The development of E1189, the ‘British cavity magnetron’

***Abstract:** No doubt that the British cavity magnetron originated from the prototype devised at Birmingham by Randall and Boot. What until today has been partially ignored is the subsequent work done by Eric Megaw at GEC, essential to obtain that powerful, versatile and easily reproducible microwave generator that everyone today simply knows as ‘magnetron’. The recent finding of samples and documents coming from the GEC Archives, after the shutdown of the GEC-Marconi, made it possible the full reconstruction of what Megaw really did in those days.*

Foreword: In 1921 A. W. Hull at General Electric for the first time described static characteristics of a device called magnetron. Actually the tube was a diode, with filament coaxial to the cylindrical plate. The bulb was surrounded by a winding, used to generate a magnetic field. The radial electric field and the superimposed magnetic field forced electrons to follow curved orbits before reaching anode. Hull noted that, gradually increasing the magnetic field, radius of the orbits became smaller and smaller, until electrons could no longer reach the plate, so causing the cut-off of the anode current. Hull also noted that, when biased near to the border between conduction and cut-off, the tube could sustain self-oscillations in a resonant circuit.

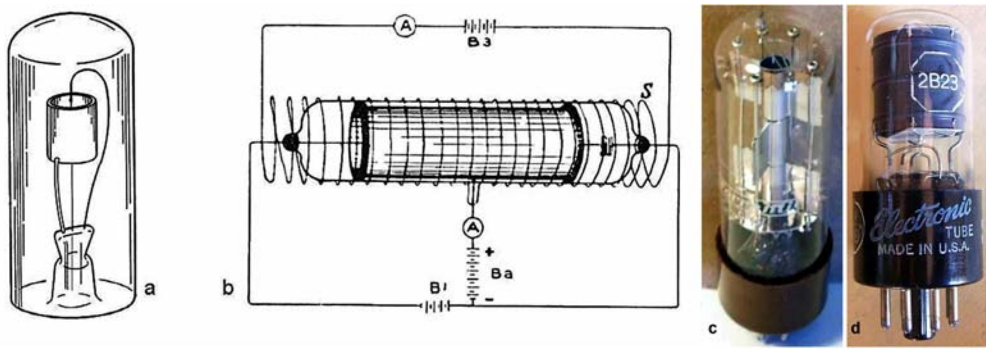


Fig. 1 – a) Draft of the Hull original diode. b) Diagram of the experimental circuit. c) Ferranti GRD7 was a didactic tube used to demonstrate the operation of Hull diode. d) 2B23 is a magnetically actuated switch.

The cylindrical anode magnetron oscillated in the so-called cyclotron mode, as result of a sinusoidal voltage built up between cathode and anode. It was found that oscillation occurred following the relation λB = constant, where B was the intensity of the magnetic field. It was also noted that the period of oscillations was equal to electron transit time from cathode to anode and back. In 1924 E. Habann proposed a split anode design, in order to have stable oscillations at higher frequencies. In 1936, Cleeton and Williams reached frequencies as high as 47 GHz with such a structure.

The split anode magnetron could also operate in a different mode, not depending upon the transit time, as far as it is small when compared with the period of oscillation. Under the effect of a strong magnetic field, electrons follow spiral trajectories, describing several complete loops and being preferably attracted by the segment having the lower instantaneous potential. In 1936 G. R. Kilgore succeeded in observing trajectories, made luminous by the ionization of a small amount of gas introduced in the bulb. Kilgore obtained efficiency as high as 25% at 600 MHz with 100W input power. Few years later, in WWII, General Electric built some split anode fluid-cooled magnetrons, capable of delivering about 150W continuous wave at frequencies between 15 and 1200 MHz. The four registered types used in radar jammers, 5J29, 5J30, 5J32, 5J33 and ZP-599 are described in ‘Very High-Frequency Techniques’, Vol. II, Radio Research Laboratory, Harvard University.

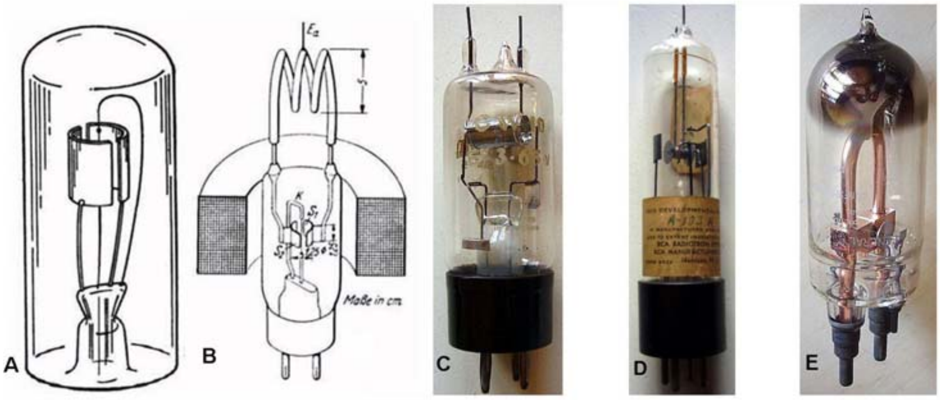


Fig. 2 – A) Early split anode magnetron. B) Complete oscillator, also showing the magnetic field generating coil, surrounding the glass bulb. C) CW10, a split anode magnetron designed by Megaw, was used in the mid thirties for UHF experiments of radio-localization. D) To operate at higher frequencies, resonating circuit was moved into the glass bulb: the line shorting loop is placed just above the anode segments in this RCA A-103A, operating at 3 GHz. E) 5J29 was a split anode magnetron designed at General Electric and capable of generating 150 W CW at 400 to 700 MHz. The tube was fluid-cooled through the hollow anode legs.

From the second half of the thirties the split-anode structure was improved adding more plate pairs or segments, in order to obtain higher efficiency and smoother operation at lower magnetic fields. In these devices, sometimes referred to as interdigital or squirrel-cage magnetrons, the plate segments were alternately connected to the ends of the resonating line.

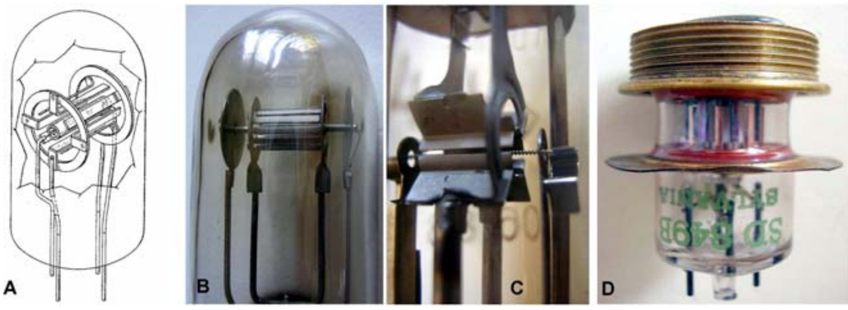


Fig. 3 - A) The draft of an eight-anode interdigital magnetron. Plate tabs all around the cathode sleeve are alternately welded to the two side rings. In the above samples two rods connect the two opposite anode rings to the external resonator. B) A 12-segment British GEC experimental magnetron, as described by Callick. Megaw built other similar devices, as this 8-segment prototype, D) The German RD4Ma uses spirally wounded tungsten cathode to increase emission. E) In the after-war segments of 3J22 are connected to copper discs to operate within an external cavity.

