WEAPONEERING THE FUTURE:

DIRECT ENERGY WEAPONS EFFECTIVENESS NOW AND TOMMOROW

Chadwick F. Fager, Major, USAF
April 2007

Blue Horizons Paper
Center for Strategy and Technology
Air War College

Report Documentation Page

Report Documentation Page						*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE **APR 2007**		2. REPORT TYPE				3. DATES COVERED **00-00-2007 to 00-00-2007**
4. TITLE AND SUBTITLE **Weaponeering the Future: Direct Energy Weapons Effectiveness Now and Tomorrow**						5a. CONTRACT NUMBER
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)						5d. PROJECT NUMBER
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air University,Air War College,Center for Strategy and Technology,Maxwell AFB,AL,36112**						8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)						10. SPONSOR/MONITOR’S ACRONYM(S)
						11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT **see report**						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**42**		

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Disclaimer

Contents

Illustrations

Page

Tables

Abstract

Direct Energy weapons can exist on the battlefield of today. Yet, the warfighter needs to know what Probability of Damage theses weapons can attain. Currently, the Joint Munitions Effectiveness Manual calculates a Single Sortie Probability of Damage for conventional Blast and Fragmentation weapons. Using Futures Research methodology allows determination of what effects Direct Energy weapons will impart in the year 2035. The Status of Futures Index (SoFI) method compares complex entities to one another across multiple dimensions. Adapting the Single Sortie Probability of Damage formula for Lasers, Microwave and Millimeter wave weapons allows a determination of their effectiveness. The required formulas for each type of Direct Energy Weapons' Probability of Damage (or Effect) are derived and explained. The Direct Energy weapons are compared to both conventional weapons and one another. Adjusting these Probability equations adjusted for various inputs enables a forecast of the future capabilities of each weapon. The current trend trajectory establishes a baseline estimate of future Probabilities of Effect. Then, disruptive technologies are analyzed for their effect on the weapons capabilities. Each type of weapon poses a unique challenge. For Laser to match the capabilities of Blast/Fragmentation weapons, the power output must be increased. Microwaves, not only require increases in power, but also advances in antenna technology. Millimeter wave weapons can currently produce the required power, but manufacturing the weapons proves an obstacle. To overcome these difficulties, new technologies must be pursued. The SoFI method allows continuous evaluation of progress toward the goal of effective Direct Energy Weapons.

Chapter 1
What you have and what you want

> *Direct energy is making world-changing, revolutionary advances from fighting wars to battling terrorism. And it's doing so today. It's happening so fast that it's the military equivalent of a military 'future shock'.*
>
> —Colonel Doug Beason, PhD.

The best way to get somewhere is to first know where you want to go. Then you need to know a way to get there, a plan. Many leaders believe conventional Blast and Fragmentation (Blast/Frag) weapons cannot advance much further technologically. If this proves true, then the next advances in weaponry must flow from somewhere else. Direct Energy weapons offer one set of promising options.

The US pursuit of Direct Energy Weapons follows three paths, each developing at a unique rate. The three primary technologies being followed as direct energy weapons include Lasers, Millimeter Waves, and Microwaves. Laser technologies receive the most attention in both the budget and the press. The US Air Force currently pursues a number of Laser weapons including the Airborne Laser (ABL), Advanced Tactical Laser (ATL) and the Personnel Halting and Stimulation Response (PHaSR). These Laser weapons exist in various stages of development, but none are fielded. The millimeter wave system produced by the Air Force is the Active Denial System (ADS); the Navy developed the Neutralizing IEDs with Radio Frequencies (NIRF) system. Microwave weapon systems are the least developed branch of the Direct Energy weapons trio. The Department of Defense (DoD) does not currently advertise the development of any weaponized microwave systems, however developmental experiments continue. In addition to these more mature systems, the services continue to pursue technologies and need a methodology to help determine which ones will bear the most fruit.

Status of Futures Index

Futures Research methods aid in solving the problem of knowing what technologies to pursue and where to invest limited resources. According to Glenn a futures studies expert at the United Nations, “The purpose of futures methodology is to systematically explore, create, and test both possible and desirable futures to improve decisions”[1]. In order to help Air Force decision makers funnel manpower, money and time in the right directions, an effort to understand the future is needed. The field of direct energy weapons is especially in need of a clear view of the future. The expense, intellect, and effort involved deserve the guidance of a clear vision of the future.

The Status of Futures Index or SOFI is one method used in future studies to help predict the path of already existing technologies. The SOFI method uses an index to combine multiple variables. Indexing finds multiple applications in the world, “The cost of living index, for example, combines the cost of food and other consumer goods in a standard ‘market basket’ to show how prices are changing. The Dow Jones Industrial Average aggregates the price of stocks of selected firms to create a number that quantifies the aggregate state of certain stocks on the New York Stock Exchange.”[2]. Individual variables are assigned weights that reflect their impact on the overall system. SOFI allows leaders to determine how a system may change over time[3].

SoFI creates a mathematical forecast that can be updated with new information. Once the variables that make up the index are determined and assigned a weight, the SoFI method then projects the future status of each individual variable. SoFI re-combines them into the index, giving an indication of what the index will register at a specific point in time. Typically, the variables are predicted along a curve reflecting the current trajectory of change. The historical path may be exponential, linear or some other curve. However, theses linear histories do not take into account disruptive factors or break through technologies. These can be represented by what researchers in the field of DE think about the possibilities of various advances. These disruptions are accounted for in the individual variables of the SoFI, and then the variables are again fitted to the appropriate line and re integrated into the index. The mathematical aspects of SoFI are especially useful when an index already exists.

Blast and Fragmentation Single Sortie Probability of Damage

The DoD currently determines the effectiveness of weapons on the battlefield using an index known as the Probability of Damage or Pd. For aviation, each sortie is evaluated against the index, arriving at a Single Sortie Probability of Damage or SSPD. The index derives from a number of variables concerning both weapons capabilities and target vulnerabilities (or lack thereof). This index can be applied not only to conventional weapons but with the correct adaptations to Direct Energy (DE) weapons as well. Once adapted for use with direct energy weapons, this index and the variables used to determine its value can be extrapolated into the future using the Status of Futures Index (SoFI) method. SoFI allows the warfighter to compare conventional weapons of today, DE weapons of today, and DE weapons of the future. The Joint Munitions Effectiveness Manual Special Effects (JMEM/FX) working group is charged with adapting the current SSPD system to account for new weapons and their effects. The JMEM/FX working group drafted various changes to the Pd calculations taking into account the abilities of DE weapons as well as the vulnerabilities of materials to DE weapons. The general SSPD formula applies both weapons variables and target characteristics to determine the weapon-on-target effect.

