# PROGRESS REPORT ON THE ADAPTING OF THE CROSSED-FIELD DIRECTIONAL AMPLIFIER TO THE REQUIREMENTS OF THE SPS

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## ABSTRACT

Progress in adapting the crossed-field directional amplifier to the SPS is reviewed with special emphasis upon (1) recent developments in controlling the phase and amplitude of the microwave power output, (2) a perceived architecture for its placement in the subarray, and (3) recent developments in the critical pivotal areas of noise, potential cathode life, and efficiency.

## Introduction and Background

The first proposed use of the crossed-field directional amplifier in the solar power satellite dates back to 1969 and 1970.[1] Since then there have been a number of successive discoveries and developments resulting in an ever-increasing better fit between the device and the severe requirements that are imposed upon the generator by the SPS.

First proposed by the author in the form of a 200 to 400 kW liquid cooled amplitron[1], the crossed-field device approach was soon changed to a passively cooled amplitron in the power range of five to ten kW because of the high desirability of passive cooling in the SPS satellite as pointed out by O.E. Maynard.[2] Such a tube was designed and the first phase of its development completed.[3]

In 1975 R.M. Dickinson of JPL proposed that because of its high efficiency, simplicity, relatively low mass, and already established high production volume and low cost, the microwave oven magnetron be incorporated into a directional amplifier package and considered for the SPS. While subsequently investigating this approach the author made two important discoveries: the first, that the microwave oven magnetron, when operated with a ripple-free DC power source and with no externally applied filament power, has an extremely high signal to noise ratio[4]; the second, that under these conditions the carburized thoriated tungsten cathode can be operated at such low temperatures that a potential life of more than 50 years is indicated under the high-vacuum and highly controlled operating conditions in space.[5,6]

The potential role of the magnetron directional amplifier in the SPS is now being further evaluated under a NASA-MSFC contract.[7] This investigation first involves an extension of the laboratory data base on the magnetron directional amplifier utilizing the microwave oven magnetron. This data, when combined with information obtained from other sources, will then make it possible to accurately define the projected characteristics of a higher powered version of the magnetron directional amplifier for SPS use, and to define a program of technology development that would result in the development of such an amplifier.

Because of the basic similarities of the magnetron and amplitron in their construction configurations and performance characteristics it is found that much of the experience gained in adapting the amplitron to SPS use is directly applicable to a similar adaptation of the magnetron directional amplifier.

The current study involves a penetrating look at all of the interfaces associated with the magnetron directional amplifier. At least one level of higher integration must be examined, and in some instances, more. The study has progressed far enough to yield a specific architecture that is shaped by these interfaces and that appears to have many attractive features.

One of the most important developments of the current activity is the precise control of both the amplitude and phase of the microwave power output from the amplifier by feedback control systems utilizing phase and amplitude references. The method by which amplitude is controlled is of overall SPS system interest in that it can be adapted to match the entire microwave generating system to the solar photovoltaic area at the point of maximum operating efficiency.

The material which follows is intended to provide the reader with: (1) a brief summation of those features of the crossed-field device that are of a desirable nature for the SPS; (2) a comparison of the amplitron and the magnetron directional amplifier for orientation purposes; (3) knowledge of the recently established architecture of the subsection of the subarray into which the amplifier is placed; (4) an introduction to the recently developed method for accurately controlling the phase and the amplitude of the microwave power output; (5) discussions of several very important pivotal areas relating to noise, tube life, and efficiency and (6) a summation of areas of concern needing additional attention.

## Features of the Crossed-Field Microwave Generator that are Desirable for the SPS

- High Efficiency: Overall efficiencies in excess of 85% have been demonstrated in an off-the-shelf magnetron used for industrial microwave heating and in certain laboratory models of the amplitron. An efficiency in excess of 80% at power levels (3 kW) low enough to utilize passive cooling has also been obtained.
- High Signal to Noise Ratio: Random noise level in a 1 MHz band down 100 dB or more at frequencies above and below carrier frequency by more than 10 MHz. The noise level may be lower because instrumentation is the limitation.
- Potential Life of 50 Years or More: Such life is possible by operating at low emission current densities that allow the low operating temperatures that have a proven association with extremely long life of carburized thoriated tungsten cathodes.

- Low Ratio of Mass to Microwave Power Output: The current estimate by the author is 0.4 kilograms per kilowatt of microwave power at the tube output. This includes the weight of the passive radiator but not the buck-boost coils which are considered a power conditioning function.

- Accurate Control of the Phase and Amplitude of the Microwave Power Output: By use of a set of phase and amplitude references and a set of phase and amplitude sensors the phase can be controlled to within ±1 degrees and amplitude to within ±3%.

- Potential to Perform the Bulk of the System Power Conditioning Requirements: The buck-boost coils necessary for output amplitude control of the magnetron can take on the added function of adjusting the input of the microwave system to operate at the optimum output voltage for the solar array.

- Minimal X-Ray Radiation: The crossed-field tube energy conversion mechanism generates negligible radiation, permitting maintenance functions during operation of the SPS.

