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SYSTEMS ARCHITECTURE
FOR ELLIOTT 401, 402, 403 & 405 COMPUTERS

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ELLIOTT 403 - WREDAC - SYSTEMS ARCHITECTURE

(Edited by D. J. Pentecost)

There follows an extract from an Elliott Brothers (London) Limited paper, undated but bearing the reference code L29, and written by Elliott's Computing Machine Division, probably some time in 1954, when negotiations for acquisition of the 403 were in progress, for the opening paragraph mentions the use of magnetic tape for data storage, rather than Elliott's usual magnetic film, and magnetic tape was required by the customer, the Weapons Research Establishment (WRE) in Salisbury, South Australia.

The full version of the paper does not appear on this web site. The parts which have been omitted, define the details of the instruction set as initially conceived, and some of these instructions were changed and new instructions were added, particularly in relation to the handling of magnetic tape. The full instruction set does appear elsewhere on this web site in paper TRD39, which was written about five years later by a member of the WRE staff. There should therefore now be no conflict between the following extract, and the later TRD39; however, if any difference should come to light, details in TRD39 are more likely to be accurate, as represented by the eventual version of the computer in use.

SPECIFICATION OF THE ELLIOTT 403 ELECTRONIC DIGITAL COMPUTER

The standard Elliott 403 contains two stores known as the high-speed store and the auxiliary store. The machine has been designed to include a magnetic tape store at a later date and the specification below describes the machine with this store as an ancillary and includes a description of the full order codes.

1. BASIC SPECIFICATION OF THE MACHINE

Digit frequency	333 kc/s
Word Length	34 digits, i.e. 102 microseconds.
Order Length	17 digits, i.e. two orders per word.
High-speed Store	512 words, consisting of 127 4-word nickel delay lines and four 1-word nickel delay lines.
Auxiliary Store	16,384 words contained on a magnetic disc rotating at 2,300 rev/min. There are 64 tracks of 256 words, and each quadrant of each track is accessible for reading or writing of 64 words in a transfer.
Ancillary Store	Two magnetic tape units operating at 100 in/sec with a stop or start time of the tape transport less than 10 milliseconds and a tape packing density of 100 digits/inch. The tape to be used is 1/4" on the spools recommended by the British Standards Institution Committee. Tape lengths are to be greater than 1500 ft.

Input	(1) Punched 5-hole teleprinter paper tape via a Ferranti Ltd high-speed tape reader.
	(2) Magnetic tape via the ancillary store.
Output	(1) Punched 5-hole teleprinter tape via a Creed output perforator.
	(2) Magnetic tape via the ancillary store.
Radix Representation and Scaling	Numbers in the machine are radix 2 operating in the range $-2 \leq x < 2$.

2. ORDER CODE

The order code employed in the machine is single address. The least significant digit, i.e. d_{16}, of each order denotes whether the order is to be interpreted as an arithmetic or as a transfer instruction. If this digit is zero then the order is an arithmetic instruction; if it is unity, the order is a transfer instruction. Since there are two orders in each word the first order (or most significant half of the word) is known as the "even" and the second as the "odd". The details of each type of order are as follows :

2.1 Arithmetic Instructions (d_0 most significant digit, d_{16} least significant digit).

$$\underbrace{d_0\ d_1\ d_2\ d_3\ d_4}_{\text{Function F}}\quad \underbrace{d_5\ d_6\ d_7\ d_8\ d_9\ d_{10}\ d_{11}\ d_{12}\ d_{13}}_{\text{Address A}}\quad \underbrace{d_{14}\ d_{15}}_{\text{B-line Register}}\quad \underset{\text{Code "0"}}{d_{16}}$$

The 2 B-line digits specify one of three storage locations (1, 2 and 3) the contents of which are added to the order as it enters the order register.

The 9 digits of the address specify, in general, the location in the high-speed store to which the 5 function digits apply. The other uses of the address digits are described in the order code functions.

The 5 function digits specify the arithmetical or logical operation of the machine as is described in the order code functions. In all cases the result of any arithmetical operation is in the accumulator.

2.2 Transfer orders (d_0 most significant digit)

$$\underbrace{d_0}_{\text{Magnetic Tape unit}}\quad \underbrace{d_1\ d_2\ d_3\ d_4}_{\text{Transfer Function}}\quad \underbrace{d_5\ d_6\ d_7}_{\text{High-speed Store Block}}\quad \underbrace{d_8\ d_9\ d_{10}\ d_{11}\ d_{12}\ d_{13}}_{\text{Track}}\quad \underbrace{d_{14}\ d_{15}}_{\text{Track Sector}}\quad \underbrace{d_{16}}_{\text{Code "1"}}$$

These transfer orders relate to transfers of words between the storage units and also the input and output devices. The four digits d_1 to d_4 designate the type of transfer which is to take place. The basic transfer unit is 64 word blocks except where otherwise noted.

The transfer orders "read from paper tape" cause the five digits on the teleprinter tape to be added to the specified part of the accumulator and cause the tape to be stepped on by one row. Similarly the "punch" transfers step the tape on by one row.

All the block transfer orders are applicable to all store block units, e.g. any of the eight 64-word blocks of the high-speed store can be transferred to any of the 256 64-word quadrants of the magnetic disc.

For all transfer orders the operation of the machine is autonomous unless another similar transfer order is received by the control unit before the first is completed. Thus it is possible, in general, for arithmetical orders to be obeyed while a transfer operation is being performed. Similarly, a transfer to a magnetic disc sector from a given high-speed store block is possible while a transfer from a magnetic tape unit is being made to another high-speed store block.

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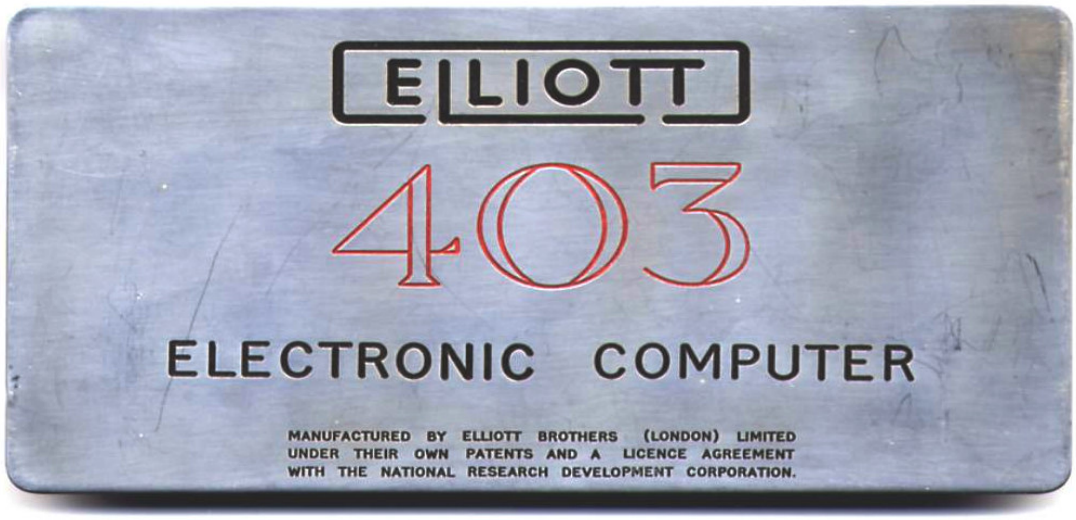
During investigations to produce the above systems architecture notes, several related articles and sections of books (including photographs) have come to light, which in part touch on the subject of the architecture of the 403. These articles were written with the history of computers being the main context, in some cases specifically in relation to the 403, and in others with the 403 being merely one of several computers discussed.