The weapons variables represent the "what you have" of the formula. The primary weapons characteristic taken into account is the miss distance probabilities of a given weapon. Current JMEM calculations assume that the proximity of the impact of a given weapon will follow a Gaussian distribution[4]. This is expressed in terms of the miss distance or error on two axis; range and deflection (left or right). Coupling the Gaussian distribution concept with the range and deflection errors leads to the ability to calculate a Range Error Probable (REP) and a Deflection Error Probable (DEP). REP and DEP are independent variable and a change in one does not necessitate a change in the other.

In addition to weapons variables, the JMEM calculations take into account target characteristics, representing the "what you want". The working group assesses each type of target and determines the square foot area of the target that can be affected by a weapon. This area is expressed in terms of Length and Width, producing Target Effective Length (Let) and Target Effective Width (Wet). Bear in mind that despite being expressed as a square foot area, the Let and Wet are only representations. For example, a tank may have a very vulnerable engine covering, but an invulnerable turret. In this case, even if the turret and engine covering are physically the same size, the engine covering will be granted a higher Let and Wet to account for vulnerability. A thorough discussion of REP/DEP and Let/ Wet calculation can be found in Anderson's "Generalized Weapons Effectiveness Modeling".

To determine SSPD you compare “what you have” to “what you want”. Weapons variables and target characteristics are all taken into account for various weapons delivery profiles. The standard equation for a Single Sortie Probability of Damage (SSPD) against a given target is seen below in Figure 1.

$$SSPD = \frac{L'et \times W'et}{\sqrt{(17.6(REP)^2 + L'et^2)(17.6(DEP)^2 + W'et^2)}}$$

Figure 1 Current SSPD equation[5]

The SSPD is a ratio of achievement to susceptibility. The equation presented above provides the basis for all future Probability of Damage indexes contained in this paper. The current SSPD equation relates “what we have” to “what we need” for our currently available Blast/Frag weapons, but requires adjustment for DE and other new weapons.

The JMEM/FX working group developed a number of new “Kill Definitions” for use with not only Blast/Frag but also Direct Energy and other weapons. The main thrust of the groups work has been to shift the index from a measure of damage to a measure of effect. The JMEM/FX proposals include modifications that take into account Information Operations, Electronic Warfare and Direct Energy weapons technologies. DE weapons differ from conventional bombs and bullets in some significant ways. These differences include the way in which DE weapons damage a target. As there name implies, Direct Energy weapons do not use matter to impart damage to a target. While retaining traditional damage criteria, JMEM/FX acknowledges the potential for new effects from these weapons that traditional Blast/Frag weapons could not achieve[6]. In order to measure and bound these effects the working group applied new concepts including; desired effect, scope, level and time.

The JMEM/FX working group defined each of these aspects of the SSPD (or SSPE for Effect) as *Effect Criteria*. *Desired Effect* – The physical, functional, or behavioral change in the state of the target or other influenced entity that a commander desires to achieve from a lethal or non-lethal attack[7]. *Scope* refers to the size of a given system affected, or the portion of a given system that is affected. For example, scope may mean a squad-sized unit all the way to a corp-sized unit. *Level* indicates the magnitude of the effect. As compared to scope, level refers to the amount of degradation. For example, a level of 20% loss of electric output or a level of 50% loss of electric output from a power transformer. Finally, the element of time indicates not only the time-on-target, but also the duration of the effect. This aspect carries forward from traditional SSPD calculations (delay soldiers for 5 minutes), but extends to the new weapons in unique ways. For example, time may be expressed in the following way: Incur a 1000% increase in e-mail delivery time for network server s starting D-1, lasting 1 hour[8]. The concepts of desired effect, scope, level, and time are essential initial adjustments to the calculation of the SSPD to account for the effects direct energy weapons have on targets.

Studying the future enables decision makers to effectively allocate resources. The Status Of Futures Index method combines multiple variables into a single indicator of the future direction of a technology. The JMEM Pd index provides an ideal bridge from current indexing weapons capabilities to future weapons promise. This paper shows what levels of effect Direct Energy weapons may realistically achieve in the future.

Chapter 2
Laser Weapons

Laser weapons offer the best known and most public of the Air Forces' Direct Energy efforts. Laser research provides an essentially linear history. Laser study and research began in the late 1950's when Schawlow and Townes published a paper extending their theory of the maser into the optical regions of the electromagnetic spectrum[9]. In the late 1970's when laser energies approached the 250kw level, the physics began to change. The mirrors used to direct the laser would melt, and other parts of the equipment began to change properties under the effects of the energy. These issues still haunt laser research, and can be categorized into three broad fields. The three challenges facing laser researchers include Beam Quality, Beam Control and Beam Power.

Beam quality refers to how much of the energy leaving a laser actually gets to the target. Many factors affect beam quality including refraction, divergence, and scattering[10]. Since the 70's scientists solved these problems one at a time. The progress made thus far enables the Airborne Laser (ABL) and the Mobile Tactical High Energy Laser (MTHEL) systems to overcome these external factors.

Beam control addresses the real world atmosphere where beam breakup poses a major problem. Beam control includes steering the laser within the cavity of the device, when it leaves the weapon and as the laser propagates through the atmosphere. Advances in materials and optics over the last 30 years helped overcome issues of beam control within the laser cavity and in the extraction of the laser. The techniques and materials used to control the laser beam are collectively called the Beam Control System (BCS).

Major advances in the BCS flowed from the Strategic Defense Initiative, including adaptive optics which allow the laser to be pre-distorted, so that the atmospheric distortions actual re-focus the beam in the desired manner. The second function of the BCS is to acquire and track the target. For ground based laser, the answers are straight forward. However, for airborne or shipborne lasers, the problem becomes more complex. In these situations the BCS must deal with turbulence from the air or sea, vibrations from the platform not to mention the position of the laser relative to the target[11]. Many researchers consider the beam control issues to be the most difficult of challenges, and the key to future laser weapons.

