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Arthur W. Guy (S'54–M'57–SM'74–F'77) was born in Helena, MT, on December 10, 1928. He received the B.S. degree in 1955, the M.S. degree in 1957, and the Ph.D. degree in 1966, all in electrical engineering, from the University of Washington, Seattle.

From 1947 to 1950 and from 1951 to 1952, he served in the U.S. Air Force as an Electronic's Technician. Between 1957 and 1964, he was a Research Engineer in the Antenna Research Group, Boeing Aerospace Company, Seattle. While there, his field included research on broad-band and microwave devices, surface-wave antennas, propagation through anisotropic dielectrics, and antennas buried in lossy media. Between 1964 and 1966, he was employed by the Department of Electrical Engineering, University of Washington, conducting research on VLF antennas buried in polar ice caps. At that time, he also served as Consultant to the Department of Rehabilitation Medicine, working on problems associated with the effect of electromagnetic fields on living tissue. In 1966, he joined the faculty of the Department of Rehabilitation Medicine. Presently, he is a Professor in the Center for Bioengineering, has a joint appointment as Professor in Rehabilitation Medicine and adjunct Professor in Electrical Engineering. Dr. Guy is involved in teaching and research in the area of biological effects and medical applications of electromagnetic energy.

He is a member of COMAR, ANSI C-95 Committee, and chairman of the 1970–1982 Subcommittee IV that developed the protection guides for human exposures to radio frequency fields in 1974 and 1982, NCRP, and chairman of Scientific Committee 53 responsible for biological effects and exposure criteria for radio frequency fields, Armed Forces National Research Council Committee on Vison Working Group 35, Commission A Radio Measurement Methods and URSI, ERMAC, and the EPA Scientific Advisory Board Subcommittee on Biological Effects of Radio frequency Fields. Dr. Guy also serves as a consultant to the NIEHS on the USSR-US Environmental Health Cooperative Program, and was a member of the NIH Diagnostic Radiology Study Section 1979–1983. Dr. Guy is a member of the editorial boards of the *Journal of Microwave Power* and IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, and is current president of the Bioelectromagnetics Society.

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A History of Microwave Heating Applications

JOHN M. OSEPCHUK

Abstract—**The development of microwave heating applications is reviewed. This field has followed the earlier application of lower RF frequencies to *induction* and *dielectric heating*. Serious activity began after World War II, directed towards a microwave oven for commercial and residential use. The broadening of interest to include scientific and industrial applications followed in the early sixties as new markets for microwave power sources were sought. The creation of the International Microwave Power Institute was one result. The marketing of a countertop microwave oven for consumers gave birth to the economically important oven business in the sixties. The growth of this field has been marked, perhaps slowed, by a series of sociotechnical events questioning the safety of microwave exposure near high-power microwave systems. Although some of this has receded, a problem of public education remains for those who will expand this field. The future development of this field will exploit a broader number of operating frequencies and will be ultimately limited by environmental regulations related to electromagnetic compatibility (or RFI), rather than safe exposure of biological tissue.**

Manuscript received February 14, 1984.

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I. INTRODUCTION AND SCOPE

NONCOMMUNICATION applications of microwave power include medical applications, such as diathermy or hyperthermia and microwave-power transmission. These areas are reviewed by A. W. Guy and W. C. Brown, respectively, in separate articles in this Special Issue of the TRANSACTIONS. The remainder of such power applications corresponds almost completely to that of *heating*, and this is reviewed here. Heating applications exist in consumer, commercial, scientific, and industrial areas. The outstanding application area is that of the consumer microwave oven and, therefore, this is given more attention herein, it being the only widespread consumer application of microwaves, in general.

It is not the intent, here, to review all noncommunication applications or all consumer applications. Instead, only heating applications are covered here, but there is some

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discussion of nonheating applications with adequate reference to literature reviews. There is also some reference to "nonthermal" interaction of microwaves with matter, but these have not led to any practical applications.

The definition of "microwaves" is somewhat arbitrary, as discussed later in more detail. Still, for purposes of practicality, the history of nonmicrowave heating applications, e.g., induction and dielectric heating or the general field of "electro heat," is not covered here. The term "microwave" refers here to the conventional definition, e.g., 300 MHz to 300 GHz, or as treated in more scientific definitions.

This history is that of *one* author and his limited number of sources and not *the* definitive history. Still, a serious attempt has been made to record all major developments and include references to the many other items of interest not treated in the historical discussions. In recognizing initial inventorship or authorship, an attempt is made to recognize parallel and independent lines of endeavor, but it is the historian's prerogative to single out those who have triggered the most practical or successful developments. Indeed, many inventors or authors may express similar concepts, but the one who reduces to practice or is closest to triggering practical application deserves special recognition and the normal course of events usually insures this.

A history is not only a relation or catalog of events and ideas, but is also an attempt to summarize the meaningful concepts and trends that unify the subject. An integrated science or design philosophy is one target in a historical study as well as any basis for technological forecasting. In this regard, we have been able to review previous forecasts in this field and analyze the reason for their varying success.

The use of electricity or electromagnetic energy for heating has not been considered a prime subject in the history or future of radio engineering. The 50th anniversary Special Issue [1] of the *Proceedings of the IRE* gives little or no attention to this subject, either when looking backward or forward. This present history suggests that microwave (or RF) heating applications will play a major role in the future of electromagnetic technology and will develop in parallel to the shifting of communications applications to nonradiating modes, e.g., fiber optics.

II. Basic Principles of Microwave Heating

In order to assess heating of materials exposed to electromagnetic fields, it is sufficient to specify the complex dielectric permittivity [2] of the material, viz.

$$\underset{\sim}{\epsilon} = \epsilon_0(\epsilon_r + j\epsilon_i) = \epsilon_0\left(\epsilon_r + j\frac{\sigma}{\omega\epsilon_0}\right) \tag{1}$$

where $\underset{\sim}{\epsilon}$ is the complex dielectric permittivity in F/m, $\epsilon_0 = 8.86 \times 10^{-12}$ F/m, the permittivity of free space, ϵ_r is the real part of the relative dielectric constant, ϵ_i is the imaginary part of the relative dielectric constant, and σ is the conductivity in S/m (mhos/m) which is equivalent to

$$\epsilon_i \cong \frac{\sigma}{\omega\epsilon_0}$$

where ω is the assumed radian frequency of the fields. The conductivity σ or ϵ_i represents [1] the loss mechanisms, whether they are of the dielectric polarization process or they relate to free carriers, i.e., they are all lumped together in one loss parameter for convenience. It is common to use an auxiliary term, called the loss tangent $\tan\delta$:

$$\tan\delta = \frac{\epsilon_i}{\epsilon_r} = \frac{\sigma}{\omega\epsilon_r\epsilon_0}. \tag{2}$$

One easily derives [3] the basic heating equation

$$P = \sigma|E_i|^2 = \omega\epsilon_r\epsilon_0 \tan\delta |E_i|^2 \tag{3}$$

where E_i is the internal electric field.

The general engineering task is to deduce the internal field distribution $E_i(r)$ and the associated power dissipation distribution $P(r)$, given a material of a certain size, shape, $\underset{\sim}{\epsilon}$ exposed to some type of applicator (antenna) of electromagnetic fields.

If the frequency is low or the object small, then quasi-static perturbation theory may apply where the components of electric fields normal to the surface of a material are related by

$$\left|\frac{E_i}{E_o}\right| = (\omega\epsilon_0/\sigma) \tag{4}$$

where E_i and E_o are internal and external fields, respectively. For bodies of even moderate conductivity (~ 1 S/m) at lower RF frequencies, we will have $E_i \ll E_o$.

For very high frequencies one applies quasi-optical techniques and at some moderately high frequencies there will be geometric resonance [4] determined by either dielectric mode or quasi-optical propagation theory. In this frequency range, there will be maximum total absorption [4] as well as penetration [3]. Furthermore, it is even possible that peak heating may be at an internal "hot spot" [5] rather than at the surface of the object. In this sense, the adage "cooking from the inside out" can apply. It is clear that this resonance range is the "microwave" range as denoted by the basic characteristic $L \sim \lambda$, i.e., the basic dimensions of the object of interest are of the order of the free-space wavelengths.

At microwave and quasi-optical frequencies, it is useful to define a penetration depth D at which fields are reduced by a factor of $1/e$. This is given by

$$D = \frac{0.225\lambda}{\sqrt{\epsilon_r}\sqrt{\sqrt{1+\tan^2\delta} - 1}} \tag{5}$$

or, for low-loss materials, $\tan\delta \ll 1$

$$D \cong \frac{0.318\lambda}{\sqrt{\epsilon_r}\tan\delta} \tag{6}$$

where λ is the free-space wavelength. One should not be deceived by (6) into thinking that low frequencies produce greater penetration and, therefore, greater heating. The penetration may be large, but if $\sigma \gg \omega\epsilon_0$, then, as discussed with regard to (4), the internal fields are small.

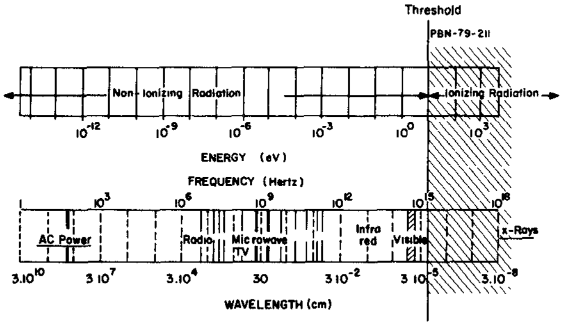


Fig. 1. The Electromagnetic Spectrum. The vertical bars denote the principally used frequencies for industrial heating, including 0.915 and 2.45 GHz.

In Fig. 1, we show the electromagnetic spectrum and denote principal frequencies of interest. Traditionally, most of the spectrum is used for communication purposes, and heating applications or "electro-heat" [6] are either at 50/60 Hz (power frequencies) by conduction or radiant heat in the infrared range. It is only in the last half-century that frequencies in the RF or microwave range have begun to be utilized in electro-heat applications. If RF frequencies are those for which $L \ll \lambda$ and microwaves those for which $L \sim \lambda$, then for most objects of macroscopic size (smaller than man) the RF range lies below 50 MHz and microwave frequencies above 300 MHz. In fact, the three principally used RF frequencies for RF heating are shown in Fig. 1, as well as the two principal microwave frequencies at 915 and 2450 MHz—the so-called ISM (industrial, scientific, and medical) frequencies.

We can see from (3) some reasons for interest in the microwave frequency range rather than the RF range for heating. For many dielectric materials [7], the loss tangent $\tan\delta$ varies little with frequency across the RF/microwave range. In this case, the heating rate (3) increases with frequency for a given internal field E_i. This suggests the desirability of going to higher microwave frequencies, whereas, at lower RF frequencies, the required internal field, and most likely the external field, may be so high as to approach breakdown. Furthermore, from (4), at low frequencies E_i may be $\ll E_o$. This may indicate that close or even contact coupling is required at low frequencies in order to prevent high external fields with associated corona or breakdown (arcing) problems.

In fact, these concepts are the real bases for the developing interest in microwave energy for industrial heating. We shall see, however, that many other factors besides technical factors have fashioned the actual history of microwave heating.

It should be mentioned that there always has been interest in so-called "nonthermal" [8] mechanisms of interaction with materials including living tissue. If such mechanisms could be verified, then some speculative applications could become more practical, e.g., weed killing, where microwave heating is impractical for economic reasons. To date, the only new information on "mechanisms" of interaction from the field of microwave bioeffect research is the phenomenon of microwave-acoustic conversion [9], [10], whereby short pulses of microwave energy create acoustic pulses. This is the explanation [11]–[13] of the microwave hearing effect but, so far, has not led to any useful practical application, perhaps because of very low conversion efficiency in common materials.

III. Early History

Before World War II, there is little evidence of work on RF heating, much less on microwave heating—since microwaves were still in their infancy. Still, the patent literature shows some loose reference to using microwave energy to affect materials for industrial purposes. Kassner, apparently a German refugee living in England and Switzerland in the late thirties, mentions such industrial application of microwaves in two [14]–[16] of his patents on spark-gap microwave generators. More specifically, another of his patents in 1937 discussed a "process for altering permanently as well as temporarily the energy content of dipolar substances by exposing them to rapidly oscillating electromagnetic fields." He thus was particularly interested in the "range of quasi-optical waves" ... "having wavelengths of the range of fractions of a millimeter ... upwards to about two meters." This clearly is the presently recognized regime of "microwaves."

Kassner believed, however, that he could achieve useful changes in materials without heating. He states that the object of the invention is not a rise in temperature but a change in the internal "energy content of dipolar substance," i.e., a change in the molecular state and hence its chemistry. In his belief in such a "non-thermal" effect, he no doubt was influenced by widespread belief [17] in the nonthermal "specific" effects from diathermy, then widely entertained by medical doctors, especially in Germany.

The only other evidence of prewar interest is a patent [18] by another German which describes the simple idea of matching some lossy dielectric load to a radiating dipole by an intermediate dielectric body around the dipole—similar to the idea of a "bolus" used in diathermy or hyperthermia [19] today.

The earliest practical roots of microwave heating logically follow work on RF heating, but even for the latter it is said [20] that "substantial industrial use did not start until after World War II." There is some reference in the "early history of industrial electronics," [21] however, to the fact that the principal high-power tube manufacturers were forced by the depression years to find new tube applications and some of these were in heating—mostly in induction heating and early diathermy work. There are some interesting historical anecdotes about observations on high-frequency (roughly 10–150 MHz) biological effects, e.g., the incidence of headaches and other sensations reported by workers testing high-power tubes, 5 to 15 kW. Evidently, there were many experiments in dielectric heating by various industries, but these were not well documented. The record [21] shows that "commercial industrial use of dielectric heating did not evolve until 1940 when a firm in Richmond, VA, developed the technique for the quick hardening of the bonding cement used in making *plywood*."

Before and during World War II, an important contribution to the ground work for RF/microwave heating was the effort to measure dielectric properties of various materials. This work was being done as a necessary task in development of the telephone and communication systems [22] as well as radar [23]. The latter work, begun under Von Hippel in the MIT Radiation Laboratory, was to continue to this day, especially under various workers in the "Laboratory for Insulation Research" under W. B. Westphal [24]. The reports issued by Westphal eventually have covered all application areas from food to oil-shale heating. It had become customary for experimenters in RF/microwave heating to send samples to MIT and Westphal for testing. As a result, a wealth of dielectric parameter data exist for most materials over a wide range of frequency and even temperature.