The articles, or relevant parts thereof, together form quite a good brief history of the 403. Rather than discard all this interesting material, it is reproduced below.

A BRIEF HISTORY OF THE ELLIOTT 403 (WREDAC) COMPUTER



The WREDAC nameplate, which was about 5" in width

Contents:

1. Recollections of the Elliott 400 series, by Laurence Clarke.

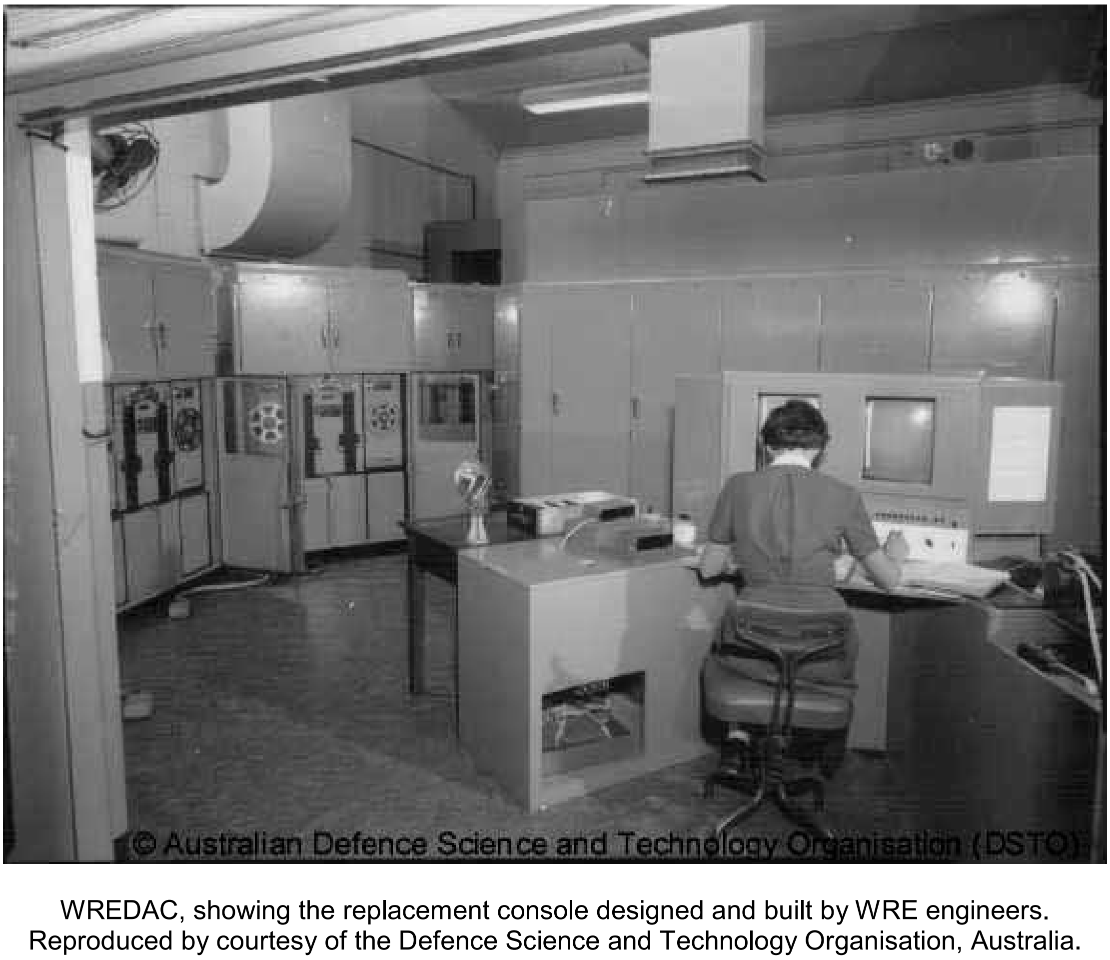
Nine 402 machines were made, which is not a lot. Almost all were still in service in 1969. During that period there were two other much larger machines made. The first was the 403 which was made for the Long Range Weapon Establishment in Australia. It was for the analysis of missile range status. This machine had pipelining in 1955!

It worked this way. We had four word nickel delay lines as the main store so we were getting somewhere near a good size immediate access store - 512 words - but it wasn't fast enough for what we needed. So orders were extracted in the single word lines (assuming no conditional transfer) and started to be decoded while the previous operation was being carried out.

It had of course a much larger magnetic disc, like the 153, and also magnetic tape units. These were manufactured by Pye to a Cambridge University design developed by Donald Wilkes. The output was offline because there was a tremendous amount of it. The magnetic tape was taken away and fed to Bull line printer, and also to a series of plotters.

I suspect that these were the first plotters to be used for output from a digital computer. They were very crude. They used Mufax weather report receivers, where there was a rotating helix which moved across the paper. An electrical signal was pulsed, and chemically sensitised paper made a mark where there was a pulse and didn't where there wasn't. With a binary disc we knew the position of the helix so we were able to get fairly accurate plotting.

The 403 machine dissipated about 15 Kw. My first task on arriving in Australia to finish the recommissioning was to switch it off, and tell the superintendent that it was staying off until the air conditioning was in proper working order. It seemed likely that the machine would be irrevocably damaged if it carried on in the Australian temperatures that were prevalent at that time.



WREDAC, showing the replacement console designed and built by WRE engineers.
Reproduced by courtesy of the Defence Science and Technology Organisation, Australia.

2. Engineering notes by Jack Smith & Peter Main

From Jack Smith's website:
WREDAC used vacuum tubes, and had nickel wire delay line storage and head-per-track disks.

It was "tested on margins" each morning. That is, the main power supply voltages were adjusted a certain amount each way from nominal (say 10%) and the machine tested to find any components which might be about to fail. [On one occasion] this resulted in half a bucket of vacuum tubes ("valves"). *[Ed: Margins testing was probably the recommended procedure, but in Peter Main's time - see his notes below - this appears not to have been the regular daily practice].*

The main "immediate access" memory was electro-acoustic delay lines for bit-serial storage of data. An electrical transducer generated longitudinal mechanical impulses at one end of a long spiral coil of wire held in slit slips of paper. A transducer at the other end was used to detect the arrival of the impulses. Damping material on the tails of the wire past the transducers was used to greatly attenuate any reflections of the pulses at the ends.

Bulk storage was on magnetic disk. Because each track on the disk had its own read and write heads, the principal determinant of access time was rotational latency; quite a fast system but with reliability problems because it did not use floating heads.

The main input was by paper tape reader and the output was by magnetic tape.

Notes by Peter Main:

Nickel wire [delay] lines. The transducer was a small coil about 3 mm diameter by 1 cm long around the wire. Of course this generated a longitudinal field, hence longitudinal waves. The receiving coil was very similar but had a small permanent magnet adjacent, the field of which was modulated by the magnetostriction effect of the waves in the wire, thus inducing a voltage in the receiving coil. On the whole the nickel wire lines were quite reliable and worked well for their vintage.

The WREDAC disk. It had a serious problem: unlike all rotating magnetic memories since, it had fixed (not flying) heads. They had to be adjusted to something like one or two thousandths of an inch off the disk surface. Of course this was almost impossible to maintain under thermal variations, so we were forever adjusting the head clearances. Some tracks had gone to negative clearance (now called a head crash!) and were useless. It was a proper beast ...

The initial orders. These were a primitive but quite clever relocating loader, resident on one of the few tracks of the disk that was sufficiently reliable. It had to be re-entered at the console, word by word in absolute binary, if the disk track failed (which did happen once in a while, but thankfully not often).