- Only One Voltage and Two Terminals Required for Normal Microwave Tube Operation: Auxiliary power is required for a few seconds to heat up the cathode and initiate emission.

- Simplicity of Construction: The crossed-field device, particularly in its magnetron form, is very simple in construction.

- High Degree of Maturation in Production and Cost: Currently, more than two million magnetrons that closely resemble a similar tube for the SPS are manufactured annually for the microwave oven.

## Definition of Crossed-Field Directional Amplifiers - Comparison of Amplitron and Magnetron Directional Amplifier

A directional amplifier is defined as a device which passes energy in both directions but which amplifies in only one direction. There are at least three ways, as shown in Figure 1, in which a crossed-field device may be used as a directional amplifier. The first is in a self-contained device called the amplitron.[8,9] The amplitron is unique among the devices in that it needs no assist from auxiliary devices to obtain its directional amplification. It is a relative broadband device and has a very small phase change from input to output as a function of a change in frequency, magnetic field, or DC current level as compared with other crossed-field directional amplifiers and linear beam tubes, as well. This feature is advantageous in many applications where a high degree of phase stability is needed. The device does have limited gain of about 10 dB. The device is widely used in radar systems.

The second way is the combination of a magnetron oscillator and ferrite circulator which converts the magnetron oscillator into an amplifier with a bandwidth over which gain can be obtained.[10] The bandwidth is dependent upon the level of the drive relative to the level of the power output of the device. Typically, a bandwidth of 15 MHz can be obtained at 2.45 GHz with a gain of 20 dB while 5 MHz is possible with a gain of 30 dB. At these gains and within these bandwidths, the efficiency will remain high and nearly constant. The very high signal-to-noise ratio is independent of bandwidth and gain.

The total range of phase shift within the device as the drive frequency is shifted over this bandwidth is approximately 180°. The center of the frequency range over which amplification occurs is at a frequency dependent upon the operating current level of the tube, the temperature of the tube envelope, and other secondary factors.

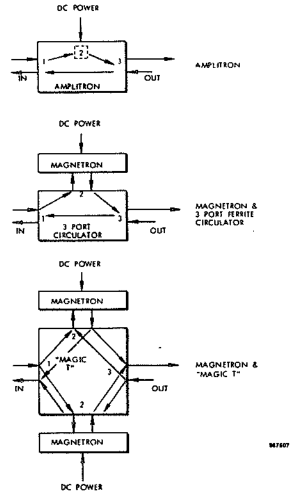


Figure 1. Directional Amplifier Approaches Utilizing Crossed-Field Devices.

As shown in Figure 1, the principle can also be carried out by means of a "magic T" or, synonymously, a 3 dB hybrid, an alternative method originally suggested for the SPS by R.M. Dickinson. A matching of the characteristics of the two tubes is required in the hybrid, but a ferrite circulator is not required.

It should be noted that the operating theory of the directional amplifier is well established.[10] They are often called "reflection amplifiers" or "locked oscillators". The principle is probably more often employed for solid state amplifier devices than for vacuum tubes.

It is important to realize that the magnetron device and the amplitron are very closely related so that development work that is done on one may be directly applicable to the other, as indeed is the case in the SPS. A set of scaling laws and design equations apply equally well to both devices in establishing their power level, voltage and current inputs, efficiency, cathode size, and other basic parameters. Both devices even use the same slow wave circuit, with which the electrons interact. However, the manner in which connections are made to this internal circuit is the basis of distinguishing these devices. As shown in Figure 2, the circuit is made reentrant in the magnetron and one output connection is made to the device, while the internal circuit in the amplitron is cut and the ends of it matched to external transmission lines.

## Overall Architecture of the Subarray Employing the Magnetron Directional Amplifier

Physically placing the microwave generator in the subarray and making the proper allowances for its many electrical and mechanical interfaces with other components and with space itself introduces the perennial systems design problem of making all the parts fit. This problem is currently being worked on as a necessary part of the MSFC study to project the characteristics of the magnetron directional amplifier and to define the technology development program to fully develop the magnetron directional amplifier.[7]

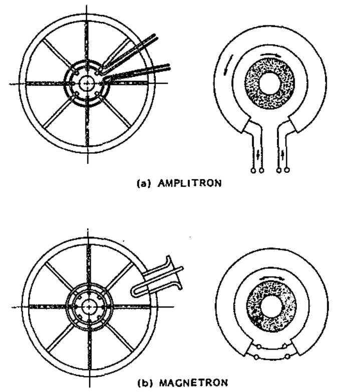


Figure 2. Diagram Illustrating the Basic Differences of Construction and Operation Between the Amplitron and the Magnetron.

It is believed that the development of the subsection shown in Figure 3 represents a substantial advancement toward the ultimate solution of this problem. The design recognizes and solves the following problems:

1. The microwave generators must dispose of their heat directly to space by operating at temperatures in the 200° to 300°C range. On the other hand, solid state devices which may be needed for many purposes cannot reliably operate at temperatures higher than 150°C and lower temperatures are preferable.