By the end of World War II, the engineering design principles [25] for RF heating were well established. It was recognized [25] that the greatest problem was that of the "coupling circuit" between tube source and load. Whereas in the pre-war environment, especially in work on diathermy and induction heating, little care was spent to control the power-source frequency and out-of-band noise, the need to control RF heating sources was recognized [26] by the FCC during and just after World War II. The first three ISM (industrial, scientific, and medical) frequency allocations were made by the FCC in 1945, viz., 13.66, 27.32, and 40.98—a trio of *harmonically related* frequencies. (Surely a reasonable procedure if RFI is to be minimized.) These were specified as "free radiation" frequencies, i.e., unlimited radiation was permitted at these frequencies from the ISM sources, but some severe limits on out-of-band radiation were imposed [26] in 1947 when the FCC adopted Part 18 of its rules. The basic limits—roughly 25 μV/m at 1000 ft (with a 5-MHz bandwidth)—have basically survived until today.

Even before the microwave oven concept was given serious attention, there was recognition [27] that RF heating should be useful in the processing of food, but it was stated [27] in 1949 that "the general usefulness of the high-frequency method in the industrial processing of such materials remains largely unproved." Analysis of dielectric data on foods up to 44 MHz and as a function of temperature produced a pessimistic outlook [27]. It was recognized that the pronounced increase in dielectric loss or conductivity as temperature increases through the freezing point of foods leads inevitably to severe problems of nonuniformity or runaway heating when attempting thawing of frozen foods. Also, it was recognized that rapid RF heating of foods seemed to require RF voltages approaching that of breakdown.

From (3), it appears that, for a given $\tan\delta$, an increase in frequency to microwave frequencies could alleviate the breakdown problem. The dominant view in the professional literature [27], however, was negative on this point. If, in fact, foods are characterized by constant conductivity σ rather than $\tan\delta$, then there is no reduction in the required E-field in (3) as frequency is raised. Thus, it was concluded [27] "as judged from these data, it appears unlikely that the use of microwave frequencies for heating high-conductivity biological materials will permit any marked reduction in the voltage required, as compared to voltages required at frequencies of the order of 10^6 to 10^8 cps."

TABLE I
EARLY MICROWAVE HEATING PATENTS

Year	No	Title	Assignee	Author
1937	2,089,966	Process for Altering the Energy Content of Dipolar Substances	None	Kassner
1939	2,161,292	Radiating Device	Lorenz	Hahnemann
1944	2,364,526	High Frequency Induction System	Radio Corp	Hansell
1946	2,398,606	Ultra High Frequency Power Measurement	Westinghouse	Wang
1946	2,400,777	Electrical Power Absorber	Westinghouse	Okress
1947	2,427,094	Super High-Frequency Wattmeter	Radio Corp	Evans
1948	2,442 114	Method of and Apparatus for Subjecting Materials to a Radio Frequency Field	Radio Corp	Brown
1949	2,461,372	Tube Forming Device	Stahl	Collins
	2,463,569	Apparatus for Treating Gaseous Media	Raytheon	Smith
	2,467,230	Ultra High Frequency Dielectric Heater	G E	Revercomb
	2,480,679	Prepared Food Article and Method of Preparing	Raytheon	Spencer
	2,480,682	Microwave Heating Apparatus Using Circularly Polarized Horn	Raytheon	Stiefel
	2,483,933	Ultra High Frequency Dielectric Heater	G E	Revercomb
1950	2,495,170	Microwave Heating of Dielectric Materials	Westinghouse	Kinn
	2,495,415	High Frequency Electromagnetic Cooking Apparatus	Raytheon	Marshall
	2,495,429	Method of Treating Foodstuffs	Raytheon	Spencer
	2,495,435	Method of Treating Foodstuffs	Raytheon	Welch

Thus, the scientific and professional view after World War II for microwave heating, particularly for the food applications, was unpromising. Still, individuals in industry had high hopes and proceeded into practical actions whatever the adequacy of the then theoretical understanding of the subject.

IV. EARLY HISTORY OF THE MICROWAVE OVEN

Despite the pessimistic view expressed in the professional literature, people in the microwave tube industry were examining microwave heating applications, possibly for the same reasons [21] the tube people looked at heating applications during the depression—namely, the bottom had dropped out of the microwave tube market when World War II ended. Then GE, Westinghouse, RCA, as well as Raytheon, all expressed some interest in heating applications, and this is reflected in some of the early patents on microwave heating shown in Table I (taken from the compilation of microwave-heating U.S. patents by Gerling [28]).

One can see that there was interest in industrial heating (e.g., of tires) as well as microwave diathermy, but the primary interest was that of the microwave oven and this arose primarily at Raytheon under Percy L. Spencer. This surge of interest is reflected in an increase of patents issued after the war in this field, as shown in Fig. 2. Of all the early patents shown in Table I, only those from Raytheon were directed toward a consumer or commercial microwave oven. The others were directed either to RF dielectric heating schemes or industrial heating applications. For example, Patent No. 2 495 170 (Kinn) described how to heat a tire by inserting into waveguide slot openings and No. 2 467 230 (Revercomb) described a conveyor system with a dielectric material passing through a waveguide.

U.S. Patent 2 495 415 issued to the then-President of Raytheon Co., Laurence K. Marshall, described a conveyor

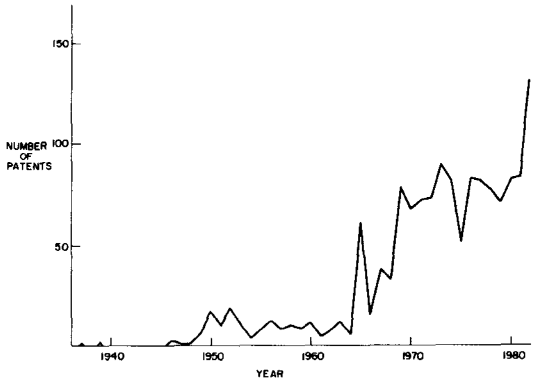


Fig. 2. The annual number of U.S. patents issued in the field of microwave heating in the last half-century.

system in which food stuff in special sealed containers would be cooked—thus providing an alternative to the conventional canning process. In a commissioned history [29] of Raytheon (pp. 180–184), the prominent role of Marshall is detailed as he is recorded as tinkering in the lab as well as prodding Spencer, Fritz, Gross, and others towards a product.

The first patent filed by Percy Spencer was 2 495 429, filed on October 8, 1945, and this describes two magnetrons in parallel feeding a waveguide. The microwave power is allowed to exit the waveguide and then impinge upon food on a conveyor belt passing by to be cooked. Although not using the term "microwave oven" and not describing explicitly a cavity, this patent for the first time suggests the 10-cm band as suitable and apparently expressed recognition of the microwave resonance in such heating. The patent reads: "... the wavelength of the energy becomes comparable to the average dimension of the food stuff to be cooked and as a result, the heat generated in the food stuff becomes intense, the energy becomes a minimum, and the entire process becomes efficient and commercially feasible." He then claimed that an egg can be hardboiled with microwave energy of only 2 kW-s versus 36 kW-s in conventional heating. Also, a potato required 245 kW-s versus 72 000 kW-s.

The basic patent, described above, issued after Spencer's Patent No. 2 480 679 which was filed after the war. In this patent, Spencer first describes a cooking cavity and uses the term microwave oven, but he illustrates the food to be cooked by the interesting example of making popcorn from corn on the cob.

Legends exist about a serendipidous discovery of microwave cooking by Percy Spencer. For example, in the aforementioned history, Percy Spencer is described as intrigued by the microwave heating power enough to send out for popcorn and then watch them pop in front of an open waveguide—or watch an egg explode when similarly exposed. The appreciation that this could be useful in a product is credited to Percy Spencer, especially in the eyes of Marshall. The legendary story in a celebrated Reader's Digest article [30], is that Percy accidentally leaned against an open waveguide and noticed a candy bar in his pocket melt.

Working under Percy Spencer were W. C. Brown, P. Derby, and N. Alstad, among others. They all remember the discovery as a gradual process involving chance and deliberate observations by many individuals, e.g., feelings of warmth near radiating tubes, experimenting with pop corn, etc. Still, Percy Spencer was in a position to trigger the company into exploiting the discovery and his participation was a key contribution.

It was mentioned already that, from a perusal of the patent literature, it appeared that companies other than Raytheon were more interested in industrial applications rather than the microwave oven. To some extent, the technical literature also reflected this situation. An article [31] in 1947 from Westinghouse emphasized the value of increasing processing speed by using high-power (many kilowatts) microwave tubes—either resnatron, split-anode, or cavity magnetrons. Applications were foreseen for rubber tires, textiles, wood products, and plastics. It was opined [34] that a solution to the unequal distribution of heating was necessary for a successful food-processing application. On the other hand, General Electric [32] in 1947 reported on a prototype oven operating at 915 MHz (or 1050 MHz initially) which was intended to thaw and heat precooked frozen meals in a restaurant. The GE authors [32] preferred 915 over 2450 MHz (or 3 GHz) because they claimed that thermal runaway was worse at 3 GHz and penetration into foods was too small. They devoted little attention to the theory of microwave heating, but they recognized [32] that "electronic heating of food produces the heat from within" and that, contrary to views [27] in the professional literature, arcing between food masses was much less of a problem at UHF than at RF frequencies below 40 MHz.

At about the same time, there appeared an English paper [33] which dealt extensively with microwave heating systems concentrating on schemes to insure uniform heating of sheets and other extended objects and on the load-matching problem. Still, little attention was paid to the role of the geometry and size of the object to be heated—other than Spencer's qualitative remarks cited earlier.

Because the FCC was establishing a frequency allocation procedure, Raytheon and GE both petitioned the FCC for a microwave-oven frequency—Raytheon favoring S-band or 2450, and GE L-Band/UHF or 915 MHz. It was argued by Raytheon that the higher frequency permitted better coupling to small loads like a frankfurter and the greater number of modes in a given cavity permitted better randomization (uniformity) of heating patterns. GE argued the advantages of penetration and less thermal runaway in defrosting. The net result was the allocation [34] of two frequencies by FCC, 915±25 MHz and 2450±50 MHz.

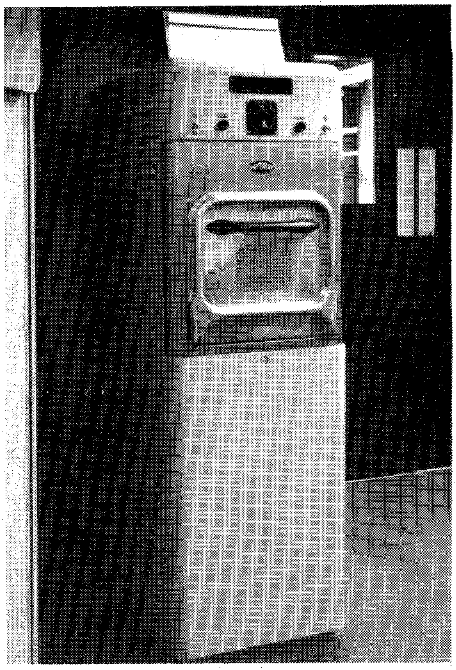
The problem of a tube development for the microwave oven was not trivial. Although a magnetron was deemed the suitable type because of its inherent efficiency, most powerful magnetrons developed during the war were pulsed tubes for radar. In 1943–1944, W. C. Brown and Palmer Derby of Raytheon developed design rules [35] for CW or pulsed magnetrons in order to insure mode stability at low anode current. With the help of the Naval Research Laboratory (Dr. John Hagen), which was interested in the potential jamming application of a CW magnetron, Raytheon developed a 100-W tube, the QK44, in 1944. This tube was later modified for use in diathermy equipment (RK5609) and was a step towards a 1-kW tube, the QK65, for commercial heating applications. Soon, it was generally recognized [36] that the magnetron with high efficiency > 60 percent was ideal for industrial heating applications.

Enthused Raytheon management sponsored [29] a contest for a name for the microwave oven and the Radarange™ was born. Marvin Bock, who later worked with Tom Phillips, today's CEO, built the first radarange, the Model 1132, which provided an output power of 1.6 kW from one water-cooled, permanent-magnet magnetron. This is shown in Fig. 3. Note that it was a free-standing white-enameled unit operating from 220 V.

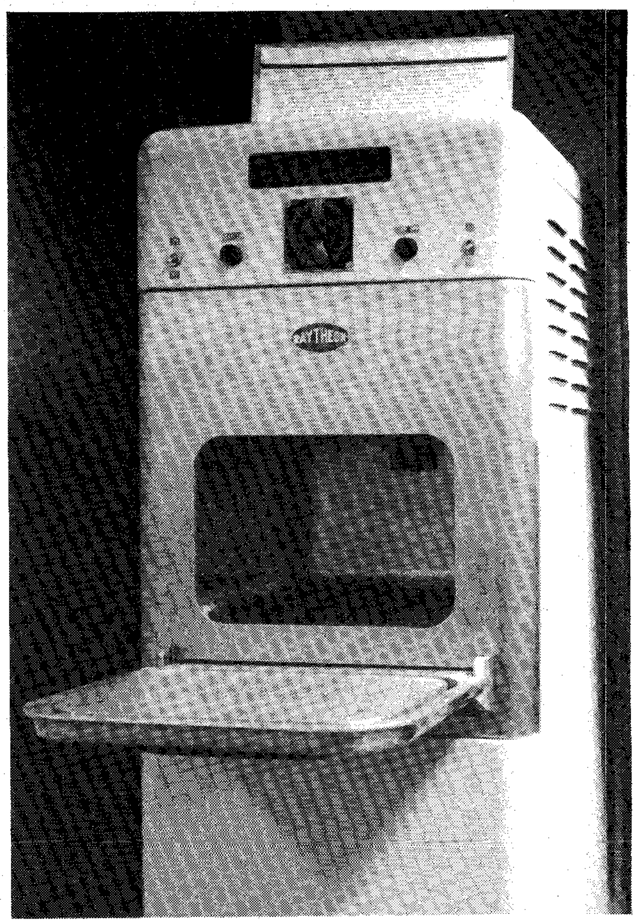
The Radarange was manufactured in various departments of Raytheon but a Radarange Division, under Fred Brooke, Jr., was established in the early 50's and a Food Laboratory was established in Raytheon's new Research Division to supply technical support. Soon, Models 1161 and 1170, both air-cooled, were marketed, the former a 1600-W floor model and the latter an 800-W countertop model. In the fifties, Raytheon had a commercial test kitchen and an Executive Chef, Alfred Haas, to help sell ovens to restaurants. In the Research Division, the Food Laboratory was headed by Dr. David Copson, a food technologist newly graduated from MIT. He was aided by Dr. Robert Decareau, another food technologist; Ed Krajewski, an engineer; and on specialized technical issues by Dr. Luther Davis, presently General Manager of Raytheon's Research Division.

