Secret Weapon

The menace of the U-boat could have turned the battle of the Atlantic against Britain if it had not been for two scientists. Working from a makeshift laboratory in Birmingham, John Randall and Harry Boot produced the cavity magnetron, which enabled surfaced submarines to be located precisely in the dark. Within two months the battle was effectively over. The more recent photograph shows the inventors with the modern version and the prototype, on table; at the time of the experiments, Grand Admiral Karl Doenitz could not have been feeling too happy that day in May 1943 as he was driving up to Berchtesgaden…

Throughout the war he had been in personal command of Germany's devastatingly successful U-boat operations. He had originated the 'wolf-pack' technique in the Atlantic which had cost the Allies hundreds of ships, thousands of lives and millions of tons of vitally-needed supplies.

The idea was simple and effective; he posted his submarines in mid-ocean, miles apart, in a long line straddling the convoy routes. There they waited, beyond the range of shore-based aircraft, for the mastheads of a convoy to appear over the horizon. When the first sighting was reported back to Doenitz at his headquarters in Lorient, he immediately signalled the nearest U-boats to converge. Thus the wolf pack gathered to intercept the convoy, shadow it by day and strike under cover of night.

They attacked on the surface; their low, black hulls almost invisible in the dark, while the merchantmen and escort vessels stood out clearly against the night horizon. Submerged, U-boats were slow and short-sighted but on the surface they were fast and maneuverable fighting ships, able to use guns as well as torpedoes against the lumbering convoys.

Wolf-pack tactics almost won the battle of the Atlantic for Germany. Violent storms in January 1943 had kept the total number of sinkings by U-boats down to 37 ships but in February the score shot up to 63 and in March no fewer than 108 Allied ships were sunk by submarines. One convoy was attacked by 40 German U-boats and 21 ships were lost.

Britain faced defeat by strangulation. Without a guaranteed inflow of fuel and raw materials, there was no way to win the war. Back in December, a report on Churchill's desk showed that Britain had only 300,000 tons of commercial bunker fuel left, enough to last a little more than two months. "This does not look at all good…" he noted.

Doenitz would not have known those figures but, even so, he could reasonably have expected, that May 22nd, to be reporting to the Fuehrer that his U-boat commanders had finally, and mortally, severed the Atlantic artery. Instead, he had rather different news to impart.

"Enemy aircraft have been equipped with a new location apparatus…" he told Hitler, "…which enables them to detect submarines and attack them unexpectedly in low cloud, bad visibility, or at night… Much of the largest number of submarines now being sunk are being sunk by aircraft… in the last month, losses have risen from 14 submarines, that is about 13 per cent of those at sea, to 36 submarines or perhaps 37, that is about 30 per cent of the submarines at sea. These losses

are too high. We must now husband our resources because, to do anything else, would simply be to play the enemy's game."

For some months, ever since Britain had broken the Enigma machine-codes which Doenitz used to control his submarines, the Admiralty had listened in to the stream of tactical signals between Lorient and the U-boat commanders. On May 23rd 1943, a sudden eerie silence descended…

Every U-boat in the Atlantic had been ordered to return to base "to avoid unnecessary losses in a period when our weapons are shown to be at a disadvantage". Doenitz assured Hitler that the withdrawal was only temporary, that new weapons and improved technology would allow the U-boats to return and triumph in the Atlantic before the year was out. In fact, the scales never again swung in Germany's favour.

Convoy SC 130, from Halifax to Liverpool, was the last to be seriously menaced. All 38 ships arrived safely on May 26th. During the 15-day voyage, escorting ships and aircraft sunk five enemy submarines.

It was virtually the end of the battle of the Atlantic: a 'volte-face' made possible by two British scientists in a makeshift laboratory under the sloping floor of a lecture theatre at Birmingham University. They were John Randall and Harry Boot.

Shortly after the outbreak of war, Randall, a physicist working on a Royal Society research fellowship, lived in Aberystwyth and, on Saturday afternoons, it was his habit to root among the technical volumes in a bookshop just around the corner from his flat in Marine Parade.

