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THE CAVITY MAGNETRON IN WORLD WAR II: WAS THE SECRECY JUSTIFIED?

by

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SUMMARY

The cavity magnetron was invented in Birmingham University and developed by the GEC for centimetric radar in World War II. Its existence was kept secret, and its deployment was delayed, in the belief that as soon as it was used the enemy would be able to adopt the technique both in radar and in countermeasures. The H_2S radar using the cavity magnetron was first used in January 1943, and a Stirling bomber with H_2S crashed a few nights later near Rotterdam. The radar equipment was recovered almost intact by Telefunken engineers. The author of a German report on the equipment, Otto Hachenberg, subsequently became a colleague of the present author in radio astronomy. He died in 2001 and his report of May 1943 was discovered among his papers. It reveals that the principle of the cavity magnetron was already well known in Germany, based on work published in Leningrad in 1936. The most serious effect of the delay in deployment of the magnetron in centimetric radar was in the anti-U-boat campaign, in which the new centimetric radar became the main contributor to the successful end of the Battle of the Atlantic.

Keywords: British radar development; cavity magnetron; German radar development; World War II

INTRODUCTION

At the outbreak of World War II in September 1939 there was an urgent need for the development of radar systems of high power in the centimetre waveband. The need was most urgent for the Royal Air Force.

After the success of RAF Fighter Command in the 1940 Battle of Britain it had been anticipated that the Luftwaffe would turn to night bombing. An Air Interception (AI) radar had been under development by E. G. Bowen (FRS 1975)[1] at the Bawdsey Research Station[2] since 1938, but there were formidable problems.

At that time the shortest wavelength on which any significant power could be generated was *ca*. 1.5 m (200 MHz). The fundamental problems of transferring equipment on this wavelength to an effective operational system for night fighters have been described by R. Hanbury Brown FRS.[3]

The Committee for the Coordination of Valve Development (CVD) concerned with the interests of the three armed services placed several contracts with the aim of developing a transmitter valve that would produce appreciable power on a wavelength significantly shorter than 1.5 m. One contract placed with Professor M. L. E. Oliphant FRS in the Physics Department of the University of Birmingham led to a revolutionary development that transformed the outlook for the AI system in the night fighters and became of great importance in the development of radar systems in the three armed services.

The cavity magnetron

When Oliphant received the contract from the CVD he initiated work on a klystron—an oscillator capable of generating power on centimetre wavelengths with which he had become acquainted during a recent visit to the USA. In the klystron, first developed by W. W. Hansen[4] and by R. H. Varian and S. E. Varian,[5] an electron beam is velocity modulated as it passes through an arrangement of cavity resonators. By December 1939 Oliphant had constructed a klystron that produced 400 W of power on a wavelength of 10 cm (3 GHz). However, it seemed impossible that a pulsed, sealed-off version with a sufficient electron beam intensity could ever be devised for airborne use.

The ultimate solution arose from a parallel investigation at Birmingham by J. T. Randall (FRS 1946) and A. H. Boot. In his Guthrie lecture to the Physical Society in 1945 Randall[6] described the sequence that first led them to the possible use of cavity resonators to enhance the power output of the simple magnetron and then to envisage a three-dimensional equivalent of the Hertz resonant wire loop. By 21 February 1940 they had built within a cylindrical copper block a series of three-dimensional resonators, which, with the cathode along the axis of the cylinder and in an appropriate magnetic field, produced 400 W of power on a wavelength of 10 cm. In April 1940, in great secrecy, contact was established with E. C. S. Megaw of the GEC research laboratory and by June 1940 he had produced two sealed-off samples capable of producing 10 kW of pulsed power on a wavelength of 10 cm.

In his biographical memoir of Randall for The Royal Society,[7] M. H. F. Wilkins FRS describes the controversy that occurred in 1945 when searches of the literature revealed that the concept of the cavity magnetron had been known elsewhere in the prewar years. In particular, in 1936–37 in the USSR N. F. Alekseev and D. E. Malairov[8] constructed a four-segment cavity magnetron that produced 300 W at a wavelength of 9 cm (3.3 GHz). Wilkins concludes that the 1940 Randall–Boot cavity magnetron evolved from Randall's concept of the three-dimensional Hertz loop and that he had no knowledge of the Soviet work or of similar attempts to develop the simple magnetron to produce significant power on centimetre wavelengths.