The extensive work by the Raytheon Food Laboratory has been documented to a large extent in a book [37] by Dr. Copson and in brief by Dr. Decareau [38]. For example, there were many variations on waveguide-aperture feeds and stirrers that found their way into products and principles [39] for obtaining uniform heating, here enunciated by Dr. William (Bill) Hall, a well-known radar expert within Raytheon. The first disclosure of choke-seals in doors was also made by Hall [40]. These avoided the arcing problems encountered in the use of contact-type seals. Many principles of microwave cooking, like time-quantity relations, were established with detailed instructions on proper utensils and cooking recipes. The use of browning elements, and a variety of accessories, were researched [37] by Copson and his associates. Techniques using agar or beakers of water were developed to assess oven heating patterns and sanitation and microbiological aspects were also studied. The technique of microwave freeze-drying of foods to eliminate need of refrigeration of foods was also extensively researched by Copson [37].

Meanwhile, new Radarange models were developed. Because most units were in restaurants, the drop-down door was a potential nuisance in crowded kitchens. Therefore, Models Mark III, IV, V, and VI, with sliding vertical



(a)



(b)

Fig. 3. The first Radarange®, Model 1132, door shut and open.

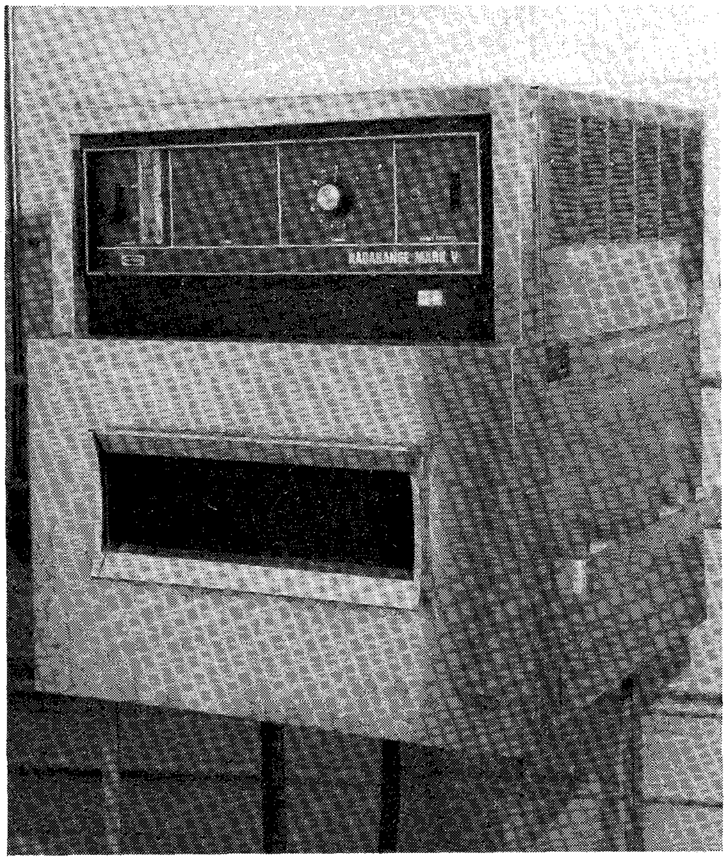


Fig. 4. A Mark V Radarange®.

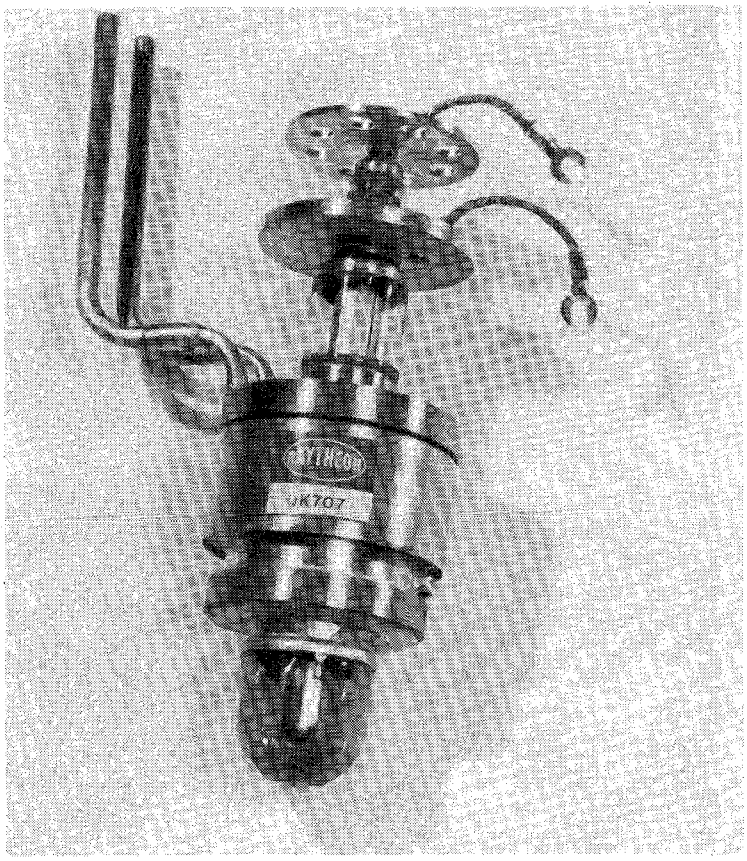


Fig. 5. QK707 magnetron, a water-cooled tube used in early Radaranges. (Photo courtesy of Raytheon Co., Microwave and Power Division.)

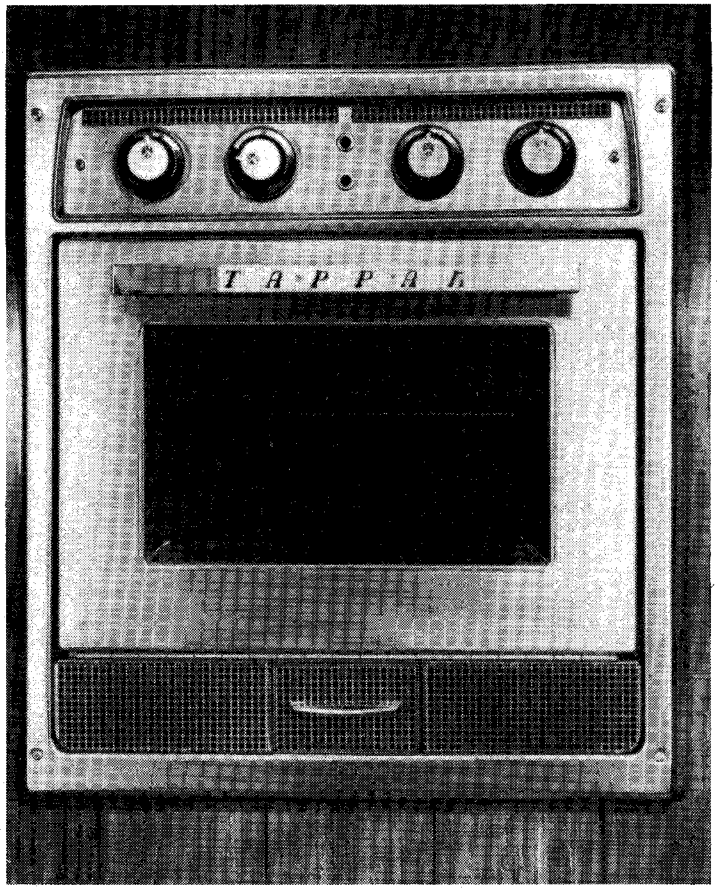


Fig. 6. The Tappan RL-1 microwave oven, designed for built-in wall mounting and operating at 220 V. (Photo courtesy of Tappan Co.)

doors, were developed. Fig. 4 shows a Mark V unit. It incorporates two Raytheon QK707 magnetrons (Fig. 5) for a nominal total power 1.6 kW. In these ovens, internal water-cooled systems were used and the required line voltage was 220 V, except for the Mark VI, a 600-W unit which was the only Raytheon Radarange to operate at 115 V.

During the fifties, Raytheon dominated the field of microwave ovens and heating applications. It was the only U.S. manufacturer of ovens for restaurants, the principal magnetron manufacturer, and obtained over half of the roughly 120 U.S. patents issued during the decade of the fifties. Furthermore, its engineers were already extensively investigating [41] the industrial applications field. The most promising areas were those of rubber extrusions, plastics, foundry cores ceramics, and food processing. Roughly 250 potential customer inquiries were processed in the last half of the fifties' decade with many experiments using Radarange ovens. They ranged from economically unfeasible applications, like sterilization of soil, through many food applications, like blanching mushrooms, to specialized jobs, like warming frozen horse serum. Although most of the activity was with 2450 MHz, some plans for work with 915 MHz and conveyor units were made. By 1960, competitors for industrial applications were foreseen in DuPont, GE, Litton, and Allis-Chalmers. Anticipated markets were modest by today's standards, viz., a potential market of rubber extruders of 3 million dollars at 10 to 20 thousand dollars for each microwave extruder.

Meanwhile, though Raytheon did not attempt to market the consumer microwave oven, it acted as an OEM and licenser for other firms which were more expert in mass-marketing. These firms included Hotpoint, Westinghouse, Kelvinator, Whirlpool, and Tappan. Power supplies, magnetrons, and basic-oven design data were furnished to each company, and the outside appearance was tailored by each firm according to its tastes. Tappan was the most persistent of these manufacturers and continued in the market, since 1955, when it introduced the 24 in-wide built-in oven with about 900 W power, shown in Fig. 6. It operated at 220 V and retailed at about $1200.00. The unit was marketed as an "electronic range" [42] and the advantages of cooking speed, cool oven and utensils, and unique reheating (or reconstitution) capability were stressed. An electric heating element at the top of the oven cavity was included to provide "browning." Various engineering innovations [43] were introduced by the Tappan engineers, led by Tom Lamb over the early years, e.g., operation of the magnetron (Litton L3189 (Fig. 7)) as a self-rectifying oscillator to simplify the power supply and the use of an electromagnet field coil driven by the magnetron anode current. By 1965, Tappan had introduced the first "microwave cooking center," with a microwave oven mounted above a conventional range which, however, retailed for well over $1000.

Thus, in the early sixties, Raytheon was supplying a modest commercial oven market to restaurants and Tappan was supplying an equally modest market to the

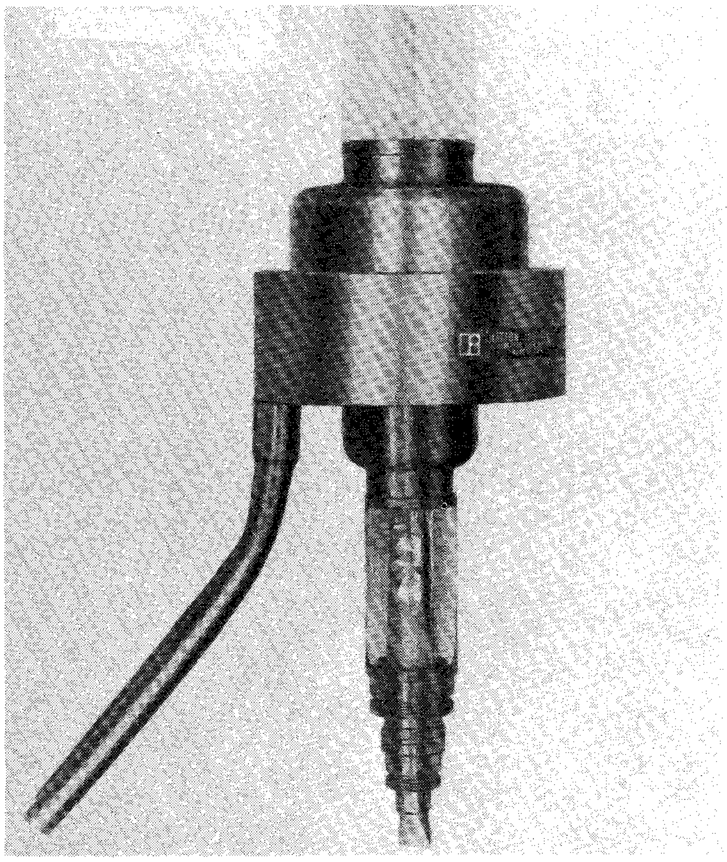


Fig. 7. The Litton magnetron L3858, made for use in early microwave ovens like the Tappan wall models. (Photo courtesy of Gerling Laboratories.)

home. There was little evidence at this point of spreading interest among other manufacturers. In the words [38] of Bob Decareau, "it is extremely doubtful if the microwave-oven business came even close to breaking even during those first ten to fifteen years. Certainly it would not have survived to give birth to the tremendous consumer microwave-oven market that exists today if it were not for someone with vision and faith in the potential of microwave cooking. That someone was Charles Francis Adams...." The latter is recorded as backing the microwave oven during its many profitless years while President of Raytheon Mfg. Co.

V. BOOM IN INDUSTRIAL MICROWAVE HEATING APPLICATIONS

Despite the continuing activity in microwave ovens in the early sixties, the prime interest of most microwave companies, including microwave tube manufacturers, was the military market—radar, ECM, and communications. To this was added the new market of space systems—though small compared to the military market. The annual sales of microwave tubes in the U.S. had risen [44] from less than 10 million dollars in 1948 to around 160 million dollars in 1962, in parallel with the very rapid increase in Federal R&D during the fifties. Although straight-line extrapolation guided microwave tube marketing executives during the fifties, it suddenly failed in 1962. As Herman Kahn [45] points out, when something is growing much faster than the GNP, it is destined to slow down. The "McNamara" tube recession had hit when DoD cut back sharply on tube procurement as well as tube R&D.

