Electron beam injected into ground generates subsoil x-rays that may deactivate concealed electronics used to trigger explosive devices

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ABSTRACT

Explosively formed projectiles (EFP) are a major problem in terrorism and asymmetrical warfare. EFPs are often triggered by ordinary infrared motion detectors. A potential weak link is that such electronics are not hardened to ionizing radiation and can latch-up or enter other inoperative states after exposure to a single short event of ionizing radiation. While these can often be repaired with a power restart, they also can produce shorts and permanent damage. A problem of course is that we do not want to add radiation exposure to the long list of war related hazards. Biological systems are highly sensitive to integrated dosage but show no particular sensitivity to short pulses. There may be a way to generate short pulsed subsoil radiation to deactivate concealed electronics without introducing radiation hazards to military personnel and civilian bystanders. Electron beams of 30 MeV that can be produced by portable linear accelerators (linacs) propagate >20 m in air and 10-12 cm in soil. X-radiation is produced by bremsstrahlung and occurs subsoil beneath the point of impact and is mostly forward directed. Linacs 1.5 m long can produce 66 MWatt pulses of subsoil x-radiation 1 microsecond or less in duration. Untested as yet, such a device could be mounted on a robotic vehicle that precedes a military convoy and deactivates any concealed electronics within 10 – 20 meters on either side of the road. **Keywords**: explosively formed projectiles, deactivate electronics, electron beam, subsoil x-radiation

1. EXPLOSIVELY FORMED PROJECTILES - AN EFFECTIVE ASYMMETRICAL WARFARE WEAPON

For over 50 years militaries have used shaped explosive charges to penetrate armor. In close proximity to the target, a shaped charge can produce a high-pressure shock wave with impressive ability to destroy what is directly in the path. Experimental devices have been able to penetrate several m of armor. In another configuration, the shaped charge can produce a plasma jet of a cone shaped metal used to form a liner. The jet properties depend on the charge shape, the energy released, and the liner mass and composition. The plasma can burn through the target and inject hot gases in the target compartment. This is what is used in HEAT or high explosive anti tank weapons. It was also used in the World War II bazooka and in more modern weapons such as Hellfire and TOW guided missiles.

We are concerned here with another shaped charge application – that of using the explosive force to deform and forge the liner into a large penetrating projectile with very high velocity such as mach-6 (fig. 1 – from Wikipedia). These explosively formed projectiles use kinetic energy as the destructive means rather than high temperature. The range is approximately 100 m while usual positioning is 4-15 m from the target. They are not deeply buried but can be covered lightly with soil or rubble or readily camouflaged with foam to resemble common roadside cement or cinderblocks. To produce the most damage to personnel, they are often aimed to strike a vehicle approximately 1 m high on the driver's side.

A small easily fabricated improvised explosive device of this type, perhaps made in an ordinary automobile repair shop, can produce the effect of a large gun. Such EFP devices camouflaged and hidden off roadsides have appeared in the arsenal of Iraqi insurgents accounting for over 170 US deaths and many more severe injuries according to news reports. They are placed in minutes, can be armed by operators out of range of electronic countermeasures and then fired at passing coalition military vehicles. Initiation can be by cable, radio control or self actuated by simple home-security type passive infrared motion detectors (fig. 2). They can be impervious to electronic jammers.

