

Basic Physics of EMP, Beam Weapons, and ABM

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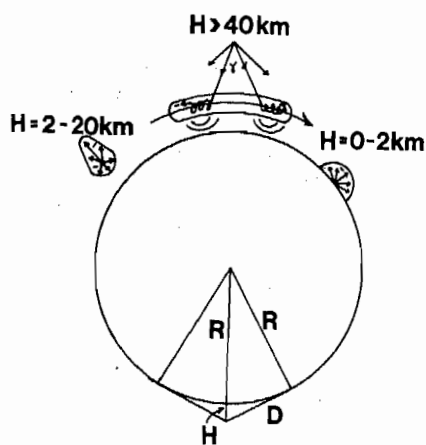
I: ELECTROMAGNETIC PULSE (EMP)

The command, control, communication, and intelligence (C³I) systems which control the US strategic forces can be vulnerable to the large electromagnetic pulses¹ ($E = 25,000$ volts/meter) that are created by high altitude (100 to 500 km) or low altitude (0 to 2 km) bursts of nuclear weapons. This vulnerability has been perceived as creating a possible instability in the arms race. If a country perceives that the use of its strategic forces could be negated by the EMP so that it could not command and control its missiles, this country might be tempted to adopt a "launch on warning" policy so that it would use its weapons rather than lose them to a preemptive first strike. The situation is not as unstable as I have characterized it because both nations have hardened their systems to partially withstand the EMP and both nations have viable, second-strike missiles based on submarines that are not vulnerable to a first strike. However, the perception of vulnerability in the land-based leg of the strategic triad (land/sea/air) can create pressures for a "now, or never", launch-on-warning response. Since some of the C³I facilities, such as the Air Force's Looking Glass command post in the sky, are more vulnerable than some of the strategic forces that they are intended to direct, and since the U.S. land-based missiles could be vulnerable to an EMP attack, it is clear that the EMP can affect military policy.

A brief discussion of the mechanism that creates the EMP is given below: In an explosion of a nuclear weapon, many of the fission fragments are created in an excited state. Since these excited states have energies of 1 MeV or more, their lifetimes are much less than the risetime of the explosion (about 10 nanoseconds); the de-excitation gamma rays are emitted promptly. These prompt gamma rays interact with air molecules and create forward scattered Compton electrons which constitute an energetic (about 1 MeV), negative current flowing radially outward from the weapon (Fig. 1). In order to have a large EMP, it is necessary to remove the spherical symmetry around the nuclear weapon. At low altitudes above the earth, a net dipole moment is created because

the Compton electrons are in the form of a hemisphere rising above the earth; the asymmetry of the rising, charged hemisphere creates the EMP. At high altitudes, the symmetry is broken because the air density varies exponentially with height above the earth so that the Compton electrons are created asymmetrically and a net dipole moment is created. The electrons created from the very high altitude bursts (above the atmosphere) follow a helical path about the earth's magnetic field lines in the very thin upper atmosphere; the centripetal acceleration of these Compton electrons creates the EMP. In addition, the x-rays following a nuclear explosion can also produce EMP effects by ionizing the atmosphere and momentarily affecting the magnetic field configuration of the Earth.

Figure 1. Electromagnetic Pulse (EMP). During a nuclear explosion gamma rays are emitted promptly from the excited states of the fission fragments; these prompt gamma rays transfer their energy to electrons in air molecules by the Compton scattering process. The EMP is generated by these relativistic electrons by several mechanisms which depend on the altitude (H) of the nuclear explosion above the earth. A surface blast at low altitudes (H = 0-2 km) causes a hemispherical, rising Compton current which creates a large net vertical dipole current. An air burst (H = 2-20 km) creates a small net vertical dipole moment because the asymmetrical



density of air which varies exponentially with height. A high altitude (H > 40 km) explosion creates Compton electrons that revolve in circles around the earth's magnetic field lines; the centripetal acceleration of the Compton electrons produces EMP radiation. Because the Compton electrons are relativistic, the EMP radiation from the individual electrons have a partial degree of coherence which can give very large E fields of greater than 25,000 V/m. The high-altitude EMP pulse can illuminate wide areas of the earth's surface; the range of the EMP is determined by its line-of-sight distance, $D = (2RH)^{1/2}$ where R is the radius of the Earth.