Researchers from all over the world experimented different structures, resonators and shapes of electrodes, in order to get stable sources of ultra-short waves. Among the others, we remember the works of Erich Habann in Germany, of Okabi and Yagi in Japan, of Alekseroff and Malearoff in Russia, the still little-known work of Henri Gutton in France who built devices with up to 48 segments, that of Klaas Posthumous at Philips and of Eric Megaw at GEC. In America Samuel at Bell patented a multi-cavity structure, while Kilgore at RCA integrated in the glass bulb the same resonator. In Italy Agostino Del Vecchio patented a water-cooled split-anode device. Nevertheless none of the magnetrons developed until 1940 could be really useful as source of radio-frequency in a radar transmitter. Their power was definitely low, limited to a few tens of watts by two major factors. The first one was that electrodes were surrounded by an evacuated glass bulb, a great limit to the removal of heat generated inside. The second factor was the use as cathode of thin tungsten wires. Their surface was too low to ensure enough emission, even when driven at the highest permissible temperature. Another severe limiting factor was the need for considerably long connections from the internal electrode structure to the external resonating lines. Moving the resonator inside the glass bulb, as in the structures devised by Kilgore, caused excessive thermal frequency drifts, in addition to the predictable low heat dissipation.

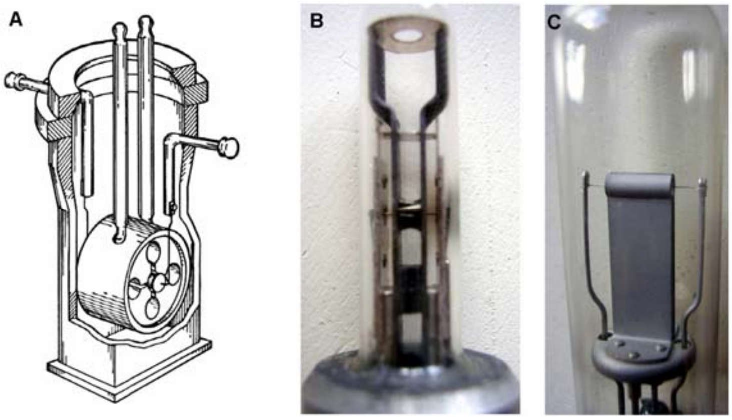


Fig. 4 - A) draft of the cavity magnetron devised by Alekseroff and Malearoff in Russia. B) In the RD2Mh interdigital magnetron a capacitive coupling is provided for the anode system. C) This RM4025, presumably designed by Siemens during the war, shows a split-anode structure with integrated 10 GHz resonator, similar to those described by Kilgore in Proc. I.R.E., August 1936.

Around the mid-1930s many countries had experimented remote detecting systems based upon microwaves generated by magnetrons, although the limited power available made it possible to observe faint echoes only when the target direction was previously known. Further developments were then oriented to more powerful systems working at lower frequencies. Only France continued developing its microwave radar, since it was born as anti-collision system, capable of detecting in the fog obstacles in front of the ship's bow, therefore not requiring high power. At the beginning of 1940 all known radio-detection systems operated approximately from 50 to 500 MHz, their transmitters using gridded triodes, designed or modified for high-power pulse operation.

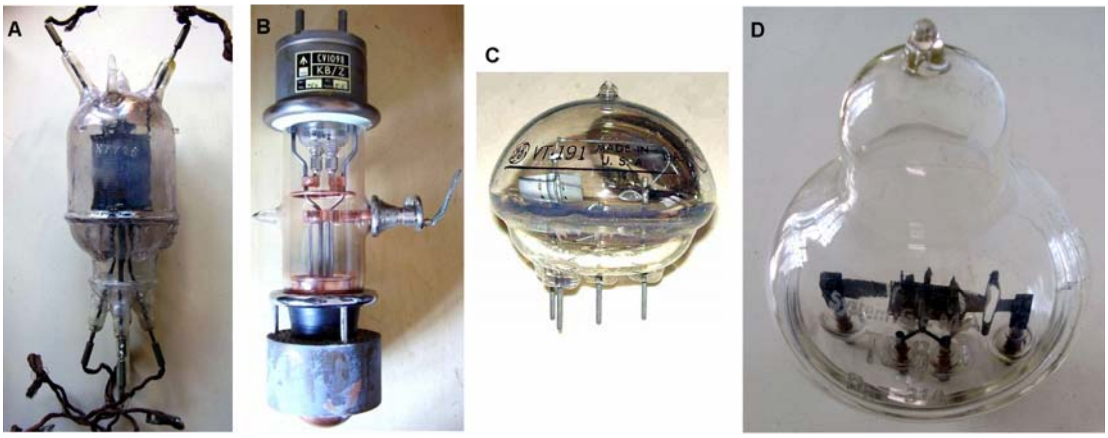


Fig. 5 - Gridded vacuum tubes in use radio-localization sets early in 1940. A) British correctly planned several evolution steps, starting from frequencies below 50 MHz. Their first power triode specifically designed for radar applications in 1936 was the hand made 'silica valve' NT57, with an emission of 3.6 A. In 1939 it was replaced by the improved variant NT57T: its thoriated-tungsten filament gave 18 A emission. B) In 1939 British GEC introduced families of advanced external anode power tubes, capable of operation in the VHF region: this VT98 or CV1098 power triode could operate up to 250 MHz with 25 A cathode emission. C) Western Electric introduced UHF 'doorknob' triodes in 1936. 316A could operate up to 750 MHz and several countries started experimenting radar systems around 500 MHz. In the Western Electric CXAS prototype a couple of improved variants of 316A generated about 2 kW (*8). Even the ASV prototype designed by Bowen used this triode, but British preferred more conservative solutions at lower frequencies. D) Germans started working with 'doorknobs' around 75 cm. They made their own improved variants of 316A, the TS1 and TS1a with specular pinout, and later still more powerful types, as this Gema TS6. Their drawback was the low output power: in the uprated Seetakt two tubes generated about 8 kW peak power.

The British cavity magnetron

Randall and Boot, two researchers of the University of Birmingham, are credited for the invention of the cavity magnetron. According to Callick their prototype was operated for the first time on 21st February 1940, generating bursts of 150 watts CW at 10 cm in a field of 1300 oersteds. It was a six cavity water-cooled demountable unit, with a filamentary tungsten cathode. The main difference from other prototypes developed elsewhere was in that the anode block was at one time the resonating system and the evacuated external envelope. The common practice in those years was to use tungsten wire for filamentary cathodes, assembling electrodes inside an evacuated glass bulb. Regardless of the particular design of the many devised types, they were all CW magnetrons, with quite low emission and unable to dissipate large amounts of heat. The real innovation of Randall and Boot was in suppressing the glass bulb, with the result that heat could be easily removed from the external anode. Their water-cooled prototype gave up to 500 W bursts at about 10 cm wavelength. A large electromagnet with five-inch gap was required to operate it.