This caused researchers to flee the tube field and it caused tube company executives to seek out nonmilitary markets. The magnetron was still being worked on at tube companies, though researchers questioned "whether the magnetron would remain an important device" [46] and, in fact, most marketers predicted its slow disappearance in favor of more sophisticated tubes like the TWT and solid-state devices. Nevertheless, a paper by Twisleton [47] showed that an 80–90-percent efficient magnetron at 915 MHz was indeed feasible at power levels of 20–30 kW. (This is the forerunner of widely used 25–40-kW magnetrons and made by RCA, EEV, and others today). Under military support, Raytheon, under W. C. Brown, had demonstrated [48] over 80-percent efficiency in a super-power (400 kW CW) amplitron at S-Band. The Litton tube division under Paul Crapuchettes had developed new CW magnetrons based on Litton's extensive background in ECM tube development. In Fig. 7, we show the L3858, a type popular in the sixties which replaced a Raytheon tube in the Tappan range. Meanwhile, the New Japan Radio Company was developing a prototype 700-W magnetron for 2450 MHz, using a thoriated tungsten cathode, an axial

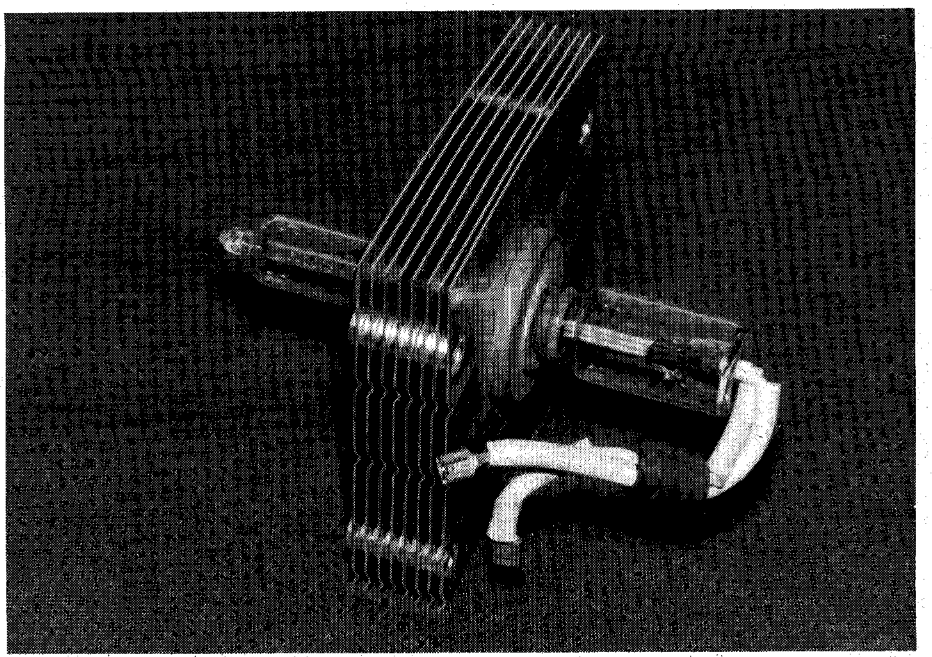


Fig. 8. The QKH1381 Raytheon magnetron, made for use in early Amana Radaranges and operated in solenoids.

probe output, and air cooling. This was further refined at Raytheon to become the QKH1381 shown in Fig. 8. The interaction-space, cathode, and anode designs established by New Japan Radio have essentially been adopted in all subsequent cooker-magnetrons for 2450 MHz, regardless of manufacturer. Although GE had dropped out of the oven market in the forties, it was now reconsidering the market and a new magnetron, the JC-300 was specifically designed [49] for an "electronic oven" to operate at 600-V anode voltage and to put out ~700 W at 915 MHz. Similarly, in Europe, tube manufacturers were reporting [50], [51] on new magnetrons for microwave heating. Furthermore, the great firm of Philips was showing interest [52] in "microwave cookers," even for the home (eventually). Magnetrons at power levels of 2 and 5 kW were described for use in microwave cookers and instructions on cavity, door design, and power supply established. Clearly, tube manufacturers believed microwave heating markets were promising. On the other hand, one British reviewer [53] felt that success of heating applications was doubtful because of "no clear indication that it offers any real advantage over more traditional methods." He felt, however, the magnetron would continue for many years in radar because of its advantages in size, efficiency, and cost.

Tube manufacturers were searching for nonmilitary markets, however. The main reason was undoubtedly reaction to the "McNamara" recession, but other factors included the recent advances in microwave power generation levels that suggested a possible role in power systems—conversion, transmission, etc. Thus, a group of U.S. engineers and scientists held a first conference [54] on "microwave power" in Orlando, FL in 1963. At the same time, it was revealed that the famous Soviet physicist, P. L. Kapitza, had been developing new crossed-field tubes ("nigotrons," "planotrons") for generation and microwave to dc conversion [55] and was seriously interested [56] in microwave power transmission and other super-power applications.

A more general analysis [57] by E. W. Herold foresaw that the future of the electron-tube lay with "non-communication power conversion" as well as optical-image devices and communication transmitters. These new applications were "cooking, industrial heating, chemical processing, thermionic energy conversion, plasma and MHD power generation, ion propulsion, particle and electron accelerators, microwave power transmission and controlled-fusion plasma apparatus." Much of this foreseen expansion of tube markets is in the area of microwave heating but Herold felt that the consumer oven was a distant reality: "We are still a long way from either the innovation in the electron tube or the innovation in marketing that will make this form of cooking universal." Herold apparently felt a new type of tube was required, viz: "an efficient plasma microwave generator with the simplicity of a fluorescent lamp." On the other hand, he was bullish on microwave heating in industrial processes because "there are applications in which no other process will do, and even present-day equipment will serve." It is apparent that Herold's analysis of future trends is sound, but his estimate of time to fruition of various applications was no better than those of anybody else. He correctly anticipated, however, that microwave-power transmission and fusion were many decades away. A few years later, two volumes [58] edited by E. C. Okress addressed formally the new field of "microwave power engineering."

Faith in a new business area was also shared by business executives. Raytheon began an industrial microwave heating group under W. C. Brown as an outgrowth of the

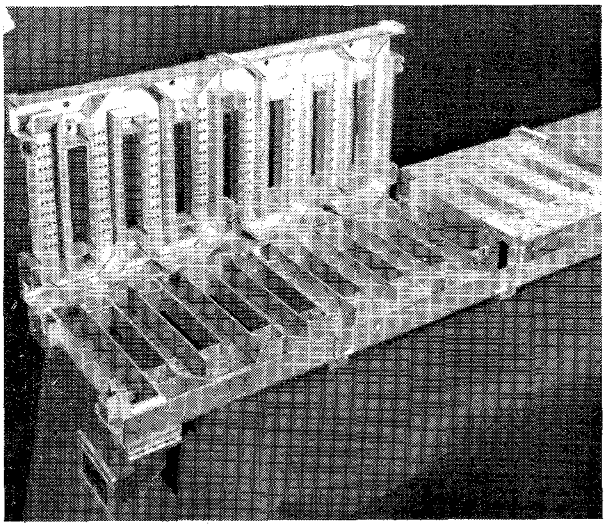


Fig. 9. A serpentine waveguide applicator, made for use in early Raytheon 915-MHz conveyor units. (Photo courtesy of Raytheon Co., Microwave and Power Division.)

super-power tube program. Technical design featured the serpentine waveguide applicator shown in opened-up view of Fig. 9 and a cold cathode 50-kW magnetron at 915 MHz. One of the first customers was Frito-Lay, which used a 50-kW conveyor for potato-chip drying. Raytheon, in the early sixties, also worked [59] on vacuum drying and drying of Nylon fibers in collaboration with DuPont. In the late sixties, this work was resumed by Val Smith at the Raytheon Waltham facility and investigation of applications in rubber extrusions, bookbind, and meat tempering was begun.

Meanwhile, DuPont's continued development eventually resulted in a successful Nylon fiber drying system consisting of a resonant cavity system shown in Fig. 10. The significant aspect of this development was the ability to heat Nylon in a controlled fashion despite the tendency for runaway heating because of a rapidly increasing function for ϵ'' as a function of temperature. This is described in papers [60], [61] by H. F. Huang.

Meanwhile, in the early sixties, there was an explosion of interest in industrial heating on the West Coast centered around the successful microwave tube companies, Litton and Varian, and a complicated series of company transitions and transactions. Varian's involvement began with a purchase of a company called Applied Radiation Company, followed by a founder of the latter helping found Cryodry, which then was bought by Armour and later became Microdry. A lasting product of these companies was the pasta-drying equipment. Meanwhile, Varian launched a heavily advertised industrial-heating group and worked on a joint program with Bechtel on a paper-drying application. Bechtel, in turn, through a subsidiary, tried to develop a "Weed Zapper" [62], [63] in Texas. Most of these applications failed and only Microdry remained in the field.

In the early sixties, Norman Moore, President of the Litton Electron Tube Division, created a new division called the Atherton Division (after his home town) to work on industrial heating. Litton worked on highway paint drying, alcohol evaporation, urethane foam heating, sand-core curing, chicken cooking, and potato-chip drying. Shown in Fig. 11 is an 80-kW conveyor system for potato-chip drying at Granny-Goose. Reviewing this system and the industrial heating business in general, Paul Crapuchettes in 1966 was still bullish: [64] "They're already cooking potato chips and removing solvents from magnetic tape with easily controlled speed and precision. Next they may be mining for gold and knocking down old buildings." Under John Gerling, the Atherton division was successfully marketing ten of the experimental 10-kW conveyor systems at 2450 MHz (see Fig. 12). One unit is still at the U.S. Natick Research Laboratories. It was thought that the largest financial promise lay in the food and biological area, and marketing was directed thereto. At that time, Atherton had an impressive staff of biologists and food technologists, including Drs. Carl Olsen and Robert Decareau.

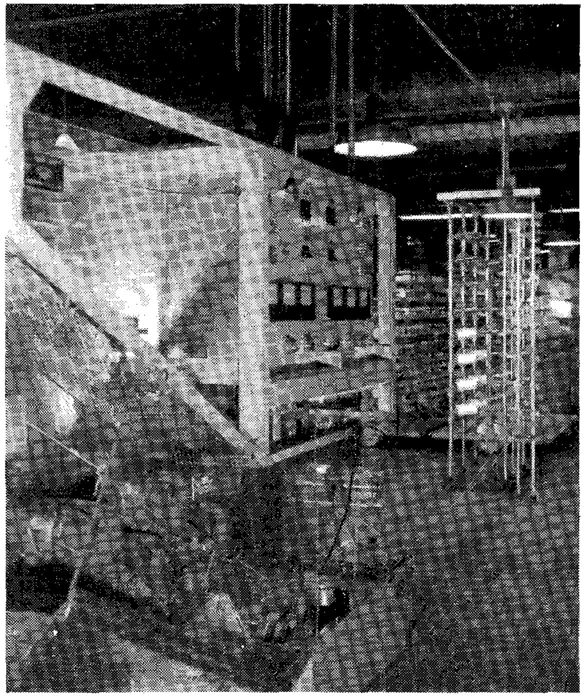


Fig. 10. A twin-resonant-cavity microwave fiber drying system used at DuPont to dry Nylon thread. (Photo courtesy of DuPont Co.)

One technique Atherton promoted under Gerling was a modular approach to systems based on a 2.5-kW Litton magnetron. During this program, they discovered that many magnetrons could be used to feed the same cavity or conveyor system without detrimental "crosstalk" or frequency locking.

For various reasons, however, all the West Coast ventures into microwave industrial heating failed despite many millions of dollars investment and great publicity campaigns. Problems of reliability, economics, and customer relations prevailed. All the potato-chip dryers failed and were to be classic case studies [65] many years later. There were mysterious problems of arcing in waveguides and applicators and fires in the food product.

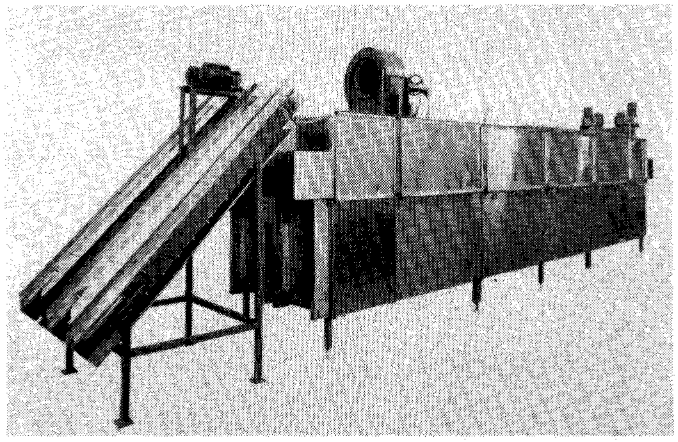


Fig. 11. Potato-chip dryer made by Litton, Atherton Division, in the sixties for Granny-Goose. (Photo courtesy of Gerling Laboratories.)

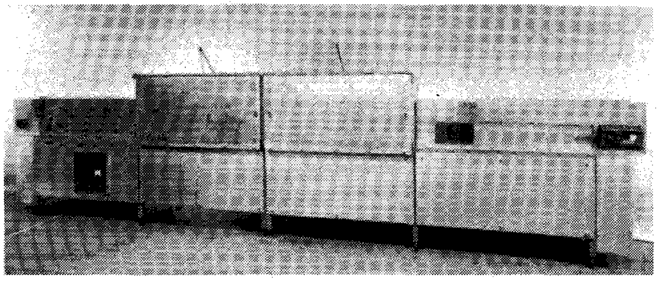


Fig. 12. A standard Atherton conveyor unit for multipurpose use, operating at power up to 10 kW at 2450 MHz. (Photo courtesy of Gerling Laboratories.)

Suspicions arose that high-power microwaves were incompatible with the "dirt" of industrial environments.

Litton did not confine itself to industrial heating alone. In 1964, Litton purchased a company called "Heat & Eat" associated with Robert Bruder, a vending salesman. Litton began developing commercial microwave ovens for restaurants and soon the Atherton Division was transferred to Minneapolis. The result was the dropping of industrial applications and the birth of its Microwave Cooking Products Division. Soon, commercial ovens like Model 500 and 550 (Fig. 13) helped Litton dominate the restaurant business by 1970. A unit like this was installed on TWA planes in 1965. The Model 500 was heralded [66] as a breakthrough because it operated at 115-V line voltage—a first and it was relatively compact.

Despite the business failures on the West Coast and the disappointment of not experiencing the sharp growth predicted by some, there was widespread professional interest in other countries, as well as in the U.S. reports [67] of substantial work in Sweden on microwave heating were made. Fundamental study of food dielectric properties and many other subjects were impressively carried out by P. O. Risman and others at SIK in Sweden.

Because professionals in the field related to many disciplines and often needed to popularize technical aspects to communicate with nontechnical (electrically) industry and other customers, it was found impossible to carry out appropriate meetings within IEEE. Therefore, in 1966, a new organization, the International Microwave Power Institute (IMPI) was founded in Canada. Important roles were played by Drs. Voss and Tinga of the University of Alberta in Edmonton, John Gerling, W. C. Brown, Jim Jolly, Bob Decareau, and Allen Supplie. Some of the founders, like Professor Dunn of Stanford University, had been studying microwave power transmission as an alternative to high-voltage lines, but these members left IMPI as interest in this subject faded. IMPI began to flourish, however. The *Journal of Microwave Power* published four issues a year with about forty papers per year with the majority in the areas of industrial heating, but with substantial coverage of applications in agriculture, biology and medicine, and food.

