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Microwaves Are Everywhere: "Ovens: From Magnetrons to Metamaterials"

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(Special Series Paper)

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ABSTRACT This article is the second in a continuing series of general interest papers on the applications of microwaves in areas of science and technology that might not be appreciated by the traditional engineer. What more appropriate application could there be than the first wide-spread commercial use of microwaves *for food preparation*. The development, use, and evolution (or lack of) of the microwave oven is the subject of this month's "Microwaves Are Everywhere."

INDEX TERMS Microwave ovens, microwave heating, magnetrons, metamaterials, commercial applications of microwaves .

I. INTRODUCTION

"First we had radio fevers induced by short-wave oscillations in the neighborhood of six meters. Now, as our cover shows, we have "Cooking With Short Waves" with us. Before we know it we shall probably be ordering our steak broiled on 7 meters, the eggs boiled on 4 meters, etc. Here's good news for our young cooks - when food is burned by "shortwave cooking," the taste does not reveal this fact! Among the other marvels performed by the new high frequency oscillator here described are the operation of lamps and motors by "radio power transmission" - and it even produces a "short-wave cocktail!" [1].

The quote above appeared as the header of a feature article titled "Cooking with Short Waves," in the international monthly magazine, *Short Wave Craft* in November 1933 (Fig. 1). It described a very popular exhibit set up and run by Westinghouse Corporation at the 1933/34 *Century of Progress* Exhibition (Chicago World's Fair). Westinghouse engineers were showcasing one of their recent technological breakthroughs – the powercaster[1] – a 1.2 m long, 15 cm diameter copper and glass encased double-ended vacuum tube operating at 10 kW and beaming into space hundreds of watts of continuous wave RF power at 60 MHz. Toast placed between its two near field electrodes was burnt in 6 seconds, and

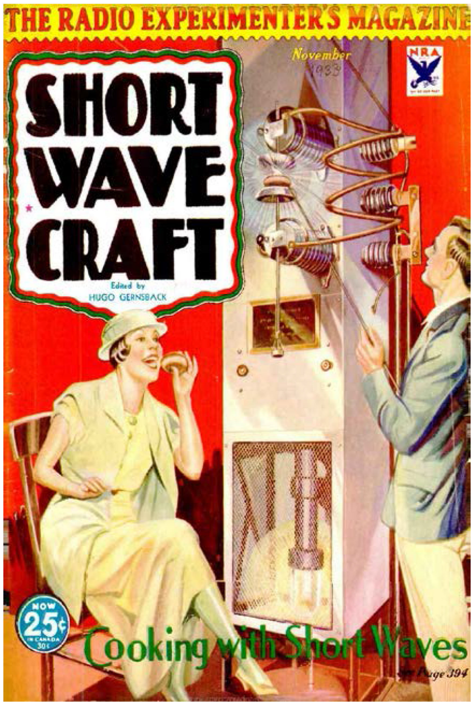

FIGURE 1. Cover from 1933 popular magazine: Short Wave Craft showing Westinghouse's powercaster – a 10 kW 60 MHz RF tube, with power beaming and cooking demonstrations – *including people!* – at the 1933/34 Chicago World's Fair [1]. Orphan image from https://worldradiohistory.com, ©Fair use.

[1]Most of the work on this, and other much higher frequency tubes was done by a Westinghouse team led by I. E. Mouromsteff between 1929 and 1934.

meat and potatoes cooked through in a few minutes. A 2.4 m diameter antenna radiated the power into free space where, amongst other demonstrations, such as igniting incandescent bulbs and driving 200 W electric motors, it was used on visitor volunteers to create "*a radio cocktail* " in which a person exposed to the RF energy would feel "*an exhilaration*," whereas "*Over-exposure to the powerful field brings on a depressed feeling or 'hangover*."' [1], page 394. In fairness to the safety considerations of the times, it was also noted that, "*Experiments to determine its practical value (i.e., in the medical community) are now being conducted in a large Pittsburg (Pa.) hospital*."

Needless to say, the concept of heating using invisible shortwave, and eventually microwave energy, was enthusiastically advertised at the time as: *"the only basic advance in the art of preparing food for human consumption since cavemen, thousands of years ago, first burned meat over a fire and heated vegetables in crude vessels of boiling water*." [1]. Although the powercaster was really not a precursor to the modern microwave oven, and heating food with RF power did not become popular until well after World War II, this early "show and tell" public demonstration of power beaming[2] and the many marvels of RF were a prescient foretelling of things to come when, during the 1940s, Britain's Sir John Randall[3] and Henry Albert Howard Boot [4], "*who, more than any others, were responsible for its invention*" [6] triggered the magnetron revolution!