The design takes care of this problem by having the generators radiate heat in only one direction. Heat normally radiated toward the face of the array is largely reflected by a thin insulation blanket. There is also a substantial temperature drop across the thin walled waveguide construction. The solid state devices are located either on the face of the slotted waveguide array or in the slots immediately back of the face which are a property of the proposed method for fabrication of the thin-walled slotted waveguides radiators. Such components may be easily attached to heat radiating sinks on the front surface, if need be.

2. Phase and amplitude sensors, phase and amplitude references, and electronics associated with the control loops for phase and amplitude control must be incorporated. The architecture of Figure 3 provides the means of putting both the references and sensors for both amplitude and phase at the point where they are needed most-right at the radiating surface of the antenna. All solid state devices that are associated with the control electronics are located in the same area where they can be operated in a relatively cool environment.

In the architecture the phase and amplitude references are fed from the backbone of the subarray through flat ducts welded to the surface of the slotted waveguide arrays. These ducts serve an additional function in that they are very effective stiffeners of the thin aluminum faces of the waveguide array. However, the fact that these ducts run all the way to the edge of the subarray governs the number of tubes and area of slotted waveguide array that are in the subsection. Thus, the whole subsection may be considered as a plug-in unit and this concept replaces the earlier held concept that each tube and its slotted waveguide array section represented a plug-in unit.

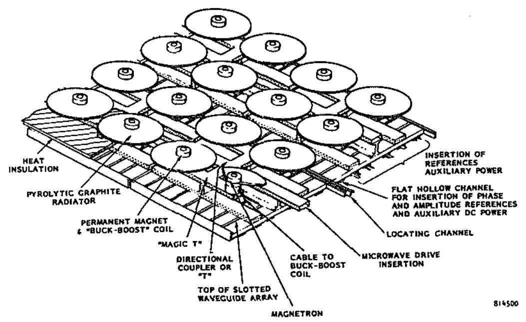


Figure 3. Assembly Architecture for the Magnetron Directional Amplifier in the Antenna Subarray. Two Subsections are Shown. Microwave Drive and All References and Auxiliary Power are Inserted from the "Backbone" of the Subarray. The Array has Two Distinct Temperature Zones. The Top is Used to Radiate the Heat. The Bottom is Used for Mounting of Solid State Components.

3. Interface with the microwave drive source. In Figure 3 the microwave drive source is not shown but it is derived from another magnetron directional amplifier identical to the ones directly attached to the waveguide radiators. At a gain level of 20 dB, one magnetron directional amplifier can drive between 50 and 100 other magnetron directional amplifiers. The microwave drive for any one subsection, as shown, is delivered to the intended tube through a waveguide which runs the length of the subsection and serves all the tubes. The energy may be siphoned off by a number of different techniques including directional couplers and the standing wave techniques used in the design of the slotted waveguide radiators.

After the power is taken off the central waveguide feed it enters one port of a "magic T", or alternatively, one of the ports of a ferrite circulator (not shown). Two magnetrons with matched performance are placed at either end of the Magic T, unequally separated in distance from the center by a quarter wavelength. The combined power of these generators then comes out of the fourth port of the device directly into the slotted waveguide array.

4. One of the interesting features of this architecture is that the cathode and magnetic circuits are operated at ground potential. This permits the power for initial heating of the filament and for energizing the buck-boost coils on the magnetron to be operated at ground potential. The anode and its radiator are isolated from ground potential by means of alumina ceramics which also support the anode and the magnetic circuit. The output of the magnetron is a coaxial probe which excites the waveguide without physical contact and therefore can remain at anode potential.

5. Sources of auxiliary power. Not shown in Figure 3 but located along the spine feeding the subsection array are sources of the auxiliary DC power needed

for the phase and amplitude control systems and for the transient heating of the filament for starting purposes. The amounts of power that are needed are relatively small, characteristically five or ten watts for each magnetron directional amplifier. This power is most easily obtained by tapping off a portion of the microwave power from the magnetron directional amplifier that drives the subsection array, then performing the desired impedance transformations at microwave frequency and rectifying the output with the highly efficient type of rectifiers that are used in the rectenna. The auxiliary power is then distributed to the individual magnetron directional amplifiers in the subsection array through the flat conduits located on the slotted waveguide array surface.

Incorporation of Phase and Amplitude Tracking in the Magnetron Directional Amplifier

The output phase of any microwave generator in the SPS, regardless of kind, must be carefully controlled in order that it not appreciably impact the overall phase budget of the subarray which must include many other factors. Open ended control for the magnetron directional amplifier and klystron is not feasible and probably only marginally feasible for the amplitron. For the magnetron directional amplifier and klystron this control must utilize a low level phase reference at the output, a comparator circuit to compare the phase of the generator output with the reference phase and to generate an error signal, and a feedback loop to make a compensating phase adjustment at the input.

The control of the output amplitude in the face of many factors that tend to change that amplitude is also essential for generating an efficient microwave beam. In the case of a crossed-field device the output amplitude can be controlled to a predetermined value by another control loop which makes use of small electromagnets that can be used to boost or buck the residual field provided by permanent magnets.