1.A. The Range of EMP. Assume that sufficient megatonnage is available for the EMP pulse, and that one must only consider line-of-sight geometry when considering covering the US with the EMP pulse. The height (H) of the blast that is necessary to cover 50% and 100% of the US is determined as follows: The extremum distance (D) from the nuclear detonation to the ground is obtained (Fig. 1) from a right triangle which has one side as the distance D, the other side the radius (R) of the earth at the location in question, and the hypotenuse extends from the center of the earth to the blast (H + R). It follows that

$$R^2 + D^2 = (H + R)^2 \cong R^2 + 2HR$$

when $H \ll R$. From this we obtain the height of the EMP blast to cover all the US

$$H = D^2/2R = (2500 \text{ km})^2/(2)(6400 \text{ km}) \cong 500 \text{ km}$$

For the case of 50% of the US, $D = 1800 \text{ km}$ and $H = 250 \text{ km}$.

1.B. The Strength of the EMP Fields. The approximate average (rms) E field generated by the EMP pulse at a location $D = 1000 \text{ km}$ from the blast is determined by assuming the following: (1) A one megaton weapon contains 10^{15} calories or $4.2 \times 10^{15} \text{ J}$; (2) The prompt gamma rays constitute 0.3% of the total energy; they have an average energy of about 1 MeV; and they are emitted over the 10 ns risetime of the blast; and (3) About 0.6% of the total prompt gamma ray energy is converted into forward-scattered Compton electrons near $\theta = 0$. (If each of the fission fragments emitted a 1 MeV gamma ray, and if 50% of these gamma rays were not absorbed by the materials of the weapon, then about 0.5% (1 MeV/200 MeV) of the energy of the weapon would be in the form of prompt gamma rays.) The amount of energy available for the EMP pulse from the 1 megaton weapons is about

$$U_{EMP} = (4.2 \times 10^{15} \text{ J})(0.003)(0.006) = 7.6 \times 10^{10} \text{ J}$$

This energy can be considered to approximately evenly distributed in a spherical shell with a volume $(4\pi D^2)(T)$ where D is the distance from the site to the blast. The thickness, T, of the EMP shell is the product of the speed of light and the time duration of the blast, or $T = (3 \times 10^8 \text{ m/s})(10^{-8} \text{ s}) = 3 \text{ meters}$. Since 50% of the stored energy resides in the electric fields, we obtain

$$U_{EMP}/2 = (\epsilon_0 E^2/2)(4\pi D^2 T), \text{ or}$$

$$E = (U_{EMP}/4\pi\epsilon_0 T)^{1/2} / D = (7.6 \times 10^{10} \times 9 \times 10^9 / 3)^{1/2}$$

$$/(10^6) = 15000 \text{ volts/meter.}$$

A more sophisticated calculation of the E field is carried out in I.C below, but this approximate estimate is sufficient to show that the E field can be quite large. The energy/cm² deposited on the semiconducting components used in C³I is of the order of

$$(7.6 \times 10^{10} \text{ J}) / (4\pi)(10^8 \text{ cm})^2 = 6 \times 10^{-7} \text{ J/cm}^2.$$

This flux of energy can be effectively multiplied by the area of powerlines, antennae or missile bodies, and the resulting electrical transients can be sufficient to destroy many of the semiconducting devices.

I.C Frequency Spectrum. A fundamental calculation of the frequency and field strength distributions from a high altitude burst involves a calculation of the magnitude of the Compton electronic charge and how this charge accelerates in the earth's magnetic field. In order to do this we must consider the relativistic expression for the radiative power,

$$P = e^2 a^2 \gamma^4 / 6\pi \epsilon_0 c,$$

from an accelerated charge where a is the acceleration and $\gamma = 1/(1 - v^2/c^2)^{1/2}$. Using this relationship, the approximate magnitude of the E field from a high altitude, 1 megaton explosion, and the maximum frequency of the EMP spectrum are determined as follows: Because the duration of the explosion is about 10^{-8} s, the maximum frequency possible for the EMP is about 100 MHz, but in practice it is considerably lower. Since the Compton electrons have a kinetic energy of about 1 MeV = $2 m_0 c^2$; $\gamma=3$ and $v/c = 0.94$. The radius of gyration (r) of the Compton electrons in the earth's field of 0.6 Gauss is

