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AN INTRODUCTION TO THE TECHNICAL AND OPERATIONAL ASPECTS OF THE ELECTROMAGNETIC BOMB

by

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About the Author

Born in Perth, Western Australia, the author graduated with first class honours in Electrical Engineering in 1984, from the University of Western Australia. In 1996 he completed an MSc in Computer Science and is currently working on a PhD in the same discipline at Monash University in Melbourne. He has over a decade of diverse industry experience, including the design of high speed communications equipment, optical fibre receivers and transmitters, communications equipment including embedded code, Unix computer workstation motherboards, graphics adaptors and chassis. More recently, he has consulted in Unix systems programming, performance engineering and system administration. The author has been actively publishing as a defence analyst in Australia's leading aviation trade journal, Australian Aviation, since 1980 and has specialised in the area of application of modern military technology to operations and strategy. His work has been published by the RAAF APSC since 1992, and USAF CADRE Air Chronicles since 1996.

Author's Note

This paper was compiled wholly from open sources which have been detailed in the references. The primary sources were IEEE Pulsed Power Conference proceedings, supplemented by a number of electrical engineering and physics fundamentals texts. All of this material has been in the public domain for half a decade or longer.

Acknowledgments

INTRODUCTION

Dependency upon a resource or infrastructure base produces a vulnerability, should this resource be denied or destroyed. Modern industrialised nations are now heavily dependent upon their fundamental computing and communications infrastructure, which is vitally important to the smooth operation of their political systems, finance sectors, government bureaucracies, manufacturing industries, road, rail, sea and air transport, and military machines. Virtually all computing and communications technology which comprises the technological foundation of this infrastructure shares a common attribute, in that it is built with modern high density semiconductor components.

This fundamental dependency upon the modern semiconductor device produces a global and pervasive vulnerability to attack by weapons which are specifically designed to damage or destroy semiconductor components. Importantly, such weapons are now both technically feasible and relatively economical to build, in comparison with established weapons of mass destruction such as the nuclear bomb.[1] A wide range of existing targeting and delivery techniques may be employed in using such weapons. These devices are electromagnetic weapons, and the foremost of these is the electromagnetic bomb (E-bomb).[2]

In principle, an electromagnetic weapon is any device which can produce an electromagnetic field of such intensity, that a targeted item or items of electronic equipment experiences either a soft or a hard kill.

A soft kill is produced when the effects of the weapon cause the operation of the target equipment or system to be temporarily disrupted. A good example is a computer system, which is caused to reset or transition into an unrecoverable or hung state. The result is a temporary loss of function, which can seriously compromise the operation of any system which is critically dependent upon the computer system in question.

A hard kill is produced when the effects of the weapon cause permanent electrical damage to the target equipment or system, necessitating either the repair or the replacement of the equipment or system in question. An example is a computer system which experiences damage to its power supply, peripheral interfaces and memory. The equipment may or may not be repairable, subject to the severity of the damage, and this can in turn render inoperable for extended periods of time any system which is critically dependent upon this computer system.

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[1] Electromagnetic bombs, due their substantially larger effective footprints in comparison with chemical explosive bombs, are often regarded as Weapons of Electrical Mass Destruction (WEMD); Kopp C., *A Doctrine for the Use of Electromagnetic Pulse Bombs*, Paper Number 15, Air Power Studies Centre, Royal Australian Air Force, Canberra, July 1993.

[2] Terminology in this area is unfortunately quite unclear. This paper will use the terms electromagnetic bomb (E-bomb), electromagnetic warhead and electromagnetic munition interchangeably, with specific references to low frequency weapons and microwave (HPM) weapons. Other terms in use are RF munition, EMP munition, EMP bomb and T-bomb.
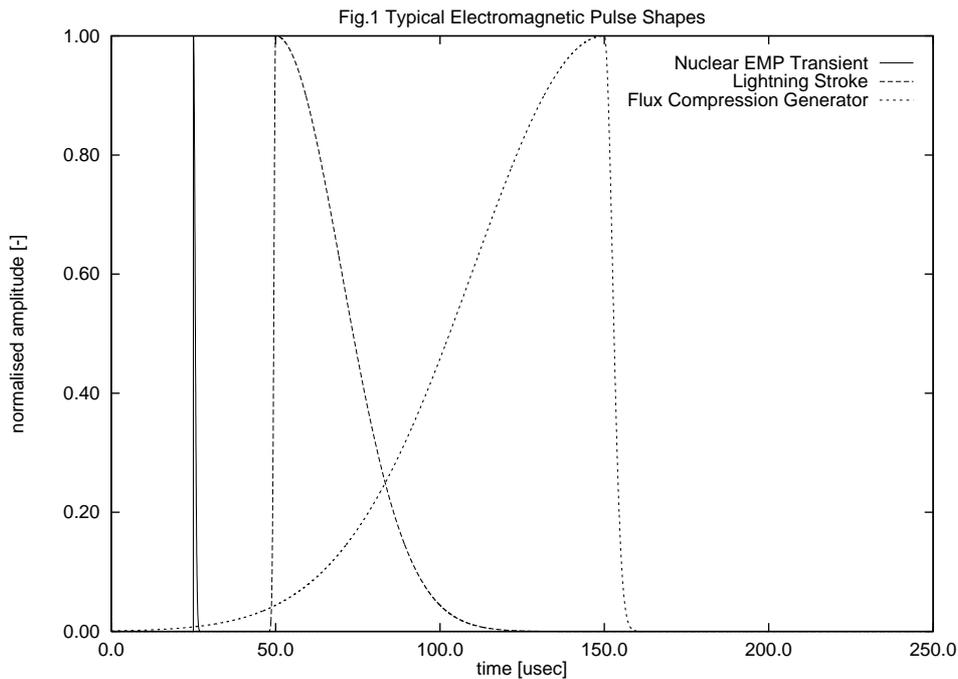
Fig.1 Typical Electromagnetic Pulse Shapes

Figure 1

The non-nuclear electromagnetic bomb or warhead is the foremost of the emerging generation of electromagnetic weapons. Applied *en-masse* it has the potential to significantly alter the balance of military power in any situation where one or both players have a strong dependency upon semiconductor based military and supporting technologies. Given the ubiquitous nature of modern semiconductor devices, particularly in modern military technology, the electromagnetic bomb promises its user the means of rapidly crippling an opponent's military, economic and arguably also political systems. Faced with the electromagnetic bomb, the semiconductor device becomes a common single point of failure for most modern systems, unless extensive hardening measures are applied.

The potential utility of electromagnetic weapons as a warfighting tool first became apparent during the period of atmospheric nuclear weapons testing, when it was found that a nuclear weapon detonated in the upper atmosphere produced an intense electromagnetic field transient over a geographically significant area. This effect was termed the ElectroMagnetic Pulse (EMP) effect, and resulted from the ionisation effects produced by the radiation from the nuclear device.[3] A nuclear EMP is a short 0.5 microsecond duration (nominally a 10 ns rise time and 500 ns fall time) pulse which by virtue of its extremely fast risetime produces a spectrum rich in harmonics, and capable of coupling quite effectively into unshielded wiring and cabling infrastructure. The result of exploding an EMP weapon will be a high voltage electrical 'spike' propagating along any conductive cables which are exposed. The high voltage spike can if sufficiently intense, produce breakdown effects in semiconductors, and if the intensity is high enough, thermal damage effects in conductive materials.

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[3] Glasstone, S., (Ed.), 'The Effects of Nuclear Weapons', *US AEC*, April, 1962, Revised Edition February, 1964.

During the Cold War, it was expected that nuclear EMP bombs would be used in the opening phase of any large scale nuclear war, specifically for the purpose of disrupting and destroying an opponent's Command Control Communications (C^3) infrastructure. The United States and the Soviet Union expended much effort in electrically hardening many key assets against nuclear EMP attack.

The development and deployment of non-nuclear or conventional electromagnetic weapons, and specifically electromagnetic bombs, will shift the threat of electromagnetic attack down from full scale nuclear war to far more likely non-nuclear confrontations. Importantly, the potential for terrorist, info-terrorist and special forces employment of electromagnetic weapons means that the probability of such attack may become very high and can no longer be considered a highly unlikely worst-case scenario.

As a result, the need for the electromagnetic hardening of assets will be a continuing and growing requirement for governments, defence forces and private industry.

The Technology Base

To construct a non-nuclear electromagnetic weapon it is necessary to build a device which can generate a very large amount of electromagnetic energy very quickly, and deliver this energy on to a target or set of targets. A diverse range of technologies may be applied to this purpose, many of which are quite mature.

The key technologies which may be applied to electromagnetic munitions design in the near term are explosively pumped Flux Compression Generators (FCG), and High Power Microwave devices, the most important of which is the virtual cathode oscillator or vircator. Much unclassified literature exists which details experimental work in these areas, and the results of this work clearly demonstrate that the construction of deployable electromagnetic warheads is now very feasible.

This paper will review the technology base and describe the basic operating principles of the most important devices. This discussion is by no means exhaustive, and will concentrate on technologies which are directly applicable to bomb and warhead design in the near term. A range of other technologies, such as MHD devices, have potential in the longer term but are still too immature at this time for practical applications.

The Explosive Flux Compression Generator

The explosively pumped flux generator is a mature technology, first demonstrated in the late fifties by C.M. Fowler at LANL (Los Alamos),[4] and later by Soviet researchers.[5] Much effort has been expended both by the United States and the CIS in

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[4] Fowler, C.M., W.B. Garn and R.S. Caird, 'Production of Very High Magnetic Fields by Implosion', *Journal of Applied Physics*, Volume 31, Number 3, pp 588-594, March, 1960.

[5] Sakharov A.D. et al, 'Magnetic Cumulation', *Doklady Akademii Nauk 165*, pp 65-68, 1966 reprinted in Sov. Phys. Usp. 34 (5), May 1991, American Institute of Physics; Sakharov A.D., Magnetoimplosive Generators', *Usp. Fiz. Nauk 88*, pp 725-734 (1966), reprinted in Sov. Phys. Usp. 34 (5), May 1991, American Institute of Physics.

the intervening period, as a result of which a wide range of generator configurations have been developed.