The amount of power required to compensate for expected variations in the permanent-magnet field with temperature and life, and minor changes in the dimensions of the tube with life are very small. With additional power, but still reasonable in the context of power dissipation from other causes, this arrangement can also adjust the operation of the microwave generator array to the most efficient operating point of the solar photovoltaic array. This would be very difficult by any other means of power conditioning because the output of the solar cell array is DC and the direct transformation from one DC voltage to another is not possible without resistive losses. Indirect methods such as transformation to high frequency AC, then an AC voltage change by transformers, and then back to DC again by rectification would appear to be highly impractical in this application where huge powers, very low mass requirements, and difficulty of dissipating the inevitable losses in the transformation process prevail.

It is of importance to note that the magnetron directional amplifier will be operating in an efficiency-saturated mode so that modest changes in operating voltage will have only a minor impact upon operating efficiency. Thus the optimized efficiency of the solar cell array will predominate in the combined operating efficiency of solar array and microwave generators.

The overall schematic for the combined phase and amplitude control of the magnetron directional amplifier is shown in Figure 4. Also shown is how this control can be related to the overall power absorption by the solar cell array. A central computer establishes the most efficient operating point (maximum power output) of the solar cell array and then adjusts the reference power output of the banks of magnetron directional amplifiers, making certain of course not to err on the side of asking for more power than is available from the array.

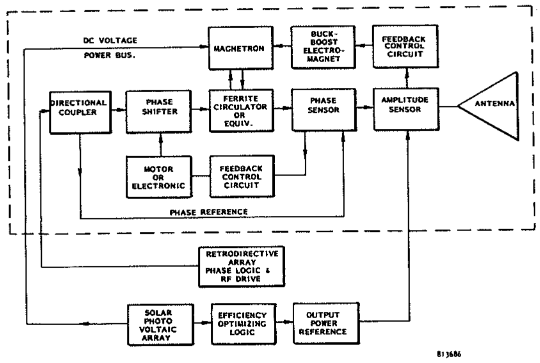


Figure 4. Schematic Diagram of Phase and Amplitude Control of Output of Magnetron Directional Amplifier. The Packaged Unit is Enclosed in Dotted Line. Relationship to SPS Overall System is Indicated Outside of Dotted Line.

The phase and amplitude tracking system requires a set of references and a set of sensors. These references and sensors are located at the front face of the slotted waveguide array where the most accurate sensing of the phase and amplitude can be made and where the solid-state sensing and control devices can find a temperature environment that they can tolerate.

The amplitude reference is a DC voltage whose value can be remotely controlled from a central source. The amplitude sensor is a crystal detector coupled to the slotted waveguide array. It provides a DC voltage which is compared with the DC voltage reference. The error voltage, after suitable gain, establishes a current in the buck-boost coils which changes the magnetic field, which in turn changes the magnetron current to change the power output of the magnetron in a direction to minimize the error voltage.

The phase control system makes use of a phased-controlled signal from a central source, a sample of the output power, and a balanced detector which compares their phases. The error signal can be used to operate a number of different types of phase shifters positioned in the input side of the magnetron directional amplifier.

A test bed, shown in Figure 5, has been constructed to check out the proposed control system. For most laboratory measurements a resistive microwave load is substituted for the slotted waveguide. The sensors are located in the waveguide approach to the load. Although the evaluations of the control systems are not complete, the initial information indicates that they behave as predicted.

Noise Emission Properties of the Amplitron, Magnetron, and Magnetron Directional Amplifier

The lack of historic data on the noise performance of CW crossed-field devices and the consequent inability to predict their behavior in the SPS application where the noise level of the transmitter is a highly critical issue understandably became a major factor in the preliminary selection of a generator approach in the reference design. In the recent time frame people within the SPS microwave system community have become aware of the very low noise data that has been obtained from the microwave oven magnetron[4,5] which is now serving as a scaled-down version of an SPS magnetron and to a lesser degree they are aware of the low noise data that was obtained from the amplitron development.[3]

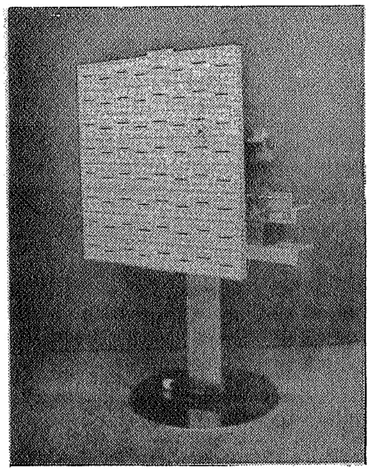

Figure 5. Test Bed for the Phase and Amplitude Tracking Investigation, Shown with Slotted Waveguide Load as an Option.

The early lack of data in this area is understandable when it is considered that the production of random noise outside of an area immediately around the signal (where it is important in communication or doppler radar applications) has been of little concern or interest in the past. However, just the converse is true in the SPS application where the high power level of the transmitter makes it mandatory to have very high ratios of carrier signal to random noise everywhere but immediately close to the carrier. Even after the importance of this noise was realized it was necessary to make special noise measuring setups to obtain more sensitive measurements of noise. In these setups the carrier signal was greatly attenuated in order to allow the noise to be visible as exhibited on a sensitive spectrum analyzer.