II. EARLY MAGNETRONS

The invention, analysis and use of the first magnetron[4] device is attributed to Albert Hull of General Electric Research Labs, Schenectady, NY, USA [8]. Hull was experimenting with vacuum tube diodes and triodes using magnetic fields to control the electron flow. He introduced a magnetic field in parallel with the axis of two concentric cylinders (anode and cathode) under an applied voltage (and heater current) sufficient to generate thermionic electrons and was able to induce spiraling electron paths that could be controlled by the voltage and magnetic field [8]. When the field and voltage were adjusted so that the spiraling electrons curved back on themselves, and did not reach the anode, no current flowed and the device could be turned off (diode operation). Near the critical field (and voltage) when the electrons just reach the anode (known as the Hull cut-off) triode operation (oscillation and amplification) can be maintained. Hull also suggested that the magnetron could be used as a radio frequency transmitter if the electrons could be forced into circular orbital paths (cyclotron resonance) [7], page 723, but this was not his major vision for magnetron applications. Generating and radiating significant shortwave energy from magnetrons was demonstrated a few years later by fellow GE researcher Frank Elder [9], and with significant application by Hidetsugu Yagi in his famous 1928 PROCEEDINGS OF THE IRE paper [10].

Much more stable resonant modes than the simple cyclotron motion of electrons between a single anode and cathode were developed as interest in stable power and higher frequency operation took hold. One early innovation that used a split-anode to bounce the electrons back and forth, but in a much higher magnetic field than is required for the cyclotron mode, resulted in a magnetron whose performance was mostly dependent on the resonant circuit and not just the field values – deemed the negative resistance magnetron. This type of operation was investigated and successfully demonstrated by Kilgore at 3.3 GHz for Westinghouse [3] and later at 500 MHz (100 W) for RCA Radiotron, Harrison, NJ [11], but neither device ever found a commercial market. A third operating mode – a traveling wave magnetron - also using a split-anode and multiple resonators, was developed by Klaas Posthumus at Philips Labs in the Netherlands in the early 1930s [12]. These variations helped pave the way for the Boot and Randall cavity magnetron that truly revolutionized the microwave power field.

During World War II, it was well recognized that effective long range microwave radar could provide significant advantage and ultimately turn the tide of victory to the first successful deployers of such a system [13]. Development focused on wavelengths shorter than 10 cm (3 GHz) to provide ample beam confinement with reasonable sized antennas as well as low loss atmospheric propagation. Power levels at the kW level were desired for long range, and the magnetron (then operating mostly in the MHz region) looked like it might provide both high power and high frequency operation if its existing stability, mode hopping tendencies, and power dissipation issues could be resolved. In the fall of 1939, a group at Birmingham University, U.K. led by Sir Marcus Oliphant[5]

[2]Note that Westinghouse had an active high power magnetron program in the late 1920s and early 1930s, led by Mouromsteff, and with noted tube engineer G. Ross Kilgore, who developed "magnetostatic oscillators" [2] with more than 100W at 500 MHz, 1W at 3.3 GHz and measurable power at 30 GHz [3]. These tubes were also demonstrated at the Century of Progress Exhibition, but as shortwave transmitters, not heating devices.

[3]Sir John Randall was trained as a biophysicist and chemist and did a lot of research on X-Ray diffraction (he studied under Bragg). He is perhaps most famous for his contributions to biology, as he led the DNA structures team at King's College, London that included Maurice Wilkins who shared the 1962 Nobel Prize in Medicine with James Watson and Francis Crick at Cavendish Laboratory, Cambridge. He was Knighted in 1962 and passed away in 1984. Wilkins wrote the extensive 45 page obituary and memoir chronicling Randall's many contributions to multiple fields of science and engineering [5].

[4]Hull implies in a very early paper delivered at an annual meeting of the A.I.E.E. in May 1921 [7], page 715, that the name was popularized by audion tube inventor, Lee DeForest, who referred to "magnetron" as a "Greeko-Schenectady name." The "tron" comes from kenotron (literally an empty tool) which was a general term that came into use around 1904 for vacuum devices. The prefix comes from the control of the device via a magnet, so magnetron would literally mean a magnet tool.

[5]Oliphant is best known for his work on atomic weapons and nuclear energy, including early fusion generators. He left Cavendish labs in 1937 to head the physics team at Birmingham that included Randall and Boot. Born in Adelaide, South Australia, he returned there after WWII to continue a remarkably successful career which included the first director of research at Australia National University, founding the Australian Academy of Science and Governor of South Australia. Oliphant was knighted in 1959 and passed away in Canberra in 2000 [14].

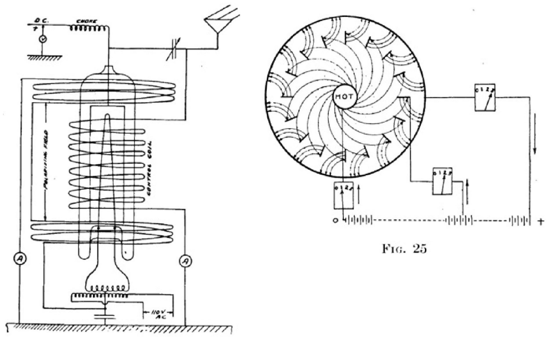

FIGURE 2. Left: Hull magnetron configured as an RF generator. The inner conical wire is the cathode and the smaller helix around it is the cylindrical anode. The magnetic field (vertical) is established by the outer solenoid (larger diameter coil). An oscillating field generates oscillating currents that radiate through the antenna (top right). Right: Axial view of a Hull amplifier concept, where electrons hit a grid and sputter off more electrons. From [7]. ©IEEE, w/perm.