Beam power gives the laser its properties, providing the ability to destroy targets. Scientists found increasing power to be an easier problem to solve than beam quality and control. This proved especially easy in the early years of laser research, using ruby lasers. However, that medium reached its peak power output at approximately 1 kilowatt forcing researchers to switch laser mediums. When this proved insufficient in and of itself, a technique of supercooling the gas enabled more power output. Despite advances in the laboratory, bringing high power lasers to the battlefield remains a challenge[12]. The systems do not yet provide the range and needed for applications more than a hundred kilometers away. Furthermore, systems in the field are large and bulky and can only fit on cargo aircraft. Despite the problems encountered, Lasers are advanced enough to provide insight into how the SSPD can be adapted for DE weapons.

Laser Single Sortie Probability of Effect

The current SSPD equation requires adjustment in order to account for Laser weapons characteristics and create a valid index. Three types of variables go into these calculations. They are variables relative to the weapon, the environment and the target.. In order to determine the effects a laser can impart, these variables must be identified and incorporated into the damage/effect calculations. For a laser, the weapons variables include: Beam Power, Beam quality, Dwell Time, Slant Range and magazine depth. The primary environmental factor to consider is atmosphere type. The target properties that must be taken into account include target susceptible length, width and thickness (gauge) of the metal involves, when applicable[13]. Each type of variable must be accounted for in the adjusted SSPD.

Variables related to the weapons itself offer the best understood inputs. Beam power when the beam leaves the laser is exactly what it seems to be; the amount of energy contained in the laser beam[14]. Beam Quality is one of the optical characteristics of a laser. According to Markham, "A 'perfect' Gaussian beam is given a value of 1, with beam qualities typically falling in the 1.1 – 1.5 range (as seen by the author *Markham*). This rating is a measure of the focusability of the laser and governs the distribution of the laser spot across the surface of the target"[15]. Dwell time refers to the amount of time the laser is actually focused on the target. Slant Range is the distance from the platform to the target and is the hypotenuse of a triangle formed by the platform altitude and ground distance. The final factor considered from the weapon is magazine depth. This is the amount of total laze time available. Dwell time effects magazine depth, because each individual dwell time takes different amounts from the magazine. Many of the laser variables correlate to either the type of laser used, or the platform from which the laser is employed. These weapons variables can be controlled by the operator, but once the laser leaves the weapon, it must deal with the environment.

The environmental variable most important for laser effects is the atmosphere. One primary factor to consider with atmosphere is aerosols, "Aerosols are the fine matter particulates in the air which are more prevalent in the lower atmosphere"[16]. These aerosols are predominantly found in the lower atmosphere[17]. After traveling through the atmosphere, the laser can now contend with the actual target.

The target itself helps determines what effect can be brought to bear. Some targets are more vulnerable to destruction than others. In the current JMEM construct this is expressed as target susceptible Length and Width. This concept carries over to Laser weapons. However, unlike conventional weapons were target susceptible length and width represent any part of a target that could be exposed to a weapons effect; Laser susceptible Length and Width is more specific. Laser susceptible length and width refer to the actual area of the target being radiated by the laser beam[18]. In the case of vehicles or metal buildings, the thickness of the metal being radiated must also be considered[19]. A modified SSPD must account for each of these factors regarding the weapon, platform, environment and target.

First the weapons properties, the "what we have" within the SSPD equation, must mathematically take into account Laser variables. The weapon characteristics accounted for in the SSPD equation are Range and Deflection Error Probable (REP and DEP). However for a laser beam there are essentially no range or deflection errors. The laser factors that make the weapon less effective are time and power. These can be combined in a number of expressions. One way to express laser energy at the target is fluence. Fluence will be considered in terms of irradiance and laze time. Irradiance is the amount of power over a given area, expressed as Watts per meter squared (W/m^2). Laze time is the duration the laser is on the target, measured in seconds[20]. Fluence is expressed as:

Fluence = Irradiance x Laze Time[21]

The next way to express laser energy at the target is how much Energy is in the Bucket. Power in the bucket is measured in Watts for each point within the bucket, and not considered as distributed over the entire surface. Laze time is again the amount of time the laser in on the target in seconds. Energy in the bucket is expressed as follows:

Energy in Bucket = Power in Bucket x Laze Time[22]

Either Fluence or Energy in Bucket could be used to express the weapon characteristics for a laser in an SSPD calculation. The initial research done by Markham and others indicates that Fluence is the more appropriate predictor of the capabilities of a laser at the target[23]. The ability of the laser to impart energy must be taken into account when determining the effectiveness of the weapon. This leads to applying the fluency of the weapon at the target and its inclusion in the numerator, representing the ability of the weapon to affect the target.

The converse of a weapons effect on the target is the targets reaction to the weapon. Therefore, changes to target vulnerability characteristics of the SSPD equation are required. The current calculations use the Effective Target Length and Width (Let and Wet). For lasers the terminology and basic application change slightly. The first conceptual change is the term susceptibility. Some targets are more or less susceptible to lasers. For example cloth and wood burn when exposed to enough laser energy where as metal melts. Because lasers are extremely precise, the effects they impart are only realized over the area of the target illuminated under the laser spot. This precision restricts the need for a Length and Width target effectiveness area. Because the laser spot is symmetric, the Let and Wet are considered to be symmetric. This symmetric susceptibility area is referred to as the "Bucket" size[24]. This results in the Let x Wet numerator portion of the SSPD equation becoming Spot Size Squared or SS^2. Different targets absorb energy differently. The amount of energy required to incur damage must be accounted for in the effective area of the target. For solid non-burning targets, this is known as Energy Required to Melt (ERM). Therefore, the susceptibility of a target to damage must take into account the ERM. The ERM replaces the REP and DEP errors from conventional weapons in the calculation of SSPD.

The weapons and target variables required for adjusting the SSPD are now known. The current SSPD equation for a bomb assumes a normal Gaussian curve for weapon accuracy and uses the Carlton damage function to determine how much damage a perfectly accurate weapon imparts[25]. Lasers do not have accuracy errors inherent in the weapon; the Gaussian curve is no longer required. This makes the mathematic simpler in regards to curve fitting, instead of a double curve, only a single curve for damage needs to be accounted for. Combining the new variable and assumptions yield the following equation for a Laser Single Sortie Probability of Effect (LSSPE):

$$LSSPE = \frac{Fluency + SS^2}{ERM + SS^2}$$

Figure 2 Derived LSSPE equation

The symmetry inherent in the laser weapons and therefore the target accounts for the consolidation of squaring terms in the denominator. Using the LSSPE equation as our

SOFI index, it becomes possible to determine where laser weapons effects both currently and at specific future dates.

