Industrial Assessment

of the

Microwave Power Tube Industry

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PREFACE

The end of the Cold War has brought significant change to the defense industry. Reductions in the defense budget have sharply curtailed defense industry sales. Most defense suppliers have responded in predictable ways. They have reduced excess capacity, streamlined processes, and revamped supplier relationships. The sum total of these actions leads to increased efficiencies and reduced defense product costs, and better value for taxpayers. However, these changes also could impact the ability of the Department of Defense (DoD) to meet its future mission requirements.

The microwave power tube industry is one of many defense related industries that have been affected by this new environment. The DoD uses microwave power tubes in a wide variety of system applications, and will continue to do so well into the next century. Additionally, the Department of Energy (DOE) uses large, high-power klystron microwave power tubes for several applications, including high energy physics, nuclear physics, and materials science research.

The DoD formed an Integrated Product Team, with DOE participation, to analyze the effects of declining expenditures for microwave power tubes on its programs. The Integrated Product Team was co-chaired by the Offices of the Deputy Under Secretary of Defense (Industrial Affairs and Installations) and the Director, Defense Research and Engineering. The team consisted of personnel from the Army, Navy, Air Force, Defense Logistics Agency, the DoD Advisory Group on Electron Devices, the Office of the Secretary of Defense, and the Department of Energy. The team made extensive use of the large amount of information previously developed for various private and government reviews. The team also contacted the key microwave tube manufacturing companies and held discussions with senior company representatives.

We welcome comments on this report. Please address them to Mr. Martin Meth, Director, Industrial Capabilities and Assessments, Pentagon, Washington, DC, 20301-3300.

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Industrial Assessment of the Microwave Power Tube Industry

EXECUTIVE SUMMARY

Microwave power tubes are used in a variety of military, civil, and commercial applications.

The Department of Defense (DoD) uses microwave power tubes in land, sea, air, and space applications; in radar systems, in electronic warfare systems, and in telecommunications systems. The Department of Energy (DOE) uses large, high-power klystron microwave power tubes for several applications, to date primarily in accelerator systems in support of research. Klystrons, traveling wave tubes (TWTs), magnetrons and crossed-field amplifiers are the most widely used microwave power tubes and are the primary focus of this assessment.

Military-unique microwave power tubes advance current technology, particularly in the areas of efficiency, power, bandwidth, and reliability. DoD considers certain microwave power tube technologies critical to military effectiveness and has identified them as such in its Military Critical Technologies List. For this reason, the U.S. Government controls the export of microwave power tube technology and products, and limits procurement of certain military-unique microwave tubes to domestic sources.

DOE purchases “off-the-shelf” high-power klystron microwave tubes that already have been developed, demonstrated, and produced. These microwave tubes generally must meet less demanding operational performance requirements and tend to be less technically complex than those used for most DoD applications. DOE generally does not restrict its microwave power tube purchases to domestic suppliers.

Other civil agencies and commercial customers use microwave power tubes for a wide variety of radar, telecommunications, medical therapy, and industrial and consumer heating applications.

Design and manufacture of microwave power tubes require complex and specialized industrial capabilities.

Microwave tube designs require engineers with expertise in many of the physical sciences. For most applications, microwave power tubes are individually designed to meet unique application requirements, and designs rarely are based on a single set of engineering protocols. Microwave power tubes are manufactured and tested using customized equipment and processes which require significant capital investments. Limited production quantities provide little incentive to standardize design or manufacturing. These customized procedures and processes have resulted in unique, application-specific products, and for some high performance applications made reproduction (matching the microwave tube to system performance, form, and fit requirements) by another manufacturer technically challenging and costly.

DoD and DOE microwave power tube applications employ complementary industrial capabilities.

The same manufacturers provide microwave power tubes to DoD, civil government agencies, and commercial customers. DOE high energy physics research applications require very large, high-power, single frequency klystron microwave power tubes. DoD uses smaller, less expensive, multi-frequency klystrons as final power amplifiers in many military radar systems. Although differing applications require different products, klystrons used for either DoD or DOE applications employ industrial capabilities common to the industry for design, development, and production.

Microwave power tube sales have declined, primarily due to reductions in defense spending.

Historically, military purchases have accounted for the majority of world-wide microwave power tube sales. With the end of the Cold War, governments everywhere have cut back on military spending. Non-military sales have not compensated for shrinking military sales. Additionally, solid-state amplifiers have replaced lower-power microwave tubes in many new applications. Some analysts have suggested that solid-state amplifiers soon will replace microwave power tubes in the majority of DoD applications. This prediction appears to be overstated. Microwave power tubes continue to provide significantly higher power output and efficiencies than solid-state devices for mid- and higher-frequency applications.

Between 1985 and 1995, U.S. microwave power tube industry sales world-wide declined from $671 million[1] to $256 million (54% of worldwide sales) primarily as a result of reduced DoD purchases. DoD microwave tube purchases for new production systems and to replenish or repair microwave power tubes in fielded systems are projected at to remain at 1995 levels, approximately $180 million annually.

World-wide sales of microwave power tubes are expected to remain flat or to decrease slightly over the next five years. Most industry experts believe that U.S. manufacturer microwave tube sales bottomed out in 1994. However, increased commercial demand may lead to increased sales of microwave tubes for telecommunications satellites and ground stations. Both U.S. and foreign manufacturers are pursuing commercial opportunities throughout the world to compensate for flat military demand.

DoD Research and Development (R&D) spending also has declined, but planned funding levels are sufficient to meet DoD requirements.

Total R&D spending by U.S. microwave power tube manufacturers declined from $114 million in 1985 to $26 million in 1995. The decline in R&D was driven by

[1] Unless otherwise noted, all dollar figures are expressed in constant FY95 dollars.

significant decreases in R&D funding from DoD and civil agencies (from $54 million in 1985 to $7 million in 1995). Corporate spending to develop new products and processes, funded by microwave power tube sales, also decreased significantly (from $44.5 million in 1985 to $14.4 million in 1995).

U.S. microwave power tube manufacturers have indicated that corporate R&D investments are being directed increasingly at commercial applications. DoD technology investments emphasize increasing performance, developing standardized design protocols, and improving manufacturability. Commercial applications do not require the same technology investment focus.

However, planned DoD technology funding levels are sufficient to maintain essential industrial and technological capabilities and meet new DoD product technology requirements. In 1990, DoD established under Navy lead a Tri-Service Vacuum Electronics Program coupling centralized microwave power tube R&D planning and coordination, and decentralized management of specific DoD technical thrusts. The Department is projecting modest growth in this program, primarily sustained by Navy funding increases. (Army and Air Force funding to meet Service-specific requirements is projected to decline to minimal levels beyond FY96.)

DOE activities contribute to, but will not change fundamentally, the long-term sales picture.

A potential new DOE program, the Accelerator Production of Tritium (APT), could boost U.S. microwave power tube manufacturer sales. DOE is considering producing tritium -- a form of hydrogen used to enhance the explosive force of nuclear weapons -- at its Savannah River Site in South Carolina. A decision is expected in 1998. This application would require new design, large, high-power klystrons. DOE microwave power tube purchases for its APT program could exceed $20 million annually for a three-year period, beginning in 2000. Annual out-year repair and replenishment purchases likely would total less than one-half of the original annual procurement value. DOE prefers that critical components, such as klystrons, for this program be manufactured in the U.S. or its territories. (This does not mean necessarily that the contract must be awarded to one of the current domestic manufacturers. The contract could be awarded to a foreign firm willing to establish a U.S.-based production and repair facility.) For the three-year period, this program could boost U.S. manufacturer klystron sales by 50 percent; total U.S. manufacturer microwave tube sales would increase by about 8 percent.

The U.S. microwave power tube industry has restructured.

Some U.S. microwave power tube manufacturers have gone out of business; some have been absorbed by other manufacturers. Most industry analysts expect such adjustments to continue.

Since 1988, the number of production floor workers has been reduced by 50 percent, from about 3010 to 1570. Over that same period, the engineering workforce has been reduced by almost two-thirds, from 840 to 315. In 1988, when sales were much higher, microwave tube manufacturer R&D, production, and technical support functions each had their own engineers. Most companies now have reduced overhead costs by consolidating these separate functions into single organizations.

Today, eight domestic companies produce microwave power tubes.[2] Although all manufacture and repair microwave power tubes, four companies account for the vast majority of U.S. industry sales. CPI, Litton Electron Devices, the Teledyne Vacuum Technology Business Unit, and the Hughes Electron Dynamics Division collectively account for about 49 percent of world-wide microwave power tube sales, 91 percent of U.S. manufacturer sales, and 93 percent of sales for DoD applications. CPI and Litton manufacture a full range of microwave power tubes. Each of the remaining manufacturers generally specialize in one or two tube types.

[2] In addition, the Stanford Linear Accelerator Center, a high energy physics research laboratory operated by Stanford University under a contract from the DOE, develops and produces some high-power klystrons in limited quantities, primarily to support its own high energy physics research programs.

Although publicly-available financial information on microwave power tube manufacturers is limited, all companies surveyed indicated they currently are operating profitably. Those manufacturers which remain are: (1) increasing manufacturing efficiencies; (2) eliminating excess capacity; and (3) targeting non-military applications.

DoD intervention to preserve industrial capabilities is not required.

Industry trends have not adversely impacted the U.S. microwave power tube industry such that direct DoD intervention is required to maintain national security. Current microwave power tube industrial capabilities are adequate to meet DoD requirements.

Further declines in DoD sales or DoD R&D investments could alter this assessment. Although the quantities of microwave power tubes purchased for new DoD systems have declined, the number of microwave tube types in fielded military systems has not declined; and DoD requirements for technical support for fielded systems have not declined. More than 160 weapon systems contain a total of more than 170,000 microwave power tubes, and many of the systems employ three to five different tube types. Some systems contain more than 200 microwave power tubes. Reductions in DoD sales may result in additional engineering workforce decreases. This could lead to situations in which firms will be less able to provide timely technical support to fielded products.

Finally, reductions in DoD sales or decreases in DoD R&D funding levels may lead to situations in which firms will be unable to upgrade existing products or meet emerging new product performance and manufacturability requirements.

DoD must better coordinate its activities and investments to ensure capabilities will be available to meet future requirements.

Because of the diverse manner in which individual microwave power tubes are procured and uncertainties in future DoD system requirements, it is difficult to precisely project the types and quantities of microwave power tubes DoD will require in future years. Changed requirements for microwave power tube types or quantities could have a significant impact on individual manufacturers.

Since changing circumstances could endanger essential engineering and product development capabilities, DoD must better monitor the U.S. microwave power tube industry and coordinate its microwave power tube activities. DoD will designate the Navy as its executive agent to: (1) identify and maintain consolidated DoD microwave power tube acquisition requirements and R&D plans, (2) monitor the major domestic microwave power tube manufacturers and key component and material suppliers, and (3) facilitate coordination among the Services and Defense Agencies, and among DoD and other U.S. Government Agencies which use microwave power tubes. The executive agent will report to the Under Secretary of Defense for Acquisition and Technology.

Section 1.0 - Microwave Power Tubes

1.1 Introduction

Microwave power tubes and solid-state devices are used to generate and amplify microwave energy -- a form of electromagnetic radiation -- for a variety of applications. DoD uses microwave power tubes such as klystrons, traveling wave tubes (TWTs), and crossed field amplifiers in land, sea, air, and space applications; in radar systems, in electronic warfare systems, and in telecommunications systems. DOE uses large, high-power klystrons to power particle accelerators used for high energy physics, nuclear physics, and materials science research. Additionally, DOE is considering developing a new capability for nuclear weapons material production, for which it also would use large, high-power klystrons.

1.2 Microwaves, a Form of Electromagnetic Radiation

Figure 1 depicts the electromagnetic frequency spectrum. Wavelengths in the electromagnetic spectrum correspond to those frequencies defined as *ultra high* (UHF), *super high* (microwaves), and *extremely high* (EHF, or millimeter waves). For historic reasons, many microwave power tubes are identified as being “microwave” despite the fact that they actually operate at longer (UHF) wavelengths and shorter (EHF) wavelengths than those actually within the “microwave” frequency spectrum. This report includes those classes of microwave power tubes which generate or amplify electromagnetic radiation with a wavelength ranging from 30 centimeters (cm) to 1 millimeter (mm), and a frequency ranging from 1 gigahertz (GHz) to 300 GHz. It also includes the klystron microwave power tubes which DOE uses for programs in its Office of Energy Research, such as high energy physics, nuclear physics, and basic energy sciences research; and for potential nuclear weapons material production. These microwave power tubes operate in the 300 megahertz (MHz) to 1 GHz range of the UHF frequency spectrum. (Figure 1 also locates the various “radar bands” within the overall frequency spectrum which are referenced in the discussion of specific microwave power tube applications in subsequent sections of the report.)

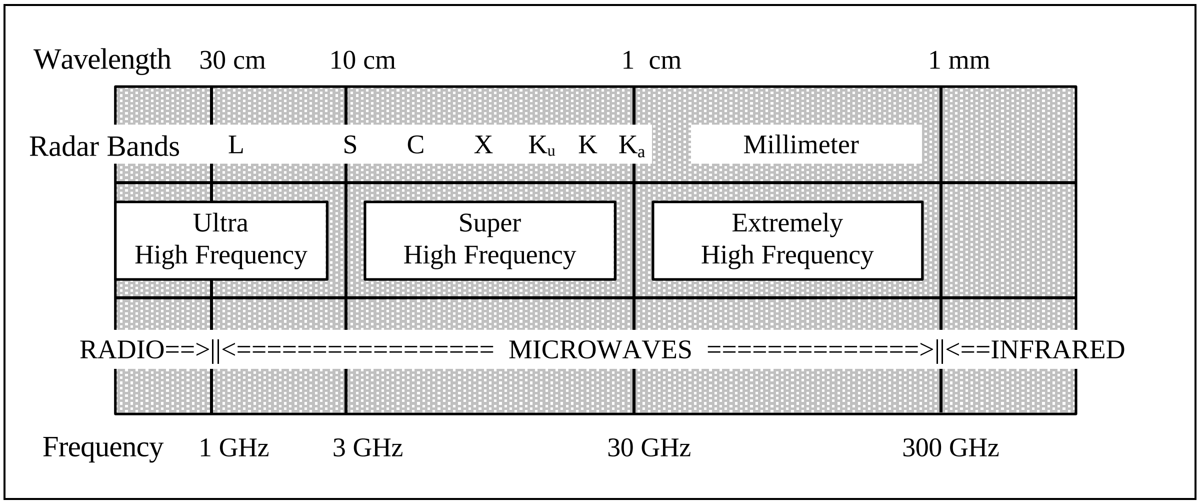

Figure 1: The Electromagnetic Frequency Spectrum

Microwaves exhibit several properties of visible light: (1) they travel in straight lines at the speed of light and are only minimally refracted by the earth's atmosphere; and (2) they can be focused into narrow beams which are subject to complete reflection when they impinge upon a conducting surface. These properties make microwaves especially useful for radar and telecommunications systems.

1.3 Microwave Amplifiers

Within the frequency range of interest, two technologies (vacuum and solid-state electronics) are used to generate and amplify microwaves. Each offers advantages for specific applications within the performance domain of radio frequency (RF) systems (see Figure 2). Microwave power tubes (the principal product derived from RF vacuum electronics) are preferred for applications requiring both higher frequency and higher power. Electron transport in a vacuum conveys as advantages to microwave power tubes such features as wide band performance, efficiency, thermal robustness, and radiation hardness. Alternatively, solid-state power amplifiers combine the power from many transistors. The advantages of charge transport in a solid-state media yield compact devices with superior reliability, and competitive efficiency and bandwidth at lower frequency and power. Solid-state power amplifiers, transmit/receive (T/R) modules, and active arrays use a variety of power combining techniques to provide competitive total power. These power combining techniques extend the applicability of solid-state devices into the region of complementarity shown in Figure 2.