GEC was already experimenting milli-micropup power triodes, capable of generating plenty of power at 25 cm, but the requirement for the AI system was to move down to 10 cm. Megaw was certainly one of the most experienced people on any kind of high-frequency tubes, especially magnetrons, on which he had published articles from early 1930s **(*15)**. He was up to date on all new studies and experimental devices announced worldwide. In 1937 for a 50 cm shipboard communication link supplied to the Admiralty he had designed a four-segment CW magnetron, the E880/NT75. He was personal friend of Henri Gutton, who in France was experimenting with innovative multi-segment structures. In 1939 he was in Paris, where he discussed with Gutton about possible solutions to increase the power of their magnetrons. We will see later the consequences of that visit. No wonder then that Megaw was asked for reproducing the Randall and Boot prototype in a sealed-off device. On April 10 he went to Birmingham, where he agreed some variants to the original prototype. Megaw designed the E1188, which used two side-arm supports for the tungsten filament and thin copper end discs. Anode block was still supplied by Birmingham, but the reduced overall size made it possible to fit it in a smaller electromagnet with 7 cm gap. The design of E1188 was completed on May 16. Tests run at Birmingham in July evidenced that it operated as the original prototype, delivering 500 W CW at about 9.9 cm. Power was substantially limited by the emission of the tungsten filamentary cathode.

Since December 1939 GEC and Megaw himself were already under pressure to make a pulse magnetron suitable for airborne use, under an Air Ministry contract. Callick gives us its description, a four-segment interdigital magnetron with spiral-wound thoriated-tungsten filamentary cathode, capable of delivering pulses of about 500 W and including an internal resonator system coupled into a waveguide **(*1)**. In April, immediately after starting the E1188 design for Birmingham, Megaw launched a new design under the subsequent number E1189. It was a new low-profile device to be operated in the pole pieces of a standard permanent magnet. Due to his experience, he assumed that the oscillation mode was independent of the axial length of the cavities. To increase the emitting surface, he decided to use as cathode a 3 mm diameter helix made of thoriated-tungsten wire, instead of the straight tungsten wire of the Birmingham prototype. On May 9, when the design was complete, Maurice Ponte brought to Megaw two samples of the M-16 magnetron with oxide-coated cathode developed by Gutton. Having carried out tests that confirmed the good results obtained in France under pulse conditions, Megaw decided to design a variant of the E1189, using an oxide-coated cathode. Both samples were ready within June 28, delivering on the bench pulses between 1 and 2 kW in a 1.100 gauss field generated by a permanent magnet. Subsequent tests on the sample with oxide-coated cathode evidenced that the pulse power could be raised to 15 kW and over, when the magnetron was operated in an electromagnet, the field being increased up to about 1.500 gauss. In his paper of 1946 **(*7)** Megaw left a detailed description of the tests performed on it, concluding:

‘***...the field required for what appeared to be maximum efficiency was too high for the existing permanent magnet. This was corrected by re-calculating the design for eight segments instead of six, keeping the wavelength at 10 cm. Fig. 11 shows details of the modified design which was later standardized for naval use as NT98.***’

The hitherto known history of the development of the British cavity magnetron ends with the second sample of the six-cavity E1189. Aside from the few lines of Megaw above, all we know of the subsequent development comes from the story written by Bowen. The eight-cavity magnetron, the one that actually worked in radar systems and that originated hundreds of thousands of units produced during the war, suddenly turned out just two months later in America, in the laboratories of Bell Telephone. Here the E1189 No. 12 brought there by the Tizard Mission was X-rayed, unveiling its internal 8-cavity design. Bowen wrote that on 7 August he was at Wembley to attend the briefing on the magnetron construction. According to Paterson, the thorough discussion went on until 3 pm. After the briefing he could pick the best performing unit out of a batch tested by Megaw himself. We know that Bowen returned to Wembley on August 11 to take the magnetron and the documentation, presumably stored into a safe from the day of the briefing.

Certainly Bowen was briefed on the six-cavity design, since he was not aware of the eight-cavity variant until 7 October, after that his sample had been X-rayed at Bell. Bowen wrote of his phone call to Megaw ‘**At first he was vague, and disbelieving - he was obviously as puzzled as I was.**’**(*3)**. Then Bowen added his own version of what he could remember from the phone call, that is the No. 12 was an odd experimental unit, built in the same batch of magnetrons with different number of cavities. Just by chance it had performed better than the others on the test bench. The common belief was therefore that the magnetron brought to America by the Tizard Mission, which made possible the practical use of radar, was the result of hasty improvisations, errors and lots of luck.

The recent findings of a laboratory prototype and of documents coming from the archives of the disappeared GEC-Marconi allow us today to reconstruct the entire history of the Megaw’s developmental work on the eight-cavity magnetron at the GEC, a master’s work that took place over a couple of weeks or so.

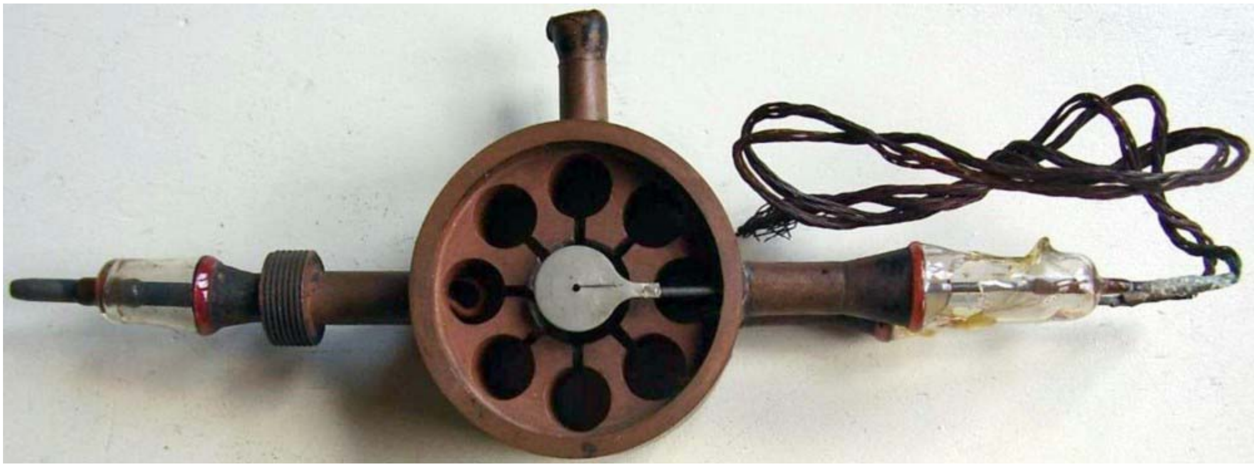


Fig. 6 - This 1189 C 328 is believed to be the first prototype of eight-cavity magnetron ever operated by Megaw in the GEC Wembley laboratories. Presumably coming from the GEC-Marconi collection.