Many measurements of signal to noise ratio over frequency ranges of as much as ±1000 MHz either side of the carrier have been made on magnetron directional amplifiers with this equipment.[4] A typical set of measurements is shown in Figure 6. The data was taken both with normal external power applied to the filament and with no external power applied. The reader's attention is to be focused on the very high signal to noise ratio that is obtained over a frequency sweep of 200 MHz with no external power applied. The signal to noise ratio is 100 dB for a 1 MHz band of noise. This corresponds to a signal to noise ratio of 130 dB per 1 KHz of noise which is greater than the 125 dB quoted for the klystron in the reference design. Sweeps of ±1000 MHz around the carrier also exhibit equally large signal to noise ratios. The reader is reminded that with these signal to noise levels even a 10 gigawatt transmitter would be radiating only one watt of noise for each megahertz of the frequency spectrum.

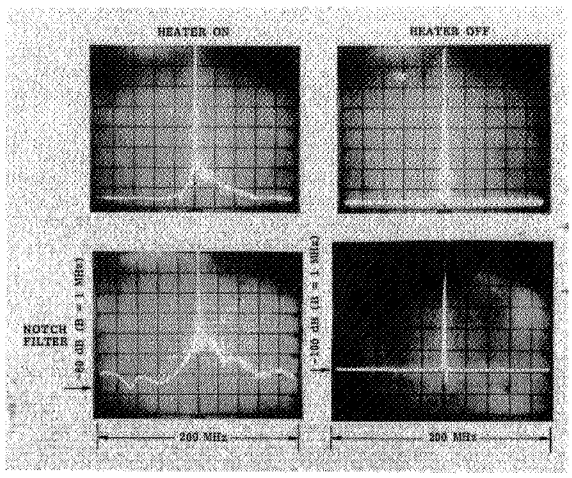


Figure 6. Spectrum of Locked Magnetron.

The signal to noise level may be substantially better than 100 dB /MHz because the measurements are still limited by equipment sensitivity. The sensitivity is currently being increased by 20 dB so that signal to noise ratios of as great as 120 dB /MHz can be measured.

It should be noted that while these noise measurements were made with a device gain of approximately 20 dB, the noise behavior remains independent of gain at high gain levels. At high gain levels the drive source appears as a small reflection factor (0.1 for a gain of 20 dB) and this has a negligible impact upon the behavior of the tube.

It should also be noted that these low noise measurements have been observed on magnetrons made by different manufacturers and in different time periods, but not on all magnetrons that have been randomly selected. However, no studies of a statistical nature have been made nor probably should be made until more sensitive measuring equipment is available. And it may be more effective to devote any limited future effort to better understanding the sources of noise in the magnetron.

There is currently no government support of any investigation into the sources of noise in the crossed-field device. However, Raytheon Company did carry on a modest effort in this area in 1979 in which special external probing equipment was built to examine the fine structure of magnetron operation with the hope of determining some of the factors that greatly impact the noise performance. Some of these results are very interesting but a discussion of their logic and implications would be so lengthy and involved that it would be outside the scope of this summary article.

Measurements of close-in phase modulation noise added by the magnetron directional amplifier[11] were also made when it was operating with a gain of approximately 20 dB. These measurements indicated a carrier-to-noise level that was typically 115 dB for a 1 KHz band of noise in the range of 10 KHz to 100 KHz removed from the carrier frequency. This represents excellent performance.

The discussion is now turned to harmonic generation. In this area there was no particular issue between the crossed-field and klystron device approach since it is known that both of these devices along with all other classes of microwave generators produce harmonics. It was apparent, however, that there was little data on the quantitative level of these harmonics in any device, partly for the reason that it is difficult to make such measurements in waveguide where the harmonics usually become accessible.

However, a method of making measurements in a small coaxial line and water load attached immediately to the output of the magnetron and matched into it with a normal loaded Q, thus avoiding the problem of multiple mode propagation, was employed. Measurements made on two representative tubes, designated as #11 and #12, are given below.[12]

HARMONIC LEVELS

| Frequency | #11 *dbc | #12 *dbc |
|---|---|---|
| $f_o$ | 0 | 0 |
| $2\ f_o$ | -71 | -69 |
| $3\ f_o$ | < -97 | -85 |
| $4\ f_o$ | -86 | -93 |
| $5\ f_o$ | -62 | -64 |

*dbc - decibels below carrier level

These findings are somewhat better than had been anticipated. The unexpected anomaly of the significant energy at the 5th harmonic is an indication of the difficulty of the a priori assessment of the more complicated characteristics of any microwave generator that may be designed for the SPS.