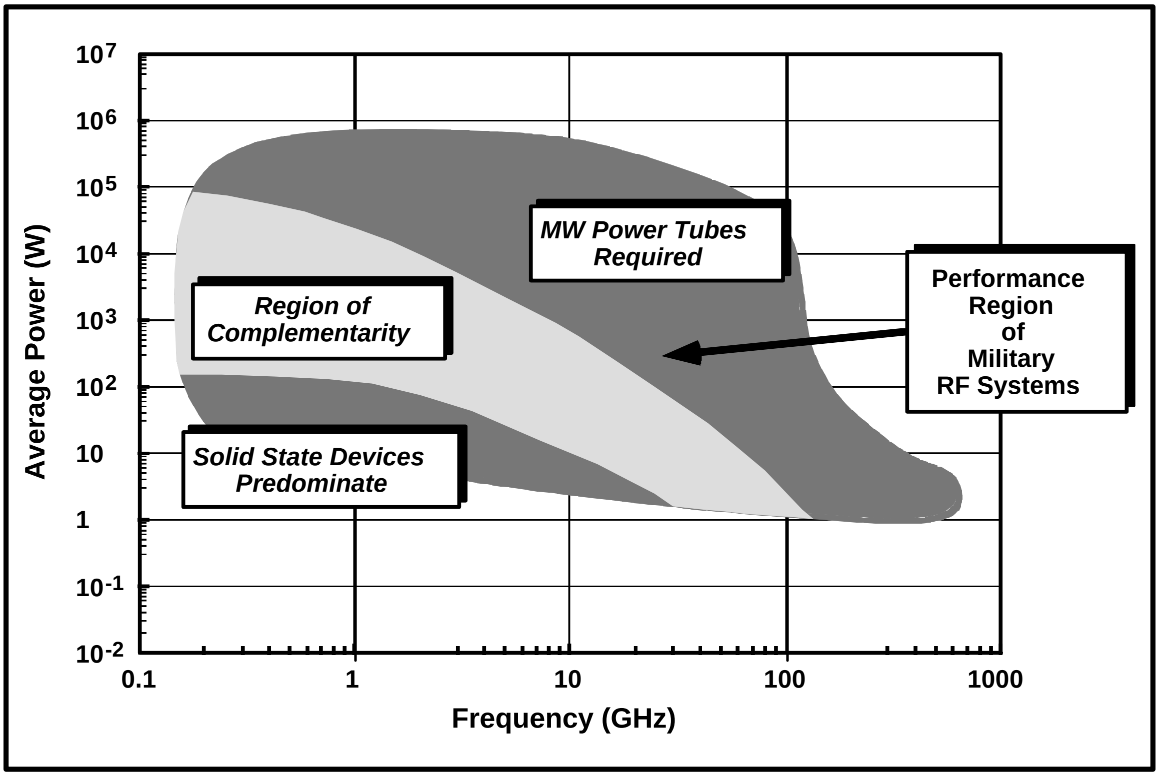

Figure 2: Devices and Military Applications

Source: U.S. Naval Research Laboratory

More recently, the Microwave Power Module (MPM), a synergistic combination of vacuum and solid-state elements, has been developed to compete in this region of modest power. By combining a low-gain vacuum power booster with a wide band monolithic solid-state driver and integrated power supply, the MPM provides the system designer a wide band building block featuring compact size, light weight, and highly efficient performance.

1.3.1 Microwave Power Tubes

Early microwave power tube development was driven by the military needs of the Second World War. Military systems utilize microwave power tubes which continually push the envelope of the state of the art, particularly in the areas of efficiency, power, bandwidth, and reliability. Non-military microwave tubes generally must meet less demanding operational performance requirements. Microwave power tubes designed for civil and commercial applications still tend to leverage features and capabilities designed for DoD applications.

Figure 3 summarizes the various types of microwave power tubes in use today.

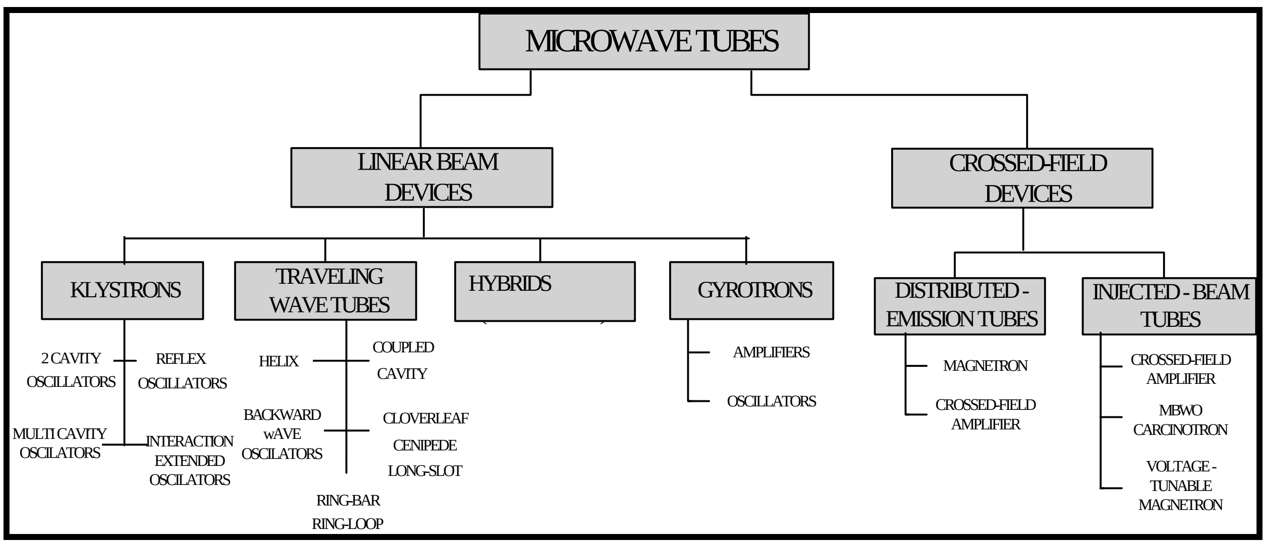

Figure 3: The Microwave Tube Family

Source: U.S. Naval Surface Warfare Center

Figure 4 summarizes microwave power tube operating characteristics and applications.

Tube Type	Frequency --------------- Bandwidth	Power Out (Typical)	Attributes ------------- Drawbacks	Applications
Klystron	0.1 - 300 GHz -------------------- 5 - 10%	10 Kw CW** 10 Mw Pulse	High Power 40-60% Efficient Low Noise ---------------------------------- Narrow Bandwidth	Radar Television Industrial Heating Satellite Uplinks Medical Therapy Science
Traveling Wave Tube (Helix)	1- 90 GHz -------------------- Wide bandwidth 2-3 octaves*	20w CW and 20 Kw CW	Broad Bandwidth -------------------------------- Power Handling Limitations Efficiency	Electronic Warfare Communications Comm'l Broadcasting Industrial Applications
Coupled Cavity TWT	1 - 200 GHz -------------------- 10 - 20%	300w CW 250 Kw Pulse	Average Power Capability ---------------------------------- Complex & Expensive Slow Wave Structure	Airborne Radar Satellite Communications AEGIS FC Illuminator
Magnetron	1-90 GHz ------------------- N/A	100w CW 10 Mw Pulse	Simple - Inexpensive Rugged ------------------------------ Noisy	Radar / Medical Industrial Heating
Crossed Field Amplifier	1 - 30 GHz ------------------ 10-20%	1000w CW 5 Mw Pulse	Compact Size 30-40% Efficient ---------------------------------- Complex & Expensive Slow Wave Structure	Transportable Radars Shipboard Radar Seeker Radars Industrial Heating
Gyrotron	30 - 200 GHz ----------------- 10% max	0.2 - 3 Mw Pulse	High Power @ High Frequencies ---------------------------------- High Voltage Req'd	High Frequency Radar Fusion Accelerators Industrial Heating

* One octave is the range defined where the highest frequency is twice the lowest, e.g. 2-4, 4-8, etc.

** DOE's APT klystrons will run at 1 Mw CW.

Figure 4: Typical Microwave Tube Characteristics & Applications

Klystrons, TWTs, and crossed-field devices (i.e., magnetrons and crossed-field amplifiers) are the most widely used microwave power tubes and are the primary focus of this assessment. Gyrotrons are newly emerging microwave power tubes, currently with limited applications.

There are wide differences in the physical size of microwave power tubes. TWTs and low power klystrons can be a few inches long and weigh several pounds. High power klystrons can be over 20 feet long and weigh two tons. Figure 5 is a photograph of a large high-power klystron similar to those used for high energy physics and ground radar applications.

Figure 5: High Power Klystron
Courtesy of Litton Electron Devices

Low power magnetrons (for example, the device on the top of a microwave oven) can be as small as a cat food container, while crossed-field amplifiers can measure two feet in diameter and weigh several hundred pounds. Selling prices for microwave power tubes also vary widely. Specialized klystrons used in high energy physics research can sell for several hundred thousand dollars. Simple magnetrons sell for less than $30, while high-power magnetrons for radar applications sell for several thousand dollars. TWTs used in electronic warfare applications sell for between $2,000 and $25,000. TWTs used in satellites sell for $100,000 or more. Figure 6 is a photograph of a TWT used in satellite applications. Appendix C contains a detailed discussion of the various microwave tubes.

Figure 6: Traveling Wave Tube Used in Satellites

Courtesy of Hughes Electron Dynamics Division

1.3.2 Solid-State Power Amplifiers

Solid-state power amplifiers (SSPAs) use transistors, not vacuum electronic devices, to amplify microwaves. Performance depends upon the characteristics of the transistors used and the efficiency of the combining technique. At lower frequencies and power, SSPAs are less expensive, more reliable, and inherently quieter than microwave power tubes. SSPAs for microwave applications are composed of many individual transistors connected in parallel, their output "summed" in a combining network to achieve power levels useful for radar or telecommunications. Each type of transistor has specific limitations due to its material properties (defect densities, carrier mobility, thermal conductivity, etc.) which determine its useful operating frequency and power output. In transistors of a given material, the output power generally varies inversely with the square of the operating frequency.

Some analysts have suggested that SSPAs soon will replace microwave power tubes in the majority of DoD applications. This prediction appears to be overstated. Microwave power tubes continue to provide significantly higher power output and efficiencies than SSPAs, for mid- and higher-frequency applications.

F.A. Olsen of Varian Associates, evaluated the current state of the technology and projected evolutionary improvements in the power output of well known microwave SSPAs.[1] Olsen concluded that: (1) microwave solid-state amplifier capability would increase by a few decibels[2] (dB) in the next decade, (2) the main solid-state progress would be in improved efficiency and lower cost, and (3) the new solid-state devices being developed are not expected to improve power performance in the mid- and higher-frequencies, where microwave power tube devices are dominant. Therefore, the applications being served today by microwave tubes will likely continue without significant

[1] F.A. Olsen, Varian Associates, Microwave Solid-state Power Amplifier Performance, Present and Future, December 1993.

[2] A logarithmic measure of power in which power doubles for every three dB.

change, particularly for mid- and higher-frequency applications.

1.3.3 Microwave Power Modules

The microwave power module (MPM), developed with DoD funding, is the most recent entry in microwave source technology. The MPM is a hybrid device that incorporates a solid-state driver, a microwave tube power booster, and a power-conditioner. The MPM is capable of meeting requirements for efficiency, noise, and power for which neither solid-state devices nor microwave power tubes alone are completely satisfactory. The solid-state driver develops a relatively low noise, low power (about one watt) signal which is amplified in a TWT power booster to provide a low noise RF output of about 100 watts. MPMs are replacing solid-state devices operating at the upper limits of solid-state amplifier power output and frequency.

1.4 Industrial Capabilities

The same manufacturers develop, produce, and repair microwave power tubes for DoD, civil agency, and commercial customers. The industrial capabilities required to develop, produce, and repair microwave power tubes generally are available from more than one microwave tube manufacturer, but they are not common to other industries. For most DoD applications, microwave power tubes are individually designed to meet unique application requirements, and designs rarely have been based on a single set of engineering protocols. Microwave tube design engineers require expertise in many of the physical sciences.

Limited production quantities provide little incentive to standardize design or to automate manufacturing. Individual microwave power tubes are designed, manufactured and tested in a manner that has resulted in unique application-specific product designs, and for some high performance applications made reproduction (matching microwave tube and system performance, form, and fit) by another manufacturer technically challenging and costly. Microwave power tubes are manufactured and tested using customized equipment and processes which require large capital investments. Piece part and assembly dimensions are tightly controlled, and specialized manufacturing skills are required, many of which are not readily amenable to automation.

DOE and other civil agencies generally purchase “off-the-shelf” (already developed, demonstrated, and produced) high-power microwave power tubes. Applications in particle accelerators, energy research, and civil radar systems require some of the largest (over 15 feet tall) and most expensive (more than $200,000 each) microwave power tubes ever built. However, these microwave tubes tend to be less constrained by size and input power requirements than those used for most DoD applications.

Despite the complexities, some microwave power tube manufacturers, however, have been absorbed by others, and the associated industrial capabilities have been successfully transferred. For example, Litton Electron Devices purchased Raytheon’s microwave power tube business and transferred Raytheon’s knowledge, processes, and equipment to its San Carlos, CA and Williamsport, PA facilities.

1.4.1 Design

Although a microwave tube is a component of a larger subsystem, its performance is a major factor in defining overall system performance. Design is critical for both performance and life expectancy. For example, the ability to locate an incoming missile and steer an intercepting missile to the target is dependent on the characteristics of the microwave signal being transmitted by the defending radar. The power of the microwave tube, the internal noise generated by the tube, and the sensitivity of the receiver determine the range at which the detection and intercept of an enemy target can occur. As another example, TWTs designed for satellite applications must be able to withstand the hostile space environment and operate for many years at high efficiency with significant constraints on weight, size, power consumption, and heat dissipation.

The need to maintain a vacuum envelope complicates the selection of materials and processes. Beryllium oxide is used for the waveguide windows through which the microwave input and output signals pass. Beryllium oxide is a carcinogen, the use of which creates health hazards and legal liabilities. The waveguide windows must be transparent to the electromagnetic energy and impervious to the outside air. Additionally, with typical output power levels of thousands of watts, dissipating unspent energy also is a significant consideration. Some tubes are air cooled, but the majority of the high-power tubes require liquid cooling. Microwave tubes for space applications are cooled by allowing heat to radiate into space. (Note the cooling fins in the TWT in Figure 6.)

The capabilities required to design application-specific microwave power tubes to meet DoD, civil agency, and commercial customer requirements are unique to this industry. Although individual companies now are developing engineering standards, tube designs rarely have been based on a single set of engineering protocols. In most cases, design modeling is incomplete and must be balanced by empirically-derived data. Microwave tube design engineers must have expertise over a large span of the physical sciences: electron optics, mechanics, magnetics, thermodynamics, physical chemistry, metallurgy, and microwave physics. Both advanced education and experience is required to develop this expertise.

1.4.2 Manufacture

The facilities, equipment, and processes used to manufacture microwave power tubes are unique to the industry, and frequently customized within the industry. Different types of microwave tubes are based on widely varying designs. The size of the microwave tube is an obvious manufacturing consideration. Even within the same tube type, size differences can be substantial, requiring different manufacturing facilities, equipment, and processes.

The need to maintain close tolerances requires customized manufacturing processes and equipment. Hundreds of precisely dimensioned pieces made of special metals and ceramics must be accurately positioned before being brazed together.[3] Electron

[3] Brazing is a materials joining process similar to soldering, but involving higher temperatures and stronger bonding materials.

optics and beam focusing must be virtually perfect to prevent meltdown of anything the electron beam strikes. For example, the electron beam in the AEGIS illuminator tube, a coupled cavity TWT, has a power density of several million watts per square centimeter. The electron beam could vaporize instantly any incorrectly positioned element. The alignment of the magnetic field with the axis of the helix in a TWT is especially challenging. Variations in the magnetic flux of the individual ring magnets require that the magnets be selected and placed individually to produce an effective final magnetic flux with minimum deviation from the axis of the tube.

These complex manufacturing considerations require a variety of customized equipment and facilities -- precision metal-cutting machines to shape the individual piece parts, brazing furnaces, bake-out ovens, clean rooms, vacuum exhaust systems, and test and burn-in stations.

The component parts frequently require chemical processing. Often, plating with precious metals such as silver or gold is required to ensure proper brazing or desired surface characteristics. The plating and chemical cleaning areas must be environmentally secure, provide adequate safety to the operators, and accommodate the safe and effective disposal of chemical waste.

Many of the manufacturing processes are labor intensive, requiring skills developed via on-the-job training and work experience. Such processes do not lend themselves readily to automation. Assembly of individual parts into sub-assemblies and sub-assemblies into the vacuum envelope require a clean room environment. The tubes must be kept clean and free of dust and other contaminants which could poison the cathode and reduce or prevent emission. To maintain a high degree of cleanliness, many tubes are assembled in laminar air-flow work-stations, with parts kept in nitrogen-charged containers until needed. In some cases, specialty welding tools (spot, laser, electron beam) are required to complete the sub-assembly. Operators often use microscopes to precisely position or inspect the parts before making the weld.

