A HISTORY OF COMPUTING IN THE TWENTIETH CENTURY

The COLOSSUS

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In October 1975, after an official silence lasting thirty-two years, the British Government made a set of captioned photographs of COLOSSUS available at the Public Record Office, These confirm that a series of programmable electronic digital computers was built in Britain during World War II, the first being operational in 1943. It is stated that COLOSSUS incorporated 1500 valves, and operated in parallel arithmetic mode at 5000 pulses/sec. A number of its features are disclosed, including the fact that it had 5000 character/sec punched paper tape inputs, electronic circuits for counting, binary arithmetic and Boolean logic operations, "electronic storage registers changeable by an automatically controlled. sequence of operations", "conditional (branching) logic", "logic functions pre-set by patch-panels or switches, or conditionally selected by telephone relays", and typewriter output.

Professor M. H. A. Newman is named as being responsible for formulating the requirement for COLOSSUS, and Mr. T. H. Flowers as leading the team which developed the machine. An indication is given that the design of COLOSSUS was influenced by the prewar work on computability by Alan Turing, who was employed in the same department of the British Government as Newman.

The partial relaxation of the official secrecy surrounding COLOSSUS has made it possible to obtain interviews with a number of people involved in the project. This paper is in the main based on these interviews, and is supplemented by material already in the public domain. It attempts to document as fully as is now permissible the story of the development of COLOSSUS. Particular attention is paid to interactions between the COLOSSUS project and other work carried out elsewhere on digital techniques and computers, and to the role that those involved with COLOSSUS played in postwar computer developments in Britain.

Details are given of the careers of the people involved, of how the basic concept of COLOSSUS was arrived at, and of how the first machine was designed and built, and of the subsequent design and and construction of a Mark II version. The paper also attempts to assess Turing's role in the COLOSSUS story, and to relate the work to contemporary work in the U.S., particularly that on ENIAC. The official photographs and the accompanying explanation captions are reproduced in the paper.

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1. Introduction

> Babbage's work in 1837 first established the logical principles of digital computers. His ideas were developed further in Turing's classical paper in 1936. The COLOSSUS machine produced by the Department of Communications of the British Foreign Office, and put into operation in December 1943, was probably the first system to implement these principles successfully in terms of contemporary technology. . . . The requirement for the machine was formulated by Professor M. H. A. Newman, and the development was undertaken by a small team led by T. H. Flowers. A. Turing was working in the same department at that time, and his earlier work had its full influence on the design concept.

These statements are quoted from the Explanatory Caption accompanying a set of photographs of COLOSSUS which were made available at the Public Record Office on 20 October 1975. (The explanatory caption is reproduced in its entirety as in the Appendix, and the photographs as Figs. 1-5). Thus 32 years later, the Government has at last declassified, at least partially, the electronic computers developed secretly in Britain during World War II. Over the years a number of requests have been made to the Government to declassify the COLOSSI. I myself made one such request in 1972, which although unsuccessful, did lead to my receiving an assurance from the Prime Minister's Office that an official history would be prepared, although this history would have to remain classified [61]. During recent years a few details about the COLOSSI have been disclosed by some of the people involved – these details were summarized in a two-page article by Michie [63]. The present release provides welcome official confirmation of the overall accuracy of this summary and indeed provides some further technical details. However the release makes it clear, by implication, that the Government still regards the detailed logical design, and the use made of the COLOSSI, as classified. My understanding is that the promised history has been completed but remains secret – fortunately the security relaxation has been sufficient for me to obtain assistance in interviewing a number of the people who were most closely involved in the design and use of the COLOSSI. The aim has been to attempt to clarify the relationship of the COLOSSUS work to other better-known work on electronic computers and devices, and thus provide an appropriate perspective on COLOSSUS with respect to the history of digital computers, both American and British. The present paper is, in the main, based on these interviews, but is supplemented by material already in the public domain. To the best of my knowledge I have managed to collate all the releasable and verifiable information on COLOSSUS and its significance in the history of electronic digital computers.

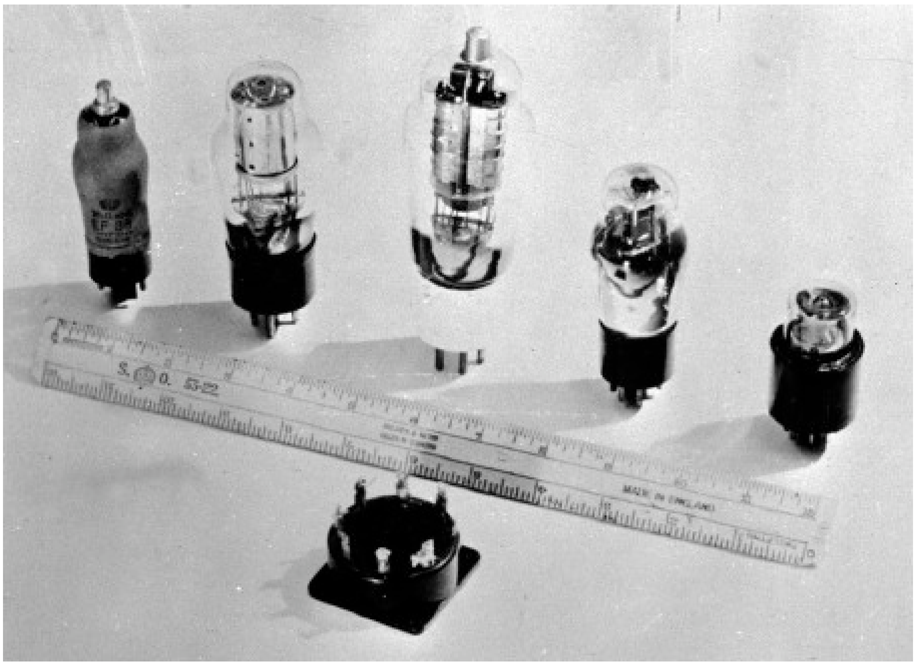

Figure 1 The valves used in COLOSSUS, showing the four valves and the photoelectric cell that were most commonly used throughout COLOSSUS. They are (left to right) EF 36, GTIC, 807, L63 and photocell RCA. In the foreground is the surface mounting octal valve holder used extensively throughout this machine.

However a word of warning is in order at this point. The people I interviewed were being asked to recall happenings of 30 or so years ago, and to do so without any opportunity to inspect original files and documents. Many of them had made conscious efforts to try and forget about their Foreign Office work as soon as they returned to their normal professions in 1945. During the war, secrecy considerations were paramount and gave rise to a rigid compartmentalization of activities so that few would have any detailed knowledge of the work of people outside their own small group. I have therefore where possible to obtain confirmation of what I learnt from each person by asking similar questions of his colleagues, and have tried to document the exact source (or sources) of each item reported. However, it is to be expected that if and when the files documenting the wartime work of the Foreign Office's Department of Communications are declassified the present account will be seen to be fragmentary and far from exact. Moreover only then will it be possible to see COLOSSUS in its true perspective as a tool developed for a particularly urgent wartime need – the present account has perforce to concentrate on COLOSSUS itself, and so runs the risk of providing a rather distorted view of the events that it attempts to chronicle.

2. Turing and Babbage

The work that Alan Turing documented in his famous paper, On Computable Numbers with an Application to the Entscheidungsproblem (published in 1937), was done while he was at King's College, Cambridge. He had gone to King's as a mathematical scholar in 1931, at the age of 19, and was elected to a Fellowship in 1935 [79]. M. H. A. Newman (Fig. 6) had been a University Lecturer in Mathematics at Cambridge since 1924, and it is believed that Turing's work was sparked off by one of Newman's lectures. This was a lecture in which Newman discussed Hilbert's view that any mathematical problem can be solved by a fixed and definite process [69]. Turing seized on Newman's phraseology, "a purely mechanical process", and interpreted it as "something that could be done by an automatic machine." He introduced a simple abstract machine in order to prove Hilbert was wrong, and in fact showed that there is a "universal automaton" which can perform any calculation that any special automaton can, if first provided with the appropriate instructions as input.

Turing thus was the first to arrive at an understanding of the universal nature of a (conceptual) digital computer which matches and indeed surpasses the philosophic understanding that I believe Babbage had attained, a century earlier, of the universality of his planned (mechanical) Analytical Engine. Babbage's phrasing was "that the whole of the conditions which enable a *finite* machine to make calculations of *unlimited* extent are fulfilled in the Analytical Engine" [2, p.28], where the term "extent" encompassed both the amount and accuracy of the data to be processed, and the length and logical complexity of the algorithm to be performed. Central to the Universal Turing Machine is the idea of having data, and input data in particular, represent a program (called a "table" in Turing's paper). A hitherto little known manuscript by Babbage [1] which has recently been published for the first time makes it clear that Babbage had reached an almost similar level of understanding. In the manuscript he points out that a fully detailed sequence of "formula cards" might be prepared by the Analytical Engine from a more abstract sequence. However, this is not to say that Turing's work was in any way derived from Babbage's – indeed there is no evidence that Turing even knew of Babbage at this time, but this topic will be returned to later.

In September 1936 Turing left Cambridge to spend a year in the Mathematics Department of Princeton University [79], where the staff included Church, Courant, Hardy, Einstein and von Neumann. He spent the summer of 1937 back in Britain, and then returned to Princeton on a Procter Fellowship, and received his Ph.D. in 1938. Von Neumann "was enormously intrigued with" [40] his idea of a universal automaton, and offered Turing a post as his assistant. This offer was refused and Turing returned in the summer of 1938 to King's College, Cambridge, where his Fellowship had been renewed [39,79]. According to the biography written by his mother, Turing was taken on as a temporary Civil Servant in the Foreign Office in the Department of Communications immediately following the declaration of war. At first even his whereabouts were kept secret, though it was divulged later that he was working at Bletchley Park [80].