Our reconstruction begins in 2017, with the casual discovery of the prototype shown in figs. 6, 7 and 8. It does not appear as a common magnetron to which the closing caps had been removed to show its internal structure. Except for the absence of the usual finned radiator and for the presence of a small copper tube from the side wall of the anode block, other details of its design are identical to those listed by Megaw for the E1189 eight-cavity type. The code 1189 C 328 is engraved on the side wall of anode block near to its edge.

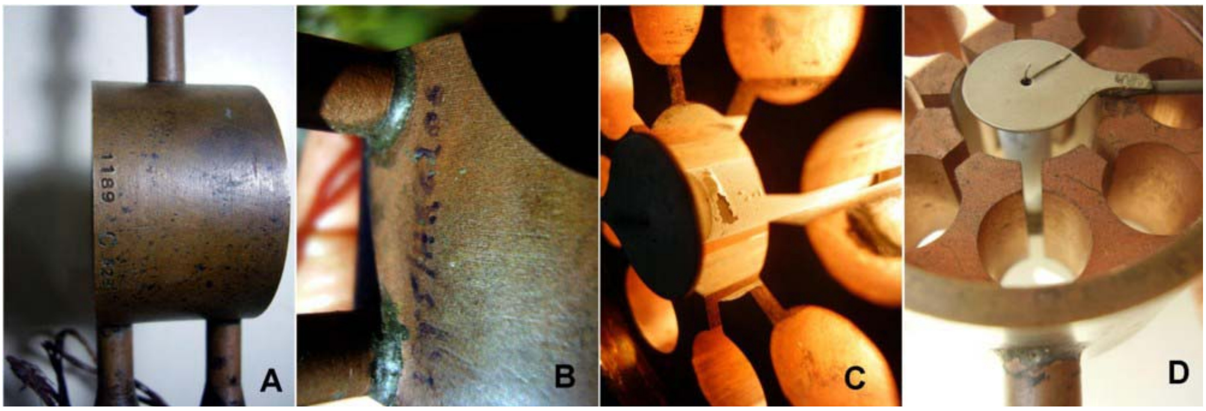


Fig. 7 - Close-up views of the prototype. A) The code 1189 C 328 is engraved on the anode block. B) A character sequence .../HR210 can be read in the partially faded marker writing. C) The cathode oxide layer is partially swollen and peeled-off, as caused by overheating. D) One of the heater ends is broken just at the edge of the corresponding cathode end baffle.

The oxide layer on the cathode surface looks in bad shape, as the tube had been stressed to extreme conditions for a long while. In some areas the oxide has become so thin as to show the bare nickel below, somewhere else the oxide is swollen and detached, like in a bubble. One of the heater ends is broken near to the welding to its corresponding end baffle. On the external wall, into a faded marker writing, characters 'HR210' can be read. Inside the anode block, near to the edges, few traces of sealing grease are still visible. No doubt that this magnetron was a laboratory prototype. Certainly it was intriguing enough to justify further investigations.

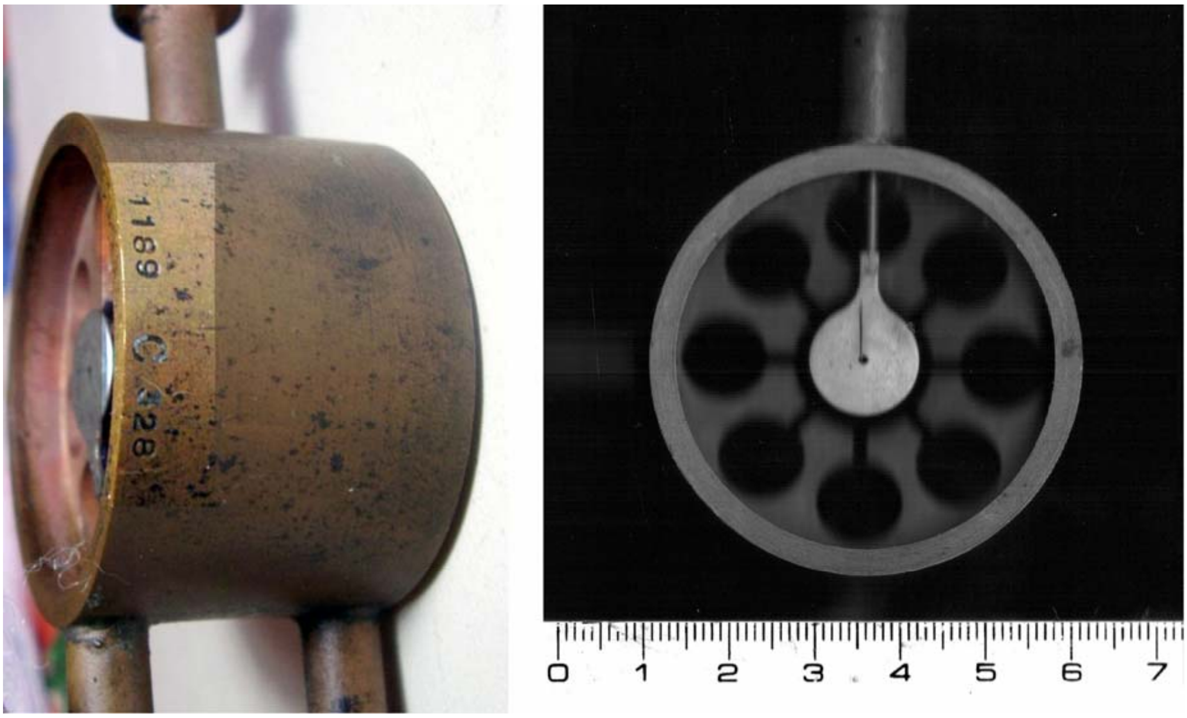
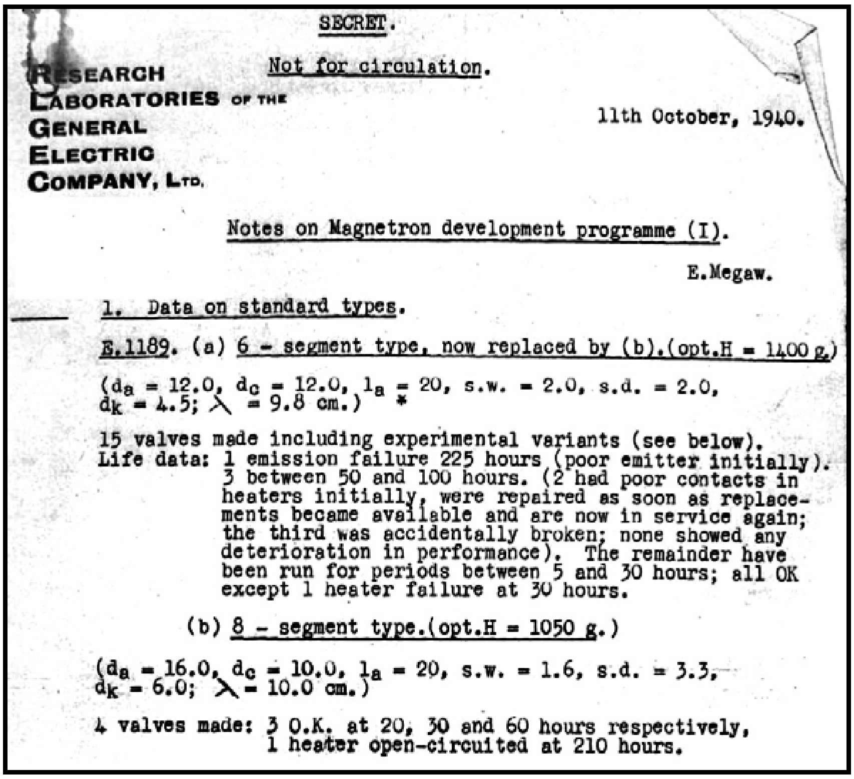