The issue of real significance is that in 1940 the Randall–Boot cavity magnetron was transformed by Megaw into a sealed-off version capable of manufacture in quantity for operational use. Further, J. Sayers cured an inherent frequency instability of the magnetron by strapping alternate segments. It was this combination of effort that, in response to an urgent military requirement, produced a cavity magnetron that quickly led to the transformation of radar systems in the three armed services.

On 19 July 1940 the first of the sealed-off Randall–Boot cavity magnetrons arrived at the Telecommunications Research Establishment (TRE). By mid-August a bulky assembly of equipment, using this magnetron and with two small paraboloids as transmitter and receiver, first detected 10 cm radar echoes from an aircraft. With remarkable speed this ground equipment was transferred to an airborne version in a twin-engined Blenheim night-fighter and the first flight trials were made in March 1941. A description of the equipment, and of the sequence that led to the first operational use of this centimetric AI in March 1942, has been given by the author.[9] During the autumn of 1940 the potential value of 10 cm radar systems using the cavity magnetron had also been demonstrated to Naval personnel and Anti-Aircraft Command. (See, for example, the Royal Society biographical memoir[10] of J. F. Coales (FRS 1970) by Sir Alistair MacFarlane FRS for an account of the important application of centimetric radar to naval gunnery.)

In September 1940 Sir Henry Tizard (FRS 1926) led a mission to the USA to acquaint American scientists with British radar developments. This most secret mission carried to America one of the first batch of cavity magnetrons produced by Megaw in the GEC Research Laboratory. The details of this mission and the disbelief of the Americans at the performance of the magnetron has been described by Bowen.[1]

Later, President Roosevelt was to describe the magnetron as ‘the most important cargo ever brought to American shores’, and, like the British, regarded the magnetron as a most vital secret to be kept from the enemy at all cost. The fallacy of this belief as revealed in a German report dated May 1943 received by the author in 2003 has produced the initiative for this paper.

H_2S: THE BLIND BOMBING RADAR SYSTEM

On 9 July 1941 the Commander in Chief Bomber Command was instructed to deploy the main bomber force against industrial targets and to destroy the transport network in Germany.[11] Photographic reconnaissance soon revealed that only one in three of the bombers reaching the vicinity of the target bombed within 5 miles of it, and of the total sorties the bombs were scattered over an area of 75 sq miles around the assigned target. This analysis confirmed Churchill’s suspicion that the bombing was ineffective and on 3 September he instructed the Chief of Air Staff that the failure of the bombing raids ‘seems to require your most urgent attention. I await your proposals for action.’[12]

This was the background to the visit of Lord Cherwell[13] FRS, scientific advisor to the Air Ministry to the TRE on 26 October 1941. He asked that urgent attention be given to the development of a radar aid that would help Bomber Command to locate its targets in Germany. In fact, the TRE had already nearly completed the development of two systems: GEE, a navigational aid, and OBOE, a precision bombing aid. Both GEE and OBOE depended on ground stations in England and their range was limited to about 300 miles for an aircraft flying at an altitude of 20000–30000 ft. Although the range encompassed the Ruhr, Cherwell was asking for a system that would enable bombers to locate their targets deep in Germany.

After that meeting P. I. Dee[14] FRS remembered an experiment performed at Worth Matravers in August 1940 with the first centimetric equipment using the cavity magnetron. To test the nature of reflection of the 10 cm radiation, R. G. Batt was told to cycle near the edge of the cliff carrying an aluminium sheet. A strong specularly reflected radar echo was observed against the background rising to the cliff edge.