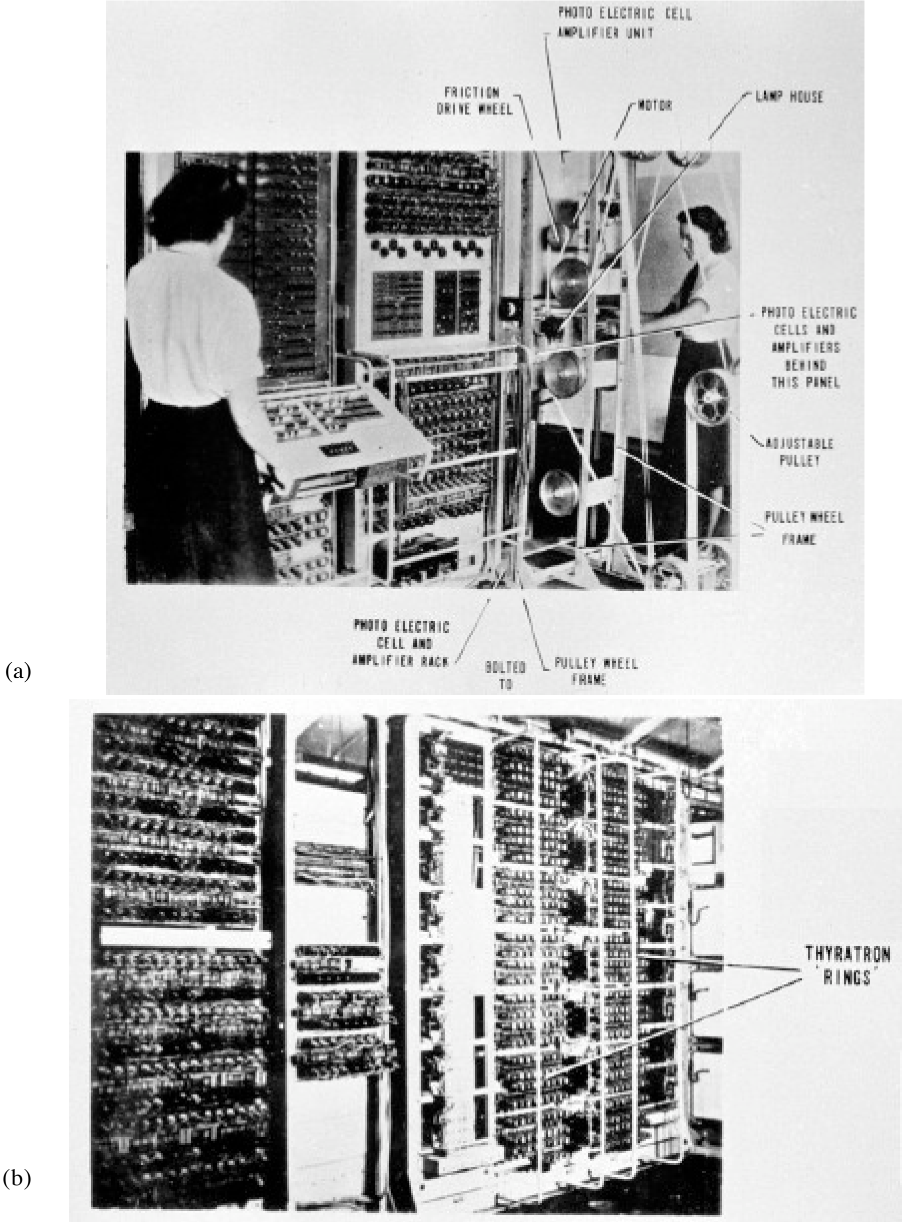

Figure 2 COLOSSUS. (a) front view and (b) back view

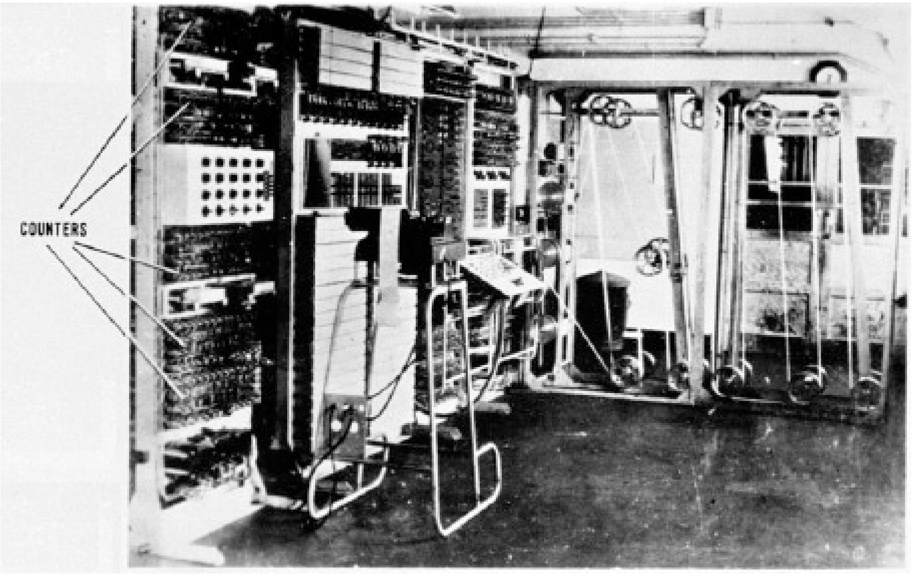

Figure 3 COLOSSUS, view of front racks and bedsteads.

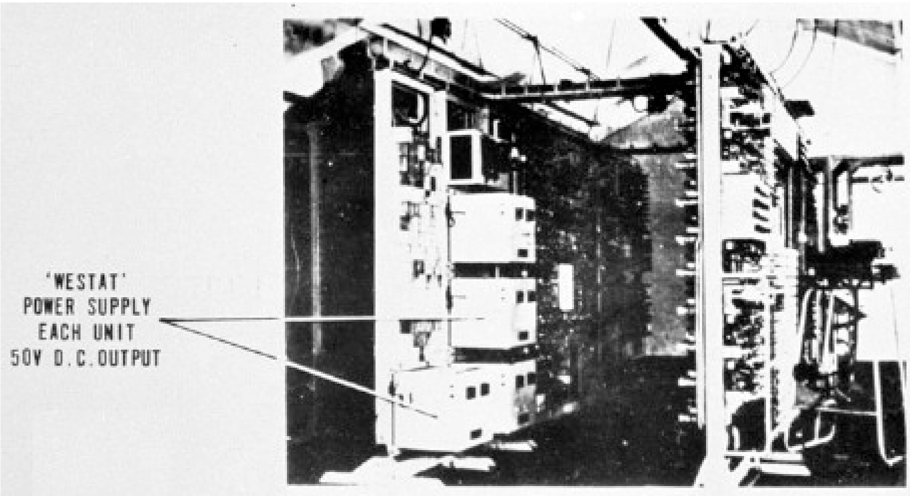

Figure 4 COLOSSUS, side view.

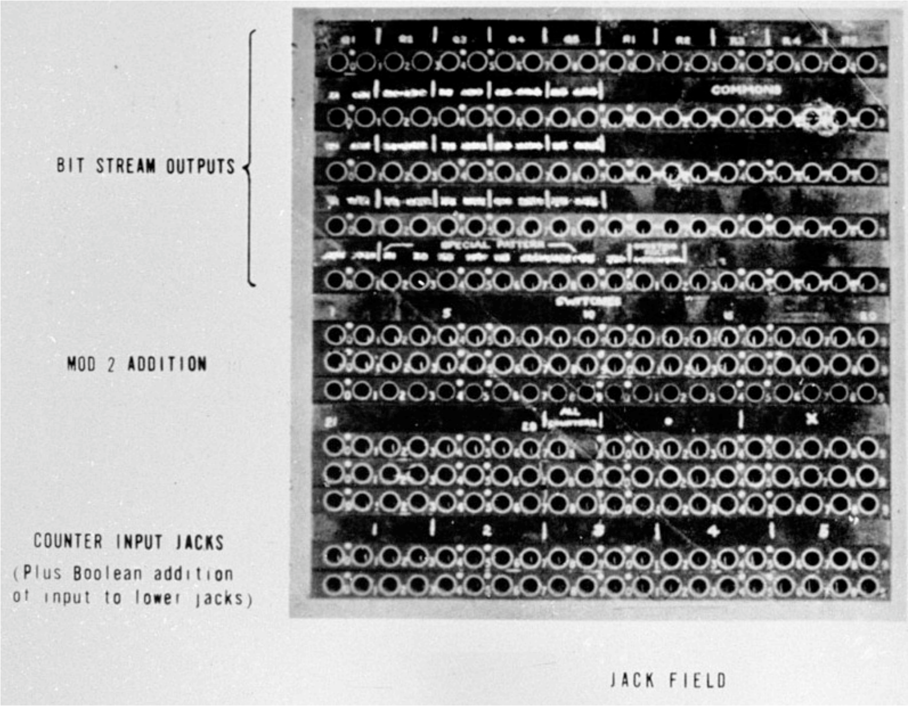

Figure 5 COLOSSUS, view of jack field

Figure 6 Professor M. H. A. Newman

3. Bletchley Park

The nature of the work that was undertaken at Bletchley Park (Fig. 7) during World War II is still secret, but statements have been appearing in published works in recent years that strongly suggest that it included an important part of the British Government's cryptologic effort. It was referred to somewhat briefly in Kahn's massive survey [50] published in 1967 and in various later books. Muggeridge described it as "a manor house . . . [where] the staff were a curious mixture of mathematicians, dons of various kinds, chess and crossword maestros [and] an odd musician or two . . ." [68, p. 128]. Seale and McConville state that during the war it housed the Government Code and Cypher School ("known to its inmates as the Golf Club and Chess Society" [75, p. 144]).

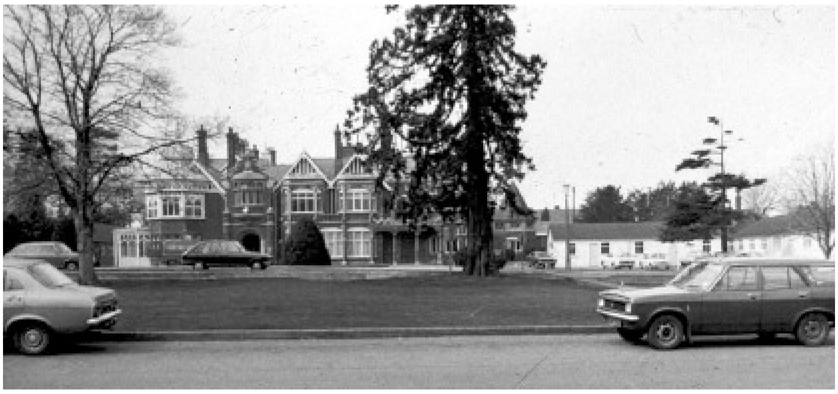

Figure 7 Bletchley Park as it is now.
Two original wartime huts can be seen on the right.

Bletchley is also referred to in Winterbotham's book [88]. The book's one reference to computers comes in the statement, "It is no longer a secret that the backroom boys of Bletchley used the new science of electronics to help them . . . . I am not of the computer age nor do I attempt to understand them, but early in 1940 I was ushered with great solemnity into the shrine where stood a bronze-coloured face, like some Eastern Goddess who was destined to become, the oracle of Bletchley" [88, p. 15].[*] (The book also made the surprising statement that Babbage worked at Bletchley Park: but this turns out to be Dr. D. W. Babbage, who is now President of Magdalene College, Cambridge. Dr. Babbage is in fact a distant relative, though not a direct descendant, of Charles Babbage [3].) Subsequently, in a lengthy newspaper article prompted by Winterbotham's book, Calvocoressi referred to the use at Bletchley of "machines called bombes which were prototype computers" [8]. The book also spurred Kozaczuk to write an article containing the claim that the Bletchley Park work was in part based on work done in Poland before the war, which had involved the construction of "bombs" which were "complex electronic

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[*] Quoted by permission of F. W. Winterbotham and of Weidenfeld and Nicolson.

units with tens of thousands of subassemblies and details" [55, p. 33]. However the brief description that he provides gives the impression that these were similar in concept to Lehmer's "photoelectric number sieve" [55], a basically electromechanical device used to tackle problems in number theory, in particular, to search for primes.

The recently published book by Cave Brown [13] also refers to a machine called "The Bomb", which was designed by Turing [13]. Quoting Cave Brown,

> Specifications were soon ready, and they were with the engineers during the last quarter of 1938. The contract went to the British Tabulating Machine Company at Letchworth, not far from Bletchley, and BTM assigned the task of building 'The Bomb' – as the Turing Engine came to be called – to its Chief Engineer, Harold Keen, and a team of twelve men . . . . It was a copper-colored cabinet some 8 feet tall and perhaps 8 feet wide at its base, shaped like an old-fashioned keyhole. And inside the cabinet was a piece of engineering which defied description. As Keen said, it was not a computer, and 'There was no other machine like it. It was unique, built especially for [its] purpose. Neither was it a complex tabulating machine.'. . . Its initial performance was uncertain, and its sound was strange; it made a noise like a battery of knitting needles as it worked . . . [13, pp. 22-23].[*]

I can in no way vouch for Cave Brown's statements, impressively detailed though they are. Indeed the dates he gives for Turing's involvement are not consistent with the statement quoted earlier from Turing's biography implying that he joined the Foreign Office in September 1939. Furthermore the description of the Turing Engine does not seem to match the implication that it was related to the concept of the Universal Turing Machine.

My investigation has concentrated on COLOSSUS, and there seems no doubt that the work on COLOSSUS postdates by a couple of years or so the work on "The Bomb" referred to by Brown and Winterbotham. I have learned from Mr. T. H. Flowers and Professor M. H. A. Newman that their involvement with the Foreign Office work dates from February 1941 and September 1942, respectively [28, 70]. This adds credence to Kahn's statement, in a review of Winterbotham's book that it was in order to solve other problems that "the Bletchley geniuses evolved perhaps the first modern electronic computer which they nicknamed 'COLOSSUS' "[52]. However questions concerning the use made of COLOSSUS are outside the scope of this paper.

4. T.H. Flowers

In 1941 Mr. T. H. Flowers (Fig. 8) was in charge of the switching group at the Post Office Research Station, which was situated at Dollis Hill in north-west London. The group at this time contained about ten graduate engineers and 50 persons in all and was the biggest group in the Research Station. Flowers had joined the Research Station as a probationary engineer in 1930 after serving his apprenticeship at Woolwich Arsenal [5, 28]. His major research interest over the years had been long-distance signalling, and in particular the problem of transmitting control signals, enabling human operators to be replaced by automatic switching equipment. Even at this early date he had considerable

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[*] Quoted by permission of Antony Cave Brown and W. H. Allen Ltd.

experience of electronics, having started research on the use of electronic valves for telephone switching in 1931. This work had resulted in an experimental toll dialling circuit which was certainly operational in 1935, as he recalls using it to telephone his fiancée, whom he married in that year. The first production system is believed to have been installed by 1939 [29, 30].

Figure 8 Mr. T. H. Flowers

However, Flowers and his switching group had worked on a great variety of different research topics – as he has put it "work was fired at us from all directions" [29, p. 3]. He had used thyratrons for counting purposes, and he had some contact with C. A. Beevers, an x-ray crystallographer who was working on a special-purpose digital calculator made from electromechanical telephone switching components [4]. This was perhaps Flowers's earliest contact with digital computation, although he did know Comrie and his work. On the analog side, he had some knowledge of the differential analyzer at Manchester University, having seen it there at an exhibition in 1937 [28], and later having Alan Fairweather, one of the graduates who had worked on it, as a member of his staff.

As war approached Flowers became involved with various special projects. One involved an electromechanical digital device for anti-aircraft ranging, originated by Dr. Hart of the Royal Aircraft Establishment, Farnborough [29]. However this project, being based on sound detection, was a cause of some embarrassment to Flowers, who had since 1937 been cleared to receive information about what later came to be known as radar. He thus knew that Hart's project was likely to be obsolete before completion, but was not able to tell the others of this fact.