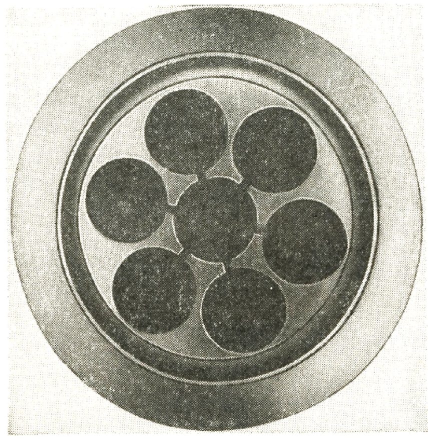

FIGURE 3. Boot & Randall 10-cm cavity magnetron – cross section. From [6] page 8. ©McGraw-Hill, Public Domain.

began working on shortwave magnetrons as well as the recently demonstrated Varian klystron [15] to be used as high-power microwave sources in the radar development effort. The team was aware of the cavity designs developed by Hansen [16], and Hansen and Richtmyer [17] at Stanford University, USA for use on klystrons, but these were not suited for the cylindrical geometry of the magnetron, which Birmingham's John Randall was tasked with trying to improve [18]. Randall and Boot's epiphany was to employ resonators weakly coupled to the electron stream to decouple the field parameters from the generation of output power, similar to the concept employed in the negative resistance magnetron. Their resonator was derived from a 2D loop wire concept first employed by Heinrich Hertz. The 3D-solid equivalent was a cylinder with a slotted wall. They arrayed six of these cylindrical resonators around the anode and coupled them through a ¼ wavelength deep slot, hoping that their limited analysis of the structure would allow them to them to hit the correct resonant frequency with their approximate calculation of the cavity diameter and length. The whole structure was formed in copper to enable rapid heat dissipation and high power operation[6].

The first test of an assembled magnetron came in the third week of February 1940 – only a few months after they had started work on the design. The tube generated 400 W CW at 9.8 cm (3.06 GHz) [18]. Within short order, the tubes were tested in pulsed mode (0.1% duty cycle) to reach much higher power levels (>50 kW). Oxide coated cathodes were added to achieve current densities of 5–20 amp/cm^2 and the tubes recorded initial overall efficiencies near 10% - kW output at 3 GHz! Alternate aluminum cathodes were even shown to be able to operate "cold" (without a heater) – the first demonstration of this effect [18]. A major problem with mode hopping and subsequent output frequency switching was solved by University of Birmingham's James Sayers, who joined together alternate resonators with copper straps (known as "strapping") and produced a π mode circuit (adjacent resonator phases 180 degrees apart) which suppressed unwanted modes and greatly increased the frequency stability [18]. General Electric Company, Wembley, UK, began making the first commercial sealed magnetron tubes in the spring of 1940. An early test of a complete radar transmit/receive system took place in May 1940 at the Telecommunications Research Lab in Swanage, England, where a submarine periscope was detected at 11 km distance [19].

By September 1940, the new British "cavity magnetron" had made its way across the Atlantic, and within a month was duplicated by Bell Labs and distributed to the newly formed MIT Radiation Lab for further development [19]. It would be mass produced in the US mainly by Raytheon. Other groups also developed similar magnetron designs based on resonant cavities [20], the most notable being Alekseev and Malairov in Russia [21] who published a 4-cavity layout very similar to Boot and Randall's. By 1944, the Boot and Randall derived cavity magnetron had been scaled successfully to 3 cm (10 GHz) and the efficiencies and output power levels had been significantly improved with power levels at 10 cm reaching 2 MW and efficiencies near 50% [19]. *The magnetron revolution had begun!* A photo of the Randall-Boot cavity magnetron cross section showing the six cylindrical resonators arrayed around the anode is shown in Fig. 3. The fully sealed mass-produced GEC version had 8 cavities (Fig. 4). An excellent and clear overview of the design and operation of magnetrons with explanatory photos can be found in [22].

III. MICROWAVE HEATING

Before sufficiently high power microwave sources such as the magnetron were available, the use of radio frequencies for heating of various substances was very limited. The powercaster described earlier did not find any significant commercial use, and during the Great Depression, Westinghouse

[6]Note that the resonant cavity magnetron (unlike the Hull cyclotron concept in Figure 2) is an oscillator and not an amplifier, so very high input power and power handling capacity was necessary to achieve the desired kW output.

