

High Power Microwaves Strategic and Operational Implications for Warfare

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By

Eileen M. Walling, Colonel, USAF

February 2000

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Colonel Eileen M. Walling, USAF, has spent most of her career in the U.S. Air Force working on directed energy technology issues. Prior to entering the Air War College, she was the Director for the Air Force's High Power Microwave Program where she was responsible for the technical oversight and direction of all electromagnetic technologies and applications for military users. During her assignment at the Pentagon, she had numerous jobs on the staff of the Air Force Acquisition Executive. She served as the Program Element Monitor for Rome Laboratory, Armament Laboratory, and Civil Engineering Laboratory. She was responsible for oversight, direction, and advocacy of nine science and technology programs with total annual funding over \$280 million. At Headquarters Air Force Systems Command, Colonel Walling managed all the Advanced Weapons Technologies and Conventional Armament Programs. Previously, she spent several years at the Air Force Weapons Laboratory directing technical efforts in adaptive optics and ground based laser programs. Early in her career, she was a Technical Systems Manager for all USAF ground communications terminals and was a Maintenance Supervisor for an USAF radar squadron in upstate New York. Colonel Walling has a Masters Degree in Engineering Physics from the Air Force Institute of Technology, a Masters Degree in Systems Management from the University of Southern California, a Bachelor of Science Degree in Mathematics and Physics from the College of William and Mary. Additionally, she has completed the Advanced Program Managers Course at the Defense Systems Management College. She is a member of the Acquisition Corps, and is certified Level III in Systems Planning, Research, Development, and Engineering. Her additional military education includes Squadron Officer School and Air Command and Staff College. A 1999 graduate of the Air War College, Colonel Walling conducted this research under the auspices of the Center for Strategy and Technology. Colonel Walling is currently assigned to the Air Force Research Laboratory at Wright-Patterson Air Force Base in Dayton, Ohio.

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Abstract

The military has long exploited the electromagnetic frequency spectrum, first with “wireless” communications in the late 1800’s, and then with the discovery of radar in the 1930’s. These technologies quickly evolved into many applications in the military, including advanced early warning, detection, and weapon fire control. Scientists and engineers continued to investigate the frequency spectrum to increase power levels and to develop additional applications.

The term “directed energy” was once relegated to science fiction. It would be difficult to find a science fiction novel or movie that does not address directed energy weapons. But “directed energy” is now a scientific fact of life with laser pointers, pagers, fax machines, and supermarket checkout scanners. However, one area of the directed energy spectrum that has received significantly less attention and support is high power microwave technology. In view of the relative paucity of knowledge about microwaves within the Department of Defense, this study examines the role of high power microwave technology and its applications for the defense establishment.

In recent years, the modern battlefield has become a “target rich” environment for high power microwave weapons. Except for the standard rifle, gun, knife, or grenade, virtually all military equipment contains some electronics. For example, in the Gulf War, the average squad or platoon of soldiers had numerous devices, ranging from radios to Global Positioning System (GPS) receivers, which they used to provide communication and information about the battlefield.

The military research laboratories have demonstrated that high power microwave technologies can produce significant effects, ranging from upsetting to destroying the electronics within military and commercial systems. The Air Force has led this technology development, and various operational communities, including the Air Combat Command and U.S. Strategic Command, have identified numerous offensive and defensive requirements that can be satisfied by high power microwave weapons.

Several high power microwave technologies have matured to the point where they are now ready for the transition from engineering and manufacturing development to deployment as operational weapons. The conclusion of this study is that high power microwave technology is ready for the transition to active weapons in the U.S. military. It reviews various applications

of high power microwave weapons in strategic and operational missions for the Air Force,¹ considers the implications of the integration of microwave technology into operational weapons, and examines numerous constraints and challenges associated with the transition of new technologies and systems into the Air Force inventory.

This study concludes that high power microwave weapons systems offer the prospect of significant offensive and defensive capabilities for all of the military services. The principal recommendations include the suggestion that the Department of Defense and the Air Force establish a High Power Microwave Systems Program Office for the purpose of developing these weapons and integrating them into the combatant commands. This systems program office should be a joint program office that involves the participation of the Army, Navy, and Marine Corps as well as other agencies. Only then will the U.S. military be able to maximize the development of microwave applications, minimize costs, and facilitate the transition of this unique technology to the military services and other government agencies. Not only should defense contractors be encouraged to develop the technical capabilities that would permit them to participate in microwave weapons programs, but this study also concludes that all U.S. military systems should be hardened to protect them against the effects of microwaves.

1. Introduction

Since the early 1980's, the Air Force has been funding scientific and technological programs that seek to develop radio frequency and high power microwave technologies as a potential class of directed energy weapon systems.² These technologies are commonly grouped under the "umbrella" of high power microwave (HPM) technologies. The electromagnetic frequency spectrum for this area ranges from the low megahertz to the high gigahertz frequencies (1×10^6 hertz to 1×10^{11} hertz). Invisible to the human eye, these frequencies range from wavelengths of 0.1 centimeters (the gigahertz frequencies) to 3 meters (the megahertz frequencies) in length.

It is not surprising that the U.S. Air Force is interested in high power microwave technology. This technology is an outgrowth of previous military and civilian research and studies in the field of radar technology and electromagnetic pulse (EMP) that started in the late 1930's and continued through the late 1980's.³ EMP encompasses frequencies between the low hertz to high megahertz frequency range. While it is typically equated with nuclear detonations, EMP is also produced by non-nuclear sources. One example is the static and distorted radio signals that occur when a car is driven beneath high voltage power lines. While this effect only disrupts the signals and does not harm the radio, in fact, EMP can produce such serious and sometimes catastrophic effects in various electronics equipment that the Department of Defense developed various hardening and shielding efforts to protect its weapons systems and subsystems against the effects of EMP.

Since the mid-1980's, the USAF has expanded this research into the higher frequencies of the high power microwave frequency spectrum.⁴ Microwave research efforts have shown that electronics are also affected at these higher frequency and power levels. By changing the power, frequency, and distance to the target, microwave weapons can produce effects that range from denying the use of electrical equipment to disrupting, damaging, or destroying that equipment. This range of effects has been given the term "D4" as the shorthand for deny, disrupt, damage, and destroy. The fact that microwave weapon systems have the added advantage of self-protection means that they can be known as a "D5" weapon when one adds "defend" to its capabilities. It is significant that microwave weapon systems will be the first systems in the inventory that can simultaneously defend against enemy attack, while offensively producing the classical military effects on enemy systems.

A common assumption is that microwave weapons systems are similar to electronic warfare systems. The relationship between a microwave weapon and an electronic warfare system is that, while both use the frequency spectrum to work against enemy electronics, microwave weapons are different from the electronic warfare systems on several counts.

Electronic warfare systems are limited to jamming, and will affect enemy systems only when the electronic warfare system is operating. When the electronic warfare system is turned off, the enemy capability returns to normal operation. Electronic warfare attacks also require prior knowledge of the enemy system, because the jamming function will work only at the enemy system's frequency or modulation. The enemy system also has to be operating in order for electronic warfare systems to effectively jam. There are numerous ways to counter the effects of electronic warfare signals. These countermeasures are often accomplished by redesigning the internal signal controls or increasing the frequency bandwidth of the system.⁵

Unlike the electronic warfare system, the microwave weapon is designed to "overwhelm a target's capability to reject, disperse, or withstand the energy."⁶ In other words, microwave weapons by their nature will produce significant, and often lethal, effects on their targets. There are four major distinctive characteristics that differentiate a microwave weapon system from an electronic warfare system. First, microwave weapons *do not rely on exact knowledge* of the enemy system. Second, they can leave *persisting and lasting effects* in the enemy targets through damage and destruction of electronic circuits, components, and subsystems. Third, a microwave weapon will affect enemy systems *even when they are turned off*. And finally, to counter the effects of a microwave weapon, *the enemy must harden the entire system*, not just individual components or circuits. The next section examines the current state of technology in the field of high power microwaves.

II. Current State of Technology

The Air Force Research Laboratory's High Power Microwave (HPM) Program continues to investigate the effects of microwave and radio frequency emissions on electronics. This program develops technologies for integrating the next-generation directed energy weapons into operational weapons for the combatant commands. Air Force scientists and engineers in the High Power Microwave Division at Kirtland AFB have made tremendous technical advancements and improvements in antennas, pulsed power technologies, and microwave sources, and have done so on both the offensive aspects of microwave as well as the defensive and protective capabilities.