$$r = \gamma m_0 v / eB = (3)(9.1 \times 10^{-31} \text{ kg})(0.94)(3 \times 10^8 \text{ m/s}) / (1.6 \times 10^{-19} \text{ C})(0.6 \times 10^{-4} \text{ T}) = 80 \text{ m}.$$

The frequency of radiation associated with this motion is $= v/r = (0.94)(3 \times 10^8 \text{ m/s}) / (80 \text{ m}) = 3.5 \text{ Mrad/s}$, or $f = \omega / 2\pi = 0.56 \text{ MHz}$.

The approximate number of prompt gamma rays emitted from the 1 megaton explosion is

$$N_T = (4.2 \times 10^{15} \text{ J})(0.003)(1 \text{ MeV} / 1.6 \times 10^{-13} \text{ J}) / (1 \text{ MeV}/\Gamma) = 7.9 \times 10^{25} \Gamma/\text{Mton}.$$

Since about 0.6% of this energy is converted to Compton

electrons, the approximate initial number of Compton electrons produced is $N_e = (0.006)(7.9 \times 10^{25}) = 4.7 \times 10^{23}$ electrons/Mton, or 75,000 coulombs/Mton. The initial centripetal acceleration for each Compton electron is about

$$a = r\omega^2 = (80 \text{ m})(3.5 \times 10^6/\text{s})^2 = 1.0 \times 10^{15} \text{ m/s}^2.$$

The initial power radiated by this electron is

$$P = e^2 a^2 \gamma^4 / 6\pi\epsilon_0 c^3 = (1.6 \times 10^{-19} \text{ C})^2 (1.0 \times 10^{15} \text{ m/s}^2)^2 \times (3^4)(6 \times 10^9)/(3 \times 10^8)^3 = 4.6 \times 10^{-22} \text{ Watts}.$$

If the E fields from the $N = 4.7 \times 10^{23}$ Compton electrons added incoherently, the EMP radiated power would be only about $(4.7 \times 10^{23})(4.6 \times 10^{-22} \text{ W}) = 220 \text{ W}$ which would not produce a very large E field. However, since the wavelength of this radiation, $\lambda = c/f = 540 \text{ m}$, is much longer than the spatial thickness of the prompt radiation, $T = c/(10 \text{ ns}) = 3 \text{ m}$, and since the velocity of the Compton electrons is approximately c , the EMP electric fields are partially additive, or coherent. Let us initially assume that all N_e electrons give coherent EMP radiation; a comparison of the field from this completely coherent situation can then be compared to the given value of about 25,000 V/m to determine the degree of coherence.

If the Compton electrons radiated coherently, the effective radiative power would be $(N_e)P = 1.0 \times 10^{26} \text{ W}$ which is similar to the power of the sun! The average value of the Poynting vector for this radiation (neglecting the $\sin^2(\theta)$ distribution) is $P/4\pi D^2$ where D is the distance from the closest Compton electrons to the site (perhaps an average effective value of 100 km). From this the average E field is given by

$$E \cong (P/4\pi\epsilon_0 c D^2)^{1/2} = ((1.0 \times 10^{26} \text{ W})(9 \times 10^9)/(3 \times 10^8 \text{ m/s})(10^{10} \text{ m}^2))^{1/2} = 5.5 \times 10^8 \text{ V/m}.$$

Since this result is about 10^4 times larger than the reported value of $2.5 \times 10^4 \text{ V/m}$, we see that, on average, only about 0.01% of the forward-scattered Compton electrons must be totally coherent. As the Compton electrons lose energy, lower frequency, longer wavelength components are added to the EMP distribution, and the radiation becomes less coherent.