In February 1941, Flowers was approached by Dr. W. G. (later Sir W. Gordon) Radley, Director of the Post Office Research Station, to work on a problem for Bletchley Park [29]. Until this time he had reported to Radley through a division head. However, even the division head was not told of the Bletchley Park request, for security reasons, and from then on Flowers reported direct to Radley. Apparently Flowers and Radley were the first Post Office people to be initiated into the work at Bletchley Park [30]. Flowers had the impression that the approach had been made at the suggestion of Dr. C. E. Wynn-Williams, and that Wynn-Williams was, with Turing, among the first people he met at Bletchley [28, 29]. However, Dr. Wynn-Williams has stated that he did not get involved with Foreign Office work until November 1941 [94]. It was Dr. Wynn-Williams who pioneered the use of electronics for high-speed counters used in nuclear physics research. At the Cavendish Laboratory in 1931 he built the first electronic binary counter, using thyratrons [92]. By 1935 such a counter had been incorporated into a device which, by means of electromagnetic relays and uniselectors, provided binary-decimal conversion and automatic printing. Wynn-Williams moved from the Cavendish Laboratory to Imperial College in 1935 and by 1939 he had built a second version of this apparatus incorporating "a programme device . . . which could control experimental conditions and carry out cycles of pre-arranged runs by remote control of the equipment" [93].

Wynn-Williams was released by Imperial College, when war broke out in 1939, to join the radar program at TRE (Telecommunications Research Establishment) as it later became known after its move to Malvern in May 1942. (Wynn-Williams was first stationed at Dundee and then from May 1940 at Swanage [96].)

Flowers's next six months were spent building a special-purpose electro-mechanical device for Bletchley Park [29]. The work was mainly done at Dollis Hill but Flowers spent a lot of time at Bletchley Park, where he interacted with Turing and Mr. W. Gordon Welchman [29]. (Welchman was a Fellow of Sidney Sussex College, Cambridge, and at Bletchley Park became Assistant Director for Mechanization [70]. After the war he spent three years as Director of Research for the John Lewis Partnership and then went to the U.S. and entered, or perhaps one should say re-entered, the computer field. He headed the applications research phase of the Whirlwind computer project at MIT for a few years, and then worked for various American and British computer companies – ERA, Remington Rand and Ferranti. Welchman in fact gave the first course on digital computers in the Electrical Engineering Department at MIT [84, 85].) Turing paid several visits to Dollis Hill at this time for discussions with Flowers, but for security reasons the majority of their meetings were held at Bletchley Park [5, 29].

Figure 9 Mr. S. W. Broadhurst

During this period one of Flowers's colleagues at Dollis Hill, Mr. S. W. Broadhurst (Fig. 9), was brought in to help with the project as soon as he received security clearance [5, 28, 29]. Broadhurst's forte was electromechanical equipment. He had, in his own words "come up the hard way, but it was quite enjoyable" – having joined the Post Office as a workman. He had taken this job to tide him over while he continued to look for an engineering job after finishing his apprenticeship with the South-East and Chatham Railway in 1923 [5, 6]. He was soon upgraded and served for a period on commissioning and maintaining one of the early automatic exchanges before being transferred to the newly formed Circuit Laboratory at Post Office Headquarters. From there he went to the P.O. Engineering Training School and later to Dollis Hill. Here he taught courses on automatic telephony, which was then a fairly new subject within the Post Office. Eventually he was promoted into the Research Branch, joining Flowers' group, in which he spent the first 18 months of the war working on various projects associated with radar.

The device that Flowers and Broadhurst built for Turing involved the use of high-speed rotary switches [29]. It could be described as a sort of computer, with a lot of the data and logic being on banks of switches [28]. However, it was a straightforward engineering job, with nothing in the way of arithmetic or programming facilities. In fact the whole project turned out to have been a mistake, as the speed requirement that was specified initially soon turned out to have been grossly underestimated [29]. Flowers has the impression that one of the reasons that they were then introduced to some of the other problems at Bletchley Park was that the people there felt somewhat guilty at having wasted his and Broadhurst's time [29].

Figure 10 Mr. W.W. Chandler

At about this stage another of Flowers' staff, Mr. W. W. Chandler (Fig. 10), joined in the work for Bletchley Park. Chandler was the youngest of the three, having joined Dollis Hill in 1936 as a trainee. His main work since then had been on voice frequency signalling for trunk lines, with a Mr. Hadfield. This he believes had been the first use of thermionic valves for switching purposes in Post Office communications [15]. In fact Flowers has described Chandler as the most "mathematical and computer-minded and electronic-minded" [28] of the three of them.

They became involved in various aspects of a quite different project that both Wynn-Williams of TRE and H. M. Keen of the British Tabulating Machine Company (BTM) were working on. Again Flowers and his colleagues found themselves getting much of their direction from Turing. The basic problem was to provide a very much faster version of an earlier electromechanical device that B.T.M. had built [29]. Chandler spent from January to May, 1942 at Swanage, where Wynn-Williams was experimenting with a device that was to use high-speed commutators [15, 16]. Flowers and his people were brought in, because of their prior experience, to provide the electronic relays which would be needed with such commutators. There were considerable difficulties with the commutators, and it was discovered and demonstrated that the problem was due to a potential drop occurring across a contact being made with a moving surface [29]. (The actual demonstration was made possible by a precision test instrument, involving a 3-inch cathode ray tube, which had been built before the war at Dollis Hill by Hadfield.)

A different approach to the problem was taken by Keen at BTM [29]. Flowers and Chandler spent some time at Letchworth with Keen, who had been trying to speed up the earlier electromechanical device and was having problems getting fast enough relays. The Flowers team proposed and demonstrated the use of hot cathode gas discharge tubes instead of relays, on grounds of both increased speed and reliability, but for various reasons their solution was not adopted [28]. However, through these various activities they had established themselves as the leading exponents of electronics at Bletchley, in time as it turned out for the beginning of the project that led to the COLOSSUS [29].

5. Newmanry and Testery

The staff at Bletchley Park were divided into different sections, each in general housed in different huts on the grounds [8, 45]. One such section was headed by Major (later Colonel) Tester and was working on yet another problem using pencil-and-paper rather than mechanized procedures and techniques. The section, and its type of work, were sometimes known as the Testery, and it was this section that Donald Michie joined initially on his arrival at Bletchley Park in the autumn of 1942 [64].

In the Testery, Michie was taught by P. J. Hilton to carry out a particular procedure. In the process was referred back to Turing, who acted as an informal consultant to the section, having developed the procedure from earlier work done by W. T. Tutte [64]. Tutte had reached Bletchley Park in mid-1941 from Cambridge University, where he had abandoned his studies for a Ph.D. in chemistry after becoming interested in combinatorial mathematics. At Bletchley he was a member of a small central research section, under Major G. W. Morgan. As Tutte himself has put it, “I think it was at Bletchley Park that I first acquired some standing as a mathematician. In 1942 1 found myself elected as a Fellow of Trinity, though only one or two of the electors can have known what it was for” [80].

M. H. A. Newman reached Bletchley Park in September 1942, where he also joined the central research section [70]. Newman on arrival at Bletchley Park had, like Michie, been assigned to the Testery. The work there required an extraordinary type of ingenuity, rather akin to solving crossword puzzles, and Newman soon realized that he was no good at it and considered resigning and returning to Cambridge. (He had gone in voluntarily, as a civilian, so could have left if he had so chosen [69].) But then he had an idea whereby Tutte’s original procedure could be assisted by mechanical means. (Tutte himself had no direct concern with the development of machinery [80].) Newman went to Commander (later Sir Edward) Travis, the head of Bletchley Park, and obtained authorization to set up a new section for this purpose [69], which was housed in what was known as Hut F [45]. By this time he had made the acquaintance of Wynn-Williams, who undertook to develop the required machine [69]. This was the machine that became known as the HEATH

ROBINSON, after a cartoonist famous for his fanciful machines intended for all sorts of extraordinary tasks [30].

The techniques used in Newman's section, the Newmanry, even with the hoped-for mechanical aid, would still involve a great deal of mathematical skill, and he started to assemble a team of mathematicians [69]. The first to arrive were Michie and I. J. Good [47, 48, 64]. Michie had only recently left school and knew little mathematics at the start. Despite this he played an important role, and learnt enough mathematics at Bletchley to continue to play a valuable role even as the work gradually became more technical [70]. Good had joined Bletchley Park in May 1941 from Jesus College, Cambridge. He had been doing research in pure mathematics, having obtained his Ph.D. about a year earlier and also having won the Cambridgeshire chess championship [45]. At Bletchley his first 18 months or so were spent in a section headed by Turing, for whom he acted as a statistical assistant. Thus by the time he joined Newman he was already a strong mathematician and statistician who also had both a taste and a talent for trouble-shooting of every kind. He and Michie with some thirty Wrens[*] as machine operators and a few electronic engineers formed Newman's entire staff during the early part of the ROINSON era [70].

6. HEATH ROBINSON

The summary published by Michie included the following details of the HEATH ROBINSON:

> The machine incorporated two synchronised photo-electric paper tape readers, capable of reading 2000 char/sec. Two loops of 5-hole tape, typically more than 1000 characters in length, would be mounted on these readers . . . . Counts were made of any desired Boolean function of the two inputs. Fast counting was performed electronically, and slow operations, [such as the later stages of the counters[**] and] control of peripheral equipment, by relays. The machine and all its successors were entirely automatic in operation, once started, and incorporated an on-line output teleprinter or typewriter [63].

In fact I have been informed that output did not use a typewriter-like device, but rather a primitive line printer, known as the Gifford printer after its designer, Mr. Tom Gifford of TRE [37]. The HEATH ROBINSON used two counters alternately so that results of one counter could be printed while the next count was continuing. The printer used a set of circular decimal print wheels, that were rotated by a common drive when a number was to be set up. Each wheel had ten contacts fixed to its side, to which the output of the appropriate decade of a counter would be fed. These contacts were used to determine how far each wheel should be allowed to rotate. The printing of a line of digits occurred after all the wheels had stopped rotating.

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[*] WRNS: Women's Royal Naval Service.

[**] See [37].

HEATH ROBINSON, and a number of similar machines, which went by such names as “PETER ROBINSON” and “ROBINSON AND CLEAVER” (the names of two London stores), was built through the combined efforts of teams at TRE and Dollis Hill [16, 63]. At TRE Wynn-Williams had assembled a small group of carefully selected people, all of whom first had to be approved by Bletchley [94]. This group and the Superintendent (A. P. Rowe) and Assistant Superintendent (W. B. Lewis) were the only people in TRE who knew what was going on, and why. Dr. Wynn-Williams undertook to produce the electronic counters and necessary circuitry but recommended that a Post Office telegraph engineer be given the tape driving and reading problem [31]. It was thus that Mr. F. O. Morrell, head of the telegraph group at Dollis Hill, became involved during the summer of 1942 [28, 61, 68]. He commissioned Dr. E. A. Speight and Mr. (now Dr.) A. C. Lynch of the physics group at Dollis Hill to produce a photoelectric reader. (Dr. Speight, incidentally, had designed much of the Post Office’s Speaking Clock [59].)