One afternoon he discovered an old English translation of the papers of Heinrich Hertz, the German physicist who had discovered radio waves in the 1880s. It was Hertz who demonstrated, for the first time, that radio waves were reflected from conducting objects like metal sheets. His work led directly to the development of radar in the Thirties, when it was realized that even an object as small as an aircraft at a range of more than 100 miles would reflect a pulse of electromagnetic energy back to its source.

In one experiment, Hertz set up small loops of wire with a gap in them and found that he could get sparks crossing the gap with a generating coil placed a certain distance away. He showed empirically a relationship between the diameter of the loop and the length of the waves coming out of the generator. Randall was to recall this paper before the year was out.

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A chain of secret radar stations stretching from Ventnor in the Isle of Wight to the First of Tay was already in operation when war was declared in September 1939. They were able to 'floodlight' the sky with electromagnetic waves to give early warning of the approach of aircraft.

The system worked supremely well, often reporting ranges of 100 miles and more, but it had severe limitations: the equipment was bulky and required huge transmitting and receiving aerials; it *could not accurately measure bearing or pick up low-flying aircraft; and it was susceptible to jamming.*

All these problems could be overcome if the wavelength were reduced to that, instead of 'floodlighting' the sky, the radar beam acted like a searchlight and 'swept' the sky. Dr. Charles Wright, then Director of Scientific Research at the Admiralty, had prophesied that the country which develop radar power on the shortest wavelength would win the war but, at the time, generating wavelengths below about 50 centimetres was thought to be impossible; a radar 'searchlight' would require a wavelength of no more than 10 centimetres.

However, the potential advantages of shortwave radar were so considerable that the 'impossible problem' was passed over to a team of scientists at Birmingham University, under the control of Professor Marcus Oliphant, head of the Physics Laboratory. The main team concentrated on a device called the Klystron, then the only known source of centimetre wavelengths likely to be of sufficient power. John Randall and Harry Boot, a research student, were given the task of trying to make a microwave receiving valve from a Barkhausen-Kurz oscillator.

Neither Randall nor Boot were particularly thrilled with their project. They were given a corner of an elementary teaching laboratory and left to their own devices while their colleagues wrestled with the formidable difficulties of the Klystron, soon to be known as the 'dog's breakfast', because it was built from so many bits and pieces.

Within six weeks the pair had proved that the Barkhausen-Kurz tube would not work as a receiver, so they quietly dropped the idea and turned their attention to the primary problem: how to generate centimetric radar waves.

Both of them were skeptical that the Klystron would ever produce sufficient power. Keeping their doubts to themselves, they began to discuss possible alternatives, one of them a device called a magnetron. The magnetron at that time was considered to be no more than an interesting electronic invention. It was capable of producing centimetre wavelengths but not at a constant frequency and was therefore thought to be useless for radar purposes.

But the more Randall and Boot thought about the qualities of the magnetron, the more convinced they became that it offered greater potential than the Klystron. One afternoon in November 1939, while they were talking about the possibilities of combining the principle of a resonator (a vital element of the Klystron) with the principle of the magnetron, Randall recalled the book he had found months before in Aberystwyth.

If the loops of wire Hertz had used in his experiment were extended cylindrically, they should form resonators and, if these resonators were drilled in a solid copper block and provided with openings into the anode/cathode space, then electrons should…Randall sketched a rough drawing on the back of an envelope while Boot started making calculations. By the end of the afternoon, they had worked out a design and finished the basic calculations.

That evening, as Randall was driving home with Professor Oliphant, he explained the concept of their 'cavity magnetron' and it was agreed they should build a prototype. Oliphant was a little doubtful but thought the idea was worth a try.

Next morning Randall and Boot set to work. The laboratory was very poorly equipped for their needs (about the only useful piece of equipment was an old electromagnet) but, what they couldn't beg or borrow, they made themselves. Top priority was still being given to the Klystron so their project was largely ignored. Undeterred, they pressed on, slowly constructing a curious Heath Robinson contraption which relied as much on sealing wax and ingenuity as it did on electronic components. When they needed a metal disc to seal the end of the magnetron, for example, Harry Boot produced a halfpenny and used that.