Fig. 8 - Left, enhanced view of the code engraved on the side wall. The letter C could be related to the third revision of the design, after the A and B types listed by Megaw in the secret document below. Right, the anode block is scanned together with a ruler as a reference, to appreciate physical dimensions of the cavities and slots. Dimensions fully agree with those given by Megaw.



SECRET.

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RESEARCH
LABORATORIES OF THE
GENERAL
ELECTRIC
COMPANY, LTD.

11th October, 1940.

Notes on Magnetron development programme (I).

E.Megaw.

1. Data on standard types.

E.1189. (a) 6 - segment type, now replaced by (b).(opt.H = 1400 g.)

(d_a = 12.0, d_c = 12.0, l_a = 20, s.w. = 2.0, s.d. = 2.0, d_k = 4.5; λ = 9.8 cm.) *

15 valves made including experimental variants (see below).
Life data: 1 emission failure 225 hours (poor emitter initially). 3 between 50 and 100 hours. (2 had poor contacts in heaters initially, were repaired as soon as replacements became available and are now in service again; the third was accidentally broken; none showed any deterioration in performance). The remainder have been run for periods between 5 and 30 hours; all OK except 1 heater failure at 30 hours.

(b) 8 - segment type.(opt.H = 1050 g.)

(d_a = 16.0, d_c = 10.0, l_a = 20, s.w. = 1.6, s.d. = 3.3, d_k = 6.0; λ = 10.0 cm.)

4 valves made: 3 O.K. at 20, 30 and 60 hours respectively, 1 heater open-circuited at 210 hours.

Fig. 9 - From Megaw's internal report on magnetron development at the date of 11 October 1940. He wrote of four valves made of the 8-segment type, one of them operated for 210 hours. The document also gives physical dimensions of electrodes.

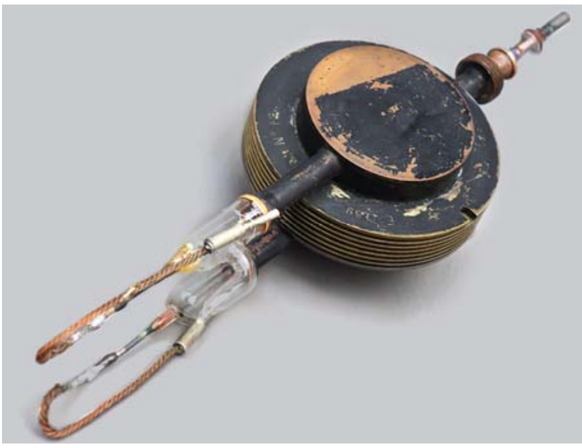

Fig. 10 - The E1189 No. 12 was the sample brought to America by the Tizard Mission, today preserved at the Ottawa Science and Technology Museum.

In his 1946 paper '**The high-power pulsed magnetron: a review of early developments**' **(*7)** Megaw wrote of two sealed-off samples. The No. 12 was the one taken by Bowen in August, while the No. 13 was used by Megaw himself for characterizing his new design. But where are the other two samples reported in fig. 9? Could our sample be one of them, maybe made after that the No 12 had started its travel to America? At first glance it would seem too different, without the finned radiator and with that strange copper tube out of its side. Nevertheless the internal structure and the code engraved on the anode block indicate that it was an E1189 experimental magnetron. Today, eighty years from those days, any answer can only be found in the papers left by Megaw and looking here and there in the sometimes cryptic documents left by other people really involved in the events. We must remember that the magnetron work was secret. The same Bowen was briefed on it only few days before leaving GEC for America. In 1990 Willshaw, a Megaw's collaborator, asked about historical inconsistencies by the late Rod Burman, gave the cryptic answer below **(*15)**:

Mr Burman:
Actually the question I wanted to ask Mr Willshaw relates to the production of the first eight-cavity magnetron as opposed to the six-cavity version. Your description and your explanation of it that it was required to improve the efficiency within the available magnet, ties up with Megaw's paper presented in 1946. If you read Dr Bowen's Radar Days, he has a rather more story-telling type of version. He describes how he turned up at the Bell Telephone Laboratories with the magnetron and they X-rayed it and found that the one that he had had eight cavities and when he rang up Megaw to find out what had happened, he was told 'oooh, my goodness, yes, I asked the foreman to make ten anode blocks with six cavities, and one with seven and one with eight and the one with seven was the one that didn't work.'
Is that really the case, or it that just a bit of historical nonsense?

Mr Willshaw:
Yes, I think that is just another bit of historical mis-management. There is no point in going to odd numbers of cavities in view of Megaw's earlier experience, although, undoubtedly, the seven-cavity one would have worked quite well but with all the mode-change problems of it, presumably.

A meager yet reliable source of information about our magnetron is the Diary of Sir Clifford Paterson, Director of the GEC Research Laboratories until 1948. He noted the relevant facts that occurred day after day, so that we can date key steps in the Megaw's developmental work. Dates could then be compared with some milestones of the Tizard Mission and with dates given by Callick and by Bowen, in order to reconstruct the entire history.

June 28th[104-105]

Randall coming on Friday re. high power magnetron. Megaw and Boyland have been making splendid progress with these. There are two types—Randall's and Megaw's—the former water-cooled and the latter air-cooled. At the moment Megaw's is on circuit and giving some 2 kW at the desired wavelength—but Randall's will follow in the next few days. Boyland's gold wire joint seems to be one of the chief features giving the striking success.

July 1st

Output from Megaw's 10 cm magnetron has risen to 4 or 5 kw and is still rising.

July 17th

The whole day at our two-monthly CVD meeting. A rather memorable occasion for we recorded (*a*) beam valve amplification at 50 cm, (*b*) Megaw's air-cooled low field magnetron, (*c*) Ramsay's mercury modulator, (*d*) two velocity modulation receiving tubes—one with resonator for 10 cm. General demand for specimens.

August 6th[113-114]

A crowd of people here from many establishments including Oliphant and Randall and Ellis. It is difficult for people to get on with urgent work when visitors are so frequent but it cannot be helped. Megaw's improved 10 cm magnetron with eight chambers appears up to expectations. Randall with Duke's assistance (we introduced him to Oliphant) has made a good copy of the air-cooled magnetron for 5 cm.