The flux generator is a device which can produce peak electrical energies of MegaJoules in tens to hundreds of microseconds of time. This is accomplished in a compact and lightweight package. With delivered power levels of TeraWatts to tens of TeraWatts, a large flux generator can produce electrical currents which are three orders of magnitude greater than those produced by a typical lightning strike.[6]

The FCG is built upon the idea of using a fast explosive to rapidly transfer a large amount of mechanical energy into a magnetic field, thereby significantly increasing the strength of the field.

A wide range of generator configurations are possible, and published literature to date details cylindrical or coaxial generators, conical generators, cylindrical implosion generators, plate, strip, spiral or helical and spherical generators.[7] This discussion will focus upon the helical FCG, as this configuration is most readily applied to bomb and warhead designs.

A flux generator must initially be primed with a magnetic flux, termed a seed or priming field, before the explosive charge can be initiated. The priming field is most commonly produced by discharging an electrical current through the generator, this current is usually termed a start or priming current. The priming current can be produced in principle by any device which is capable of producing a current pulse which is often hundreds of thousands to millions of Amps of current. The device which is most commonly used for this purpose is a high voltage capacitor bank, although small Magneto-Hydrodynamic (MHD) generators,[8] homopolar generators and smaller FCGs could also be used for this purpose.

The starting point for the discussion of generator operation is a description of its construction. A typical helical FCG, such as the Los Alamos Mk.IX design,[9] comprises a generator winding or stator, into which a tube of explosive or armature is placed.

The armature is typically a precisely machined tube of copper, which is filled with a fast high energy explosive. Any fast explosive with stable detonation or burn characteristics may be used, and published experiments describe the use of B and C-type compositions, or PBX-9500 series compositions. These may be cast into the

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[6] 'The EMP - A Triangular Impulse', 2.29, *A Handbook Series on Electromagnetic Interference and Compatibility*, Don White Consultants, Maryland, 1978.

[7] Reinovsky R.E., Levi P.S. and Welby J.M., 'An Economical, 2 Stage Flux Compression Generator System', *Digest of Technical Papers*, 5th IEEE Pulsed Power Conference, p. 216, IEEE, New York, 1985; Caird R.S. et al, 'Tests of an Explosive Driven Coaxial Generator', *Digest of Technical Papers*, 5th IEEE Pulsed Power Conference, p. 220, IEEE, New York, 1985; C.M. Fowler, R.S. Caird, 'The Mark IX Generator', *Digest of Technical Papers*, Seventh IEEE Pulsed Power Conference, p. 475, IEEE, New York, 1989.

[8] Fanthome, B.A., 'MHD Pulsed Power Generation', *Digest of Technical Papers*, 7th IEEE Pulsed Power Conference, IEEE, New York, 1989, p 483.

[9] C.M. Fowler, R.S. Caird, 'The Mark IX Generator', *Digest of Technical Papers*, Seventh IEEE Pulsed Power Conference, p. 475, IEEE, New York, 1989.

armature, or fitted as machined blocks. The explosive is best initiated with a plane wave generator such as an explosive lens, as this ensures that an asymmetrical burn front does not distort the armature shape and compromise generator performance.

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Figure 2

The stator winding is typically made from a heavy duty copper wire, wound on a mandrel. Larger generators may also split the winding into segments, to optimise the inductive characteristics and current carrying capability of the stator during operation. A typical segmented winding will have conductors bifurcated at segment boundaries.

Larger generators often have the cavity between the stator and armature purged of air, and filled with a gas, such as Sulphur Hexafluoride, which will not experience breakdown effects at high field strengths.

The magnetic forces produced during the priming and the operation of the generator could potentially tear the stator apart. To prevent this a structural jacket of non-conductive material is placed around the stator. Any material with suitable mechanical and electrical properties may be used, be it concrete, fibreglass or non-conductive composites using fibres such as Kevlar. Fibreglass or Kevlar Epoxy composites would be most suited to warhead applications, where weight is an important issue.

In operation the explosive is initiated when the priming current has peaked. The explosive burn will distort the armature, shorting the armature and the stator and bypassing the start current source. As the burn progresses the armature will form a conical shape, with a typical angle of 12 to 19 degrees of arc, which propagates along the length of the generator. The propagating short compresses the magnetic field and reduces the winding inductance, which causes the winding current to ramp up until the generator disintegrates.

Ramp times of several tens to hundreds of microseconds have been demonstrated, with peak currents of tens of MegaAmperes[10] and peak energies of tens of MegaJoules. The generator is in effect a large current amplifier, and current multiplication ratios of hundreds and higher have been described.[11] Flux generators have been successfully cascaded in experiments conducted by LANL and AFWL, with a smaller generator priming a larger generator.[12]

For munitions applications, the cylindrical form factor of the helical generator is most suitable, as it allows the axial stacking of components. The principal technical issues in adapting existing designs lie in matching the generator's output current to the intended load, such as a microwave tube. This may be accomplished by using passive

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[10] A useful comparison here is that a typical lightning strike produces a 30,000 Amp current, which is typically 1000 times smaller than the current produced by a large flux generator; *High Energy Microwave Laboratory Fact Sheet*, USAF AFMC, Phillips Laboratory, Kirtland AFB, 1994; Reinovsky R.E., Levi P.S. and Welby J.M., 'An Economical, 2 Stage Flux Compression Generator System', *Digest of Technical Papers*, 5th IEEE Pulsed Power Conference, p. 216, IEEE, New York, 1985; C.M. Fowler, R.S. Caird, 'The Mark IX Generator', *Digest of Technical Papers*, Seventh IEEE Pulsed Power Conference, IEEE, New York, 1989. p 475.

[11] C.M. Fowler, R.S. Caird, 'The Mark IX Generator', *Digest of Technical Papers*, Seventh IEEE Pulsed Power Conference, p. 475, IEEE, New York, 1989; Reinovsky R.E., Levi P.S. and Welby J.M., 'An Economical, 2 Stage Flux Compression Generator System', *Digest of Technical Papers*, 5th IEEE Pulsed Power Conference, p 216.

[12] Reinovsky R.E., Levi P.S. and Welby J.M., 'An Economical, 2 Stage Flux Compression Generator System', *Digest of Technical Papers*, 5th IEEE Pulsed Power Conference, p 216; *High Energy Microwave Laboratory Fact Sheet*, USAF AFMC, Phillips Laboratory, Kirtland AFB, 1994.

pulse shaping networks, high current transformers and explosive switching devices.[13] The appropriate use of such components will produce a current pulse with suitable waveform shape and timing to satisfy the requirements of the load device. Where a generator is to be directly used as a low frequency munition, a simple low inductance coaxial load may be attached to the end of the generator.

It is worth noting that while some FCG designs can be fabricated for a cost of the order of thousands of dollars, it is often a very difficult device to design well, and can require a substantial effort in analysis, modelling and prototype testing.

High Power Microwave Devices - the Virtual Cathode Oscillator

The lethality of the flux generator is constrained by the limited coupling efficiency of a low frequency pulse, which is typically spectrally constrained to below 1 MHz. Substantially better coupling efficiencies may be achieved by the use of HPM devices, which can in turn deliver much better lethality.

A wide range of HPM devices have been described in the published literature. The relativistic klystron, the magnetron, the slow wave device, the reflex triode and the spark gap generator may all be used to produce useful levels of HPM emission.[14]

The vircator is the most suitable of the current generation of HPM devices for use in munition applications, as it is a simple, cheap, robust one shot broadband device capable of producing tens of GigaWatts of microwave power.

The operating principles of the vircator are significantly more complex than those of the flux generator. The vircator is based upon the principle of accelerating a powerful electron beam to relativistic velocities, which causes electrons to punch through a foil or mesh anode. The electrons which have passed the anode form a bubble of space charge, termed a virtual cathode, behind the anode. The virtual cathode is under the proper conditions unstable, and if placed in a microwave cavity will oscillate in the microwave band. Large peak power levels may be extracted from the oscillating virtual cathode, using established microwave engineering techniques. The anode will typically vaporise or melt after about a microsecond of operation.

Because the frequency of the oscillation is critically dependent upon the parameters of the electron beam, vircators have a propensity to mode hop and drift in frequency with variations in beam current. If the beam current is suitably manipulated, the vircator can be chirped over a relatively wide band of frequencies.

Published experiments suggest peak power levels ranging from 170 kW up to 40 GW within the centimetric and decimetric (D through K) bands.[15]

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[13] Goforth J.H. et al, 'Experiments with Explosively Formed Fuse Opening Switches in Higher Efficiency Circuits', *Digest of Technical Papers*, 7th IEEE Pulsed Power Conference, p 479, IEEE, New York, 1989.

[14] Granatstein V.L. and Alexeff I., *High Power Microwave Sources*, Artech House, Boston, London, 1987; Heoberling R.F. and Fazio M.V., 'Advances in Virtual Cathode Microwave Sources', *IEEE Transactions on Electromagnetic Compatibility*, Volume 34, Number 3, p 252, August 1992.

[15] Thode L.E., 'Virtual-Cathode Microwave Device Research: Experiment and Simulation', Chapter 14 in *High Power Microwave Sources*, 1987; Heoberling R.F. and Fazio, M.V., 'Advances in Virtual

A number of vircator configurations exist, the most common of which are the axial and the transverse vircators. The axial vircator (AV) is the simplest of the two, and has produced the best power levels in experiments. It is built into a cylindrical waveguide structure, and very commonly uses a transition to a conical horn antenna as a means of extracting power from the cavity. Whereas the axial vircator typically oscillates in a Transverse Magnetic (TM) mode, the transverse vircator oscillates in a Transverse Electric (TE) mode. Current is typically injected into the side of a TV cavity.