Hardware diagnosis. There were virtually no hardware diagnostic programs - most faults rendered the computer completely inoperable and had to be located the hard way, using a one- or two-instruction loop entered at the console, then scoping the various waveforms.

Testing on margins. The facility existed to vary the supply voltages for margins testing, but we had great difficulty getting the machine to work at all on margins (more than one simultaneous fault would usually arise, making diagnosis very difficult), and the practice was little used while I was there. Most valve replacements arose from testing modules out of the machine, on a module tester (also supplied by Elliotts).

Mean time between failures. A few hours without failure would have been regarded as a fairly good day. Apart from the disk and the input paper tape reader, almost all failures were valve failures, and most of them were due to reduced emission.

The replacement console. The original console provided with the machine was pretty minimal - sufficient to load and run programs, but hopelessly inadequate for any software debugging (or hardware, for that matter). So the decision was made, rather late in the time I was there, to build a more sophisticated console, which was installed in 1958. The functional design was done by Jack Bowie in conjunction with his boss, the head of the Maths Services department, John Allen-Ovenstone. The electronic design and construction was done by another department of WRE known as Lab 11 which did electronic design and instrumentation in general.

I can only tell you what I observed during the commissioning phase of the equipment, shortly before I left WRE. The main feature was a pair of black-and-white TV picture tubes, to display the contents of selected areas of memory. The display consisted of perhaps 32 words (at a guess), each of 34 bits, arranged as lines of zeros and ones on each tube. The interesting feature, from my point of view as an engineer, was that the zeros and ones were generated by "beam-writing", accomplished by magnetic deflection. The electronics in those early days of transistors (which were widely used in the device) to provide magnetic deflection to write 0's and 1's on the TV screen were impressive, though the quality I saw in the first trials was poor. Probably it was later improved during development.

The 34 bit word. *[Ed: In the earlier 400 series computers, of the available 34 bits in each word, only 32 were available to the programmer. In the 403, engineering changes were made to allow all 34 bits to be used, so providing a greater range of orders in the instruction set. This benefit was not continued with the later machine, the 405, which first came on to the market about a year later].* I heard (from Ovenstone, I think - both he and Bowie were at Borehamwood for the commissioning of WREDAC) that Elliotts put the two guard bits to good use in the 403. I had not heard that they had any problems with it - certainly there were no problems of that kind with the machine when I knew it *[1957-58],* but to judge by the heavily marked-up logics we had to work with, there had been teething troubles.

Second, an interesting anecdote. In studying the prints for the logic of the 403 one day, I noticed an odd condition: the machine would always wait at least one word time for a memory access, even when the required word was available immediately. That meant that memory latency varied from 1 to 4 word times, when it should have been only 0 to 3. A simple wiring change rectified the condition, and speeded the machine up by some 15%. The programmers were delighted. In retrospect, it might have been the case that the inefficiency was a left-over result of changes the Elliotts engineers had to make when getting the 34-bit machine working. Just a speculation ...

3. Notes by Don Fenna

Applications. Tracking missiles was our primary business. The films from pairs of kinetheodolites were the prime source. Read by those human computers in semi-automatic readers to produce the frame-by-frame output of the filmed azimuth and elevation plus the measured offset from the central cross hairs of the marker spot on the object, paper tape was the medium of transfer to the electronic computer. Peter Goddard had developed the original programs to get the tracking picture from WREDAC. I took them over in early 1957, writing totally new programs on a vector basis, replete with my new elegant subroutines etc. I can't remember what Peter then applied himself to. John Sanderson and Pat Clarke worked on the performance of specific missiles. John Penny was saddled with the troublesome task of telemetry.

The telemetry data arrived on magnetic tape, for which WREDAC had two pioneer drives *[made by Pye of Cambridge in the U.K.]* but the arriving data had first to be processed through a big transfer machine. Comprehending telemetry is utterly dependent on the timing, since the different channels of data have no explicit identifiers or even distinguishing features. With that early equipment trouble seemed to be far more common than success, leaving the poor programmer processing everything only to find that there had been a slip in the timing somewhere.

The operators routinely ran the data through the production programs. Programmers did all their own operations for programs in test (and took over the production ones when there was trouble). Testing a program was very difficult until the cathode ray tube displays were installed. There were, of course, no error codes printed out or anything like that; the program just went haywire or into oblivion. For larger programs one would then insert a temporary exit to see if you reached that point, then adjust it forward or backward according to the evidence, Simulating the computer in one's head as one tried to see what had gone wrong was an excellent mind-developer. As the computer often went wrong itself, failure of a program often lead to an hour or more of study to ascertain just what had gone wrong in the electronics.

In October 1957 the USSR put Sputnik I into orbit. We at WRE were asked if we could track it, using our kinetheodolites and associated programs. Established to track objects at about 10 km altitude, the instruments were sited about that far apart. For an object in orbit at over 150 km altitude the pairs of sight lines were nearly parallel, but we did our best. With IBCM's in our impending future, two widely spaced telescopes were already being installed (at Woomera and near Perth, i believe). Called Baker-Nunn cameras, these were motorized and could be programmed to stay on a fixed sky object as Earth moved or even to track a moving object. With precisely timed shutter closures allowing precise measurement of position via known stars, these gave us much better data for tracking Sputnik. I adapted my programs to deal with this new situation, with curvature of Earth having to be accommodated for instance. [It was amusing therefore, when I began teaching cartographic science in 1992, to read this story in a book, relating the tracking of Sputnik as the opening contribution to the enhanced accuracy we now have in our knowledge of the planet being mapped.]

Besides programs using doppler techniques for tracking, the key other work that I was involved with concerned the safety screens for Black Knight, the first ICBM to be fired at Woomera. I had to develop sets of curves, to be etched on observational windows and radar plotting paper, such that were the missile to cross any one in the contrary direction it would be blown up by the Range Safety Officer using his remote trigger. Fortunately none of the dozen fired erred to such degree from the intended path (and neither did my curves).

John Penny, John Weadon and I also developed a floating-point simulator which, appearing in 1958, made WREDAC among the earliest to offer such facility.

Pye magnetic tape drives. The two tape drives on WREDAC ran with vacuum pockets to cushion the braking, but often that feature proved inadequate, snapping the tape when their servo mechanisms responded inadequately. They were slow by any subsequent standards. I didn't work much with them, but seem to think they had one bit per frame, dually recorded. They may have had 100 frames per inch, and did 100 inches per second, but certainly no more than that.

Don also comments on the 34-bit word issue, mentioned above:
34-bit word reliability I'm surprised that Peter Main doesn't see instability of 34 bits a problem in his time; to my memory it was a frequent problem. Add timing problems from the disc and we typically were lucky to get 50% functionality. [*Ed: John Penny agrees with Don Fenna on this point, saying: "*WREDAC was very unreliable, and 50% up-time in a week was about the best we could get. I know that Jack Bowie and his assistants had to work continually to keep it going at all.*"]*

4. Australian Computing, the Second Generation, by Trevor Pearcey

Weapons research, WREDAC, and the Second Computer Conference

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By 1957, when the first three academic computing laboratories had been in operation for about one year, several Commonwealth Government departments had developed to a point where high-speed computing was essential to the continuance of their programmes. Foremost among these were the technical departments, particularly the Weapons Research Establishment (WRE), responsible for the Anglo/Australian guided weapons test firing at Woomera and their analysis at Salisbury, South Australia, and the Aeronautical Research Laboratory at Fisherman's Bend, Victoria.

...

At WRE, telemetry and ground flight data were being collected faster than they could be handled by conventional means, causing serious delays to the trials programme. Performed by large numbers of people, computation was as slow and expensive as it was labour intensive- so much so that WRE had commenced the design and construction of an improved version of the CSIR Mark I under Major Jacoby.