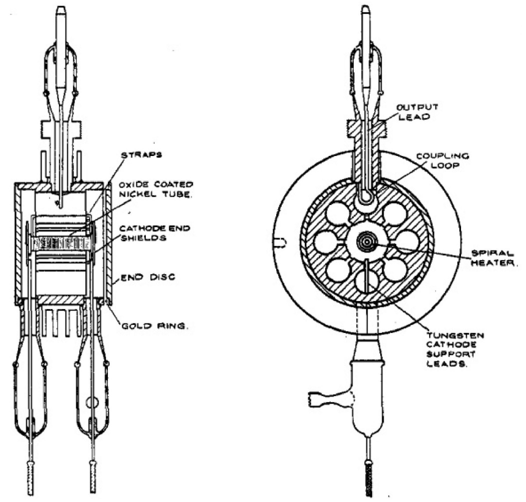

Fig. 4. Sealed off pulsed magnetron.

FIGURE 4. General Electric Company, Wembley sealed production magnetron. From [19] page 726. ©IEEE, with permission.

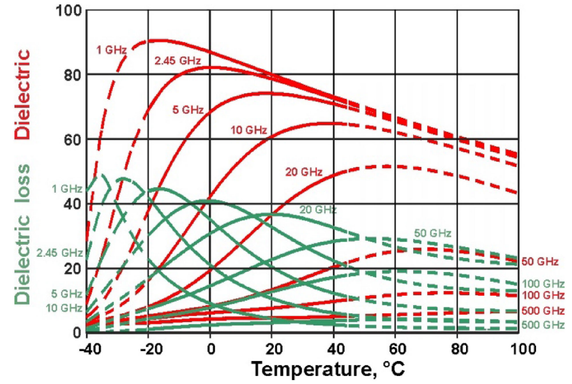

FIGURE 5. Plots of real (RED) and imaginary (GREEN) dielectric permittivity for pure water as a function both of temperature (x-axis) and of frequency (assorted curves). Note that at freezing (0 °C) for example, the loss will be very high even at 10 GHz ($\varepsilon_I = \varepsilon_r = 40$, tan$\delta = 1$) and the field penetration very small (1/e = 0.165 cm). At 1 GHz ($\varepsilon_I = 10$, $\varepsilon_r = 88$, tan$\delta = 0.1$) the loss is still high, but the penetration is 50 times deeper (1/e = 9 cm). At 2.45 GHz: $\varepsilon_I = 20$, $\varepsilon_r = 82$, tan$\delta = 0.24$ and 1/e = 1.8 cm. At 30 GHz: $\varepsilon_I \approx 21$, $\varepsilon_r \approx 13$, tan$\delta = 1.6$ and 1/e is only 0.06 cm! Chart from M.F. Chaplin, LSBU, London, with permission [29]. Data plotted on chart using measurements from [30].

and other radio tube manufacturers cut back on their research and design activities while they searched for applications of their new high power RF technologies [3]. There was already a pretty clear understanding and significant literature on the impact of microwaves (ultra-shortwaves) on exciting polarizable dielectrics [23] and there were at least some potential medical applications (mostly diathermy) being explored both in the US [24], [25] as well as in Germany [26]. In 1933, the commercially available General Electric GEJ-239 magnetron oscillator could produce RF frequencies up to 400 MHz at 60 W CW with an output coupler that could be tied to a resonant circuit in which samples could be placed [24].

RF heating is based on the complex permittivity [27]: $\hat{\varepsilon} = \varepsilon_0\ (\varepsilon_r + j\varepsilon_i\ )$, where ε_0 is the free space permittivity in F/m, ε_r is the real part of the dielectric constant, and $\varepsilon_i\ = \sigma/\omega\varepsilon_0$ is the imaginary part, with σ the conductivity in S/m and $\omega = 2\pi f$ the applied frequency. The RF absorption comes from σ via excitation of free carriers or electric polarizability (dipole absorption) and is conveniently expressed by the ratio of $\varepsilon_i\ /\varepsilon_r \equiv tan\ \delta = \sigma/(\omega\varepsilon_0\varepsilon_r)$. The power dissipated, or the heating of the material at a given internal location is then given by $P_i(x, y, z) = \sigma|E_i(x, y, z)|^2 = \omega\varepsilon_0\varepsilon_r tan\ \delta|E_i|^2$, where E_i is the field inside [27]. For a sample that is small compared to the wavelength there is very inefficient power absorption. When the sample is on the order of the wavelength there can be significant or even resonant absorption, and when the sample is large compared to the wavelength there will be an exponential penetration of the power $P_{inside} = P_{surface}e^{-\alpha x}$, where x is the depth in cm, and α is the absorption coefficient in cm^{-1}. The field drops to $1/e$ of its surface value at a depth D, [27]: $D = (0.225\lambda_0)/\{\sqrt{\varepsilon_r}\sqrt{\sqrt{(1 + tan^2\delta)} - 1}\ \}$, where λ_0 is the wavelength in free space. When $tan\ \delta <<1$, $D \approx 0.318\lambda_0/(\sqrt{\varepsilon_r}\tan\delta)$.