As part of the research program, numerous systems, both military and commercial-off-the-shelf, have been tested against microwave emissions in controlled experiments. The resulting information has increased the technical understanding of the susceptibility and vulnerability of these various systems to high power microwave emissions. This information is of vital importance because it forms the basis for shielding and hardening efforts to protect current and future U.S. weapons systems from microwave weapons that may be available to other states. At the same time, it is essential to protect U.S. weapon systems from the "friendly" microwave system emissions that can inadvertently cause fratricide or suicide.

The Air Force technical community also performs numerous technological demonstrations to support the requirements of the operational communities. The Air Force microwave program managers closely assist the operational communities, including the Air Combat Command and U.S. Special Operations Command, in their efforts to develop requirements for future weapons systems.⁷ The Air Force microwave community also works closely with the other services and Department of Defense and Department of Energy agencies (e.g., the Defense Threat Reduction Agency and the national laboratories) so that the defense establishment can share the information that will lead to the development of weapon systems for the twenty-first century.⁸

High Power Microwave Terminology and Characteristics

It is essential for the defense establishment to understand the distinctive characteristics of high power microwaves, and the ways in which these

characteristics can be utilized in designing new weapon systems. Because microwave weapons offer a dramatically new method of warfare, the ability to identify and explain these distinctive characteristics will help the defense establishment become more familiar with this technology and its military applications in the twenty-first century.

Entry Points. There are numerous pathways and entry points through which microwave emissions can penetrate electronic systems. If the microwave emissions travel through the target's own antenna, dome, or other sensor opening, then this pathway is commonly referred to as the "front door."⁹ On the other hand, if the microwave emissions travel through cracks, seams, trailing wires, metal conduits, or seals of the target, then this pathway is called the "back door."¹⁰

Microwave Effects. The fact that microwave emissions affect electronic targets from the inside-out means that they do not physically destroy the target. Rather, microwave emissions invade the electronics and destroy or disrupt the individual components, including integrated circuits, circuit cards, and relay switches. Microwave weapon systems have the ability to produce graduated effects in the target electronics, depending upon the amount of energy that is "coupled" to the target. Here, "coupled energy" means the energy that is received and subsequently transmitted deeper into the electronics through the circuitry pathways that exist within the target itself. In the microwave technical community, the ability to "scale," or increase, the effects is often described as "dial a hurt."

Microwave Lethality. Electronic components are extremely sensitive to microwave emissions, especially the integrated circuits, microelectronics, and components found in modern electronic systems. The lethality of electronic effects can vary from deny, which means to upset or jam; to degrade or "lock-up" the system; to damage or "latch-up" the system; or to destroy it. The power density received at the target will vary from microwatts/square centimeter (10^{-6} watts/cm²) to milliwatts/square centimeter (10^{-3} watts/cm²), depending upon the distance between the microwave weapon system and the enemy target. The effects are dependent upon the amount of power generated by the weapon, the distance between the weapon and target, the characteristics of the microwave emission (frequency, burst rate, pulse duration, etc.), and the vulnerability of the enemy target. Each of these degrees of effectiveness bears further discussion.

The term “*deny*” is defined as the ability to eliminate the enemy’s ability to operate without inflicting harm on the system.¹¹ A microwave weapon can achieve this result by causing malfunctions within certain relay and processing circuits within the enemy target system. For example, the static and distortion that high voltage power lines have on a car radio causes no lasting damage on the radio after the car leaves the area. Thus, the “*deny*” capability is not permanent because the affected systems can be easily restored to their previous operational condition.

The meaning of “*degrade*” is to remove the enemy’s ability to operate and to potentially inflict minimal injury on electronic hardware systems.¹² Examples of this capability include signal overrides or insertion, power cycling (turning power on and off at irregular intervals), and causing the system to “lock-up.” These effects are not permanent because the target system will return to normal operation within a specified time, which obviously varies according to the weapon. In most cases, the target system must be shut off and restarted, and may require minor repairs before it can operate normally again.

The idea of “*damage*” is to inflict moderate injury on enemy communications facilities, weapons systems, and subsystems hardware, and to do so in order to incapacitate the enemy for a certain time.¹³ Examples include damaging individual components, circuit cards, or the “mother boards” in a desktop computer. This action may create permanent effects depending upon the severity of the attack and the ability of the enemy to diagnose, replace, or repair the affected systems.

Finally, the concept of “*destroy*” involves the ability to inflict catastrophic and permanent injury on the enemy functions and systems.¹⁴ In this case, the enemy would be required to totally replace entire systems, facilities, and hardware if it was to regain any degree of operational status.

Target Repair. Any enemy target will be affected by a microwave weapon system if it is within the lethal range of that weapon. The ability to diagnose and repair damaged or destroyed components or circuits requires experienced technicians and electrical engineers. It will often be the case that several weeks of detective work, including sophisticated “autopsies” of the damaged or destroyed items, are required to repair the system. Once the cause has been diagnosed and determined, in theory the item can be repaired or replaced if there are adequate parts and repair facilities.¹⁵ The reality is that because microwaves can enter a system through multiple entry points, it is likely that numerous circuits and components will be damaged. The tech-

nician's job is more difficult because even after the entire system is evaluated, repairs and replacements of components or circuits may not return the system to its full operational capability. The entire system must be examined, and the most serious damage may be the hardest to adequately diagnose.

*Susceptibility and Vulnerability.*¹⁶ By their nature, microwave weapons do not discriminate between friendly electronics and enemy electronics. In order to protect friendly forces from enemy microwave emissions, it follows that friendly systems must be hardened against microwave frequencies. While the U.S. currently leads in the development of microwave weapons, and the threat from an enemy microwave weapon is small, the more immediate problem is the potential for fratricide or suicide from "friendly" microwave weapons. While countermeasures and hardening techniques are being developed to protect friendly forces and systems, relatively few of these techniques have been incorporated into current systems or new systems that are under development. Current friendly systems will require modifications to attain this level of protection. One conclusion of this study is that future U.S. military systems should be hardened during the design phase.

Area Weapon. A microwave weapon is an area weapon whose "footprint" is determined by the frequency, field-of-view of the antenna, and range to the target. Most antennas have a field-of-view that can be measured from several to tens of degrees. The fact that a microwave does not require precise aiming means that the microwave weapon can operate with far less stringent pointing and tracking requirements than those that are required for laser weapons or conventional "smart" munitions. The "footprint" of a microwave weapon can be a two dimensional area for targets on the ground, or a three dimensional conical volume for targets that are in the air or in space. This "footprint" means that a microwave weapon can attack multiple targets simultaneously. For example, while the primary target may be an enemy communications van, an enemy surface-to-air missile that is within the conical footprint of the microwave weapon also will be affected. Another advantage of a microwave weapon is that the antenna may appear to be a monolithic shape, but actually be composed of numerous phased array emitters, which would allow a microwave antenna to be incorporated conformally into weapon system, such as the wing or fuselage of an aircraft.

Insensitive to Weather. As with lasers, high power microwave emissions travel at the speed of light. However, unlike lasers, microwave frequencies are insensitive to weather, which means that microwave emissions can penetrate clouds, water vapor, rain, and dust. To cite a common example, radar as well as radio and television stations transmit well through fog, snow, or even torrential rain. The implication of this insensitivity is that high power microwave weapons can be used in any weather conditions, which is particularly advantageous in military operations because there are relatively few weapons in military arsenals that can function regardless of the weather.

Long Reach, Deep Magazine, Scalable Size. Microwave emissions, traveling at the speed of light, are 40,000 times faster than the swiftest bullet—the ballistic missile.¹⁷ It takes about 13 milliseconds (13×10^{-3} seconds) for a microwave telecommunications signal to travel from New York to California. In addition, with current technology the range for a tactical microwave weapon could be in the ten's of kilometers, and future advances in microwave technology should permit the development of even longer ranges. At the same time, microwave weapons have a “deep magazine,” which means that they can emit energy as long as there is sufficient power. The implications is that the majority of microwave weapons systems would not be “single use” assets because they do not emit expendables in the traditional form of conventional bombs and bullets. Finally, the size of microwave weapons will depend upon the target, delivery application, and desired effects, and thus microwave weapons are well suited for covert military operations. It is conceivable that “hand-held” missions could employ a system that weighs less than ten pounds. Indeed, man-portable devices could weigh in the tens of pounds; vehicular/pod-mounted devices would weigh in the hundreds of pounds; and airborne systems would weigh in the thousands of pounds.¹⁸ The point is that microwave weapons are inherently flexible.