Rather large currents can be generated by the EMP. The voltage developed along the length of a 20 m missile could be as much as $V = (25,000 \text{ V/m})(20 \text{ m}) = 500,000 \text{ V}$. Since the inductive impedance of a missile at 1 MHz is about $Z = 10 \text{ ohms}$, the current flowing along the surface

of the missile could be as high as

$$I = V/Z = (5 \times 10^5 \text{ V})/(10 \text{ ohms}) = 50,000 \text{ Amperes.}$$

By coupling through various inductive and capacitive transfer impedances, this current can produce voltage transients on the center conductors of the cables in the missile on the order of 1 to 100 volts. While this amount of voltage will only burn out the most sensitive semiconductors, it could upset the digital circuitry and nullify its computer logic. Much larger voltages could be developed on these logic elements if one considers the voltages developed on the powerlines to the missile sites, but it is possible to overcome these difficulties by shielding and hardening the electronics with filter circuits and fiber optics.

II: PARTICLE AND LASER-BEAM WEAPONS

The superpowers are currently developing weapons that would utilize the kinetic energy (in the GeV range) of particle beams or the energy content of laser beams to destroy incoming missiles, surface cruise missiles, ships, or satellites. The particle-beam and laser-beam weapons might be mounted on the surface of the earth, in the space shuttle, or on satellite stations in space. These weapons have to be described as futuristic since there are many technological obstacles that must be overcome before they would become operational. In addition, these weapons would be vulnerable to countermeasures by the attacking force. These weapon systems have been described³ in some detail by K. Tsipis, et al, and we will discuss only their more general² properties.

II.A. Energy Deposition. The flux of energy (J/cm^2) that would preignite the chemical explosives around a nuclear weapon in the incoming missile can be estimated. Following Tsipis, et al, assume that a temperature rise of 500°C can preignite the explosive material which has a density of $\rho = 0.8 \text{ g}/\text{cm}^3$ and a molecular weight of about $M = 50$. In addition, assume that the absorption length for 1 GeV electrons is about 10 cm; the beam loses about 10% of its energy in 1 cm. The energy density needed to predetonate the chemical explosive is $Q = Cp\Delta T/M$ where ΔT is the temperature rise and the specific heat $C = 3R = 25 \text{ J}/\text{mole}\cdot^\circ\text{C}$ (since $T > \theta_D$, the Debye temperature). We obtain

$$Q = (3R)\rho\Delta T/M = (25)(0.8)(500)/50 = 200 \text{ J}/\text{cm}^3.$$

Since about 10% of the energy is deposited in 1 cm, the

energy intensity of the beam must be about 2000 J/cm^2 in order to deposit 200 J/cm^3 in the chemical explosive. This same flux of energy would raise the temperature, ΔT , of the aluminum missile:

$$Q = 200 \text{ J/cm}^3 = (3R)\rho \Delta T/M = (25)(2.7)(\Delta T)/27 ,$$

which gives $T = 80^\circ\text{C}$. This modest temperature rise would begin to cause some internal stresses and misalignment in the missile. Doses about 8 times larger ($16,000 \text{ J/cm}^2$ and 1500 J/cm^3) would raise aluminum to its melting temperature of 660°C . In addition, the particles can cause havoc with the semiconducting components in the guidance systems; energy densities as low 25 J/cm^3 can cause shifts in the switching thresholds of the circuit elements and 1000 J/cm^3 can destroy the elements. The energetic particles would create centers for trapping, and recombination which would reduce the lifetime of the minority carriers.

11.B. Beam Current and Angular Resolution. What minimum beam current of 1 GEV electrons would be necessary to preignite the chemical explosive in the incoming missile? Assume that the size of the beam is dictated by the 1 meter diameter of the missile booster and that the pulse duration is determined by the velocity of the missile, $v = 10^4 \text{ m/s}$. What angular accuracy ($\Delta\theta$) would be required to disable a missile which is 1000 km away and above the atmosphere?