There may be several sequential brazing operations (which often take place in a continuous product flow furnace) required as the tube components are assembled. Extremely thin sheets of precious metal or precious metal alloys (gold, silver, or platinum) are used as braze material at the interfaces of the various parts. The braze material must be cut carefully to provide exactly the right amount of material to “flow” and complete a vacuum tight joint when heated to the appropriate temperature. The temperature must be controlled carefully so that the earlier brazes which completed the sub-assemblies are not remelted.

The final assembly, completing the vacuum envelope around the sub-assemblies, takes place in a large vacuum or hydrogen furnace. An inert gas furnace atmosphere or vacuum is used to prevent oxidation during the operation. The air is evacuated from the tube at the elevated temperature and then “baked out” to remove trapped gases in the metals within the vacuum envelope.

After the tube has completed bake-out, the vacuum envelope is sealed and the tube is packaged. Magnetic materials are installed. Potting compound is added to aid in maintaining the structural integrity of the assembled tube and to maintain the correct orientation of the magnetics and the proper separation of high voltage leads and connectors. If liquid coolant is to be used, the connectors will be added during packaging. At this point, approximately 75 percent of the cost of the tube has been incurred. *In situ* testing can provide only limited insight into the ultimate performance of the tube. It is only after the tube has been sealed that its performance can be demonstrated. After the tube has been “packaged,” it is sent to “burn-in” and final test.

1.4.3 Test

Fully instrumented computerized test sets exercise the tube sufficiently beyond the limits of its expected performance to ensure appropriate safety margins. Typically, production test sets are automated and provide the operator essentially with a performance booklet (including spectrum analysis of the output signal, power output, precise frequency measurement, and complex noise measurement) for each microwave tube.

Most instances of new DoD electronic systems using microwave tube technology "push" the performance envelope. Designing, developing, building, and assembling test equipment to test the new tubes require similar advances in test equipment. The test equipment often becomes the pacing element in engineering development contracts and it is not uncommon for the manufacturer to have to build its test set from scratch.

After test, the tube may be placed in aging equipment similar to the test set (comparable system operating voltages and signals). Performance will be monitored to insure that the tube continues to operate satisfactorily, but none of the detailed tests of the test set will be run. If a premature failure is to occur, it will usually happen during this "burn-in" period.

1.4.4 Repair

Because of their relatively high unit costs, microwave tubes are candidates for repair when they are accessible and expected to operate for extended periods of time. Manufacturers will evaluate a returned tube to determine if it is repairable. If the tube can be repaired, it will be "depackaged" down to the vacuum envelope assembly and inserted into the manufacturing flow at the appropriate location to begin the rework process. Repair costs depend on the particular failure mode. Generally, a tube that loses its vacuum while in operation will suffer catastrophic damage and must be discarded. Some applications, such as space systems microwave power tubes and munitions sensors, cannot be repaired once deployed. About 25 percent of the value of DoD microwave power tube purchases are to repair failed tubes.

1.4.5 Implications of Application-Unique Product Design, Manufacturing, and Test

Lack of Standardization

Even within the same facility, microwave power tube designs have reflected the individual philosophy of the designer. Microwave tubes have been developed with widely varying designs, even for tubes with nearly identical applications. In the past, neither DoD nor industry emphasized the use of common parts, components, or processes. Manufacturability (designing for production) and "repairability" (designing for repair) rarely were considered. For new designs, this is beginning to change. Standardized designs are being implemented for common sub-assemblies such as electron guns, pole-pieces and collectors. Microwave tube manufacturers are attempting to utilize common parts in different product lines when feasible. However, these standardization activities generally do not address repair or replacement of microwave power tubes in currently fielded systems.

DoD has tried to encourage standardization by developing an interactive computational design framework populated with up-to-date design tools. The Microwave/Millimeter Wave Advanced Computational Environment (MMACE) project, an element of the DoD Vacuum Electronics Initiative, is intended to provide the community with an integrated software capability to design, simulate, prototype, and manufacture complex tube designs. The MMACE design process reinforces standardization, while the interoperability of design tools through the data exchange framework accelerates the design process by allowing improved product optimization. The MMACE project responds to the complexity of power tube design by providing progressively improved design tools through DoD sponsored development and the adaptation of commercial and public domain codes.

Risks Associated With Developing Alternative Sources

A survey of five major Air Force electronic warfare systems revealed that of the 21 different types of microwave power tubes used, 14 were provided by single sources. This is typical of the prevailing microwave power tube acquisition environment. Because of the wide differences in microwave power tube designs and manufacturing equipment and processes within the industry, the DoD would face some measure of risk (technical challenge, time, dollars) if it were forced to *quickly* develop alternate suppliers for specific microwave tubes. Each of the military services has had difficulty finding and qualifying second sources that can replicate existing high performance microwave tube and system output characteristics. For example, DoD and a second contractor invested several years and several million dollars in an ultimately unsuccessful attempt to create a suitable alternate source for a critical microwave tube, despite having access to data from the original manufacturer. The complex interactions of many important, and sometimes not completely understood, microwave tube performance variables collectively lead to specified tube and system performance. Consequently, it is difficult to replicate microwave tube and system performance requirements. Without a close systems match in performance characteristics of the alternative microwave tube, some modifications to interface elements (software, power supplies, etc.) of the system would be required, or some system performance degradation accepted. Such modifications can significantly increase costs, reduce system availability, and increase risk. The potential problem is exacerbated somewhat by the fact that the Military Departments are moving to "lean logistics". In most cases, DoD maintains a microwave tube inventory of only a few months. If a sole source manufacturer of microwave power tubes used in current DoD applications exited the market, difficulties or delays in qualifying a second source to provide replacement microwave power tubes could degrade operational effectiveness.

Section 2.0 - Microwave Power Tube Sales

2.1 Introduction

Historically, military purchases have accounted for the majority of world-wide microwave power tube sales. With the end of the Cold War, governments everywhere have cut back on military spending. Non-military sales have not compensated for shrinking military sales. Solid-state amplifiers have replaced lower power microwave tubes in many new applications, reducing market size even further. World-wide sales of microwave power tubes are expected to remain flat or to decrease slightly over the next five years. Some microwave power tube companies have gone out of business; some have been absorbed by other manufacturers; others have restructured. Most analysts expect industry adjustments to continue. However, increased commercial demand may lead to increased sales of TWTs for telecommunications satellites and ground stations. Both U.S. and foreign manufacturers are pursuing commercial opportunities throughout the world to compensate for stagnant military demand.

2.2 World-Wide Sales

Comprehensive world-wide microwave power tube sales trend information is not available. However, the Electronics Industry Association (EIA) did perform a "snap shot" analysis of 1995 world-wide microwave power tube sales (Figure 7). Total world-wide sales were estimated at $476 million.[4] (This does not include the substantial volume of microwave power tubes used in the Russian and Chinese markets, for which information was not available.) U.S. manufacturers accounted for $256 million (54 percent of the total). U.S. companies also account for the majority of world-wide sales of helix and coupled cavity TWTs. This is due primarily to large sales to DoD. Non-U.S. manufacturers, led by Thomson TTE, account for the majority of world-wide sales of klystrons and crossed-field devices, mostly for non-military applications. English Electric Valve (EEV, United Kingdom) and Nippon Electric Corporation (NEC, Japan) also have significant microwave power tube production capabilities.

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[4] Unless otherwise noted, all dollar figures are expressed in constant FY95 dollars.

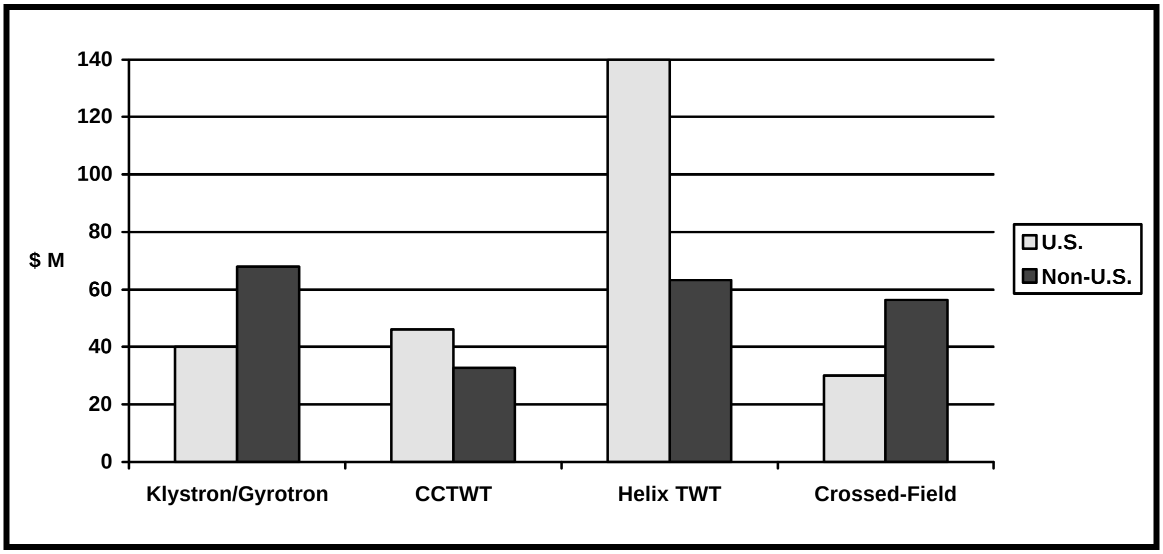

Figure 7: U.S. and Non-U.S. Manufacturer Microwave Tube Sales (1995)

Source: EIA/Industry Data

The 1995 EIA sales figures indicate that four of the top seven manufacturers are U.S. companies (Figure 8).

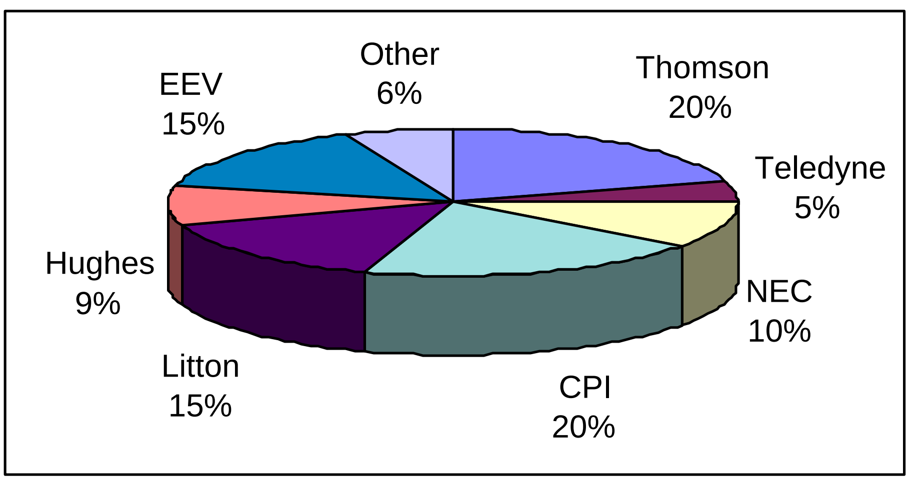

Figure 8: 1995 Market Shares - Leading Microwave Tube Manufacturers

Source: EIA/Industry Data

2.3 U.S. Industry Sales

Between 1985 and 1995, U.S. manufacturer microwave power tube industry sales declined 62 percent -- from $671 million to $256 million (Figure 9). During this same period, DoD purchases declined 68 percent (from $570 million to $180 million) and U.S. manufacturer non-DoD sales declined 25 percent (from $101 million to $76 million).

The relative importance of DoD purchases to the industry has thus declined over time. In 1985, sales for DoD applications accounted for 85 percent of U.S. manufacturer microwave power tubes. In 1995, DoD purchases represented 70 percent of U.S. manufacturer microwave tube sales, and 38 percent of world-wide sales.

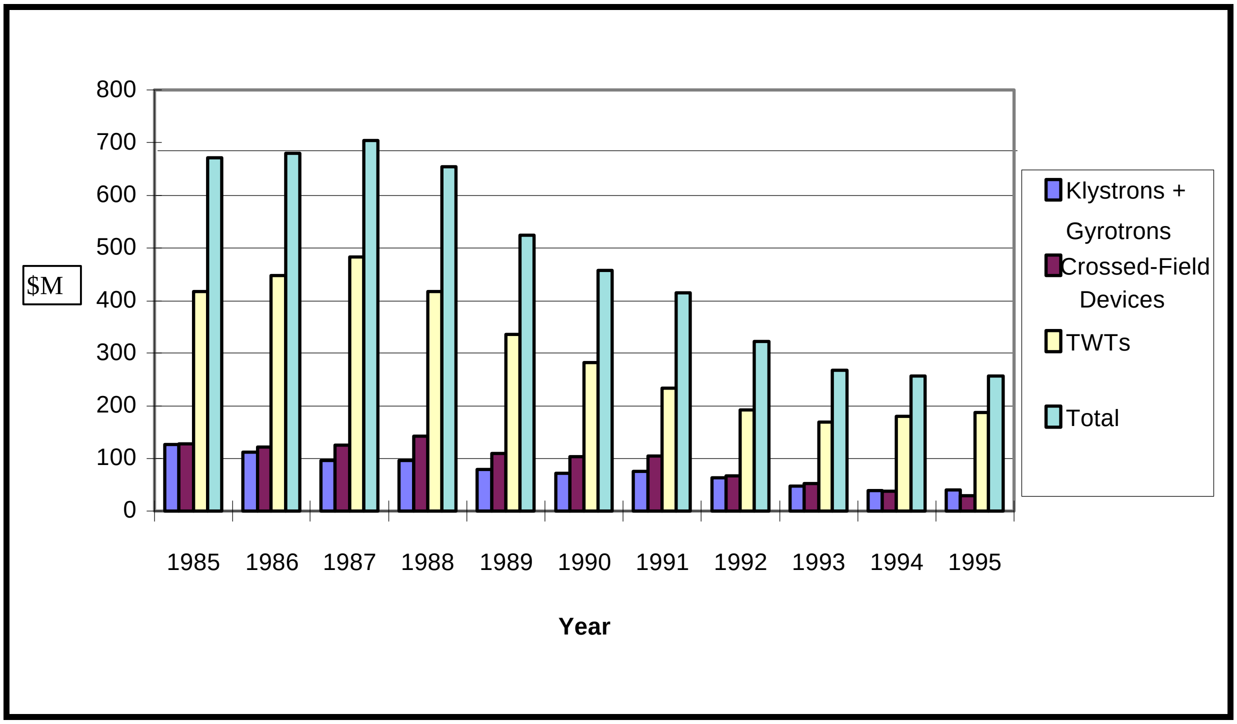

Figure 9: U.S. Industry Microwave Tube Sales (FY95$)

Source: EIA

Figure 10 summarizes 1995 U.S. manufacturer microwave power tube sales, by application area. The electronic warfare demand is exclusively military. DoD, other U.S. government agencies, and commercial customers use microwave power tubes for radar, space, and communications system applications. Primarily due to increased commercial demand projections, sales of space TWTs are projected to grow as much as 30 percent annually for the next several years.