Logistics Support. Microwave weapons systems are powered by some form of electrical energy that is stored in batteries, and can be drawn from a host system (such as aircraft engines) or an internal power source. The vast majority of microwave weapons systems are able to fire multiple bursts of microwave power over a long period of time. The reason is that these weapons do not have “expendables” in the traditional sense because microwave weapons will emit microwave energy as long as there is sufficient power. The logistics support associated with these microwave weapons sys-

tems—the ground crew, supply, maintenance, and repair—is significantly less than what would be required for a conventional weapons system.¹⁹ For some of the missions that are examined in the following section, the microwave weapons will be “single shot” devices that are powered by an explosively-generated electrical pulse, which means that the logistics support for these microwave weapons systems will be equivalent to that for conventional munitions.

Collateral Damage. Microwave weapons systems offer great advantages in minimizing collateral damage.²⁰ To begin with, microwave weapons (except explosively-driven devices) will affect only electronics and will not cause physical or structural damage to facilities. While any vulnerable electronics system within the weapon’s footprint will be harmed by the microwave emissions, the same is not true for physical facilities and structures. By far the most important reason that microwaves minimize collateral damage is that these emissions are not harmful to people or structures.²¹ To reduce the effects on “non-combatant” systems on a particular area (e.g. systems within a hospital zone), microwave weapons can be programmed to cease or reduce emissions over that area.

High Power Microwave Technology Program

The three major technical activities that must be closely coordinated and integrated in the development of microwave weapon systems are the microwave source and antenna, the effects/lethality testing and hardening, and the development of applications for microwave weapons.

Microwave Sources and Antennas. USAF scientists and engineers have made great progress in developing higher power microwave sources that operate at different frequencies and antennae that can transmit at these higher power levels. The technological community has also made great strides in developing new and innovative ways to reduce the size, weight, and volume of microwave sources and antennae, while simultaneously increasing power levels. For example, one microwave source radiates one gigawatt of power in a few nanoseconds (10^{-9} seconds) and weighs less than 45 pounds. Another example is a microwave source that radiates 20 gigawatts of power in a few nanoseconds and weighs 400 pounds.²² To comprehend these power levels, the total daily power generated by the Hoover Dam is 2 gigawatts.²³

It is precisely the development of multiple types of microwave sources, which operate at different frequencies and power levels, that enables the development of various military applications. Numerous advances in antenna development have kept pace with the microwave source development. As the frequencies changed and power levels increased, the antenna engineers have developed designs and refined techniques that maximize power output, while minimizing size and weight.

Effects/Lethality Testing and Hardening. Since high power microwaves are non-discriminatory and attack all electronics, it is critical to examine and test numerous weapon systems to assess their susceptibility and vulnerability, including both foreign and U.S. systems.²⁴ Once the susceptibility levels are established, engineers devise methods to modify and “harden” U.S. systems in order to protect them not only from potential enemy emissions, but also from “friendly” emissions. The technical community in the U.S. Air Force has tested various modification designs and integrated these into several programs, including the F-16 aircraft and the Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) pod.²⁵ In the case of foreign systems, these tests establish the lethal levels of the frequencies and power that will deny, disrupt, damage, or destroy these systems. All of these tests also guide the technological community in their efforts to develop improved microwave sources.

Microwave Weapons Applications. The U.S. Air Force technical community has devised numerous applications for microwave weapons that are designed to satisfy the requirements established by the operational commands. There are current technological programs in the areas of information warfare (IW), suppression of enemy defense (SEAD), and aircraft self-protection.²⁶ In 1997, the Office of Secretary of Defense (OSD) approved the first Advanced Concept Technology Demonstration (ACTD) for a high power microwave device.²⁷ A number of other application programs are also maturing to the point where the operational commands are conducting demonstrations of these capabilities.

III. Types of High Power Microwave Weapons

The Department of Defense's Joint Vision 2010 outlines the strategic vision for the military, which is to attain the full spectrum dominance that exists when the adversary can be dominated across the full range of military operations. To meet U.S. national security needs in the twenty-first century, the concept of "full spectrum dominance" rests on four operational concepts—dominant maneuver, precision engagement, full-dimension protection, and focused logistics—with information superiority as a universal requirement within each.²⁸

In the U.S. Air Force's *Global Engagement: A Vision for the 21st Century*, the objective is to contribute to full spectrum dominance through its six core competencies—air and space superiority, rapid global mobility, precision engagement, global attack, information superiority, and agile combat support—which are also supported by global awareness and command and control.²⁹ The question is how high power microwave weapons support the strategic visions outlined by the Department of Defense, the capabilities brought by microwave weapons to military operations, and the types of microwave weapons that the United States will need in the future.

To answer these questions, the Air Force Research Laboratory's Directed Energy Directorate, located at Kirtland AFB in New Mexico, conducted an evaluation of how directed energy technologies will satisfy the six core competencies identified in *Global Engagement*.³⁰ This evaluation included high power microwave technologies, as well as the various laser technologies that are being developed by the Air Force. As shown in Table 1, high power microwave technologies will contribute to U.S. military capabilities in several important ways.

Table 1. USAF Core Competencies and High Power Microwaves³¹

Core Competencies	Advantages to Microwave Weapons
Air & Space Superiority	Deny, degrade, and destroy enemy electronic systems. Provide rapid force deployment. Neutralize enemy response.
Global Attack	Speed of light, all-weather electronic attack. Enable dynamic force employment. Enhance security of operations.
Rapid Global Mobility	Improved air and ground force protection. Non-lethal, long range denial option. Aircraft self-defense capability.
Precision Engagement	Precise/selective electronic attack. Minimum collateral damage and casualties. Non-lethal weapon force protection.
Information Superiority	Deny enemy situational awareness. Protect friendly systems.
Agile Combat Support	Protect deployed forces with minimal logistics. Light-weight systems and small fuel requirements.

In 1998, the Air Force Research Laboratory commissioned a study to identify promising applications for directed energy (DE) weapons using airborne platforms in tactical roles and missions. The Directed Energy Applications for Tactical Airborne Combat (known as “DE ATAC”) Study seeks to identify those USAF requirements that are needed to develop and integrate these weapons into the operational commands.³² The first phase of the DE ATAC Study was completed in November 1998. Interestingly, microwave weapons, rather than lasers, constituted the top four applications in the areas of precision-guided munitions, large aircraft shield for self-protection, small aircraft shield for self-protection, and unmanned combat air vehicles (UCAV).³³ During the second phase of the study, which began in December 1998, each of these four weapons applications were subjected to further investigation. The remainder of this section is devoted to a review of each weapon.

Precision Guided Munitions (PGMs)

The lethality of conventional precision-guided munition is limited to the blast and fragmentation footprint of the weapon. A 2000-pound precision munition has a blast and fragmentation radius of about 35 meters and produces a footprint of approximately 4000 square meters. As targets move closer to the center of this area they will experience greater damage and destruction than targets which exist at greater distances.

A conventional precision munition can be compared with a precision-guided munition that also contains a high power microwave device. As with a conventional munition, a microwave munition is a “single shot” munition that has a similar blast and fragmentation radius. However, while the explosion produces a blast, the primary mission is to generate the energy that powers the microwave device. Thus, for a microwave munition, the primary kill mechanism is the microwave energy, which greatly increases the radius and the footprint by, in some cases, several orders of magnitude. For example, a 2000-pound microwave munition will have a minimum radius of approximately 200 meters, or footprint of approximately 126,000 square meters. However, targets that are vulnerable to blast and fragmentation of the munitions will not escape the microwave energy.³⁴

The most significant opportunity for the employment of microwave munitions will be against hardened targets, some of which are extremely hard, if not impossible, to damage or kill with conventional munitions. For example, during the Gulf War, the U.S. Air Force developed a 5000-pound weapon (known as the GBU-28) within several weeks for the specific purpose of destroying hardened Iraqi targets.³⁵ However, even this smart munition cannot guarantee that the target will be killed because an impact error of even several feet may make the difference between destruction and survival.