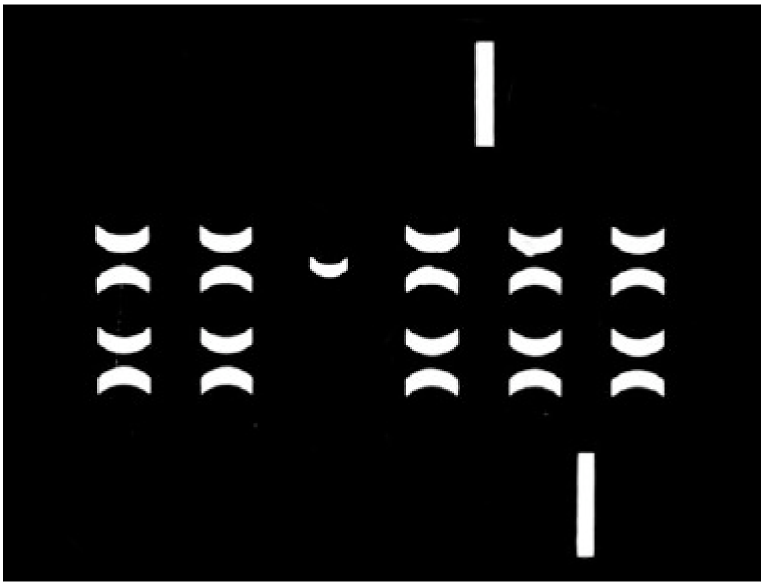


Figure 11 Mask used in photoelectric reader (70% actual size)

Speight and Lynch were not told [32] of the intended purpose of the photoelectric reader, which they knew as the Mark I Telegraph Transmitter, or more exactly the “Transmitter, Telegraph, Mark I”. Since some of the components that they used had originally been intended for apparatus for RAF Fighter Command at Bentley Priory, when it was found that the reader was for “B.P.” many people assumed that this stood for Bentley Priory. Their first design was a prototype constructed hurriedly from whatever components could be found, that was followed by a more considered design. Both designs used double-crescent masks in order to produce a nearly rectangular pulse of light as a circular hole crossed the mask. One of the photographic masks from the second design of reader has survived, although now broken, as is shown in Fig. 11. This was used to read two successive rows of five hole tape simultaneously, and to detect the sprocket hole in order to produce a timing pulse. Each reader incorporated a number of lenses, and much of the optical work was done by Dr. Speight's assistant, Mr. D. A. Campbell. The prototype used Type CMG 25 photocells (gas-filled) and the second design vacuum photocells [58]. It seems probable that the second design was used for HEATH ROBINSON as well as COLOSSUS, although there is some uncertainty as to the speed at which the reader was operated on the HEATH ROBINSON. Some accounts of the speed of HEATH ROBINSON give it either directly, or via comparisons with COLOSSUS, as being about 200 rather than 2000 char/sec., [15, 29, 62, 69] while Dr. Lynch has stated that the specification of the first reader called for a speed of 1000 char/sec [58]. This confusion seems to have arisen due to the fact that although the electronics of Robinson were capable of operating at 2000 characters/sec, in practice the operating speed was limited by several factors:

a) the deionization time of the initial stages of the thyratron counters. By selecting suitable valves 2000 characters/sec could be achieved for a time.

b) the length of the tape. A finite time was needed for the printing operation and with a short tape the machine had to be run more slowly to provide this.

c) the length and strength of the tape. Long tapes, even with the friction drive assistance, placed more strain on the paper at the sprocket drive and were usually run more slowly. [16, 31]

Morrell took Speight and Lynch's reader, and used the output from the sprocket holes as a carrier, which he phase modulated with the character hole outputs to derive pulses which were counted [31]. He also produced an auxiliary machine, which was used to produce the tapes that formed one of the two inputs to the HEATH ROBINSON [33, 67]. This machine was a straightforward piece of electromechanical engineering, incorporating plugboards and sets of keys. Input data could be set up on the plugboards and the keys were used to control the choice and sequencing of the data [67].

The TRE and Dollis Hill halves of the HEATH ROBINSON, which was not in fact a particularly large machine, were put together, it is believed, at Bletchley Park in about April 1943 [94]. By this time a third skilled mathematician, Dr. Shaun Wylie, had arrived, and others soon followed. From this time on the work benefited from numerous discussions, usually chaired by Newman, which later became more like formal meetings, although they always remained free and easy, and produced a great flow of good ideas [70].

Once the machine was considered operational Professor Newman and his staff took it over, though people from TRE and Dollis Hill remained available to deal with teething troubles [94]. There were at the start very considerable reliability problems, mostly concerned with the paper tape reading mechanism [29, 45, 64]. This mechanism involved a rigid shaft with two sprocket wheels which engaged the sprocket holes of the two tapes, keeping the two in alignment [62]. The paper-tape loops could not withstand the wear and tear caused by the sprocket wheels, and would break. This would mean that the job would have to be started over again from the beginning [29]. Eventually, this problem was solved by Morrell, who designed a system for driving the tapes by pulley, that is, by friction, and using the sprockets for tape alignment only [33]. However, even then it was still the case that the machine would often produce slightly different results from repeated runs using the same tapes, something that Newman was very put out about [29]. This problem was perhaps due to the method of obtaining pulses for counting. Another problem was that things could get out of phase due to tape shrinkage, which mattered because there was a 2-in. gap between the sprocket drive and the point at which the sprocket hole was read [15, 37]. In fact according to Newman the machine even had a tendency to seize up and catch fire [69]!

Over and above all this it took quite some time to develop an effective methodology, and to gather the logical data which would enable the HEATH ROBINSON to be at all effective. Thus Newman, who had done the enormous amount of work and persuasion necessary to get the project authorized and the machine built, came under tremendous pressure to produce results, though he remained exceedingly determined and confident. Somewhat premature attempts were made to use it operationally, but in the evenings Good and Michie, with the aid of a few volunteer Wrens and electronic engineers, undertook the research that was first needed [64]. (The Wrens served as machine operators, and the engineers did maintenance work and very minor machine modifications as required.)

All of this activity paid off handsomely in that it completely proved the correctness of Newman's intentions. Thus, although the ROBINSONs produced only a small amount of output which was of value in itself, they played an important role in preparing the way for COLOSSUS [64, 71].

7. The First COLOSSUS

Some time after the start of the HEATH ROBINSON project Flowers and Broadhurst, who up to that time were unaware of the work, were brought into the project [31]; Newman has the impression that this was at Turing's suggestion [69]. Flowers' original task was to redesign the electronic counter, which had proved to be unreliable. However he soon formed the view that the sprocket wheel problem was unlikely to be solved mechanically, so he proposed a much different solution, one involving considerable electronic complexity [29]. This approach was therefore very much in contrast to that of Wynn-Williams, who preferred to use as few valves as possible, favouring electromagnetic relays instead. Flowers on the other hand was confident that switching circuit networks involving even large numbers of valves could be made to work reliably. As one of his colleagues has put it: "The basic thing about Flowers was that he didn't care about how many valves he used" [15, p. 5], although of course efforts were made to keep the number of valves within reasonable bounds [37]. He knew from his prewar experience that most valve failures occurred when, or shortly after, power was switched on. He realized that, given appropriate design practices, electronic equipment that could be left on permanently could be expected to achieve a high level of reliability, although this remained to be proven in a large machine [28]. Wynn-Williams though, being at TRE, was probably influenced by the experience of radar sets that were used intermittently, and in adverse environments.

Flowers proposed that he and his colleagues design and build a machine that was to have no fewer than 1500 valves. This is, as far as I can ascertain, considerably in excess of anything else that had been tried to that time in Britain or the U.S., for radar or for purposes of logical or numerical calculation. (Indeed this is nearly twice the number of valves that were used in the Pilot ACE computer, built at NPL after the war [97].) It is thus hardly surprising that many people were unconvinced by these proposals, although Newman was on Flowers's side. Failing to get official support from Bletchley Park, Flowers instead got the project authorized by Radley, the Director of the Dollis Hill Research Station [15, 29].

In the incredibly short space of 11 months the machine that the Bletchley Park people were to christen the COLOSSUS was built [5, 28, 29]. The construction was carried out at Dollis Hill by technicians in Flowers's group [15]. The electronic design was done mainly by Flowers and Chandler with Broadhurst concentrating on the auxiliary electromechanical equipment [5]. The photoelectric reader was a redesigned version of the one used on HEATH ROBINSON, working at 5000 characters/sec [33, 63]. The electronic counters were biquinary [34], based on those developed before the war by W. B. Lewis, who had been at the Cavendish Laboratory with Wynn-Williams [56]. Lewis played an important, though perhaps unwitting, role in the COLOSSUS story through his book on counting circuits. Flowers credits this book [57] as an important landmark in his own understanding of electronics: "When he produced this work a lot of things I had learnt in the past suddenly clicked. I knew about Eccles-Jordan and trigger circuits but it never occurred to me very clearly how to use them to substitute relays and stores" [28, p. 15]. When Flowers tried out Lewis's original circuit he found it didn't work properly for him, so he produced a redesigned circuit [15, 24] that didn't require such accurate components, which was later patented [26]. Apparently the key change in this redesigned circuit was the use of the EF 36 valve with its short grid base, which made the potential dividers in the circuits less critical [37]. Flowers's counter circuits were much more sophisticated than Lewis's, using, for example, the screen and suppressor grid connections for various purposes, such as reset to zero. Cathode follower drive and readoff circuits were also employed.

A small team of junior technicians who also helped in the electronic design of COLOSSUS were mainly responsible for commissioning the machine, which became operational at Bletchley Park in December 1943 [28, 29]. The machine was assembled and tested at Dollis Hill using short loops of tape on which repetitive patterns had been punched [17]. This turned out to be an advantage because the patterns facilitated the synchronization of an oscilloscope. The machine was then partially unwired prior to transportation to Bletchley Park, where it was reassembled [15]. As luck would have it, the first job that was run on the COLOSSUS at Bletchley Park happened to take only ten minutes – jobs could equally well take several hours. Moreover, when the job was repeated it produced exactly the same results again. No wonder that, as Flowers puts it: "They just couldn't believe it when we brought this string and sealing wax sort of thing in and it actually did a job. They were on their beam ends at the time, ROBINSON just hadn't got enough output, they wouldn't go fast enough, and suddenly this bit of string and sealing wax, in about ten minutes . . . and then they started to take notice!" [29, p. 12] (This reference to string and sealing wax is of course too modest – the prototype must have been well engineered, since with 1500 valve circuits which had to operate consistently there was no room for ad hoc construction methods.)

What Flowers had done was to generate some of the required data electronically within the machine, so that only one input data tape was required. The problem of keeping two tapes synchronized vanished. Furthermore, by using the pulses obtained from reading the sprocket holes to generate timing signals, the sprocket wheel itself could be dispensed with [29]. It therefore became necessary to provide means for setting up the machine before a run so as to have it generate the required sets of data from parameters stored in thyratron rings. For this purpose plugboards and sets of keys) based on those incorporated in the auxilliary tape preparation machine used with the ROBINSONs, were built into COLOSSUS. Therefore the bother and time needed to produce a second tape were eliminated [33]. More important, after the first COLOSSUS was made available to the mathematicians they began to make use of it to do processes that were not possible on ROBINSONs, by making the dynamically generated data dependent on the result of instantaneous processing [28, 69].

Turning to the question of electronic design, the prototype COLOSSUS included the following historically significant features:

(a) It used a clock pulse to synchronize and time operations throughout the machine. It was this feature that made the size of the machine possible by eliminating cumulative timing errors.

(b) It used binary hard valve electronic circuitry on a large scale. It was this that contributed to its reliability because there were no valves (other than in the tape reader photocell amplifiers) that were not either cut off or conducting representing the 0 or 1 condition.

(c) It had a shift register (five step).

(d) It used two-state circuits and clock control, meaning that the machine could operate at any speed down to zero. (The photocell amplifiers were the exception.) This meant that the machine could be 'hand-stepped' for test purposes.

(e) It used cathode followers to isolate the operation of the switching circuits from the output.

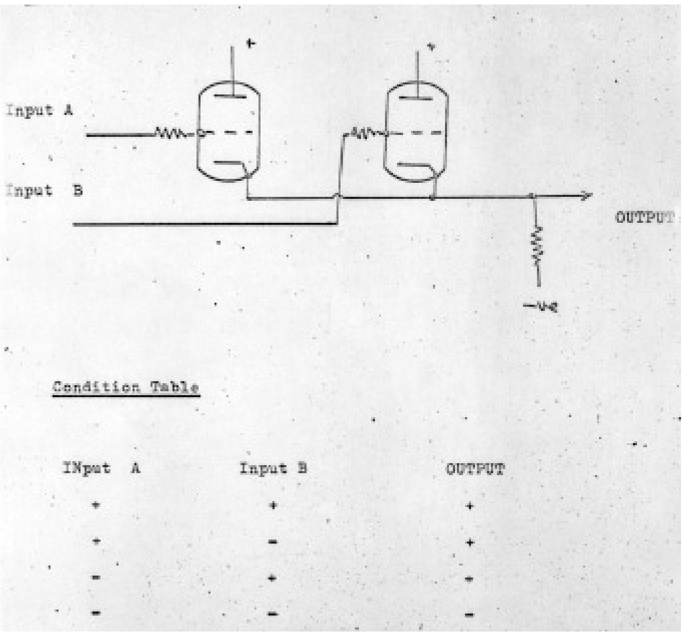
Reconstructed diagrams of the basic circuits Flowers designed for the prototype COLOSSUS are given in Figs. 12-16 [37].

8. The MARK II COLOSSUS

The last major figure in the COLOSSUS story, Dr. A. W. M. Coombs (Fig. 17), joined in at about the time the first machine was commissioned [5]. After leaving University and joining the Post Office in 1936, he had been almost wholly involved in various items of war work and became experienced with a great variety of electromechanical equipment and with electronics, but not electronic switching. He had been brought into the Foreign Office work in October 1943. He was to have undertaken further work related to HEATH ROBINSON at Dollis Hill but the advent of COLOSSUS changed all that [15, 29].

As soon as the first COLOSSUS, the string and sealing wax prototype as he called it, was working Flowers asked for advance warning of any requirements for further machines [29]. This was not forthcoming at first, but he took the precaution of arranging for manufacture of some of the more time-consuming components. Then in March 1944 the group was told that more machines were required by 1 June. There was no conceivable way of meeting this requirement, but Flowers undertook to get the production of an initial set of three machines started, and to try and get one machine working by the deadline [15, 30].