The central technical issues in designing a vircator for a munitions application lie in the achieved pulse duration, the stability of oscillation, the achievable bandwidth and peak power, the conversion efficiency, typically of the order of one percent, and the efficiency of coupling power from the device. The latter can become a major problem, as high field strengths can cause many insulators to electrically break down, thereby compromising device efficiency.
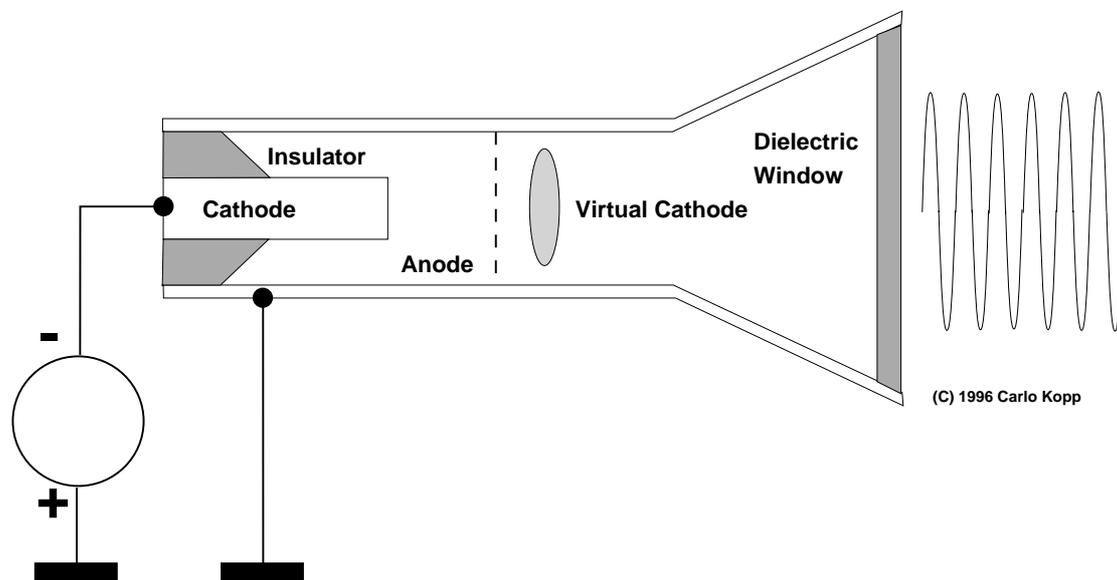

FIG.3 AXIAL VIRTUAL CATHODE OSCILLATOR

Figure 3

Technical Issues in the Design of an Electromagnetic Warhead

The design of an electromagnetic munition, either for bomb or missile applications, is not a trivial task. A number of complex issues must be addressed, including the necessary electrical characteristics to achieve required lethality, packaging, weight, reliability, robustness and integration with the delivery vehicle.

Electromagnetic warheads may in principle be built as low frequency devices, using a flux generator alone, or as microwave devices, using a flux generator to power a

Cathode Microwave Sources', *IEEE Transactions of Electromagnetic Compatibility*, Volume 34, Number 3, August 1992, p 252.

microwave vircator. Combined effects warheads, which use an oversized flux generator together with a vircator to produce low frequency and microwave damage effects, are also a possibility.

Such warheads may be packaged as bombs to be delivered by aircraft as free fall munitions, or used in glidebombs as an unpowered standoff munition. Providing that sufficient performance can be packaged tightly enough, such warheads could also be fitted to standoff missiles, cruise missiles, Anti-Ship Missiles (ASM), Surface-to-Air Missiles (SAM) and Air-to-Air Missiles (AAM).

The starting point for any discussion of warhead design must be lethality, because it constrains performance requirements which determine size and weight, these in turn constraining means of delivery.

Lethality Issues in Electromagnetic Warheads

Determining the lethality of an electromagnetic warhead is a difficult task, which does not lend itself to simple analytical methods. This is for a number of very good reasons.

The first of these is that various types of target will have widely differing levels of electromagnetic hardness, which is a measure of their ability to resist a given field strength at a given frequency. Differing behaviour of shielding, different transient arrestor devices, different wiring geometries, varying tolerances in semiconductor susceptibility and variations in relative field orientation to the target will contribute to this situation. We can expect different manufacturers implementations of similar equipment types to exhibit quite different levels of susceptibility.

Coupling efficiency, a measure of what proportion of delivered power is coupled into the target, may vary significantly due to differences in wiring geometry and shielding performance, as well as the obstructing, shielding and absorption effects of surrounding building or platform structures. Good examples are modern buildings with steel structural frames, and naval vessels and aircraft with metal skins.

Semiconductor Susceptibility

The primary electrical damage mechanism we are interested in is electrical breakdown due to the effects of exposure to high voltages. Electrical breakdown mechanisms will be quite specific to the type of device exposed, and importantly require very little energy to initiate.

In bipolar semiconductor devices, a high voltage across a reverse biased PN junction will rip carriers from the lattice, eventually producing an avalanche effect. If the power supply in the equipment can deliver sufficient energy, thermal damage will subsequently result and the device will be destroyed. Silicon Radio Frequency (RF) Bipolar Junction Transistors (BJT), which are widely employed in communications, radar and EW equipment, typically have safe voltage ratings between 15V and 65V.[16]

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[16] *Motorola RF Device Data*, Motorola Semiconductor Products Inc, Arizona, 1983.

In Metal Oxide Semiconductor (MOS) and other Field Effect Transistor (FET) devices, the primary damage mechanism is an electrical breakdown of the device Gate dielectric. The result of exposing a FET device to excessive Gate voltages will be a leakage current which may be sufficient to render the device inoperable, or degrade its performance significantly. As with BJTs, further secondary damage effects may be produced by the equipment power supply. Breakdown voltages against equipment earth and supply rails are typically less than 10 or 15 Volts for generic Si CMOS, NMOS, GaAs FETs, high density DRAMs. Microprocessors running with 3.3 or 5 Volt rails will tolerate only several Volts beyond the rail voltages.[17]

Many devices employ internal structures to absorb electrostatic discharges at the device pins, however such structures may or may not survive repeated or sustained exposure to high RF voltages. Many communications interfaces employ protection transformers in order to meet regulatory requirements, such transformers have typical ratings between 2 and 3 kV.[18] Pulse arrestors using gas discharge devices or ferrite beads may also be employed. Both transformers and arrestors may be ineffective if the field strength is high enough, as energy may couple through via stray capacitance, common mode capacitance, or saturation of the ferrite material.

If the defence provided by shielding or protection devices is breached, RF voltages as low as tens of Volts may damage or destroy semiconductor components, and lesser voltages produce temporary disruption of operation. Devices which are damaged may continue to operate, but fail intermittently, resulting in a substantial expense in equipment debugging time and a significant disruption of operations.

Clearly the objective of a warhead designer should be to ensure that a maximum of electrical energy is coupled into the target equipment to maximise damage effects.

Coupling Mechanisms

The literature recognises two primary coupling mechanisms via which internal components within equipment may be attacked.

Front Door coupling will take place when energy couples in through an antenna, such as is used by radar, communications or EW equipment. Antennas are designed to gather energy and thus may efficiently concentrate received energy in receiver circuits. Energy from a weapon can then destroy RF semiconductor devices.

Back Door coupling is a more complex mechanism, and occurs when energy is coupled into wiring and cables, via which it propagates inside equipment and damages components which may be accessible via conductive, inductive or capacitive paths.

A low frequency or combined effects munition using a flux generator will produce a single high voltage spike and ringing on fixed electrical wiring and cabling. This transient will propagate along the cable and destroy any sensitive components which

[17] *Micron DRAM Data Book*, Micron Technology Inc, Idaho, 1992; *CMOS Databook*, National Semiconductor Corporation, Santa Clara, 1978; *Motorola RF Device Data*, Motorola Semiconductor Products Inc, Arizona, 1983.

[18] 'NPI Local Area Network Products', *SMD Transformers*, Nano Pulse Industries, Brea, 1993.

it may access.[19] Because the fixed power, communications and networking wiring infrastructure typically follow streets, corridors and risers with cable runs of hundreds to thousands of metres, good coupling efficiencies may be achieved. This is because any cable run will comprise multiple linear segments which are typically at close to right angles, therefore whatever the relative orientation of the weapon field, one or more segments will provide very good coupling efficiency. Networking cables (eg 10/100 Base-T Ethernet) use fast low loss dielectrics and are thus very efficient at propagating such transients with minimal loss.

Increasing Target Hardness ←   → **Increasing Bomb Power Increasing Coupling Efficiency**
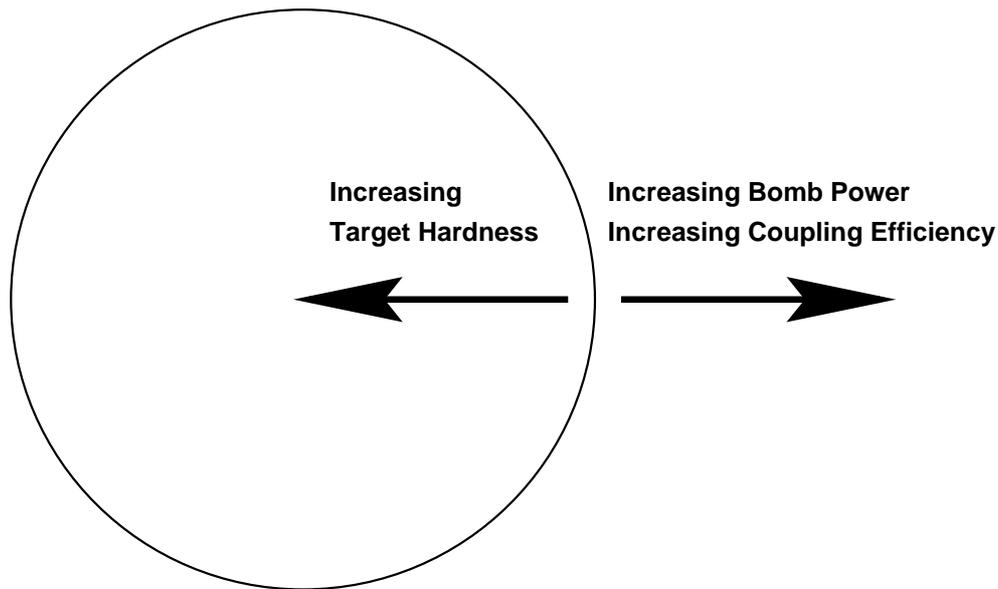
(C) 1996 Carlo Kopp

FIG.4 E-BOMB LETHAL RADIUS

Figure 4

Flux generator based munitions also have the potential to destroy data repositories which use magnetic storage media such as tapes. The near field produced in the close proximity of a large flux generator would be easily greater in magnitude than the magnetic coercivity of most modern magnetic materials. Archives using older magnetic media would be significantly more vulnerable to such attack, due to the lower coercivity of the medium.

