes is made on the basis that there are a lot of such problems. In the machine there are emergency compartments left for the provision of more cathode-ray tubes up to a maximum of 16.

J. Fedako (Eckert-Mauchly Computer Corporation): Did you mean to imply you can't print-out while computing?

B. W. Pollard: I merely meant that the Teleprinter is an awfully slow device at ten characters a second. However, in the output system, once the five digits have transferred to the output staticisers the machine is immediately released for further computation and the machine will only be stopped if another print-out order was called for, whilst the printing operation is going on. In other words, exactly the same system as the ERA 1101, which was described earlier this afternoon.

J. Brustman (Remington Rand): I have two questions. What is the dot and what is the dash time? Secondly, do you use any focusing or defocusing time and, also, do you use any automatic devices for holding, such as gain control, et cetera?

T. Kilburn: The defocus time is 1.8 microseconds and there is the "meditation" period of 1.2 microseconds whilst the computing circuit wonders what the answer is. There is then the focus time corresponding

* This joint discussion covers both this and the preceding paper by F. C. Williams and T. Kilburn on the University of Manchester Computing Machine.

to the dash period which is 4 microseconds followed by a blackout period, during movement to the next digit, a total of 10 microseconds. Speed of operation has not been a prime object of design. We have been content to accept the natural speed of operation of the components used in the machine and we have taken full advantage of the fact that we knew we were going to have a large storage capacity in the machine, giving quite a good speed of operation. Automatic control is applied only to the gain of the pick-up amplifier.

G. E. Reynolds (United States Air Force, Cambridge Research Center): I have a question for Dr. Kilburn. The random number generator that you mentioned—may we have a few details?

T. Kilburn: It operates on the principal that one takes a noise source and allows it to control a counter. The state of the counter is inspected every so often and the nought or one obtained is put in the accumulator of the machine and moved upwards before the next nought or one is put in. This continues until a 20-digit number is assembled in the accumulator.

E. Blumenthal (Eckert-Mauchly Computer Corporation): I would like to ask of either speaker the reason for using a servo system for the master oscillator to control the drums rather than the sprockets and using that as your oscillator.

T. Kilburn: This is an opening sentence in a debate that never ends, in England. I will tell you why we did that, and you can be the judge as to whether it is right or wrong.

In the early stages, we did not know whether or not we would have more than one drum inside the machine. If we did require this, then we should have had to synchronize the second drum to the first. Thus we faced this problem of locking in the drum to a master oscillator immediately. The servo-mechanism is extremely reliable.

The Whirlwind I Computer

R. R. EVERETT

PROJECT Whirlwind is a high-speed computer activity sponsored at the Digital Computer Laboratory, formerly a part of the Servomechanisms Laboratory, of the Massachusetts Institute of Technology (M.I.T.) by the Office of Naval Research (O.N.R.) and the United States Air Force. The project began in 1945 with the assignment of building a high-quality real-time aircraft simulator. Historically, the project has always been primarily interested in the fields of real-time simulation and control; but since about the beginning of 1947 most of its efforts have been devoted to the design and construction of the digital computer known as Whirlwind I (WWI). This computer has been in operation for about 1 year and an increasing proportion of project effort now is going into application studies.

Applications for digital computers are found in many branches of science, engineering, and business. Although any modern general-purpose digital computer can be applied to all these fields, a machine is generally designed to be most suited to some particular area. Whirlwind I was designed for use in control and simulation work such as air traffic control, industrial process control, and aircraft simulation. This does not mean that Whirlwind will not be used on applications other than control. About one-half the available computing time for the next year will be assigned to engineering and scientific calculation including research in such uses supported by the O.N.R. through the M.I.T. Committee on Machine Methods for Computation.

These control and simulation problems result in a specialized emphasis on computer design.

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Short Register Length

WWI has 16 binary digits and the control problems are usually very simple mathematically. Furthermore, the computer is almost always part of a feedback rather than an open-ended system. Consequently, roundoff errors are seldom troublesome and the register length can be shortened to something comparable to the sensitivity of the physical quantities involved, perhaps five decimal places or less.

WWI has a register length of 16 binary digits including sign or about four and one-half decimals. The register length was chosen as the minimum that would provide a usable single-address order, in this case five binary digits for instruction and 11 binary digits for address. In a future machine we would probably increase this register length to 20 or 24 binary digits to get additional order flexibility; the increased numerical precision is less important.

For scientific and engineering calculation, greater than 16-digit precision is often required. There is available a set of multiple-length and floating point subroutines which make the use of greater precision very easy. It is true that these subroutines are slow, bringing effective machine speed down to about that obtained by acoustic memory machines. It is much more efficient occasionally to waste computing time this way than continuously to waste a large part of the storage and computing equipment of the machine by providing an unnecessarily long register.

High Operating Speed

WWI performs 20,000 single-address operations per second. Control and simulation problems require very high speeds. The necessary calculations must be carried out in real time; the more complex the controlled system is, the faster the computer must be. There is no practical upper limit to the computing speed that could be used if available.

Where the problems are large enough, and these problems are, one high-speed machine is much better than two simpler machines of half the speed. Communication between machines presents many of the same problems that communication between human beings presents.

Great effort was put into WWI to obtain high speed. The target speed was 50,000 single-address operations per second, and all parts of the machine except storage meet this requirement. The actual WWI present operating speed of 20,000 single-address operations per second is on the lower edge of the desired speed range.

Large Internal Storage

WWI now has 1,280 registers. A large amount of high-speed internal storage is needed since it is not in general possible to use slow auxiliary storage because of