Michie's summary of published statements about the COLOSSI indicates that the production or MARK II machines were five times faster than the prototype [63] – "an effective speed of 25,000 characters/sec was obtained by a combination of parallel operations and short term memory." Five-stage shift registers were used to give access to five sequential characters simultaneously, even though the basic clock rate remained unchanged at 5000 characters/sec [37]. In addition, although testimony is not entirely clear on this point, it seems probable that starting with the first production COLOSSUS, extra facilities were provided that had not been available on the ROBINSONs or the prototype COLOSSUS [64]. These facilities included wired logic processes and a "logic switching panel" comprising rows of key switches on which Boolean functions could be set up to control the logical operations performed by the machine [35].



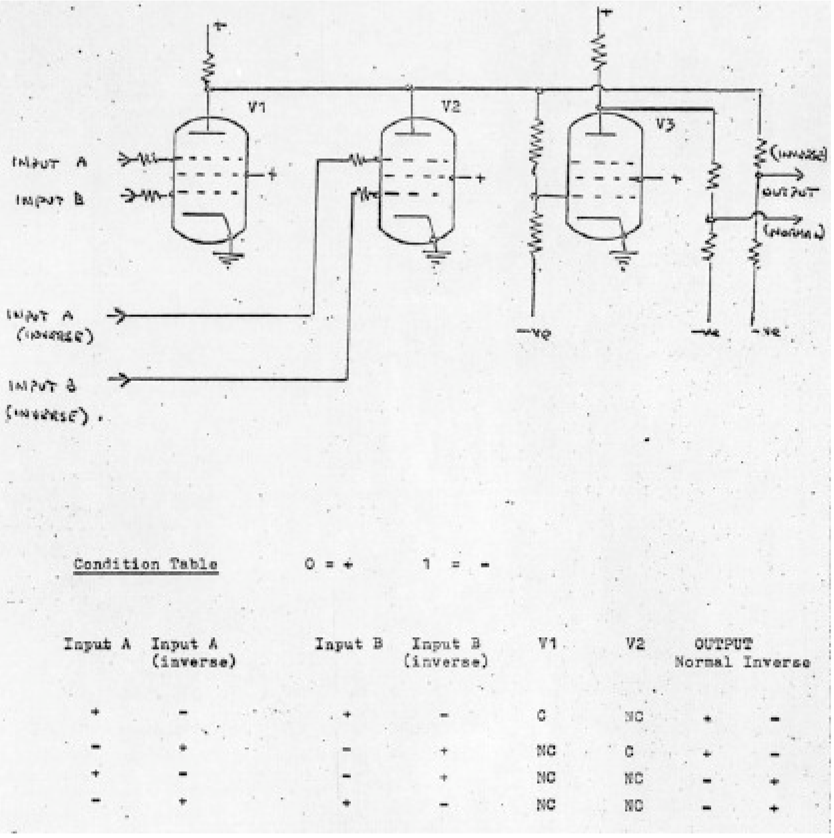
Condition Table

INput A	Input B	OUTPUT
+	+	+
+	-	+
-	+	-
-	-	-

Figure 12 Boolean addition circuit in COLOSSUS.

Although the basic logic and Flowers's original circuit technology remained virtually unchanged, the MARK II COLOSSUS involved extensive redesign of the prototype. For example, an additional counter was provided, more use was made of shift registers, and a number of detailed modifications made to the original circuitry [37]. The design work was divided up between Flowers, Broadhurst, Chandler and Coombs, who remembers Flowers literally tearing his basic logic diagram into pieces and handing out one each to be redesigned [15, 29]. Their designs were then handed over to various less senior engineers, including Oswald Belcher, Freddy Wraight, and Stan Willis, who laid out the circuits on standard panels and supervised the actual construction. This was done in what was essentially a factory, set up for the purpose in the Dollis Hill Research Station.

To save time the first MARK II machine was assembled on site at Bletchley Park, rather than at Dollis Hill [17]. The commissioning of the machine was the responsibility of Chandler and a colleague, Wilfred Saville. By 31 May it was nearly complete. Flowers, Broadhurst, Chandler, Coombs and Saville were all at Bletchley Park, but they could not get the machine to work. Eventually, in the early hours of 1 June, the others went home to get some sleep, leaving Chandler to work on, since the trouble was in the part he had redesigned. In his words, “The whole system was in a state of violent parasitic oscillation at a frequency outside the range of our oscilloscopes [and then] by way of diversion, at about 3.00 a.m. a nearby radiator started leaking, sending a pool of warm water towards the equipment!” [16]. He eventually found a means of curing the problem and at nearly 4.00 a.m. left Norman Thurlow, one of the maintenance engineers, to finish the required rewiring. The others others arrived back at 8.30 a.m. to find that the machine was working. The deadline had been beaten – and it was just five days to D-day, 6 June 1944!



Condition Table 0 = + 1 = -

Input A	Input A (inverse)	Input B	Input B (inverse)	V1	V2	OUTPUT	
						Normal	Inverse
+	-	+	-	C	NC	+	-
-	+	-	+	NC	C	+	-
+	-	-	+	NC	NC	-	+
-	+	+	-	NC	NC	-	+

Figure 13 Binary addition circuit as used in COLOSSUS. All valves are Mullard EF 36. Input and output voltages typically +20 (= 0) or -30 (=1). Valve conditions: C, conducting; NC, non-conducting.

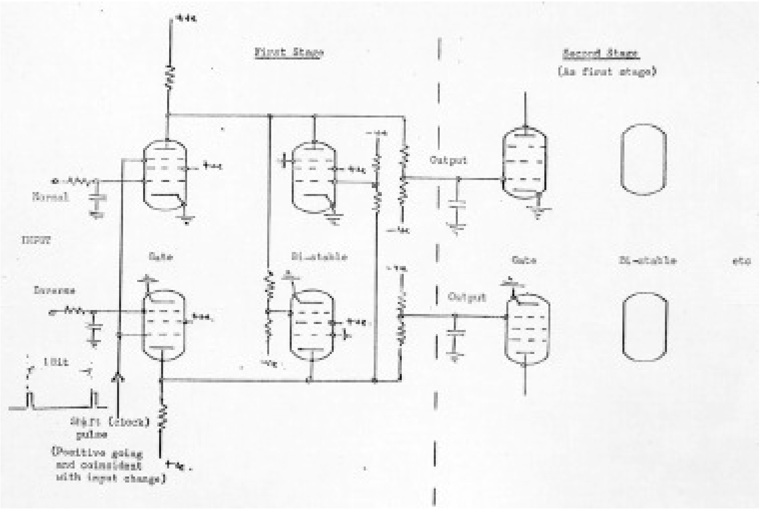


Figure 14 Shift register as used in COLUSSUS – circuit element.

Several more MARK II COLOSSI were soon installed, but during all of this time Newman and his mathematicians were having frequent discussions to explore the possibilities that had been opened up by the COLOSSI, and their requirements for further facilities [70]. One such request arose from some successful experiments on one of the machines. These were carried out by Good and Michie, and involved making manual connections and reconnections while the machine was actually operating, and observing the effects on its outputs [64, 66]. Apparently hard-wired facilities were later provided for doing these manipulations automatically, internally and at high-speed. Professor Newman's recollection is that several production machines had been delivered before these facilities were provided, and so greatly speeded up a particular task that the COLOSSI were being used for – however it was not possible to obtain confirmation of these points from the machine designers [46, 70]. It is not clear how much additional electronics was involved in the various new facilities that were incorporated in some of the MARK II machines. Even the earliest of these, it is believed, incorporated about 2400 valves, as well as much relay and other electromechanical equipment for data input and output [15, 30, 36]. The MARK II COLOSSI were apparently still fairly similar in appearance to the prototype, though Chandler and Coombs decided after close inspection that the recently released photographs are of one of the MARK II machines rather than the prototype [15].

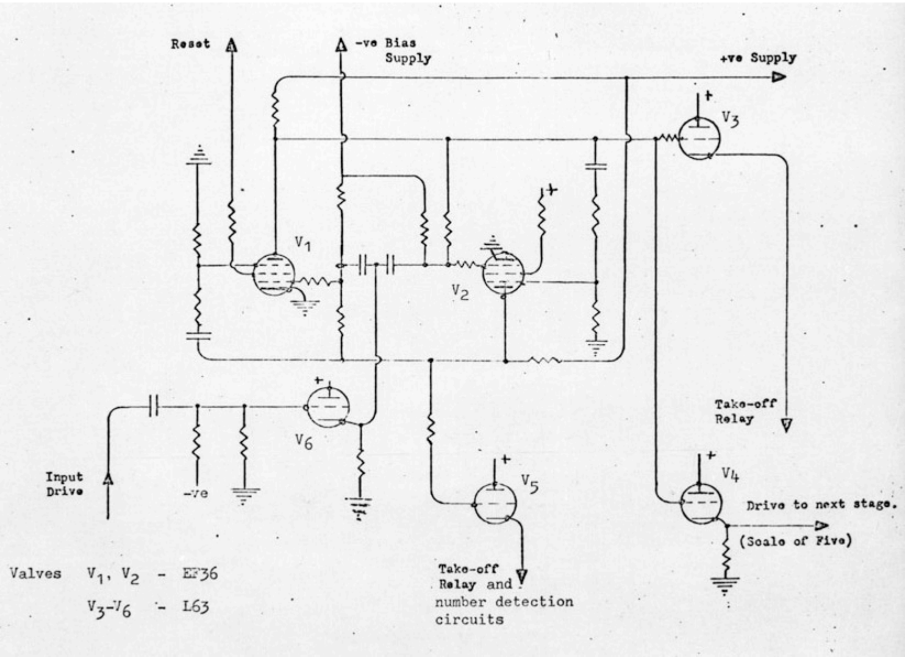


Figure 15: Biquinary couner as used in COLOSSUS – scale of two circuit elements. Valves V_1 and V_2 are EF 36; V_3-V_6 are L63.

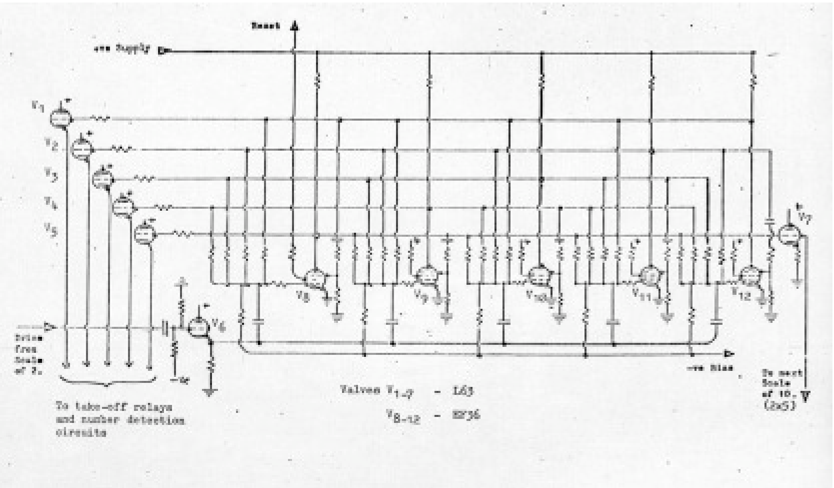


Figure 16 Biquinary counter as used in COLOSSUS – scale of five circuit elements. Valves V_1-V_7 are L63; V_8-V_{12} are EF 36.

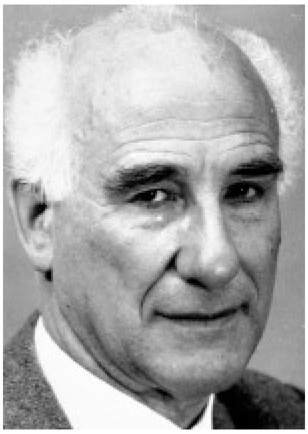


Figure 17 Dr. A. W. M. Coombs

Production of the COLOSSI took up about half the total workshop and production capability at the Dollis Hill Research Station [28]. Construction of the panels for the first two or three machines was undertaken by a staff of wiremen there, but subsequently the panels were built at the Post Office factory in Birmingham under Dollis Hill supervision. The racks on which the panels were installed were standard ones from Post Office stores, but the frames on which the tape pulleys were mounted (called the "bedsteads") were built by the Dollis Hill workshops. The racks were wired together for the first time at Bletchley Park, an operation that took two or three weeks, since there was a lot of inter-rack wiring [15]. In 1944, Coombs was placed in charge of the work at Dollis Hill when Flowers was promoted [62]. Published claims have been made that in all a total of about ten COLOSSI were manufactured [63],. but the official explanatory caption merely states that after the first machine "a considerable number of further machines was built and gave reliable and effective service until the end of the war". What happened to them afterward has not been revealed.