Investigation into the Designing of Magnetrons with Cathode Life of 50 Years

It is well known from the theory and experience associated with properly carburized thoriated tungsten cathodes that such cathodes can have extremely long life if they are operated at low temperatures in a good vacuum.[13,14] An investigation of the application of this knowledge to the design of long life cathodes for SPS magnetrons was precipitated by a question raised by a NASA representative about the life of tubes with carburized thoriated tungsten cathodes that had exhibited very high signal to noise ratio when power from the external heater source was set to zero.[6] The resulting investigation not only indicated that very long life can be achieved but also led to the discovery of an apparently overlooked feedback mechanism in the magnetron that maintains the emitting surface of the cathode at a temperature just sufficient to supply the needed current that flows from the cathode to the anode.[15] This mechanism assures that the tube will determine its own long life, independent of external circumstances with the exception of compromised high vacuum and demand for increased anode current beyond the design value.

The investigation that was made began with the use of an optical pyrometer to observe the brightness temperature of the magnetron cathodes through optically transparent windows in specially constructed tubes. The arrangement is shown in Figure 7. The tube is fitted inside of a magnetic solenoid so that the magnetic field and therefore the operating voltage of the tube can be varied. Most measurements were made without the application of any external heater power to the filament.

It was observed that the only parameter that had a significant impact upon the cathode temperature was anode current. It had previously been assumed, for example, that cathode bombardment power would increase with greater magnetic field and greater power input. By contrast, it was observed that when the anode current was held constant and the magnetic field varied over a range of two to one to give an increase of power input by approximately the same amount, the cathode temperature remained the same to within ±10°C, or not much greater than the resolution of the optical pyrometer.

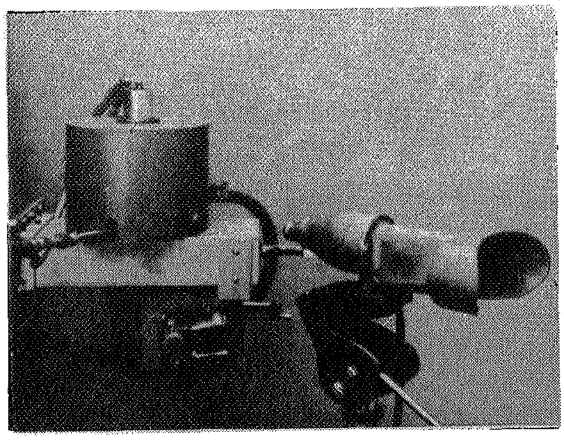

Figure 7. Test Arrangement for Viewing the Temperature of the Filament-Type Cathode in the Microwave Oven Magnetron as a Function of Anode Current, Applied Magnetic Field, and Microwave Load. Optical Pyrometer is in the Right Foreground. Transparent Window is Visible Outside of Solenoid-Type Electromagnet.

The variation of cathode temperature with anode current is shown in Figure 8. The slope of this curve is nearly the same as that obtained from the Richardson-Dushman equation which predicts temperature limited emission density as a function of true temperature. If the Richardson equation is matched to the true temperature of 1896° Kelvin that corresponds to a brightness temperature of 1500°C, then a reasonable value for the constant A of the equation is obtained. The emission as a function of temperature may then be obtained and as the three points on Figure 8 indicate follows closely the experimental data.

It has been established from life test evaluations that the life of a carburized tungsten cathode is a very steep function of the operating temperature. The difference between life at 2000°K and 1900°K is a factor of ten.

From the great body of design data that is based upon many laboratory investigations as well as life test data, an operating temperature of 1900° Kelvin is associated with a potential life of 500,000 hours or more than 50 years, as derived from the curves and the notes on Figure 9, if the cathode is made from 0.040 inch diameter wire that is 50% carburized.[13,14] This is a reasonable design and a reasonable operating temperature for a cathode that could be used in a magnetron designed for SPS use.

Of course, life test data for 50 years is not available. But the design data of Figure 7 would have predicted a life of 130,000 hours for each of a lot of 12 tubes manufactured by Machlett for use in the WWV transmitter. The filament wire was 0.035 inch in diameter and 20% carburized, and the tubes were run at 1950° Kelvin. The 12 tubes had a total running time of 850,000 hours and there had been no failures when the equipment was retired from service. Some of the tubes had been operated at 86,000 hours or 2/3 of the predicted life. Considering that there were no failures among the 12 tubes this test would indicate that the use of Figure 7 is conservative practice.

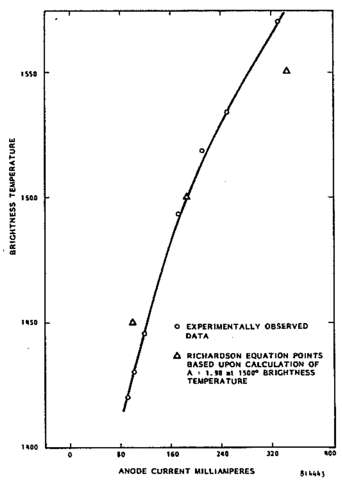


Figure 8. Cathode Brightness Temperature and Associated Points of Temperature Limited Emission as Function of Anode Current in the Microwave Oven Magnetron.