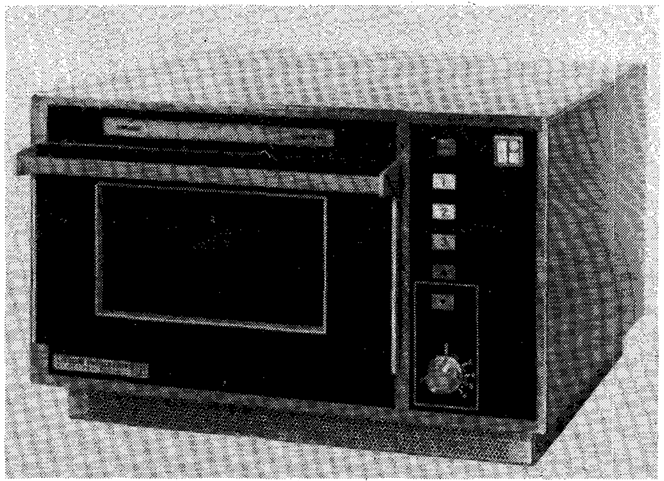


Fig. 13. The Litton commercial Model 500 microwave oven for restaurant use in the sixties. (Photo courtesy of Gerling Laboratories.)

The membership of IMPI rose to several hundred by 1970 and annual symposia with several hundred attendees were being held. Professional interest remained high, particularly as the surprise growth of the microwave-oven industry occurred in the late sixties.

Another sign of progress during the sixties was the founding [68] of the *Microwave Energy Applications Newsletter* by Dr. Robert Decareau. In the first issue [68], Dr. Decareau pointed out that, in the food-processing field alone, paid equipment totalling more than a megawatt of microwave power and valued at more than two million dollars" had been installed. He also noted that the test marketing of a countertop microwave oven by Amana Refrigeration, Inc., could mean that the "huge home oven market may be on the verge of a major promotion effort." Thus *MEAN* was intended to cover mainly food processing and microwave ovens, and was bullish in its outlook.

VI. THE COUNTERTOP MICROWAVE OVEN

In the midsixties, as Litton was about to close down the Atherton industrial heating operation, its manager, Dr. Norman Moore, anticipated [69] some type of boom in the long-stagnant consumer oven business. After pointing out that in 1966 there were almost 10 000 ovens in homes, he predicted significant increases in built-in and countertop units at 220 and 110 V. He felt the domestic market would

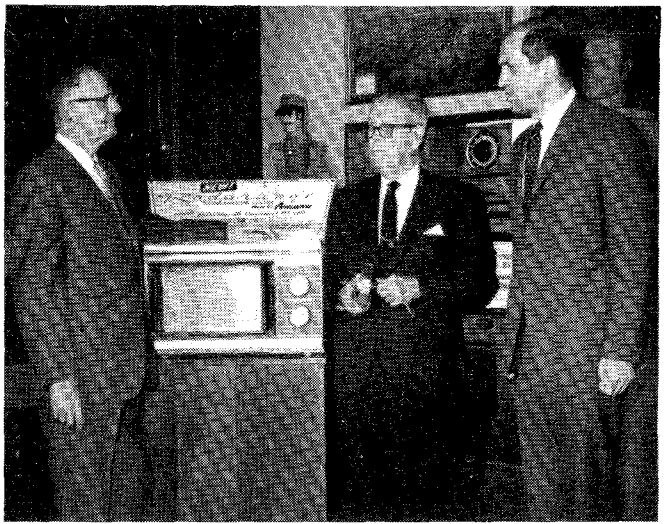


Fig. 14. The Amana Radarange®RR-1 is introduced at a press conference in Boston during the late sixties with (left to right) George C. Foerstner, President Amana Refrigeration, Inc.,; Percy L. Spencer, inventor of the microwave oven and then Senior Vice President, Raytheon Co.; and Thomas L. Phillips, the President of Raytheon Co. (Photo courtesy of Dr. Robert Decareau.)

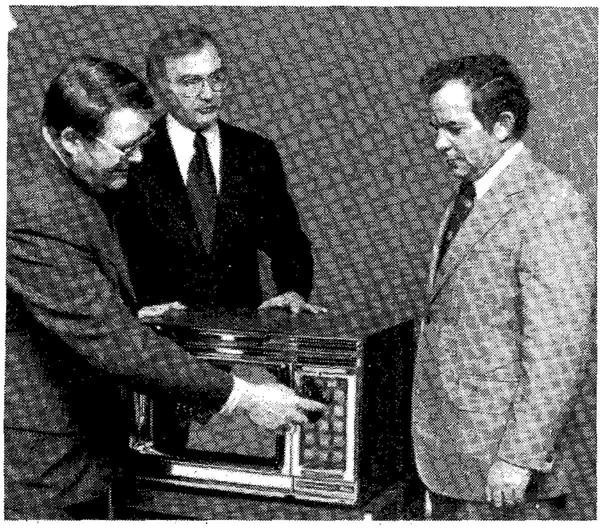


Fig. 15. The first "touchamatic" Radarange® using microprocessor controls with Richard A. Foerstner, Vice President, Engineering; Daniel R. McConnell, Vice President, Planning; and Richard D. Maxwell, Senior Vice President, Engineering of Amana (~1976). (Photo courtesy of Dr. Robert Decareau.)

move ahead when "innovators ... are still going to have to ignore the doubts and the risks and plunge ahead in the act of faith ... if they would be leaders in this domestic market." Furthermore, he felt an appropriate expression of the credo of such innovators is: "Anyone who accomplishes anything of significance has more confidence than the facts would justify."

Some journalists were even more bold in their anticipation. Brinton [70], in 1966, based on views of Ed Scott at Tappan, predicted: "Home-microwave cooking could be a two-million tube market in ten years. This is 48 times the size of the Vietnam-inflated 1966 CW magnetron market of about 38,000 tubes." It was pointed out that, although Tappan's 230-V free-standing microwave ranges had a price of about $1000 (some $360–$400 being the price of a Litton-Atherton magnetron), a sales increase of over 100 percent was still expected in one year. Furthermore, Roper Co. and Amana were planning to enter the market. Amana had specific plans for a countertop oven, the RR-1, operating at 115 V and selling at about $495! Clearly, this meant a drastically reduced tube price. How was this to happen and would it in reality?

Actually, the marketing of the Amana RR-1 did trigger the explosion of the microwave oven market. The events and the people who brought this about are legendary [71]–[73]. The Amana company was acquired by Raytheon in 1965. Raytheon had already developed, at New Japan Radio Co., a prototype low-cost magnetron. Raytheon's technical background coupled with Amana's expertise in manufacturing and marketing were the combination to trigger the consumer oven market. In Fig. 14, the key individuals, Tom Phillips of Raytheon and George Foerstner of Amana are shown with Percy Spencer at the public announcement of the new Amana Radarange RR-1 in 1967. One could say these were the individuals with faith earlier described [69] by Moore.

The achievement was also based on creative design engineering and product planning. Key individuals included were Richard A. (Dick) Foerstner, the chief design engineer at Amana for the new product. Dick, though a mechanical engineer, quickly absorbed a practical knowledge of microwaves and personally guided the product into manufacturing and in succeeding years built up one of the leading engineering groups[1] on microwave ovens. Fig. 15 shows the RR-9, the first oven to use a microprocessor with Dick Foerstner, Dick Maxwell, and Dan McConnell—all part of the Amana team. The design procedure was reported by Foerstner [74] and McConnell [75]. Improvements over the years have featured unique door seal improvements by Ironfield [76], Bucksbaum [77], and Osepchuk [78], as well as new rotating antenna feed systems by Simpson [79].

Other important advances over the years have included the refinement [80], [81] of ceramic-metal cooker magnetrons in in Japan. Samples of tubes current around 1980 are shown in Fig. 16. These were available at less than $25 per unit to the manufacturer. Fig. 17 shows how cooker-magnetron quantity and price have changed along with the growth of the microwave-oven market.

An early and novel entry into the consumer microwave-oven business was the Heath Co., which, under G. Duffner, designed and marketed a microwave-oven kit for final assembly by the consumer. By 1972, this unit had dropped from the market and one can suspect that the FDA did not greatly encourage the do-it-yourself kit for microwave ovens.

By 1971, Litton introduced its first consumer microwave oven and under President Bill George, Verle Blaha, VP engineering, and Dr. Charles Buffler, the product line became a major producer [82], along with Amana, and a

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[1] Successful interaction of marketing, home economics, and engineering followed the efforts of A. Meier, R. Renne Kamp, J. Kammerer, D. Trout, and J. Bennett.

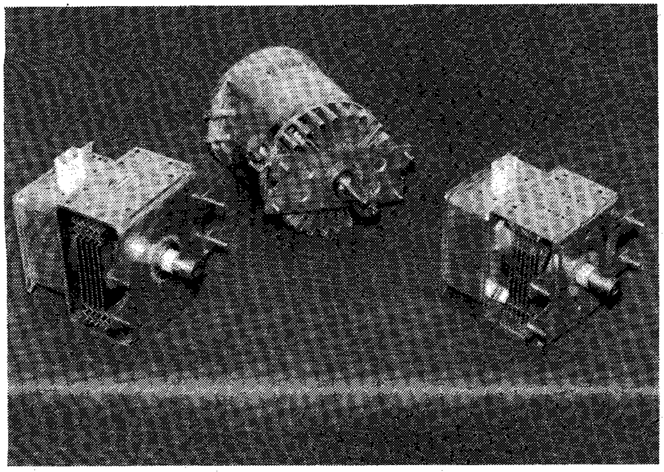

Fig. 16. Ceramic-metal cooker magnetrons of the seventies and eighties. Left, 2M170 (Hitachi); middle 2M53-M (Matsushita)—used in the midseventies with axial air flow; right 2M172AJ (Toshiba). These tubes use integral permanent magnets (ferrite, usually).

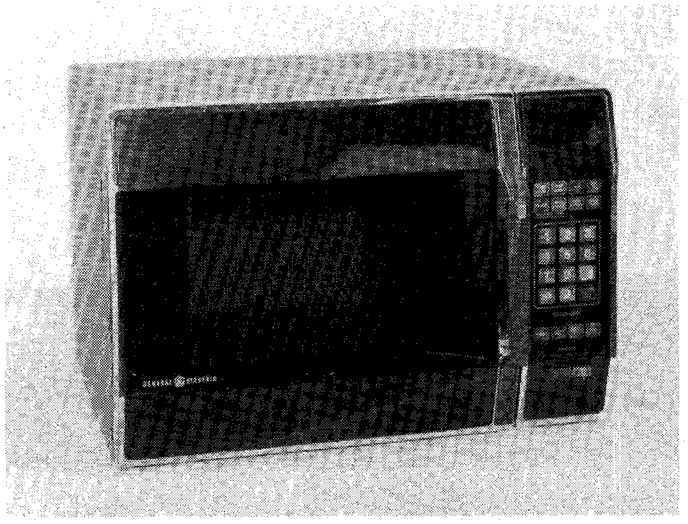

Fig. 18. General Electric Model FT-110 countertop microwave oven introduced in the late seventies.

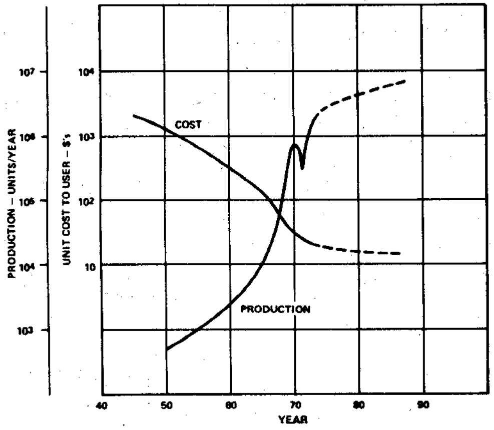

Fig. 17. Production figures and user unit costs of cooker magnetrons past and projected (taken from H. K. Jenny, "Electron tubes—A technology forecast," *Technology Trends* (75CH1005-8 TFA), IEEE, NY (1975)).

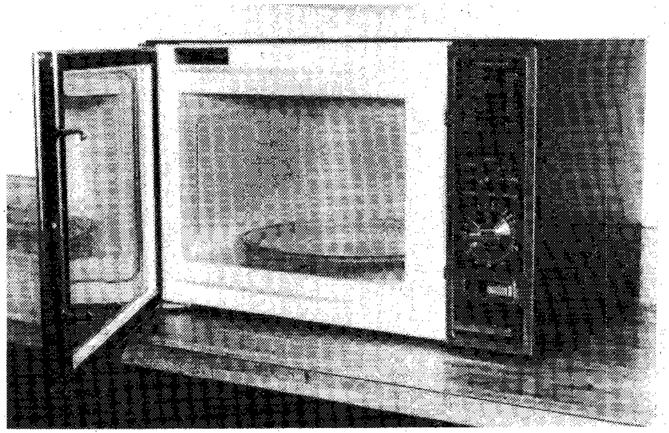

Fig. 19. The Sharp R-6740 carousel microwave oven with a five-level variable cooking controls—A model of the seventies. (Photo courtesy of Dr. Robert Decareau.)

large staff of over 100 engineers, draftsmen, and technicians was built up to handle development of new models.

Other U.S. companies that participated in the growth of the countertop market included Tappan, Roper, Magic Chef, and, for short periods, Admiral Corp. and Sage Laboratories. Late entries were Whirlpool Corp. and General Electric. GE, in agreement with its stance around 1950, initially felt in the sixties that the market growth would be in a 915-MHz combination range. This was their principal product until the early 70's, when they shifted into a 2450-MHz countertop product. Later on, the 915-MHz unit was dropped after roughly 60 000 were produced. GE figured prominently in the marketing of a compact oven ("the space-saver") to be mounted over a regular range. An example of a GE oven, circa 1980, is shown in Fig. 18.

Meanwhile, Japanese manufacturers, including Toshiba, Hitachi, Matsushita, and Sharp were actively importing into the U.S. market. The group was led by Sharp, but the Matsushita group became a major factor, especially after its acquisition of Motorola Consumer Products Division and marketing of "Quasar" as well as "Panasonic" brands. Sharp became a major competitor [83] in the U.S. market during the late seventies. Shown in Fig. 19 is an example of a Sharp oven featuring the carousel rotating turntable to improve cooking uniformity. By 1977, Sharp reported having manufactured a total of 2 000 000 ovens.