Using the energy intensity of 2000 J/cm^2 (Sec. 11.A), the energy delivered to an area of 1 m^2 (dictated by the diameter of the missile) is $(2000 \text{ J/cm}^2)(10^4 \text{ cm}^2) = 2 \times 10^7 \text{ J}$. In order to keep the area of the beam on the missile for a single shot (without continuous tracking), the time duration of the pulse must be less than $t = (1 \text{ m}/10^4 \text{ m/s}) = 0.1 \text{ msec}$. The energy in the pulse is $VIt = 2 \times 10^7 \text{ J}$ where $V = 10^9 \text{ volts}$ and I is the current in amperes. Solving for I , we get

$$I = (2 \times 10^7)/Vt = (2 \times 10^7)/(10^9)(10^{-4}) = 200 \text{ A}.$$

If the beam was intended to melt aluminum or destroy semiconducting components, the current and energy of the beam must be at least five times higher, or 1000 amperes and 10^8 J . It has been estimated that the efficiency of producing a pulse of particles is about $1/6$, thus it takes about $6 \times 10^8 \text{ J}$ to make the 1000 ampere pulse. Since it takes about 0.9 pound of coal to generate a kwh = $3.6 \times 10^6 \text{ J}$, it would take about 150 pounds of coal (or 1000 pounds of TNT) to generate one pulse; the large amount of any type of fuel would certainly complicate the logistics of placing either particle- or laser-beam weapons on a space station. For comparison sake, there

are already existing high-voltage, low-current accelerators, such as the Fermilab's proton accelerator which has a current of 0.1 milliamperes at an energy of 500 GeV, and there are low-voltage, high-current electron accelerators used in the fusion program which have a current of 10^6 amperes (per beam) at an energy of 2 MeV. Because the earth's magnetic field will deflect long-range, charged particle beams, a beam of neutral hydrogen atoms (produced from H^- beams passing through a stripper gas) might be considered. The present technology is not yet capable of these requirements as the Los Alamos Meson Factory is capable of developing currents of only 0.15 amperes of H^- ions at 1 GeV.

In order to "shoot a bullet 1000 km away with a bullet", the beam must be aligned to within an accuracy of $\Delta\theta = 1 \text{ m}/10^6 \text{ m} = 10^{-6}$ radians. Since this kind of accuracy would be difficult to carry out, it is likely that the beam current would have to be correspondingly increased to compensate for a larger spread in the beam size at the target. If $\Delta\theta \approx 10^{-5}$, the current and total energy of the beam would have to be increased by a factor of 100; if the target was considerably closer, this would not be necessary.

11.C. Burning a Hole in the Atmosphere. Since relativistic electrons and protons of about 1 GeV lose about 0.2 GeV/km when they pass through air, they would not be able to penetrate through the entire atmosphere. Particle beam weapons that were located on the surface of the earth would have to be able to "burn a hole in the atmosphere" in order to reduce energy losses and make the weapon viable over longer distances. If the air density in the "hole" in the atmosphere was reduced by a factor of ten, then the energy loss rate would be reduced to 0.02 GeV/km, and the beam would then lose about 0.2 GeV (20% of the beam energy) to pass through the entire atmosphere of 10 km. Approximately how much energy would it take to reduce the density of the air by a factor of ten in a "hole" that had an area of 1 cm^2 and was 1 km long? The density of air is 1.3 kg/m^3 and its specific heat at constant pressure is $1000 \text{ J/kg}^\circ\text{C}$.

Using the perfect gas law, $PV = nRT$, we see that the temperature must be raised from about 300 K to 3000 K in order to allow a reduction in the density, n/V , by a factor of 10. The mass of the heated air in the atmospheric hole is $(1.3 \text{ kg/m}^3)(10^3 \text{ m})(10^{-4} \text{ m}^2) = 0.13 \text{ kg}$. The amount of energy required to heat the "hole" is

$$Q = mC\Delta T = (0.13)(1000)(2700) = 3.5 \times 10^5 \text{ J}.$$

Additional energy would be lost by the partial heating of the air forced out of the hole, by the loss of scattered radiation and secondary particles, and by turbulence.

Our value of 0.4×10^6 J/km is a lower bound value and it is about 25% of the more accurately calculated³ value of 1.5×10^6 J/km. This energy loss is about 1%/km of the beam's energy of 10^8 J; a 10 km path would use 10% of the beam's energy; this is similar to the energy that would be lost by the beam as it passed through the hole. At this time it is unclear how long the high energy beam would remain in the hole over these extended distances.