A microwave weapon couples in two back door modes. The first of these is by producing standing waves on exposed wiring,[20] via which RF energy can directly damage interface devices, as well as enter equipment cavities and excite internal resonances. The second mode of coupling is directly through ventilation holes, grilles,

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[19] 'The EMP - A Triangular Impulse', 2.29, *A Handbook Series on Electromagnetic Interference and Compatibility*, Don White Consultants, Maryland, 1978.

[20] Taylor C.D. and Harrison C.W., 'On the Coupling of Microwave Radiation to Wire Structures', *IEEE Transactions on Electromagnetic Compatibility*, Volume 34, Number 3, August 1992, p 183; Sander, K.F. and Reed, G.A.L., *Transmission and Propagation of Electromagnetic Waves*, Cambridge University Press, 1986; Ramo, S. et al, *Fields and Waves in Communications Electronics*, John Wiley and Sons, New York, 1965.

gaps and poorly secured panels. Any aperture of a suitable size will behave like a slot radiator.

Once a resonance is excited within the equipment cavity, a potentially very high field strength may be achieved at an antinode in the standing wave pattern. Internal wiring, Printed Circuit Board (PCB) tracks, and inductive or capacitive paths may then couple energy from the spatial standing wave in the equipment and propagate it to susceptible components. Shielding panels with inappropriate connection to a chassis may also be excited to resonance and directly couple into the cavity.

As a microwave weapon offers superior coupling performance, can be focussed precisely and has the ability to bypass many types of protection device, microwave weapons have the potential to be much more lethal than pure flux generators.

Determining Munition Lethality

As is readily apparent, the exact prediction of a weapon's P[kill] is for all practical purposes impossible. However, if we can empirically determine order of magnitude voltages for given damage levels on given types or classes of equipment, we can produce a baseline for estimating the lethality of the munition. Once we know the voltage, we can then determine required field strengths for typical wiring geometries and lengths, and in turn determine the required weapon power and distance.

As an example, given the knowledge that a microwave standing wave of kiloVolts to tens of kiloVolts of amplitude on wiring or cabling associated with a given piece of equipment will produce a hard kill, it is not difficult to determine that a field of kiloVolts/metre or tens of kiloVolts/metre at several GigaHertz of frequency will produce such voltages. If we then assume a desired lethal footprint for the weapon of 400 to 500 metres diameter, or about 0.2 square kilometres, we will need a 10 GigaWatt microwave warhead operating at about 5 GHz.[21] The choice of frequency in this instance represents a compromise, in that shorter wavelengths generally offer better coupling performance, better power transfer performance and better antenna performance for a given antenna size. However, shorter wavelengths impose greater demands upon the microwave tube, and below 3 cm wavelength (> 10 GHz) begin to suffer from atmospheric quantum absorption effects.

A 10 GW warhead operating at about 5 GHz is easily within the reach of current technology.[22] Figure 4 depicts the relationships between lethal footprint size and target hardness, bomb power and coupling efficiency. As bomb power and coupling efficiency are increased, the achievable footprint is increased in size. However, should target hardness be increased, then the achievable lethal footprint is reduced.

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[21] Kraus J.D., *Antennas*, Second Edition, McGraw-Hill, 1988; Taylor C.D. and Harrison C.W., 'On the Coupling of Microwave Radiation to Wire Structures', *IEEE Transactions on Electromagnetic Compatibility*, Volume 34, Number 3, August 1992, p 183.

[22] Thode L.E., 'Virtual-Cathode Microwave Device Research: Experiment and Simulation', Chapter 14 in *High Power Microwave Sources*, 1987.

Improving Munition Lethality

The lethality of an electromagnetic warhead can be improved by increasing the power coupled into its intended target set. This is accomplished by increasing bomb output energy and by achieving the best possible coupling efficiency.

Bomb energy is maximised by using as powerful a flux generator and vircator as can be accommodated in the packaging volume available, by maximising the duration of operation, and by minimising losses incurred inside the bomb, as power flows between stages. Power which is not emitted is wasted at the expense of lethality.

Coupling efficiency may be maximised by exploiting all available coupling opportunities.

A pure flux generator bomb could use an external wire antenna to improve power transfer out of the weapon, as the efficiency of the flux generator winding as a loop antenna is quite poor. This is because the loop size is much smaller than the wavelengths associated with the 1 MHz bandwidth of such a device. Some improvement to generator lethality can be provided by using an explosive switch to sharpen the cutoff of the generator, thereby increasing the harmonic content of the output transient.

Because microwave bombs can be easily focussed using a compact antenna which can be large in relation to the wavelength used, two techniques can be exploited to improve lethality.
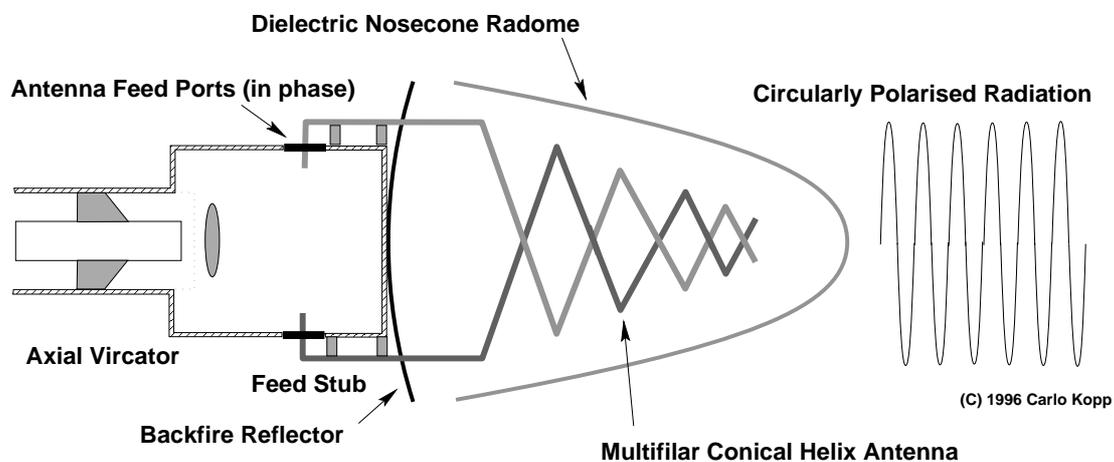

FIG.5 EXAMPLE OF VIRCATOR/ANTENNA ASSEMBLY

Figure 5

The first of these is chirping the vircator over as wide a band as possible, in order to excite any resonances which may exist over this band, and couple through apertures with as wide a range of sizes as possible.

The second of these is to employ a circularly rather than linearly polarised antenna, in order to couple into apertures and resonant structures with arbitrary orientations in

relation to the weapon. While a linearly polarised antenna may be cheaper, it can exploit only half of the opportunities available, should we assume a uniform distribution of aperture and resonance orientations.

A circularly polarised wideband antenna for this application would typically be a tapered helix or conical spiral design, specifically built to handle large peak powers with minimal losses. An example of an integrated antenna/oscillator assembly is depicted in Figure 5.

Lethality can also be increased, as noted previously, by initiating the weapon at a lower altitude. This will however be at the expense of footprint size, and is a case of trading coverage for lethality.
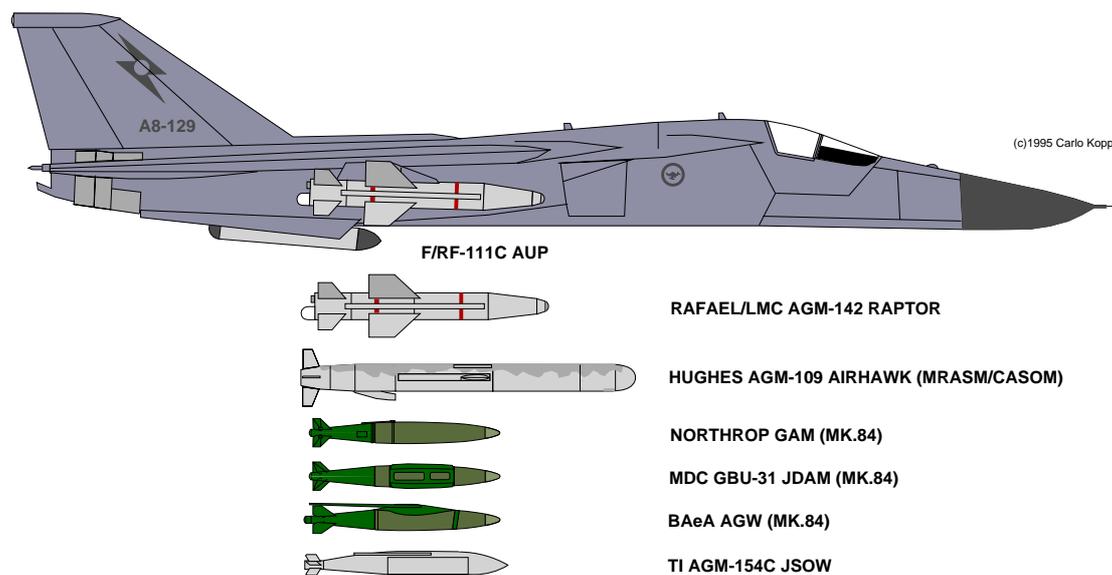

**FIG.6 COMPARISON OF STANDOFF, FREE-FALL AND GLIDE WEAPONS**

Figure 6

Packaging and Integration Issues

As noted previously, electromagnetic warheads can in theory be used as bombs and missile warheads. From a lethality perspective, bombs will be the preferred choice as they provide a substantially greater volume for internal hardware, and can exploit the launch aircraft's internal power to precharge their priming source prior to release, using a smaller battery to maintain losses after release. As a missile must carry its whole energy supply with it, a warhead installation for a missile will be split between the flux generator and microwave hardware, and the complete priming source and its power supply. The energy density (J/kg) of the power supply will be a critical constraint to achievable performance in bomb and missile borne warheads.[23]

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[23] Kopp C., *A Doctrine for the Use of Electromagnetic Pulse Bombs*, Working Paper Number 15, Air Power Studies Centre, Royal Australian Air Force, Canberra, July 1993.

Some measure of these relationships can be gained from Figure 6, which depicts a strike aircraft, an air launched cruise missile, a standoff missile, two GPS guided bombs and two GPS guided glide weapons. The GPS guided bombs and AGW glidebomb employ the Mk.84 warhead form factor which allows circa 1,000 kg for the warhead and its priming source.[24] The cruise missile, standoff missile and JSOW glide weapon employ 400 to 500 kg warheads with proportionally lower volume available. If we assume the same technology base, and power output proportional to the weight/volume of the warhead, we find that the missile warhead can accommodate only a flux generator and microwave installation with about 60 per cent of the size and performance of that carried by a bomb.