The phenomenal growth of this industry was reviewed by many, including McConnell [84] and George [85]. Fig. 20 shows the growth of annual sales from below 10 000/year in the early sixties to over 1 000,000 units/year in 1975. In the mid-eighties, the sales figure was leveling at around 5 000 000 units per year. As pointed out by George [85], the selling price of these ovens did not drop radically during the growth period, although abortive attempts were made in this direction in the early 70's. The mature product which dominates the market includes features such as variable power, special cooking modes including defrost, temperature probes, digital readout, programmable modes with microprocessor, browning elements, and combination with convection or conventional ranges. The mature product has an average selling price not far below the original selling price of the Amana RR-1, i.e., around $400 and,

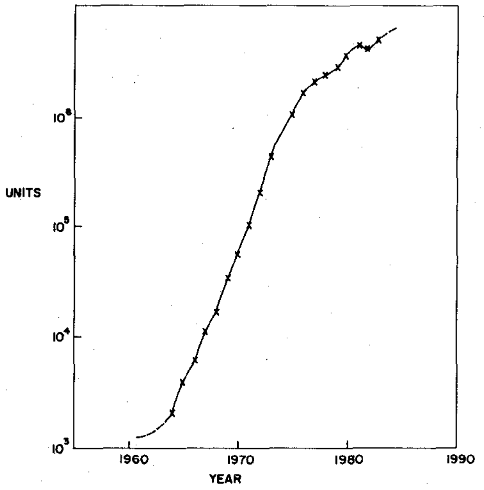

Fig. 20. Annual sales of domestic (consumer) microwave ovens in the U.S.

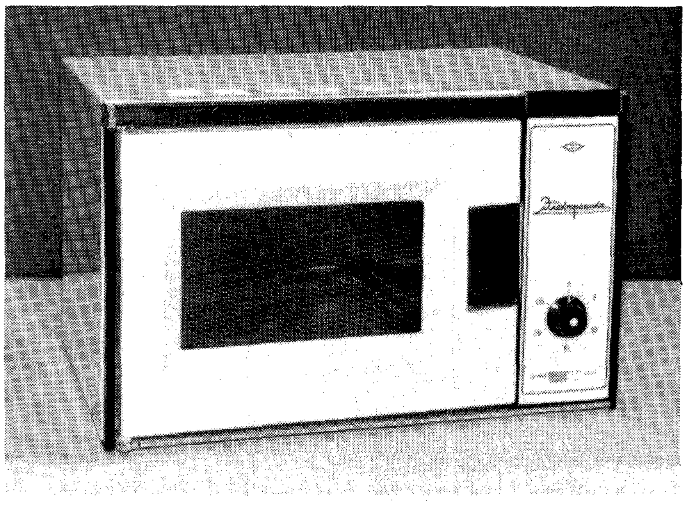

Fig. 21. The "Elektronika" microwave oven made in the USSR, ~ 650 W; designed for operation at 220 V 50 Hz (early eighties).

therefore, the product is a major appliance and reflects the desire for versatility by the consumer. This average price is reported [86] to be dropping in 1983, but the reliability of these data are questionable since other data from the same source appear questionable, e.g., an estimate of only 70 million dollars consumption of magnetrons in the U.S. for 1983, which must include a substantial military sales, as well as over 5 000 000 cooker magnetrons.

Marketing of microwave ovens in the rest of the world has begun first in Japan, where market penetration has exceeded 40 percent of households, and, to a lesser extent, in Western Europe, Scandinavia, and Israel, but ovens have been produced and marketed even in the USSR. As early as 1971, the USSR was promoting [87] its "superhigh frequency ovens"and by the early eighties an economical countertop oven, shown in Fig. 21, was marketed [88].

Technical advances for microwave ovens included "solid-state power control," [89] ferrite gaskets for door seals [90], microprocessors [91] for timing and power control, and even development [92], [93] of solid-state power sources—even though the practical application of the latter seems quite distant. An important event was the introduction of the ferro-resonant half-wave doubler power supply, which used a single semiconductor diode for rectification (see A. E. Feinberg, U.S. Pat. 3 396 342 and applications bulletin by Varo Semiconductors, Inc.).

Accompanying the growth of the market has been the development of many accessories and special food development. One of the first accessories was the "browning dish" [94] by Corning. Besides the development of the many types of utensils and containers [95], there has been the marketing [96] of coffee-makers, popcorn makers, grills, and many other adjunct devices for use in microwave ovens. A very large industry in teaching microwave cooking classes and writing many cookbooks has engaged a large group of home economists also. Literature supporting the industry and the microwave cooking field has largely been generated in the *Microwave Energy Applications Newsletter*, published by Bob Decareau, and the publications of IMPI and the Association of Home Appliance Manufacturers (AHAM).

The latter organization, with a key role played by John T. Weizeorick, has been the major organization in coordinating technical activities and consumer relations for the microwave oven industry. Technical activities include not only standards development in conjunction with UL (Underwriter's Laboratory), IEC (International Electrotechnical Commission), and the FCC, but also with the FDA in regard to the radiation safety question. The role of AHAM and IMPI are touched upon later.

VII. RADIATION SAFETY AND HAZARDS OF MICROWAVE HEATING

Although there had been some legendary [97] fear of microwave energy dating back to World War II, the subject of microwave-radiation hazards was little known by the general public until 1968, when Congress passed the Radiation Control for Health and Safety Act of 1968 (P.L. 90-601) [98]. This law was precipitated by the scare of x-radiation from color TV, but it was broadened by Congress to include all kinds of potential radiation from electronic products, including microwave/RF and acoustic energy—presumably as a prudent step, and not because of any practical health or safety problem involving microwave/RF energy.

The Bureau of Radiological Health (BRH)[2] within the FCA had the charter to develop safety or "performance" standards relating to electronic product radiation. After P.L. 90-602 was passed, an advisory committee, The Technical Electronic Products Radiation Safety Committee (TEPRSCC), was formed to review standards development by BRH. For whatever reason, BRH decided to develop a performance standard on leakage of microwave energy

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[2] Before 1969, this group was known as the National Center for Radiological Health (NCRH). Since 1983, the name was changed from BRH to NCDRH (the National Center for Devices and Radiological Health).

from microwave ovens. The Association of Home Appliance Manufacturers coordinated the actions of oven manufacturers in negotiating with BRH. Many meetings were held with BRH and TEPRSSC over two years, with interest focussing on the power density of leakage measured at 5 cm from the oven. This is a measure of "emission" rather than "exposure" and there was confusion [99] between these values. Although the then-consensus standard [100] on safe "exposure" limit was 10 mW/cm^2 (ANSI C95.1-1966), a very conservative application of this limit was made by proposing the same number for the emission value at 5 cm because [99] "that was as close as the human eyeball" could possibly be located to an oven. Other medical scientists [101], who were involved in developing ANSI C95, proposed a higher permissible leakage at 5 cm because the inverse-square law would dictate much lower whole-body exposure values at several feet from the oven. A final choice of 1 mW/cm^2 at 5 cm when new and 5 mW/cm^2 at 5 cm thereafter, with an arbitrary standard load of 275 ml of water, was made for the Federal emission standard [102] on microwave ovens. This was recognized as very conservative, e.g., an implicit safety factor of 10 000 or more, in the medical literature [103].

Nevertheless, for various reasons, the perceived risk of microwaves increased in the early 70's. There were a series of articles questioning [104] safety of microwave ovens based on the opinions of a very narrow section [105] of the professional, medical, or scientific communities. In this context, a specially-convened meeting [106] of the U.S. Surgeon General, BRH, and manufacturers was called to deal with the fact that a large percentage (e.g., 10–30 percent) of old ovens manufactured before 1970 leaked more than 10 mW/cm^2 under standard test conditions. Manufacturers agreed to repair such ovens and the perception of risk was heightened since some noncompliance with a conservative leakage limit was equated with unacceptable risk and hazard.

Because there was much misinformation in the popular media and microwave/RF hazards were generally exaggerated, there was discussion within MTT-S of the IEEE on the need for some way for IEEE to correct this misinformation and to provide factual information to media, legislators, and the general public. Dr. Leo Young, then a Director of IEEE, proposed [107] and guided IEEE's founding of the Committee on Men and Radiation (COMAR). Its first chairman was Mark Grove of the Walter Reed Institute of Microwave Research, with A. H. Ecker, D. R. Justesen, and J. M. Osepchuk as the other initial members. In succeeding years, COMAR was to grow and address [108] a series of socio-technical events involving microwave energy and its alleged hazard to society.

The most well-known of such events was the coincidence in 1973 of allegations [109] by Consumer's Union that microwave ovens were a significant radiation hazard and allegations [110] by Dr. Milton M. Zaret before hearings chaired by Senator Tunney that, "There is a clear, present and ever-increasing danger to the entire population of our country from exposure to the entire non-ionizing portion of the electromagnetic spectrum." These allegations were widely publicized by television, radio, and print media and public distrust heightened, but the growth in sales of microwave ovens was only temporarily slowed. These allegations were swiftly rebutted [111] by many scientists engaged in bioeffect research, including Professor S. M. Michaelson (Univ. of Rochester), Professor A. W. Guy (Univ. of Washington), and Drs. Budd Appleton and Tom Ely. The latter pointed out [112] that jockey shorts promoted by CU posed a far greater hazard to temporary sterility of males than microwave leakage. M. Brady wrote [113] from Norway to suggest the humorous contrast between the warning signs proposed by CU as necessary near microwave ovens and the absence of such signs when primitive man first learned to utilize the heat of fire. Even East European scientists, like Dr. P. Czerski, pointed out [99] that the oven "emission" standard was equivalent to safe exposure limits in Eastern Europe.

Since 1973, there have been occasional media campaigns stimulating new fears of microwaves, particularly those associated with the book writer, Paul Brodeur, who authored *The Zapping of America* [114]. COMAR [115] and others [116] have rebutted Brodeur's allegations, but the heritage has been some lingering distortion, misperception, and heightening [117] of fear of microwave radiation. These have probably contributed to some slowing in acceptance of microwave heating, especially in some industrial situations where management is sensitive to employee fears. Cooperation [118]–[122] between IEEE, particularly MTT-S and COMAR, IMPI, and a new society, BEMS (The Bioelectromagnetics Society) (1979), and other organizations over the years has been important in developing printed sources of and forums for accurate information on this subject.

Eventually, even Consumer's Union has accepted [123] the microwave oven and dropped its generalized warnings against its use. There remains, however, some suspicion, even in the semi-professional literature [124], about possible "non-thermal" effects that might invalidate U.S. safety standards.

In parallel with the generalized fear of microwaves that developed in the 1970's, specific allegations of unique hazards to wearers of pacemakers from microwave ovens evolved. These were initiated after the publication of a report [125] of interference to implanted cardiac pacemakers by microwave ovens. This, in turn, prompted the U.S. Army [126] and other agencies to require warning signs around microwave ovens. This was opposed [127] by BRH because the RFI was not unique to microwave ovens, and because the true solution was in introducing shielding and filtering into cardiac pacemakers. The latter were done in the early 1970's and modern pacemakers are very unlikely to suffer interference in today's EM environment. Still, many local governments have repeated attempts to introduce such warning signs but they have been mostly rebutted and the U.S. Army has since rescinded its sign requirement. The continuing legend of the pacemaker-oven hazard link has been debunked [128] by the author. It is likely [128] that the original incident [125] involved significant spurious-signal radiation [129] from early microwave ovens at around 200 MHz and not 2450 MHz.

Real hazards of microwave ovens include, in addition to ordinary hazards of electricity and heat, the hazards associated in explosions of small objects super-heated in microwave ovens because of possible internal hot-spot phenomena [5]; nonuniform heating that could either char food in overheated spots or fail to destroy micro-organisms in cold spots, and a variety of oven malfunctions that could cause food- or oven-fires. The latter include reported [130] self-starting of ovens equipped with microprocessor controls by line-voltage transients or other unknown causes, failure of controls to shut off ovens, and use of arc-provoking metallic objects inside ovens. Precautions against such hazards have been prepared by AHAM [131], individual companies in their cookbooks and use and care manuals, and in government reports and press releases.

Thus, the hazards of microwave ovens are fairly delineated, although some legendary fears survive, e.g., the fear that the actual process of microwave cooking somehow changes the chemical potential for harm in the food, even though FDA in 1968 [132] had determined that microwave/RF heating was safe for use in heating food.

Standards are continually being refined to provide safe exposure limits and to prevent annoying or even hazardous RFI. This is being done by improving exposure standards like ANSI C95.1-1982 [133], RFI regulations [134], and environmental limits which, in principle [135], should deal both with bodily hazard and RFI problems. In 1983, the EPA (Environmental Protection Agency) of the U.S. is still developing [136] guidance for federal agencies on safe exposure limits in the environment. Because it will be years before they result in enforceable federal regulations, individual states [137] have already issued environmental standards.

In the meantime, industry is organizing [137] to support sound federal standards, public education, and sound research on bioeffects and side effects. In addition, the Committee on Man and Radiation of the IEEE continues towards public education by issuing position papers [138], a review volume [139], and working toward an educational film for public distribution.

VIII. Buildup of an Established Industrial Microwave Heating Market

A study of Fig. 2 shows that the number of U.S. Patents issued in this field increased tremendously after the late sixties. Most of this is a reflection of the growth in the consumer oven business, but a substantial number of patents refer to the industrial applications and the continued development of this market, albeit a modest one. The peak in 1965 is not related at all to microwave ovens, but reflects a great interest world-wide (majority non-U.S.) in industrial applications—perhaps reflecting the West Coast boom, publications like that of Herold [57], and general reaction to the "McNamara" recession. At that time, there was very little Japanese authorship in the U.S. Patents of Fig. 2. By the early eighties, however, as the consumer oven became a great business, the authorship by Japanese of U.S. Patents in this field was close to 30 percent.

For an overview on what was developing in industrial microwave heating, we must rely on the trade press and, to some extent, on the publications of IMPI. In 1967, observers were unduly optimistic [140] with predictions of a "$200 million new industrial commercial market." In this review, microwave power transmission, potato-chip dryers, chicken-cooking, and paper and wood drying all seemed like viable applications. The novel use of a fringe-field traveling-wave illuminator (e.g., a slow-wave structure) instead of a conventional folded waveguide applicator seemed to make drying of photographic film at microwave frequencies desirable. And, in 1968, the reviews [141] still had an optimistic tone, as there were added new applications, such as curing of molded polyurethane autoseat cushions, butyl-rubber curing, alcohol separation, and plasma chemistry. A knowledgeable source was quoted as saying [141]: "a megawatt per month of CW microwave power is being sold in this country for industrial, commercial, and consumer applications." This statement was far from true if "consumer applications" were ignored. In 1969, there was a notice [142] of a successful application of microwave heating to curing of "tan oak" wood in Oregon. But, by 1972, a reviewer [143], though using the identical headline of 1967, viz., "Industry warming to microwave power," was much less than bullish. His assessment was [143]: "Unlike domestic microwave ovens, which are enjoying a very rapid growth in sales lately, the industrial use of microwave power for heating and drying is moving at a glacial pace." He then concluded, per authoritative sources, that the industrial market was hovering about $2 million per year for the last 25 years and would grow to a respectable $20 million per year by 1980 if emphasis shifted to sound marketing. The firms then active were Raytheon (under Dick Edgar and George Freedman) and Genesys Co. (California) (under J. Gerling). The emphasis then was on rubber-curing.