The computing system finally adopted owed its design to John Allen-Ovenstone. **...** Through his effort and foresight, a scheme was devised for integrated automatic collection and handling of telemetry radio-doppler and radar data collected on magnetic tape in analogue form during flight together with other ground-sited flight data at Woomera. This data was to be converted to digital form at Salisbury, then subjected to calibration corrections and numerical analysis by a central electronic computer system. The final choice for that system was an Elliott 403, somewhat modified to Ovenstone's specifications.

Called the WREDAC, this 403 was one of a series of commercially produced, vacuum-tube based, stored-program computers which had a magnetostrictive sonic delay store of 512 thirty-four-bit words for the currently executing segment of program and its subject data, and a larger, 16,384-word magnetic disc which ran synchronously with the delay store. The instruction format was of the one-address type similar to that of the EDSAC. Program and some of the data were input from five-channel paper tape while range data were input digitally from a quarter-inch wide magnetic tape onto which the original analogue data from the range were converted by special input converters'. Output was to paper tape, teleprinter and similar quarter-inch wide magnetic tape. The output on magnetic tape was then passed to an 'output converter' * which produced final graphical output on modified facsimile printers. This process of data handling set by Ovenstone - magnetic-tape-conversion, computer reduction, magnetic-tape-conversion - survived for the next twenty years, although converters and computers were replaced by solid state electronics and half-inch magnetic tape based systems like IBM 709/1401.

...

The WREDAC was publicly exhibited during the second Australian Computer Conference which was held at the Weapons Research Establishment, Salisbury, from 3 to 8 June 1957. Largely instigated by Ovenstone, this 'Conference on Automatic Computing and Data Processing', was attended by 150 delegates and produced sixty-three papers of high quality.

* *[Comment from Peter Goddard: 'The output converter was called WREDOC and was put in by Elliotts some time after WREDAC'].*

The WREDAC at the Weapons Research Establishment, Salisbury, South Australia.
The photo is taken from 'Computing in Australia',
and shows the new console, with Patricia Yates operating.

5. Extract from "Fire across the Desert", by Peter Ralph Morton

[N.B. Editor's notes, not in the original publication, are enclosed in italicised brackets, thus, and are based mostly on texts written by Peter Goddard in April 2006].

In September 1953 LRWE's *[Long Range Weapons Establishment's]* Data Processing Committee met for the first time, and the next month had an important paper to consider from John Ovenstone, modestly titled 'Notes on data-processing at LRWE' and drawing together many strands in the discussions and planning which had been going on all year. The twenty-one pages of Ovenstone's 'Notes' offered a broad specification for the prospective computer and for the various converters that would take recordings from the telemetry, doppler, radar and missile tracking systems and transform them into the digitised form readable by the machine. In addition, Ovenstone described the output converters which were necessary for the computer to print its results or draw its graphs. Altogether the notes comprised a bold and perceptive plan which was almost wholly realised over the next few years.

In due course a telemetry converter using about 300 valves was built to a design by Barlow *[George E Barlow, a Senior Scientific Officer]*, Leo Cohen of Information Studies Group and Fred Thonemann of Techniques Division, *[both thought to be parts of LRWE]*. This converter and others produced input for both the first computer, WREDAC, and its successor the IBM 7090. To take the telemetry converter as an example, the process was to play the twenty-four channels of data recorded from the flying missile through the converter at one-tenth of the recorded speed. In the converter the waveform was sampled regularly and a series of digital pulses generated, the number of pulses being proportional to the strength of the sample. A marker signal of a precisely known frequency was recorded on one track so that when it and the telemetry data were compared, errors due to variation in the speed of tape transport could be eliminated. The digital code representing the values of the telemetry voltages in the original recording were transferred to a secondary tape, along with the reference frequency, which also gave a measure of elapsed time. This secondary tape, along with other similar tapes from the doppler and other converters, formed the computer input.

These advances presupposed the replacement of film by magnetic tape for all data recording except the strictly optical. The British distrusted magnetic recording and were loath to abandon the use of film for telemetry. They had a point. The telemetry signals coming from a missile in flight are often noisy and weak. A human reader could learn to discount the spikes of noise on the film record; not so a machine, which was merely counting cycles in the frequency modulated signals and could easily misinterpret the noise spikes. The British also expressed misgivings that the proposed converters and the computer would be too interdependent; that is, the failure of one part of the system would cause delays in the whole. But the Australians were set on the course which would put them well ahead of the British and ahead of the Americans by 1956. They were in a unique position. The British had a bigger labour pool to draw on, and could also get their contractors to tackle some of the data reduction, so they were not so urgently drawn to automating as fast as possible. The Americans, with their myriad contractors and their many ranges, which often had traditional service rivalries behind them, did not have the same incentive to seek standardisation. Australia was suffering from an acute shortage of labour, but it did have only one Range run by one authority, and all three services used it under civilian scientific control. The most compelling argument of all was the prospect of dealing with stupefying masses of data as the trials programs expanded over the next few years to take in the service trials of the first generation of guided weapons. In the two years 1955 and 1956 they had the prospect of reading 400,000 points of trajectory, velocity and attitude data, or about 800 points a day In addition they would be calibrating six million telemetry points. Even at 100 per cent efficiency, this was around 200,000 man-hours of work. It would take up to 200 more Computers* to tackle such a load manually, from a specialised labour market already drained dry. And finally WRE would be processing as much as 600 *kilometres* of film a year!

["Computers" - with a capital 'C' - were Assistant (female) Computing Grade 1, aged 16 upwards with say good GCE-equivalent qualifications in mathematics, (or after university study in mathematics and physics and promotion, Assistant (female) Computing Grade 2), who were paid adult wages to attract them and compensate for the need to travel 15 miles out of Adelaide to Salisbury. There were about 30 or so, and these Computers did the film reading, worked desk calculators (Marchant or Friden) and some also operated the mainframe computer. (The two Computer grades are referred to by Morton later in this book extract as Assistant Computer and Senior Computer)].

THE WREDAC ERA

By early 1954 LRWE had given up any thought of building its own computer. Too many other tasks were now pressing for attention and LRWE now wanted a reliable, commercial machine that could go to work at once. When Headquarters offered the Establishment Pearcey's now obsolete CSIRAC, therefore, Chief Superintendent Bareford rejected it without hesitation. It was, he said, too slow and not well enough engineered; it had never passed a reliability test and was cumbersome to program. LRWE was facing a massive data reduction and processing task to meet the needs of service trials of the first generation of guided weapons. It wanted the best and most modern equipment to do it with.

Ovenstone's specification in his 'Notes' for an ideal computer were not extremely onerous. The capacity to handle input in large quantities was more important than sheer calculating power. The total storage which he saw as necessary, both internal memory and that on a magnetic drum store, was in modern terminology less than 64 kilobytes. Even so, it was by no means simply a matter of placing the order and taking delivery of a device in a crate. In the mid-1950s computer manufacture was entirely a bespoke trade, and it was impossible to buy one 'off the peg'. When the suppliers spoke of having a computer 'in commercial production' they meant they were making a few, or at most a few dozen, machines; and each one was probably being tailored to the customer's requirements during manufacture.