Microwave munitions are not limited to precision-guided weapons, but may be “packaged” in several sizes, ranging in size from artillery shells, to scatterable mines, and 2000-pound munitions. This diversity in the size and packaging of microwave munitions increases the number of potential applications, in particular when one considers the missions that could be performed by the other military services.

Large and Small Aircraft Shields for Self-Protection

For the last several decades, surface-to-air and air-to-air missiles have constituted a significant threat to aircraft. These missiles are guided by a variety of sensor systems, including infrared, radio frequency, electro-optical, laser-guided, or any combination thereof. The majority of the missiles on the global market employ infrared missiles and radio-frequency missiles, but the problem is that there are no weapon systems in the U.S. inventory that can actively counter these missiles.³⁶

Surface-to-air missiles can be broken into the two categories of man-portable and vehicle-mounted. In recent years, rebel forces and terrorists have acquired many shoulder-mounted man-portable air defense systems (known as MANPADS), including the Russian SA-8 and Stinger missile, which are relatively inexpensive and easy to operate. Larger missiles, such as the Russian SA-10, have also appeared in many regions of the world.

Large military aircraft, such as the C-17, the C-130, and the Airborne Laser (ABL), are tempting targets, especially because these relatively slow-moving aircraft are not highly maneuverable during take-off and landing. While some of these large aircraft and most of the small fighter aircraft are already equipped with self-protection systems (chaff and/or flares) that may defeat the older, less sophisticated missiles, these systems do not have the capability to actively engage incoming missiles.

Importantly, however, a high power microwave system that was either permanently mounted or pod-mounted could actively engage an incoming missile. The microwave system would be triggered by the aircraft's missile warning sensor, which would provide information on the location of the missile and limited information on its trajectory. The concept would be to fire a microwave system in order to flood that region of the sky with microwave energy. When this microwave energy enters several systems within the missile, the missile is likely to experience drastic changes in its flight trajectory. This rapid change in trajectory can produce several failure mechanisms in the missile, some of which are catastrophic—ranging from missile body failure because of high “g-force” turns, to warhead fuze detonation and forcing the missile to change direction and eventually run out of fuel.

In this operational condition, microwave weapons offer several significant advantages. First, as an “area weapon” that can engage numerous missiles within the target area, it will simultaneously affect all missiles within

that area. Second, the microwave beam can be rapidly retargeted, especially if one uses phased array antenna systems, in order to provide protection in several directions. Third, the microwave weapon may be sized and packaged to protect most aircraft. Microwave systems for large, less maneuverable, and slower aircraft can be mounted internally, and yet still possess sufficient power to engage missiles at longer ranges. Rough calculations suggest that a microwave weapon system on large aircraft would not severely reduce the amount of cargo or the range of the aircraft.³⁷ Microwave systems for smaller, faster, more maneuverable aircraft could be mounted in pods, and while these pods will produce some drag, the increased protection will outweigh the penalty.

These microwave weapon systems can be used by the other military services for the purpose of protecting their systems from guided missiles. The smaller microwave weapons can be mounted on Navy fighters, Army tanks, helicopters, and ground vehicles. The larger microwave weapons can be used to protect Navy and Coast Guard ships as well as ground facilities from guided surface-to-surface or air-to-surface weapons.³⁸

Unmanned Combat Air Vehicles (UCAV)

Unmanned air vehicles are not new to the military forces, as exemplified by the *Predator*, *Hunter*, *Dark Star*, and *Global Hawk* vehicles that are in the inventory or under active development. While the missions for these vehicles vary, all have a reconnaissance and surveillance capability, and in that sense could become a “combat” vehicle with the addition of a microwave weapon system. This approach has several advantages.

The microwave UCAV weapon could operate as an autonomous pre-programmed vehicle or be linked to a controller on the ground or in an airborne platform, such as the Airborne Warning and Control System (AWACS) or Joint Surveillance and Target Attack Reconnaissance System (JSTARS) aircraft. An autonomous UCAV armed with a microwave weapon could be programmed to fly against fixed targets, while a microwave UCAV controlled by a human operator could be used to attack mobile targets.

These weapons can fly for several hours, which would give it the ability to fly deep into hostile territory, especially if the vehicle incorporates low-observable stealth technology, cruises at high altitude, and then descends to lower altitudes for the attack. In the case of mobile targets, microwave UCAVs could employ their reconnaissance and surveillance capabilities to

search and locate them, and then attack those targets once the controller has verified the targets.

During an attack, the microwave system would draw power from the vehicle's engines to generate the microwave energy. As long as the vehicle has fuel, it can attack enemy targets. The projected maximum capability for a microwaveUCAV is approximately 100,000 pulses of microwave energy (or shots) per mission. However, in the case of a typical engagement, a microwave weapon could fire multiple pulses at the target to ensure that it was destroyed or disabled. If one assumes 1,000 pulses per target, it is conceivable that a microwaveUCAV could attack on the order of 100 targets per mission.³⁹ In addition, a microwave system could be used to protect theUCAV from enemy missiles if the enemy has the ability to detect low-observable aircraft.

IV. Strategic and Operational Applications

The significance of microwave weapons is that they provide a range of strategic and operational capabilities in both offensive and defensive operations, and in that sense will change how the military conducts operations. The discussion in this section focuses on operations that could be performed by microwave weapons for the U.S. Air Force as well as the U.S. Army, Navy, and Marines, and potential civilian applications.

Suppression of Enemy Air Defenses

If friendly forces are to gain air superiority and supremacy, aircraft must be able to fly into enemy territory and attack targets without being stopped by enemy aircraft or missiles. To ensure air supremacy, one of the first missions to be completed is the suppression of the enemy's air defense systems, which include tracking the radars, targeting radars, communications, and missile guidance, control and intercept functions that are necessary for locating, tracking, targeting, and attacking friendly aircraft.

One way to attack and destroy an enemy's air defense system is with a combination of both precision-guided and "dumb" conventional munitions. Since the explosive kill and damage radius of a 2000-pound munition is on the order of 35 meters, the effects of explosive blast and fragmentation will have only minimal effects on equipment located beyond that distance. One way for the enemy to ensure that its air defense system will survive is to physically separate the individual systems by ensuring that the tracking radar is located some distance from the targeting radar. In this case, it will be necessary for friendly forces to attack the entire air defense system with multiple munitions if it wants to ensure that it is destroyed. However, a reasonable estimate is that a single high power microwave weapon could destroy the entire air defense system. In this case, there are several microwave weapons options that could accomplish this mission, including microwave precision-guided munitions, microwave unmanned combat air vehicles (UCAVs), or microwave self-protection pods on the attacking fighter aircraft.

The concept for the employment of a microwave precision-guided munition would be the same as that of a conventional munition. It would have the same blast and fragmentation pattern as a conventional munition, and thus operate as a "single shot" device. However, for the microwave munition, the

primary kill mechanism is microwave energy rather than an explosion. As described earlier, the footprint of a microwave munition is at least 100 times greater than that of a conventional munition. In the event that enemy air defense systems are located within this area, the detonation of the microwave weapon will lead to their instantaneous damage or destruction, depending on the specific details of the attack. In addition, the blast and fragmentation effects will also physically damage or destroy the targets that lie within its range or footprint.

In theory, a microwaveUCAV could be employed to destroy numerous targets, including the enemy's air defense network. As a multiple-shot weapon that can emit microwave energy as long as it has sufficient fuel to continue flying, aUCAV armed with a microwave weapon could be programmed to fly a designated route over known sites or "flown" by a controller over mobile air defense sites. In that case, the microwaveUCAV could destroy the electronics in the air defense network, and thereby destroy or at least degrade the entire network.

Command and Control and Information Warfare

The objective of command and control and information warfare, is to give friendly forces the capability to limit the enemy's ability to control and direct its military forces. At present, this mission is accomplished by using conventional munitions to attack enemy command and control facilities. If an enemy's command and control function is to be effectively destroyed, friendly forces must be able to prevent enemy commanders from maintaining contact with their forces. The reality of modern warfare is that military commanders are in a state of virtually total dependence on radios, telephones, satellite communications, computers, and faxes for communication with military units. A microwave weapon would present an extremely effective instrument for use against these enemy systems, in particular microwaveUCAVs and microwave munitions.