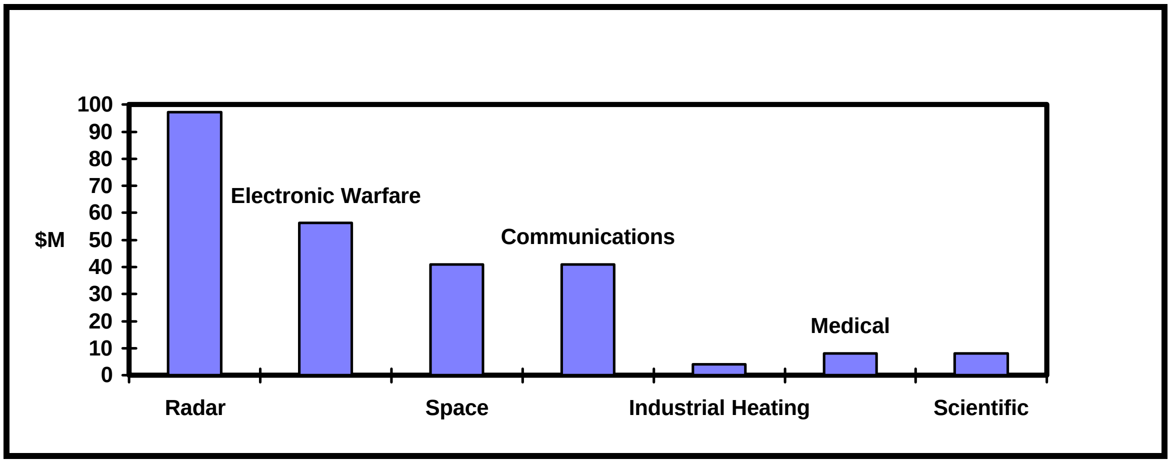

Figure 10: U.S. Microwave Tube Sales (FY95) by Application Area

Source: Technology Service Corporation[5]

The EIA's annual report of microwave tube sales indicate that 10-15 percent of U.S. manufacturer 1995 sales are for exports. Additionally, "sales" associated with microwave power tube repairs can represent as much as 25 percent of individual company total sales. (Microwave power tubes typically sell for thousands of dollars, and failed tubes are returned to the manufacturer for possible repair.)

The importance of DoD sales varies among the four largest U.S. manufacturers -- ranging from a high of 85 percent to a low of 60 percent. DoD sales are projected to remain flat, but increases in commercial applications (particularly for communications and space applications) could boost sales. Each U.S. microwave power tube manufacturer is seeking to increase its commercial sales, but only one firm forecasts the majority of its future sales shifting from DoD to commercial customers.

[5] Technology Service Corporation has supported the Crane Division of the Naval Surface Warfare Center for more than 20 years studying logistic trends and forecasting requirements for microwave tubes for which the Center is responsible.

Section 3.0 - Requirements

3.1 DoD Requirements

Early microwave power tube development was driven by the military needs of the Second World War. Military systems utilize microwave power tubes which continually advance technology, particularly in the areas of efficiency, power, bandwidth, and reliability. Non-military microwave tube applications generally require less demanding performance. Microwave power tubes designed for civil and commercial applications still tend to leverage features and capabilities designed for DoD applications.

Precisely determining outyear DoD microwave power tube quantities is made difficult by limited visibility primarily due to the manner in which individual microwave tubes are procured and used, and uncertainties in future DoD systems requirements.

Microwave power tubes used in a new military aircraft radar sometimes are procured by a major subsystem contractor such as Northrop Grumman to support a prime contractor such as McDonnell Douglas. However, in the case of the Navy’s AEGIS Program, the microwave tubes used for the SPY-1 radar are procured directly by the Navy and supplied to the contractor as government furnished equipment. In the case of electronic warfare (EW) applications, new systems (including the microwave power tubes) may be procured directly by a program office specializing in EW systems. Replacement microwave tubes, a significant portion of industry sales, are generally procured by the logistics support elements of the Military Services or by the Defense Logistics Agency. These diverse procurement practices make it difficult for DoD to precisely determine the types and quantities of microwave power tubes collectively procured for DoD applications. Warner Robins Air Logistics Center, the Air Force Center for EW systems, publishes an annual brochure that includes long range forecasts of the Air Force’s EW microwave tube requirements. The Navy has substantially centralized its management of microwave tubes at the Naval Surface Warfare Center, Crane Division, in Indiana and provides the most detailed forecasts of the three Services. The Army does not provide similar forecasts.

Figure 11 summarizes the number of microwave power tubes in service in DoD subsystems. A wide variety of DoD subsystems use microwave tubes: Airborne Fire Control Radars (APG-63, 65, 66, 68, 70, 71, 73, and 76); Airborne Search Radars (APS-116, 137); Airborne ECM systems (ALQ-99, 131, 135, 137, 155, 161, 162, 172, 184, 188, 196); Shipborne Surface Search Radars (SPS-10, 55, 64, 67); and Shipborne Air Search Radars (SPS-39, 40, 48, 52, SPY-1). These microwave power tubes must be repaired or replaced periodically. The Advisory Group on Electron Devices has estimated that at least 60 percent of the subsystems now using microwave power tubes still will be in active service in 2010.

Service	**Estimated Number of Microwave Power Tubes in DoD Subsystems**[6]
ARMY	35,000
NAVY	80,982
AIR FORCE	61,361
MARINES	2,500
TOTAL	179,843

Figure 11: Microwave Tubes in Use by U.S. Military

Source: Technology Services Corporation

Although projections are subject to uncertainty, DoD microwave tube requirements for new production systems, and for replenishment or repair of microwave power tubes in fielded systems, are projected to remain at a approximately $180 million annually.[7]

[6] Pod-mounted ECM devices and similar systems were assumed to be procured at a ratio of 30 percent of the total number of available aircraft.

[7] This projection assumes the new Navy ship class Surface Combatant 21st Century will use solid-state power amplifiers.

3.2 DOE Requirements.

DoD and DOE microwave power tube applications employ complementary industrial capabilities. Although differing applications require different products, klystrons used for either DoD or DOE applications employ similar industrial capabilities for design, development, production, and support. DOE accelerator applications require very large, high-power, single-frequency klystrons, which are not compatible with DoD applications. DoD uses smaller, less expensive, multi-frequency klystrons as final power amplifiers in many military radar systems. However, new military radar systems are being designed to use TWTs and solid-state devices which offer smaller size, higher efficiency, wider bandwidth, and lower cost. DoD now is purchasing klystrons for spares, replacements, and new production of older systems. For example, the Air Force is developing a new wide band klystron for its fielded Airborne Warning and Control System (AWACS). The increased bandwidth of the new tube will allow a single klystron to provide the frequency coverage of the previous two-tube configuration, the second wide band klystron becoming, in effect, an on-line spare.

DOE requirements for microwave power tubes are based on ongoing research programs and potential new production of nuclear weapons material. DOE purchases “off the shelf” microwave power tubes to support high energy physics research. Some of these klystrons were made by foreign manufacturers. They met application requirements, were available within the desired time, and were purchased at competitive prices. These purchases, however, have not been substantial when compared to total annual U.S. manufacturer microwave power tube sales. In aggregate, DOE’s purchases of foreign klystrons have averaged about $4 million per year over the past 20 years, less than 2 percent of 1995 U.S. manufacturer microwave tube sales, and about 10 percent of 1995 U.S. klystron sales.

The Stanford Linear Accelerator Center (SLAC) is a high energy physics research laboratory operated by Stanford University under a contract from the DOE. The SLAC develops some high-power klystrons, primarily to support SLAC's own high energy physics research programs. It has a substantial capability to design, develop, and test, and a limited capability to manufacture, large high-power klystrons for in-house research applications. Under the terms of its contract with DOE, the SLAC may not perform any non-DOE-funded work without the specific, written approval of the DOE contracting officer. In addition, the SLAC is a Federally Funded Research and Development Center (FFRDC). Federal acquisition regulations applicable to FFRDCs prohibit their use for quantity production without legislative authorization.

In the case of nuclear weapons material, the DOE is considering developing a new capability to produce tritium. Tritium is a form of hydrogen used to enhance the explosive force of nuclear weapons. DOE has initiated a program which may establish a new tritium production capability at the DOE Savannah River Site in South Carolina.

The program -- the Accelerator Production of Tritium (APT) -- is now in the development phase. Part of the effort is devoted to the development of a new high-power inductive output amplifier known as a "klystrode". If developed successfully, this tube will be much smaller in size and weight, and have as much as 20 percent greater efficiency, than existing klystrons. The new klystrode would operate at 700 MHz and deliver 1 MW of continuous wave power. In FY96, DOE awarded a R&D contract to Communications and Power Industries (CPI) to develop the new microwave power tube. DOE plans follow-on contracts in FY97 and beyond to develop and test one or more prototypes. If the accelerator approach is selected for tritium production, approximately 100 klystrons or klystrodes will be required annually for a three year period beginning in 2000. DOE purchases for APT microwave power tubes could exceed $20 million annually over the three year period, which could boost U.S. manufacturer klystron sales by about 50 percent and total U.S. manufacturer sales by about 8 percent. Subsequently, about 2005 and for the next 40 years, approximately 45 tubes will be repaired and 25 new tubes purchased each year. Each new klystron/klystrode is projected to cost in excess of $200,000.

DOE has indicated that a secure source of supply of tritium is essential to maintain the U.S. nuclear weapons stockpile. Therefore, it prefers an APT acquisition strategy which would have klystrons/klstrodes and other critical components manufactured in the U.S. or its territories. (This does not necessarily mean that the contract must be awarded to one of the current domestic manufacturers. The contract could be awarded to a foreign firm willing to establish a U.S.-based production and repair facility.)

3.3 Other U.S. Government Requirements

The FAA has 526 radars in operation, using approximately 1140 microwave power tubes. Support requirements call for the procurement of about 155 new tubes and another 175 tube repairs, annually. These requirements are expected to decline in the coming years as newer solid-state systems are put into service. Some 100 microwave tubes, used in four different radar systems, will be retired. Nonetheless, about 40 to 50 percent of the radars currently in active service (with the FAA and in foreign countries) will need microwave tube support for the next 15 to 20 years.

EIA and industry data indicate that approximately 30 percent of microwave tube sales are to non-DoD customers (U.S. civil government agencies and commercial customers). There will clearly be an increasing requirement for microwave power tubes qualified for space applications as civil U.S. government and commercial satellite use grows. Microwave power tubes also will continue to be used for non-DoD applications in navigation and weather radar, medicine, and industrial heating. However, future requirements projections in these areas are not available.

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Section 4.0 - U.S. Microwave Power Tube Industry

4.1 Manufacturers

Microwave power tube manufacturers usually are lower-tier suppliers selling products meeting a subsystem manufacturer's specification. Figure 12 lists the eight domestic companies now producing microwave power tubes, and the types of microwave power tubes each manufactures.[8] Although eight domestic companies, plus SLAC, manufacture and repair microwave power tubes, four companies dominate the U.S. industry. Communications & Power Industries (CPI)[9], Litton Electron Devices, the Teledyne Vacuum Technology Business Unit, and the Hughes Electron Dynamics Division collectively account for about 49 percent of world-wide microwave power tube sales, 91 percent of U.S. manufacturer sales, and 93 percent of sales for DoD.

Manufacturer	**Coupled Cavity TWT**	**Helix TWT**				**Klystron**				**Gyrotron**	**Magnetron**		**Crossed Field Amplifier**
		Low 100w	Med 500w	High CW	High Pulse	Low	Med	High CW	High Pulse		Low	High	
CPI - Palo Alto	x	x	x	x		x	x	x	x	x			
CPI -Beverly					x						x	x	x
Litton -San Carlos	x	x	x	x	x			x	x				
Litton - Willamsport					x	x	x				x	x	x
Hughes	x	x	x		x								
Teledyne			x	x									
Triton Services		x	x		x		x		x				
Northrop Grumman		x	x										
MPD											x		
Burle											x		

Figure 12: U.S. Microwave Power Tube Manufacturers

Source: U.S. Naval Surface Warfare Center

[8] In addition, the SLAC, a high energy physics research laboratory operated by Stanford University under a contract from the DOE, develops and produces high-power klystrons in limited quantities, primarily to support its own programs.

[9] CPI is comprised of what was formerly the six electron device divisions of Varian Associates.

CPI and Litton manufacture a full range of microwave power tubes. Each of the remaining manufacturers generally specializes in a particular microwave tube type. For example, Hughes' Electron Dynamics Division is the only U.S. manufacturer of microwave power tubes used in satellites. Hughes has captured approximately a 50 percent share of the world satellite microwave tube market. Today, Hughes' major competitor for space tube sales is Thomson TTE (an electronics business subsidiary of France's Thomson-CSF). NEC (Japan) has a small portion of the market, but is intending to grow.

Northrop Grumman accounts for a relatively small percentage of the industry's overall sales volume. However, it maintains a strong research and development (R&D) capability. Northrop produces microwave power tubes for its own use, although it also purchases tubes from other manufacturers. Northrop has been a leader in developing and producing the microwave power module. Triton Services (formerly a division of ITT), MPD (formerly a division of General Electric), and Burle are small companies with limited microwave power tube sales.

Most U.S. microwave power tube manufacturers operate their production facilities on a one shift per day, five days per week basis. However, Hughes' Electron Dynamics Division is operating its space TWT production line on a three shifts per day, seven days per week schedule to meet increased commercial space requirements.

In 1985, U.S. manufacturers led the world in both microwave tube sales and technology. Today, U.S. microwave tube manufacturers still hold a lead in total sales, but foreign products are being used for some DoD applications. For example, the system contractor uses a Thomson TWT to meet power handling requirements in the shipboard version of the Cooperative Engagement Capability equipment. No U.S. microwave power tube could simultaneously dissipate heat from the helix and provide the required output power level at the desired high frequencies. Furthermore, Thomson developed an innovative method to provide the necessary match between the output waveguide and the output section, further lowering the amount of heat to be removed during tube operation. U.S. industry representatives have stated that their efforts to meet the application requirements were hindered by shortages in experienced engineering personnel.

In the early 1990s, the system design agent for the ERINT missile program surveyed the U.S. microwave tube industry for a K_a band TWT for use in the missile seeker. AEG (Germany) was the only vendor with a proven TWT capability with the desired power, size, weight, and bandwidth at K_a band. In the mid-1990s, when the Patriot PAC-3 missile upgrade was being designed, there was a requirement for a TWT with similar characteristics. AEG still was the only microwave tube manufacturer which could meet performance requirements. The K_a band TWTs available from Litton, Hughes, and Thomson could not satisfy the desired power, bandwidth, and size requirements.[10] (Thomson recently acquired AEG.)

4.1.1 Personnel

As shown in Figure 13, the U.S. microwave tube industry has downsized. Since 1988, production floor workers have been reduced by 50 percent. More importantly, the engineering force responsible for designing the tubes and the test equipment used to insure the tubes perform as specified, declined by almost two-thirds. The greater reduction in engineering personnel primarily can be attributed to the fact that the prospects of developing new microwave tubes which would require their expertise was low.

[10] The Army has contracted with CPI to develop an alternative tube for the application.

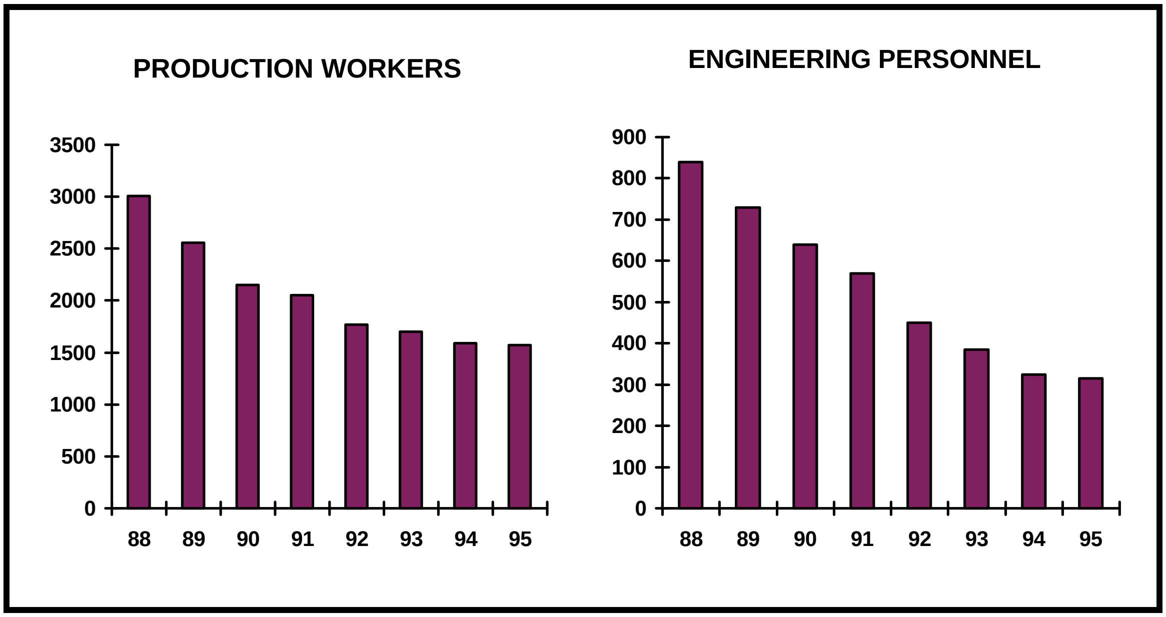

Figure 13: Microwave Power Tube Industry Personnel

Source: EIA

Previously, microwave tube manufacturer R&D, production, and technical support functions each had their own engineers. The decline in the number of engineers has led most companies to consolidate these separate functions into single organizations. However, the number of microwave tube types in fielded military systems has not declined; and DoD requirements for technical support have not declined. More than 160 weapon systems contain a total of more than 170,000 microwave power tubes, and many of the systems employ three to five different tube types. Some systems contain more than 200 microwave power tubes. Given the significant academic preparation and experience required to produce a capable microwave power tube design engineer, further drawdowns may lead to situations in which firms will be less able to provide timely technical support to fielded products.