At the time of Cherwell's visit in October 1941 a 10 cm AI system in a Blenheim was being tested by using a rotating paraboloid in the nose of the aircraft. Dee asked B. J. O'Kane and G. S. Hensby, who were carrying out these tests, to modify the scanner to rotate at a depressed elevation so that echoes from the ground over which the aircraft was flying could be observed. O'Kane and Hensby first flew the system at a height of 5000 ft, and echoes from the town of Salisbury were clearly visible on the cathode-ray tube. After several more encouraging flights they photographed the cathode-ray tube: the photographs when flying over Salisbury Plain clearly revealed the towns of Salisbury and Warminster and military encampments. Dee rushed the wet prints to A. P. Rowe,[15] the head of the TRE, who exclaimed, 'this is the turning point of the war', and in that enthusiastic moment transmitted the news to Cherwell, who in turn arranged meetings with the Secretary of State for Air and the Air Staff. As a result on 23 December 1941 the TRE was directed to proceed urgently with further tests leading to an operational system.

On 29 December the present author was summoned to Rowe's office and was asked to drop his work on an advanced AI blind firing system and take charge of a new group to develop this blind bombing system for operational use. After objecting, the author was again summoned to Rowe's office and on 30 December 1941 was ordered to proceed as directed—'there is no alternative'. In that manner the present author became closely involved in a remarkable inter-Allied dispute over the operational use of the cavity magnetron that 60 years later was to lead to the writing of this paper.

Cavity magnetron versus klystron

The transference of the 10 cm radar in the Blenheim to an operational system did not immediately seem to be difficult. The basic cavity magnetron transmitter, the modulator and the receiver could be those already being manufactured for the AI night fighters. In the early days of 1942 that soon transpired to be a total misjudgement.

The Air Staff directive made two conditions that created formidable problems. The first was that the system was to be used in the new four-engined bombers then beginning to emerge from the production line. The altitude of operation was to be 20000 ft (compared with the 7000 ft of the Blenheim flight) and the nose of the bomber could not be used for the rotating paraboloid. The solution to use a truncated paraboloid in a Perspex cupola underneath the fuselage of the bomber and the problem that caused have been described by the author[9] and are not relevant here.

The second directive was that a klystron, not the cavity magnetron, must be used as the transmitter. The cavity magnetron was regarded as a most important Allied secret and no possible risk could be taken of flying it over enemy territory. The principle of the klystron was well known and, as distinct from the magnetron, it was destructible. Even the initial flights using a prototype magnetron equipment in April 1942 at high altitude led to grave doubt that a sealed-off klystron of a size that could possibly be made airborne could produce a fraction of the transmitter power necessary for an operational system.

A contract had been placed with the firm EMI, of Hayes, Middlesex, to produce manufactured versions of the equipment and they proceeded to design a transmitter that used a klystron. Late in July 1942 this system was eventually flight tested in a four-engined bomber, which confirmed the doubts about the viability of a klystron system. Before these klystron tests could be made, a major tragic accident was to force a decision to abandon the klystron as a transmitter.

Test flights using the original cavity magnetron as a transmitter had continued in the Halifax bomber. During a routine meeting at Defford airport on 6 and 7 June 1942 with four members of the EMI team they asked if they could be given a demonstration of the performance of the magnetron system. On the afternoon of Sunday 7 June the Halifax crashed in the Wye valley, killing all on board.

By a tragic irony the Prime Minister had minuted the Secretary of State for Air on the day of that crash, as follows:[12]

Prime Minister to Secretary of State for Air *7 June 42*

> I have learnt with pleasure that the preliminary trials of H_2S have been extremely satisfactory. But I am deeply disturbed at the very slow rate of progress promised for its production. Three sets in August and twelve in November is not even beginning to touch the problem. We must insist on getting, at any rate, a sufficient number to light up the target by the autumn, even if we cannot get them into all the bombers, and nothing should be allowed to stand in the way of this. I propose to hold a meeting to discuss this next week and to see what can be done.

The meeting with the Prime Minister in the Cabinet Room on 3 July took place under different circumstances from those he envisaged when he minuted the Secretary of State on 7 June. He showed little sympathy with the loss of the Halifax carrying the only working H_2S equipment. He said that was only one aircraft and we had lost 30 over the Ruhr in the previous night. When told of the difficulties he thumped the table and said he must have two squadrons fitted by October: 'Our only means of holding the enemy'.[16]

His demand was impossible to meet but led to a concentration of effort on the highest priority. Most significantly, the Air Staff directive to use the klystron was withdrawn so that all research and manufacturing effort could be concentrated on the cavity magnetron version. On 15 July the Secretary of State for Air had ruled that development work on the klystron for H_2S should cease and that the two H_2S squadrons should be equipped with the magnetron version—but that a decision on their operational use would depend on the war situation: 'if the Russians hold the line of the Volga'.