LOW FREQUENCY E-BOMB - GENERAL ARRANGMENT MK.84 PACKAGING
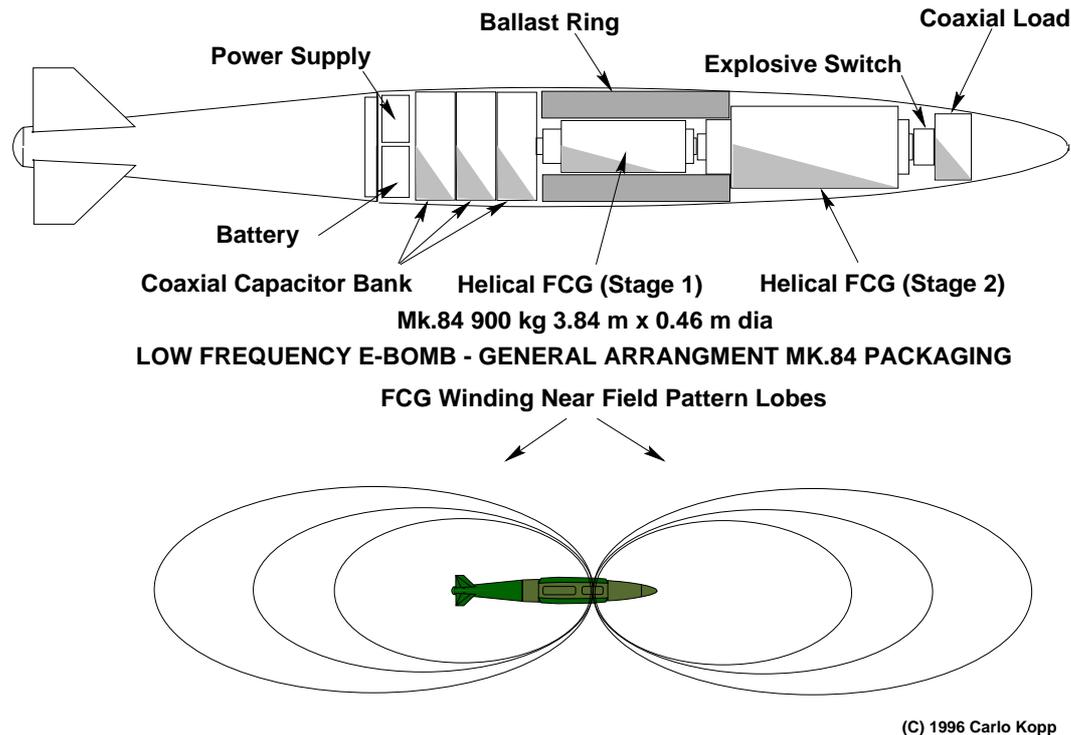
FIG.7 LOW FREQUENCY E-BOMB WARHEAD (MK.84 FORM FACTOR)

Figure 7

The ratio of generator/microwave hardware to priming source hardware improves with the energy density of the priming source, therefore there is a significant payoff in using the best possible supply technology.

As noted earlier, the coaxial geometry of the axial vircator and the helical flux generator make them the preferred options for warhead designs. Figure 7 depicts a low frequency bomb warhead using a pure flux generator, with a coaxial short circuit load. The warhead employs a two stage arrangement, with a coaxial form factor capacitor bank used as a priming source for the first stage of the generator cascade.

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[24] *B-2 Precision Weapons*, unclassified briefing, Northrop-Grumman Corporation, September, 1995, unpublished material; Pergler R., *Joint Standoff Weapon System (JSOW)*, unclassified briefing, Texas Instruments, Inc., December 1994, unpublished material; *Joint Direct Attack Munition (JDAM)*, unclassified briefing, McDonnell Douglas Corporation, 1995, unpublished material.

The high voltage supply is used initially to convert 400 Hz power from the aircraft's Mil-Std-1760 umbilical to charge up the capacitor bank, after the weapon is released the supply feeds from the internal battery to maintain charge. The ballast is employed to maintain identical ballistic properties to a standard Mk.84 weapon. The generator winding is employed as an antenna, and an explosive switch is used to sharpen the cutoff of the generator. The warhead has a fibreglass load bearing external skin made in two halves.

The warhead depicted in Figure 8 is derived from the preceding design, and employs an axial vircator tube feeding a conical horn to produce a HPM output. A pulse shaping network and explosive switch are used to provide the tube with a suitably shaped current pulse. The antenna illuminates the target through a dielectric nosecone, using similar low loss materials to a radar nosecone.

Whereas a warhead designed into a standard bomb form factor can be shipped to a deployment site as a complete assembly, and fitted with a tailkit when ready for use, a missile warhead will have to be fitted at the manufacturing plant. A warhead suitable for the AGM-109 and AGM-142 missiles would have to be packaged into a cylindrical form factor with a diameter of 21 inches and a length of 64 inches. Given the identical diameter of these weapons, a common warhead could be used.
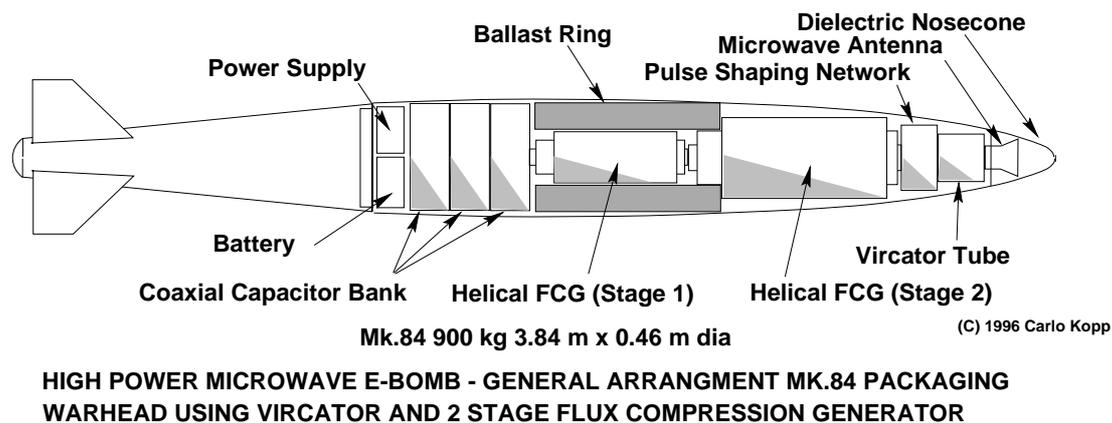

HIGH POWER MICROWAVE E-BOMB - GENERAL ARRANGMENT MK.84 PACKAGING
WARHEAD USING VIRCATOR AND 2 STAGE FLUX COMPRESSION GENERATOR

FIG.8 HPM E-BOMB WARHEAD (Mk.84 FORM FACTOR)

Figure 8

The conclusion we may draw from packaging constraints is that electromagnetic bombs rather than missile warheads should be preferred from a lethality perspective, and that very high energy density priming supplies will be required before a warhead with respectable lethality can be packaged into smaller missiles.

Operational Aspects of Electromagnetic Warhead Use

To understand the operational implications of electromagnetic bomb and warhead use it is useful to explore the conventional operational cycle for strike operations. This cycle comprises initial reconnaissance, targeting, weapon delivery and bomb damage assessment (BDA).

Significantly, as we will find, weapons using electromagnetic warheads can be readily integrated into existing operational cycles and deployed capabilities for warhead delivery. As a result we can conclude that operational deployment in the next five to ten years is a feasible proposition.

Reconnaissance and Targeting

The purpose of reconnaissance is to detect, locate and identify potential targets or target sets for attack. All prestrike reconnaissance is conducted in the context of the strategic, operational or tactical situation at hand. Therefore specific types of target will be sought.

Electromagnetic bombs and missile warheads may be profitably applied to Electronic Combat operations, Strategic Strike operations, Offensive Counter Air (OCA) operations and Combat Air Support operations.[25] In each of these contexts, specific target types with specific signatures will need to be detected and identified.
In Electronic Combat operations, the objective is to inflict attrition upon an opponent's electronic assets, which may be C3 sites, strategic early warning, GCI and acquisition radars, and fire control radars associated with SAM and AAA systems. The intended outcome is the crippling if not total destruction of the opponent's Integrated Air Defence System (IADS).

In Strategic Strike operations, the objective is to inflict paralysis upon an opponent's fundamental information processing infrastructure, in the context of the Warden model.[26]

In OCA and Combat Support operations, the objective is to inflict attrition upon the opponent's air and general warfighting assets respectively.

Fixed target installations, naval vessels and fielded military forces may all be found by means of conventional photographic, satellite, radar and electronic reconnaissance. The latter is of particular importance since most active targets will be emitting and this will allow their positive identification, regardless of camouflage which may defeat optical or radar reconnaissance tools. The principal tools for electronic recce are the Electronic Support Measures (ESM) receiver or the Emitter Locating System (ELS), which in modern implementations will use interferometric, phase-rate-of-change and time-of-arrival techniques.

Hidden targets which do not overtly radiate transmissions may however be detected and identified via the use of Unintended Emissions (UE),[27] more commonly known as Van Eck[28] or TEMPEST radiation. UE is the result of switching transients in

[25] Kopp C., *A Doctrine for the Use of Electromagnetic Pulse Bombs*, Working Paper No. 15, Air Power Studies Centre, Royal Australian Air Force, Canberra, July 1993.

[26] *ibid*.; Warden J.A. III, Col USAF, 'Air Theory for the Twenty-first Century', Chapter 4 in Schneider B.R, Grinter L.E., *Battlefield of the Future, 21st Century Warfare Issues*, Air University Press, Maxwell AFB, September 1995; Szafranski, R., Col USAF, 'Parallel War and Hyperwar', Chapter 5 in Schneider B.R. and Grinter L.E., *Battlefield of the Future: 21st Century Warfare Issues*, Air University Press, Maxwell AFB, September 1995.

[27] Herskowitz D., 'The Other SIGINT/ELINT', *Journal of Electronic Defence*, April, 1996.