The SoFI for Laser Weapons

Values from current lasers and laser models can be entered into the LSSPE equation above to provide baseline effectiveness. A standard target will be represented by a military truck. Trucks are common to most battlefields and represent a midway target between "hardened" targets such as tanks and "soft" targets like humans. For comparisons sake, the target susceptibility or spot size will remain constant for present day and future day calculations. This spot size will be .0036m^2. The reason for this is, "both to capture the entire spot size, and to limit the area over which we are attempting to cause the desired effect."[26]. This target requires an ERM of 2500 Joules/cm2 to achieve the desired effect. Holding the spot size and ERM constant allows us vary the fluence level and to determine an effect.

Examining fluence as the variable means changing the irradiance and time a laser is fired from its platform. For simplicity, we will consider the platform to be at a specific slant range from the target for each year forecasted. The slant range of 10500 ft. allows today's lasers to achieve an effect at that distance and creates a non-zero baseline. At a slant range of 10500m, it is predicted that the Advanced Tactical Laser will deliver an irradiance of 548.31 W/cm^2 [27]. The laser must be held on the target for 5 seconds to achieve a fluence of 2741.5J/cm^2, just over the required fluency to melt the truck hood. Given both the Spot Size (SS), fluency and ERM it is possible to determine the LSSPE for a truck hood as 1.06 That means that more than 100% of the time the ATL will achieve melt-through of the target at a distance of 10500m for a time of 5 seconds. This reflects currently known lab data, and was of course set up to achieve the goal. However if the amount of time the laser is allowed to strike the target is shortened by half (maybe due to defensive maneuvering) the LSSPE shrinks to .702! This leads to the conclusion that despite the ability of today's lasers to achieve impressive results, there is still room for improvement.

Laser type plays an important part in determining a lasers weapons capability. Laser type effects both Power and Laze time/magazine depth. The trajectory of the chemical laser is the most chronicled of the Laser types. The table below shows a rough timetable of chemical laser power increases:

YEAR	POWER	YEAR	POWER
1960	0W	1980	1000 kW
1968	138kW	2003	≈ 2000kW
1978	400kW		

Table 1. Laser Power History[28]

This table reflects a doubling of power every 10 years. Although powerful, chemical laser weapons have numerous drawbacks including size and a limitation in the number of shots fired, both linked to the amounts of chemical involved[29]. The second type of laser, solid state, got off to a slower start. Despite this, solid state lasers have reached the 25kW level within the last few years[30]. If solid state lasers follow the same growth timeline as chemical lasers, by the year 2035 a 1 Megawatt solid state laser should exist. To produce an LSSPE of 1.06 would only require half a second. Unfortunately, the thirty years required to achieve a Megawatt class solid state laser may be too long.

Changing the LSSPE Trajectory

Examining today's technology and the current trend line shows that power and magazine depth have the greatest impact on laser weapon effectiveness. This increases the fluency of the laser, leading to a higher LSSPE at a greater range. The trajectories of the two main laser weapons technologies do not look likely to produce the power levels needed. According to Dr. Sheldon Meth, "The fact remains that chemical lasers have to lug a portable chemical plant into the field. The fact remains that solid-state lasers require too much power and "coolant" to be practical in combat."[31]. Therefore, the technologies having the most impact on laser power and magazine depth must be pursued.

Three areas of laser development offer the ability to reach new power and magazine depth levels; Fiber, Air and liquid Lasers[32]. Fiber lasers use the core of a fiber-optic like strand as a laser pump. The advantage of fiber lasers is that while each laser can be optimized, combining multiple fiber lasers allows both an increase in power output and potentially new applications[33]. Although called Air Lasers, lasers using liquid oxygen could increase the power output of lasers for the same weight cost. Air Lasers would shed the need for a separate cooling system, increasing overall laser efficiency[34]. Liquid lasers add to the advantage of air lasers by not only promising to incorporate the coolant system into the laser, but also the power management system. This technology might truly reduce the weight of a laser system. Each new technology would not just enable an SSPD of 1.0 or higher, but offer it at a greater range and lighter weight. The only way the US will be able to achieve higher LSSPEs with Laser weapons is to adapt these new technologies into fiber, air and liquid Lasers weapons.

Chapter 3
Microwave Weapons

The next most technologically advanced class of Direct Energy weapons is High Powered Microwaves. Although less well known than lasers, they hold an equal potential for usefulness on the battlefield of the future. While lasers offer a straight forward history, High Powered Microwaves (HPM) developed less evenly. In fact the normal microwave technologies used in ovens and for communications played minor roles in the development of HPMs. The technologies used to create HPMs derived from research into nuclear weapons effects. Since the late 70's the technology has accelerated. The Navy currently fields an HPM system designed to counter Improvised Explosive Devises (IEDs). The Navy's Neutralizing IEDs with RF (NIRF) system is currently in use in Iraq. Nevertheless, issues facing HPMs include controlling the effects of the waves on unintended targets and shielding friendly systems[35]. HPMs will continue to be fielded as more uses are discovered and researchers weaponize systems in the laboratory.

Microwave Single Sortie Probability of Effect

HPM weapons offer their own unique adjustments to current SSPD calculations. As with lasers, these adjustments fall into three broad categories. Again the variables involved are, weapon variables, environmental factors and target properties. The weapons variables which must be accounted for with HPM weapons include transmitter power, carrier frequency, antenna gain, angle, and wave polarization[36]. Propagation is the primary environmental factor to consider with HPMs propagation is effected by range and atmospheric loss[37]. Finally the target must be taken into account. Currently the data for HPM weapons regards electronics, but the properties of electronics could be extended to other target types as well. Target properties for electronics include Radio Frequency (RF) coupling area and the component effect level/vulnerability[38]. Each set of variables requires independent examination.

HPM weapon variables stem from the energy output at the weapon. Transmitter power (P) refers to the power output within the HPM weapon. Antenna gain (G) is the gain imparted on the Microwave by the devices antenna. Angle is relevant in two planes, (θ,φ). Wave polarization (p) refers to the orientation of the wave pattern emitted, either right or left polarized. As the beam leaves the antenna, it passes through the environment.

Propagation through the environment is effect by range (R), the distance from the weapon to the target and by atmospheric loss. A major consideration in atmospheric loss is the ionization of the air, causing diminished range of a microwave pulse[39]. This ionization is unique among the three DE weapons examined. Like lasers, HPMs can be affected by the aerosols in the atmosphere[40]. These effects culminate in atmospheric loss, expressed as L. Despite atmospheric losses, the beam eventually reaches the target.