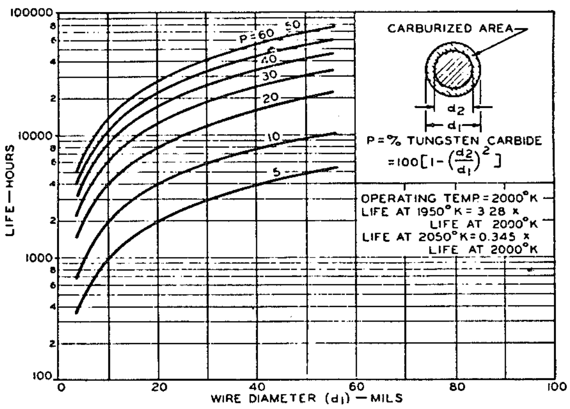


Figure 9. Thoriated-Tungsten Filament Life Curves as Function of Wire Diameter and % Carburization. Note Increase or Decrease in Life as Function of Temperature as Noted.

These tubes were also high power and high voltage tubes, similar to the projected SPS magnetron and subject to the same cathode failure mechanisms if the vacuum inside of the tube were not sufficiently good.

The conclusion is that a very good argument can be made for extremely long cathode life in the proposed SPS magnetron. The argument is based upon observations of low operating cathode temperatures in operating magnetrons, an internal mechanism that will automatically keep the cathode temperature as low as possible over closely controlled operating conditions in the SPS, an enormous body of experience and information on the carburized thoriated tungsten cathode that is well documented in published papers and books and the correlation of the long life of the Machlett tubes with predicted life.

## Crossed-Field Device Efficiency

Crossed-field electron tubes of the magnetron and amplitron type are properly recognized as the most efficient of microwave generator devices. But the highest electronic efficiency, defined as the efficiency with which DC power is converted into microwave power, is associated with a high ratio of the magnetic field B to a design parameter $B_0$ which is proportional to frequency as shown in Figure 10. But the theoretical electronic efficiency is always degraded to some degree by the circuit efficiency, and can be degraded by improper design of the interaction area and other design parameters as well. When the $B/B_0$ ratio is high and the tube otherwise properly designed the measured electronic efficiency has exceeded 90% as exhibited by the commercially available 8684 magnetron. For reasons largely related to the physical size and cost of the permanent magnet, crossed-field devices are almost always designed in the range of $B/B_0$ of four to six. This is true of the microwave oven magnetron whose operating characteristics have recently been intensively evaluated.

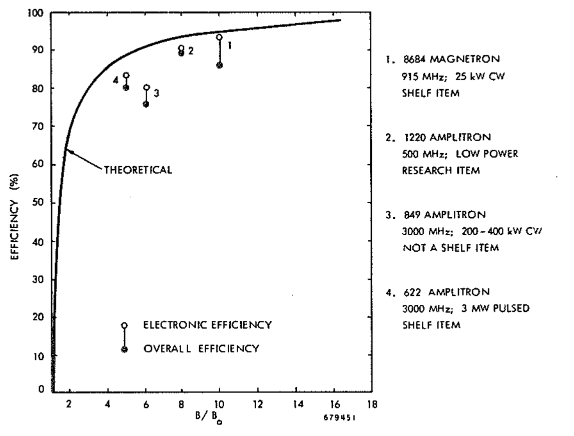


Figure 10. Magnetron Efficiency as a Function of $B/B_0$ Ratio.

However, the microwave oven magnetron can have its permanent magnet removed and be operated in an electromagnet. When this has been done the measured overall efficiency can be considerably increased as shown in Figure 11. The measurement of 82±1% efficiency was carefully measured after extensive preparation and precaution and then a balance was made between the DC power input and the sum of the microwave power output and the power dissipated in the anode as an additional precaution.[16] After taking a carefully measured circuit efficiency of 95% into account, the electronic efficiency was computed to be

86%. To this may be added at least one and perhaps two percentage points to take into account the amount of backbombardment power that was needed to heat the cathode to a temperature sufficient to provide the emission (No external filament power was used).

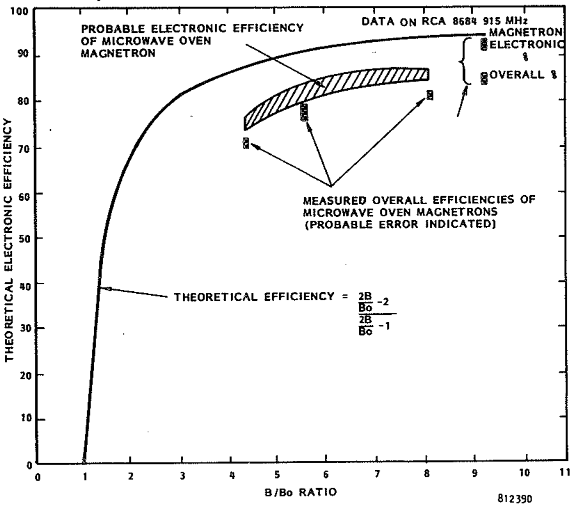


Figure 11. Theoretical and Experimentally Observed Electronic Efficiencies of Conventional Microwave Oven Magnetron and 915 MHz Magnetron. Electronic Efficiency is Efficiency of Conversion of DC Power into Microwave Power. Overall Efficiency Includes Circuit Inefficiencies which can be Ascertained from Cold Test Data.