Lord Hirst paid us a visit and was wheeled round to various rooms with myself, B.P.D. and R. Le R. looking after him—a delightful episode.

August 7th[115]

Schoenberg, Blumlein, Condliffe and Broadway with Bowen came for a thorough discussion of AI. It took a whole morning and until 3 o'clock. The general exchange of views and experience was helpful and the atmosphere of co-operation most encouraging.

Fig. 11 - Events related to the development of the cavity magnetron, as reported by Sir Paterson.

The Paterson's diary tells us that on June 28 at least one of the two E1189 six-cavity prototypes had been put into operation with promising results. Megaw dates early operations one day later. We could assume that the sample with thoriated tungsten cathode was tested first, maybe with a mechanical keyer, because of its intrinsic resistance to long input pulses. Tests on the second sample would have necessarily required the completion of the thyratron pulser described by Megaw. He details the tests conducted in the following two weeks on the prototype No. 2, the one with the oxide-coated cathode, up to obtaining power in the order of 15 kW in the field generated by a powerful electromagnet. Megaw points out how he estimated the power of back-bombardment in a five to ten percent of the mean input power, the value being greatly influenced by the load coupling. With 6 μs pulses the magnetron continued to operate even removing the heater supply.

On July 17 two important decisions were taken in the CVD meeting about magnetrons. The first one, also confirmed by Megaw, was the production of further copies of the six-slot E1189: **'General demand for specimens'**. The second decision was about a **'Megaw's air-cooled low field magnetron'**, likely the proposed eight-cavity variant. The next key date is August 6, when '**Megaw's improved 10-cm magnetron with eight chambers appears up to expectations**' at the presence of Oliphant, Randall and Ellis. Just the next morning Bowen was at Wembley to be thoroughly briefed on the magnetron construction details until 3 pm. After the briefing Bowen picked the best performing magnetron, the No. 12, out from a batch tested by Megaw himself.

So far the sequence of events at the GEC. Now let us open a window on the related Tizard Mission. The British had correctly assessed that their industry would not be able to produce the magnetron quantity necessary for military needs. Machining and drilling the anode copper block to the required tolerances was at the time a painstaking and time consuming job **(*14)**. We learn from Callick that until the end 1941 the total production of NT98 by GEC and BTH was around 2.000 units, while shortly later Raytheon alone will build up to 2.400 magnetrons a day **(*14)**.

On 8 July, few days after the successful tests of the E1189 samples, Lord Lothian, British ambassador in Washington, submitted a direct appeal to Roosevelt: ***'The British Government have informed me ... that they would greatly appreciate an immediate and general interchange of secret technical information with the United States, particularly in the ultra short wave radio field. ...'***. London was ready to send a small group of British military officers and scientists to the United States ***'to give you the full details of any equipment or devices in which you are interested without in any way pressing you beforehand to give specific undertakings on your side'***. The appeal concluded ***'for our part, we are probably more anxious to be permitted to employ the full resources of the radio industry in this country [the United States] with a view to obtaining the greatest power possible for the emission of ultra short waves than anything else.'*** On 11 July Roosevelt accepted the British proposal. Probably the encouraging tests on six-cavity E1189 had given the green light to the mission that Tizard had been preparing for a long time.

From the acceptance of the British proposal, everything had to be carefully planned to send a working sample of the Megaw's magnetron to America. It was, as we know, the most valuable secret that the British could offer to gain the unconditional help of America. Furthermore that prototype had to be reproduced in volume by American industries, to fulfill the same British needs. In short it was the very purpose of the mission itself. This consideration alone is enough to raise doubts about the reconstruction left by Bowen and universally accepted until today.

The recent discovery of a period theme from the GEC Archives Collection, today still loaded in the site of Trevor Wright, http://www.trevorwright.com/GEC/Archive/index.html, finally confirms our first thoughts about the true story of the eight-cavity magnetron designed by Megaw.

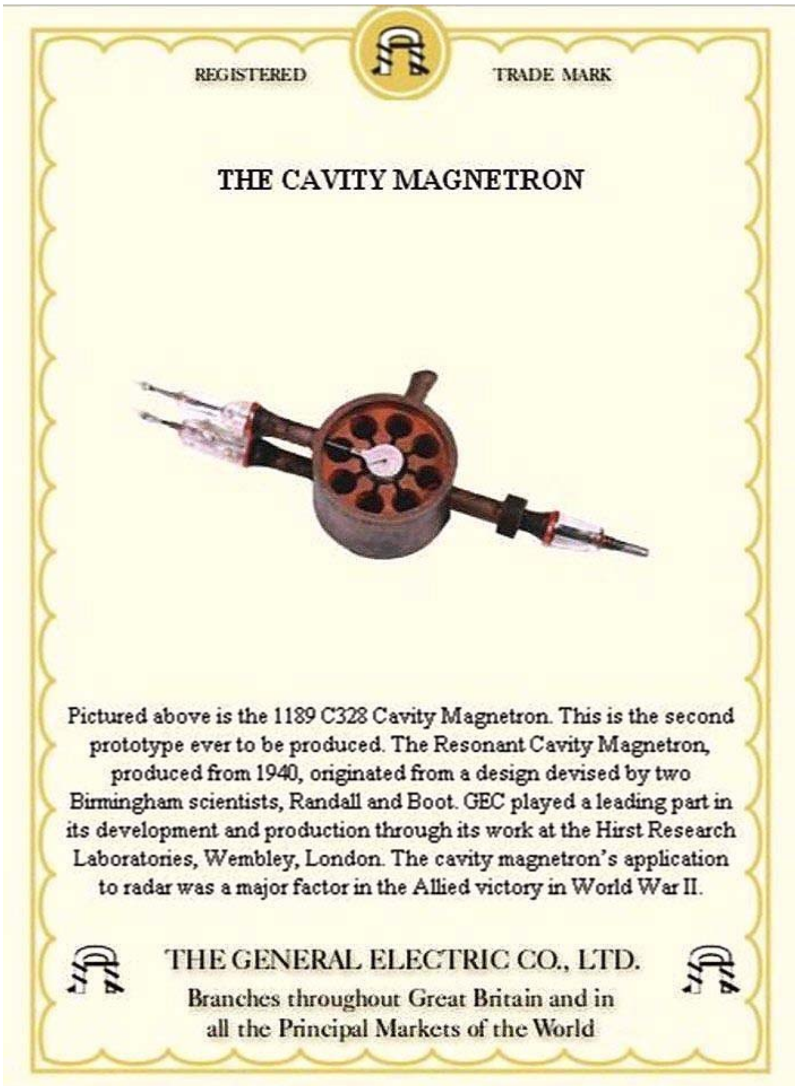

Fig. 12 - The above page, from the GEC on-line Archives Collection, shows the photo of the second prototype build of the Megaw's eight cavities magnetron. Its shape is identical to that of our sample above. Even its code, 1189 C328, is the same of the code engraved on the anode block of our sample. According to Trevor Wright this sample was held in the GEC Collection at Marconi Research Centre in Chelmsford, UK.