Design work continued right up to the end of the war, since no two COLOSSI were the same [5, 15]. Apparently a whole series of smaller specialized machines and attachments (with various intriguing names) were built by Coombs's group for Bletchley Park [15, 29]. Flowers also designed at least one other machine after the COLOSSUS – the SUPER ROBINSON [37, 62]. This involved four data tapes, and to some-extent went back to the use of sprocket wheels in order to keep the tapes synchronized. The problem that it addressed could have been solved electronically, but Flowers and his people did not have the time, and the problems of tape wear caused by the sprocket wheels had been largely solved by Morrell [29]. The SUPER ROBINSON was a hybrid, which used COLOSSUS circuit technology to a very large extent, its multiple tape inputs being roughly synchronized by the sprocket drive, and then electronically synchronized to the clock pulse derived from one tape [37]. However, I am told that neither SUPER ROBINSON nor any of the other specialized machines could be regarded as a further major step towards the modern computer, either by virtue of the amount of electronics it involved, or its logical power [5, 15, 28, 29, 64]. All were special purpose machines for which, in effect, the program was wired in or set up with keys. They were nearly all mixed relay/electronic machines, without as much electronics as COLOSSUS. They therefore can be presumed to be of little significance with respect to the development of the modern digital computer.

9. An Assessment

A proper assessment of the COLOSSI as precursors to the modern general-purpose computer is hampered by the lack of detailed information concerning the functions they performed, and the facilities that were provided for controlling their operation. As it is we must rely mainly on the official explanatory caption (Appendix 1), where we find among the list of features:

> Electronic storage registers changeable by an automatically controlled sequence of operations,
> Conditional (branching) logic,
> Logic functions preset by patch panels or switches, or conditionally selected by telephone relays,
> Fully automatic operation.

To these we can also add, from previously published sources,

> variable programming by means of lever keys which controlled gates which could be connected in series or parallel as required [27],
> calculated complicated Boolean functions involving up to about 100 symbols. [43],

although it is possible that these apply only to the MARK II COLOSSI.

Certainly it seems fair to classify the COLOSSUS as a special-purpose program-controlled electronic digital computer. It was, however, externally programmed, and there is no question of its having been a stored-program computer. This final step in the invention of the modern computer had to await the development of a practical high-speed store, capable of holding a large number of binary digits. The only variable stores on the COLOSSUS were gas tubes and hard valve trigger circuits [33].

There were other programmable computers in existence in 1944, but as far as is known none were electronic [74]. The use of electronics permitted a thousandfold increase in internal speed over contemporary relay or electromechanical devices. The first of Zuse's computers to work successfully, the Z3, had been completed in 1941, but this was built out of telephone relays, as were the Bell Laboratories Relay Interpolator and Ballistic Computer (completed in September 1943 and May 1944, respectively). The Harvard MARK I, which was entirely electromechanical, had been demonstrated at Endicott in January 1943, but became operational at Harvard in May 1944. All of these machines were tape controlled, and so could have programs of considerable length and complexity, but none had conditional branching facilities, an omission that would have surprised Babbage. On the other hand, digital electronics had, as far as we know, been used only for single-purpose devices. The most complex of these was Atanasoff's linear equation solver, although both Zuse and Vannevar Bush had investigated the idea of a program-controlled electronic digital computer. (More details of Bush's work are given in Section 13.)

Program control by means of plugboards was available on punched card machines, and was well known to Flowers and his team. In fact Flowers has assessed the prototype COLOSSUS as probably being less programmable than some contemporary IBM machines [33]. However. because of its additional logic switching panel, the MARK II COLOSSUS was much more flexible than the prototype. Although a special purpose device, it turned out to have considerable generality within its own subject area, more in fact than Newman and his team had asked for [69], although Newman himself was a strong believer in the importance of having flexibility in the design of the machine [45]. This flexibility was exploited fully once it was appreciated, and the COLOSSUS ended up by being used for several types of job that had not been anticipated when the machine was first designed. For example, early in 1945 Wylie showed that without any modifications or additions the MARK II COLOSSUS could perform a task which had hitherto been the responsibility of the Testery, and was thought of as one which could not be mechanized [70]. (An account I had received early in my investigations had implied that this task was made possible by the hardware which simulated the manual connections and reconnections described in Section 8, but it now seems that this was not the case [64].) A number of other diverse tasks were performed using the machine, but all were related to the particular work with which the Newmanry and the Testery were concerned [29, 45].

Clearly the machine with which the COLOSSI are most aptly compared is the ENIAC. The ENIAC project was started in May 1943, and the machine was first used in late 1945 or early 1946. It was a much larger and faster machine than the COLOSSUS, having about 18,000 valves, and being able to store 20 ten-digit decimal variables. It had conditional branching facilities, and was programmed using pluggable cables, a process that could take a day or so, although later a method of programming which involved manually setting values into a function table was introduced [74]. Like COLOSSUS, it was built for a very special purpose, the solution of differential equations such as those occurring in ballistics problems – it was first known as the Electronic Difference Analyzer [95] – but it was in fact also used for a variety of other suitable numerical calculations [83].

The distinction between special-purpose and general-purpose digital computers is of course very blurred, unless one equates "general purpose" to some sort of finite approximation to a Universal Turing Machine. Neither COLOSSUS nor ENIAC therefore is general purpose in this sense, so that the opening sentences of the explanatory caption might perhaps be somewhat misleading with respect to the capabilities of COLOSSUS

This leaves the question of the relative extent to which ENIAC and COLOSSUS were "special purpose". ENIAC had facilities for addition, subtraction, multiplication, division, the extraction of square roots, and could test the sign of a number and whether two numbers were equal. It used punched card input and output. According to Weik [83] it was used not only for ballistics calculations but also weather prediction, atomic energy calculations, thermal ignition, random number studies, wind tunnel design and other specific applications.

At present our assessment of the extent to which COLOSSUS was a special-purpose computer must depend mainly on the remembered knowledge of people who were closely involved, particularly Chandler, Good and Michie. Quoting Chandler, "We could say that if a count exceeded a certain value you would do one thing, if it was less than a certain value you would do another thing, so this was conditional branching logic" [15, p.21]. Good recollects that Geoffrey Timms showed that COLOSSUS could be plugged up so as to do multiplication: "It took a great deal of plugging and it wasn't worthwhile . . . but the flexibility was such as to let it be used for something for which it was not designed . . . it was a Boolean calculating machine . . . it was rather general just because it dealt with binary symbols, but it wasn't designed to be an ordinary number cruncher" [45, p. 14-15]. Finally Michie's summing up of the situation is

> The use of COLOSSUS to do other things unconnected with the purpose for which it was built, although possible, would have been strained and artificial . . . we could fake up some of the properties of branching on a condition, essentially through manipulations of the data tape, but that sort of thing stopped a long way short of a Turing Machine or any of its linguistic or hardware embodiments . . . my impression is that COLOSSUS would not be very far away on the scale of ascent [towards a general purpose computer] from the ENIAC [64, p. 12].

It seems that a reasonable summing up would be as follows: ENIAC and COLOSSUS (which preceded it by nearly two years) were both program-controlled electronic digital computers, the one specialized towards numerical calculations, the other somewhat more specialized, in this case toward Boolean calculations of a particular type. Each was a splendid achievement of great importance. But it was among the ENIAC group that the final step towards the modern computer was first taken, namely, the design of a practical stored-program computer, the EDVAC. The apportionment of credit for this work between Eckert, Mauchly, von Neumann and Goldstine is a matter of some controversy, not appropriate to enter into here. There is a possibility that Turing also had some direct influence in this matter, but this is unproven (see Sections 12 and 14).

10. The COLOSSI in operation

Newman's section had expanded rapidly, even before the first COLOSSUS was completed. Its hut was replaced by a brick building, still referred to as Hut F for convenience, and later another building, Hut H, was added to house some of the COLOSSI [45]. The next mathematicians to join the section included, in approximate order of arrival, J. H. C. Whitehead, Oliver Atkins, Michael Ashcroft, Gordon Preston, Geoffrey Timms and Joe Gillis, followed after a pause by others [64]. As Newman has put it, his section had a lot of outstanding people in it, and included some who were, or were to become, the best mathematicians in Britain [69].

In addition to their mathematical duties, these people all manned a duty officer rota [64]. The duty officer served as an operations manager, directing the flow of jobs on and off the machines. In the early days it was typical for a mathematician to sit at a machine, interact with it while it operated, and be closely concerned with deciding what tasks should be run. This involved a form of analysis and decision making that has been characterized as somewhat similar to that involved in playing chess [45]. Some of the procedures that later evolved became codified into decision trees that could be followed independently by the operators. These were Wrens, with a Senior Wren as Chief Operator responsible for several machines, and the scheduling of their job queues [45, 69]. It was a long time before those involved were to see again a room whose pattern of activity so closely matched that of a modern large computer installation [64].

The COLOSSI were maintained by Post Office personnel. The maintenance engineers were chosen from among those working on the COLOSSI at Dollis Hill, and typically would have prior experience of maintaining telephone exchanges. Chandler was placed in charge of the general installation, but did not move to the Bletchley area. Instead he traveled daily from Dollis Hill so as to continue to keep in close touch with the work going on there [15].

The COLOSSI achieved very high levels of reliability. Such problems as did occur were in general not due to valves but to such things as the typewriter and photoelectric reader [15, 29, 45]. This must have been largely due to the care that was taken to design the machines so that standard components could be incorporated. This was done using safety factors to allow for components having characteristics which were some way from, and would drift even further away from, their nominal values [15, 28]. It was difficult to get good resistors since the normal source of prewar supply was Germany! A scheme was devised that involved classifying resistors according to their closeness to the intended value [16]. Thus Group A might be 15-20% above nominal value, Group B 10-15%, etc. Care would be taken to use resistors from just a single group in a given trigger network or perhaps on a particular rack – this technique was introduced by Coombs.

The first week or so of operation would serve to weed out the poor valves –a calculation of the number of valves involved in the various machines indicated that this totalled somewhere between 20,000 and 30,000 [15] – and the valve holders were more of a problem than the valves themselves, so some critical valves were wired in directly [5, 28]. The photoelectric cells gave a certain amount of trouble because sensitivity could decrease after a long series of consecutive tape "holes" [37]. The paper tape itself caused some problems – the edges of the tape would saw their way through the hardened steel pins that served as tape guides [15]. During one test a machine was run successfully at 9700 characters/sec, but then the tapes kept breaking – in Dr. Coombs's words "If you got a very long tape which broke, by the time you could do something about it there was tape everywhere, all over the place, festoons of it!" [15, p. 13]

11. Secrecy and Priority

One cannot attempt to picture the environments within which the COLOSSI were built and used without some appreciation of the circumstances under which the work at Bletchley Park and Dollis Hill was undertaken. Wartime conditions must have given a great sense of urgency [49] – Broadhurst can remember occasions driving back toward London and seeing the city ablaze from high ground. Dollis Hill itself suffered some minor bomb damage, but none is recalled at Bletchley Park [5, 15].

Within Bletchley Park itself, as at all wartime defense establishments, security precautions were applied. People in one section normally knew little or nothing about the work of other sections, although there was active liaison between the Testery and the Newmanry. Discussion of work would be avoided outside the particular hut. At lunchtime Newman and a group of his staff might lunch together, but even in an otherwise empty cafeteria there would be no thought of discussing their work. Instead the conversation would usually be about mathematics and brainteasers of all kinds [28, 64].

At Dollis Hill very few people had any knowledge of Bletchley Park or the tasks undertaken on the machines. Paperwork was kept to a minimum. Flowers's team was initially not allowed to use the drawing office, so circuit diagrams were drawn freehand. The individual panels from which the machines were made were small enough that it was quite impossible for the wiremen who were assembling them (either at Dollis Hill or Birmingham) to figure out what the circuits were for [5, 15, 29].

The workmen therefore had to take on trust the importance of their task, which was such that unusual amounts of overtime were called for. On one occasion it was arranged that Flowers invite Newman and a uniformed high-ranking officer to Dollis Hill specifically in order that the people there could have evidence that the work was fully appreciated. Flowers remembers that the visitors "were absolutely flabbergasted because as far as they were concerned nothing had happened for months yet they found [the] men working like hell – great forms of wiring being done and. panels going through – they just couldn't believe it, and it had a good effect on both sides" [28, p. 21].

The Dollis Hill people had priority on stores and in the Post Office factories, and did not have to account for anything [5, 28]. When they asked for automatic typewriters instead of teleprinters these were flown over from the U.S. with reserved places, no questions asked. Perhaps the best anecdote is Chandler's, who remembers telephoning an official in the Ministry of Supply yet again to ask for another couple of thousand EF 36 valves and being asked, "What the bloody hell are you doing with these things, shooting them at the Jerries?" [15, p. 15]

12. Turing's Role

The explanatory caption states that Turing's "earlier work had its full influence on the design concept" of the COLOSSUS. This is one of the points I have concentrated on trying to elucidate during the interviews with people who took part in the design and use of the COLOSSI.

Questions of influence are always difficult to assess. In the case of work at Bletchley Park this is especially true, not just because of the unavailability of original records, but also because of the atmosphere in which the work was carried out. The sense of urgency, the spirit of cooperation and the lack of an audience combined to make people very much less conscious of the attribution of individual credit than would, understandably, have been the case in more normal times [64].