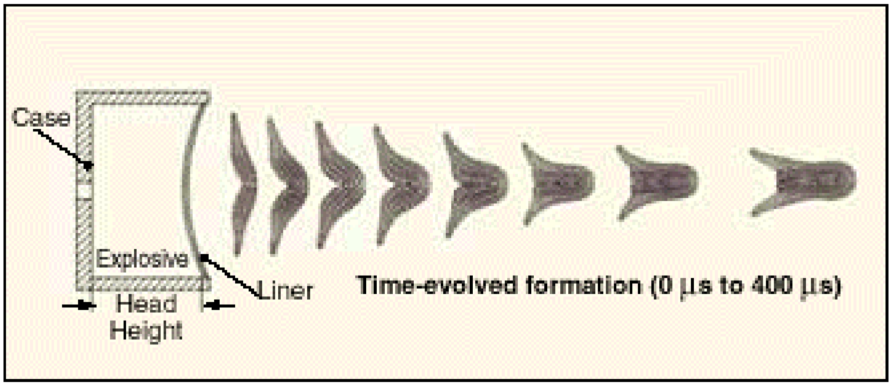

Figure 1. Formation of an EFP warhead

A typical EFP is comprised of a metallic liner (usually copper or steel), an explosive- containing case (usually steel) with one open end, an explosive section, and an initiation train. The case could be fabricated using steel pipe - easily available in an oil-producing country. Very often there is also a retaining ring to position and hold the liner-explosive subassembly in place. The device is designed so that the explosive forms the liner into a high velocity projectile.

A shaped charge, by design, focuses all of its energy on a single line, making it very accurate and controllable. When size is added to that accuracy, the effect can be dramatic. These are able to penetrate the side armor of Abrams M1A1 or A2 Main Battle Tanks, Bradley Fighting Vehicles and up-armored Humvees. Target penetration is much less than that of a plasma jet, but the hole diameter is larger with more armor backspall. Estimates of projectile temperature by incandescence color suggest a mean value of about 450°C and, since copper melts at 1083°C at atmospheric pressure, at least the surface is solid.

Explosive reactive armor, explosives sandwiched between metal plates mounted on a tank side, is effective against plasma jet devices since the heat can detonate the reactive armor. The resulting explosions partly counteract the weapon since it drives the destructive energy backwards. However EFP are not hot enough to detonate the explosive reactive armor. Also the explosions are dangerous to military and civilian personnel outside the vehicle.

EFPs are very effective weapons for insurgents and terrorists with a history that includes the IRA and Hezbollah. EFPs are not capable of destroying an army but they can disrupt, impede and demoralize even a technically and numerically superior foe. The problem addressed here is that camouflaged off-road EFPs are very effective weapons in asymmetrical warfare and are taking a high toll of US and coalition forces and there seems to be little defense available other than interdiction efforts and using extreme and cumbersome amounts of armor.

2. EFP TRIGGERING ELECTRONICS MAY BE A WEAK LINK

We want to explore if the inexpensive common electronics often used to trigger EFPs are an exploitable weak link in this simple but effective weapon system.

Radiation damage in microelectronics is related to either the total amount of radiation absorbed or the rate at which radiation is absorbed. Total radiation damage is not a good strategy for us to follow since that will very likely lead to situations producing human hazards as will be shown below. However, perhaps we can take advantage of the susceptibility of ordinary electronics to short pulses of radiation.