Significant heating of an object is therefore dependent not only on the conductivity (which determines the penetration of the fields), but also very directly on the wavelength scale. If we add in the real part of the permittivity and take into consideration the microwave beam properties with reflection and refraction, sample geometry and uniformity, and thermal diffusion, accurate analytics for any particular heating problem can be quite challenging [28]. However, it is apparent from the power dissipation equation above, that for a given internal field strength, the heating will go up with frequency, and that for the scale of a typical dinner plate food item and the range of tan δ for water at different frequencies and temperatures (Fig. 5), effective penetration and heating favors wavelengths in the cm range (1–30 GHz). Higher frequencies cannot penetrate sufficiently, and much lower frequencies require very high fields, and can have poor coupling unless making use of direct contact or inductive heating. In the years following WWII, emphasis was thus placed on frequencies in the low GHz region, where both the historic development of microwave power sources and serendipity converged.

In quantifying the frequency range and effectiveness of dielectric heating using microwaves, there was a great need for characterizing materials. Much of this work was spurred by the burgeoning communications field in the years before WWII and then by the race for developing and deploying radar systems. The most comprehensive compilation of microwave properties of materials – *one which this author still uses today* – came out of Arthur von Hippel's,[7] Laboratory for Insulation Research, at MIT [32].

Although there were a few attempts after WWII to harness the power available from magnetrons of the time, including

[7]Arthur R. von Hippel left Germany with his family in 1933 after a distinguished early career that included links to Hilbert, Courant, Pohl, Debye, Born, Wien, and Bohr. He eventually settled in Massachusetts, founding the Laboratory for Insulation research at MIT in 1939 where he spent 50 years working on the characteristics and properties of dielectrics. He passed away at age 105 in 2003 [31].

using newly developed microwave delivery systems (flexible waveguide and horn antennas) at around 1-3 GHz [33], it was not at all clear (*despite the claims at the 1933 Century of Progress Exhibition*) that the problems of uneven heating, hot spots, and thermal runaway (due to dramatic changes in absorption as the temperature increased non-uniformly in a sample [34]), would give way to any useful commercial applications in the food industry [35]. The lower frequency RF heating (MHz range) applications were already well enough established to have FCC band allocations for industrial, scientific, and medical (ISM) use at 13.66, 27.32 and 40.98 MHz by 1945 [36]. Additional ISM bands centered at 915 MHz[8] (33 cm), 2.45 GHz[9] (12.2 cm) and 5.85 GHz[10] (5.1 cm) were established in 1947 specifically for cooking[11] (and some medical and industrial heating applications that utilized high powers in a localized environment) after petitions from Raytheon and GE [27]. Local power levels were unrestricted, but out of band interference was tightly regulated.

The person most notably credited with the invention of an actual product for the commercial heating of food via microwaves [27] is Raytheon's Percy Spencer whose patent was filed in October 1945 [39], and describes a pair of magnetrons fed into a waveguide and illuminating wavelength scale food items passing by on a conveyer belt. He appropriately references the 10 cm band (3 GHz) as being the most appropriate for resonant heating of similar sized food and compares the energy required for microwave heating, versus conventional heating, when he states [39], "*With the system described, I have found that an egg may be rendered hardboiled with the expenditure of 2 kw.-sec. This compares with an expenditure of 36 kw.-sec. to conventionally cook the same. I have also found that with my system a potato requires the expenditure of about 240 kw.-sec., which compares with 72000 kw.-sec. necessary to bake the same in an electric oven …I have observed similar results with other foodstuffs. In each instance, where the wavelength of the energy is of the order of the average dimension of the foodstuff to be cooked, the process is very efficient, requiring the expenditure of a minimum amount of energy for a minimum amount of time.*" Percy followed up this patent with another one [40] that describes popping corn directly on the cob through an RF transparent bag that is inserted into a "microwave oven" operating around 1 GHz. He even talks about pre-salting the corn cob before popping!

Although Percy was not the first to cook with microwaves, he was an active proponent of its merits, and his team at Raytheon dramatically increased the magnetron output power and came up with an inexpensive way of fabricating the complex anode structure by welding together thin punched out disks [41]. He credits serendipity for his passion as he related to a writer/friend in an article about his life in a popular US magazine in 1958 [42], "*One day a dozen years ago he (Percy) was visiting a lab where magnetrons, the power tubes of radar sets, were being tested. Suddenly, he felt a peanut bar start to cook in his pocket. Other scientists had noticed this phenomenon, but Spencer itched to know more about it. He sent a boy out for a package of popcorn. When he held it near a magnetron, popcorn exploded all over the lab. Next morning he brought in a kettle, cut a hole in the side and put an uncooked egg (in its shell) into the pot. Then he moved a magnetron against the hole and turned on the juice. A skeptical engineer peeked over the top of the pot just in time to catch a faceful of cooked egg. The reason? The yolk cooked faster than the outside, causing the egg to burst.*"