The microwaveUCAV could be pre-programmed, or actively controlled, to attack enemy command and control facilities as well as individual units that are dispersed on the battlefield. By attacking individual units, the use of microwaveUCAVs would ensure that enemy forces cannot effectively coordinate their combat efforts between units after command is severed. The microwaveUCAV weapon also can be used to attack commercial facilities, including radio and television stations, in order to limit the enemy's information from commercial sources and potentially restrict information to the

civilian population. Thus, microwave munitions could be used primarily for the purpose of attacking enemy command and control facilities. As a “single-shot” device, it will be necessary to deliver multiple microwave munitions against individual enemy units to destroy their communications capability.⁴⁰

Close Air Support

The purpose of close air support is to assist friendly ground forces when they are fighting enemy ground forces. It usually consists of direct fire by conventional munitions and large caliber aircraft guns (20 or 30 millimeter guns) that is used against enemy tanks, artillery, and forces. A reasonable assumption is that microwave weapons could be used to damage and destroy the electronic systems in the enemy’s front-line equipment. Potential targets would include the enemy’s command and control systems, radio and satellite communications, artillery targeting capability, and the guidance and control functions on guided munitions. The ability to destroy the enemy’s command and control and targeting functions would effectively prevent the enemy from using its weapons. To accomplish this mission, the two microwave weapons options are the microwave UCAV and microwave weapons that are mounted on pods on close air support aircraft, such as A-10 aircraft or Army helicopters. While an autonomous or pre-programmed microwave UCAV would be less useful in the changing circumstances of a modern battle, there would be great operational value to a controlled microwave UCAV. In this way, U.S. military forces would be able to direct microwave emissions against enemy forces and thereby limit the effects of fratricide on friendly ground forces.

Battlefield Air Interdiction

With microwave weapons, U.S. military forces would have the capability for striking enemy supplies, equipment, and troops behind the enemy’s front lines. A microwave weapon could be used to attack and disable enemy airfields by damaging and destroying electronics in airborne aircraft, aircraft on the ground, air traffic control equipment, communications facilities, radars, and ground defense systems. A microwave UCAV weapon would be able to disrupt, damage, or destroy electronic controls and processes in industrial or manufacturing facilities, and it could attack the electronic components of those items being produced and stockpiled. Such a weapon

would be able to prevent supplies from reaching the enemy forces by attacking the supply lines and enemy sea, ground (through trucks or convoys), and air transportation capabilities. A microwave munition would be effective against railways because the explosive detonation would cause physical damage to the tracks, rails, and trains, while the microwave emissions would damage electronic equipment in locomotive engines.

Space Control

For the purposes of space control, microwaves could be used as a defensive or offensive weapon. In that capacity, it could protect friendly satellites from guided kinetic-kill weapons as well as attack satellites that provide information, directly or indirectly, to enemy forces.⁴¹ One advantage to microwave weapons is that these do not produce debris, whereas all other proposed weapons will cause the physical damage that could lead to the disintegration of the satellite or result in catastrophic failure. The resultant cloud of debris is extremely dangerous to other satellites because even a small piece of this debris, roughly one cubic centimeter in size, could destroy a satellite. Another advantage relates to the unlimited magazine that is inherent in microwave weapons. Proposed laser systems, such as the space-based laser, use a limited magazine of chemicals to produce the laser beam, and these chemicals must be replenished. While other types of weapons, including explosive or kinetic kill weapons, are “single-shot” devices, a microwave weapon utilizes electrical energy to produce the microwave emissions, and this energy can be obtained from the host vehicle’s engine, rechargeable batteries, or other power sources (such as solar panels for a space-based system). In this sense, microwave weapons would have significant potential for space-control missions.

V. Challenges Posed by Microwave Weapons

If directed energy will represent an important element of warfare in the twenty-first century, then it must be understood that the transition of this technology into the operational military will raise a number of important challenges. There are signs that microwave weapons will represent a revolutionary concept for warfare, principally because microwaves are designed to incapacitate equipment rather than humans. Bearing this distinction in mind, this section focuses on some of the challenges that the development of microwave weapons will raise for the U.S. defense establishment.

Technological. The fundamental technological challenge for microwave weapons is to be able to engage targets at longer ranges and at higher power levels. To accomplish this, it will be necessary to expand research and development activities to improve microwave sources, antennas, and power generation/conditioning systems. At the same time, if platforms are to carry these weapons, the microwave systems must become more compact and rugged. Increasing the power levels, while simultaneously reducing the size of these microwave systems, will be extremely challenging and technically difficult. The Air Force should also develop microwave devices that can be repetitively pulsed at high rates and use wideband frequencies so that U.S. forces can attack enemy targets that are hardened against selective frequencies.

As microwave technologies have matured, there are growing opportunities to integrate these into weapon systems. The challenge faced by all technology programs is getting technology into the hands of the operational user. Since microwaves offer dramatic new ways to attack the enemy, the operational community must be convinced that this technology provides an effective way to conduct military operations. As in previous programs, the operational users and the systems centers must become advocates of a weapon system and invest significant resources. One option is to establish a microwave program office as the first step toward gaining the support of the operational community.

The majority of high power microwave research has been performed by government personnel at the military research laboratories. The U.S. Air Force has performed the bulk of the basic research and exploratory development at Kirtland Air Force Base in Albuquerque, New Mexico, and continues to expand the state of knowledge in microwave technologies. Be-

cause the military laboratories have limited manufacturing capabilities, the advanced technology development of microwave technologies has been performed by several U.S. contractors that have experience with high-power microwaves. However, the military industrial complex for this technology is quite small due primarily to the initially large costs of research and development. There are few contractors, whether large or small corporations, that have high power microwave experience. In order to develop and produce the variety and quantity of microwave weapons systems that the operational commands will need, the production base of U.S. manufacturers and contractors must be accelerated to meet the emerging requirements for the use of microwave technologies and systems.

Release of Sensitive Technologies. The development of microwave technologies is proceeding at a rapid pace in view of the number of nations that are investigating their potential value as weapons.⁴² The Department of Defense maintains a list of technologies that are critical to the military, known as the Military Critical Technologies List, which consists of the technologies that should not be transferred to foreign governments or firms. One measure of the international interest in microwave technologies is the number of states, including Australia, the United Kingdom, Russia, and Sweden, which have purchased or are actively developing microwave technologies for military purposes.⁴³

To control access to microwave technologies, their sale or transfer must, as with all significant military technologies, be approved by the United States. At present, all foreign government requests to transfer or sell technology are coordinated through the State Department and the Department of Defense (including the military services and agencies). This process also involves the Department of Commerce when there is a transfer of this technology to commercial enterprises in other states. In view of the critical nature of microwave technologies, these are included on the Military Critical Technologies List, which means that all requests for access to this technology will be reviewed by the major national security bureaucracies. The Department of Defense is responsible for ensuring that these technologies remain on this list for the foreseeable future and that proper coordination is maintained between the various government departments and agencies.⁴⁴

The decision to sell microwave technologies on the international market has significant military and political implications for the United States. The first is that the United States must consider whether the sale or transfer of high power microwave systems to other states will see those technologies

used against the United States or its allies. In addition, the United States must decide whether to provide information about hardening electronic systems, and how to prevent the release of information that reveals the vulnerabilities of its own military systems. The point is that before the United States can make the decision to sell or transfer microwave technologies, the major national security bureaucracies and the Congress, among other institutions, must engage in detailed discussions about the implications of safeguarding these technologies.

Legal. As with all new weapon systems, it will be necessary to resolve whether the use of microwave weapons is consistent with U.S. and international laws and treaties. Before these weapons are introduced into the U.S. inventory, the Department of Defense's General Counsel is charged with reviewing whether any proposed weapon system will violate U.S. and international laws and treaties, including the Law of Armed Conflict and other legal directives.⁴⁵ Microwave weapons are no exception. Before microwave weapons are incorporated into the operational community, the Air Force General Counsel must first review the weapon system and make a recommendation, which includes considerations of the medical and biological effects as those relate to the "pain and suffering" that the weapon system may inflict.⁴⁶ If approved after a rigorous review, the Air Force lawyers and program managers must prepare for a review that will be conducted at the Department of Defense. This is a time consuming process that can last more than nine months, but it assures that programs are thoroughly investigated before the program is formally initiated.