HPM weapon effects depend greatly on the targets' properties. HPMs are most useful against electronics, which will be the focus of the target property discussion. Radio Frequency (RF) coupling area (A_e) considerations pose a key decision for targeting. According to Walling, there are two ways for HPM energy to enter an electronics target, front door or back door[41]. These are defined as follows, "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.' 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.'"[42]. The electronic component effect refers to the level of damage to which the component is susceptible. As with lasers, each factor concerning the weapon, environment and target needs to be incorporated into the modified index.

Knowing the relevant variables concerning HPMs, they must be fit mathematically into the standard SSPD equation. The first known variables are the characteristics of the microwave as it leaves the weapon –the "what we have". The second sets of variables concerned are the atmospheric effects. The properties of both were discussed above can be combined into a single function, expressed as:

$$S_T\ (f,t,F,q,f,p) \text{ where } S_T = \frac{P\ G\ L}{4pR^2}$$

Figure 3 S_T: Power Density on the Target equation[43]

This measurement can be thought of as the first part of the "what we have" variable and is part of the numerator in the SSPD equation. However, this is not sufficient, because like physical targets and bombs, only certain parts of targets are vulnerable to microwaves.

The second part of "what we have" is how much of the target can potentially be effected. The part of the target vulnerable to Microwaves is designated as the RF coupling area. The RF coupling area (A_e) is a function of target Carrier frequency, angle and target carrier polarization[44]. RF coupling area will be unique to each target and weapon combination and is expressed as:

A_e **(f,** θ,φ**,p),** (expressed as an area)

Figure 4 RF Coupling Area[45]

Although the characteristics of the Microwave as it leave the weapon are known, just as important for effect is the characteristics of the actual Microwaves that reach the target. The combination of the characteristics of the microwave at the target and the vulnerability of the target is called Power Density Required (P_R). In order to calculate the P_R use the following calculation: $P_R = S_T \times A_e$ [46]. Power Density Required, although a misnomer, represents the entire effected the weapons is able to impart at the target.

The characteristics of the target represent the "what we need" or denominator portion of the new HPM-SSPD equation. This is called the Electronic Component Effect Level (C). The component Effect Level is a function of the target Pulse Duration and Target Pulse Repetition Frequency, expressed as $C(\tau,F)$. The $C(\tau,F)$ will be a unique measurement for each microwave target and must be determined through experimentation and modeling.

The variables and their relationships above can be inserted into a SSPD style formula. This will be our Microwave Single Sortie Probability of Effect (McSSPE) index. Taking the approach of dividing what we have by what we need, it can be determined that the equation for McSSPE is as follows:

$$\text{McSSPE} = \frac{P_R}{C} = \frac{S_T \text{ x } A_e}{C(\tau,F)}$$

Figure 5 Derived Initial Microwave Single Sortie Probability of Effect Equation

The entire equation can be expressed as:

$$\text{McSSPE} = \frac{\frac{(PGL)}{(4pR^2)} \text{ x } A_e}{C(\tau,F)}$$

Figure 6 Derived Entire Microwave Single Sortie Probability of Effect Equation

This resultant equation is similar to the laser equation in that it compares J/cm2 to one another. This is logical since both Microwave and Lasers are direct energy devices. The difference stems from vulnerability. This difference is similar to the differences in vulnerability in conventional weapons; some targets are more vulnerable to blast while others are more vulnerable to fragmentation.

The SoFI for Microwave Weapons

Using known numbers for Microwave weapons, we can determine where these weapons are on the McSSPE index today. This sets a baseline for comparison against future technologies. From Dr Zhihua we learn that an audio frequency diode has a C of 5x10J/cm^2 [47]. A modern microwave weapon can produce a 400w/cm2 effect at the transistor from a range of 10km, giving us our S_T [48]. A typical transistor may have a vulnerability area of 2.5 μm^2 or 2.5x10 cm^2. This results in an McSSPE of 2. This is an excellent result, until it is recalled that the range is only 10km. Double the range and you cut the result to a quarter (McSSPE =.50). Despite this fact, increases in HPM power and range capabilities have increased over time.

Using the McSSPE equation as the SOFI index for Microwave weapons allows a extension of the effects of changes in Microwave technologies from the present into possible future scenarios. The device that generated the numbers above transmitted in the Gigawatt range[49]. However, like chemical lasers it takes multiple truckloads of equipment to generate that level of power. The US Air Force High Powered Microwave device, Shiva Star, can generate 1 terawatt of power. However Shiva Star is a test machine only[50]. Mobile, single shot weapons can generate over 10 Gigawatts, but only have a range of about 500m. On the other end of the spectrum, mobile devices capable of multiple shots can only generate around 100kW[51]. The timeline for microwave development is as follows:

Year	Power	Range
1982	$1x10^{12}$ (Terawatt)	Lab Building
1989	$1x10^{9}$ (Gigawatt)	5000m
2003	$10x10^{9}$ (Gigawatt)	500m

Table 2. Microwave Power History (AFRL)[52]

The current power increase trend for microwave weapons is slightly less than 1 Gigawatt per year. On this trajectory, by the year 2035 Microwave weapons should reach the 35 GW class. Using a power increase of 35 times in the McSSPE equation creates a 70km range and a McSSPE of 1.0. However, the trend in range from the above table is to shorten. If a disruptive technology is not found, the Effects will not be achieved.

Changing the McSSPE Trajectory

Like lasers, the single biggest input that we can control regarding microwave weapons is power. However, we can control more than just the power source. Two technical research areas that will improve the McSSPE of microwave weapons are better power sources and better antennas. In the area of pulse generation, efforts to make more efficient switches within the generator will prove critical in increasing power output. One type of switch that could revolutionize pulse power generation are Pseudowswitches[53]. In the area of antenna gain, an increase would act as a multiplier for the power source. One promising technique is waveguide deformation. Traditional steering of phased array antennas would make minor adjustments in the frequency of multiple slot antennas to steer the beam[54]. Waveguide deformation would use small amounts of pressure on the waveguide to adjust the physical orientation of the slot antennas, thus mechanically steering the beam[55]. Investing in these technologies increases the P_R portion of the McSSPE equation. This will allow higher single sortie success rates at greater ranges.