[28] van Eck W., 'Electromagnetic Radiation from Video Display Units: An Eavesdropping Risk', *Computers and Security*, 1985, p 269.

equipment, such as computers, peripherals, switchmode power supplies, display monitors, local area networks, electrical motors, variable cycle power controllers, and internal combustion engine ignition systems, leaking out through ineffective shielding. It can also result from superheterodyne receiver local oscillators leaking out through antennas.
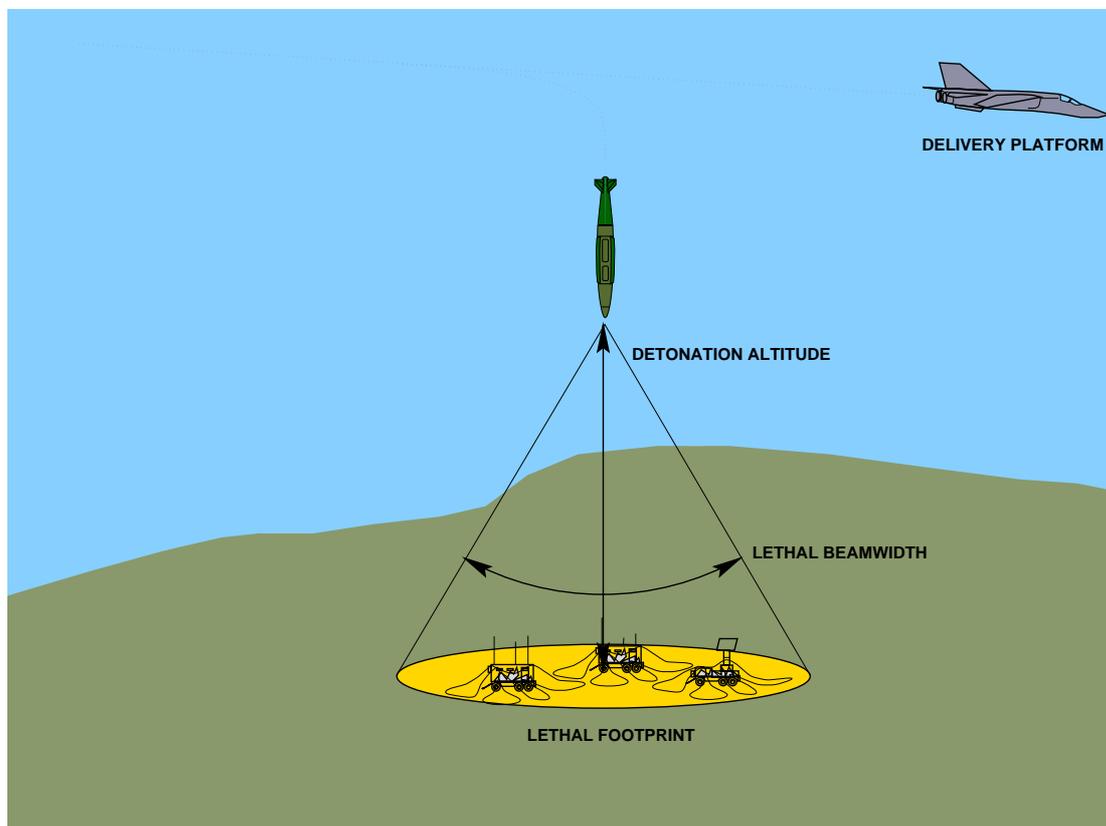

FIG.9 LETHAL FOOTPRINT OF A HPM E-BOMB IN RELATION TO ALTITUDE

Figure 9

Importantly, from an electronic reconnaissance perspective, these emissions are quite unique to their source, and therefore can be used to identify it. This is particularly true for emissions from computer equipment and local area networks, as these will exhibit regular repetitive patterns.

While UE typically occurs at power levels many orders of magnitude lower than intentional emission, regular patter could allow the use of correlation techniques to significantly increase receiver sensitivity.[29] Further work is needed in this area to determine the feasibility of building an Unintentional Emitter Locating System (UELS), which could be fitted to reconnaissance or strike aircraft, or UAVs. This is not a novel approach to this type of problem, as USAF Pave Pronto AC-130 gunships deployed over the Ho Chi Minh Trail during the latter phase of the South East Asian conflict employed the Northrop/Lockheed AN/ASD-5 Black Crow DF receiver which

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[29] Dixon R.C., *Spread Spectrum Systems*, John Wiley and Sons, New York, 1984.

was specifically designed to detect and track the emissions from automotive ignition systems.[30]

From the perspective of the targeteer, a wide range of tools exist and further tools may be produced, which will allow the detection, identification and location of targets for attack with electromagnetic bombs or warheads.

The important issues which will need to be addressed in targeting are the acceptable level of electrical collateral damage, which may be a particular issue for treaty bound nations,[31] and the selection of aimpoints and initiation altitudes to achieve the best possible damage level against hostile assets within the intended footprint of the weapon. Selection of weapon types will also be an issue, as certain types of targets may be more suitable for attack with low frequency weapons, and other targets with microwave weapons.
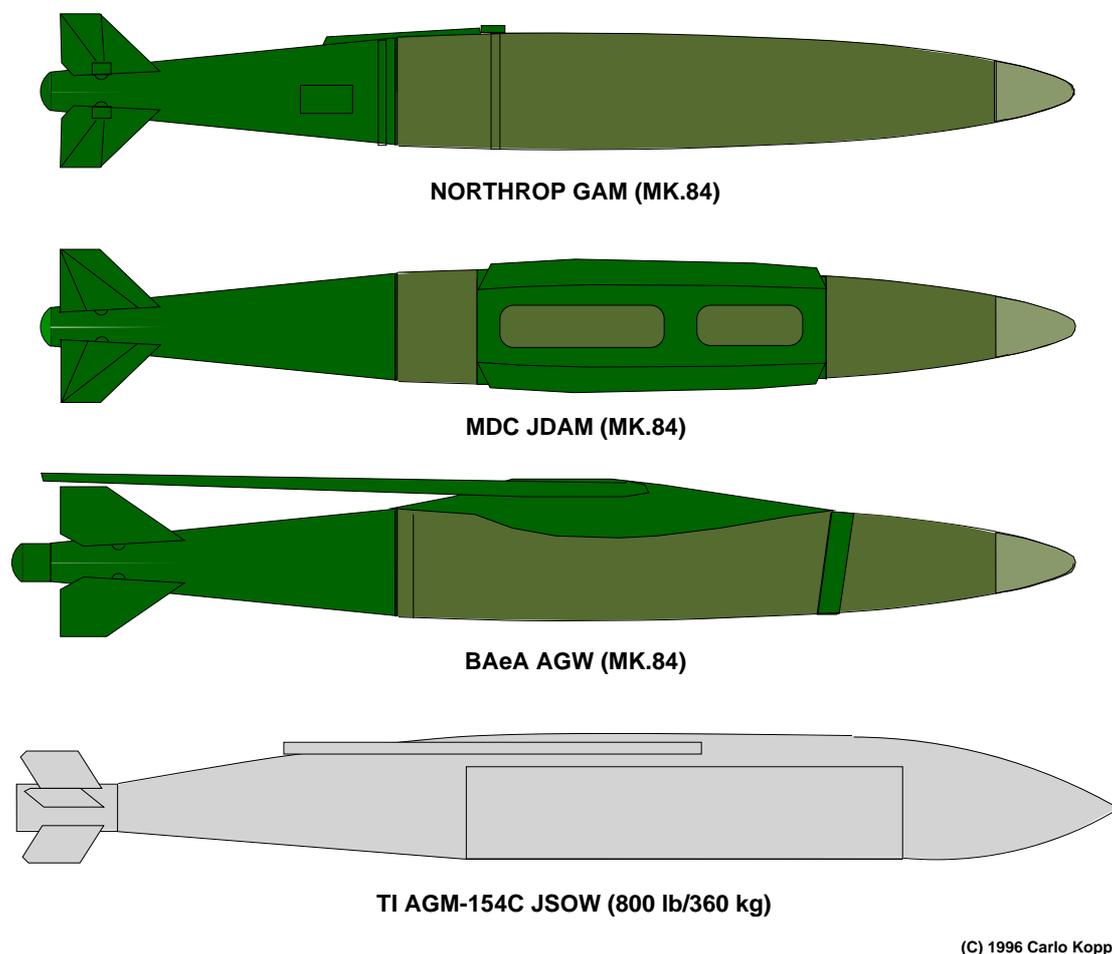
NORTHROP GAM (MK.84)

MDC JDAM (MK.84)

BAeA AGW (MK.84)

TI AGM-154C JSOW (800 lb/360 kg)

(C) 1996 Carlo Kopp

FIG.10 GPS GUIDED BOMB/GLIDEBOMB KITS

Figure 10

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[30] 'EW Systems: AN/Designated Hardware', *International Countermeasures Handbook*, 10th Edition, Cardigg Publishing, Colorado, 1985, p 86;

[31] DI(AF) AAP1003, *Operations Law for RAAF Commanders*, Chapter 8 The Law of Aerial Targeting, First Edition, Air Power Studies Centre, Canberra, 1994.