On February 21st 1940, the cavity magnetron was finally ready to be switched on for the first time. A car headlamp bulb with its cap removed was connected to the power outlet and then, with some apprehension and no little excitement, Randall threw the switch. The bulb lit and burned out. A laboratory assistant was sent down the road to a nearby garage to buy a bigger bulb. That too burned out as did successively bigger and bigger bulbs throughout the day. The inventors knew then that they had succeeded in generating high power but that was not the crucial factor. What of the wavelength?

A week passed before they were able to set up the necessary equipment to measure the wavelength. It comprised two parallel wires, connected to the power source, along which ran a neon bulb. As the bulb crossed each half wavelength, it brightened and then dimmed. All that was required to measure the frequency was to divide the number of times the bulb lit by the length of the wire. The answer came out to 9.8 centimetres.

No-one knew precisely, scientifically, how the cavity magnetron worked (two distinguished professors of applied mathematics in Britain and several in the United States spent much of the war working out the theory and there are still even today areas of doubt) but of course it did not matter – it did work!

Shortwave radar, generated by the cavity magnetron, was to play a significant role in winning the war: by improving the accuracy of anti-aircraft fire, it was to save thousand of rounds of ammunition; it was used to direct night-fighters intercepting enemy bombers; it gave the strategic bombing of Germany hopeful impetus. Most important, it defeated the U-boats in the battle of the Atlantic.

News of the invention was immediately passed to the Government, other scientific research organizations, the Services and to industry, although it remained top secret. At Birmingham, more people were drafted in to help in the development of the magnetron which was soon taking priority over the Klystron.

In May 1940, the first centimetric radar set using the cavity magnetron was ready for testing in a small wooden hut in the grounds of the Telecommunications Research Establishment near Swanage. It was even less beautiful and more Heath Robinson than the curious complex of wires, valves, transformers and rectifiers that Randall and Boot had devised, yet again it worked. On the first day it was tried, it picked up echoes from a small boy riding his bicycle along the cliffs. By July it was receiving useful signals from cars and aircraft and in September it detected a submarine at a range of seven miles.

In the autumn of 1940, the cavity magnetron was the most important of all the closely-guarded British scientific secrets included in the famous 'black box' which Sir Henry Tizard took to the United States and which President Roosevelt later described as "the most valuable cargo ever to reach our shores". It was also the spur which led to the establishment of the Radiation Laboratory at the Massachusetts Institute of Technology: the beginning of the scientific co-operation between the two countries which still exists today.

The Royal Navy was the first of the Services to use shortwave radar, after watching the demonstration at TRE (Telecommunications Research Establishment) in September in which a submarine was followed seven miles out at sea. At that period of radar development, it was virtually impossible for ships to detect surfaced U-boats at night.

A new corvette, the Orchis, was used for trials of centimetric radar in April 1941. The difficulties of adapting the equipment for operational use were enormous because of the rolling and pitching of the ship, the vibration from the engines and the dynamic effect of gunfire but, by the end of the year, 50 ships (including the Queen Elizabeth and the Queen Mary) had been fitted with centimetric radar. On April 14th 1942, the first U-boat was sunk with the direct help of the new equipment.

If fitting shortwave radar into ships caused problems, installing the same equipment into aircraft was a nightmare. It was nearly two years before all the difficulties could be overcome, thus shortwave radar with its greater range and accuracy was not available to combat the major German night offensive against Britain in the winter of 1940-41 but it played an important role in defeating the night bombers in the 'Little Blitz' of 1943-44.

While operational use of shortwave radar was being channeled, in the main, through TRE, at Birmingham the team working on the cavity magnetron were constantly producing further refinements, shorter wavelengths and higher power. One of the scientists was James Sayers who was to come up with a significant modification called "strapping". Early magnetrons had the tendency to jump from one frequency to another if too much power was put through them – Sayers cured this by strapping alternate resonators together with short pieces of wire.