Turing, clearly, was viewed with considerable awe by most of his colleagues at Bletchley because of his evident intellect and the great originality and importance of his contributions, and by many with considerable discomfort because his personality was so outlandish. Many people found him incomprehensible, perhaps being intimidated by his reputation but more likely being put off by his character and mannerisms [15, 64]. But all of the Post Office engineers who worked with him say that they found him very easy to understand. Broadhurst characterized him as "a born teacher – he could put any obscure point very well" [5, p. 7]. Their respect for him was immense, although, as Chandler said, "The least said about him as an engineer the better" [15, p. 8]. This point is echoed by Michie, who said, "He was intrigued by devices of every kind, whether abstract or concrete – his friends thought it would be better if he kept to the abstract devices but that didn't deter him" [64, p. 7].

Turing had a strange obsession with self-sufficiency, both in everyday life and in mathematics, where he could not forbear to discover all the well-known subsidiary results as well as the main theorem, causing great waste of time for himself and extra trouble for his readers, who had to learn his non-standard notations and proofs. Yet embedded in this were deep and profoundly original ideas. [64, 71]

He seems to have worked on a wide variety of mathematical topics during this period. Good's post-war book [42] indicates that during the war Turing developed a technique for facilitating Bayesian probability calculations. Good has since written that Turing "anticipated, in classified work, a number of statistical techniques which are usually attributed to other people" [44]. In fact his very important statistical method [46, 65, 70, 71] was rediscovered and developed further by Wald and called "sequential analysis" [82].

As described in Section 4, the early projects that the Dollis Hill people carried out for Bletchley Park were done in close cooperation with Turing, and Flowers recollects that during the period that they were involved with the HEATH ROBINSON they were seeing him every day [29]. Apparently he did not have any direct involvement in, or influence on, the design or use of COLOSSUS [33, 69]. His visits to Dollis Hill occurred prior to the start of the COLOSSUS work, and Newman does not remember his presence at any of the meetings that Newman and Flowers held at Bletchley Park [69]. Turing's prewar work on computability was well known, and virtually all of the people I have interviewed recollect wartime discussions of his idea of a universal automaton [5, 15]. (Flowers, incidentally, also recalls lunchtime conversations with Newman and Turing about Babbage and his work [28].) Good has written that "Newman was perhaps inspired by his knowledge of Turing's 1936 paper" [43, 46]. However, Newman's view now is that although he and his people all knew that the planned COLOSSUS was theoretically related to a Turing Machine, they were not conscious of their work having any dependence on either these ideas or those of Babbage [69].

The Turing Machine did provide a conceptual background for Turing's extracurricular work on, and discussions of, the idea of "thinking machines" [64]. In the main these discussions were with some of the younger scientists at Bletchley Park – the more senior ones tended to disapprove of such science-fiction-like topics. He concentrated on game playing as an arena in which to test out his ideas, and on chess in particular. It was through a common interest in chess that Michie got to know Turing, and to become involved in the idea of "machine chess". Because of the methods of recruitment to Bletchley Park, those of Turing's circle there who played chess at all tended to be Masters or at least experts. By their standards Turing was a beginner, as was Michie. They were in fact evenly matched and used to meet for regular games at a pub in Wolverton. Turing developed his ideas on thinking machines quite extensively during the war. According to Michie the fundamental notions that were discussed then, and which originated with Turing, included the idea of look ahead, of backing up by the minimax rule, of using an evaluation function to assign strategic values to the terminal nodes of the look-ahead tree, and the notion of quiescence as it would now be called (Turing called them dead positions) as a criterion for cutoff of the look-ahead process. His first paper on the topic of thinking machines was in fact prepared a year or so after the end of the war, but not published until many years later [78].

The one other aspect of Turing's role that I would dearly like to clarify is his reputed war-time meeting with von Neumann [48, 75]. The story, or rather legend, is that the meeting was of critical importance to the development of the modern computer. Regretfully, my further investigations have not thrown much further light on this matter. Turing is known to have made at least one wartime visit to the States. According to Cave

Brown, he visited the States sometime before May 1942, to describe how the "Turing Engine" worked, and again in 1943, but his biography described just one visit, in November 1942 [13, 79]. I. J. Good believes that the visit had some connection with the atomic bomb project, as he recollects Turing posing him a problem concerning the probability of the explosion of one barrel of gunpowder, set among others on a two-dimensional grid, causing the other barrels to explode [45]. It is known that Turing visited Bell Labs, where he met Claude Shannon, but apparently they did not talk about programmable computers [51]. He saw one or two of the early Bell Labs Relay Computers, but showed very little interest in them [76]. Von Neumann visited Bell Labs in about 1942, and saw the nearly completed Ballistic Computer. He also visited Britain during the war, and Newman reports that he met him during this visit, but that von Neumann did not visit Bletchley Park [74].

This then is where the investigation must rest. For my part I am now disinclined to believe the legend, although I think that the situation was probably summarized well by Frankel when he wrote [38]

> Many people have acclaimed von Neumann as the 'father of the computer' (in a modern sense of the term) but I am sure that he would never have made that mistake himself. He might well be called the midwife, perhaps, but he firmly emphasized to me, and to others I am sure, that the fundamental conception is owing to Turing – insofar as not anticipated by Babbage, Lovelace and others. In my view von Neumann's essential role was in making the world aware of these fundamental concepts introduced by Turing and of the development work carried out in the Moore School and elsewhere. Certainly I am indebted to him for my introduction to these ideas and actions. Both von Neumann and Turing, of course, also made substantial contributions to the 'reduction to practice' of these concepts but I would not regard these as comparable in importance with the introduction and explication of the concept of a computer able to store in its memory its program of activities and of modifying that program in the course of these activities.

13. The American Scene

Flowers and his colleagues did not learn about any of the American work on electronic or electromagnetic digital calculators and computers such as those at Bell Labs, Harvard, Iowa State, IBM, MIT or the Moore School, until close to or after the end of the war [5, 15, 28, 69]. The ENIAC project had only just started by the time the first COLOSSUS was operational, but such was the secrecy surrounding COLOSSUS that it is very unlikely that any knowledge of it could have reached the Moore School. When Flowers and Chandler visited there in 1945 they were unable to reveal anything at all about their wartime work for Bletchley Park. As far as I can determine the immense amount of testimony and documentary evidence about the ENIAC project in the litigation concerning the validity of Eckert and Mauchly's patents contains no mention of Bletchley Park or the COLOSSUS [69].

It is unclear to what extent scientists and engineers working on similar problems at Bell Labs, IBM and elsewhere in the States were in touch with the work of Flowers and his team, but there is no evidence at all of any American involvement in the design of COLOSSUS [5, 15, 69]. Although special purpose machines were being developed in the

States during the war, as is the case with COLOSSUS, they are not as yet fully declassified. However, my correspondents were able to provide me with some details of the American work – enough, I believe, to put the COLOSSUS in a proper perspective.

One large relay machine was built by S. B. Williams at Bell Labs. The machine was quite flexible but had no arithmetic [9-11]. Williams built most of the Bell Labs series of relay computers, and the existence of his machine had at least a small influence on the decision to develop the early Ballistic Computers [76].

An American machine which in concept was similar to the HEATH ROBINSON, and which preceded it, was developed by Vannevar Bush starting in 1936 [9, 25]. Bush is of course famous for, among other things, his invention in 1930 of the differential analyzer, but he also worked on digital devices. In a set of memoranda written in 1937 and 1938 he proposed and investigated some of the design problems of a program-controlled electronic digital computer. This work led to a research project at MIT, the Rapid Arithmetical Machine Project, sponsored by the National Cash Register Company (NCR), in which various basic electronic circuits, such as registers and counters, were developed [72]. Another project at MIT, sponsored by Eastman Kodak and NCR, grew out of a device, the Rapid Selector, that Bush had invented in 1936 [7, 87]. This device was intended for the automatic retrieval and photographic copying of information held on reels of 35-mm microfilm, using photoelectric scanning of coded identifiers. Both research groups were disbanded in 1942 because their staff were required for military projects elsewhere. The Rapid Selector group, which was led by John Howard and included Lawrence R. Steinhardt, had been working on the Bush's HEATH ROBINSON-like machine from late 1940.

This machine incorporated electronic counters and two photoelectric tape readers. The tape was apparently backing tape from 70-mm photographic film, rather than ordinary telegraph tape. (Such backing tape has sprocket holes cut in it with the same care as in the film itself.) Each character was represented by a single hole placed at one of forty positions across the tape. Apparently the machine was linked to more or less standard tabulating machines where plugboards could of course be plugged to do a variety of functions [10, 23].

Bush's machine was completed by John Howard and Lawrence Steinhardt and it functioned in a desultory fashion for many years [9]. After the war John Howard, Howard T. Engstrom and Charles Tompkins were part of the group that founded Engineering Research Associates Inc. (ERA) [23]. All three had been in a Navy communications operation and had close contacts in Britain, and close acquaintance with Turing [18]. It has been claimed, though without supporting evidence, "that ERA, under contract to the Navy, produced one of the world's first three computers, a powerful top-secret intelligence computer known as Machine 13" [22]. In fact this was an electronic computer called ATLAS, developed under a multiproject Navy contract, which was delivered in 1950. It was a single-address machine, with 24-bit parallel arithmetic and word organization, and magnetic drum storage [19, 24]. An earlier relay version, named ABEL, with the same order code, was later handed over to George Washington University [89]. A commercial version of the electronic computer was produced under the designation ERA 1101 (this of course being binary for 13) [19].

My information is that there were no earlier or contemporary electronic machines in the American communications operations that matched the size or complexity of

COLOSSUS [9]. A group of sophisticated American devices, operating in about 1942, was based on the use of counting and optical matching techniques, rather than complex electronic circuits [12, 23-25]. One machine used glass plates because of a concern for dimensional stability, later found to be exaggerated, and other machines used 35- or 70-mm film instead. One device enabled 20,000 bits to be represented on each frame of the film. Both Flowers and Coombs vaguely recollect learning about some such machine [15, 29].

Various other machines were developed in the U.S. during the war for related purposes, including ones whose electronic complexity matched, and in fact exceeded, that of COLOSSUS [24]. However American special-purpose electronic devices that pre-dated COLOSSUS were much simpler. For example one device that involved the use of electronics for calculation purposes was invented by Arnold I. Dumey. Two versions of this machine, which involved perhaps 300 valves, and which probably postdated HEATH ROBINSON, were completed. They calculated in real time the expected value of the number of successes in a set of trials plus and minus a certain fixed number of standard deviations. Only if the observed number fell outside the calculated limits was printing of the result permitted [23]. Dumey later had responsibility for a larger device, involving approximately 4000 valves, which became operational a year after the end of the war. There were devices incorporating even more valves. The largest such operational device that Dumey had any involvement with had no less than 10, 000 valves. As he himself puts it, “The most interesting thing about life at this time was the way every new electrical invention was tried out as soon as possible in some new device.. Yet the only early improvement on COLOSSUS was in a more compact way of holding and running the tapes” [25].

The above meagre details undoubtedly give a totally inadequate impression of the quantity and variety of machines that were developed, and of the importance of the work that was done in the U.S. in this field during the war. They are given here merely to buttress the statements I have received from both sides of the Atlantic concerning the COLOSSUS, namely, that it had no rivals or precedents as a programmable electronic computer, and that there were no links between it and the ENIAC project [15, 24, 64, 69].

14. The Aftermath

Official awards were made to a number of the people involved in the Bletchley Park work, after the war, but of a quite inadequate nature in my opinion. Newman considers the O.B.E. awarded to Turing, which apparently he accepted somewhat as a joke, quite ludicrous in relation to his achievements [69]. Flowers was awarded an M.B.E. and a £1,000 Award to Inventors, but as Coombs has said, “If it had been £10,000 or £100,000 it still wouldn’t have been too much” [15, p. 33]. Broadhurst and Coombs received £100 awards, but Chandler, being on a more lowly engineering grade received nothing at all [5]. These matters are perhaps of little importance, and certainly all of the Dollis Hill group are unanimous in describing their work for Bletchley Park as the most satisfying thing they have ever done.

Most of the group had continued full-time work for Bletchley Park until the end of the war, but Flowers ceased his full-time involvement after his promotion in 1944, when he handed the responsibility for the work over to Coombs, although Coombs continued to report to him [28]. Instead Flowers started to become involved in the Post Office planning for work to be carried out on the telephone system after the war had ended. He did take part in a visit of inspection to Germany on behalf of Bletchley Park two months after the cessation of hostilities [29]. The party included Alan Turing and the man who was in charge of work on radio reception for Bletchley Park. They went in order to see what communications research the Germans had been doing during the war. The visit started on 15 July 1945 and was due to last six weeks, but Flowers returned after ten days, having visited Frankfurt and Eberbach.