The specifications were circulated among interested British firms, and Barlow and Ovenstone went to England in May 1954 to spend some six weeks looking at the various machines on offer. Two contenders were the English Electric DEUCE and the Ferranti MARK 1, but Barlow and Ovenstone decided both had insurmountable problems. The prototype DEUCE was barely complete and an unknown quantity; nor could a copy be built and delivered by June 1955. The Ferranti machine's neat appearance concealed the fact that it was not built out of the replaceable plug-in units that were thought essential for easy servicing. Ferranti made a valiant last ditch effort to overcome the servicing objection, but it could do nothing about the technical disadvantage that its machine stored data electrostatically, which raised questions about radio interference when there were large transmitters nearby, as at Salisbury. Eventually the contract for the supply of a 'High Speed Digital Computer No. 403 (and Ancillary Equipment)' went to the London-based firm of Elliott Bros, for a machine at a total quoted cost of £106,625. Elliott's analog computers had a good reputation, and also their 403 used nickel delay lines for the volatile memory, storing 136 pulses in each line, and so were less susceptible to electrical interference. But Elliott's secured the contract for WREDAC (originally called 'Cobber', for no obvious reason) mostly because of their low quoted price. This was divided equally between the partners under the prevailing Sandys Agreement.

Even at the time there were those who had misgivings about this decision. The knowledgeable Jacoby* had strongly urged the purchase of an American computer - specifically, an IBM 701 - as early as 1954, before the final commitment to WREDAC had been made. Two colleagues who accompanied him to a demonstration of the 701 in New York still recall him saying in some excitement, 'This is the machine you should be buying, not wasting your time on WREDAC. This is the machine. I know you're not listening; I know all that, but you're crazy.' Probably Jacoby was correct. If a decision to purchase from IBM had been made when WREDAC was ordered, then the outcome, taking bureaucratic delays into account, would probably have been the installation of an IBM 704 capable of running the Fortran language and doing all of WRE's work for years to come. Dollar currency shortages and the political realities were against any such decision as the British fought to retain and extend their markets in the post-war period.

[Major Jacoby was the officer in charge of the Mathematics Services Section in 1950, and after two or three years, he was appointed to the Washington Joint Chiefs of Staff Office. It is thought that he was on loan from the Australian Army signal people.]

On 29 September 1954 the first manufacturing progress meeting for WREDAC was held at Elliott's headquarters amid a flurry of telexes querying and replying to minor details. Many things had to be settled, including questions of interfacing. Many conventions, even for instance the very basic one as to whether the pulse which represented a '1' in binary arithmetic should be positive or negative in voltage, were not then standardised. Another example was Ovenstone's suggestion of a teleprinter code in which all the numerals were represented by using only two of the five possible holes in the paper input tape. This was a good idea, because it allowed a fast visual check of the complete tape - any code with more or less than two holes could not be a number - but it was not the code Elliott's normally used. Before a data converter being built in Australia could feed into the input terminals of a computer being built in England, all these points and many more had to be resolved.

Barlow and Ovenstone had discussed many of these matters with Andrew St Johnston and Dr Lawrence Ross of Elliott Bros during their visit, but inevitably some details had been omitted or misunderstood and many letters and telexes passed to and fro clearing up the misunderstandings. But the details which occupied the first progress meeting were more pedestrian in nature. They concerned the number of metal cabinets and their arrangement, the provision of cooling air, the determination of a work schedule to meet the tight installation date of July 1955, packing and shipping the equipment and its cost and the manufacture of the tape transport mechanisms which would be necessary to read Range data from the as yet unbuilt converters into the new computer.

The bulky WREDAC and its spares eventually arrived in Adelaide by sea in September 1955, anxiously attended by three Elliott technicians, who had come to supervise its installation and put it through the acceptance trials. At this time it still lacked its output converter and printer. (WREDAC did not run a printer directly. It produced an output tape which allowed it to get on with more work while the slow output devices then available printed or plotted the data.) The complete equipment filled thirty-six tall racks, half of them holding the computer itself and half the converters for telemetry, doppler and radar data. Ranged nearby were two Telereaders, two Boscars*, an Oscar* and a kine reader. The film readers originally produced punched cards for feeding into the Holleriths, but WREDAC could not read cards, only paper tape. Attached to the film readers, therefore, were Creed teleprinters and tape perforators to produce the input tape that WREDAC could handle.

[LRWE acquired film reading equipment that generated numeric output on punched cards in 1954 for further calculation on BTM tabulators and multipliers etc. There were three types of unit acquired. One came from Telecomputing Corp Burbank, which digitised crosshair movement on a screen enlarging 35mm film, and had been designed for use by the US oil industry. Another was the Benson-Lehner Oscar, which was designed to digitise unmagified paper oscilloraph recordings and was not much used. The Boscar (Boresight camera) reading was used for film frame by frame enlargement and digitising the displacement of a point on the missile image (X&Y) from the centre of the graticule from the kine theodolite of which we knew the Azimuth and elevation. With two or more cameras one could calculate XYZ at up to 20 times per second with Contraves instruments. 35 mm film again].

The computer's permanent disk memory was a physically impressive feature. It was nothing like the small sealed hard disk units of the 1980s which read and write megabytes of data with minimal maintenance. This disk was a platter, 46 centimetres in diameter, sitting inside a large cabinet with double doors. Above it was a mass of eighty individually adjustable pick-up heads, each of which had to be set just one-fiftieth of a millimetre above the surface - too close and the disk would be scratched; too distant and the head did not receive enough signal. (If the disk did get scratched, though, a head could simply be moved across the disk to find an undamaged spot.) Even while the disk was stationary, a constant flow of warm oil bathed the bearings to avoid any rough starting which might cause the heads to score the delicate oxide surface. Like all computers of its day WREDAC was far from being, as the jargon has it, 'user friendly'. Quite the reverse. It needed constant attention from operators who knew exactly how to get the results they wanted, as well as a team of maintenance staff to fix it each lime an error occurred in the calculation sequence.

A year passed before WREDAC ran properly. Despite the installation team leader's confident assertion on his return to England in November 1955 that 'when he left the actual commissioning was effectively over', six more months passed before the two remaining Elliott technicians at Salisbury even attempted to run the acceptance tests. There were many problems. Not for the first or last time, equipment designed in temperate climates worked less than successfully in Australia. Ambient temperatures in the mid-30s that summer played havoc with the electronic circuitry, which itself produced many kilowatts of waste heat to be disposed of by uncertain air-conditioning. Some problems certainly arose from faulty design. In the circuitry which fed the delay line memory, the valves specified, 12AT7 double triodes, were being driven much too close to their performance limits. After a few hundred hours the normal slight decline in the electron emissivity of their cathodes, which would have been inconsequential in any other application, started to corrupt the data passing through them. A good quarter of the 500 valves in question had been replaced by mid-February. Ovenstone wanted a better valve with a firm guarantee of a two-year life, but he never got it. The life of a valve in the demanding memory driver circuits was always relatively short, although eventually the maintenance engineers worked their way round the difficulty by screening the performance of new ones and putting only the 'pedigree' valves in the most exigent positions.

In the time-honoured way, supplier and customer tended to blame each other for WREDAC's teething troubles. WRE criticised the poor standard of workmanship, while Elliott accused the Salisbury engineers of fiddling with precision equipment without knowing what they were doing. In a generous move Elliott eventually replaced the entire disk unit at no charge, but this cut no ice at WRE, where the firm's performance in rectifying the faults was later judged to have been 'something less than spectacular'. A more balanced judgment should stress that everyone at the time was down near the bottom of the learning curve when it came to computers. Elliott's Computer Division was desperately overloaded with orders. While trying to fill the order from WRE it was simultaneously building a similar machine for the Pascal institute in Paris and another for exhibition. The Division moved to a new site in the middle of the Australian job, and the whole firm was short of trained and skilled staff. It was only in June 1955 that the company, responding to strong pressure from WRE to meet its schedule, first resorted to shift work. Even then the testing was cut short, but WRE mistakenly thought this was better done at Salisbury in any case.

At the end of the December 1956 quarter Ovenstone said optimistically: 'For the first time since the Range commenced operation there was no backlog of trial calculation over the Christmas period and, despite the shortage of skilled programming and maintenance staff, a reasonable service to the establishment was maintained.'