Curiously, none of the scientists at Birmingham were aware at the time of the real contribution they were making to the war, not even the two men who had made the 'centrimetric revolution' possible, John Randall and Harry Boot, knew that their invention had opened up new dimensions *of warfare. Harry Boot would occasionally take a new cavity magnetron along to one of the Government research establishments to demonstrate or test it – on one well-remembered occasion he had to stay overnight en route and left the device for safe-keeping with a mystified sergeant at the local police station.*

As more and more magnetrons were produced for ever wider applications, so the danger increased that the Germans would discover the secret of centimetric radar by shooting down a British aircraft and finding the valve. The risk was increased because the copper anode cylinder of the magnetron was virtually indestructible. One trial of a new explosive blew a 10ft hole in the side of an aircraft but only reduced the magnetron to recognizable fragments which any physicist could have put together in a few minutes. Fear of discovery by the enemy caused delay in the use of one of the most remarkable developments of centimetric radar – H2S – which was eventually to make feasible the accurate bombing of Berlin.

In the autumn of 1941, it became clear that all was not well with operations for the strategic bombing of Germany. Aerial photographs proved beyond doubt that a large number of bombs missed their targets by miles. The problem was passed to the TRE. Their brief was to produce a radar aid which would enable Bomber Command to attack unseen targets. Philip Dee, one of the team working on the application of centimetric wavelengths, had the idea that the rotating shortwave radar beam scanning the terrain under an aircraft would be able to differentiate between town and countryside. On the first test flight over Southampton, strong echoes were picked up from the town on a cathode ray screen in the aircraft. A few days later flights were made over cloud in the Midlands and photographs taken of the screen indications on a number of towns. When the still-wet prints were laid on the desk of A.P. Rowe, the head of TRE, he took one look at them and said ; "This is the turning point of the war." (History was not to support his remark because, while H2S solved most of the night-aiming problems, the strategic bombing of Germany never lived up to the hopes of its proponents).

Technical development of H2S to the point at which it would provide a clear picture of the terrain over which a bomber was flying caused many headaches for the special team set up at TRE. It was not until September 1942 that a prototype Halifax fitted with a radar scanner mounted in a Perspex blister under the aircraft and connected to a Plan Position Indicator (the now familiar radar screen) started service trials. The equipment could be tuned with such delicacy that the screen would pick up a clear, moving picture showing coastline, rivers, woods and even small towns.

On the night of January 30th 1943, in appalling weather seven Sterlings and six Halifaxes fitted with H2S took off for Hamburg to mark targets for the main force following on their tail. That raid was the start of the devastation of Germany's major cities. By the end of the year Berlin was under constant attack and the H2S equipment had improved to such an extent that, not only the lakes surrounding the city were visible, but even Templehof airfield could be clearly identified.

Fears that Germany would discover the secret of shortwave radar proved, in the event, to be unjustified. One aircraft fitted with a cavity magnetron crashed near Rotterdam but, inexplicably, German scientists showed little interest in the curious equipment it carried. Early on, in the H2S programme, it had been decided that the equipment being developed should be adaptable for use against submarines although it was the demands of Bomber Command which really occupied the attention of the scientists despite the ominous events in the Atlantic.

ASV (Air to Surface Vessel) radar at that time operated on a 1½-metre wavelength. Used in combination with a searchlight mounted under the fuselage of an aircraft, it had scored notable successes in night attacks on U-boats in the Bay of Biscay in the summer of 1942. Before the autumn, however, the Germans had developed a listening device which enabled U-boat commanders to detect the approach of an aircraft using ASV radar. As the number of U-boat sightings decreased in the winter months, the tonnage of Allied shipping sunk in the Atlantic increased monthly until, in the early spring of 1943, it had reached alarming proportions.

As soon as Coastal Command became aware that their 1½-metre ASV radar was no longer effective, they began pressing for centimetric radar, which would not only render the German's listening device useless but, with its longer range, would greatly increase the area of ocean which could be searched. Unfortunately, Whitehall was totally committed to the strategic bombing of Germany and thus Bomber Command had priority for the new 10-centimetre equipment. The arguments within the Cabinet, between the Admiralty and the Air Ministry, and between Bomber Command and Coastal Command, were heated and bitter and occupied many weeks during that long, cold winter of 1942-43.

It was not until the situation in the Atlantic had become so desperate that total defeat was not only possible, but likely, that Bomber Command was at last persuaded to release some of its precious shortwave radio equipment. At the same time Coastal Command were given more very long range aircraft, and convoy escort vessels were fitted with a 10-centimetre radar antennae mounted on the gun directors, vastly improving the accuracy of their guns. This combination turned the tide of the battle in the Atlantic with such dramatic speed that the Germans were taken totally by surprise.