The Delivery of Electromagnetic Munitions

Electromagnetic warheads may be delivered by bomb, glidebomb or by missile. A bomb will require that the delivering aircraft penetrate hostile air defences to a suitable release range from which the target may be engaged. Missiles offer significant standoff ranges, which avoid the problems associated with defence penetration, but due to their smaller effective footprints can inflict damage only to much smaller areas. A missile will therefore be used only for specific high value targets which justify the cost of the basic weapon, which is typically of the order of $1M.
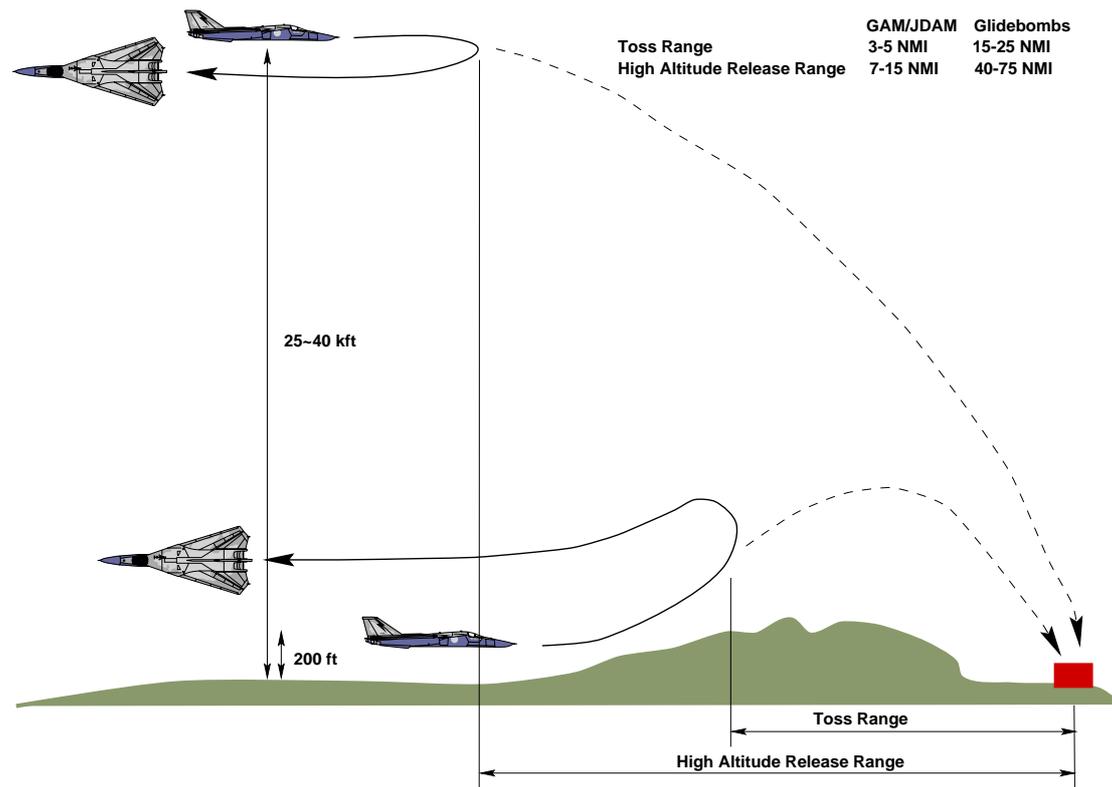
	GAM/JDAM	Glidebombs
Toss Range	3-5 NMI	15-25 NMI
High Altitude Release Range	7-15 NMI	40-75 NMI

25~40 kft

200 ft

Toss Range

High Altitude Release Range

FIG.11 DELIVERY PROFILES FOR GPS/INERTIAL GUIDED WEAPONS

Figure 11

Bomb Delivery

A significant problem with the delivery of bomb warheads as unguided or 'dumb' bombs is accuracy, as Circular Error Probable (CEP) values for low level toss delivery can be of the order of the weapon's lethal radius. This would have been a major impediment to the effectiveness of electromagnetic bombs, if it were not for the recent evolution of GPS aided bombs. A GPS aided bomb uses a 'smart' tailkit equipped with an inertial navigation package and a GPS receiver, which provide such weapons with CEPs between 6 to 12 metres, subject to the accuracy of the delivering aircraft.[32] Such weapons are fully autonomous, all weather capable and employ

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[32] The most accurate GPS guided bomb is at this time the recently deployed Northrop GAM on the B-2. High accuracy is achieved by programming the bombs before release with the same constellation of

intelligent guidance algorithms which allow the weapon to engage the target with a preprogrammed trajectory shape. If fitted to an electromagnetic bomb, the weapon can be programmed to attack a target with an optimal engagement geometry.

Safe distance for the delivering aircraft could be an issue for a low altitude level delivery, as is the case with larger explosive bombs. Given that this profile is no longer frequently used, as toss delivery is preferred to avoid point defences surrounding the target, this issue should not arise in practice.

The recent operational deployment of the Northrop GAM GPS Aided Bomb kit,[33] and the impending deployment of the MDC GBU-31 and 32 JDAM bomb kits[34] marks the beginning of the life cycle of this important family of weapons. The GPS aided bomb is the optimal low cost delivery vehicle for electromagnetic warheads, as it is cheap ($20,000 to $40,000 per round), suitably accurate, will be widely available, and importantly, can be delivered by any aircraft with a Mil-Std-1760 interface and suitable nav attack software. The JDAM is expected to become the standard guided bomb used by most Western air forces, and therefore will be universally supported by both tactical and strategic aircraft. As it is intended to supplant existing laser guided bombs, it may by default also become the standard free fall munition in RAAF service after the turn of the century.

The US is not the only nation developing GPS aided munitions. British Aerospace Australia is currently developing the Agile Gliding Weapon (AGW), which is a glidebomb kit for a Mk.82 or Mk.84 warhead. Derived from the DSTO Kerkanya demonstrator,[35] it is in effect a 'winged JDAM'. The AGW if released from high altitude can glide for up to 140 km. Slightly more expensive than the JDAM, the AGW allows conventional aircraft to engage targets from well outside the range of area defence SAMs, with high accuracy.

The Texas Instruments AGM-154 JSOW family of gliding dispensers[36] could also be adapted to an electromagnetic warhead, although this weapon's small payload of 450 kg would limit its effectiveness in this application.

The combination of a stealthy bomber and an electromagnetic bomb with a GPS aided tailkit promises to be an exceptionally effective asset for both Electronic Combat and Strategic Strike operations. An F-117A could carry a pair of autonomous 2,000lb

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satellites as is used by the bomber, therefore the bombs experience a very low relative error in relation to the bomber. The highly accurate APQ-181 radar is then used to precisely locate the target in relation to the bomber. It is worth noting that a similar technique could be used on the F-111C AUP, as the Pave Tack could be used to accurately locate the target, using its rangefinding mode. The JDAM, intended for deployment on the B-2, will have appropriate firmware embedded to support such a mode of operation. If used in this fashion, an F-111C could engage multiple closely spaced targets with a concurrent multiple JDAM drop. Software changes to the AUP offensive avionic system would be required in order to support this mode.

[33] *B-2 Precision Weapons*, unclassified briefing, Northrop-Grumman Corporation, September, 1995, unpublished material.

[34] *Joint Direct Attack Munition (JDAM),* unclassified briefing, McDonnell Douglas Corporation, 1995, unpublished material.

[35] Kopp, C., 'Australia's Kerkanya Based Agile Gliding Weapon', *Australian Aviation*, Aerospace Publications, Canberra, October 1996, p 28.

[36] Pergler R., *Joint Standoff Weapon System (JSOW),* unclassified briefing, Texas Instruments, Inc., December 1994, unpublished material.

GBU-31 JDAMs, while the B-2A can carry no less than sixteen 2,000lb GAMs or GBU-31s. A single B-2 bomber delivering electromagnetic warheads could cripple significant portions of an opponent's air defence system, C3 network or economy in a single sortie, with total surprise and total impunity.

The USAF Phillips Laboratory at Kirtland recently awarded a $6.6M contract to Hughes Missile Systems[37] for the development of a SEAD weapon technology demonstrator. This program is reported to include the definition of design goals, and the design and testing of brassboard hardware using government supplied hardware. Earlier reports[38] suggest the existence of a related program focussed on counter C3 warfare and OCA capabilities. It is expected that this program will produce a bomb warhead with a flux generator driven vircator, should this design proceed to production we can expect it to become the first operationally fielded electromagnetic bomb.

Missile Delivery

A number of missile types could be adapted to carry electromagnetic warheads. Indeed the first reported experiments involving an electromagnetic warhead were conducted using a USAF/Boeing AGM-86C Conventional Air Launched Cruise Missile (CALCM).[39]

In principle, any missile capable of carrying a 400 kg class warhead would be suitable both in terms of volumetric capacity and payload range performance. Other than the CALCM, viable candidates are the AGM-142 Raptor, a supersonic standoff missile with a range in excess of 50 NM, which is carried by USAF B-52 and soon also RAAF F/RF-111C AUP aircraft, and air and surface launched derivatives of the BGM/AGM-109C/D Tomahawk family of missiles.

Let us consider the following example, based on established technology.[40] We will assume the design of a common 21 inch (533 mm) diameter warhead for use in the AGM-142 and AGM/BGM-109 missiles. This warhead would be built into a load bearing fuselage section 64 inches (1630 mm) long, which would enable direct replacement of the unitary warhead in the AGM-142. The AGM-109 would require appropriate structural modifications to accommodate a new forward fuselage payload section, ideally identical to the proposed warhead section for the AGM-142.

To provide reasonable lethality over a useful footprint for a high value weapon, we will assume a 2-5 GW vircator, coupled by transformer to a two or three stage flux generator with an aggregate current multiplication ratio of between 100 and 400. Such a generator would need a priming source of between 10-30 kJ, which in this instance would be built with existing high energy density high voltage capacitor and battery technology. This occupies about 35 per cent of the available volume. Existing flux

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[37] 'Hughes to Build HPM SEAD Demonstrator', *Journal of Electronic Defence*, February, 1996, p 29.

[38] 'USAF Looks for HPM SEAD Solution', *Journal of Electronic Defence*, September, 1995, p 36.

[39] Fulghum, D.A., 'ALCMs Given Non Lethal Role', *Aviation Week & Space Technology*, February 22, 1993.