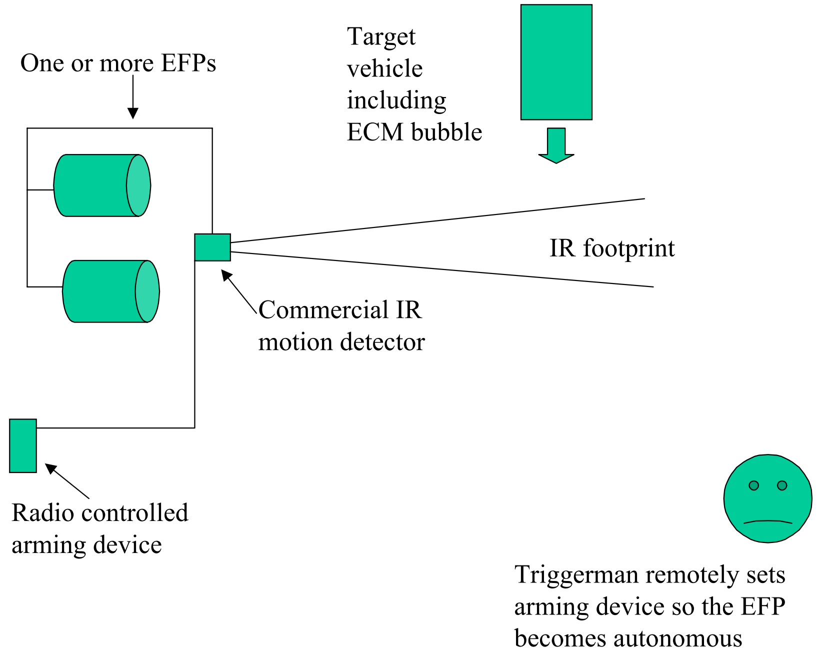

Fig. 2. Schematic layout of an explosively formed projectile after positioned by an insurgent. The triggerman sees an approaching target vehicle and arms the device with a cell phone or other wireless method while out of range of the target's electronic countermeasure (ECM) bubble. The device is then set to fire autonomously when the target vehicle enters the infrared footprint.

The primary effects of natural space radiation on spacecraft electronics have been well studied[1]. There are separate effects based on total ionizing dose and on single events or dose rate. Total ionizing dose creates bulk-oxide and an interface-trap charge that reduces transistor gain and shifts the operating properties (e.g., threshold voltage) of semiconductor devices. Total ionizing dose accumulation will cause a device to fail if first, the transistor threshold voltage shifts far enough to cause a circuit malfunction, second, the device fails to operate at the required frequency, and/or third, electrical isolation between devices is lost.

Single events occur when a cosmic ray or other high-energy particle impinges on a device. The particle generates electron-hole pairs as it passes through the semiconductor and those free carriers are collected at doping junctions. The net effect is that the circuit is perturbed and may lose data (called a single-event upset). The passage of a sufficiently energetic particle through a critical device region can even lead to permanent failure of an IC due to single-particle-event latchup, burnout, or dielectric/gate rupture. Dose rate is important since electrons and holes can safely migrate out if the rate of generation is low enough. In general, components that exhibit such effects are not acceptable for space applications unless the latchup can be detected and mitigated.

There exists a major class of effects that are related to the rate at which radiation is absorbed in circuits. These effects include upset, latchup, burnout and snap-back (a mode leading to thermal damage). All these effects are a consequence of radiation generated photocurrents in p-n junctions.

Electron-hole pairs generated in the depletion region of a p-n junction by ionizing radiation are swept out by the high electric fields present in this region. The promptly collected charge is termed the prompt photocurrent. Carriers generated within a diffusion length of the depletion region will diffuse to the depletion region where they are collected. These photocurrents sum in digital integrated circuits to produce transient currents that can cause changes in logic levels at digital gates due to charging and discharging of gate capacitances or transistors being turned on or off. If the dose rate is high enough, the product of photocurrent and resistance causes a drop in power supply voltage across the metal resistance and the power supply voltage actually present at the memory cell can drop below that value required to hold the data storage in the memory cell and an error is introduced in the memory cell. This phenomenon is called rail-span collapse.

Another important effect of high dose rates is latchup. This effect is observed when p-n-p-n four layer regions are connected to form parasitic thyristors or silicon controlled rectifiers. Photocurrents cause these devices to be switched to a high conducting state that will remain even after the radiation pulse has passed. If this low impedance path is across the power supply, the circuit will draw a large current. This high current condition will remain unless the power supply is dropped below the holding voltage of the parasitic silicon controlled rectifier. The power supply can be permanently damaged.

One method for inhibiting such parasitic silicon controlled rectifier action is gold doping of the base and the collector of the parasitic n-p-n transistor. Gold doping decreases the minority carrier lifetime of the elements of the parasitic transistor path by providing additional impurity states in the forbidden band. As the parasitic transistor gain is proportional to the minority carrier lifetime, the thus degraded parasitic transistor gain reduces the probability of it turning on to cause the system to latch up.

Generally the fabrication methods to harden circuits against ionization dosage add costs and are closely guarded secrets protected by either government or industrial classifications. Some of the components can be partly shielded from external radiation but, obviously, infrared detectors could not be shielded and still function.

3. INJECTING AN ELECTRON BEAM INTO THE GROUND TO GENERATE A SUBSOIL SOURCE OF X-RAYS

We have an idea that might allow deactivation of EFPs controlling electronics from a distance.