The stage has already been set for the introduction of microwave weapons into the U.S. military inventory. The legal review of the first microwave system was completed when the Department of Defense issued its preliminary approval on February 3, 1998.⁴⁷ Until the legal system becomes more familiar with the unique operational aspects of microwave technologies, it is likely that future reviews will be equally lengthy.

A related legal issue, and one that has proven to be controversial, is whether a weapon technology will contribute to the weaponization of space. Since the Eisenhower administration, the policy of the United States has been that space should be reserved for peaceful purposes.⁴⁸ While high power microwaves could be used for defensive and offensive purposes against satellites, the development of these weapons could be designed in such a way that satisfies the U.S. policy of remaining in compliance with existing international laws and treaties that govern the peaceful use of

space.⁴⁹ Nor should it be assumed that it would be necessary to deploy microwave weapons in space for these to be effective against space assets.

Testing and Countermeasure Hardening. All systems that use electronics are susceptible to electromagnetic emissions, and accordingly, all platforms and weapons must be protected from microwave emissions. In order to protect these systems, shielding and hardening methods must be devised in order to mitigate the undesirable effects from enemy emissions and minimize the risks of fratricide and suicide posed by friendly microwave weapons. For systems still in advanced development, the most timely and cost effective method is to integrate these protective countermeasures, i.e., hardening measures, into critical subsystems during their design phase. Such techniques include using hardened components, redesigned circuit boards, and increased shielding for vulnerable areas.

Systems that are already in the inventory or are making the transition to procurement must undergo tests to determine their vulnerability to microwaves. Once their vulnerabilities have been determined, shielding and retrofit modifications can be designed and installed within the critical subsystems. While it might be preferable to harden an entire weapons system, the most cost-effective method is to harden only the critical subsystems.

The U.S. Air Force must decide which weapons systems should be tested and hardened against microwave emissions. The majority of Air Force systems have not been tested against microwaves, and only two systems, the F-16 and the LANTIRN (Low Altitude Navigation and Targeting Infrared for Night) pod, have been tested. Hardening fixes are being installed in these systems during scheduled upgrades.⁵⁰ The biggest impediment to the hardening effort is the reluctance of the program office to provide systems for testing because they fear that this testing will cause irreparable damage to their unique and costly systems. However, these tests can be performed using low power-level coupling to determine the vulnerability of the systems. Another reason for the reluctance of program offices is the fact that they must allocate additional funding for these testing and hardening programs. In addition, the schedule for weapon systems may have to be extended to incorporate all the hardening modifications, which further increases the overall costs of the program.

To ensure that weapons systems retain the necessary level of hardness against microwave emissions, the Air Force should establish a microwave hardness program to routinely check weapons systems to validate their

hardness protection, and to also upgrade these systems to new hardness levels.

Battle Damage Assessment. Damage assessment has always been critically important to the operational commander because it determines whether the target has been neutralized, or if additional sorties are required to accomplish the mission. The problem with microwave weapons is that damage assessment is often difficult. Unlike the obvious damage that is caused by conventional weapons, microwave weapons affect the electronics inside the enemy systems, and thus do not leave “smoking holes” in the ground. The development of microwave weapons will compel the defense establishment to create new methods for assuring the operational community that the use of microwave weapons has successfully completed the mission.

Organizational. It is inevitable that organizations in the research and development system will feel threatened by a microwave program office. One reason is that some missions for specific weapons systems may become obsolete once microwave weapons are introduced into the military. Furthermore, there will be some manned missions that will become extinct because there will be cases in which unmanned platforms armed with microwave weapons will provide an alternative to the use of manned platforms.

It is likely that the U.S. Air Force will want to create a product center for the development of microwave weapons, but the Air Force systems product center that gains the microwave program office will create organizational conflict. All four of the Air Force systems centers can articulate plausible reasons for them to manage the microwave program office. For example, since the majority of the applications deal with aircraft, the microwave program office could be assigned to the Aeronautical Systems Center at Wright-Patterson AFB, OH. The Air Armaments Center at Eglin AFB, FL, could lobby for this program office because the applications are designated as weapons. The Electronics Systems Center at Hanscom AFB in Massachusetts could request this program because it controls all the various electronic warfare program offices. Finally, the Space and Missile Center at Los Angeles AFB in California could argue that it should be the focal point for the program because some of the applications involve space control missions.

The broad observation is that the development of microwave weapons will have implications for the microwave weapons programs which are conducted by the other military services. One solution may be to establish a

joint program office. Since the Air Force has invested the most money and developed the majority of the microwave technologies, it arguably should take the lead in developing a joint program office. But it is unclear how the other services program offices and product centers would become involved in the systems, testing, and hardening programs.

Economic Concerns. A significant challenge faced today by the military's acquisition programs and daily operations is economic. As with all programs for developing new technologies, the extremely tight budgets mean that new programs must compete for resources in a fierce political environment. The question for the military services is whether microwave weapons provide a cost-effective instrument for conducting military operations. While this paper cannot answer this question in any detailed fashion, the combination of microwave technologies and unmanned aircraft may create important and potentially cost-effective means for defending U.S. interests.⁵¹

VI. Conclusions

Just as nuclear weapons had a dramatic effect on U.S. national security strategy during the Cold War, the development of microwave weapons also may have a significant effect on U.S. military capabilities in the twenty-first century. The development of microwave weapons will lead to new employment methods and tactics for all of the military services, including the Air Force. The ability to integrate microwave technologies into the weapons and doctrines of the U.S. military will lead to the development of innovative solutions to the problems and missions faced by the operational community. The revolutionary aspect of microwave technologies is that these weapons will be the first directed energy systems that have both offensive and defensive capabilities. For this reason, it is imperative for the U.S. Air Force as well as the Army, Navy, and Marine Corps to develop high power microwave technologies, and most importantly to increase the power levels of microwaves and decrease the size and weight of these weapons.

To take the specific case of the U.S. Air Force, it must fund more demonstration projects if it is to reduce the risks of the transition from microwaves as experimental systems to weapons that are available to the operational commands. More specifically, it is time for the Air Force to establish a microwave systems program office that has overall responsibility for the engineering and manufacturing development, as well as the follow-on production, for microwave weapons.⁵² This microwave program office should have the authority to respond quickly and decisively to operational requirements. At the same time, this office should develop new ways of doing business, including the use of simplified contracting rules acquisition authority, so that microwave technologies can be developed and integrated efficiently and cost effectively into operational weapon systems. Ideally, a microwave systems program office must have a broad charter to develop the new microwave technologies and systems that will strengthen the operational capabilities of the United States military.

Since there are numerous operational applications for which microwave technologies are well-suited in all of the military services, the Air Force should establish a joint program office and assume the role as the lead service.⁵³ Such an organization will help to reduce overall development costs and is likely to accelerate the pace of technological advancements beyond that which would occur if each of the military services pursued its own microwave program. A key to success will be whether the first microwave

weapons system is quickly integrated into the operational commands and established as a militarily-effective and cost effective weapon system.

It is equally essential that the program director and each of the subordinate program managers possess significant technical experience in the development of directed energy technologies, and preferably in the area of high power microwaves. This office also must ensure that individuals from the operational commands are integrated within the program so that they have the ability to provide the operational expertise which is essential to developing new military technologies. While it is not imperative for the program managers to be co-located with the program office, the program managers must maintain close contacts with the technical experts within the Air Force Research Laboratory as well as technical programs in the other military services if they are to be informed about new developments in microwave technologies.⁵⁴

The Department of Defense should test all weapon systems to determine the degree of vulnerability to microwave emissions and devise solutions for hardening these weapons against friendly as well as enemy microwave emissions. A corollary is to develop a maintenance and hardness surveillance program to ensure that U.S. weapon systems are protected from the threat posed by microwaves. Furthermore, it is imperative for the United States to continue its efforts to limit the transfer of microwave technologies to other nations. Finally, the United States should encourage the commercial market and industrial enterprises to invest in high power microwave technologies as this will help to increase competition and reduce the overall costs of developing microwave weapons. In this way the United States can take advantage of the revolutionary capabilities inherent in microwaves and protect itself at the same time.

Glossary

Back Door—Electromagnetic signals enter and propagate into the target through circuitry and paths that were not intended for signal entry. Pathways can be cracks, seams or seals.