[40] Fowler C.M., Caird R.S. and Garn W.B., 'An Introduction to Explosive Magnetic Flux Compression Generators', *LANL Report LA-5890-MS*, Los Alamos National Laboratory, March 1975.

generator technology would provide suitable gain in the remaining volume to drive the vircator. The vircator uses a downward facing horn antenna.
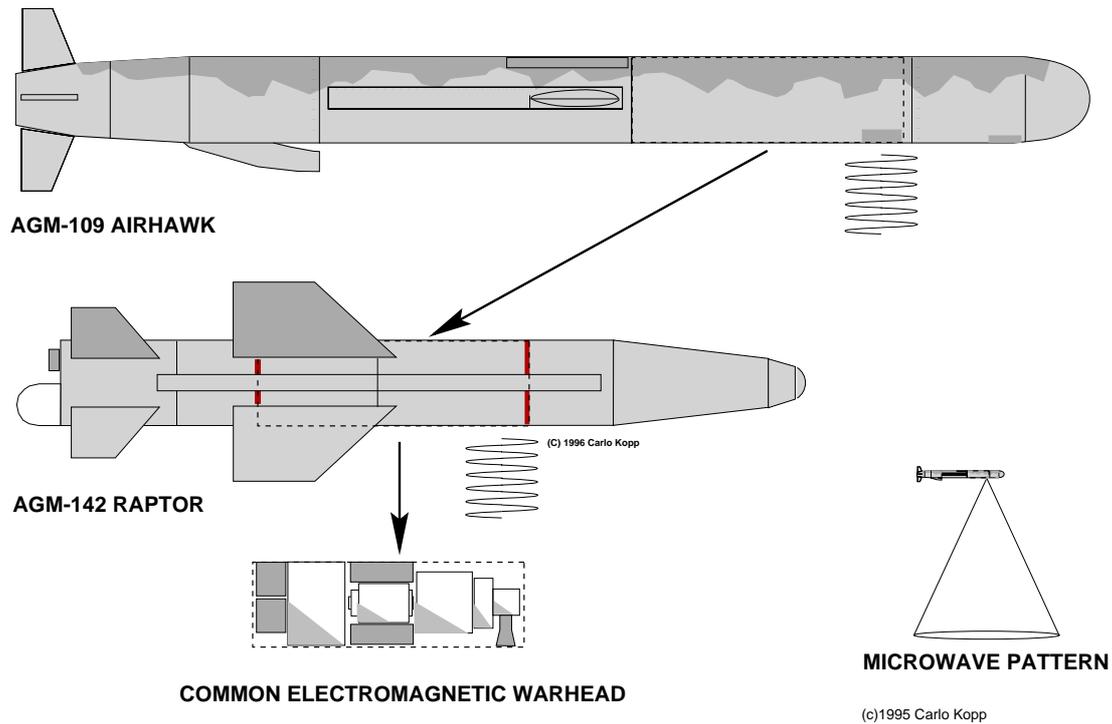

FIG.12 MISSILE WARHEAD INSTALLATION

Figure 12

The AGM-142 would not require repackaging of its internal guidance electronics in order to fit the warhead.[41] As late models of the missile have provisions for GPS navigation, the missile's video datalink and thermal imaging nose seeker would be removed, a GPS receiver fitted and the navigation software altered for pure GPS/inertial guidance. The datalink command uplink channel would be retained. Target GPS coordinates would be downloaded to the missile via its Mil-Std-1760 interface just before launch. The fusing system for the electromagnetic warhead would require a firing signal from the navigation computer. Nose ballast would be required to maintain the missile's proper centre of gravity, as the electromagnetic warhead would weigh in at less than 50 per cent of the weight of the explosive warhead.

Operationally, such a weapon would be programmed with target coordinates and then fired at the intended target. In the instance of a static prebriefed target, the missile would fly to a programmed altitude and position above the target and initiate its warhead. If the target is a naval vessel, the command uplink would be used to periodically update the missile with the current target position, while the software in the missile would use a Kalman filter[42] to predict the target's position from previous

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[41] Kopp C., 'The AGM-142 Raptor, The RAAF's New Standoff Weapon', *Australian Aviation,* Aerospace Publications, Canberra, December 1996.

[42] Kalman Filters (KF) are algorithms which are used in aircraft and cruise missile navigation system software, and Doppler radar target tracking software, to provide the best possible estimate of vehicle or

updates. Providing that updates are frequent enough, a 30kt surface warship will not escape the missile.[43]

Integration with the AGM/BGM-109 Tomahawk would be slightly more complex. The existing nose section, with the guidance and navigation systems, would need to be fitted via an adapter section to the warhead section. Standard Tomahawks use a sub-calibre penetration warhead mounted in a fuel tank. Fitting the new warhead would be done at the expense of a large proportion of the missile's fuel, thereby decreasing range by an amount of the order of 40 per cent. The missile would only be suitable for prebriefed targets.

Should much smaller yet still effective warheads be constructed, then these could be profitably applied to air to air missiles (AAM). An AAM which uses inertial and datalink guidance, such as the Amraam, could be employed to break up incoming formations, or to engage individual aircraft. Aircraft which are aerodynamically unstable are critically dependent upon their electronic flight controls. Should these be disabled the aircraft would simply become unflyable. However, in many circumstances even a mission kill caused by disabling mission avionics could be worthwhile.

Another area where electromagnetic warheads could be profitably used is in Surface to Air Missiles (SAM). Many SAMs are large enough to carry an electromagnetic warhead and these could again be used to cause mission kills, or importantly disable a penetrating aircraft's defensive EW systems, prior to a hard kill. A typical scenario would be a situation where jamming by inbound bombers prevents an effective shot with a conventionally armed SAM. A SAM with an electromagnetic warhead could be flown under datalink control and initiated close enough to the bomber (formation) to

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target position from a 'noisy' source of position measurement. Providing that an update rate is used which is faster than the rate at which the target can change its position, the estimate of the target's position can be very close to its actual position and thus a respectable CEP can be achieved. The KF is today a very mature technology, the KF algorithms in the F-111G or F-111C AUP Operational Flight Programs (OFP) would be a typical example, providing these aircraft with excellent navigational and bombing accuracy.

[43] It may be argued that a GPS/inertially guided variant of the AGM-142, using a datalink receiver for midcourse updates and a conventional explosive warhead, would be a viable and cheaper all-weather alternative to the standard optically guided version of the missile. The complex refrigerated thermal imaging seeker and wideb and video datalink are the most expensive single component of the existing design, and removing these would significantly reduce the cost per round. While unassisted GPS using absolute (WGS-84) coordinates would limit accuracy to a CEP of 12-13 metres, at least two techniques exist which could be used to provide accuracy suitable for killing hard targets. The first is the use of wide area differential GPS (Kelly D.A. et al, *Navigation and GPS Lessons Learned from the EDGE Program*, unclassified USAF paper, 1995), where differential updates are broadcast via satellite or fixed beacons, received by the launch aircraft and datalinked to the missile during flight, together with target position updates if necessary. The second technique is the use of a common satellite set and an accurate imaging Synthetic Aperture Radar, as is done with the B-2/APQ-181/GAM/GATS weapon system [see Footnote #32]. In this arrangement, target coordinates are calculated relative to the bomber's position in space and datalinked to the missile. As the missile and the bomber see almost identical GPS errors by virtue of tracking identical satellites, the principal sources of error are inaccuracies in the range and bearing calibration of the radar. The B-2/APQ-181/GAM/GATS system has demonstrated CEPs of less than 7 metres. A contemporary jam resistant GPS receiver can be as cheap as USD 5000 per unit; Kopp C., 'GPS - US Direct Attack Munition Programs', *Australian Aviation*, Aerospace Publications, Canberra, October 1996, p 52.

disrupt or disable the onboard EW equipment, thereby allowing a subsequent shot or shots with conventional SAMs.

Anti-Ship Missiles could also benefit from an electromagnetic warhead, particularly in circumstances where a sinking may not be permissible under prevailing Rules of Engagement (ROE). A surface warship which has experienced electrical hard kills against most of its critical systems will be unable to defend itself, or make a useful contribution to operations. This is a good example of what is termed a firepower kill (F-kill), rendering the target operationally ineffective.

Bomb Damage Assessment

> Bomb Damage Assessment (BDA) following strikes with electromagnetic warheads is the single most problematic aspect of using such weapons operationally, and is likely to become the single greatest impediment to the wider operational use of such munitions.

Unlike conventional explosive weapons, determining whether a soft or hard kill has been achieved with an electromagnetic warhead will be quite difficult. This is for a number of good reasons.

Emitting targets such as radars or communications equipment may continue to transmit even if their receivers, signal processors and data processing subsystems have been electrically damaged or destroyed. While under attack, the operators may shut the equipment down, and therefore the success of the attack may not be readily apparent, as there is no simple means of determining whether the inoperative system is shut down due to damage. If an ESM or ELS is tracking the emitter when the weapon is initiated, and emissions cease at exactly that time, then it is reasonable to assume that the emitter has experienced a hard kill.

Strategic targets such as telephone exchanges, satellite communications, key microwave repeater nodes, government offices, finance industry sites, broadcasting facilities and large production facilities[44] generate continuous electromagnetic emissions and if successfully attacked will cease to do so.

Determining the success of an attack upon a non-radiating and/or hidden target will be even more difficult, and it may be necessary to observe enemy actions over a period of time to determine whether the site is still operational. The availability of the UELS equipment defined above would resolve much ambiguity in such situations, as it would provide an indication of whether the equipment in the site is still operating. If the UELS is tracking emissions from the target when the weapon is initiated, and the emissions cease and do not reappear after a short period of time, then a hard kill may be assumed with reasonable confidence.

If an electromagnetic munition is used to attack an airbase or naval asset, success may become readily apparent from a rapid drop in sortie rates or activity. A critical site or asset, the use of which is required continuously, will not remain inactive unless it is

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[44] Kopp C., 'The E-bomb - A Weapon of Electrical Mass Destruction, Proceedings of InfoWarConV', *NCSA*, September, 1996. See also Schwartau W., *Infowar and Cyber-terrorism*, Second Edition, Thunders Mouth Press, 1996.

unable to operate, and thus BDA may be accomplished in such instances by observing activity levels after the attack.

Unless specific intelligence is available, the level of hardening which an opponent may have installed at any given site, or the hardness of the equipment in use may be unknown. Older Soviet Bloc equipment, built with thermionic devices, may resist very high field strengths and may require attack with explosive munitions instead.

The wide use of COTS equipment in military and civilian systems alike will nevertheless introduce a large degree of susceptibility across a wide range of target sets, therefore a combined attack with both electromagnetic and explosive munitions may be a worthwhile strategy to adopt. In this fashion, an electromagnetic munition can be used to suppress the whole site, and a conventional munition used to destroy a specific aim point such as the site radar mast or communications building.

Conclusions

The design and deployment of electromagnetic warheads for bomb and missile applications is technically feasible in the next decade. Such munitions can be profitably applied to both strategic and tactical targets, and may be delivered by a wide range of existing aircraft and missiles.

Areas which will require significant research and development effort in the near term are the packaging of electromagnetic warheads, the integration of warhead components, compact high energy priming source technology, and tools for reconnaissance and BDA using Unintended Emissions.

Providing that satisfactory solutions can be found for these problems, electromagnetic munitions for bomb and missile applications promise to be an important and robust weapon in both strategic and tactical operations, offering significantly reduced collateral damage and lower human casualties than established weapons.