Chapter 4

Millimeter Wave Weapons

The history of millimeter wave weapons is more obscure than that of other DE weapons. However, this technology is arguably the furthest along. The Active Denial System 01 could be ready to send to Iraq next year. This system makes its targets feel intense heat and pain while under its beam. This non-lethal application of Direct Energy promises a new branch for applying the technology. The primary issue facing ADS and other millimeter wave systems surround its long term health effects on targets. Nonetheless, millimeter wave systems offer promise in crowd control and non-lethal enemy suppression.

Many of the adjustments to the current SSPD equation required by Microwave Weapons transfer directly to Millimeter Wave Weapons. The weapons factors of transmitter power, carrier frequency, antenna gain, and angle all apply. Environmental considerations also include similar considerations to those of both laser and microwaves. The primary differences in the adjustments required by Millimeter Wave Weapons concern the target.

Millimeter Wave Weapons target people, not electronics. The primary target considerations are exposure including both shielding and time. The weapon factors to consider with Millimeter waves are the same as those outlined for Microwaves. The environmental factors are also similar, but with one major difference. Millimeter waves do not ionize the atmosphere[56]. Therefore ionization factors do not need to be considered.

SSPD equation differs from microwaves to millimeter waves because of the variables regarding the target. Where HPM weapons primarily effect equipment, especially electronics, Millimeter waves effect animals. The primary effect of Millimeter wave weapons is to produce thermal energy, which is heat, at the point of exposure[57]. Exposure incorporates both the amount of skin exposed to the Millimeter waves and how long they are exposed. Millimeter wave effects calculations must take into consideration the shielding of the target. Like other Direct Energy weapons, the factors unique to Millimeter Wave weapons must be included in the new index.

Millimeter Wave Single Sortie Probability of Effect

The SSPD equation for Millimeter wave weapons will utilize a similar equation as the Microwave weapons but with slight variations. Though the power output from the weapon and the power received at the target are calculated in the same way, atmospheric losses for the millimeter wave weapons are much less because the air does not ionize. This will be reflected in the S_T term of the equation. Additionally the effected area will not be an RF coupling area, but actual exposed skin area. This reality will also be reflected in the Component Effect Level, which shall be called the Human effect level (H) for microwave weapons. Like the component effect level for Microwave Weapons, H will need to be determined through modeling. Given these changes to the equation, a Millimeter Wave Single Sortie Probability of Effect (MmSSPE) is created:

$$\text{MmSSPE} = \frac{P_R}{H} = \frac{S_T \times A_e}{H}$$

Figure 7 Derived Initial Millimeter Wave Single Sortie Probability of Effect Equation

The entire equation can be expressed as:

$$\text{MmSSPE} = \frac{\frac{(PGL)}{(4pR^2)} \times A_e}{H}$$

Figure 8 Derived Entire Millimeter Wave Single Sortie Probability of Effect Equation

The primary difference in the McSSPE and MmSSPE will stem from the target properties. For the MmSSPE results from lab tests on rats or other animals will need to be extrapolated to determine effects on humans and thus derive valid A_e and H values.

The SoFI for Millimeter wave Weapons

Current lab tests show that Millimeter Wave weapons are effective, but again at relatively short ranges. The Active Denial system has been tested are ranges of 700m. Lab tests have shown that systems similar to the ADS produce 75mW/cm^2 amounts of power at the target, representing the S_T [58]. The amount of area exposed was 1cm in diameter, producing an area of effect (A_e) approximately 7.8x10^{-5} cm^2 [59]. Although no experiments have been conducted to specifically determine H values, given anecdotal evidence from Beason and others, it can be determined that the S_T and A_e provided are effective.[60] If it is assumed that the weapon was 100% effective, or an MmSSPE of 1.0, then the H can be determined to be .00058 J/ cm^2. This is a good start, but like the Microwave system the range is extremely short, only 700m. Increasing the range to 1000m reduces the MmSSPE to approximately .48, a reduction to less than half by going only 300m further away.

Millimeter wave weapons technology is still in the early stages of development relative to microwave and laser technologies, so trends are less certain. As recently as

1997 a laboratory device creating a 45W output was relatively high powered[61]. Such as device would have created the 75mW/cm^2 value shown above. Documentation shows that tests have for biologic effects of Millimeter wave exposure have reached the 1mW/cm^2 using lenses[62]. This represents a 25% increase in the later same year, on a non-weaponized system. Assuming that 1 year passed between the creation of the two devices, a modern device would be able to reach the 4mW/cm^2 . If this trend continues until 2035 we can expect to see devices creating 9 – 10 W/cm^2; a 9000 magnitude increase in power. More importantly this represents an incredible increase in range to around 80km (all of which will not be realized due to line-of-sight and atmospheric loss). These results will maintain a MMSSPE of 1.0. However, the data for the Millimeter Waves represents a small sample, it is likely the trend will flatten as time moves on.

Changing the MMSSPE Trajectory

Improving the MMSSPE of future microwave weapons means improving power output of the weapon. Like Microwave weapons, this means improved power sources and better antennas. In the case of millimeter waves, the power sources are already available. Traveling Wave Tubes (TWTs) can produce high powered millimeter waves; however they are difficult to manufacture[63]. Research efforts must be conducted into creating consistently high quality TWTs in order to make high power millimeter wave weapons practical in combat situations. Another power source includes traveling wave amplification. Recently Carlston has developed a sheet-beam method for traveling wave amplification[64]. Millimeter wave weapons can also get a boost through the use of higher gain antennas. Antennas producing not only greater gain, but also that are physically smaller must be pursued if a greater use of millimeter wave weapons will ever be seen on the battlefield. If the Single Sortie Pd or MMSSPE of millimeter wave weapons is to meet the range and kill requirements of 2035, the weapons power output must be increased through improved manufacturing techniques.

Chapter 5

Where to Go, How to Get There

The three branches of Direct Energy weapons research took different paths to arrive at a useable stage. For the most part, Direct Energy weapons will be available to the US military in the very near future. These weapons are no longer science projects for the far off future, they are here now. To that end, the warriors must begin to seriously study these new weapons. This paper demonstrated one method to accomplish that goal. Developing methods to measure the effects and success of the weapon helps the operator to plan for and use the weapons. The various SSPD equations shown above should provide a starting point for gauging the usefulness of Direct Energy weapons in the near term.