11.D. Laser Beam Weapons. Either a 25 kJ pulsed laser or a 1 MW continuous laser is capable of destroying nearby aircraft. However, since laser beams do not readily pass through fog or rain, the laser-beam weapons could not be counted on to defend against a surprise attack on a rainy day. For this reason, the laser-beam weapons (if they are ever deployed) would probably be used above the atmosphere. Let us determine the necessary energy for a laser pulse to destroy a missile 1000 km away using these assumptions: (1) It takes a pulse of about 1000 J/cm² (Sec. 11.A) to create an impulsive failure in thin metal targets such as missiles; (2) The HF chemical laser has a wavelength $\lambda = 2.7 \mu\text{m}$; and (3) The beam extraction mirror of the laser has a diameter $d = 4$ meters. The finite diameter of the extraction mirror causes a diffraction broadening in the laser beam

$$\Delta\theta = 1.22\lambda/d = (1.22)(2.7 \times 10^{-6} \text{ m})/4 \text{ m} = 0.8 \times 10^{-6}.$$

This effect will broaden the radius of the laser beam 1000 km away to

$$r = (\Delta\theta)(1000 \text{ km}) = 0.8 \text{ m}.$$

Since it takes about 1000 J/cm² of absorbed energy to partially melt and crack the missile body, the energy in the laser pulse must be $(1000 \text{ J/cm}^2)(\pi)(82 \text{ cm})^2 = 2 \times 10^7$ J for the case of total absorption by the missile body; if the missile reflects 90% of the energy, ten times as much energy will be needed, or 2×10^8 J. This energy requirement is considerably larger than the presently contemplated 25 kJ pulsed CO₂ lasers ($\lambda = 10.6 \mu\text{m}$) being developed for the fusion program. If the weapon was a 1 MW continuous laser, then the laser would have to be focused on the target for $t = (2 \times 10^8 \text{ J})/(10^6 \text{ J/s}) = 200$ seconds = 3 minutes. The energy content of the H and F fuels is about 1.4×10^6 J/kg; if the laser had an efficiency of 10%, it would take about

$$(2 \times 10^9 \text{ J})/(1.4 \times 10^6 \text{ J/kg}) = 1400 \text{ kg}$$

of fuel for one pulse from the HF laser. Thus, lasers in the visible region ($\lambda = 0.5 \mu = \lambda_{\text{HF}}/6$) are being studied.

III. ABM SYSTEMS

There are a variety of systems, other than particle and laser beams weapons (Sec. II), that are being considered⁴ to destroy incoming missiles. In this section we will briefly consider the basic physics of (III.A) the Low Altitude Defense System (LoADS), (III.B) the high altitude Spartan ABM (1969), and (III.C) simple and novel systems. This appendix will not discuss the broader political, legal, and strategic aspects of the ABM. (See the chapter by A. Carnesale in this book).

III.A. Low Altitude Defense System (LoADS). This system is similar to the Sprint system that was considered in 1969, but it is intended to operate at lower altitudes, below about 50,000 feet. As in the case of Sprint, the fast neutrons from a 20 kiloton (kt) explosion are used to destroy the solid-state electronics and to disarm the nuclear warhead by the absorption of neutrons in the fissile material of the incoming warhead. Since 1 kt (4.2×10^{12} J) is the equivalent of the total fission of about 55 grams of fissile material (0.23 gram moles), the number of neutrons escaping from a 20 kt fission warhead is about

$$(20 \text{ kt})(0.23 \text{ g moles})(6 \times 10^{23})(3 - 2) = 3 \times 10^{24} \text{ n.}$$

In this simple calculation, we have assumed that one neutron/fission ($3 - 2$) escapes from the warhead. The number of neutrons/cm² at a distance of 400 meters is about

$$(3 \times 10^{24}) / (4\pi)(4 \times 10^4)^2 = 1.5 \times 10^{14} \text{ n/cm}^2.$$

This neutron flux at 400 m is similar to value of 2×10^{14} presented in Glasstone and Dolan⁵ and it is capable of disarming a nuclear warhead under certain conditions.

