Def Sci J, Vol 35, No 4, October 1985, pp 443-450

Nuclear Weapon and Military Equipment

S. NATARAJAN

Department of Applied Physics, Institute of Armament Technology, Pune-411025

Received 24 October 1983, revised 12 November 1984

Abstract. Military equipment must survive a, nuclear attack if enough personnel required to operate them remain combat effective. To achieve this goal, the criteria that determine equipment survivability should be established and any new design should incorporate these criteria to evolve a hardened design. An analysis of the overall response by considering the response to each individual nuclear environment can result in a balanced overall hardened system. The paper discusses the criteria required to be known.

1. Introduction

Nuclear weapons are well known for their devastating effects viz. blast, thermal radiation and the initial or prompt nuclear radiation. All these effects damage defence equipment besides causing human casualties. One of the relatively less known effects accompanying a nuclear explosion, viz. the electromagnetic pulse (EMP), can impair the performance of modern military equipment which rely heavily on solid state technology and can even damage them without any effect on the human beings. This EMP has a range, depending on the height of burst (HOB), at which other prompt nuclear effects are insignificant. Thus, a knowledge of the origin of the EMP and its interaction with a weapon system coupled with a knowledge of the other effects is necessary to ensure equipment suvivability if enough personnel required to operate them remain combat effective. Such a programme is known as nuclear survivability programme.

Prediction of effects of nuclear weapons is difficult because of considerable advances in weapons[1] since 1945. An energy research and development administration report has given some puplic details of the achievements of 30 years of US nuclear testing[2]. The report mentions that 74 different types of weapons have been tested; at one time or other 50 of them have been accepted for stockpile and 26 of them are currently deployed in 33 weapon systems. Hardly a theoretically possible development has been left unexplored. But, a thermonuclear weapon has never been used in a combat nor a ballistic missile ever tested with a live warhead. Therefore, it is almost impossible to predict how technical systems would work under conditions in which they have never been tested. The best one can do in making models is to try to include as many dimensions of the problem as possible, make the most informed guesses as to the values of the relevant parameters and attach large probable errors to the results[1].

2. Nuclear Explosion Phenomenon

For a chemical explosion, the detonation, velocity is around 6000 m/s. That is, a one KT sphere of radius 5.5 m will detonate within a milli-second. The product gases will have a temperature of about 3000°K and initial pressures of about 2,00,000 atm. Almost all energy released in a chemical explosion is converted into shock energy. On the contrary, a one MT nuclear explosion produces about 4. 18 x 10^{15} J in about 1 μ sec resulting in very high temperatures and pressures within the core of the weapon. In early stages, radiation is the only means by which this energy of detonation is dissipated. The energy radiated during this phase consists principally of soft X-rays that are absorbed by surrounding air of about one metre radius. This heated mass of air constitutes the fireball. As the fireball expands, part of the thermal energy goes into shock wave. As the shock wave moves ahead of the fireball, it compresses the air in front of it and renders it opaque to the radiations from the fireball within. The thermal energy received at a target before the shock front detaches itself from the fireball constitutes the first thermal pulse. For a 20 KT weapon, the duration of the first thermal pulse is around[3] 11 ms. This pulse roughly carries with it only 1 per cent of thermal energy.

When the energy in the shock-wave is degraded because of its continued expansion, the opacity of the shocked air decreases steadily. with time and hence after about 15 ms (for a 20 KT weapon) radiations received at a target, from the fireball within, again increase. The radiations from the fireball now are in the visible and 'infra-red regions, due to its lower temperatures, in contrast to the soft X-rays emitted in the first phase. This second pulse carries with it 99, per cent of the energy. of the weapon and is responsible for first, second and third-degree burns at different distances and also for retinal burns and firestorms started by the ignition of combustible material. The duration of the thermal pulse is around 1.3 sec. for a 20 KT weapon and it is evident that the first thermal pulse in insignificant. The duration of the second pulse is determined by the yield of the weapon, e.g. for a one kT weapon, the duration of the second pulse is about 0.3 sec. whereas for 100 kT and 10 MT weapons, the second pulse is about 3 sec and 30 sec. respectivly.