Key developmental capabilities also were severely reduced during the corporate downsizing. As measured by both engineering employment and R&D income (see Section 5.2), the industry's capability for advanced product development has never been lower in the modern era. Any near-term recovery of this capability within the manufacturing sector will be inhibited by flat world-wide demand projections for microwave power tubes. Further engineering workforce drawdowns may hinder U.S. manufacturer ability to design and develop new microwave power tube products to meet emerging DoD new product requirements.

The Air Force conducts a focused program in vacuum electronics research and education through the Advanced Thermionic Research Initiative (ATRI) at the University of California at Davis. The ATRI program provides a multi-disciplinary education in engineering and physics at the Masters and Ph.D levels that develops new microwave power tube engineers, and also provides an opportunity for continuing education to the existing engineering workforce. Within the past year, 6 of the 21 students in the Davis program have graduated and taken positions in the microwave power tube industry. Since 1978, an average of 15 students per year have graduated from this and similar programs sponsored by DoD. Like engineers in the aerospace industry, microwave power tube engineers frequently move from one company to another throughout their career.

4.1.2 Financial Assessment

Publicly-available financial information on microwave power tube manufacturers is limited. However, all surveyed companies indicated they are currently operating profitably. The companies are: (1) increasing manufacturing efficiencies; (2) eliminating excess capacity; and (3) targeting non-military applications.

4.2 Component and Material Suppliers

Key microwave power tube component and material suppliers, as identified by the U.S. manufacturers, are listed in Figure 14. These suppliers: (1) provide essential specialized components and materials for which there is little demand outside the microwave power tube industry, (2) support multiple microwave tube manufacturers, and (3) represent a select few “demonstrated capability” suppliers. Additionally, most of the suppliers focus primarily on business applications not associated with microwave power tubes. (Appendix B contains more information on each supplier.)

The suppliers cover the spectrum from small privately-owned companies to business units within major corporations. For example, Union City Filament is a privately-owned company with approximately 38 employees, while Osram-Sylvania employs 1400 and is part of Osram GMBH, Germany, a $1.7 billion company in 1995.

Supplier	**Product**	**Comment**[11]
Brush Wellman	Beryllium related products	Single material producer
Ceradyne	Beryllium oxide (BeO) products for helix TWTs, advanced ceramics	Single producer for BeO products, ceases production in January 1998
Coors Ceramics	Advanced ceramics	One of several sources
H. Cross	Tungsten tape for helix TWTs	Sole domestic producer
Osram-Sylvania, Inc.	Tungsten wire	Single supplier to H. Cross, tube components a minor business segment
Union City Filament	Tungsten wire heaters	One of two suppliers
Semicon Associates	Cathodes, rare earth magnets, special metals	One of two suppliers
Spectra-Mat	Cathodes	One of two suppliers
CSM Industries	Molybdenum products	One of several sources
Electron Energy	Samarium-cobalt (rare earth) magnets	One of several sources
Hitachi Magnetics	Rare earth and other specialty magnets	No current contracts

Figure 14: Key Microwave Tube Suppliers

Source: DoD (Industrial Analysis Support Office)

The availability of beryllium oxide (BeO) is probably the single most important supplier issue currently facing the industry. BeO is an important material used in both the fabrication of helix support rods for TWTs and in waveguide windows. BeO exhibits high thermal conductivity and excellent electrical insulating and dielectric properties,

[11] A single source supplier is one which is the only source for a particular product now, but other sources are available if needed (given time and money to qualify similar, but not identical, manufacturing

characteristics which make it ideal for helix support rods. Helix support rods conduct heat from the helix to the shell of the TWT while insulating the helix from the shell. These same characteristics -- high thermal conductivity and good insulating and dielectric properties -- also make BeO an excellent material for waveguide windows. However, Ceradyne, the leading producer of precision ceramics using BeO, recently announced that it will discontinue producing beryllium oxide-silicon carbonate (BeO-SiC) products due to health hazards and the resultant legal liabilities. Ceradyne's customers have stated that there is no suitable substitute today with a high enough thermal conductivity to replace BeO. Pure beryllium is used for other applications, for example, the cathodes of some crossed field amplifiers. In these applications, a microscopically thin layer of BeO forms on the surface of the beryllium cathode. The thin layer of BeO has excellent secondary emission properties. It provides electrons in a cascading fashion such that there is an ample supply of electrons to build the amplifying spoke. Microwave tube manufacturers are exploring alternatives. Additionally, the Office of Naval Research at the Naval Research Laboratory (NRL) is sponsoring research in the use of synthetic diamond as a substitute material.

H. Cross is the sole domestic supplier of tungsten filament tape, a component essential to all helix TWTs. H. Cross is a small privately-owned firm that has a stable business and at this time does not appear to be a cause for concern. All of its processes and equipment are proprietary. Approximately 12 percent of its sales are for tungsten filament tape.

Osram-Sylvania, Inc. (OSI) is the single supplier of tungsten wire to H. Cross, which then processes the wire into tungsten filament tape. Another supplier, Elmet-Phillips, also sells tungsten wire, but the use of its wire reduces manufacturing yields for H. Cross' tungsten filament tape. OSI's production of tungsten wire is crucial to the manufacture of microwave tubes. However, OSI's primary customer base is lighting manufacturers. Its specialized tungsten wire for H. Cross represents less than one percent of its business. OSI

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processes or products). A sole source supplier normally has some genuinely unique equipment, process, facility, or technology and is the only one capable of producing the product.

has indicated that it may discontinue production of specialized tungsten wire to concentrate on its lighting customers.

4.3 Conclusions

Industry trends have not adversely impacted the U.S. microwave power tube industry such that direct DoD intervention is required to maintain national security. Current microwave power tube industrial capabilities are adequate to meet current DoD requirements. However, declines in projected purchases for DoD applications could alter this assessment. Changed requirements for microwave power tube types or quantities could have a significant impact on individual manufacturers and could endanger essential engineering and product development capabilities. DoD must better coordinate its microwave power tube activities and monitor the major domestic microwave power tube manufacturers and key component and material suppliers.

(In some cases, manufacturers supplying certain microwave power tubes which continue to be required for DoD applications decide to no longer supply such tubes. DoD deals with these situations on a case-by-case basis. The Department evaluates its projected requirements and potential options to ensure its requirements are met. Potential options include, but are not limited to, life-of-type buys, alternative sources, and alternative products.)

Section 5.0 - Technology Investments

5.1 Introduction

Military system requirements have been the primary drivers for product and process development investments within the microwave power tube industry. With the dramatic downturn in military procurements, that dependence has diminished as the industry looks more aggressively toward commercial opportunities for future growth. Unlike the military arena, where significant emphasis is placed on performance superiority in power, bandwidth, efficiency, and reliability, commercial applications do not require the same technology focus. Military requirements are further complicated by the multiplicity of distinct systems, a situation that dictates a wide variety of product designs each requiring unique parts, components, and manufacturing processes. DoD technology investments, therefore, are focused not only on improving performance, but also, and increasingly, on developing standardized design protocols and improving manufacturability.

Despite significant reductions in technology investments, current and planned DoD technology development funding is adequate both to sustain required development capabilities and to meet emerging DoD product technology requirements. However, reductions in projected DoD sales or decreases from planned DoD R&D funding levels may lead to situations in which firms will be unable to upgrade existing products or meet emerging new product requirements.

5.2 Research and Development

Funding to industry to develop and improve new microwave tube products and processes has decreased as corporate sales have decreased (Figure 15).

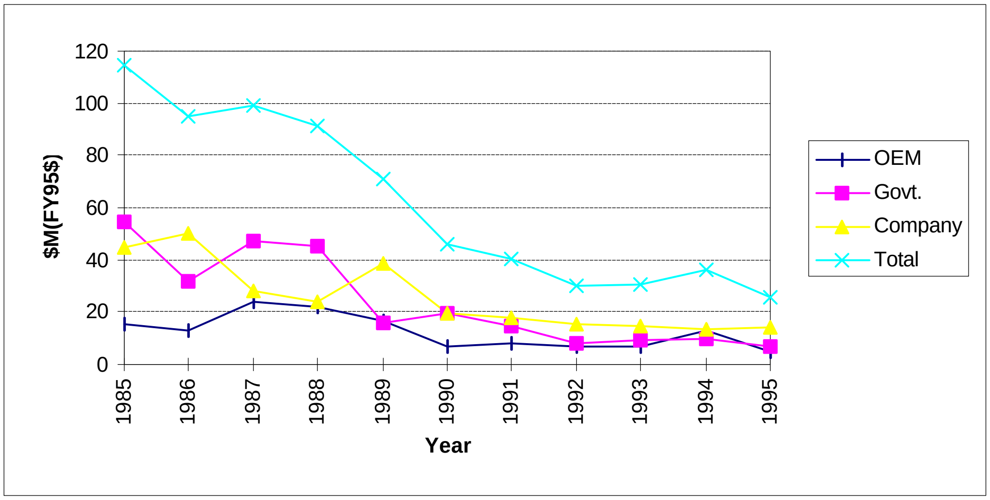

Figure 15: Microwave Tube Manufacturer R&D Investments
Source: EIA

DoD draws on the combined talents of scientists and engineers from the industrial, academic, and government sectors to meet its vacuum electronics research and development (R&D) needs. However, since successful R&D is that which has an operational impact, new device concepts or general advancements in the technology ultimately must be implemented in industry where the microwave power tubes are manufactured.

Total R&D funding to the microwave power tube manufacturers (including contributions from all sources) declined from $114 million in 1985 to $26 million in 1995. As reported by the EIA, total R&D funding to the industry is divided into three source categories: funding directly from the government (both DoD and civil agencies), funding from original equipment manufacturers (OEMs) (much of which is actually government funding, through a system manufacturer, for a specific product application), and finally, internal corporation investments. (Typically, about one-third of the total DoD vacuum electronics R&D funding goes to the microwave tube manufacturers, one-fourth goes to government laboratories, and the remainder to other institutions such as universities and other businesses.)[12]

[12] Additionally, DOE provides several million dollars per year to operate the SLAC. A small portion of this amount is used to support the development of more powerful klystrons for particle accelerator applications.

The decline in total R&D to the industry has been driven by significant decreases in government funding (from $54 million in 1985 to $7 million in 1995) and OEM funding (from about $15 million in 1985 to $4.6 million in 1995). Corporate funding to develop new products and processes is made possible by microwave power tube sales, and also has decreased as a result of declining DoD sales. In the aggregate, internal R&D investments by U.S. microwave power tube manufacturers have declined from $44.5 million in 1985 to $14.4 million in 1995.

Although the absolute value of microwave power tube R&D funding to the industry has declined significantly, R&D as a percentage of sales has not (Figure 16). Total R&D appears to have stabilized at about 10 percent of sales. As a percentage of sales, corporate R&D has not significantly declined, fluctuating between 7.4 and 3.6 percent. Most recently, between 1990 and 1995, corporate R&D has increased from 4.3 to 5.6 percent of sales.

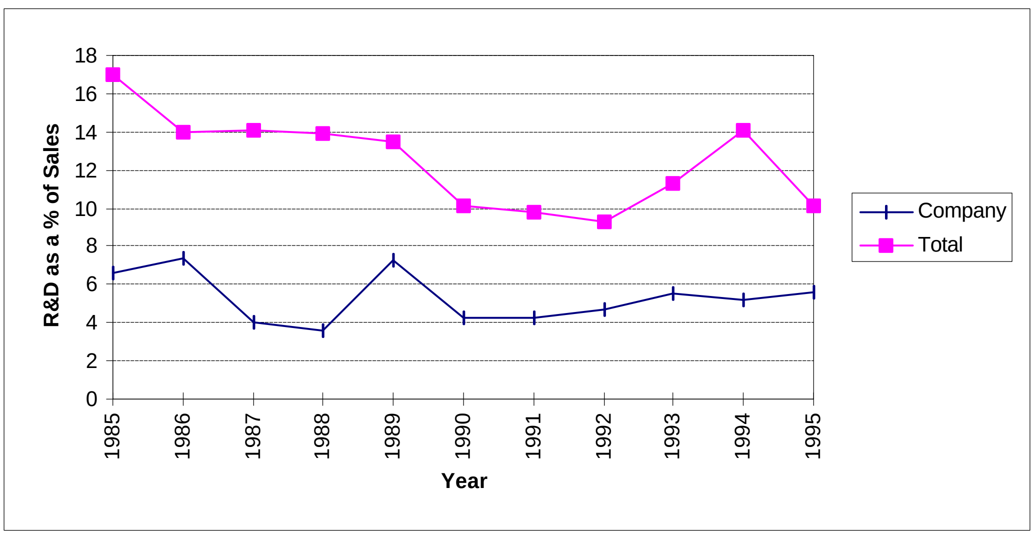

Figure 16: Microwave Tube Manufacturer R&D as a Percent of Sales

Source: EIA

The companies have indicated that corporate R&D investments are being directed increasingly at commercial applications. Absent increased sales for DoD applications, continued direct DoD investments probably will be required to develop new military microwave power tube products, and upgrade existing military products.

5.2.1 DoD Actions

In October, 1988, the decline in the value of R&D investments led the DoD Advisory Group on Electron Devices (AGED) to conduct a Special Technology Area Review on microwave and millimeter wave power tube R&D. The review highlighted R&D needs from both industry and Service perspectives. It addressed microwave power tube and solid-state needs for airborne radar and electronic warfare, microwave power tube requirements for the surface Navy, and the status of microwave tube technology overseas. In 1990, the AGED issued a report, entitled "Microwave Tubes: A National Security Concern," that identified microwave power tube technology as a critical element of the national defense. The report noted that the depth and vigor of the vacuum electronics community had been weakened by the long-term decline of investment in power tube technology and recommended augmented funding over a period of time sufficient to rejuvenate the technology infrastructure. Specific report recommendations addressed management, funding, and manpower issues. Under *management*, the report recommended the DoD establish a tri-Service vacuum electronics program to channel new investment into several basic technology areas. This unified and focused program was to be developed from tri-Service needs and inputs. Concerning *funding*, the report recommended additional funds to augment existing Service investments. More specifically, the new funding was to establish a "core" effort focused on five high pay-off areas of research and development: Microwave Power Modules, High-Performance Millimeter-Wave Devices, Computational Techniques, Design for Low Cost, and Vacuum Microelectronics. The report recommended the DoD sustain an annual investment in exploratory and advanced development totaling between $25 million and $30 million. *Manpower* concerns focused on re-establishing a dynamic personnel base and facilities sufficient to support the increased R&D funding. These objectives were to be accomplished by developing incentives for industry to retain graduate engineers and scientists by utilizing engineers educated through the Air Force ATRI program. More generally, the program was designed to maintain vacuum electronics research capabilities in the academic sector through enhanced support of problem solving at the frontier of scientific endeavor -- plasma physics, computational physics, non-linear dynamics, microstructure fabrication, accelerator design, and theory.

DoD responded to the report in several ways. First, the Defense Advanced Research Projects Agency (DARPA) began a five-year Vacuum Electronics Initiative centered on the two high-risk, high-payoff areas identified in the AGED report: RF vacuum microelectronics and second-generation gyro-amplifiers. Next, additional R&D funding appropriated by Congress for the FY91 and FY92 defense budgets was used to establish a Tri-Service Core Program focused on common Service issues with high impact: Microwave Power Modules, Computational Techniques, Design for Low Cost, High Performance Millimeter-Wave Devices, Supporting Technology, and Exploratory Concepts. Finally, DoD Program Budget Decision (PBD) 208 empowered the Navy to maintain the Tri-Service Core Program through an exploratory development program sponsored by the NRL. The Tri-Service Core Program represents the central element of DoD's response to the recommendations of the AGED report. It complements the DARPA Vacuum Electronics Initiative and Service-specific elements of the Department's total vacuum electronics R&D program.