III.B SPARTAN. The SPARTAN ABM was intended (in 1969) to intercept incoming missiles high above the earth. Since the explosion would take place above the atmosphere in a vacuum, the energy going into the shock and blast mode would be essentially zero, and the fraction of the energy delivered as thermal radiation would be enhanced. This system is no longer being considered because the very high altitude burst would develop an EMP pulse (Sec. I) which could disarm our own C³I systems. Nevertheless, for historical reasons it is of interest to discuss briefly this system.

If one assumes that the average temperature of the exploding warhead is similar to the core of the sun (18×10^6 K), the most probable photon energy can be obtained from Wien's law, and it is about 7 keV, or in the soft

x-ray region. If one assumes that the SPARTAN uses a 2 Mt warhead ($2000 \times 4.2 \times 10^{12}$ J), and that 75% of its energy goes into thermal radiation, the heat flux at a distance of one km is about

$$(0.75)(8.4 \times 10^{15} \text{ J}) / (4\pi)(10^5 \text{ cm})^2 = 5000 \text{ J/cm}^2.$$

The 7 keV x-rays penetrate about 0.004 cm in aluminum and would cause severe heating at this flux of energy (Sec. II.A).

III.C Simple and Novel ABM Systems. This section will briefly discuss two systems, Swarmjet and Dust Defense which rely on the kinetic energy of impact to destroy an incoming re-entry vehicle (RV). A Swarmjet ABM system would work as follows: After radar has detected an attacking RV, a launcher containing many small, rod-like projectiles is sent to the neighborhood of the RV. When the Swarmjet is near the incoming RV, the rod like projectiles are spread into a pattern which would destroy the RV upon impact. In addition, others have considered developing a large cloud of dust particles by exploding a nuclear warhead at the surface of the Earth near the silo which is to be defended. Since the incoming RV has a velocity of the order of 10^4 m/s; the kinetic energy of one gram of dust (with respect to the RV) is about

$$(0.5)(0.001 \text{ kg})(10^4 \text{ m/s})^2 = 0.5 \times 10^5 \text{ J/g}$$

which is about 10 - 100 times greater than chemical explosives.

REFERENCES

1. S. Glasstone and P. Dolan, THE EFFECTS OF NUCLEAR WEAPONS, Departments of Energy and Defense, Washington, D.C., 1977, Chapters 8 and 11; W. Broad, Science 212, 1009, 1116, 1248 (1981); Ricketts, FUNDAMENTALS OF NUCLEAR HARDENING OF ELECTRONIC EQUIPMENT, Wiley, New York, 1972; L. Ricketts, J. Bridges, and J. Millette, EMP RADIATION AND PROTECTIVE TECHNIQUES, Wiley, 1976; V. Gilinsky, Phys. Rev. 137, 1A, 50 (1965).
2. D. Hafemeister, Am. J. Phys. 51, 215 (1983).
3. G. Bekefi, B. Feld, J. Parmentola, and K. Tsipis, Nature 284, 219 (1980); M. Callahan and K. Tsipis, HIGH ENERGY LASER WEAPONS: A TECHNICAL ASSESSMENT, Program in Science and Technology in International Security, MIT, Cambridge, MA, 1980; K. Tsipis, Sci. Am. 245, 51 (Dec. 1981).
4. Chapter 3 in MX MISSILE BASING, Office of Technology Assessment, Washington, DC, 1981; ABM: AN EVALUATION OF THE DECISION TO DEPLOY AN ANTIBALLISTIC MISSILE SYSTEM, edited by A. Chayes and J. Wiesner, Harper and Row, New York, 1969; WHY ABM: POLICY ISSUES IN THE MISSILE DEFENSE CONTROVERSEY, edited by J. Holst and W. Schneider, Pergamon, New York, 1969; A. Carnesale, Chapter 12 of this book; D. Hafemeister, Am. J. Phys. 41, 1191 (1973).
5. S. Glasstone and P. Dolan, THE EFFECTS OF NUCLEAR WEAPONS, Departments of Energy and Defense, Washington, DC, 1977, page 366.