Damage—Inflict moderate injury to enemy facilities, systems, and sub-systems hardware that will incapacitate the enemy for a certain time frame. This action may be permanent, depending upon the severity of the attack and the ability of the enemy to diagnose, replace, and/or repair his systems.

Deny—Remove the enemy's ability to operate without inflicting harm to hardware or software systems. This action is not permanent, and systems can be easily restored to operational levels.

Degrade—Change or insert false signals or data into enemy information flow, either directly or indirectly. Inflict minimal injury to hardware. Examples include signal overrides/insertion, power cycling (turning power on and off at irregular intervals), and computer "lock-up." This action is not permanent and target systems will return to normal operation within a specified time frame, depending on the characteristics of the weapon. Some minor repairs may be required.

Destroy—Inflict catastrophic injury to the enemy functions and systems to render these useless. This action is permanent. The enemy would be required to totally replace entire systems, facilities, and hardware to regain his operational status.

Front Door—Electromagnetic signals enter and propagate into the target through the primary sensing circuitry of the target and the paths designed to carry signals into a system. Pathways can be antennas, domes, or other sensor "windows." An example would be the propagation of a signal into the enemy's radar through its receiver circuitry.

Hardening—Techniques that protect electronic components and circuits from high power electromagnetic emissions. Standard techniques include components that shield, filter, and/or limit currents through the circuitry.

In-Band—Electromagnetic signals that operate in the same frequency band that the target sends, receives, and processes. An example would be to transmit at 10 GHz signal to jam or damage a 10 GHz radar.

Lock-up—The electrical state of components, circuits, or pathways are temporarily altered, but these items remain altered even after microwave

emissions are terminated. The affected system must be reset (often by turning the system off, and then back on) to regain functionality.

Latch-Up—A severe form of lock-up in which some internal components may be degraded by the microwave emissions. Cycling the power to the system may not return it to normal function immediately. More aggressive maintenance action may be required, and other cases the system will eventually function normally.

Lethality—The degree of injury inflicted by an electromagnetic emission on a system or subsystem.

Out-of-Band—Electromagnetic signals are outside the frequency band that the target sends, receives, and processes. An example would be to transmit a 300 MHz signal to damage or upset a communications system that operates in the 500 MHz frequency band.

Survivability—The ability of a system or subsystem to withstand an attack of electromagnetic signals.

Susceptibility—The weakness of a system or subsystem when it is influenced by electromagnetic signals. Susceptibility means that the system can be affected.

Upset—Temporary alteration of the electrical state of one or more components, circuits or electrical pathways. When the microwave emissions are terminated, these items will return to normal function. No lasting effects will be seen.

Vulnerability—The ability of a system to be exploited.

Wideband—Electromagnetic signals over a wide range of frequencies (e.g., a microwave source that can emit pulses between 200 MHz - 3 GHz).

Acronyms

ACTD	Advanced Concept Technology Demonstration
AF	Air Force
AFB	Air Force Base
AFRL	Air Force Research Laboratory
ABL	Airborne Laser
AWACS	Airborne Warning and Control System
D4	Deny, Disrupt, Damage or Destroy
D5	Defend, Deny, Disrupt, Damage, or Destroy
DE ATAC	Directed Energy Applications for Tactical Airborne Combat
DoD	Department of Defense
EMP	Electromagnetic Pulse
GHz	Gigahertz
GPS	Global Positioning System
HPM	High Power Microwave
IW	Information Warfare
JSTARS	Joint Surveillance and Target Attack Reconnaissance System
LANTIRN	Low Altitude Navigation and Targeting Infrared for Night
MANPAD	Man-Portable Air Defense System
MHz	Megahertz
NM	New Mexico
OSD	Office of Secretary of Defense
PGM	Precision-Guided Munition
R&D	Research and Development

SEAD	Suppression of Enemy Air Defenses
SPO	Systems Program Office
TX	Texas
UCAV	Unmanned Combat Air Vehicle
U.S.	United States
USAF	United States Air Force
WMD	Weapons of Mass Destruction

Notes

1. While this study focuses primarily on U.S. Air Force applications for microwaves, it does not preclude similar applications for the other services.

2. Prior to 1984, the funding for high power microwave research was held in multiple project lines in two Program Elements (PE 0602601F and PE 0603605F) at the Air Force Weapons Laboratory. In 1985, separate and distinct project funding lines were established for this research in these two Program Elements.

3. Air Force funding for electromagnetic pulse hardening research was held in two Program Elements: PE 0604711F and PE 0604747F.

4. This unclassified study on microwaves excludes specific details on frequencies, power levels, susceptibilities, vulnerabilities, weapon effects, and lethalties. For more detailed information, please contact the High Power Microwave Division, Directed Energy Directorate, Air Force Research Laboratory (AFRL/DEH), 3550 Aberdeen Drive, Kirtland Air Force Base, NM, 87117.

5. Bandwidth can be defined as the range of frequencies that a system receives, transmits, or operates within. For example, a radio that operates between 10 megahertz to 50 megahertz has a bandwidth of 40 megahertz. Another radio that operates between 75 megahertz to 100 megahertz would have a smaller bandwidth of 25 megahertz. Electronic warfare systems are designed to attack specific frequencies, but cannot attack all frequencies. A system that operates over a large frequency bandwidth is less vulnerable to an electronic warfare attack because the attack will be limited to only a few frequencies.

6. David M. Sowders, Capt, USAF, et. al., *High Power Microwave (HPM) and Ultrawideband (UWB): A Primer on High Power RF*, PL-TR-95-1111, Special Report, Phillips Laboratory, March 1996, p. 7.

7. Operational Commands, such as the Air Combat Command, participate in Technology Product Integration Planning Teams (TPIPTs) with the technological community.

8. The military services and government agencies coordinate these programs through the Joint Radio Frequency Coordinating Technical Interchange Group (JRFCTIG).

9. Sowders, p. 76.

10. *Ibid.*, p. 79.

11. *Ibid.*, p. 81.

12. *Ibid.*

13. *Ibid.*

14. *Ibid.*

15. This general principle is based on analyses and reports performed by senior electrical engineers and technicians on damaged circuitry, which were conducted at Kirtland AFB in Albuquerque, New Mexico.

16. The terms “susceptibility” and “vulnerability” are sometimes used interchangeably. Susceptibility means that a system may be affected by a specific frequency or set of frequencies, while vulnerability means that the system can be exploited by those frequencies. A system may be susceptible to microwave radiation, but may not be vulnerable, especially if it has been hardened.

17. Jeff Hecht, *Beam Weapons, The Next Arms Race* (New York: Plenum Press, 1984), p. 266.

18. *HPM Overview Briefing*, High Power Microwave Division, Directed Energy Directorate, Air Force Research Laboratory, Kirtland AFB NM, February 1998.

19. On the basis of preliminary cost analysis, it is expected that an unmanned combat air vehicle concept will require approximately 70 percent fewer logistics personnel and support. This analysis was performed by the High Power Microwave Division at Kirtland AFB, NM in 1998.

20. In recent conflicts, U.S. civilian and military leaders have emphasized the importance of minimizing collateral damage.

21. Biological and biomedical research in the electromagnetic spectrum has been performed by researchers, scientists, and medical personnel for the Air Force Research Laboratory. This research is conducted by the Human Effectiveness Directorate that is located at Brooks AFB in Texas.

22. *HPM Source Technology Review & Assessment*, High Power Microwave Division Overview Briefing, undated.

23. “Hoover Dam—How It All Works,” January 4, 1999, <http://www.hooverdam.com/workings/main.htm>.

24. For reference, these tests are usually performed at low power levels in order to prevent damage to expensive, and often unique, systems.

25. William Baker, “Air Force High-Power Microwave Technology Program,” *JTCG/AS Aircraft Survivability*, p. 9.

26. These programs are managed within the High Power Microwave Division, Directed Energy Directorate, Air Force Research Laboratory, Kirtland AFB NM.

27. Charles Perkins, DUSD(AT), is the point of contact for this effort.

28. *Joint Vision 2010*, p. 1.

29. *Global Engagement A Vision for the 21st Century*, Department of the Air Force, p. 9.

30. Barry Hogge, Chief Scientist of Directed Energy Directorate, AFRL/DE, *Assessment of the Aerospace Expeditionary Forces Studies Recommendations Briefing*, May 1, 1998.