Ovenstone predicted that WREDAC would soon be working for eight hours of a ten-hour day. Although this was not an unreasonable assumption judging by other computer users' experience, it proved to be far too optimistic because for a time WREDAC got worse, not better. One problem was the change-over from punched cards to the paper tape handled by WREDAC. American computers and data--processing machines at the time used punched cards, because they had evolved from business machines which also used them. British computers stored their data on cheap paper tape, because they had come out of university laboratories which were used to working with readily available telegraphic punched tape machines. The American film readers originally produced punched cards, but had been modified in Australia to use tape when WREDAC was introduced. This was a handicap, because the operators found that an error which previously had been easy to correct by punching a new card and throwing away the old one was much more troublesome when a whole new tape had to be punched instead. For this and other reasons WREDAC had a rather feeble performance even compared to much slower machines. Just before the computer symposium at WRE in 1957 H. L. Barman of Rolls-Royce wrote to Director H. L. Brown asking for details of WREDAC's performance so that he could compare them with his firm's IBM 650, a machine with a drum memory that was much slower than WREDAC. He mentioned that they were getting 134 hours of useful output per week with an hour a day scheduled for maintenance and an average of 34 minutes a week breakdown, which gave them an overall efficiency of 99.6 per cent. The comparison with WREDAC was embarrassing then and would become more so. Even two years later, in 1959, the machine was providing only about 30 hours a week of useful computing time, and half of that was absorbed by program testing and other work.

Eventually WREDAC was made to work with reasonable reliability. Colour-coded cable gradually replaced the tangle of white wiring. Elliott had used single strand wire to connect the plug-in units and when it broke, as it sometimes did, it was almost impossible to find where it was meant to go. WRE staff added extra circuitry and finally put the power supplies out on the veranda of the building - something they had wanted to do from the beginning. This reduced some of the heat load and better air-conditioning coped with the rest. A report published in early 1959 said rather defensively that despite its limited hours WREDAC was processing very much more data than had been handled before its introduction.

This was true: depending on how the calculation was done, up to ten times as many data points were being produced. One reason why WREDAC did not make a better showing was that the demand for computational services had risen so much that it cancelled out the gains. An embattled Maths Services Group were constantly under fire from other Divisions of WRE, particularly Systems Assessment (SAD) and Aerodynamics (AD). In using computers it is very much the case that the appetite grows by what it feeds on. SAD had developed an elaborate technique whereby it took the measurements of the actual flight trials at Woomera of the new guided weapons Red Duster and Red Shoes in digital form, and then had the data converted to analog form to serve as input for their laboratory simulators. This process used up machine time at a fearful rate and was always urgent. The complaint of people working in AD was that their work did not carry the same urgent priority of much of the missile trials work, so that often they found themselves well back in the queue. Maths Services tried to shift the load by pushing the Red Duster data conversion work back on the contractor, Bristol Aeroplane in England, and by analysing only the most critical parts of each trials record. Certainly there was little hope of improving the rate of output. By 1959 the WREDAC staff were already working two or three shifts plus some overtime in an attempt to catch up, but this was producing labour problems. WRE could order its employees to do shift work and, while junior staff were obliged to accept it, the senior staff (who had to be on duty as well, to solve WREDAC's problems) did not take kindly to being employed, as Ovenstone put it. 'all night and morning on work of a not very inspiring type'. In 1958 well-trained computer staff were at a premium in Australia, and there were plenty of vacancies for research programmers in Sydney and Melbourne at comparable salaries. Ovenstone himself left to take a senior position with the Department of Defence to establish their data-processing system. A mild state of warfare broke out between the two departments of Supply and Defence as Ovenstone went on to poach as many of the more senior and capable computer scientists as he could. By early 1959 there had been an alarming number of resignations. To stay at WRE meant staying with WREDAC, something that offered little chance of professional advancement given the machine's obvious limitations. WRE could not abandon the machine so soon after installation, but trying to keep it running was not a prospect to inspire any bright young man with a career to build.

There were problems, too, among the more junior staff, most of whom were women. For them there were only two grades, Assistant Computer or Senior Computer, and although the wages were good for juniors there was no career structure for those who were looking for further promotion. Not that WRE could offer much inducement for its Computers to see their work as a career. Public Service rules made resignation mandatory on marriage, and although re-employment as a temporary worker was possible or even probable afterwards, it was not guaranteed. The private firms on the Salisbury site placed no barriers in the way of married women and were willing to pay more than the government rate for a skilled computing assistant. Such policies cost WRE dearly in checking and rereading faulty work. One estimate is that every kinetheodolite point was calculated twice and every piece of telemetry data perhaps three times, partly from the need to correct processing mistakes by inexperienced staff working under pressure.

In November 1960 Trials Superintendent J. Clegg was able to report at last that the reliability of WREDAC had risen above the 80 per cent mark. By then, though, the statistic was of little moment. WREDAC was thoroughly obsolete and WRE had ordered its successor.

WREDAC REPLACED

It had become obvious by mid-1959 that WRE could not delay much longer in ordering a replacement, even though WREDAC had given less than four years' service and, with its accompanying output converters, printers, plotters and additional tape machines, had cost the partners about £300,000. The final impetus for a new purchase came from the forecasts of the work that would result once the continent - spanning flights began in 1960 of the intermediate range ballistic missile, Blue Streak. These trials were expected to continue for years on a grand scale. To give only one example of the work they would generate, the powerful ballistic cameras which were to record the payload's re-entry into the atmosphere had to be calibrated regularly against a star background, much as the ground speed cameras had been calibrated in the early days of the bombing range. There were to be up to fifty of these cameras. Checking just one ballistic camera would take three hours of WREDAC computing time, provided there were no data or machine faults. This never happened: WREDAC's 'mean free error path' lasted fifteen minutes. Even allowing for the spasmodic nature of trials work, the immediate future called for a computer with twenty times WREDAC's capacity.

In March 1959 the difficult decision on the type of machine to be purchased was put in the hands of the Data Processing Committee. Barlow, who had become the first civilian to fill the position of Defence R&D Representative in the United States, forwarded details of some suitable American machines. He enclosed brochures for the Univac Scientific, the Honeywell 800, the Philco Transac 2000 and the new transistorised IBM 7090, the first model of which was due to be delivered to the Vanguard Computing Center early in 1960. The 7090 cost over $US3 million, but IBM already had many government orders for it. One group alone had ordered seven.

Certainly there were many different opinions to canvass, since everyone was most eager to learn from experience. Bill Watson, Acting Superintendent SAD, spoke for everyone when he insisted that 'the opinion of several experts is needed - if only to ensure we do not buy a "bunny"'. Watson emphasised the need to bear in mind the needs of users other than the trials staff. Digital simulations of missile behaviour, which would eventually render most analog techniques obsolete, were then on the horizon. Buying the right digital machine could mean that the services would need only 'one digital machine which could do sums on all weapons, instead of having an analog machine for each weapon.' Watson also wondered whether some of the strain could be taken off WREDAC. The calibration of telemetry, for instance, was done on the computer, which for Watson was like 'using a stone crusher to break a peanut.' Perhaps the replacement of WREDAC could be deferred by purchasing some specialised equipment.