Although this efficiency may seem high, actually it is from six to eight percent lower than it should be, and considerably below that of the 8684 previously referred to and also shown in Figure 11. The reason for the degraded efficiencies that seem to occur for all $B/B_0$ ratios is not fully understood. A contaminated field pattern does exist in the tube in the cathode-anode interaction area and there may be some leakage current, although small, around the end shields. But there are probably other factors as well.

To the author's knowledge there has never been a dedicated effort to maximize the efficiency of the crossed-field device, with but one exception. The one exception was an effort made on an amplitron device and resulted in an overall efficiency of 90% ±3% (Figure 10). It therefore seems probable that if there were a dedicated effort to optimize the design for efficiency an efficiency of 90% could be achieved from an SPS tube. The procedure would be to use high $B/B_0$ ratios, make certain that the end shield and pole piece design were proper, make certain the cathode potential always remained at a neutral potential with respect to the vanes, contour the vane tips, and design for high circuit efficiency.

## Areas of Concern Needing Additional Attention

Although the magnetron directional amplifier has been operated at very high carrier-to-noise levels, confidence in such performance and the potential to improve on that performance must be based upon an improved understanding of what causes the noise. Recent experiments would seem to indicate that the random noise that is observed is not an inherent property of the basic energy conversion mechanism in the crossed-field device but is rather associated with one or more extraneous mechanisms that are complex and difficult to comprehend. It is expected that various hypotheses may be generated to explain them but that there will be little confidence in these hypotheses until special tubes are constructed to test them.

Similarly, in the area of efficiency, there is the concern for the missing six to eight percentage points in efficiency in the microwave oven magnetron and more than that in the experimental amplitron. Presumably, most of this efficiency loss can be accounted for by the contaminated field patterns in the interaction area; therefore tubes with good field patterns should be constructed to check this hypothesis.

Of particular concern are complications arising from the desire to operate the SPS tube at relatively high magnetic field to obtain high efficiency and at high ratios of voltage to current to assure long cathode life, but measurements of signal to noise from the microwave oven magnetron run with these conditions indicates a lower signal to noise ratio. It should be noted that under these conditions the rather primitive end-geometry arrangement to contain the space charge may allow current leakage from the interaction area that can lead to noise. The condition may be further exacerbated by a change in the shape of the magnetic field caused by magnetic saturation of the pole tip.

To better understand these areas of concern it seems clear that some special experiments requiring a special experimental tube will be needed.

## BIBLIOGRAPHY


1. W.C. Brown, "High Power Generators of the Crossed-Field Type" in Journal of Microwave Power, Special Issue on Satellite Solar Power Station, Volume 5, No. 4, Dec. 1970. pp. 245-259.

2. "Microwave Power Transmission System Studies" Raytheon Contractor_Report ER75-4368 NASA CR-134886, December 1975.

3. W.C. Brown, "Design, Fabrication and Testing of a Crossed-Field Amplifier for Use in the Solar Power Satellite" NASA CR-159410 Contract NAS3-20374 LeRC.

4. Raytheon Briefing Document on "Crossed-Field Directional Amplifier for Use in the Solar Power Satellite" - to JSC and MSFC in September 1978.

5. "Microwave Beamed Power Technology Improvement", JPL Contract # 955104 with Raytheon Company. Monthly Progress Report #9 for March, 1979.

6. Technical Letter of September 12, 1978 to Robert O. Piland from W.C. Brown.

7. "Satellite Power System (SPS) Magnetron Tube Assessment Study" MSFC Contract NAS8-33157 with Raytheon Company.

8. W.C. Brown, "Description and Operating Characteristics of the Platinotron - a New Microwave Tube Device", Proceedings of the IRE, Vol. 45, No. 9, pp. 1209-1222, Sept., 1957.

9. W.C. Brown, "The Platinotron: Amplitron and Stabilotron", in E.C. Okress, Crossed-Field Microwave Devices, Vol. 2, Academic Press, 1961, pp. 165-209.

10. E.E. David, "Phasing by RF Signals" in E.C. Okress, Crossed Field Microwave Devices, Vol. 2, Academic Press, 1961, pp. 375-399.

11. Microwave Beamed Power Technology Improvement, JPL Contract #955104, with Raytheon, Monthly Progress Report #10 for April 1979.

12. Microwave Beamed Power Technology Improvement, JPL Contract #955104, with Raytheon, Monthly Progress Report #14 for August 1979.

13. W.H. Kohl, "Handbook of Materials and Techniques for Vacuum Devices" Reinhold Publishing Corp, 1967, pp. 487-491.

14 Ayer, R.B., "High-power Industrial Vacuum Tubes Having Thoriated Tungsten Filaments," AIEE Trans., 72, Pt. 1, 121-125, (May 1953).

15. "Microwave Beamed Power Technology Improvement," JPL Contract #955104 with Raytheon Monthly Progress Report #5 for Nov. 1978.

16. "Microwave Beamed Power Technology Improvement," JPL Contract #955104 with Raytheon Monthly Progress Report #10 for April 1979.