31. *Ibid.*

32. "Directed Energy Study Kicks Off," Air Force Research Laboratory, Office of Publish Affairs, DE Release # 93-32, June 26, 1998, <http://www.fas.org/spp/starwars/program/news93/93-32.html>

33. The fifth application is advanced sensor applications which use laser technologies for numerous applications, including war effects confirmation, air-to-ground combat identification, chemical and biological weapons detection, and above-ground target identification. The term "war effects confirmation" is the new phrase for battle damage assessment.

34. The blast and fragmentation radius of a 2000-pound microwave munition will be slightly less than that of a conventional 2000-pound munition.

35. During Desert Storm, the author was a member of the Air Force's Rapid Response Team while stationed at the Pentagon, and was directly involved in the evaluation and selection of the GBU-28.

36. The Air Force is actively pursuing a technology program to develop a laser-based weapon system, known as the Infrared Countermeasure (IRCM) program. However, this technology is being designed to defeat only the existing inventory of infrared-guided missiles. Given the technical challenges and limitations of this laser program, there are questions whether this IRCM system can defeat advanced infrared missiles or any of the other types of guided missiles.

37. With the exception of the M1-A1 tank, cargo aircraft reach their volume limitation long before their weight limitation. Quick calculations have shown that the weight penalty imposed by a microwave system would represent a reduction of less than 100 nautical flight miles.

38. For additional information on Navy applications, see Captain William J. McCarthy, *Directed Energy and Fleet Defense: Implications for Naval Warfare*, (Maxwell AFB, AL: Center for Strategy and Technology, Occasional Paper No. 10, December 1999).

39. The High Power Microwave Division at Kirtland AFB, NM performed the preliminary analysis for a Microwave Unmanned Combat Air Vehicle in 1998.

40. An important point is that microwave munitions, which rely on an explosive mechanism to produce microwave energy, would damage facilities and produce collateral damage, depending on the distance from the target.

41. Direct information that includes GPS coordinates, information concerning reconnaissance/surveillance activities, communications, and weather forecasting, among

others. Indirect information involves radio and television broadcasts because these could provide knowledge of intelligence value to the enemy.

42. One mechanism for the proliferation of information about electromagnetic weapons and their availability is the internet, which in itself has profound implications for terrorist uses of microwave technologies. As an example of designs have been placed on the internet, see Carlo Kopp, "The E-Bomb—a Weapon of Electrical Mass Destruction." For websites that contain information on microwave weapons, see http://www.info-sec.com/denial/denial_012308a.html-ssi or the website of Texas Engineering Solutions, at <http://www.plano.net/~pevler/>

43. Neil Munro, *The Quick and the Dead: Electronic Combat and Modern Warfare*, (New York, NY: St. Martin's Press, 1991), pp. 173-175; Carlo Kopp, "The E-Bomb—a Weapon of Electrical Mass Destruction," Infowar.com & Interpact, Inc. n.p.; on-line, Internet, November 5, 1998, http://www.infowar.com/mil-c4i/mil_c4i8.html.ssi; statement of Ira W. Merritt, Chief Concepts Identification and Applications Analysis Division, U.S. Army Space and Missile Defense Command, in "Proliferation and Significance of Radio Frequency Weapons Technology," Testimony before the Joint Economic Committee, U.S. Congress (Washington, D.C., February 25, 1998), pp. 14-15.

44. The United States has supplied major weapons systems to its allies for decades. In the case of technologies that are relevant to microwave weapons, a number of nations now own F-16 and C-130 aircraft, as well as computers, radios, and other communications equipment that were produced in the United States.

45. The only international treaty that restricts the use of electromagnetic weapons is the Nairobi International Telecommunications Convention, dated January 10, 1986. However, the U.S. is not a party to this treaty, per U.S. Code 502, dated January 1986. Additionally, the treaty provisions do not apply during warfare. See briefing by Kirk Hackett, *Policy: Legal and Ethical Constraints Concerning Non-Lethal Weapons*, briefing, undated.

46. All biological and medical studies for high power microwave technologies are performed by the Human Effectiveness Directorate, Air Force Research Laboratory, Brooks AFB, Texas.

47. Kirk Hackett, *Policy: Legal and Ethical Constraints Concerning Non-Lethal Weapons*, briefing, undated.

48. Major Roger C. Hunter, *A US ASAT Policy for a Multipolar World* (Maxwell AFB, AL: Air University Press, 1992), pp. 16-17.

49. National Science and Technology Council, *Fact Sheet: National Space Policy* (Washington, DC: National Science and Technology Council, 1996), n.p, February 2, 1998, at <http://www.hq.nasa.gov/office/oss/spacepol.htm>, which specifically states that, "U.S. space capabilities will support the U.S. inherent right of self defense and our defense commitments to allies and friends. U.S. space capabilities should be able to defend against enemy attacks. U.S. space capabilities will be able to counter hostile space systems and services. And, consistent with treaty obligations, the U.S. will develop,

operate and maintain space control capabilities to ensure freedom of action in space and, if directed, deny such freedom of action to adversaries.”

50. Baker, *op. cit.*

51. For example, one can compare the cost of maintaining and operating microwave weapons with other weapon systems currently in the U.S. arsenal. In the case of air operation that seeks to defeat three enemy air defense systems, the cost of a conventionally-armed F-15 fighter aircraft could be greater than that of an unmanned combat air vehicle (UCAV) armed with a microwave weapon. Let us assume that the F-15 aircraft is loaded with conventional 2000-pound MK-84 munitions. Each munition produces a fragmentation and blast footprint of 4000 square meters, and typically two munitions are allocated for each target to ensure a high probability of kill. An F-15E aircraft can carry up to three MK-84 munitions and has a fuel capacity of approximately 23,000 pounds. Approximately 70 percent of the ground crew is engaged in handling and loading conventional munitions, while the other 30 percent of the crew is responsible for aircraft fueling and maintenance. In this hypothetical mission, six munitions are required to attack three air defense systems, which means that two F-15E aircraft are required to fly the mission. The aircrews would fly to the targets, release the munitions to kill the enemy systems, and then return to base for additional missions and aircraft refueling.

In the case of a UCAV armed with a microwave weapon, 100 pounds of fuel could generate the microwave energy sufficient to attack 100 targets per sortie. The microwave UCAV requires fewer support personnel because only 30 percent of the above ground crew is necessary for fueling and maintenance activities. The other 70 percent could be reallocated to other missions, because no expendable conventional munitions are required for the microwave weapon. If the microwave UCAV destroyed the three enemy air defense systems, it would still have plenty of fuel for attacking additional targets. The difference in cost is dramatic. The microwave UCAV requires less fuel and can attack a larger number of targets than the F-15E. The microwave UCAV requires fewer support and logistics personnel. It also is safer because it can operate either autonomously or through ground-control data links from friendly territory. However, the procurement cost of a weapon system is just one portion of its entire cost, as most of the costs are incurred after the system goes into the inventory for fuel, maintenance, modification, operations, and training, all of which are grouped into the financial term “life cycle cost.” A general observation is that while detailed analyses are necessary, microwave weapons systems may have lower life cycle costs than the current systems that perform similar functions. It also should be noted that in this example the microwave UCAV does not require conventional munitions and uses substantially less fuel to perform the same mission. Another benefit with the microwave UCAV is the elimination of all the cockpit crew requirements for human health and safety (e.g., ejection seats, oxygen systems, environmental controls, etc.), which in turn greatly reduces the maintenance requirements, as well as the initial design and procurement costs. This example is based on a preliminary analysis performed in 1998 by a team headed by Kirk Hackett, High Power Microwave Division, Directed Energy Directorate, Kirtland AFB, Albuquerque, New Mexico.

52. Until a microwave program office can be established, a non-traditional program office, as exemplified by the “Big Safari” program office, could direct several small programs. Author interview with Lt Col Mark Franz, November 5, 1998, Kirtland AFB, NM. Franz is the current Chief of the High Power Microwave Division and the former Deputy Director of the Big Safari System Program Office.

53. This is obviously a sensitive issue for the other military departments. For now, the Air Force has the greatest experience in the development of microwave technologies, but one suspects that there is a reasonable bureaucratic solution to the question of which military service should lead this effort.

54. *Ibid.* Rather, as shown by the “Big Safari” program, placing these managers at contractor sites serves to increase communication among the teams and reduce the overall cost of development.

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