Spencer put a team together at Raytheon in the late 1940s to start exploiting the new 2.45 GHz ISM band for commercial food preparation. The magnetron offered the possibility of very high power at high efficiency, but it needed to be operated CW, and most of the tubes developed for radar applications during the war effort were pulsed. Apparently, the US Naval Research Lab also had an interest in CW tubes for possible RF jamming applications [27] and contributed to the development effort. Raytheon (who had produced about 80% of the US magnetrons during WWII) had developed a CW tube in the mid-1940s – the QK44 – which produced up to 100 W at 3 GHz [41], but efficient food preparation needed ten times this power. In response to this need, Raytheon developed the QK65 magnetron which included an axially mounted vacuum-sealed radiating antenna feeding directly into an output waveguide and could deliver up to 1500 W CW at 2.45 GHz [41]. Around the same time (1947), GE's R.B. Nelson published the design and specs on a new 5 kW, 60% efficient, CW, water cooled magnetron operating at 1050 MHz [43]. This 1 GHz unit was used in the first successful frozen food thawing experiments at GE [34] where thermal runaway was found to be a big problem at 3 GHz. There was a considerable amount of "black art" that went into these new high power CW tube designs, especially in forming and holding the correct oscillation mode, responding to line fluctuations and load changes, and efficient coupling of the output power. It is noteworthy that in Nelson's references section he states, [43] "*So much of the literature on modern magnetron developments is unpublished that no attempt has been made at references to original sources.*"

IV. THE EARLY MICROWAVE OVEN

After the establishment of the ISM bands at 915 and 2450 MHz, it did not take long for Raytheon to act on its desire to broach the food preparation market with a commercial appliance. Management held an employee naming contest and came out with the "Radarange™" (model 1132) which boasted a 1.6 kW output power from a water-cooled magnetron with a permanent magnet. It operated on 220 V,

[8]"In Region 2 *(North and South America)*, the frequency 915 Mc/s is designated for industrial, scientific and medical purposes. Emissions must be confined within the limits of ±25 Me/s of that frequency …" Ch. III, Art. 5, Note 212 [37].

[9]Ch. III, Art. 5, Note 220 [37].

[10]Ch. III, Art. 5, Note 228 REF [37].

[11]"A recent important development of industrial apparatus is an electronic cooker which not only cooks foods evenly from the inside out,but completes the cooking process in a matter of seconds as compared to minutes with older methods." [38].

FIGURE 6. Raytheon model 1132, the first Radarange™. Reproduced from [27] Fig.3. ©IEEE w/permission.

was almost 2 meters high, and was not yet quite ready to take the cooking world by storm (Fig. 6) [27]. The magnetrons for these early food heating applications were still very similar in basic design, at least for the anode structure, to the cylindrical cavity magnetron developed by Randall and Boot and mass produced during the war years. Much of the refinements were in the cathodes, packaging, and output power structures. Fancier cavity designs that became popular, like the rising sun configuration this author was first introduced to at the Columbia Radiation lab, were confined to higher frequencies and higher powers [41]. A significant innovation in the anode structure had taken place however, with the much more bulky cylindrical cavity structure of the earliest tubes giving way to denser "vane" shaped cavities (circular segments with angled walls) composed of 10 or even 20 separate resonators (see Fig. 4 in [22]). This signficantly more compact resonator geometry was originally patented by Mouromsteff at Westinghouse in 1942 [44] and had also been proposed by Kilgore before WWII but never patented [3].

The early introduction, by Spencer, of a smallish (oven-scale) fully confined, all-metal food heating chamber [39] was a major design innovation for commercial deployment in the food preparation industry. The cathode (typically thorium dioxide impregnated metal mesh) was still a major problem because, although it was a primary emitter, it still had to pre-heat for more than a minute before the tube oscillations could be engaged. Charles Litton (founder of Litton Industries) had developed a thoriated-tungsten filament-style (helix) cathode that was a primary emitter of electrons and could be operated at very modest temperatures [45]. This became the L3858, 2.5 kW magnetron tube which Litton Industries used in the early 1960s. Raytheon began with a water-cooled tube, the QK707 in its first ovens (licensed to Tappan Appliances, Ohio). This tube employed a large solenoid magnet, had a 20 vane-style anode, weighed 12 kg (without the power supply) and produced 700 W. In a joint venture with New Japan Radio starting in 1961, the oven tube was greatly refined and miniaturized, starting with the Raytheon QKH1381 and then improved further by New Japan Radio into a 700 W, 12 vane, quick-turn on, air cooled, thoriated filament style cathode-type magnetron [46] (Fig. 7). This design became an industry standard, and part of Japan's Sharp Corporation's very successful entry into the 2.45 GHz radarange market in the mid-1960s. In the 915 MHz market, GE was still the dominant player, although the future was trending towards the 2.45 GHz band due to smaller size and much lower cost. The magnetrons in this frequency range (915 MHz) however, had unprecedented efficiency with the record held by J.R.G. Twisleton of AEI Ltd., U.K. who reported 80% at 20-30 kW [47].