There was little mention of industrial heating in a 1975 review [144] and, in 1976, although there was highlighted a report [145] of a 1.6-MW dielectric heater at 4 MHz for wood drying, and a 1.5-MW solid-state induction heater at 180 Hz for forging, there was only oblique reference to "microwave ovens for treating metals or for processing semiconductors." By 1979, a quite sober assessment [146] had evolved. The market in 1977 was a mere $4 million and the reasons for slow growth were judged to be economic, on the one hand, and "fear" on the other. The real price of electricity had been going down steadily before 1970, but since 1970, it had steadily risen [147] with a boost after the energy crisis years in the midseventies. Perception of risk had become significant for some potential users of microwave power. The market, by 1984, was of the order of $10 million per year, but growth was still modest and painful. Only a few firms, like Raytheon, Cober, and Microdry, were left in the microwave industrial heating business.

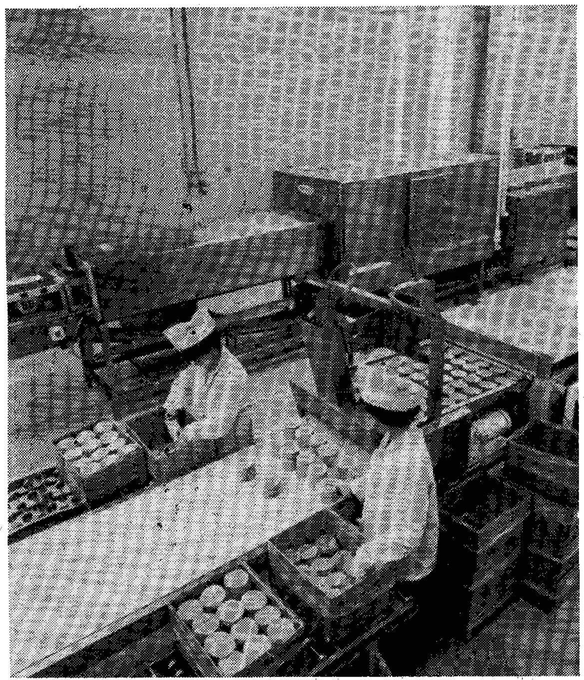

Fig. 22. Meat-tempering tunnel conveyor (Raytheon) which operates at 915 MHz with power levels up to 200 kW. (Photo courtesy of Raytheon Co., Microwave and Power Division.)

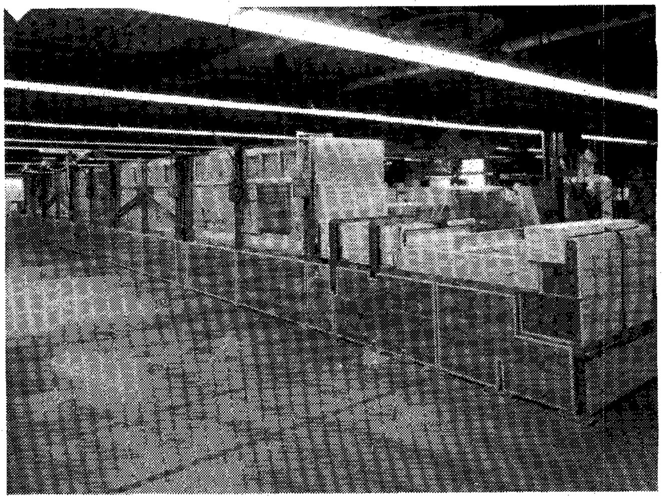

Fig. 23. A 150-kW system operating at 2450 MHz for use in curing sand cores in the foundry industry. (Photo courtesy of Raytheon Co., Microwave and Power Division.)

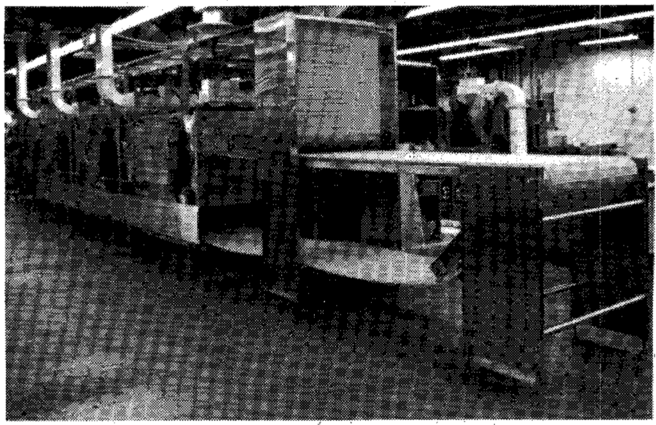

Fig. 24. A 240-kW bacon-cooker conveyorized system which operates at 915 GHz. (Photo courtesy of Raytheon Co., Microwave and Power Division.)

Still, there are established applications and some developing ones. Since the late sixties, the Raytheon group, led by G. Freedman, W. Widugiris, and, most recently, by Dick Edgar, has led the U.S. activity. The principal success is in the meat-tempering application where frozen blocks of meat are heated to a tempering temperature in the range of 22–27 °F, where the product can be sliced, diced, and repackaged. The typical tempering unit is a conveyor-fed long multi-mode cavity or "tunnel," as the one shown in Fig. 22, into which is fed 25–200 kW of microwave power at 915 MHz. The overall system efficiency is 50–70 percent and the typical cost [148] has been ~ \$0.80/Btu/hr for capital cost and \$.05/1000 Btu operating cost. The benefits to the food producer include reduction of tempering time from several days to minutes, reduction of required floor space, and fewer environmental and food quality problems. It is estimated that there were ten such units installed in 1973 [149], 25 in 1976 [150], and close to 200 in 1984 [151]. It is now estimated that these units process an annual food product worth about \$10 billion (representing throughput rates of up to 12 000 lbs. per hour per installation).

Another area that has been moderately successful is the curing or vulcanization of rubber extrusions with 2450-MHz units. Multimode cavities are fed by many cooker magnetrons of 0.7–1.0-kW output to a total of 25–100 kW. It has been found that the tubes do not lock in frequency and excellent distribution of heating results in the product being heated.

Another spectacular application involves the application of ~ 150 kW for drying sand cores in the foundry business. Such a unit is shown in Fig. 23. Other current applications have included bacon-cooking, and a giant tire preheater (60 kW). Fig. 24 shows a 240-kW bacon cooker which operates at 915 MHz. Some past applications not currently in use included a "school-lunch" machine designed for reheating precooked lunches in special styrofoam containers (Amoco). Technical trials in a Washington, DC, school showed technical success and customer satisfaction, but the application is not economically viable in view of the traditional parsimony of local school committees. Another interesting application is that of "oyster-shucking." Though technically successful [152] and of technical interest [153] because it seems to involve thermal-mechanical shock conversion mechanisms, it was not commercially successful because of economic reasons. A competing technique utilizing a laser has also been reported [149].

Shown in Fig. 25 is a multipurpose oven for 915 MHz which can provide up to 25-kW power at 915 MHz, together with infrared heat, as well as a partial vacuum. This unit was made for experimental use at the U.S. Army Natick Research Laboratories under Dr. Robert Decareau. Also shown in Fig. 25 is Charles Gilliatt, a versatile designer of microwave power systems during the 60's and 70's at Raytheon.

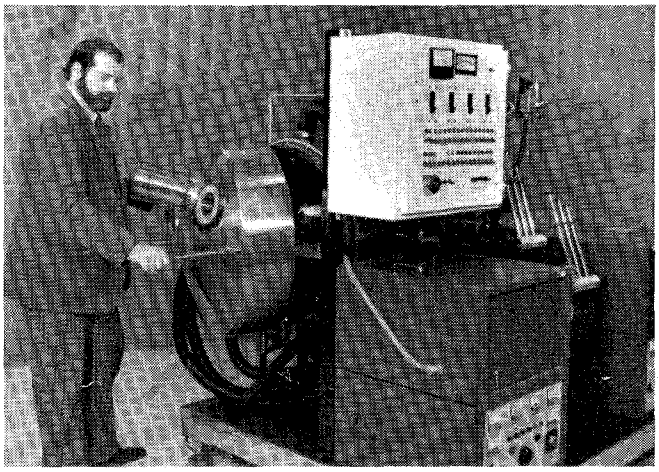

Fig. 25. A multipurpose oven with up to 25 kW of power at 915 MHz, infrared, vacuum capability, etc., used in experiments at the U.S. Army Natick Research Laboratories—with Charles Gilliatt, Raytheon design engineer. (Photo courtesy of Raytheon Co., Microwave and Power Division.)

Other successful applications have included donut proofing and frying machines [149], [150], [154] operating at 2.5 to 20 kW at 2450 MHz with a throughput of 400 to 1800 dozen donuts per hour. As many as 20 such units have been in operation, but recent experience shows little growth in this area. The drying of pasta has been a success [155] with over 20 installations, mostly produced by Microdry in the U.S., installed. The units provide 10–60 kW of power at 915 MHz, combined with hot-air drying in a multisection conveyor system. The advantages include reduced process-time (up to 90 percent), reduced space requirements, and reduced bacteriological plate counts. As shown in Fig. 26, such a unit comprises a large installation.

Most recently, it has been reported [156] that a microwave rendering system appears successful. An experimental unit with 144 commercial cooker-magnetrons (~ 1 kW) are applied to a conveyor system to process up to 20 000 lbs of raw material in a single 30-hr run. It is expected that a system with 120 5-kW magnetrons would yield a capacity of 5000 lbs per hr.

There are many other areas which have been investigated with varying degrees of success, but without commercial exploitation, to any significant extent. One of these areas is the very thorough investigations of agricultural applications by S. O. Nelson [157], [158], a research scientist in the Dept. of Agriculture, particularly the control of insects with microwave or RF energy. Another area of considerable promise is the use of RF heating [159] to retort oil-shale *in situ*. This has been investigated [160] by Texaco and Raytheon in a joint project, but dropped for economic reasons in the early 1980's.

A promising application is continuous heat sterilization [161] of food products with microwave power. In one scheme [161], a food product already sealed in individual pouches is heated to about 250 °F. The objective is to eliminate the need for refrigeration and provide suitable food rations for field use.

Another class of promising applications is that of microwave vacuum drying. A system designed to dry grain is described by Decareau [162]. It operates at a partial vacuum of 3.4–6.6 kPa to permit moisture evaporation at 20–52 °C with about 6.0-kW microwave power at 2.45 GHz.

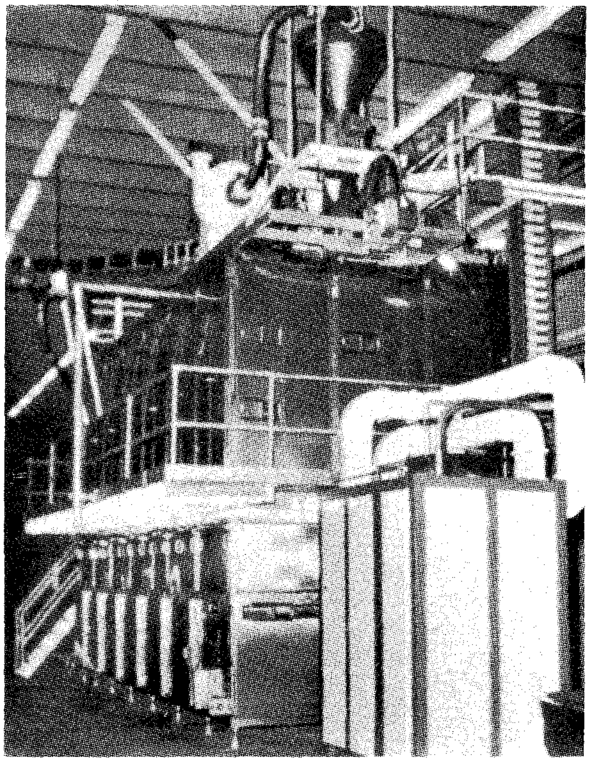

Fig. 26. A typical installation (Microdry) for drying of pasta, which combines hot air with 10–60 kW of microwave power at 915 MHz.

Another class of applications is that of plastics fabrication for which dielectric heating is widespread. Microwave systems have been proposed [163] but have yet to see widespread application.

The history of microwave industrial applications in Europe parallels that in the U.S. As Meisel [164] points out, big companies were engaged in the sixties but left the field by 1970. However, activity continued into the seventies, primarily in France and England, with some activity in Germany (Püschner) and Sweden (Risman). Highlights include 24–40-kW tempering tunnels at 2450 MHz, which are achieved by installing a number of 2.5-kW magnetrons alternately above and below the conveyor belt. A unique development under Meisel [164], [162] in France is a microwave-vacuum dryer using 400–4000 W at 2450 MHz at a vacuum of 2–20 torr. The output product is, for example, dried fruit concentrate, concentrated milk, or coffee extract. The unit shows a drying capacity of 2–4 l per hour.

Despite the optimism of Meisel, development during the 70's in Europe has been sluggish. Thus, in a 1978 review [165], most of the papers are directed toward laboratory studies rather than industrial application.

By 1982, activity [166] in the U.K. had shown successful microwave applications in meat tempering and rubber curing—just as in the U.S. Hulls [166] suggests that the term "dielectric heating" apply to microwave as well as RF applications. According to Hulls, many potential microwave applications fail simply because RF systems are cheaper and often perform just as well, e.g., in the widespread plastics business.

In a special issue [167] of the *Journal of Microwave Power* edited by Hirokazu Takahashi of Toshiba, the field of microwave heating in Japan is reviewed. A similar history to that in the U.S. is related by Kase and Ogura [168]. As in the U.S., the only large business to evolve is the domestic oven despite the fact, as Kase and Ogura point out, that most of the domestic use is related to reheating and special precooking and drying in the household. The domestic oven market peaked in 1974 at about 1.5 million ovens per year, with a decline to less than 1.0 million in 1977 as a 25-percent market saturation was reached. The industrial market in Japan has been steady at around an installed capacity of 500 kW per year since the early 70's. Some of the successful applications seem peculiar to Japan, like cigarette heating, mold inhibition in pastries, puffing, and drying systems (e.g., 100 kW at 2450 MHz) to produce specialty foods like rice-cake and seaweeds. Although most equipments operate at 2450 MHz, a few, especially in the growing field of meat tempering, operate at 915 MHz, despite the fact this is not an ISM allocation in Japan.