By April 1943, the nerves of enemy submarine crews were stretched to breaking point. The whole idea of the wolf-pack technique depended on the U-boats being able to operate on the surface at night. Centimetric radar turned night into day for Allied aircraft and escort vessels, making wolf-pack tactics suicidal.

As a last desperate counter-measure, Admiral Doenitz ordered his commanders to dive at night and stay on the surface in groups of three and four during the day to fight it out with the aircraft. It was a terrible mistake: in a straight fight, the U-boats were no match for Coastal Command, now vastly superior in numbers, weapons and equipment. So it was, less than two months after the Battle of the Atlantic looked won, Doenitz was forced to admit that it was lost.

The Ingredients

Radar is not transmitted in a continuous beam but in a series of pulses, or waves, which are reflected back to source. The precision of information received depends on the length of the wave: for example, if two aircraft one-tenth of a mile apart are to register on a radar screen as separate ‘blips’, the pulse must be less than one-millionth of a second in duration (comparable to a flash of lightning).

At the beginning of the war, there was no device capable of generating short wavelengths of sufficient power. The Klystron, on which all hopes were initially pinned, was a device in which a beam of electrons was driven through two resonant cavities electrically coupled together. Centimetric wavelengths were produced but the electrons could not be driven through the resonators with sufficient force.

The magnetron was a form of diode invented in America in 1921. By forcing a whirlwind of electrons round and round inside a cylinder of metal, it, too, could produce centimetric wavelengths but of even less power than the Klystron.

By assimilating the resonant cavities of a Klystron into a magnetron, Randall and Boot produced sufficient power *and* short wavelengths. The cavity magnetron worked rather in the same way that an air-raid siren is able to produce such a powerful sound. In a siren, a straight blast of air is blown through a series of cavities in a rotating slotted drum. In a cavity magnetron, the electrons emitted by the cathode are submitted to a magnetic field and are swept through a series of oscillatory circuits. The oscillations are maintained in the resonant cavities, producing very powerful, very short electromagnetic waves.

The two men who had made so much possible – Randall and Boot – were initially rewarded with a prize of £50 from the Royal Society of Arts for "improving the safety of life at sea". The announcement of the award was made the same day that the atom bomb was dropped on Hiroshima, thus it attracted little attention. After the war, however, they applied to the Royal Commission for Awards for Inventions and, with Sayers, shared a prize of £36,000. Sir John Randall, after a distinguished academic career in biophysics, worked in the field of molecular biology at Edinburgh University while Dr. Harry Boot became senior principal scientific officer employed by the Ministry of Defence. Both tended to describe their invention in the most reserved and modest terms.

"I suppose you could say it was like being struck by lightning," Dr. Boot admitted reluctantly, when explaining how they came across the concept of the cavity magnetron. "I think the trouble is that too many scientists are much too logical; they don't want to take a risk or simply make a calculated guess. At the time it really was a forlorn hope that any of us would be able to come up with a method of generating centimetre wavelengths, so we felt that any idea was worth a try."

"I think we were damned lucky, really," said Sir John, "that our over-simplified calculations, based on intuition as much as anything, were near enough the mark for the cavity magnetron to work when we switched it on for the first time. How did we feel? Well, I suppose you could say we were both surprised and delighted. But there were no extravagant scenes of jubilation."

There never have been any extravagant scenes of jubilation about the invention of the cavity magnetron: a curious irony in view of the attention, plaudits and glory heaped on lesser events of the period. Barnes Wallis and the Dam Busters have been glorified in a best-selling book and a film. Much is known about the strange explosive devices cooked up in Winston Churchill's 'toyshop'. There has been massive celebration of the Spitfire and thousands of words written about developments which achieved little except capture the public imagination.

But about Randall and Boot and their astonishingly imaginative invention, hardly anything is known. Yet it was really important, it really worked and it sprang from a genuine British strength – our enormous resources in pure science and especially physics. Without the cavity magnetron, it is just conceivable that the battle of the Atlantic would have been lost. If the battle of the Atlantic had been lost, it is just conceivable that the whole war might have been lost.

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Excerpts from the above article taken from The Sunday Times.