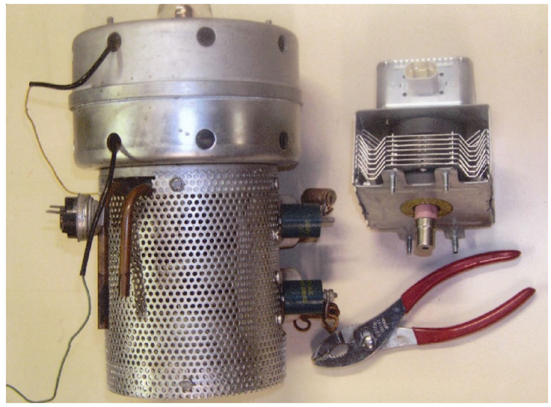

FIGURE 7. Photo of older Raytheon water cooled QK707 magnetron and redesigned and miniaturized version of the QKH1381 air cooled magnetron tube for 2450 MHz. From [46] page 47. ©IEEE, with permission.

In addition to the fast-turn on cathode, other major refinements included permanent magnets, ceramic vacuum jackets to replace the lower heat capacity glass tubes (which could also melt under some circumstances), lower voltage operation, single cavity-coupled output power arrangements, and methods for scrambling the RF mode pattern in the metal chambers that held the food to try and mitigate hot spots and thermal runaway. Metal mode "stirrers" (rotating vanes) were introduced early on in the cooking chamber [48], and a novel "choke" flange around the door (quarter wave long overlapping plates) was introduced to avoid the need for a firm metal-to-metal seal preventing RF leakage [49], [50]. Japan's Sharp Corporation also added a spinning carousel under the food plate to help distribute the uneven RF energy which

FIGURE 8. Portion of an early advertisement for the Amana RR-1, circa 1967. List price was approximately $US 500. © Whirlpool (Amana), with permission.

was dependent on the load geometry, position, and dielectric properties.

Magnetron design continued to move forward with perhaps the most significant advance being the invention of an amplifying tube in the mid-1950s by W.C. Brown. It was originally termed a "platinotron" [51] but was later more generally known as a cross-field amplifier (CFA) [41]. Brown introduced a slow wave structure into the magnetron wherein spiraling electrons made their way around a coaxial cylindrical resonator path where they could bunch and gain power. This innovation resulted in a series of super-high-power tube developments that took CW magnetrons into the hundreds of kW range with high efficiency and significant bandwidth [52]. This innovative tube design opened up many high power industrial heating functions (including potato chip drying!) as well as military radar, satellite communications, and power beaming applications. Although klystrons and traveling wave tubes generally had higher power capabilities, the cross field amplifiers had extremely high efficiency and thus were very compact. Osepchuk [27] describes in detail the boom in commercial heating applications enabled by high power RF tubes during the 1960s.

V. THE COOKER MAGNETRON BOOM

According to Osepchuk [27], the commercial success of the radarange concept is largely due to the efforts of the Amana Corporation which was acquired by Raytheon in 1965. The key players: Raytheon's Percy Spencer (Senior Vice President) and Tom Phillips (President), and Amana's George Foerstner (President) and Dick Foerstner (Vice President and Chief Engineer), introduced the Amana Radarange™ RR-1 in 1967. Despite the passing of more than 50 years, this microwave oven looks much like the ovens of today (Fig. 8). The RR-1 had a New Japan Radio company magnetron with ceramic casings, a permanent ferrite magnet, rapid fire cathode, operated off 115V (earlier units utilized 230 V), and cost less than $500.

The number of production cooker magnetrons skyrocketed from less than 10,000/year in 1965 to over 1,000,000/year by 1970 as more manufacturers began entering the market [27]. By the mid-1980s, the demand had climbed to five million units a year, and today over seventy million microwave ovens per year are being sold [53]! Magnetron prices are now in the $10/unit range and ovens average around $100 each! Since the RR-1, there have been many refinements including further size reductions, rectified AC rather than DC operation, slightly better efficiencies and cold start-up processes, integration of sophisticated microprocessor controls and power level variation, transient suppression, and other consumer serving features. Replacement sources for the 2.45 GHz microwave cooker magnetron have been proposed since the 1970s. but have never taken hold. These included higher efficiency 915 MHz systems, which have all but disappeared, a radically different type of tube layout – the Kumpfer tube, low voltage and voltage tunable magnetrons, multi-beam klystrons and most recently solid-state power amps [54]. So far none of these alternatives has been able to usurp the original strapped-vane helical cathode designs derived from Boot and Randall's 1940 cavity magnetron revelations.