American opposition

The belief that the magnetron was a vital Allied secret led to an extraordinary situation in July 1942. The American scientists had been informed of the development of the blind bombing H_2S system, and shortly after the Prime Minister's meeting at which he demanded 'two squadrons by October' an American deputation arrived in the TRE. Headed by I. I. Rabi, the deputy director of the Radiation Laboratory, and including E. M. Purcell (FRS 1989), there was an unpleasant encounter at which they argued that if we persisted in using the system operationally then the Germans would quickly discover the magnetron secret and thereby possess information that would severely endanger Allied operations. Furthermore they maintained that attempts to use a 10 cm airborne equipment in America had completely failed to reveal targets on the cathode-ray tube as we claimed. This reputed failure was underscored by letters from E. G. Bowen (who had remained in the USA after the Tizard mission) and by D. M. Robinson, who had been sent to the USA by the TRE after a request from the Americans to establish more detailed contact on radar in the centimetre waveband. A despatch from Bowen reported that he had failed to obtain any radar response from towns equivalent to the size of Sheffield, and at the moment in January 1943 of the first successful operational use of H_2S Dee received a letter from Robinson in which he wrote that it ‘was time to carry out proper scientific tests of the proposal’. These strange American failures have never been explained.[17] Subsequently when the American 8th Air Force began operating over Germany from England they suffered tragic losses in their attempts at precise daylight bombing and urgently demanded that the British H_2S be fitted in their bombers,[18] and before the end of 1943 they were campaigning for the American 3 cm (10 GHz) system (H_2X) to be used by the RAF instead of the TRE 3 cm H_2S.

The first operational loss of H_2S

Churchill’s demand for two squadrons by October (1942) was impossible to meet—at that time after the crash of the Halifax containing the only prototype magnetron H_2S not a single airborne system was available. Under the immense pressure associated with the highest priority, by December 1942 two squadrons of the Pathfinder Force (8 group bomber command) each had 12 bombers fitted with H_2S—12 Stirling bombers and 12 Halifax. The Secretary of State for Air had ruled that the magnetron could not be used operationally unless the Russians held the Germans on the line of the Volga. This condition was deemed to have been satisfied after the destruction of the German 8th Army in the battle of Stalingrad, and on the last night of January 1943 the Pathfinder Force used the H_2S-equipped bombers to mark targets in the city of Hamburg. A few nights later (early February 1943) an H_2S-equipped bomber was shot down and crashed near Rotterdam.

The German discovery of the H_2S equipment

In 1977 the author visited the large German steerable radio telescope at Effelsberg, near Bonn. The visit was concerned with astronomical matters and with the collaboration between the radio astronomers at Effelsberg and those at Jodrell Bank. At a dinner after the business of the visit, the director, Professor Otto Hachenberg, raised the subject of scientists in the war years and turning to the present author remarked, ‘I am well aware of your wartime occupation because as a young man then working in Telefunken I was sent to investigate the equipment in a bomber that crashed near Rotterdam in 1943.’

Professor Hachenberg died on 24 March 2001. His successor as director, Professor R. Wielebinksi, during the course of sorting the papers left by Hachenberg found documents written by Hachenberg in 1943 about the equipment in the British bomber that had crashed near Rotterdam. Wielebinski was present at the conversations during the author's visit to Effelsberg in 1977 and, remembering the references then made to World War II activities of scientists, kindly sent to the author in the spring of 2003 a summary of Hachenberg's report. After a further request Professor Wielebinski was able to locate the full report, which reached the author in November 2003.