Our sample looks identical to that shown in the GEC page above but it is not the same. Definitely it differs in the small glass damages to the heater spacers, Moreover the filament in the above photo looks intact at the welded joint to the cathode end baffle, while in our sample it is broken at the bent. Now, given that the sample in the GEC page was actually the second prototype of eight-cavity magnetron ever produced, our sample can only be the first one ever made. We also note that these two laboratory prototypes with their rather unusual shape, added to the two sealed-off samples serialized as E1189 No. 12 and No. 13, give a total of four units built, in full agreement with what Megaw wrote in his internal report **(*2)**.

Carefully rereading the documents so far available and correlating the facts and circumstances described in them, the whole story becomes clear. The eight cavities design was not the result of casual experiments and of lucky circumstances. The low-profile E1189, although inspired by the prototype of Randall and Boot and even considering the frequent contacts with Birmingham, was widely the result of Megaw's own work. He masterfully blended his personal knowledge of the subject, the solutions proposed by Randall and Boot and the encouraging results achieved by Gutton in that new design, which would make practical the use of microwaves in radar systems in a few months. Then the most plausible scenario can be summarized as follows.

April 10, 1940

Megaw met Randall and Boot for the first time, proposing minor variants to their prototype. By using thin copper end caps, coaxial output to a loop into one of the cavities and side-arm supports for the filamentary cathode, he started designing the E1188, a CW magnetron capable of delivering 500 watts in the 2.5 inch gap of an electromagnet. The six-cavity anode blocks, 40 mm high, were still supplied by Birmingham. (*1, *7).

April 1940

Assuming that larger diameter cathodes would provide greater currents and that the oscillation mode was independent of the axial length of the cavities, few days later Megaw started designing a new low profile magnetron suitable for airborne use. The E1189 was air-cooled, intended to be operated in the 40 mm (1½-inch) gap of a standard magnet. The cathode was a 3 mm diameter helix of thoriated tungsten wire. The anode length was reduced to 20 mm. On May 9 Maurice Ponte brought to Megaw two samples of the M-16, with oxide-coated cathodes. After encouraging pulse tests, Megaw decided to work out a revised design, using 4.5 mm diameter oxide-coated unipotential cathode. (*1, *7).

June 28, 1940

Both six-cavity samples were completed, giving pulses in the order of 1 kW in the field of a standard magnet, about 1.100 oersteds. Megaw noted the effect of back-bombardment on the second sample, the one with oxide-coated cathode: with 6 µs pulses, it continued to oscillate even removing the heater supply. In a few days, in a field of about 1.400 oersted generated by an electromagnet, the peak power of the second sample raised to over than 15 kW. Megaw roughly estimated the cathode temperature increase due to back-bombardment by measuring the heater resistance (*7, *13). Likely he had realized quite soon that the design had to be modified to eight-cavity to operate efficiently in the low field of a permanent magnet.

July 8. 1940

The Tizard Mission had the green light from the British government. No doubts that the cavity magnetron was one of its key subjects.

July 17. 1940

During the CVD meeting at Wembley the discussion dealt about building more samples and even about a 'Megaw's low-field magnetron'. Likely the decision was taken of assembling a small lot of the six-cavity type, while authorizing Megaw to try that eight-cavity variant he was proposing.
Megaw could start all the activities to build samples modified to eight-cavity.

July 29 to August 5, 1940

Basing upon hours of operation from the Megaw's internal report (*2) and assuming that tests were ran about ten hours per day and were all interrupted after the approval of the low-field design at the end of August 6, we can date approximately their completion and the subsequent start of the bench operation for each one of the four samples.

- First 1189 C 328 wax-sealed prototype started oscillating around July 29 or 30
- Second 1189 C 328 wax-sealed prototype started operating around August 1
- E1189 S/N 12, the one of the Tizard Mission, started operating around August 4
- E1189 S/N 13 started operating around August 5

August 6, 1940

From the Paterson's diary: '*A crowd of visitors at GEC, including Oliphant, Randall and Ellis. The Megaw's improved 10 cm magnetron with eight chambers appears up to expectations*'. Sir Paterson takes the picture of the official approval of the eight-slot design review, based upon the successful operation of the four samples, totaling about 200 hours. Tests were likely stopped all together after the approval. We can assume that just Megaw, Paterson and very few other people could have shared the approval that evening.

August 7, 1940

Bowen was at Wembley to be briefed on the magnetron construction. Almost certainly the briefer was not aware of the decision taken few hours before to approve the new design. As consequence Bowen was briefed on the six-cavity design. Soon later he picked the best operating unit out of a batch tested by Megaw himself: it was the E1189 No. 12. (*3).

August 11, 1940

Bowen returned to Wembley to pick up the selected magnetron and the accompanying documentation, almost certainly kept in a safe from August 7.

October 6. 1940

It was a Sunday when the E1189 No. 12 was operated at the Bell Whippany Laboratory, delivering pulses in excess of 15 kW. There is an inconsistency in the magnetic fields given in the BSTJ Vol. XXV, April 1946 at pages 270 and 271. Probably the sample was operated at 1.100 gauss, according to the test label, while the design in the folder gave 1.500 gauss.

October 7, 1940 **The magnetron was X-rayed at Bell unveiling its eight-cavity anode design. Bowen was urgently called by phone. Early the next day he was at the Bell's headquarters in New York, where he had left the folder with designs and blueprints few days before. To his immense surprise, he was shown the blueprint of the six-cavity and then the X-ray of the eight-cavity sample he had brought. Being right at Bell it was easy for him to call Megaw and ask him where that fake magnetron came out. We know the answer from the story told by Bowen.**

The story that emerges from the recent discoveries and the reconstruction made starting from the documents of the time is that the British eight-cavity magnetron development was not the result of random experiments, mistakes, confusion and lucky coincidences. On the contrary, as with other British achievements, it was the result of carefully planned and coordinated work in charge of a brilliant person, Megaw. He succeeded in a true miracle, designing, building, testing and fully characterizing the new magnetron in a couple of weeks or so, while manufacturing a backup batch of the previous six-cavity type. He built four samples to the new design, two of them being used in accurate laboratory tests, with special attention to the effects of the back bombardment at any power level. Confirmation of the verification work is given by the small copper tube placed on the side wall of the laboratory prototypes identified as 1189 C 328.

I personally came to the belief that the copper tube, which is identical in shape and size to the two feed-through heater connectors, is what remains today of a peephole, a glass window purposedly installed to measure the cathode temperature by pyrometric methods. This belief derives from the careful reading of the paper written by Megaw himself in 1946, '*The high power pulsed magnetron: a review of early developments*' **(*7)**.