We cannot end this short historical look-back without mentioning how the "metamaterials" portion of the title fits in. On a lecture trip way back in December 2006, I had the great privilege of visiting ETH Zurich and to meet with noted electromagnetics field theorist and high frequency microwave electronics professor, Rüdiger Vahldieck[12] and his group. In one of my chats with faculty members I was introduced to a university project funded by BSH Germany (a major appliance designer and manufacturer spun off from Bosch and Siemens in the 1960s). The company wanted to find a cheaper and more reliable microwave door seal than the fairly expensive serrated metal choke structure currently in widespread use. ETH's Martin Gimersky told me about an idea they were exploring to replace the metal choke seal with a fully manufacturing compatible metamaterials filter structure. At the time I thought this might be the first commercially viable application for the burgeoning new field! Four years later I was very pleased to see the thesis from ETH of Matthew Mishrikey [55] (now at TE Connectivity, Boston, MA, USA) wherein he described, amongst other projects, his successful work on a metamaterials 2.45 GHz bandstop filter that can be directly integrated into the door of a microwave oven [56] with performance equal to that of modern choke filter structures (Fig. 9)! On that note, it is time to conclude this brief historical diversion.

VI. REVIEWER ADDITIONS

One of the reviewers kindly provided some additional historic notes on magnetron developments outside the U.K. and the US that are worth mentioning. I have filled in some details and added some references for these notes, which I loosely summarize below.

[12]Rüdiger Vahldieck was a prolific and tireless microwave educator and active participant in so many professional organizations and conferences it is hard to count them all up. At the peak of his career he tragically passed away from brain cancer in 2011.

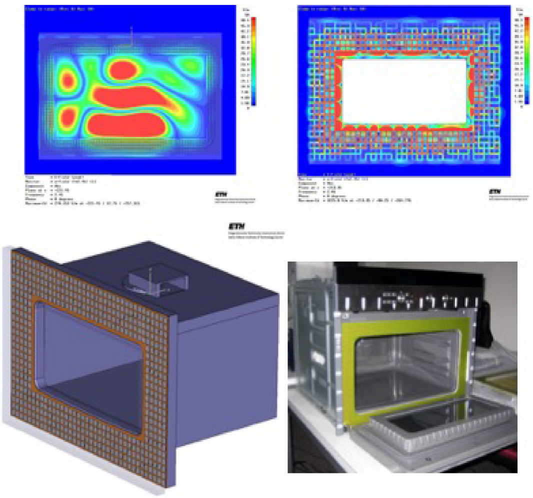

FIGURE 9. A metamaterials based microwave bandstop filter for 2.45 GHz designed and analyzed by ETH graduate student Matthew Mishrikey. Top left: EM analysis showing field confinement inside the oven (door made transparent to see the fields inside). Top right: EM analysis of the fields propagating laterally out through the metamaterial filter around the door window. Lower left: Metamaterial structure from the oven face. Lower right: Actual door model during RF leakage tests. From [55] (Figs. 5.19, 5.20, 5.21 and 5.29) with permission.

Heinrich Greinacher, a Swiss physicist at the Physik Institut der Universitat, Zurich derived equations for electron motion in a coil-generated magnetic field and diagrammed an electron tube device very similar to that of the Hull magnetron in 1912 [57]. Although Greinacher did not get his solenoid encased diode tube structure to oscillate, his designs and formulation were accurate (see [57] Fig. 1).

Following Hull's developments, Erich Habann at University of Jena, Germany produced a dissertation in 1924 on the then new magnetron tube and predicted the conditions for negative resistance that allowed oscillations to overcome circuit losses. He demonstrated 100 MHz output and was the first to employ two cathodes [58].

At the same time, and independently, August Zácek at Charles University, Prague, Czechoslovakia developed a magnetron with an output frequency close to 1 GHz [59].

Shortly after Yagi's breakthroughs on generating and radiating cm waves [10], Kinjiro Okabe at Tohoku University, Sendai, Japan, published results on a slotted anode type magnetron at wavelengths from 70 to 5.6 cm (5.36 GHz).

Finally, it should be pointed out that in Nov. 1936, German engineer Hans Erich Hollmann filed a US patent (granted in July 1938) on a magnetron design with 4 split-wall cylindrical waxing moon-shaped cavities surrounding the anode core [61]. Hollmann's device is most similar to the Alekseev and Malairov design [21] and was well in advance of the independently developed Randall-Boot innovation of the 1940's.

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Two comprehensive reviews on the historical development of microwave heating and the commercialization of the microwave oven were prepared by Raytheon engineer and microwave pioneer, John M. Osepchuk: (1) a 25 page article celebrating the IEEE Centennial in 1984 with 185 references and many historic photos [27] with a follow-up article in 2009 [54] and, (2) a more recent review in 2010 of cooker magnetrons [46]. A good portion of the information presented in this paper was derived from John's excellent narratives. The author would also like to thank Professor Martin Chaplin of London Southbank University, U.K. for Fig. 5, Professor Rick Temkin of MIT and Dr. Ninoslav Majurec of JPL for reproductions of the image in Fig. 3, Alex Siegel for reference [28], and Matthew Mishrikey for approving Fig. 9 which was assembled from several figures in his thesis.

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