Hachenberg's report: *Englisches Radar-Gerät*

This report dated May 1 1943 refers to the equipment found in the British bomber 'of the type Halifax or Short Stirling'.[19] It is therefore evident that between the crash of the Stirling bomber early in February 1943 and the writing of this report less than 3 months later, Hachenberg had also investigated the H_2S system in a Halifax bomber of the Pathfinder Force. The German name given to the H_2S was 'Rotterdam'. It is also evident that Hachenberg had interrogated some of the captured crew members—one of whom reported that the city of Nuremberg appeared on the Braun tube (cathode-ray tube) 'about the size of a pfennig'.

The report makes it clear that the Germans quickly identified the H_2S as a blind bombing system, but it is the detail in the report that is so surprising. The photographs accompanying the report are of individual units, all of which are easily identified except the transmitter unit, which carried an explosive device intended to hinder identification of the cavity magnetron. In fact, the report is an accurate account of the function of every unit.

However, there is one important exception. The description of the cable connection from the magnetron unit to the rotating scanner is described in detail. In the first H_2S systems there was a dipole at the focus of the paraboloid—the straightforward aim was to achieve appropriate matching of the impedance of the magnetron output to the dipole: Hachenburg is not clear that this was the only reason for the matching arrangements which involved the common transmit–receive device. This is, perhaps, hardly surprising since, as he told the author during the 1977 meeting, he failed to understand the purpose of what seemed to be a smashed glass tube. This was the common transmit–receive device (which contained a glass tube filled with argon at low pressure). The arrangement was a short circuit or an open circuit according to the power level and so enabled the same aerial and feed to be used for transmission and reception, with a considerable reduction in the bulk of the equipment to be accommodated in an aircraft. The magnetron was essential for 10 cm operation, but for the fullest effect it had to be considered as part of a system in which the transmit–receive tube was important.

The great surprise in that report is the stimulus for writing this paper—namely that the cavity magnetron is described precisely, ending with the comment that 'Der Wirkungsgrad der Magnetronanordnung, die übrigens den Nachbau eines hier bekannten russischen Patentes darstellt, beträgt etwa 10%' ('The efficiency of the magnetron—it is worth mentioning that this is a replica of a known Russian patent—is about 10%').

Implications for World War II

The discovery of the cavity magnetron by Randall and Boot in February 1940 made a great impact on the operations of the Allied armed services. The intense secrecy that now transpires to have been quite groundless severely delayed the operational use of equipment using the magnetron. At least eventually the Allies made excellent use of the cavity magnetron—but the Germans did not do so. In 1945, after the end of the war in Europe, a German version of the original 1943 H_2S system was received at the TRE. It was an exact copy of the first operational H_2S—together with some minor errors—but there is no evidence that the Germans used the system or any part of it operationally. Evidently the previous invention of the magnetron by Alekseev and Malairov was known in Telefunken, but not in England.

The explanation of the German neglect of the potential value of centimetric radar is contained in a letter from Professor Wielebinski to the author dated 24 February 2003:

> It is correct that in your conversation with Professor Hachenberg in 1977 he insisted that the principle of the magnetron was known in the Telefunken company but by 'higher order' (Hitler himself?) the engineers were told to continue the longer wavelength radar development rather than go to short cm waves. Hachenberg said that some sort of a magnetron was used as a test signal generator in the laboratories but never optimized for airborne use.

Although this might seem surprising, a similar order was given to A. P. Rowe (the Superintendent of the TRE) as the German armies surged across France in the spring of 1940. Then it seemed most improbable that any research or development of centimetric radar could possibly have any relevance to operations in the war and that all possible effort should be concentrated on the installation, maintenance and use of the metre-wave radar already available. At that critical moment W. B. Lewis (FRS 1945), Rowe's deputy, persuaded him not to enforce the order on the group of half a dozen newly recruited scientists working on centimetric developments in a small wooden hut remote from the main establishment at Worth Matravers[20].

The delay in the deployment of centimetric techniques had little effect on RAF night fighters, because these were not expected to be operating over enemy territory. There was, however, a very serious delay in the deployment of H_2S in the Pathfinder Force of Bomber Command and in the anti-U-boat operations by Coastal Command.