In 1990, with these changes, DoD expanded its overall 6.2 and 6.3A science and technology (S&T) program in vacuum electronics to include five interactive elements: the DARPA Vacuum Electronics Initiative, the Tri-Service Core Program, and the existing Service-specific investments of each Service. In aggregate, these elements constituted approximately a $24 million per year effort that continued through FY95 (Figure 17). A Tri-Service/DARPA Steering Committee, under Navy lead, coordinates the overall program. The program is based on Steering Committee central planning and coordination, coupled with distributed management of specific technical efforts.

	Current Year Dollars (Millions)						
Year	**Army**	**Navy**	**A. F.**	**DARPA**	**BMDO**	**Total**	**Phase**
1988	2.16	2.85	1.19	-	2.35	8.55	N/A
1989	1.96	5.12	1.40	-	3.09	11.57	
1990	0.89	6.88	1.84	-	2.85	12.46	
1991	0.97	15.92	0.73	9.20	0.97	27.79	I
1992	1.14	13.17	0.54	6.76	0.60	22.21	
1993	1.75	17.80	0.60	6.27	2.23	28.65	
1994	0.71	14.71	1.33	3.65	1.89	22.29	
1995	0.59	15.29	1.96	3.63	0.84	22.31	
1996	0.54	12.84	1.27	-	1.05	15.70	Transition
1997	0.60	11.21	0.68	-	0.98	13.47	II
1998*	0.40	14.57	0.50	-	0.70	16.17	
1999*	0.40	14.85	0.71	-	N/A	15.96	

* Based on FY98 President's Budget

Figure 17: DoD 6.2 and 6.3A Funding of RF Vacuum Electronics Technology

(Sources: OSD Science and Technology Reviews and the Naval Research Laboratory)

Dynamics within government and the industry make it appropriate to view the long-term sustained vacuum electronics development effort recommended by the AGED report as a two-phase program. As noted above, the DARPA funded initiative was planned as a five-year endeavor. Similarly, the "core" program established by PBD 208 came to an end in FY96. Thus, Phase 1 effectively began in FY91 and was completed in FY95.

More recently, DoD has begun actions to continue the Tri-Service program until FY03. The Department will initiate Phase II, beginning in FY97 and continuing through FY03, with FY96 serving as a transition year. The DoD is projecting modest growth in the program, primarily sustained by increases in the Navy S&T budget, to $18.9 million in FY03. As shown in Figure 17, the Navy provides the predominant share of the DoD S&T investment. Army and Air Force funding to meet Service-specific requirements is projected to decline to minimal levels beyond FY96. New systems may have performance requirements which can be met most effectively by a microwave power tube not already available. In such cases, additional Service funding may be necessary to adapt emerging product technologies to meet Service-specific new product requirements.

5.2.2 Tri- Service/DARPA Vacuum Electronics Program

Despite the dramatic downturn in defense microwave power tube procurement and subsequent industry consolidation, Phase I of the Vacuum Electronics Program has achieved substantial technical progress. The program developed a new "super component" -- the Microwave Power Module (MPM). The MPM is expected to have a large impact on a wide variety of military systems, plus significant commercial application potential. The third version of the Microwave and Millimeter-Wave Advanced Computational Environment (MMACE) effort is scheduled for release in early 1997. The millimeter-wave gyro-amplifier project offers exciting opportunities for new radars for both military and space applications. New material systems such as man-made thin diamond films are being exploited for their potential in developing high-power-density components.

Microwave Power Module (MPM)

The MPM combines the best features of vacuum electronics and solid-state technology to obtain performance not attainable by either technology alone. The MPM facilitates the development of compact, lightweight, highly efficient, and affordable RF transmitters that will enable new system applications, yet be suitable for retrofit or mid-life upgrades of existing electronic warfare, radar, and communications systems.

The concept calls for the integration of a solid-state driver with a vacuum power booster, along with the necessary high- and low-voltage power conditioning, to yield high-efficiency low-noise operation in breakthrough packaging. The most aggressively packaged MPM (7.5 in^3, liquid cooling) delivered more than 100 W (CW) over the 6 to 18 GHz band with an overall DC-to-RF efficiency of 35 - 45 percent. Larger conduction-cooled packages (up to 21 in^3) also have been demonstrated. MPMs have been demonstrated as a single module, in linear arrays, and in power-combined transmitters. The power module concept is being extended to higher frequencies (18 to 40 GHz) in the Millimeter MPM (MMPM) variation and lower frequencies (2 to 6 GHz) in the C-band MPM (CMPM) variant. MPM technology is being put to use in several rapidly developing system-related efforts. For example, the MMPM is being investigated with the MILSTAR Program Office, the CMPM with the Cooperative Engagement Capability Program Office. One of the most noteworthy MPM transitions within the last year involved the power module for the synthetic aperture radar transmitter and K_u-band communication link for the Predator Unmanned Aerial Vehicle (UAV), which has seen service in Bosnia.

MPM demand estimates are uncertain at this time. However, several vendors are anticipating a market of 10,000 to 30,000 MPMs per year, developing over the next decade. (These estimates are derived from the impact of high-volume decoy programs and other single-module applications in UAVs, as well as projected electronic warfare array and potential phased-array radar developments. After performance, low acquisition costs will be the largest single factor that will attract users. Estimated initial unit costs for the MPM are in the $5,000 to $10,000 range for the anticipated production volume.) The estimated long-term MPM market value is between $50 million and $300 million, only a portion of which would displace conventional vacuum electronics products. Most MPMs would be used in new applications enabled by its small size and weight relative to RF performance capability.

Computational Techniques

Computational Techniques research supports the development of a comprehensive computing environment extending from electromagnetic device design to final product fabrication. These projects are expected to reduce design-cycle costs and times dramatically, and improve device performance and reliability. The Microwave and Millimeter-Wave Advanced Computational Environment (MMACE) is the centerpiece of the effort. MMACE Version 2.0 was released in March 1996 to the microwave power tube industry and to Government users in the Army, Navy, Air Force, and NASA. (Version 3.0 is scheduled for release in March 1997.) Version 2.0 includes a suite of generic public domain codes for microwave and millimeter-wave power tube design, and is supported by HP-UX 9.x on HP 9000/700 workstations and Sun OS 4.1.x on Sun Sparcstations. Version 3.0 will extend the capabilities of the system, its ease of use, and its inclusiveness of codes, including a commercial code used by the industry. Raytheon, the MMACE system integrator, is using MMACE internally in radar antenna design, and is considering its use in the electro-optical and acoustical areas. Additionally, several DARPA computer-aided design projects also are considering MMACE.

High-Performance Millimeter-Wave Amplifier

High-Performance Millimeter-Wave Amplifier research responds to recent advances in threat technology that have heightened interest in the development of all-weather capabilities for such applications as high-resolution command guidance for ship self-defense, detection of low observables, and broad-band jamming applications. A C-band gyro-twystron development effort at NRL yielding 80 kW peak power, 37 dB gain, and 1.6 percent bandwidth at an efficiency of 25 percent, is the foundation for the current gyro-klystron and gyro-twystron development effort within the NRL Radar Division's 94 GHz Millimeter Wave Radar project. Furthermore, a gyro-TWT amplifier (also at NRL) has achieved record power-bandwidth performance (25 dB saturated gain over a 20 percent 3 dB bandwidth with 8 kW output in the 32 to 39 GHz band). This device provides a five-fold enhancement in the state-of-technology for power-bandwidth products at K_a-band. Communication and Power Industries (CPI) is under contract to the Army Research Laboratory to develop a 200 W peak power extended interaction amplifier operating at 140 GHz for use in ballistic missile defense applications. However, the High-

Performance Millimeter-Wave Amplifier development effort supports emerging needs for all three Services.

Design for Low Cost

Design for Low Cost projects will improve the affordability of high-performance vacuum electronic devices by better utilizing simulation and modeling during research and development, and developing generic manufacturing methodologies and procedures to increase reliability and yield while reducing cost and cycle time. Successes include:

- An improved ALQ-131 Band 5 TWT for the Air Force that will likely be included in the upgraded AN/ALQ-131.
- An AEGIS crossed-field amplifier (CFA) used in the AN/SPY-1 radar for the Navy. Electromagnetic particle-in-cell codes and thermal finite element codes were coupled to design high-temperature vanes in the circuit of the CFA, thereby extending the duty cycle from 2 percent to greater than 8 percent. This simulation approach to CFA design eliminated the need for approximately ten experimental devices -- with an estimated cost savings of $250,000 to $400,000 and cycle time reductions of approximately 10 months. The high-duty CFA will be introduced as a baseline upgrade in FY98 for CG-57 class cruisers and DDG-51 class destroyers in the Final Power Amplifier stages of the AN/SPY-1/D(V).
- A broadband TWT which was to be used in a helicopter-borne jammer for the Army. The Army program has been canceled and the low-cost TWT has not been implemented in any system. The study, however, shed light on the use of low-cost parts in the fabrication of a high-performance TWT.

Vacuum Microelectronics

Vacuum Microelectronics concepts are unfolding rapidly as solid-state and vacuum electronic technologies are being linked creatively. The field emitter array (FEA), a gated electron emitter, combines the advantages of electron transport in vacuum with the ease of solid-state microfabrication techniques. FEAs are currently being evaluated in two innovative circuit concepts -- the twystron and the klystrode -- which are inductive output amplifiers with potential size reductions and efficiency enhancements. Advances in baseline FEA technology have already benefited less demanding applications, such as field emitter displays (FEDs), with applications from avionics to large-scale combat information center displays.

Supporting Technologies

Supporting Technologies research supports a wide variety of microwave power tube technologies and, among several goals, seeks to find materials that may be substituted for current, less reliable, materials. Already, significant improvements in device performance, packaging, reliability, and cost have been achieved through exploitation of opportunities in such diverse areas as magnetics, dielectrics, and electron emitters. For example, man-made diamond is being evaluated for use as a BeO replacement in rod supports and power extraction windows because of its outstanding thermal and mechanical properties. Additionally, steady advances in thermionic cathode technology have increased reliable cathode emission to over 10 amps/cm^2, resulting in improved performance at millimeter-wave frequencies (e.g., 5 kW pulsed power at 95 GHz from a TWT). Secondary electron emission data have been developed for use in computer simulations to analyze the high-duty AEGIS CFA. Additionally, secondary emitter studies have resulted in more cost effective processing.

Exploratory Concepts

Exploratory Concepts investigates high risk or novel concepts within a structure that facilitate the ready transition of new ideas into defense systems. This thrust, which has been merged with the other thrusts according to the topic of investigation, focuses university developmental efforts on DoD problems and accelerates the transition of innovative ideas to industry. Currently, key efforts include the development of state-of-the-art concepts with high impact on RF power, weight, and size at a given efficiency and bandwidth in gyro-amplifiers, vacuum microelectronics, and high-perveance sheet beam optics; the exploration of concepts based on high-perveance electron beam and enhanced distributed RF circuits; and the investigation of how to exploit these concepts across a wide range of frequencies using both slow-wave and fast-wave approaches.

5.3 Manufacturing Research and Development

The importance of delivering to a systems contractor, on schedule, a microwave power tube that performs to a demanding specification has frequently overshadowed cost. It was only after the system was operating and the microwave tubes needed to be repaired or replaced that cost became an issue. The DoD now places more emphasis on initially designing products that will minimize the cost of both original acquisition and subsequent ownership. However, fielded military systems use microwave power tubes that were not designed with volume manufacturing cost considerations in mind. Replacing and repairing these devices will continue to demand more of scarce DoD resources until the manufacturing processes used to produce and repair them are improved.

The Navy embarked on a Product Improvement Program over a ten year period that significantly reduced the costs of ownership of many of the tubes used in the AEGIS SPY-1 radar. Figure 18 summarizes the improvements that were realized. The cost of the various microwave power tubes used on an AEGIS Cruiser was reduced from $3,256,800 in 1983 to $1,579,200 in 1993. Improvements in microwave tube Mean-Time-Between-Failure (MTBF), coupled with reductions in repair costs as well as initial acquisition costs, have resulted in a decrease in operating costs from $4.52 per tube per hour in 1983 to $0.59 per tube per hour in 1993. Overall, the Navy estimates it has realized better than a 10:1 return on its investment to date.

Tube	**1983**			**1993**		
	Cost	MTBF	$/Tube/Hr	Cost	MTBF	$/Tube/Hr
CFA	$30,000	6,000	$5.00	$14,000	45,000	$0.31
D/PD	35,000	6,000	5.83	20,000	30,000	0.67
SWT	2,800	1,800	1.55	1,000	2,000	0.50
40w TWT	20,000	12,000	1.67	12,000	20,000	0.60
CWI TWT	66,000	1,300	50.77	37,800	5,100	7.41
System (SD)	$3,256,800		$4.52	$1,579,200		$ .59

Figure 18: AEGIS Microwave Tube Product Improvement Program
Source: U.S. Naval Surface Warfare Center

5.4 Conclusions

Technology investments, whether made possible by sales or by direct investment, are key to the industry's ability to meet cost-effectively DoD's future microwave power tube requirements. The U.S. Navy is the Tri-Service R&D investment manager and funds the majority of DoD microwave power tube R&D through the exploratory development program at its Office of Naval Research. Since the Navy also is one of the largest users of microwave power tubes, the DoD will designate it as its Executive Agent (EA) to monitor the U.S. microwave power tube industry and ensure that industrial capabilities will be adequate to meet DoD requirements into the future. The EA will (1) identify and maintain consolidated DoD microwave power tube acquisition requirements and R&D plans, (2) monitor the major domestic microwave power tube manufacturers and key component and material suppliers, and (3) facilitate coordination among the Services and Defense Agencies, and among DoD and other U.S. Government Agencies which use microwave power tubes. The executive agent will report to the Under Secretary of Defense for Acquisition and Technology.

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Section 6.0 - Foreign Microwave Power Tube Manufacturers

There is a vigorous and growing foreign microwave power tube manufacturing capability. Most developed nations have some indigenous capability to design and manufacture microwave power tubes.

France - Thomson TTE is a subsidiary of Thomson-CSF and is the largest foreign microwave tube manufacturer. Its growth is the result of aggressive acquisitions. It has acquired many of the major microwave tube manufacturers in Western Europe. Thomson now owns the microwave power tube divisions of Germany's Siemens and AEG. Thomson is fully capable in TWTs (up to 40 GHz), klystrons (high-power research devices), and magnetrons for all military and civil applications. Thomson TTE is closest in overall capability to the major U.S. suppliers. Its products are used on several DoD systems and have been purchased by the DOE as well.

United Kingdom - English Electric Valve is fully capable in magnetrons and TWTs for military and civil applications. It produces klystrons, predominantly for the television industry and communications, but also for high-power scientific applications. English Electric Valve has a complete line of millimeter wave magnetrons covering frequencies up to 96 GHz.

Japan - Nippon Electric Corporation (NEC), and to a lesser extent, New Japan Radio Company, have a growing capability in space based TWTs and some klystrons. Recently, they are aggressively trying to enter the market for K_u and K band space TWTs. Additionally they are seeking long term agreements with space craft producers world-wide, offering to make the internal investments necessary to increase their production rates.

Italy - Alenia and Alelco have a strong focus on satellite-based TWTs for communications.

Russia - Istok and Almaz (Saratov) have strong military and civil capabilities in nearly all types of microwave power tubes. Most Russian microwave tube manufacturers have compromised at least one tube performance characteristic (i.e., bandwidth, life expectancy, duty cycle) to optimize other features. Russian companies have strong capabilities in gyrotrons, gyro-TWTs, gyro-klystrons, and other very high-power microwave tubes.

China - Najing Electronic Device Institute and Bejing Electron Tube Factory produce TWTs, klystrons, magnetrons, and older microwave tube types (thyratrons, triodes and tetrodes). They are known to be well behind western technology. Many of their microwave power tubes are copies of earlier Russian tubes. They are working to develop a capability to build high-power microwave tubes (with Russian designs/assistance).

Section 7.0 - National Security Considerations

7.1 DoD

In an increasingly global market, DoD wants to: (1) take full advantage of the benefits offered by access to the best global suppliers, and (2) promote consistency and fairness in dealing with its allies. However, although the DoD is willing to depend on reliable foreign suppliers, it is not willing to accept foreign vulnerability or other risks to national security. (See Appendix D for a more complete discussion of DoD policy on the utilization of foreign sources.) Microwave power tubes clearly represent a militarily important technology:

1. Decisions to restrict DoD microwave power tube procurements to domestic sources are made on a case-by-case basis, depending on the application for which the microwave tube is intended. The Military Services have determined that certain microwave tubes should be procured from domestic sources -- applications where U.S. military mission effectiveness would be degraded if microwave tube operating characteristics were known to potential adversaries. (Typically, both microwave power tube and system operating characteristics can be deduced by examining the microwave tube.)