The plan is to direct an electron beam from a portable linear accelerator (linac) via a plasma barrier that contains the vacuum, through the atmosphere and into the ground near where EFPs could be located. A rule of thumb is that the range of electrons (in gm/cm^2) is half the energy in MeV. We expect to use electron beams of 30 MeV, that have range of approximately 120 m in air (1.2 mg/cm^3) and 12 cm in common topsoil (1.2 gm/cm^3). Transformation of electron beam energy into x-ray energy (via bremsstrahlung) is relatively efficient under these conditions. Conversion efficiency of electron beam energy to x-ray energy is k*V*Z. according to Evans[2]. According to one source, k = 1/750. It is important for these calculations to know the x-ray output with some accuracy. X-ray production efficiency at 30 MeV with a soil target (Silicon Z is 14) is 22% or over 50 fold higher compared to medical x-ray tube efficiency of 0.1 to 0.2% (15 kV to 100 kV) (Tungsten Z is 74, Molybdenum Z is 42). We are not concerned about damage to the anode that limits output of x-ray tubes. Our device would produce a bright and mostly forward directed source of x-rays in a subsurface plume to disable localized unhardened circuitry as shown in fig. 3.

The common constituent elements of soil (Si, O, N, Al, Ca, C, Na, Mg, P, K), all have exponential x-ray mass attenuation coefficients between 0.01 and 0.02 cm^{-1} at 20 MV. Using an average mass attenuation of 0.015 cm^{-1}, 1 meter of soil would attenuate 22% of 20 MeV x-rays. Considering the Megawatts of x-rays expected (see below), there should be ample x-ray intensity so that one short pulse can damage or deactivate any unhardened electronics within several meters.

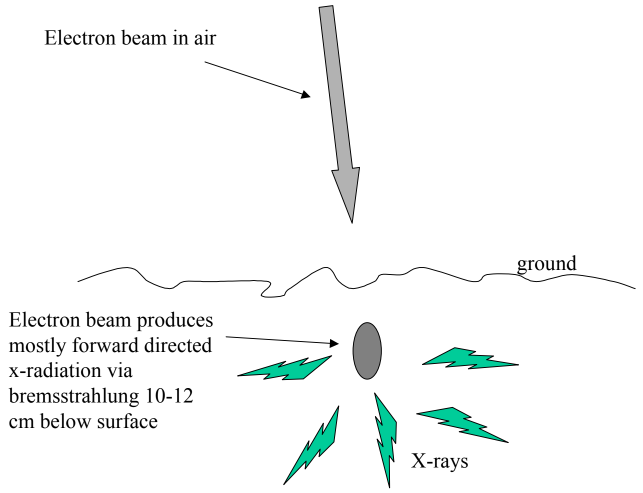

Fig. 3. An electron beam at 30 MeV energy is produced by a linear accelerator. The current is pulsed on for 1 microsecond per second at a current of 10 amps. The beam exits the linear accelerator through a plasma gate that permits electron passage but retains the vacuum inside. The beam is directed into the ground where the energy is converted to x-radiation by bremsstrahlung in a plume approximately 10-12 cm below the point of impact. This radiation is mostly forward directed and will penetrate soil with approximately 22% attenuation per meter of travel. The radiation is intended to deactivate any buried electronics that fire explosively formed projectiles.

By using high peak x-ray intensity with low repetition rate we should be able to maximize damage to nearby electronics and, as discussed in the next section, minimize biohazards to operators and bystanders.

According to Dr. J Potter of JP Accelerator Works[3], it is possible to produce 10 amp short pulses (one microsecond or shorter – perhaps as low as one nanosecond) of electrons at 30 MeV using a 1.5 m linear accelerator (linac) driven by a klystron. Considering the 22% efficiency of x-ray production at that energy, this will produce 66 Mwatts of x-ray energy. A duty cycle of 0.0001% would require approximately 300 W. Such a device could be used to sweep the off-road terrain in front of the lead vehicle on both sides of the road before a convoy enters the area. Conceivably all non-hardened electronics including the infrared detector within perhaps 10 - 20 m of the road on either side could be rendered inoperative.