Implications

The Status of Futures Indices for each Direct Energy weapon indicates a potentially bright future if managed properly. The current trajectory of lasers puts them at a Pd/Pe of 1.0 barely possible at the 30 year mark for a laze time of 0.5sec from ranges similar to current blast/frag weapons. Microwave data is less conclusive. Trend data shows Microwave power increases should place distance ranges at 70km in 30 yrs! But empirical data shows a reverse trend due to atmospheric ionization shortening the range. The Millimeter wave trend line shows a very steep rise in range, power and dwell time. However, data for the Millimeter wave weapons is less available and has a shorter history. In all the SoFI indications for the current trajectory of Direct Energy Weapons is positive, but does not indicate a major shift to DE from

Blast/Frag before the year 2035. If Direct Energy weapons are to meet their full potential, disruptive new technologies must be found.

Recommendations

The Direct Energy weapon types of Laser, Microwave and Millimeter wave weapons each require unique investments. Over the next 30 years radical improvements needed in laser power and magazine depth to reach Pd/Pe of close to 1 .0 at ranges close to conventional weapons. This may be achieved by pursuing Fiber, Air or Liquid Lasers, or some combination of these with one another or current Chemical and Solid State Lasers. For Microwaves, new power sources and better antennas needed for 1.0 at reasonable ranges. Pseudoswitches offer a new direction for microwave power generation while multiple slot antennas could provide radical advances in antenna capabilities. For MMWs, power is here now, but very difficult to manufacture. The Main effort in regards to Millimeter wave weapons should be in improving the supporting industries. If some or all of these radical new technologies increase the effectiveness of the weapons, the various indices can help guide decision makers and warriors not only to the future, but to victory when they reach it.

Conclusions

Knowing how to use a weapon on its initial deployment would prove a great utility to the warrior. The leader can use the indexes outlined for the Laser, Microwave, and Millimeter wave Single Sortie probability of effects to predict their future usefulness. By applying the current trajectory of technological advance to the LSSPE, McSSPE, and MMSSPE the state of the various technologies in 2035 was forecast. Each weapon class offers the promise of great effect by the year 2035, but each one must overcome some hurdles. In the case of lasers, better power, deeper magazines and lighter equipment are needed. Microwaves also need to increase power output if they are to move from niche applications to replacing conventional weapons. Millimeter Wave technologies are perhaps the best positioned for growth, with adequate power already available. Millimeter wave technology needs a boost in manufacturing technology. To achieve improvements on any of the Direct Energy technologies, new strategies must be pursued. As new technologies are created, how they improve the weapon with respect to its effect on a target must be evaluated. Warriors in the year 2035 will need to know that the weapons they are using will achieve the effect required.

Glossary

JMEM	Joint Munitions Effectiveness Manual
LSSPE	Laser Single Sortie Probability of Effect
McSSPE	Microwave Single Sortie Probability of Effect
MMSSPE	Millimeter Wave Probability of Effect
SSPD	Single Sortie Probability of Damage
USAF	United States Air Force

For definitions, use the Definition style, as shown below:

laser. Any of several devices that convert incident electromagnetic radiation of mixed frequencies to one or more discrete frequencies of highly amplified and coherent visible radiation.[65]

microwave. Any electromagnetic radiation having a wavelength in the approximate range from one millimeter to one meter, the region between infrared and shortwave radio wavelengths.[66]

Millimeter wave: Any electromagnetic radiation having a wavelength in the approximate range from Ten millimeters to one millimeter.[67]

Endnotes

Notes

[1] Jerome C. Glenn, "Futures Research Methodology," in *UNU Millenium Project*, ed. Jerome C. Glenn (United Nations, 2007), 1-3.

[2] Ibid., 4/1.

[3] Ibid., 5/22.

[4] Colin Michael Anderson, "Generalized Weapon Effectiveness Modeling" (Naval Postgraduate School, 2004), 4.

[5] Ibid., 22.

[6] JTCG-ME, "Jtcg-Me Appendix A," ed. Joint Technical Coordinating Group for Munitions Effectiveness (DOD, 2006), 1-3.

[7] Ibid., 3.

[8] Ibid., 4.

[9] Doug Beason *The E-Bomb* (Cambridge, MA: Da Capo, 2005), 61.

[10] Ibid., 65.

[11] Ibid., 66-68.

[12] Ibid., 73.

[13] James Markham, A. , "Categorizing High Energy Laser Effects for the Joint Munitions Effectiveness Manual" (Air Force Institute of Technology, 2005), 26-32.

[14] Beason *The E-Bomb*, 70.

[15] Markham, "Categorizing High Energy Laser Effects for the Joint Munitions Effectiveness Manual", 31.

[16] Ibid., 32.

[17] Ibid.

[18] Ibid., 30.

[19] Ibid., 37-38.

[20] Ibid., 33.

[21] Ibid.

[22] Ibid., 34.

[23] Ibid., 60-62.

[24] Ibid., 30.

[25] Anderson, "Generalized Weapon Effectiveness Modeling", 17.

[26] Markham, "Categorizing High Energy Laser Effects for the Joint Munitions Effectiveness Manual", 50.

[27] Ibid., 60.

[28] Beason *The E-Bomb*, 68-78.

[29] Sharon Weinberger, "100 Kilowatts or Bust," *Aviation Week and Space Technology*, 5/22/2006 2006, 1.

[30] John McHale, "Future Weapons: Solid-State Lasers," *Military and Aerospace Electronics* 2006, 29.

[31] Sheldon Z. Meth, "Disruptive High Energy Laser Technology," in *DARPATECH* ed. DARPA (DARPA, 2005), 191.

[32] Ibid., 192.

[33] L.N. Durvasula, *High Power Fiber Lasers* (Defense Advanced Research Programs Agency, 2002).

Notes

[34] Meth, "Disruptive High Energy Laser Technology," 1.

[35] Beason *The E-Bomb*, 184.

[36] Linda Lambertson, 2/28/2007 2007.

[37] Ibid.

[38] Ibid.

[39] J Kim, S.P. Kuo, and Paul Kossey, "Modeling and Numerical Simulation of Microwave Pulse Propagation in Air Breakdown Environment" (paper presented at the Advisory Group for Aerospace Research and Development, Ottawa, Canada, 1994), 21-1.

[40] R.L. Armstrong et al., "Micro-Sized Droplets Irradiated with a Pulsed Carbon Dioxide Laser: Measurements of Explosion Breakdown Thresholds" (paper presented at the Advisory Group for Aerospace Research and Development - High Powered Microwaves, Ottawa, Canada, 2-5 May, 1994 1994), 25-1.

[41] Eileen M. Walling, "High Power Microwaves Strategic and Operational Implications for Warfare," in *Air University Pres* (Maxwell AFB, AL: Center for Strategy and Technology, Air University, 2000), 4.