2. To limit transfer, the export of microwave tube technology and microwave tube products has been controlled under both the U.S. Munitions Lists and the Commerce Control Lists since World War II. In 1992, the delegates of the western nations reaffirmed the military importance of microwave tubes by including them in the International Industrial Core List of the Coordinating Committee on Multilateral Export Controls. This group has been superseded by the Wassenaar Arrangement (formally New Forum). The 1994 International Industrial Core List ranked microwave power tubes 11th in importance of the 80 electronic technologies listed.

3. The DoD Military Critical Technologies List provides a technical foundation for export controls and for technology licensing, and represents a technical guide and reference for intelligence collection. Figure 19 is an extract from the 1996 Military Critical Technologies List. It identifies which microwave power tube technologies the DoD considers critical.

Technology	**Military Critical Parameters (Min level to assure superiority)**	**Critical Materials**
TWT - Pulsed or Continuous	Operating frequency above 46GHz Cathode Heater turn on < 3 sec to rated power	Tungsten Wire Tape Molybdenum Wire Tape APBN Boron Nitride Rods Cathode Nickel
Coupled Cavity Tubes	An Instantaneous bandwidth > 10% or a peak power > 50 KW	70/30 Cupronickel Cathode Nickel
Helix Tubes	Bandwidth > one octave, and average power times frequency > 2 Bandwidth < one octave, and average power times frequency > 4	Same as TWT
Crossed Field Amplifiers	A gain > 17 dB or noise figure < 35 dB	Corning 77 glass Rhenium Tungsten Wire
Impregnated Cathodes	Turn on time to rated power < 3 sec, or producing continuous emission current density at rated operating conditions exceeding $10A/cm^2$	none

Figure 19: Critical Microwave Tube Technologies
Source: Military Critical Technologies List

4. Traveling wave tubes were one of only two “components” included in a 30 item list by the Defense Investigative Service of technologies targeted by foreign intelligence collection activities.

7.2 Export Restrictions and Licensing

The ability of U.S. microwave power tube manufacturers to penetrate non-U.S. markets is dependent on their ability to secure export licenses for proposed sales. The Department of Commerce reviews export license requests for commercial applications. The Department of State reviews, with Defense Technology Security Agency (DTSA) consultation, export license requests for microwave power tubes intended for military applications. Although licenses to export microwave tubes to unfriendly nations such as Iran are refused routinely, DTSA has indicated that less than 5 percent of license requests are denied due to military operational considerations. However, industry representatives have reported that export licensing procedures limit their ability to respond rapidly to overseas sales opportunities, putting them at a disadvantage compared with their non-U.S. competitors.

7.3 DOE Weapons Material Production

In late 1998, DOE plans to decide if it will initiate the construction phase of its APT program. DOE has indicated that due to the critical need for a secure source of supply of tritium to maintain the U.S. nuclear weapons stockpile, it prefers an accelerator acquisition strategy which would have klystrons/klystrodes and other critical components manufactured in the U.S. or its territories.

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Section 8.0 - Conclusions

8.1 Characteristics of the Industry

A. Microwave power tubes are used in a variety of military, civil, and commercial applications.

B. DoD considers certain microwave power tube technologies critical to military effectiveness. For this reason, the U.S. Government controls the export of microwave power tube technology and products.

C. The design and manufacture of microwave power tubes require complex and specialized industrial capabilities.

- The complex nature of microwave power tube performance characteristics result in application-specific product designs, and for most DoD applications make reproduction (matching microwave tube <u>and</u> system performance, form, and fit) by another manufacturer technically challenging, time consuming, and costly.

D. U.S. microwave power tube manufacturers rely heavily on sales to the DoD and face tough international competition in a flat global market.

- Total world-wide sales are expected to remain flat or to decrease slightly over the next five years. However, the demand for telecommunications satellites and ground stations is projected to grow as much as 30 percent per year for the next several years.
- Although the value of its microwave tube procurements is not expected to grow, DoD's need for microwave power tubes will remain strong for the foreseeable future. DoD applications being served today by microwave tubes will likely not be converted to solid-state devices.
- DoD applications represent 38 percent of world-wide sales (excluding the Russian and Chinese markets) and 70 percent of U.S. manufacturer sales. These sales provide U.S. manufacturers a strong base from which to compete.

E. As sales declined 62 percent between 1985 and 1995, the U.S. microwave power tube industry downsized significantly.

- Production factory floor employment has declined 50 percent since 1988.
- The engineering workforce has declined by almost two-thirds over the same period.

F. Key microwave power tube suppliers provide essential specialized components and materials for which there is little demand outside the microwave power tube industry; support multiple microwave tube manufacturers; and represent a select few demonstrated capability suppliers. Additionally, most of the suppliers focus primarily on business applications not associated with microwave power tubes.

8.2 Research and Development (R&D)

A. Corporate funding to develop new products and processes is made possible by microwave power tube sales, and has dropped significantly as a result of declining DoD sales.

B. As a percentage of sales, corporate R&D has not significantly declined. Most recently, between 1990 and 1995, corporate R&D increased from 4.3 to 5.6 percent of sales.

C. The companies have indicated that corporate research and development investments are being directed increasingly at commercial applications.

D. The U.S. Navy, as the Tri-Service R&D investment manager funds the majority of DoD microwave power tube R&D through the exploratory development program at the Office of Naval Research. Army and Air Force R&D to meet Service-specific requirements is projected to decline to virtually zero beyond FY97. Total outyear DoD funding for exploratory and advanced development in this area is projected to grow from $16 million in FY97 to $18.9 million in FY03.

E. The U.S. Naval Research Laboratory is the focal point for DoD R&D in vacuum electronics. It has the dual mission of maintaining a core in-house capability for vacuum electronics R&D and serving as the DoD lead manager of the Tri-Service Vacuum Electronics program.

8.3 DOE Activities

A. DoD and DOE microwave power tube applications employ complementary industrial capabilities.

- The same manufacturers provide microwave power tubes to the DoD, DOE, other civil agencies, and commercial customers.
- Klystrons used for either DoD or DOE applications employ industrial capabilities common to the industry for design, development, and production.
- DOE exclusively uses very large, single frequency, high-power klystrons.
- DoD uses smaller, less expensive, multi-frequency klystrons as final power amplifiers in many military radar systems. Generally, new military radar systems are designed to use TWTs and solid-state devices which offer smaller size, higher efficiency, wider bandwidth, and lower cost. Current DoD procurement of klystrons is limited to spares, replacements, and new production for older systems.

B. DOE activities contribute to, but will not change fundamentally, the long term sales picture of the U.S. microwave power tube industry.

- The DOE will continue to support the R&D of high-power klystrons at the Stanford Linear Accelerator Center for applications in high energy physics research. It also will continue to purchase high-power klystron tubes on the world market based on best cost, quality, and availability. Such offshore purchases do not dramatically affect U.S. industry.
- The DOE will continue to develop new technology "klystrodes" with U.S. sources for its APT program. DOE prefers U.S. sources for future klystrons/klystrodes for the APT. Such sales could provide a significant boost to U.S. manufacturers.

8.4 Adequacy of Industrial Capabilities to Meet DoD Requirements

A. DoD intervention to preserve industrial capabilities is not required. Current microwave power tube industrial capabilities are adequate to meet DoD requirements. However, absent increased sales for DoD applications, continued direct DoD investment will be required to develop new military microwave power tube products and upgrade existing products.

- Although publicly-available financial information is limited, all surveyed U.S. microwave power tube manufacturers indicated they are currently operating profitably. They are increasing manufacturing efficiency, eliminating excess capacity, and targeting non-military applications to compensate for flat military sales projections.
- DoD has begun to feel the impact of the decline in the number of microwave power tube engineers. Some developmental efforts have been impaired by reduced engineering capability and the stress associated with downsizing. Further drawdowns may lead to situations in which firms will be less able to respond to requests for new designs and less able to provide timely technical support to fielded products.
- A focused DoD R&D investment strategy is required to advance the technology and improve manufacturability to meet future DoD system program performance improvement and cost reduction requirements.
- If maintained at planned levels, corporate and U.S. Government R&D funding is adequate to maintain essential industrial and technological capabilities and to meet DoD new product technology requirements. New systems may have performance requirements which can be met most effectively by a microwave power tube not already available. In such cases, additional Service development funding may be necessary to adapt emerging product technologies to meet Service-specific new product requirements.
- Because microwave power tubes are components within larger subsystems and systems, microwave tube purchases for DoD applications generally are not coordinated. DoD has had limited visibility into the industry as a whole, and into the plans of individual DoD program offices and systems contractors.

B. DoD must better coordinate its activities and investments to ensure capabilities will be available to meet future requirements.

C. DoD will designate the Navy as its Executive Agent (EA) to monitor the U.S. microwave power tube industry and ensure that industrial capabilities will be adequate to meet DoD requirements into the future. The EA will:

- Identify and maintain consolidated DoD microwave power tube acquisition requirements and R&D plans.
- Monitor the major domestic microwave power tube manufacturers and key component and material suppliers.
- Facilitate coordination among the Services and Defense Agencies, and among DoD and other U.S. Government Agencies which use microwave power tubes.
- Report to the Under Secretary of Defense for Acquisition and Technology.

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APPENDIX A

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APPENDIX B

Component and Material Suppliers

BRUSH WELLMAN INC. - Brush Wellman is located in Cleveland, OH, and manufactures engineered materials. These materials are generally premium priced and are often developed or customized for the customer's specific process or product requirements. The product lines are supported by research and development activities, modern processing facilities, and a global distribution network. Customers are widely diversified.

The Elmore, Ohio, complex is the primary processing facility. This facility employs diverse chemical, metallurgical and metal working processes in the production of beryllium, beryllium oxide, beryllium alloys and related products. Beryllium ore concentrate from the Delta, Utah plant is used in all beryllium-containing products. Brush Wellman is the only fully integrated producer of metallic beryllium, beryllium alloys, and beryllium oxide powder in the western world. Brush Wellman accounts for approximately 85 percent of the U.S. beryllium market and about 70 percent of the world market.

Sales are made to approximately 6,515 customers. Government sales, principally subcontracts, accounted for about 1.3 percent of consolidated sales in 1995, as compared to 3.2 percent in 1994, and 6.1 percent in 1993. Sales outside the U.S., principally to Western Europe, Canada and Japan, accounted for approximately 34 percent of sales in 1995, 33 percent in 1994 and 29 percent in 1993.

CERADYNE CORPORATION - Ceradyne is a small, publicly-held firm located in Costa Mesa, CA. The company develops and manufactures advanced ceramic products and components for industrial, defense, consumer and microwave applications. Ceradyne's cathode development and production are handled through its Semicon

Associates division in Lexington, Kentucky. Fused silica products are produced at Ceradyne's Thermo Materials division in Scottdale, GA.

Ceradyne's revenues increased to $23.4 million in 1995 and are projected to grow in 1996. Ceradyne employs approximately 120 people and expects to increase sales through 1998. Ceradyne's investment in ceramic R&D is approximately $400,000 to $500,000 for 1996 and is expected to increase slightly in 1997. Microwave tube products represent about 34 percent of Ceradyne's business

Ceradyne is not the sole producer of precision ceramic material, but in some cases is the only qualified source. Ceradyne currently has three domestic competitors: Greenleaf, Livermore, CA: General Ceramics, Haskell, NJ; and San Jose Delta Assoc., Inc. Santa Clara, CA. There are no known foreign competitors. Ceradyne's customers include CPI, Hughes, Litton, and NEC.

Raw materials utilized in the production of Ceradyne's precision ceramics include magnesium oxide, aluminum nitrate, aluminum oxide, beryllium oxide (BeO), and silicon carbonate (SiC). Except for beryllium oxide powder, raw materials are readily available from several commercial sources. Beryllium oxide powder is available from Brush Wellman. However, beryllium oxide is a carcinogen. Ceradyne has announced that it will discontinue producing beryllium oxide-silicon carbonate products due to health hazards and the resultant legal vulnerabilities.

COORS CERAMICS COMPANY (CCC) - CCC is a subsidiary of ACX Technologies, the largest U.S.-owned independent manufacturer of advanced technology ceramics. CCC has 15 manufacturing facilities throughout the U.S. and Europe.

CCC participates in three market segments of the advanced technical ceramics industry: structural, electronic, and advanced electronic packages. The world-wide market for these products is estimated to be between $2 - $3 billion. CCC has approximately 20 percent of the structural and electronic ceramics market, estimated at nearly $1 billion, and approximately 3 percent of the advanced electronic ceramic package market. Approximately 28 percent of CCC's sales are international, primarily to Western Europe and the Far East. Net sales for ACX Technologies in 1995 were $910.8 million. Coors Ceramics sales were $271 million.

H. CROSS - H. Cross is the sole domestic supplier of tungsten filament tape; a critical component of helix-type traveling wave tubes. It is a privately held small business, founded in 1939, located in Weehawken, NJ. There are no domestic competitors and the only other known supplier is Metal Works Planse, located in Austria. Tungsten filament tape represents approximately 12 percent of H. Cross' total annual sales. The lighting industry is the dominant customer. Total sales for 1994 were $4.8 million. Current employment is 53 and the company projects a slight increase to 60 within the next two years.

H. Cross is a rolling mill that produces ribbons, sheets, strips and wire to tolerances of 0.00005 inches (five one hundred thousandths of an inch) using raw materials such as molybdenum, tungsten, tantalum, and rhenium. The manufacturing process for tungsten filament tape is so complex that it takes approximately two years to fully train a machine operator. All equipment used in this manufacturing process was developed and built by the company. The process is proprietary. H. Cross also supplies molybdenum/rhenium sheets to Semicon Associates for TWT cathode production.

H. Cross procures its tungsten wire from Osram-Sylvania, located in Towanda, PA, the single supplier. H. Cross maintains a one million dollar stockpile of this wire to offset potential problems due to a 26 week order lead time. H. Cross is trying to develop alternative sources to their current vendor. Both potential alternate sources are located outside the U.S.

OSRAM-SYLVANIA, INC. - Osram-Sylvania, Inc., (OSI) located in Towanda, PA, is a subsidiary of Osram GMBH, Munich Germany. It is considered a large business and is privately-held. The company manufactures many different types of tungsten and molybdenum wires for many different application and end users. OSI presently employs approximately 1,400 at this location. Corporate sales for Osram, GMBH were in excess of $1.7 billion in 1995.

OSI's customer base primarily is lighting manufacturers. It also supplies tungsten wire to H. Cross Inc. OSI's tungsten wire production relating to the microwave tube industry represents less than 1 percent of its total business. The company identified major lamp producers such as Phillips and General Electric as competitors. OSI has announced that it may discontinue its tungsten wire product line to focus on core markets. The lead time for the tungsten wire has increased from 4-6 weeks to 26-40 weeks in the past few years.

The production process for tungsten wire involves eleven steps, none of which are unique. OSI starts the production process with tungsten ore and ore concentrates from various suppliers worldwide. No environmental concerns or issues are evident and the company has no R & D investment in this product line.

UNION CITY FILAMENT - Union City Filament, located in Ridgefield, NJ is a small, privately-held company of approximately 38 employees. Union City's primary business is the forming and winding of tungsten wire heaters used in traveling wave tubes. The company also manufacturers various tubes (x-ray), vacuum devices, and formed tungsten products. Tungsten wire heaters account for 50-60 percent of the company's total yearly sales. Customers include Litton, CPI, ITT, and Raytheon.

Union City Filament has one U.S. competitor for the heater. The manufacturing process (forming and winding of tungsten wire) is unique but at the same time very antiquated. There are no current or projected R&D investments. The company projects increasing employment from 38 to 45.

Union City Filament has two suppliers for tungsten wire: Osram-Sylvania (German-owned, located in Towanda, PA) and Philips Elmet (Lewiston, ME). Union City Filament is concerned that its tungsten wire supplier base may be reduced to one.