As a countermeasure, insurgents could shield their electronics but it is doubtful that this would be very effective since the transient radiation field is so high. Even if they attenuate the radiation by several orders of magnitude it would probably not be enough to prevent damage but this needs to be investigated.

4. POSSIBLE RADIATION HAZARD

Integrated x-ray intensity over some reasonable time can result in birth defects, damage to tissue and organs, and future risk of disease including cancer. To place the radiation hazard in some perspective, let's compare integrated x-ray energy over time for the electron beam device and a medical x-ray. Medical x-ray is roughly a few watts for 1/2 second or so. We plan to use shorter pulses but for argument's sake let's consider 66 Megawatts for 1 microsecond per second. Let's assume the energy is 95% contained below ground. Using these numbers over the one second period of interest, the integrated x-ray energy above ground is roughly equivalent to a medical x-ray. This does not consider that the energies used in medical x-rays are chosen for their high cross-section to biologically relevant structures and resulting ability to provide medically useful imaging contrast. So for someone standing in the wrong place, the biological impact of the x-ray pulse we are considering is probably less than a medical image. It may prove optimal to operate at lower duty cycles. If we operate with 0.01 microsecond pulses, we would be 2 orders of magnitude below the integrated radiation from a medical image.

While there is well known risk of disease from integrated exposure to radiation (anchored at the low end by atom bomb survivor data), what can be said about the radiation hazard from a very short pulse of radiation? Is there any effect similar to what we have discussed for unhardened electronics? It seems there is little to be found in the medical literature. However, from the field of radiation oncology, there is some information that may be relevant. After a person is diagnosed with breast cancer, the tumor is surgically removed using either mastectomy (which takes the entire breast) or by lumpectomy (which involves just cutting out the tumor with a cm or so of healthy tissue as margin). In the lumpectomy case, there is a small chance that cancer will reappear in the remaining breast tissue. That is called local relapse and can be very serious. It has been determined that after lumpectomy, exposing the remaining breast tissue to x-radiation will significantly reduce the chance of local relapse. If the tumor is on the left breast, care is taken so that the heart is not exposed to radiation since that will cause coronary problems later. Thus the level of radiation used is sufficient to cause tissue and organ damage. Radiation oncologists have determined that the radiation after lumpectomy is better given in fractions over several weeks rather than all in one setting. They can give the same total exposure with less damage to healthy tissue by dividing the radiation into fractions. These results are based on studies involving thousands of patients. So, at least in this oncology case, pulsed radiation damage to healthy tissue seems opposite to pulsed radiation damage to electronics. The biologic injury increases with total integrated exposure of course but the damage is not increased and may even be decreased if the same total radiation is given as a series of shorter intermittent exposures. This information suggests that we might have some latitude to use short pulses of radiation to deactivate electronics in an environment where personnel might get some exposure. However, far more investigation is needed if we are to pursue this subject. We definitely need to insure that any integrated radiation dose is well below what is received in a medical imaging study.

Unless a bystander has a pacemaker or other such electronics, there seems to be no equivalent damage mode like latchup or rail-span collapse for radiation dose rate in a biological system. In asymmetrical warfare in developing countries it is unlikely that pacemakers are a problem but this will have to be considered.

The biology governing radiation damage to tissue and the physics governing radiation damage to electronics seem to favor the use of short pulsed radiation for our application. As a general statement, using pulsed radiation to disable EFP electronics should be pursued while carefully considering safety for innocent bystanders and equipment operators.

5. FURTHER AREAS OF INVESTIGATION

There is much to learn before we can design and build a practical system that meets useful requirements. Answers to specific questions are needed before we could say with any confidence that a workable device could be designed, built and safely operated. These are listed below as separate topics:

5.1 Need more information about EFPs

a. We need to know more about EFP design, positioning, depth of placement, size, material, method of activating and firing, and possible distance from target.
b. Insurgents are innovative – what can they do for countermeasures against our device?
c. Need more information about EFP electronics. What about memory or stored software?
d. How long does it take to put an EFP in place?
e. Can they shield electronics against electron beam and x-rays? High Z material is more efficient for production of x-rays so that may partially offset the extra x-ray attenuation.
f. Aiming of EFP needs to be within 1 m. How is device aimed? Optically by lining up target with two aiming points on device? Or is it even cruder than that? EFP devices used in our military are aligned on a tripod with accurate optical sighting means.
g. How accurate is trajectory? It is difficult to imagine that accuracy is within 1 m at 100 m distance. Information that device is placed 4m to 15m distant from target is believable. If EFP is 100 m off road, it is doubtful that we would be successful. If the EFP is < 20 meters off road, we could be successful.