In the technical literature, extensive reviews [169], [170], as well as short review articles [171], [172], still conclude that there are many potential successful applications of microwave power which await correct economic conditions and optimum practical design. In the chemical literature, as well as the engineering literature, there are many, of the order of 50, articles on microwave power applications per year on a diverse array of uses, for example, the "microwave desulfurization of coal" [173] or "nonthermal" applications like "cell fusion" [174].

Despite the slow growth, there is reason for optimism. Edgar [151] points out that most microwave developments are "technical successes but dismal business failures," mainly because of the absence of appropriate marketing skills. Decareau [162] also points out that microwave equipment manufacturers generally are weak in in-house competence for the technical fields to which they sell. In addition, there are technical reasons, such as the primitive state of engineering, e.g., the fact that very little of the electromagnetic spectrum has been exploited until now.

As the microwave-oven market has expanded, companies have expanded advanced R&D on microwave ovens, e.g., the work of Quine and others at GE, Freedman and others at Raytheon, and Buffler at Litton. Some introduction of food technologists has been made and, if industrial applications were to expand, one could hope for similar expansion of appropriate professional competence within microwave manufacturers' organizations.

IX. THE INTERNATIONAL MICROWAVE POWER INSTITUTE (IMPI)

It has already been pointed out that noncommunication applications of microwaves involve interdisciplinary communication, an art still not mastered, but is one of the reasons IMPI was founded in Canada in 1966. Aggressive leadership by two Canadian engineers, W. A. Voss and W. Tinga, was a key to the successful buildup of this Institute. Dr. Tinga served as executive director and Dr. Voss served as editor of the *Journal of Microwave Power* for many years. Later individuals, such as J. Jolly, B. Krieger, G. Freedman, and R. Schiffman in the U.S. and P. Giles (U.K.) and M. Meisel (France), helped continue the Institute in its unique function. R. Schiffman was President for many years and helped guide its administrative offices from Alberta to New York City and then to Virginia.

TABLE II
BREAKDOWN OF ATTENDANCE AT IMPI SYMPOSIA

	(Percentage Breakdown)			
	1968	1973	1977	1983
Equipment Mfgrs (incl tubes)	27	23	7	18
Scientific and Industrial Applications	17	34	7	11
Materials Applications	26	8	6	10
Medical & Biological Appl	9	13	5	3
Appliance Mfgrs	7	10	36	25
Food Mfgrs	10	7	21	17
Independent Home Economists and Food Technologists	4	4	18	16

The membership grew to a stable range of 300 to 400 during the 1970's, but, in the late 70's after the founding of the Bioelectromagnetics Society, there was a loss of members with interest in medical applications. On the other hand, there was a great influx of home economists in the 70's as the microwave oven business developed. Thus, around 1979, IMPI was organized into two sections—the Cooking Appliance Section (CAS) and the Industrial, Scientific, Medical, and Instrumentation section (ISMI). Membership has been in the range of 700 to 1000 in the 80's, but most of this is in CAS. The *Journal of Microwave Power* continues its publication of technical articles while the newsletter, *Microwave World* (a successor to Dr. Decareau's newsletter MEAN) serves the interest of home economists involved in microwave cooking.

The shift in IMPI's activities is also shown in the breakdown of attendees at IMPI's annual meetings—cf., Table II. One can see that, in the lates sixties, attendees were mostly from a wide range of industrial applications, especially in materials processing, as well as medical and biological ones. In recent years, these groups have been less represented at IMPI meetings, while those connected with the food industry or appliance manufacturers have become the dominant group within IMPI—including independent consultants like Gerling Laboratories.

As the microwave-oven business has grown, the role of the Association of Home Appliance Manufacturers (AHAM) for microwave oven manufacturers in relations with government, the media, and professional societies has grown under the leadership of John T. Weizeorick and Richard Prucha. A record of positive contributions to the overall field has been the result [175].

The membership in IMPI has roughly been distributed as 50 percent in the U.S., 20 percent in Canada, and 30 percent in Europe and Japan. Less than 3 percent of the members are in Eastern Europe, but there is reason to believe microwave heating is being developed there, although poorly reported in the technical literature.

The MTT Society of IEEE has cooperated with and maintains liaison with IMPI. Publication within IEEE jour-

TABLE III
FREQUENCY ALLOCATIONS FOR ISM APPLICATIONS[a]

Frequency, MHz	Region	Conditions
6.765-6.795	worldwide	special authorization with CCIR[b] limits, both in-band and out-of-band
13.553-13.567 26.957-27.283 40.66-40.70	worldwide	free radiation bands
433.05-434.79	selected countries in Region 1[c]	free radiation bands
433.05-434.79	rest of Region 1[c]	special authorization with CCIR[b] limits
902-928	Region 2[d]	free radiation band
2.40-2.50 × 10^3	worldwide	free radiation band
5.725-5.875	worldwide	free radiation band
24.0-24.25	worldwide	free radiation band
61.0-61.5 122-123 244-246	worldwide	special authorization with CCIR[b] limits, both in-band and out-of-band

[a] Ref. 178

[b] CCIR - "International Radio Consultative Committee" of the International Telecommunications Union (ITU).

[c] Region 1 comprises Europe and parts of Asia, the selected countries are the Federal Republic of Germany, Austria, Liechtenstein, Portugal, Switzerland, and Yugoslavia

[d] Region 2 comprises the Western hemisphere.

nals is not extensive, but there are some examples [176], [177] of recognition of this field in IEEE publications. Future developments will, no doubt, involve more sophisticated aspects which may reflect a more extensive involvement of IEEE.

X. CONCLUSIONS AND OUTLOOK

The microwave-heating field has become firmly established after the establishment of the microwave oven as a major appliance in U.S. and Japanese homes, and the universal spread to other countries is a matter of time. The industrial market lags, but, for technical reasons [57], it is sure to come into its own. Resistance on economic or risk perception grounds is difficult to address but progress is being made.

One reason for technical optimism is the recognition that past achievements have exploited only two of the officially assigned ISM frequencies, 915 and 2450 MHz, and very little of the entire spectrum. Thus, it is unlikely that optimum frequencies have been available for many applications. In 1979, the World Administrative Radio Conference issued [178] a revised list of ISM frequency allocations, including some new frequencies shown in Table III. One can see that assigned frequencies at 5.8, 24.125 GHz, and at millimeter-wave frequencies have yet to see any significant application.

In the 1970's, IMPI proposed [179] that many more frequencies than shown in Table III be allocated for ISM and, to the degree possible, they be harmonically related. Thus, IMPI proposed that 4.9, 7.35, and 9.8 GHz be allocated, but these were denied; however, it is to be noted that the millimeter-wave frequencies (61.25, 122.5, and 245 GHz) are harmonics of 2.45 GHz. Similarly, a proposal by Litton for an allocation around 10 GHz for microwave ovens was denied [180]. Between 40 MHz and 915 MHz, there are no ISM frequencies in the U.S., so that optimum frequencies for some large objects may not be available in "free radiation" bands such as 915 or 2450 MHz. It remains to be seen whether in the future non-ISM frequencies are utilized, even if it requires stringent measures to prevent microwave leakage at levels which could cause RFI.

Still, in the future, there will be applications requiring free radiation—whether in large-scale applications such as oil-shale retorts [160], microwave-power transmissions, and the solar-power satellite system [181], or in the use of microwave radiant heating [182] of people in homes.

In the distant future, it is predicted [183] that most communication and radio, television services will be by cable or fiber-optic networks, i.e., nonradiating means. On the other hand, there is reason to believe that, as microwave heating applications increase, there will be many "free radiation" applications and a greater contribution of microwave-heating transmitters to the electromagnetic environment.

In the future, therefore, there will be more emphasis on the interference aspects of ambient electromagnetic radiation and less emphasis on "radiation hazards." Thus, one can foresee a three-tier division [136] of limits on electromagnetic radiation—the highest levels to prevent bodily harm, the intermediate level to prevent hazardous and damaging interference to electronic equipment, and the lowest to prevent annoying interference. On the other hand, there will be a greater introduction of susceptibility standards [184] into the electronics business.

As educational efforts [137], [138] proceed, the perception of "microwave heating" will be more rational and become more acceptable by consumers as well as industries. One can then expect a long sequence of technical innovations that will make microwave heating applications more useful and successful. Even now, there are those who, while hampered by fears of ionizing radiation in promoting food sterilization by gamma irradiation, suggest [185] wistfully that their radiation is merely "ultramicrowave" and, hence, no more dangerous than a microwave oven.

ACKNOWLEDGMENT

In order to attain a high degree of accuracy and completeness in this history, the author had requested information from over fifty individuals involved in the microwave heating field since World War II. Major contributions were received from J. Gerling, R. Edgar, W. C. Brown, W. Stone, R. Decareau, and T. Lamb. In addition, material and suggestions were received from P. Derby, N. Alstad, M. Brady, R. Schiffman, J. Weizeorick, and many people from the microwave oven industry, AHAM, and IMPI. The cooperation of all in such a difficult task is greatly appreciated. Finally, the author is grateful to the librarians at the Raytheon Research Division, Adamson, Buono, and Grenda, and his secretary, M. Olsen, for their usual faithful support.

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Upon joining Raytheon in 1950, he conducted research on ridge-waveguide, magnetrons, and helped develop the first high-power backward-wave oscillator in the United States. During 1956 and 1957, he was technical liaison for Raytheon at the microwave tube research laboratories of Compagnie Generale de Telegraphie san Fils at Paris, France. From 1957 to 1962, he was head of several research projects on crossed-field devices.

From 1962 to 1964, he was chief microwave engineer for Sage Laboratories, in Natick, MA. In 1964, he rejoined the Raytheon Research Division in Waltham, MA. He has directed various projects in the field of microwaves (tubes, ferrites, plasmas), image tubes, and physical electronics. In recent years, he has consulted for Amana and other Raytheon Divisions on radiation hazards, and investigated various aspects of Radarange technology, especially those involving leakage and safety. He was appointed Consulting Scientist in December, 1974, a position he still holds. He has published and presented many papers in the fields of microwaves and radiation hazards and holds over ten patents. He was guest editor for the special issue (February 1971) on Biological Effects of Microwaves of the *IEEE Transactions on Microwave Theory and Techniques*. He was editor of the *Journal of Microwave Power* (1970–1971) and is the editor of the recent IEEE Press volume of reprints on *Biological Effects of Electromagnetic Radiation*.

Dr. Osepchuk was National Lecturer (for 1977–1978) of the MTT Society (IEEE) on "Microwave Radiation Hazards in Perspective." In addition, he was the General Chairman of the *1978 Symposium on Electromagnetic Fields in Biological Systems* which was co-sponsored by IEEE-MTT-S and IMPI. He was on the Program Committee and a Session Chairman for a Symposium on "Health Aspects of Non-Ionizing Radiation" which was held on April 9–10, 1979, under the sponsorship of the New York Academy of Medicine.

He is a Fellow of the IEEE and the International Microwave Power Institute, and member of Phi Beta Kappa, Sigma XI, and the Bioelectromagnetics Society. He is a past chairman of the Boston Section of the IRE Professional Group on Electron Devices, a past member of the National Administrative Committee of the IEEE Group on Microwave Theory and Techniques and the Board of Governors of the International Microwave Power Institute. He is also a member of various committees of ANSI C95 (Chairman of Subcommittee 2 and Secretary of Subcommittee 4), the Association of Home Appliance Manufacturers (AHAM), and is presently a member of the IEEE Committee on Man and Radiation, and the National Administrative Committee of the IEEE Society on Social Implications of Technology.

In recent years, he has helped organize seminars for medical, legal, and executive personnel on effects and hazards of electromagnetic energy (the Homestead Seminars). He chaired an organizing committee in 1983 which led to the formation of the Electromagnetic Energy Policy Alliance (EEPA). This Alliance was founded by eight leading manufacturers and users of electromagnetic energy and is aimed at technical and public information activities which will enhance a rational perspective towards electromagnetic energy associated with modern electricity and electronics.

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50 Years of Radio Astronomy

PETER G. MEZGER

I. INTRODUCTION

CONTRARY to most other branches of science, the birth of radio astronomy can be very accurately pinned down. In the early thirties Carl Guthe Jansky, an engineer at Bell Telephone Laboratories, was investigating atmospheric noise at 14.6-m wavelength with a highly directional antenna. He found that the antenna noise attained a maximum which shifted in time by 4 min per day, the difference between stellar time and solar time. He identified the direction of the maximum intensity with the position of the center of our Galaxy. He had discovered what we now know to be the diffuse galactic synchrotron emission, caused by relativistic electrons, which gyrate in the galactic magnetic field. Jansky published his discovery of the galactic origin of the observed antenna noise in the *Proceedings IRE* in 1933. Therefore, this year, we celebrate the 50th birthday of radioastronomy.

Jansky's discovery was first taken up by Grote Reber, an amateur astronomer, who built his own radiotelescope using a parabolic reflector. He made the first sky survey at a wavelength of 1.9 m and published his first map of the radio sky in 1944. Fig. 1 shows how the "radio"-Galaxy looks if seen with a modern, high-resolution telescope such as the 100-m telescope at Effelsberg (Fig. 2).

Contrary to the optical spectrum a very broad-band continuum emission is the dominant component of the cosmic radio radiation. It was therefore close to an astronomical sensation when in 1951 Ewen and Purcell discovered the 21-cm hyperfine structure line of atomic hydrogen, the most abundant element in interstellar space. The possibility of a detection of this line was predicted in 1944 by a Dutch graduate student, Hank van der Hulst.

Optical spectral lines need for their excitation temperatures of some thousand degrees Kelvin, while radio spectral lines can be collisionally excited already at temperatures of a few degrees Kelvin. Optical observations, therefore, relate predominantly to hot ionized gas such as stellar atmospheres or HII regions. Radiospectroscopy, on the other hand, with the detection of the Hλ 21-cm line and a series of detections of (today more than 200) molecular spectral lines, opened for astronomy a completely different window. It allows us for the first time to observe the very cold interstellar gas and especially the interior of giant molecular clouds out of which stars form.

Development of advanced microwave technology during World War II had a tremendous influence on the development of radio astronomy after 1945, providing both the equipment and the well-trained engineers and physicists, who became the first generation of radioastronomers. The half power beam width (HPBW) θ_A of the antenna characteristics of a radio telescope with aperture diameter D is given by

$$[\theta_A/\text{arcmin}] \simeq 4.2\,10^3\,\lambda/D$$

with λ the wavelength. For the 100-m telescope (the largest fully steerable telescope) at a wavelength of $\lambda = 2$ cm, the HPBW (or angular resolution) is only ~1 arc min, comparable to the angular resolution of the naked human eye. This has to be compared with the angular resolution of

Manuscript received December 23, 1983. This paper was first presented at the 13th European Conference, Nürnberg, West Germany.

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0018-9480/84/0900-1224$01.00 ©1984 IEEE