This suggestion gained no support, but one thing which did unite all opinion at WRE was that the Establishment should give up thermionic valves and go for one of the latest generation of solid-state machines using individual transistors. There was only one British transistorised computer in the offing, the EMIDEC 2400. It was not a strong contender. It had a comparatively small memory and was only about eight times as fast as WREDAC. It used an inordinate 35 kilowatts of power and hence would have needed almost twice as much cooling as WREDAC. Worst of all, from the WRE point of view, it was only a prototype which was unlikely to be finished before 1962. The political pressure to buy British had abated since WREDAC had been bought, for by this date even MoS establishments like Aldermaston had either bought or were looking at American computers. Of the two American machines then available that met WRE requirements, the IBM 7090 and the Philco Transac 2000, the former was judged the better, especially because a large library of programs was available for it. Experience with the bespoke WREDAC had shown the high cost of having to write software for oneself for every new problem. The value of having access to a large library of programs was obvious and a purchase of the IBM 7090 would give that, since the introduction of the Fortran language allowed program code written for earlier valve machines to be recompiled and run on the transistor one.

At the Board of Management meeting of 8 March 1960 the vote was to hire the 7090 for $US330,000 a year with an option to buy after the first year. The order went straight to IBM just five weeks before Blue Streak was cancelled. Two WRE scientists, Peter Goddard and Barry McDowall, went to the States to learn how to program the 7090. The first reports were not too favourable, but IBM, unlike Elliott a few years before, had the production capacity and the engineers to remove the gremlins intrinsic to any new design. The 7090 was delivered to WRE at the end of 1960 and officially handed over to the Minister for Supply, Alan Hulme on 13 February 1961.

Some fifty people applied to attend the Fortran course held before the new machine was installed. WRE also joined SHARE, one of the first user groups established by aerospace programmers in California, and started to receive programs from many other US sources. This presaged a change in the use of the computer. Formerly programming had been the preserve of a few initiates who could cope with WRE-DAC's peculiarities, and they tended to have a rather proprietorial attitude to it. R. G. Keats of Systems Assessment Division (SAD) was one of those who argued for more general access to the new machine. As mentioned earlier, SAD had been a persistent critic of Maths Services Group, and SAD could not be ignored as its modelling work was of growing significance in the economical production of new weapons systems. After some resistance Keats got his way and WRE started to allow its individual engineers to write the code for their own task and submit it to the data-processing office for running. SAD benefited greatly from the change, becoming a major user of the new machine to the extent of some 400 hours a month of central processor time. Maths Services still provided expert advice and assistance; it did not attempt to provide a general programming service. Other groups were happy to leave the entire business of writing programs and running them to the data-processing department.

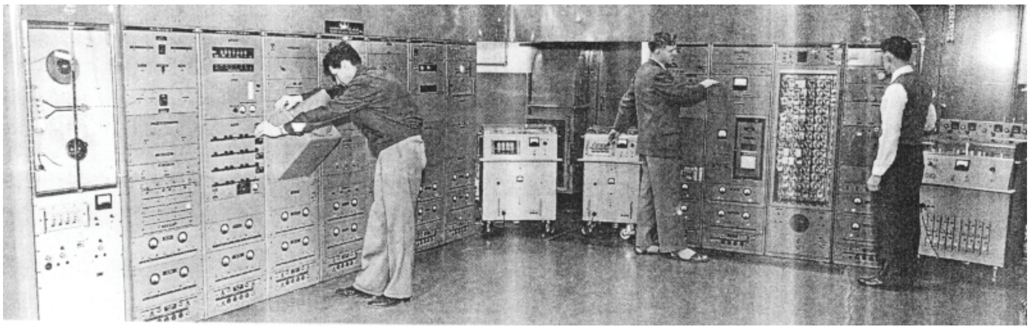
The method of handling the Range data did not change much with the new machine but followed the pattern established in the early years of Woomera. Work was still handled in batches as it had been with WREDAC but with greater efficiency and smoothness. The replacement first of paper tape, and then punched cards, by magnetic tape was the chief cause. Film and magnetic tapes from Woomera passed through a records office whence they were sent to various sections, one for each project. There, under the direction of a mathematician, a team of Computers would assess the quality of the films and tapes and decide which parts were to be processed. The kinetheodolite films were read on the Boscars and converted to punched cards, then the data from one kinetheodolite was merged with that from another and differenced in a 407 Accounting machine. The results were tabulated for checking and, when all visible errors had been eliminated, the cards were sent to the computer with a request for a trajectory calculation. Other film records were reduced on a Telereader, a general purpose film reader which could also measure angles.

These machines and the new computer allowed a great expansion in dataprocessing capability, as the following table shows:

Comparative Loads and Costs		
	Trajectory points calculated per day	Cost of each calculated point
1955-56 (pre-WREDAC)	800	$A4.00
1956-57 (WREDAC)	1000	50c
1963-64 (IBM 7090)	3000	10c

To make the whole system as reliable as possible throughout, it was advantageous to upgrade the data converters as soon as possible. Computer Electronics (CE) Group, then under the direction of Barlow who had returned from his American posting, was given the job of rebuilding the converters and making them compatible with new telemetry systems then being introduced. The circuitry was transistorised and built on small printed circuit boards. Some of the boards in the new doppler converter, the last completed, used resistor/transistor logic microcircuits which were the forerunners of integrated circuits and were then becoming just cheap enough to compete with discrete transistor circuits. CE Group also revamped the sturdy Ampex FR400 tape recorders which had begun their life attached to WREDAC, by fitting a vacuum tape chamber and new digital electronics to increase their data capacity from 200 bits/inch to 600 bits/inch. It is a tribute to the workmanship of both the tape machines and the converters that they were still attached to the computer system in 1986. But by then little of the data they converted was coming from Woomera.

WREDAC continued to run in parallel with the IBM 7090 for a time, but as its programs were converted to run on the newer machine it became more and more redundant. Its attendant maintenance staff were expensive, and at the end of 1962 Barlow recommended that WREDAC should be disposed of. He suggested that rather than being broken up it might be offered free to the South Australian Institute of Technology. Others more cynical or more realistic correctly averred that no one could afford to take on WREDAC even as a gift. Its ultimate fate is hazy. A few parts did go back to Britain as spares, but most of it probably ended as scrap. The electronics revolution had taken WREDAC from being the *dernier cri* in data-processing to the junk heap in less than a decade.

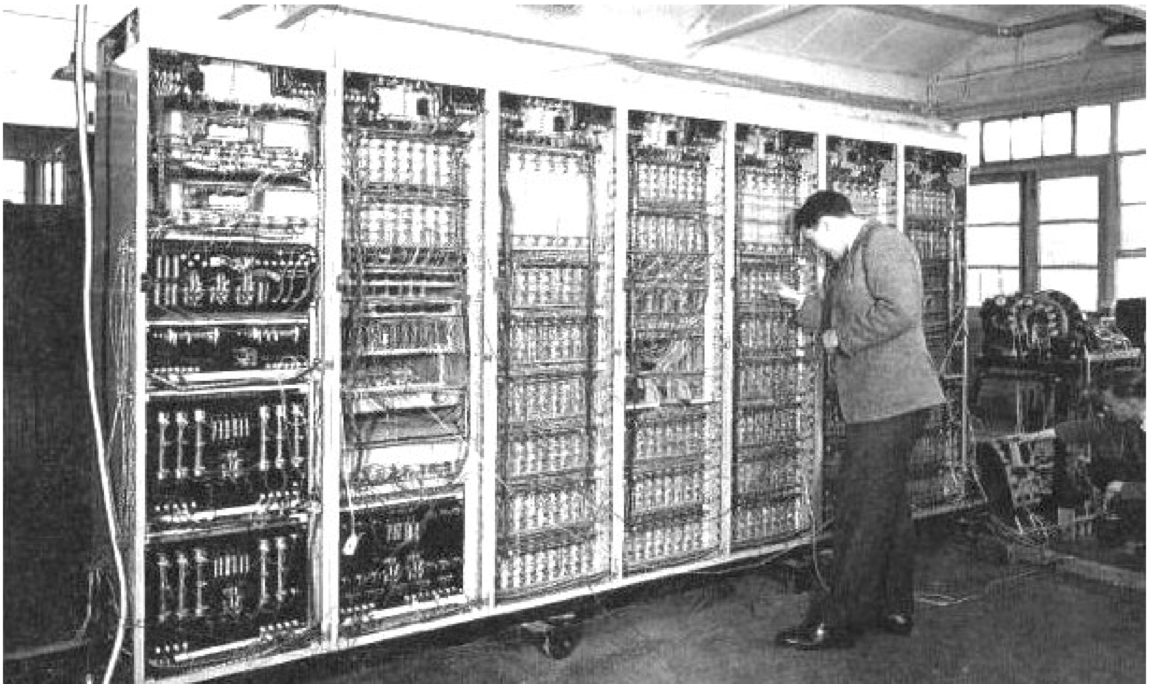


Above: The WRE developed telemetry and doppler converters

John Ovenstone (L), who laid down WRE's requirements for its first automatic data processing facility. Peter Goddard (R), of Maths Services Group, who later became the head of its successor, Computing Services Group.