SEMICON ASSOCIATES - Semicon is a publicly-held company located in Lexington, KY. It is a subsidiary of Ceradyne Inc. of Costa Mesa, CA. Semicon is a small business manufacturer of dispenser cathodes for microwave tubes, gas lasers, ion sources, flash lamps, and CRTs. It also produces electron gun subassemblies and rare earth cobalt magnets for microwave tubes, porous and copper tungsten for special applications and coupling switches. Semicon has 75 percent of the U.S. microwave tube cathode market and currently supplies TWT cathodes to CPI, Teledyne, and Hughes (represents 40 percent of Semicon's business).

In 1995, Semicon Associates reported sales of $5.8 million and profits of $0.6 million, up from 1994, and expected to further improve in 1996. Approximately 68 percent of Semicon's business is with U.S. commercial customers, 31 percent with foreign customers, and 1 percent with other U.S. government customers. Although the majority of Semicon's sales are listed as commercial, many of those commercial customer products are used in DoD systems. Semicon employs 82 people and is projected to employ 125 people by 1998.

Semicon's TWT cathodes are assembled by hand on a custom order basis. The manufacturing processes involves pressing, sintering, and machining tungsten powder into billets and cathode pellets. The pellets are mounted on a support structure, heaters installed, and emissive materials impregnated into the pellet. The various refractory metal components are brazed or welded together. The cathode emitting surface is treated to ensure cleanliness and best possible emission. In most cases, a thin film is applied to the emitting surface, by sputtering, to enhance the performance of the cathode. The essential raw materials and critical components utilized for the production of cathodes, along with their suppliers, are tungsten powder--General Electric Co., molybdenum--CSM Industries, molybdenum/rhenium sheets--H. Cross, cathode heaters--Union City Filament.

SPECTRA-MAT, INC. (SM) - SM is the other major supplier of cathodes to the microwave tube industry. It is located in Watsonville, CA. It designs, develops, and manufactures microwave power tube and laser components for the high technology electronics and aerospace industries. SM employees own 97 percent of the capital stock. SM sales for 1996 are projected to be $4.9 million. Current employment is 80. The company projects a gradual increase in both sales and employment through 1998.

SM's major product lines are cathodes and thermal management products. Cathode sales accounts for 25 percent of its business. SM makes no investments in cathode R&D. The company provides a broad range of custom, complex dispenser cathode components and assemblies. It also designs and develops inner gun assemblies for vacuum envelope assemblies for the high-power tube market. Major SM microwave tube customers include Hughes, CPI, English Electric Valve, Stanford Linear Accelerator Center, Toshiba, Thomson-CSF, and Litton Industries.

The essential raw materials and critical components utilized for the production of SM's cathodes include tungsten powder--General Electric, molybdenum rods--Philips Elmet Corp., rhenium alloy--Rhenium Alloy Inc., rhenium/tungsten wire--Osram-Sylvania Inc.

CSM INDUSTRIES, INC. - CSM, located in Euclid (Cleveland), OH is a privately-held small business that manufactures a full range of molybdenum products, including sheet, plate, alloys of powders and remelt material, and clad molybdenum products. Molybdenum is used as microwave collector material and the helix material for TWTs. Pure molybdenum sheet comprises approximately 75 percent of the company's business as their Cleveland plant. CSM's customer base for this product includes Hughes, CPI, Northrop Grumman, and Eureka X-ray.

CSM has several domestic and foreign competitors. CSM has two plants which manufacture molybdenum products. Its Coldwater MI facility takes the ingot powder (ammonium dimolybdate), processes and refines it to produce molybdenum ingot rolling slabs. The Cleveland facility takes the input slabs and rolls them into useable end product. Ammonium dimolybdate is currently supplied by Cyprus Climax, Fort Madison, IA. CSM has developed two additional sources for this material and does not foresee any problems in the future. It would take approximately 4 to 6 months to develop a new supplier of this material.

CSM's current employment level at its Cleveland plant is 100 employees. Based on CSM's current level of business, employment is projected to increase slightly to 110 in the upcoming year. CSM's research and development investment is approximately $300,000 annually at the Cleveland facility. The manufacturing processes used by CSM to produce molybdenum materials are company proprietary.

ELECTRON ENERGY CORPORATION - Electron Energy Corporation (EEC), located in Landisville, PA, manufactures samarium-cobalt (SmCo) magnets. EEC is a small privately-held company of approximately 100 employees. In addition to producing magnets for TWTs, EEC also produces SmCo magnets for inertial devices such as gyroscopes and accelerometers, and permanent magnet rotor assemblies for motors, generators, and couplings. While 100 percent of the business is comprised of rare earth magnets and magnet assemblies, TWT applications account for 60 percent of the overall business.

Company sales for 1996 are $6.8 million and are expected to increase steadily to $7.5 million by 1999. Employment increased from 60 in 1995 to a current level of 100. A slight increase is projected over the next three years, up to a total of 115 employees in

1999. There are currently no environmental issues which could impact magnet production. EEC states that it is the only producer in the world capable of measuring and controlling the temperature coefficient of the magnets to the level required to address applications such as inertial devices. EEC is developing newer technology and processes for the production of bonded magnets. The company's R&D investment level today is approximately $500,000, with future projections of $200,000, annually.

The principal raw materials used to produce magnets are pure cobalt and rare earth metals. EEC has three cobalt suppliers: Metal Resources (London, England), Falcon Bridge (Pittsburgh, PA), and Memaco (Westlake, OH). Cobalt supply has not been a problem; however, the price is volatile. The current price is $28/pound. The U.S. Government sells cobalt from the strategic metal stockpile. EEC has obtained rare earth metal (samarium) from Research Chemicals (Phoenix, AZ) since the late 1960s. Research Chemicals recently was sold to Rhone Poulenc, a French company. Samarium is priced at $30-40/pound. China has also become a producer of rare earth metals. EEC foresees no current or projected problems concerning the supply of raw materials or its ability to produce magnets for TWTs.

EEC's customer base consists of all the major domestic and foreign microwave tube companies. EEC's competitors include Semicon (Lexington, KY), Ugimag (Valparaiso, IN), Recoma (Boonton, NJ), Vacuumschmelze (Hanau, Germany), Magnetic Sales (Culver City, CA) and Dexter (with locations in the U.S., Germany and UK)

HITACHI MAGNETICS CORP. - Hitachi Magnetics, located in Edmore, MI, manufactures permanent ceramic, rare earth, cast and sintered specialty metals magnets. It is a medium sized, private company that is a subsidiary of Hitachi Metals America. The company employs approximately 500 at this location and had 1995 sales of $58 million. Presently it has no orders with microwave tube manufacturers, but Hitachi does have the capability, within a reasonable lead time, to support the needs of any manufacturers. Previous customers included Hughes Aircraft, Varian, Litton, and Raytheon.

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APPENDIX C

Types of Microwave Power Tubes

Klystrons

The klystron generally is referred to as a "linear beam" device because it utilizes a magnetic field in line with its electric field. The energy distribution of the beam is altered as it travels through a resonant cavity. The resonant cavity is excited by an input signal such that the beam is "velocity modulated" (some electrons are slowed, some accelerated). Farther down the tube, the electrons "bunch" as the faster electrons overtake the slower electrons. As the bunched electrons pass through another resonant cavity, that cavity is excited at the same frequency as the input cavity, but at a much higher power level. This amplifies the signal. Klystrons range in length from less than a foot to over 20 feet and operate with voltages ranging from a few hundred to several thousand. Output power can range from 10 kilowatts (continuous) to 10 megawatts (pulsed).

Klystrons are used as final power amplifiers in many military radar systems. However, new generation military radar systems are being designed using traveling wave tubes and solid-state devices. Civilian agencies continue to use klystrons in many of their radar systems. For example, the Federal Aviation Administration's Terminal Doppler Weather Radar uses a klystron amplifier because solid-state devices cannot generate the waveforms needed to detect severe weather and wind-shear conditions. The WX-88 NEXRAD -- the next generation radar, presently in use by the National Weather Service and NOAA, uses a broadband klystron transmitter. Additionally, although the FAA is upgrading its Air Route Surveillance radars to a solid-state configuration, a significant number of its radar systems using high-power klystrons will remain is service for another 15 to 20 years, requiring replenishment klystrons. (Note that the FAA "derates" the microwave tubes used in its radar applications. It emphasizes longer life and therefore does not "push" microwave tube performance limits as stringently as does the DoD.) Klystrons also are used in satellite earth stations and commercial television transmitters, and in medical applications for radiation therapy and magnetic resonance imaging. Finally, DOE uses highly specialized klystrons in exotic scientific applications to power particle accelerators for pure scientific investigation and for the accelerator transmutation of atomic waste. They may also be used to power a new linear accelerator being contemplated by the DOE to produce tritium -- an essential ingredient in U.S. nuclear weapons. Laboratories such as Los Alamos National laboratory, Sandia National Laboratory, and Stanford Linear Accelerator Center use large klystrons for research purposes. Specialized klystrons for scientific applications can each cost several hundred thousand dollars.

Traveling Wave Tubes (TWTs)

The TWT is an important member of the linear beam family of microwave power tubes. It is similar to the klystron in that a pencil beam of electrons is generated in an electron gun and kinetic energy is converted into RF energy as the beam interacts with an RF circuit. Unlike the klystron, the interaction occurs continuously as an increasing traveling wave instead of discrete steps in cavities. The most common form of RF circuit used is a simple helix. The TWT's advantage is "bandwidth". It can instantaneously amplify signals over a range of frequencies – several octaves. Coupled Cavity TWTs (CCTWTs) operate on the same principal as the helix TWT. The principal difference is bandwidth. The helix TWT uses a helix type of RF circuit to obtain its bandwidth. A CCTWT uses other types of circuits which do not have the same bandwidth capability, but can produce higher power. The CCTWT is used in radar applications where high gain, reasonable efficiency, and modest power (between 10 - 100 kilowatts) is required.

DoD uses helix TWTs widely in electronic warfare applications for "deceptive jamming," making the platform appear to be either ahead of or behind its real position, or to make the range uncertain. Helix TWTs also are used in many communications applications, and as amplifiers in satellites and in the earth stations of satellite communications systems. CCTWTs produce high average power which makes them useful for airborne radar applications, especially in fighter aircraft. TWTs generate very little "noise" (extraneous signals) which make them ideal for commercial broadcasting and magnetic resonance imaging. TWTs for electronic warfare applications can cost between

$2,000 and $25,000, depending on required power level and bandwidth. TWTs for satellite applications can cost several hundred thousands of dollars.

Magnetrons

The magnetron -- a “crossed-field” device -- differs from the klystron in that its magnetic field is perpendicular to the electric field. In the magnetron, the electrons emitted from the cathode are drawn toward the anode (an even number of resonant cavities arranged radially around the cathode) by the electric field. At the same time, the magnetic field causes the electrons to move perpendicularly to the force of the electric field. As the electrons move away from the cathode, they cross the gaps of the anode cavities and electron bunching occurs. “Spokes” of resonant electrons are formed which rotate around the cathode. When the electron spokes cross the gaps of the anode cavities at the resonant frequency of the cavities, the spokes are reinforced and the signal grows. Microwave energy is extracted through a cavity coupled to an output waveguide.

Magnetrons are oscillators and usually operate in a pulsed mode. They are used extensively in commercial airliner weather and collision avoidance radar, in almost all military and commercial navigation and weather radar systems, in some of the less-expensive medical therapy equipment, and in various industrial heating applications, including the ubiquitous microwave ovens. Magnetrons can generate a lot of power in a small volume and are very efficient. They also are relatively inexpensive. Magnetrons used for microwave ovens sell for less than $30. Magnetrons for high-power radar applications sell for several thousand dollars.

Crossed-Field Amplifiers

The crossed-field amplifier (CFA) might best be described as part magnetron and part TWT. Like a magnetron, it has an electronic interaction space using electric and magnetic fields which are perpendicular to each other. It is like a TWT in that the electronic interaction is with a traveling wave on a slow wave structure. The slow wave structure is a helix like a TWT, but also an anode like a magnetron. Unlike a magnetron, a CFA amplifies an input signal. The input signal is launched on the slow wave structure, or delay line. The signal propagates along the delay line at the same velocity as the electron stream. The interaction results in a growing wave of electrons which is coupled off the circuit at the output port. CFAs, like magnetrons, are highly efficient; but they also are somewhat noisy. CFAs often are chosen as power amplifiers for radars where space and DC-to-RF conversion efficiency are at a premium, for example in mobile ground systems and shipboard installations like the Aegis.

Gyrotrons

A gyrotron, a more recent development, looks like a linear beam device but performs like a combined linear beam and crossed-field device. It is large, heavy, expensive, and employs very high voltages and high magnetic fields generated by superconducting solenoids. It can do what no other microwave power tube can do -- generate very high-power levels at millimeter wavelengths. The gyrotron promises important advances in fusion and because of the high resolution possible with its millimeter wavelengths, great improvements in radar imaging. DOE sponsored much of the initial gyrotron development as the source for plasma heating in fusion reactors. Gyrotrons are used for plasma heating in Japan, Europe, Russia, and the U.S. (at Princeton University and General Atomics). Gyrotrons also are used in industrial heating, such as sintering ceramics.

APPENDIX D

Utilization of Foreign Sources

The end of the Cold War has brought dramatic changes to the relationships between the Department of Defense (DoD) and the national and world economies. During the Cold War, both the Congress and the Department established restrictions on the use of foreign sources for certain procurement requirements. For DoD, these restrictions, incorporated into the Defense Acquisition Regulation Supplement (DFARS), were designed to preserve a base for furnishing needed supplies or services in case of a national emergency or industrial mobilization. Today, instead of planning for an attack by the Soviet Union and its allies, DoD bases its wartime planning needs on a requirement to fight and win two nearly simultaneous major regional conflicts while primarily using existing resources, including stockpiled material.

With significant changes in military missions, sharp reductions in defense spending, and absent widespread mobilization requirements, DoD wants to take full advantage of the benefits offered by access to the best global suppliers and promote consistency and fairness in dealing with our allies, while also assuring that an adequate industrial base is maintained to support defense needs. For this purpose, DoD and many friendly governments have established reciprocal procurement agreements that waive their respective "buy national" laws and put each others' industries on par as potential suppliers. Consequently, DoD often relies upon foreign suppliers.

Although DoD is willing to depend upon reliable foreign suppliers, it is not willing to accept foreign vulnerability, which poses risks to national security. Therefore, under specific circumstances, DoD can, and does, restrict specific procurements to domestic sources for mobilization base and other reasons.

In addition to the foreign product restrictions set forth under DFARS 225.71, a DoD component may exclude foreign sources from a solicitation for mobilization base reasons, with appropriate approvals. A decision to exclude foreign sources from a defense procurement on mobilization base considerations (that is, the authority under Federal Acquisition Regulation (FAR) 6.302-3(a)(2)(i) or FAR 6.202(a)(2)), must be approved by the Under Secretary of Defense (Acquisition and Technology) for procurements over $50 million. For procurements up to $50 million, the decision must be approved as prescribed by FAR 6.304 and DFARS 206.304 or FAR 6.202(b) and DFARS 206.202(b).

Aside from mobility base considerations, there are other exceptional conditions (described in DoD Handbook 5000.60-H, *Assessing Defense Industrial Capabilities*, Section 5.2, and summarized below) which may warrant excluding foreign suppliers from specific procurements.

- Foreign sources may pose an unacceptable risk when there is a high "market concentration" combined with political or geopolitical vulnerability. (For example, a sole source foreign supplier existing only in one physical location and vulnerable to serious political instability may not be available when needed. Note that market concentration alone is not sufficient reason to exclude foreign sources; there must also be a credible threat of supply disruption due to political instability. Sheer physical distance from the US is not by itself a risk which merits foreign source exclusion.

- Suppliers from politically unfriendly or anti-American foreign countries, as defined by statute or US Government policy, are not to be used to meet US defense needs.

- A US source may be needed for technologies and products that are either classified, offer unique warfighting superiority, or could be used by foreign nations to develop countermeasures. However, the Department has agreements with many allied and friendly nations for safeguarding classified military information. Foreign sources cannot be excluded on the basis of a need to protect classified or unique technologies or products; this must be determined by individual circumstance.

- Suppliers that cannot or will not provide products for military applications for political reasons are not feasible sources.

- The DoD is required by law or regulation to purchase a particular product or service only from US sources (for example, set-asides for small business concerns, Section 8(a) competitions, use of authorized sources and restrictions imposed by DoD Appropriations and Authorization Acts and other statutes).

The contracting officer, working in concert with the program manager, must obtain approval determination through the normal contract approval process, to incorporate these exceptions into a procurement action.