The delay occurred in 1942 when, for 9 months, the Air Staff and ministerial directives were that the klystron, not the magnetron, must be used as a transmitter in the H_2S development. This meant that the finest group of development engineers in the country working in EMI on the contract to build the equipment wasted valuable months in concentrating on the development of the klystron as a transmitter. A. D. Blumlein and three other members of the group were killed in the crash of the Halifax bomber on 7 June 1942, and very little of their experience was used in the development of the TRE prototype magnetron version of H_2S. Had the entire available TRE plus EMI effort been concentrated on the magnetron system from early 1942, there is little doubt Churchill's demand for two squadrons to be fitted by October 1942 would have been realized.

This implies that the operational use of H_2S by the Pathfinder Force (8 group bomber command) could have been 4 to 5 months earlier than 31 January 1943. The navigational aid GEE had been operational since March 1942 and the bombing aid OBOE since 20 December 1942, and thus the major effect of the delay on Bomber Command only involved operations beyond the range of the Ruhr. The effect of the delay on the anti-U-boat operations by Coastal Command was more serious.

The U-boats based in the ports along the French West coast traversed the Bay of Biscay by night to reach the shipping lanes in the north Atlantic. By 1942 the shipping losses had reached 600000 tons per month—a cause of great concern to Churchill and the War Cabinet.[21,22] The U-boats travelled on the surface by night to charge their batteries. RAF Coastal Command Wellington aircraft operating over the Bay by night were equipped with an ASV (Air to Surface Vessel) radar working on a wavelength of $1\frac{1}{2}$ m. In June 1942 a retractable searchlight (Legh light) had been fitted to the aircraft and when a radar echo was found the searchlight was lowered beneath the aircraft so that the target could be identified before releasing depth charges. Until the autumn of 1942 the consequent attacks on the U-boats crossing the Bay at night on the surface had a significant effect on the shipping losses in the north Atlantic. However, by August 1942 the Germans had fitted the U-boats with a radio receiver (known as Metox) which detected the radar signals from an approaching aircraft and the U-boats could then dive before being attacked.

The replacement of the $1\frac{1}{2}$ m ASV by a modified 10 cm version originally designed for Bomber Command did not occur until the early months of 1943. As it happened the German Naval Enigma code was being broken regularly at this time, and the movements of U-boats were monitored. When operations began even with a few Coastal Command Legh light 10 cm ASV-equipped aircraft on 1 March 1943 the effect was immediate. The shipping losses had again reached over half a million tons per month. In March and April 1943 the RAF Wellingtons fitted with 10 cm ASV depth-charged 24 U-boats that were crossing the Bay of Biscay on the surface at night. Dönitz ordered the U-boats to remain on the surface and fight. The consequence for the U-boats was catastrophic and on 24 May Dönitz withdrew the whole fleet from the North Atlantic. On 21 September Churchill announced in the House of Commons that no merchant vessels had been lost in the North Atlantic for the 4 months ending on 18 September. In a radio broadcast Hitler complained that the ‘temporary setback to our U-boat campaign is due to a technical invention of our enemies…’.

The inference is that, but for the ban on the magnetron for the H_2S programme in 1942, 10 cm ASV radar could have been in operation in the autumn of 1942 when the German Metox enabled the U-boats to detect the $1\frac{1}{2}$ m ASV radar. The published records of monthly shipping losses[21,22] reveal that between $1\frac{1}{2}$ and 2 million tons of merchant ships could have been saved if the 10 cm ASV had followed immediately when the $1\frac{1}{2}$ m ASV was made ineffective by Metox.

Countermeasures

The German failure to develop centimetric techniques had important consequences for the RAF both in Bomber Command and in Coastal Command. The deployment of any new radar system by either side was usually followed very rapidly by countermeasures, but there was a long interval before there was a German reaction to the introduction of 10 cm radar. In March 1943, when the 10 cm ASV operations over the Bay commenced, the Germans did not realize that the change in wavelength from $1\frac{1}{2}$ m to 10 cm had occurred. It had been expected that they would immediately replace the Metox $1\frac{1}{2}$ m receiver by a 10 cm receiver but it was not until 8 or 9 months later, in the early autumn of 1943, that there was evidence that the U-boats were diving on the approach of the 10 cm ASV-equipped aircraft. Metox had been replaced by the 10 cm equivalent (Naxos), but from the German aspect it was too late. It seems that they believed that the RAF Wellingtons were homing on to some radiation from the U-boats. For the RAF this was an unexpected relief of several months, during which a 3 cm ASV had been developed. In any event the U-boat campaign never recovered from the 1943 episode and the shipping losses remained below 50 000 tons per month for the remainder of the war.