[42] Ibid.

[43] Lambertson.

[44] Ibid.

[45] Ibid.

[46] Ibid.

[47] Zhu Zhihao, "Trends of Microwave Development," (National Air Intelligence Center, 1996), 4.

[48] Ibid., 8.

[49] Ibid.

[50] Michael Abrams, "Dawn of the E-Bomb," *IEEE Spectrum* (2003): 24.

[51] David A. Fulgnam, "New Energy Direction," *Aviation Week & Space Technology*, 11/8/2004 2004.

[52] Walling, "High Power Microwaves Strategic and Operational Implications for Warfare."

[53] Martin Gunderson, James Dickens, and William Nunnally, "Compact, Portable Pulsed-Power," ed. Univ. of Southern California (USAF, AFRL, 2006), 3.

[54] Clifton Courtney, Donald Voss, and Tom McVeety "Antenna Beam Steering Concepts for High Power Applications," ed. Andrew Greenwood (Albuquerque, N M: USAF, AFRL, 2004), 1.

[55] Ibid., 2.

[56] Beason *The E-Bomb,* 114.

[57] Ibid.

[58] Robert Blystone, "Millimeter Wave Induced Bioeffects," (San Antonio, Tx: Trinity university, 2006), 41.

[59] Ibid., 13.

[60] Beason *The E-Bomb*.

[61] Robert M. Rolfe, Brian S. Cohen, and Michael B. Marks, "A Preliminary Survey of Department of Energy Microelectronics Capabilities Related to Department of Defense Needs," ed. Robert M. Rolfe (Alexandria, VA: Instute for Defense Analysis, 1998).

Notes

[62] Eleanor Adair, "Infrared Lasers & Millimeter Waves: The Links between Microwaves and Laser Optics," ed. Eleanor Adair (Brooks Air Force Base, TX: Air Force Research Laboratory, 1999), 6.

[63] John H. Booske, "Micro Fabricated Traveling Wave Tubes for High Power Millimeter Wave and Thz Regime Sources," ed. Robert Barker (Arlington Va.: AFOSR NE, 2006), 3.

[64] B. Carlston et al., "Technology Development for a Mm-Wave Sheet-Beam Traveling Wave Tube," *IEEE Transactions on Plasma Science* 33, no. 1 (2005): 1.

[65] Beason *The E-Bomb*, 21-29.

[66] Ibid.

[67] Ibid.

Notes

Bibliography

Abrams, Michael. "Dawn of the E-Bomb." *IEEE Spectrum* (2003): 7.

Adair, Eleanor. "Infrared Lasers & Millimeter Waves: The Links between Microwaves and Laser Optics." edited by Eleanor Adair, 456. Brooks Air Force Base, TX: Air Force Research Laboratory, 1999.

Anderson, Colin Michael. "Generalized Weapon Effectiveness Modeling." Naval Postgraduate School, 2004.

Armstrong, R.L. , A. Biswas, R.G. Pinnick, and J.D. Pendleton. "Micro-Sized Droplets Irradiated with a Pulsed Carbon Dioxide Laser: Measurements of Explosion Breakdown Thresholds." Paper presented at the Advisory Group for Aerospace Research and Development - High Powered Microwaves, Ottawa, Canada, 2-5 May, 1994 1994.

Beason , Doug. *The E-Bomb*. Cambridge, MA: Da Capo, 2005.

.Blystone, Robert. "Millimeter Wave Induced Bioeffects." 62. San Antonio, Tx: Trinity university, 2006.

Booske, John H. "Micro Fabricated Traveling Wave Tubes for High Power Millimeter Wave and Thz Regime Sources." edited by Robert Barker, 15. Arlington Va.: AFOSR NE, 2006.

Carlston, B., S. Russell, L. Earley, F. Krawczyk, J. Potter, P. Ferguson, and S. Humphries. "Technology Development for a Mm-Wave Sheet-Beam Travelling Wave Tube." *IEEE Transactions on Plasma Science* 33, no. 1 (2005): 8.

Courtney, Clifton, Donald Voss, and Tom McVeety "Antenna Beam Steering Concepts for High Power Applications." edited by Andrew Greenwood, 26. Albuquerque, N M: USAF, AFRL, 2004.

Durvasula, L.N. *High Power Fiber Lasers*: Defense Advanced Research Programs Agency, 2002.

Fulgnam, David A. "New Energy Direction." *Aviation Week & Space Technology*, 11/8/2004 2004, 1.

Glenn, Jerome C. "Futures Research Methodology." In *UNU Millenium Project*, edited by Jerome C. Glenn: United Nations, 2007.

Gunderson, Martin, James Dickens, and William Nunnally. "Compact, Portable Pulsed-Power." edited by Univ. of Southern California, 20: USAF, AFRL, 2006.

JTCG-ME. "Jtcg-Me Appendix A." edited by Joint Technical Coordinating Group for Munitions Effectiveness: DOD, 2006.

Kim, J, S.P. Kuo, and Paul Kossey. "Modeling and Numerical Simulation of Microwave Pulse Propagation in Air Breakdown Environment." Paper presented at the Advisory Group for Aerospace Research and Development, Ottawa, Canada 1994.

Lambertson, Linda. 2/28/2007 2007.

Markham, James, A. . "Categorizing High Energy Laser Effects for the Joint Munitions Effectiveness Manual." Air Force Institute of Technology, 2005.

McHale, John. "Future Weapons: Solid-State Lasers." *Military and Aerospace Electronics* 2006.

Notes

Meth, Sheldon Z. "Disruptive High Energy Laser Technology." In *DARPATECH* edited by DARPA: DARPA, 2005.

Rolfe, Robert M., Brian S. Cohen, and Michael B. Marks. "A Preliminary Survey of Department of Energy Microelectronics Capabilities Related to Department of Defense Needs." edited by Robert M. Rolfe, 102. Alexandria, VA: Instute for Defense Analysis, 1998.

Walling, Eileen M. "High Power Microwaves Strategic and Operational Implications for Warfare." In *Air University Pres*, 52. Maxwell AFB, AL: Center for Strategy and Technology, Air University, 2000.

Weinberger, Sharon. "100 Kilowatts or Bust." *Aviation Week and Space Technology*, 5/22/2006 2006, 4.

Zhihao, Zhu. "Trends of Microwave Development." 11: National Air Intelligence Center, 1996.