This visit caused a postponement of a visit by Flowers and Chandler to the States, which had been originally planned for early 1945. The visit was in connection with a project concerning radar, the Data Recorder Project [15, 29]. The Ministry of Supply needed a means for testing auto-following radar. This was to involve recording data from radar and from a kine-theodolite, which were both tracking an aircraft, and then using these data to compare the two. Stibitz had been involved in some such work on data recording, and the plan was to learn about this, and about American work on digital computers.

According to Goldstine, John Womersley, the Superintendent of the newly created Mathematics Division of NPL, was the first person from Britain to visit the ENIAC project [40]. He was in the U.S. from February to April 1945. The fact that Womersley had come back with information about American developments nearly caused Flowers's and Chandler's trip to be cancelled, but it turned out that he did not have the level of knowledge about the engineering aspects of the American machines that they needed [29]. After their visit was fixed Flowers invited Professor Hartree, who had also recently returned from a trip to the Moore School, to come to Dollis Hill to brief them [15].

The two traveled to the States at the beginning of September 1945, and stayed for approximately six weeks. During this time they visited the Aberdeen Proving Ground, Bell Labs, Harvard, MIT, the Moore School, and the University of Vermont. At Bell Labs they met S. B. Williams, and saw the Relay Interpolator. They attended a series of lectures by Williams and his team on the Model V relay computer, which was then nearing completion. They were most impressed by the way the work was organized, and in particular by the fact that the maintenance manuals were already being written – they have no recollection of any maintenance manuals ever being written for the COLOSSI! They found that Stibitz had already left Bell Labs for the University of Vermont, so they traveled to Burlington by rail, and spent a weekend with him [15, 28].

At MIT they met Sam Caldwell who was then making a differential analyzer which was in part digital. Their visit to Harvard University enabled them to meet Howard Aiken and Grace Hopper and to see the Harvard MARK 1. In all these visits they had to avoid any mention of COLOSSUS, and be very discreet about their own expertise in digital electronics. This applied even with S. B. Williams, although from one or two comments he made they realized that he must have had some involvement with the sort of work that they had been doing [15].

At the Moore School they met von Neumann, Eckert and Mauchly, saw the ENIAC, and learnt about the plans for EDVAC. Flowers was surprised to find that Lewis's original biquinary counter circuit had been used in the ENIAC without any trouble, perhaps because the Moore School people had had access to more uniform components than he had. One other recollection he has of the visit is of being told by Eckert of the problems of making the first delay line work. Flowers and Chandler were impressed by ENIAC but a bit appalled at the amount of electronics – of course by this time the plans for EDVAC had already made the design of ENIAC obsolete [15, 28-30]. Yet again their visit must have been a discreet one – Goldstine, who gives considerable detail about the sequence of early visitors to the ENIAC, mentions only that in addition to Comrie, Hartree and Womersley, "two others connected with the British Post Office Research Station also came" [41, p. 21].

Shortly after their return to Britain Flowers was taken off the Data Recorder Project by Radley, who wanted him to resume work on the telephone network. Coombs replaced him, and for the next few years he and Chandler worked together, first on the data recorder itself, and then on digital computer design, since a means of analyzing the recorded data was required. For a time they worked closely with NPL and thus Chandler resumed close collaboration with Turing, although it was Coombs' first encounter with him [15]. Turing had been invited to join NPL at Newman's suggestion [41]. However, he apparently spent some time after leaving Bletchley Park on further classified work at a different establishment, involving the actual construction of electronic equipment. No details of this work have been revealed [79].

Within a short time of joining NPL, Turing had produced a set of proposals for an "Automatic Computing Engine" [77]. This report postdated and referenced von Neumann's famous draft report on EDVAC [81], but went considerably further, being much more detailed, and containing the full concept of a stored-program computer. In fact it has been said that "Turing's proposal is one of the first complete designs for a stored-program computer (possibly the first)" and that "what we now regard as one of the fundamental characteristics of the von Neumann machine was as far as we know suggested independently, if not originally by Turing" [12]. (In von Neumann's report data and instruction words were differentiated, and only the address field of an instruction could be modified.)

Turing's report seems to have marked the real start of the ACE project. It was formally presented to the NPL Executive Committee on 19 March 1946 by Womersley and Turing. Womersley's accompanying memorandum summarises Turing's proposal, which he states is based on the plans for EDVAC although he claims that von Neumann's EDVAC report "contains a number of ideas which are Dr. Turing's own" [90]. No mention is made of Turing's wartime work, but it is surely significant that one of the points listed in the argument for building the ACE is that "Commander Sir Edward Travis, of the Foreign Office, will give his support." The Executive Committee's formal decision was one of unanimous support [91], but the project went through many changes and vicissitudes. For a while the plan was, in accordance with Turing's wishes, that the machine be built for NPL by Chandler and Coombs at Dollis Hill [28]. However this fell through, and they went on and designed and built the MOSAIC [20], which was largely based on an early version of the ACE design [14, 15, 28]. Turing grew disenchanted with the lack of progress at NPL, and after a sabbatical at Cambridge joined Newman at Manchester University in late 1948 [54].

Newman had gone from Bletchley Park to Manchester, where he took the Chair of Pure Mathematics in October 1945 [69]. Two members of his section, I. J. Good and David Rees, went with him [54]. Newman was very interested in Turing's work, and in the impact that computers might have on mathematics. P. M. S. Blackett, who had been Director of Naval Operational Research during the war and so was conversant with the Bletchley Park work, as well as radar and the various other scientific contributions to the war effort, was already at Manchester [15]. He encouraged Newman to apply to the Royal Society for a grant "for a projected calculating machine laboratory at Manchester

University" [54]. Professor Hartree, who is often credited with having played a very important role in promoting and obtaining support for the first postwar computer developments in Britain, particularly those at Cambridge, was closely involved in these matters. Apparently he visited Bletchley Park shortly after the end of the war to see the COLOSSI, the invitation having been made expressly to gain his support for the proposed project [45]. Support was forthcoming, and the Royal Society grant was awarded in July 1946. This enabled Newman to send Rees to the States that summer to attend the Moore School lectures at which the plans for EDVAC were presented. Later that year he himself visited the Moore School and saw ENIAC whilst spending a period at the Institute for Advanced Study, Princeton [15, 40].

Blackett had a hand also in getting F. C. Williams to Manchester from TRE in late 1946. Williams in turn arranged that Tom Kilburn should join him from TRE shortly afterward [69]. They learned from Newman the basic principles of von Neumann's stored program computer, then fully designed but not yet operative [70, 86]. Within 18 months they had designed and built an experimental prototype stored-program electronic computer, believed to be the world's first. The work at Manchester was therefore at quite an advanced stage when Turing arrived in September 1948, taking the nominal title of Deputy Director of the Computing Machine Laboratory, although he was actually in Newman's Mathematics Department [54]. Newman's belief is that Turing appreciated that the computer project was a more professional piece of engineering than anything he could compete with, and so turned his attention to work on morphogenesis [15]. He did take some part in the work of the computer project, his most important contribution being the specification of input-output facilities [86]. He also did some programming, and wrote the first Manchester programming manual. Newman also had some involvement with programming but his one notable claim to fame with respect to computer design is that of being an inventor of the index register [54, 69].

These, then, are the known links from the Bletchley Park work to postwar British computer development. Flowers and Broadhurst did not have any such involvement – their post-war careers were spent in telecommunications research and development. Flowers remained as Head of the Switching Division in the Post Office Research Department until 1964. During this time he was mainly concerned with electronic exchanges of various types – initially with cold-cathode switching and later with solid-state-time-division multiplex switching. He and his group were centrally involved in the first work in Britain on electronic exchanges, and completed the basic design of an all-electronic exchange by about 1950. In 1964 he took the post of Head of the Advanced Development Group in Standard Telephones and Cables Ltd., from which he retired in 1970 [29, 35, 60]. Similarly, Broadhurst continued to work in the Switching Division, where he was responsible for the design of register-translators for telephone exchanges. He did design one special purpose computer, but this was an analogue computer, a "traffic machine", used for calculating the expected traffic through an exchange. Later, he led the team that developed the original ERNIE, a machine using a random-number source to select the numbers of winning Premium Bonds. He retired from the Post Office in 1963 and served as a consultant to the Telephone Equipment Manufacturers' Association for some years following [5, 60].

Chandler and Coombs separated after their work on MOSAIC. Coombs designed an early speech interpolation system for use in transatlantic cables, but not in fact the one that was eventually employed. In 1961, he began working on problems of pattern recognition, and in particular the problem of recognizing typescript multifont postcodes (ZIP codes). Chandler went back to work for the Foreign Office, but returned in 1968 and joined Coombs in the work on pattern recognition machines [15, 60]. It was this work that led to their meeting Donald Michie again, who was by this time Professor of Machine Intelligence at Edinburgh University. The influence of his wartime discussions with Turing had been great, and he had maintained contact with I. J. Good and Turing until the latter's tragic death in 1954, though it was not until 1960 that he first started to use computers for his researches into machine intelligence [64].

15. Conclusions

Goldstine has expressed surprise that, despite the ravages of war, "Great Britain had such vitality that it could immediately after the war embark on so many well-conceived and well-executed projects in the computer field" [40, p. 321]. It is my opinion that the COLOSSUS project was an important source of this vitality, one that has to date been largely unappreciated, as has the significance of its place in the chronology of the invention of the digital computer. It is unfortunate that the continuing secrecy surrounding many aspects of the project makes its proper evaluation so difficult. For this reason I choose to let some quotations from those associated directly with the machine serve as a conclusion to this account.

> The basic picture – a few mathematicians of high repute in their own field accidentally encounter a group of telephone engineers, of all people . . . and they found the one really enthusiastic expert in the form of Flowers, who had a good team with him, and made these jobs possible, with I think a lot of mutual respect on both sides. And the Post Office was able to supply the men, the material and the maintenance, without any trouble, which is a great tribute to the men and the organization (Broadhurst [5]).
>
> The value of the work I am sure to engineers like myself and possibly to mathematicians like Alan Turing, was that we acquired a new understanding of and familiarity with logical switching and processing because of the enhanced possibilities brought about by electronic technologies which we ourselves developed. Thus when stored program computers became known to us we were able to go right ahead with their development (Flowers [27]).
>
> It was a great time in my life – it spoilt me for when I came back to mundane things with ordinary people (Flowers [28]).

Appendix[*]

Babbage's work in 1837 first established the logical principles of digital computers. His ideas were developed further in Turing's classical paper in 1936. The COLOSSUS

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[*] Explanatory caption accompanying a set of photographs of COLOSSUS that were made available at the Public Record Office in London on 20 October 1975.

machine produced by the Department of Communications of the British Foreign Office, and put into operation in December 1943, was probably the first system to implement these principles successfully in terms of contemporary electronic technology. COLOSSUS was distinguished by the following features:

punched paper tape inputs operating at 5000 characters per second;
photo-electric tape readers,;
bistable hard-valve circuits performing counting, binary arithmetic and Boolean logic operations,;
electronic storage registers changeable by an automatically controlled sequence of operations;
conditional (branching) logic;
logic functions pre-set by patch-panels or switches, or conditionally selected by telephone relays;
fully-automatic operation;
solenoid operated electric typewriter output.

COLOSSUS used approximately 1,000 hard valves and 500 gas-filled ones. It operated in parallel arithmetic mode at 5,000 pulses per second. The requirement for the machine was formulated by Professor M. H. A. Newman, and the development was undertaken by a small team led by T. H. Flowers. A. Turing was working in the same department at that time, and his earlier work had its full influence on the design concept.

The attached World War II photographs[*] depict various aspects of COLOSSUS and a set of reproductions has been annotated to show some of its major features. A considerable number of further machines was built and gave reliable and effective service until the end of the war.

Addendum

Since this paper was prepared the British Government has for the first time made available at the Public Record Office a substantial number of the messages that were deciphered at Bletchley Park during World War II. This release of information has enabled much more substantial and authoritative accounts to be produced of the role of Bletchley Park, and of its impact on the war, than have been available hitherto. Particularly noteworthy are those by R. Lewin, “Ultra Goes to War: The Secret Story” (Hutchinson, London, 1978), and by P. Beesly, “Very Special Intelligence” (Hamish Hamilton, London, 1977). A three-volume history of British Intelligence in World War II, which deals with the activities of Bletchley Park, has been approved for publication. The first volume will be published by Her Majesty's Stationery Office in 1979. Also since the paper was written, the author has had further correspondence with Professor Good, Professor Michie, and Professor Newman concerning the various uses made of COLOSSUS. It is now apparent that it was the technique, developed by Good and Michie, involving manual connections and reconnections while the machine was running

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[*] Public Record Office Number FO 854/234 (Crown Copyright Reserved).

(described in Section 8) that led to the COLOSSI being used to mechanize very important tasks that had hitherto been carried out manually in the Testery. The work by Wylie referred to in Section 9 concerned some quite different aspect of the set of problems on which the COLOSSI were employed.

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