[Peter Goddard comments on the above telemetry and doppler equipment: "I believe these were analogue to digital converters built by Thonemann and Barlow's men in Lab 11. The equipment was not part of WREDAC itself of course, but was an essential component of the trials data processing schema."]

Above: Operating the WREDAC punched paper tape equipment.
Left to right: Barbara Lane (later Biggins), Bronte Walter (later Morrison), and Robin Fleming.
The WREDAC (403) cabinets and original console are on the right.



Part of the WREDAC computing equipment under test

6. WREDAC References: People and Documents in Australia

Below is a list of WREDAC references to people involved in the WREDAC project in Australia, and a list of WREDAC documents.

WREDAC People

Who	Why
G E Barlow	WRE - paper in 1957 conference
R W Boswell	Acting controller WRE 1957 – paper in 1957 conference
I C Hickfuss	WRE - paper in 1957 conference
J H L Cohen	WRE - paper in 1957 conference
John Allen Ovenstone or John Allen-Ovenstone	WREDAC manager
D L Overheu	
F F Thonemann	WRE - paper in 1957 conference
W C J White	WRE – paper in 1957 conference

WREDAC Documents

Reference	Title	Date	By	Where	Comment
TM50	An introduction to programming for automatic digital computors	1955	J Allen-Ovenstone	CSIRO Lindfield serials, JDeane	WREDAC programming manual
TRD-TM-39	An introductory coding manual for the WRE digital automatic computer	?	DL Overheu	NAA series D4884, JDeane	Revised TM50, some machine description, order code, loader format
Letter	To Jack Bowie, RWE	6 Feb 1956	Barry Cole, Elliott Bros	NAA JDeane	Cover letter for revised drawings etc, refers to the 403 as “Cobber” ! 3pp
-	Output converter load on alternator	Apr 1956	?	NAA JDeane	Tables of voltages and power consumption. 11pp
-	The BULL AN71 printer	?	?	NAA JDeane	Description, drawings & notes
Conference proceeding, June 1957 Salisbury S.Aust	Data processing & automatic computing machines	June 1957	various	UNSW Library RQ510.78/2, JDeane	Many WREDAC papers (plus CSIRAC, SILLIAC, UTECOM & UK items)
Tech Note TRD3 (or TRD-TN-3)	Floating arithmetic calculations on the Weapons Research Establishment Digital Computer	May 1959	JP Penny, D Fenna and JN Weadon	NAA series D4884, JDeane	
L.213.10.3	Fast interpretive routine for floating arithmetic	1959	?	NAA, JDeane	S/w write-up & listing
Tech Memo TRD-TM-35	Implementation of recommendation no.10 of tech note TRD2	1960?	D L Overheu	NAA, Jdeane	Argument for replacement of WREDAC incl performance info

DRAFT	A proposed system to obtain the information displayed by WREDAC in punched tape form	?	?	NAA J Deane	8pp
-	WREDAC logic for AMPEX tape units	?	?	NAA JDeane	8pp
Book	Fire across the desert	Aust Govt Pub	Peter Morton	J Deane etc	History of Woomera includes WREDAC info

Abbrev:
NAA National Archives of Australia
WRE Weapons Research Establishment (Salisbury S.Aust)

Technical drawings from National Archives of Australia
(JDeane's copies are on A3 sheets)

TITLE	SOURCE	DRAWING	DATE	SIZE
Circuit automatic carriage printer	WRE	MSK54	09/10/57	A0
Circuit automatic carriage printer	WRE	MSK93	08/05/58	A0
Clock, Reset, Strobe waveforms	WRE	MSK80	24/02/58	A1
Clock, Reset, Strobe waveforms	WRE	MSK108	23/06/58	A1
Layout of computer room	WRE	MSK56	22/10/57	A1
Tape unit connection board	WRE	MSK_	10/02/57	A1
Mod. dual paper tape logic	WRE	MSK26	07/01/57	A1
Magnetic tape unit power circuit	WRE	MSK60	26/11/57	A1
Block schematic diagram HS magnetic tape store	WRE	MSK94	09/05/58	A1
Transistor BYT unit	WRE	MSK137	22/12/58	A2
Power connections and interlock for high speed tape unit (PYE)	Elliott	D358CM	-	A0
Number generator	WRE	MSK106	12/06/58	A2
Block diagram display	WRE	MSK121	11/09/58	A2
Magnetic o/load relays	WRE	MSK86	11/04/58	A2
Flying stop	WRE	MSK118	13/08/58	A2
Suppression logic	WRE	MSK130	03/11/58	A1
B line logic	WRE	MSK109	23/09/58	A1
Order store order register	WRE	MSK97	11/12/58	A1
Magnetic tape control logic	WRE	MSK75	22/09/58	A1
Magnetic tape reading logic	WRE	MSK74	22/09/58	A1
Magnetic tape writing logic	WRE	MSK73	22/09/58	A1
Display No.2 gating	WRE	MSK71	-	A1
Display logic	WRE	MSK70	10/01/58	A1
HS store display gating part 'A'	WRE	MSK68	08/01/58	A1
HS store display gating part 'B'	WRE	MSK69	08/01/58	A1
Paper tape input & output logic	WRE	MSK100	05/11/58	A1
Arithmetic unit	WRE	MSK91	05/05/58	A1
Power circuits power supplies	WRE	MSK50	01/07/57	A0
Control circuits power supplies	WRE	MSK48	01/07/57	A0
Instructions for operation and maintenance of magnetic tape storage equipment for use with digital computer	PYE	-	-	23pp
Magnetic tape units	WRE	-	-	5pp
GA 1/4" tape head & capstan unit	PYE	Fig.3	-	A2
GA 1/4" tape head & capstan unit	PYE	Fig.4	-	A2
Sub-assy solenoid	PYE	Fig.5	-	A3
Tape box unit	PYE	Fig.6	-	A2
GA 1/4" tape servo unit	PYE	Fig.7	-	A2
Servo amplifier for Elliott Bros tape storage equipment	PYE	Fig.8	-	A2
Wiring diagram for control unit	PYE	Fig.9	-	A2
Wiring diagram for output unit	PYE	Fig.10	-	A2

Automatic safety unit	PYE	Fig.11	-	A2
Wiring diagram for safety unit	PYE	Fig.12	-	A2
Interlock circuits for Elliott Bros tape storage equipment	PYE	Fig.13	-	A2
Shaft	PYE	AHK1252	17/01/55	A2
Transistor erase switch	WRE	MSK102	05/08/58	A3
Power supplies for BYT units	WRE	MSK138	05/01/59	A2