Back bombardment of the cathode in high frequency power tubes was well known at GEC since the early 1930s. Megaw was certainly a very expert person, but at the time no one could have experience on tubes using oxide-coated cathodes and capable of generating ten kilowatts or more at 10 cm. The only existing magnetron with similar characteristics, the six-cavity E1189 No. 2, had been operated for the first time just a couple of weeks before or so. Due to its all-metal construction, Megaw had only approximately estimated the cathode temperature increase due to back bombardment by the indirect resistance variation of the heater. This technique could have provided accurate results for filamentary cathodes, but it was definitely inaccurate in our case. The oxide and the underlying interface layers could be easily damaged by overtemperature, up to complete peel-off. By the way the geometry of the eight-cavity design differed considerably from that of the six-cavity, with cathode diameter increased from 4.5 to 6.0 mm. Therefore any previous observation on the six-cavity sample was not applicable to the new design. Here the Megaw's own words referred to the tests on the E1189 No. 2:

'The output at 6 microsec was independent of heater voltage down to zero with the oxide-coated sample, and its success was regarded as completely established. An early mercury-vapour triode (E1191) modulator was used. The wavelength was near 9,8cm for both valves. Within a fortnight peak outputs of 10 kW had been measured in a water load with an input of about 10 kV, 8 A, 30 microsec, 50 pulses/sec; the field of about 1400 oersteds was provided by an electromagnet. With higher inputs, powers estimated at over 15 kW were obtained, but with the large pulse length used persistent flash arcs occurred at this output. The cathode bombardment power was estimated by heater resistance change in No. 2 (the one with oxide-coated cathode ***) at 5-10% of the mean input, increasing appreciably as the load coupling was reduced.'***

The two laboratory prototypes, the first is the sample in our hands, confirm that Megaw ran extensive tests on his new design, while the two sealed samples were in progress to be assembled. Eventually all the four eight-cavity E1189 magnetrons listed by Megaw have been traced out. Today is cleared even the historical mis-management Mr. Willshaw **(*15)** referred to in his conversation with the late Rod Burman. The last question is why Megaw at phone gave Bowen the answer he gave? Since the involved people can no longer answer this question today, we can only make assumptions, based on the sequence of events. We must remember that the eight cavities revision had been approved only on August 6 by the small committee of scientists described by Paterson. Likely, the approval took place in the evening, after each sample was further tested, even according to specific requests of visitors. At the end of the day, once the eight-cavity design was finally approved, we must assume that Megaw himself removed the best sealed-off sample from the test bench, adding its test label. Then he put it together with other six-slot units ready for delivery, which included the six-slot that should have left for America if the eight-cavity variant had not worked properly. Eventually he left instructions for Bowen to take the best performing sample the next day, after his briefing on the magnetron which he would bring to America. We can assume that the briefer had previously prepared the necessary material, the documents that Bowen would have to illustrate once in America. Obviously it was material related to the six-cavity design, the only one approved until the evening before. Then Bowen selected for his mission the sample No. 12, which was stored with the documents in a safe, until he picked them all on August 11.

Now let us imagine Megaw's reactions when he got the phone call, two months after these events, well knowing that the magnetron he had given to Bowen was eight-cavity and hearing the other on the phone talking of a wrong sample, with eight cavities instead of six. Anyone else in his place would have been 'vague and disbelieving'. Eventually he realized the mistake due to haste, since on 7 August the magnetron had been only approved by the scientists, while the documentation used to prepare the briefing the day after was not yet updated. Probably he tried to explain in a few words that formally at that date the No. 12 was still experimental. This led to the misunderstanding that has come down to our days and that Megaw and his colleagues never tried to clear up, as proves the Willshaw's sibylline answer to the Rod Burman's direct question on the subject. Could Megaw have avoided the mistake in the documentation? Almost certainly not. He will have communicated the update of the drawing in the days after August 6, according to the normal internal procedures, but the Bowen's briefing had been planned well before the approval of the new design.

Immediate successors of the Megaw's E1189

The sample No. 12 brought to America by Bowen since November originated the first qualification batch of 'Chinese copies' at Bell Telephone, with the Bell experimental code 1259M. One of these is on display in the online collection of the Birmingham University, record 147, ID number BIRRC-P0901. About sixty more samples were made by Western Electric with its own developmental code D-160052. In England the E1189 was slightly simplified in the radiator design and approved as NT98. The Bell / WE samples originated volume productions by the related factories Northern Electric in Canada, as REL 3D, and by Australian Standard Telephones and Cables, as NTA98.

In the United States Western Electric introduced its own improved variants for airborne applications, with the three frequency selections, 706A, 705B and 706C.

The frequency variant E1198 for airborne use was approved as CV38, also manufactured as REL 3C by Canadian Northern Electric.

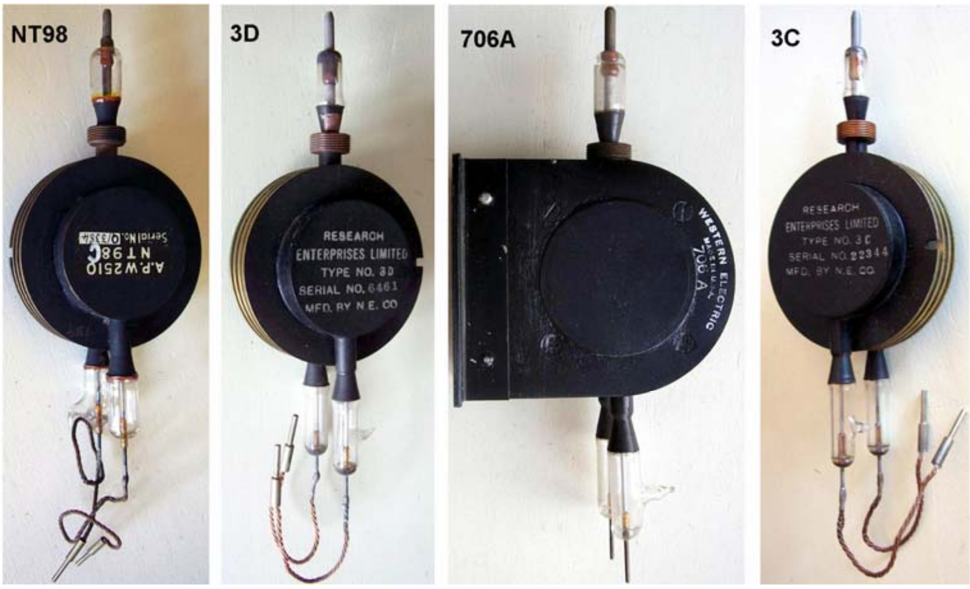

Fig. 14 - Early magnetrons directly derived from E1189. [NT98](#) was the Admiralty code for the Megaw's tube with simplified four fins radiator. Used in Type 271 radar. [Type 3D](#) was the E1189 made by Northern Electric for Canadian REL: thousands made for GL IIIC radar systems. [WE 706A](#) was improved by side mounting brackets and more efficient radiator for airborne use. It was also used un the transmitter of the SCR-519 airborne set. [3C](#) was the REL equivalent of the British E1198/CV38, a frequency variant used in AI Mark VII through 1941.

From 1942 these types were manufactured only for maintenance, being gradually replaced by the strapped variants with increased efficiency. Almost all the unstrapped magnetrons produced were scrapped at the end of the war to recover copper and mainly the gold rings used to seal the end caps with the low-temperature diffusion process devised by Boyland at GEC **(*7)**.

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All the tubes photographed in color, but that in fig. 10, are in the ase-museoedelpro collection

Last edited on February 13, 2021 by Emilio Ciardiello