5.2 Need more information on x-rays production by bremsstrahlung

What is the size of the x-ray plume? This is very likely not a problem but we need to make certain that the electron beam does not spread excessively in air on the path to the target.

5.3 Need to learn about x-ray damage to circuitry

What peak and average x-ray intensity is needed or optimal to damage circuitry? In particular, is 1 microsecond per second of relatively intense radiation optimal for deactivation? How low can we go? Are common electronics used in EFPs of the type that can be readily damageable with pulsed x-radiation? Can insurgents get hardened electronics or is that a controlled technology?

5.4 What are possibilities and limitations of linear accelerators?

What can be done with a portable linac, i.e., electron beam energy, current, peak and duty cycle, size, power requirements, klystron driver, power supply motor and electrical generator? According to J Potter, high peak current at low duty cycle is a favorable configuration. It is simple to turn on the RF and then pulse the electron gun. Pulses as low as 1 nanosecond per second may be possible. Peak currents as high as 100 amps are possible.

5.5 Need to investigate electron beam exit window. Plasma window or thin membrane?

Plasma window could be the best method. Look at Hershcovitch plasma device reported by NASA[4]. Acceleron, Inc of East Granby, CT is a licensee of the plasma window technology. Reportedly they can do electron beam welding in atmosphere.

5.6 What is best positioning of linac?

Should we mount the linac on a Humvee or do we need a helicopter? Since the range of the electron beam in air is about 100 m, a linac could be suspended below a helicopter at 10-20 m above the ground. Can it ride ahead of a convoy, say in a Humvee (manned or robot)? Do we need to clear a road just before convoy arrives?

5.7 Will there be any radiation hazards to bystanders or equipment operators?

This is a critical topic. We can't operate in a mode that can cause health problems to innocent bystanders or equipment operators. We also need to consider transmutation. Stable Ni to radioactive Fe for example. Also, while the electron beam is losing energy in the atmosphere, does it emit hazardous radiation that we should be concerned about or is the energy safely dispersed as thermal? Will we need to commission a lab study of mice for example to test for particular radiation hazard to very short x-ray pulses? We also need to consider that birth defects can result from radiation.

5.8 Need to have system easy to operate by a person with ordinary PC skills.

5.9 Will device cost be acceptable?

We need to know what costs are acceptable for such a device and whether we can build this device at that cost. Depending on cost, it may itself become a target.

6. CONCLUSIONS

By taking advantage of the known susceptibility for damage of unhardened electronics to single ionization events and biological hazard apparently that is only related to integrated radiation, a possible safe method of deactivating EFP devices has been identified (patent pending). The theory and basic concepts are feasible and seem reasonable but at this time we do not know if it is realistic and practical. Many questions that are listed above remain to be addressed. Primarily, we need to determine if the electron beam generated x-rays will be energetic enough to reliably damage EFP electronics a reasonable distance away and yet not be hazardous to operators or bystanders. To our advantage, there seems to be significant design latitude available to us by using very short radiation pulses. It is recommended that this project move forward.

We are not suggesting that this is a complete solution to the EFP problem. Some of these devices are mechanically operated or are controlled by cables so this technology would not play a role.

While we direct this idea to address the EFP problem, it could also apply to other weapons that are controlled by electronics that are not radiation hardened. Asymmetrical warfare is the new reality and is the result of the uncontested conventional strength of the US military. With the availability of electronics and high explosives and the easy access to the internet to disseminate weapon-making skills, we are more than likely to see EFP type devices in future conflicts. Effective countermeasures are highly needed.

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