In Bomber Command a powerful argument against the operational use of H_2S was that the Luftwaffe would immediately fit their night fighters with a 10 cm receiver for homing on to the bombers' 10 cm transmissions. In spite of the evidence from the investigation of Hachenberg of the crashed H_2S bomber in February 1943 it was several months before evidence accumulated that such homing was occurring, and that the Luftwaffe were attacking the bombers from below and astern. This was rapidly turned to the advantage of the bombers' rear gunners by the introduction of a simple equipment linked to the H_2S that enabled the rear gunner to see a radar echo from the attacking fighter.[23] This equipment, code-named Fishpond, was fitted to every bomber coming off the production line with remarkable speed.

Conclusion

The recent discovery of a secret German report written by Professor Hachenberg a few months after the crash of a British bomber near Rotterdam in February 1943 reveals that the principle of the cavity magnetron was already known to the German scientists, and that nothing was gained by delaying its use operationally.

The unnecessary delay of 9 months in the operational use of the magnetron may not have had serious consequences for RAF Bomber Command because the navigational aid GEE and the precise bombing aid OBOE became operational in 1942 with a range covering the Ruhr. In contrast, the delay had a most serious effect on the operation of RAF Coastal Command against the U-boats crossing the Bay of Biscay at night. The gap of several months between the compromise of the $1\frac{1}{2}$ m ASV by the U-boat Metox listening receiver and the change of ASV radar to 10 cm cost the Allies the loss of $1\frac{1}{2}$ to 2 million tons of merchant shipping in the North Atlantic.

It is extraordinary that the Germans did not immediately recognize that the ASV radar wavelength had been changed, although they had the evidence from Hachenberg's report that the Allies had operational 10 cm airborne radar systems. The sequence of events is a clear illustration of a vital difference in the relations of the scientists to the operational Commands. With the Allies the integration was complete; in Germany it was almost non-existent. When Dönitz ordered the remaining U-boats to return to their home ports late in May 1943 this marked the effective end of the devastating U-boat campaign—a sequence of events initiated by the failure of the Germans to develop centimetric techniques and their disbelief in the possibility that the Allies were able to use an airborne centimetric system operationally.

It has often been suggested that in the scientific aspects of World War II the Allied scientists were superior to the Germans. There is no substantial evidence that this was so. The evidence from the present paper supports the view that the real differences lay in the contrast of the relation of the scientists to the operational Commands.

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Notes

1 E. G. Bowen, *Radar days* (Adam Hilger, Bristol, 1987).

2 On the outbreak of war this became AMREI (the Air Ministry Research Establishment), then MAPRE (the Ministry of Aircraft Production Research Establishment) and then the TRE.

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10 A. MacFarlane, 'John Flavell Coales', *Biogr. Mems Fell. R. Soc. Lond.* **49**, 119–131 (2003).

11 C. Webster and N. Frankland, *The strategic air offensive against Germany 1939–1945* (HMSO, London, 1961), vol. 4, pp. 132–133.

12 W. S. Churchill, *The Second World War*, vol. IV (*The hinge of fate*) (Cassell, London, 1951), p. 250.

13 Professor F. A. Lindemann was elevated to the peerage as Lord Cherwell in 1942.

14 P. I. Dee FRS, then in charge of the TRE centimetre research group, was appointed Professor of Physics in the University of Glasgow after the war.

15 A. P. Rowe CBE, the Superintendent and later Chief Superintendent of TRE. For his account of these events see his *One story of radar* (Cambridge University Press, 1948).

16 Lovell, *op. cit.* (note 9), chapter 14.

17 B. Lovell, *Astronomer by chance* (Basic Books, New York, and Macmillan, London, 1990), chapter 6.

18 Lovell, *op. cit.* (note 9), chapter 23.
19 The Lancaster bombers fitted with H_2S were not yet in service in the Pathfinder Force.
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