2.1 Damage from Thermal Radiation and its Mitigation

Poly vinyl chloride (PVC), foam rubber and nylon, that are extensively used in vehicles because of their attractiveness from the point of view of weight, ease of handling and cost, get ignited and burn. The required thermal energy of 60-70 cal/cm^2 for surface melting or darkening is delivered by one MT and 100 kT weapons at slant ranges of approximately four and 1.6 km respectively on a normal clear day[4]. Nylon guys supporting aerials are melted by the thermal pulse. Minimizing the effects of thermal gradients in a structure resulting from thermal exposure is important in the design of a structure because thermal stresses created in joints between dissimilar metals could be sufficient to break the bond or buckle the plate[5]. Though material degradation arising out of exposure to thermal radiation may not be sufficient to nullify a weapon system, it cannot be overlooked because the thermal pulse is closely followed by the blast wave that would be impacting a weakened structure.

The best hardening technique against thermal radiation is to use a highly reflective surface where possible and permissible. This reflects most of the radiation and no significant changes in surface characteristics occur. To protect electronics, propellants, ordnance and pessonnel inside protection structures, insulators may be used to keep the heat deposited in the surface material from being conducted to the sensitive components.

2.2 Damage from Blast and its Mitigation

The compressed air moving at very high speed constitutes the blast. Around 50 per cent of the yield of a weapon goes into blast energy provided the HOB is below 30 km. If a weapon is exploded above 30 km, no blast wave is produced, because air is very thin at these attitudes. Blast causes most obvious equipment damage. Any exposed weapon system will suffer damage both from the shock-front which strikes it as a gigantic hammer and from the high winds that follow the blast. Targets are specified as diffraction-sensitive if they are damaged by the peak over-pressure; targets can also be damaged by the extremely strong winds in which case they are called as drag-sensitive. The super structure of ships gives several examples of drag-sensitive targets such as masts, spars, towers and antennas. Depending on the structure, shape and size of the equipment, a given target may be more sensitive to one type of loading than the other.

An important parameter in assessing damage to a weapon system from blast is the duration of the over-pressure phase which determines the time for which the target is acted on by it. To illustrate, the overpressure needed to render a tank unbattleworthy from a one kT explosion is 310 kN/m^2; this overpressure occurs for a one kT weapon at a range of 170 m. On the other hand for a one MT weapon, the same damage will be sustained by a tank at a range of 2700 m (16 times larger than for a one kT weapon though the yield is 100 times more) by an overpressure of 151.6 kN/m^2 (roughly half the value for a one kT) because for megaton weapons the blast wave is longer and so affects the target for a longer time. Thus, the defence specification given to the supplier should include the over-pressure-time pulse shape[5].

Functional requirements determine the structural design; this design should be such as to maximise stiffness and ductility. These are to be consistent with weight, cost and suitability for the application. Seals, blast valves and size of openings should be selected to provide the needed protection from pressure build-up during the positive phase. In addition, the sealing mechanism should allow for rapid decline of overpressure in the negative phase in order to reduce the tendency of the component to burst from internal perssures. As drag coefficient is dependent on target shape, streamline principles can be applied. Reflected pressure problems can be minimized by control of shapes wherever possible.

2.3 Transient radiation damage and its mitigation

In considering prompt nuclear radiation environment on the functioning of electronic systems, attention must be paid to both neutrons and gammas. Since the neutron carries no charge, it can easily penetrate solids and collide with atoms in the lattice without any coulombic scattering. Since the neutron is considerably more massive than the γ photon (the mass ratio in theory is equal to infinity), it can dislodge an atom from the lattice site; the average energy needed for this process6 is about 35 eV and thus one must take into consideration the displacement damage caused by the high energy neutrons produced in a nuclear explosion. Displacement damage depends on the angle of impact of the neutron, its energy and the mass of the atom struck. Any such displacement produces severe strain in the crystal structure resulting in changes in thermal, electrical and mechanical properties. These deleterious effects of neutrons depend on the total dose received and their energy. Because weapon materials have considerable influence on neutron capture and hence on the neutron energy of the neutrons that escape from the burst point, there is considerable difficulty in expressing the relation between neutron dose, yield of the weapon and distance. Thus, the actual number of neutrons emitted per kiloton of explosive energy yield and their energy distribution may not only differ depending on fission or fusion weapons but also for weapons of the same kind'.

Thus, three distinctive mechanisms exist for radiation effects on electronic equipment* : (i) Ionisation arising out of dose rate contributed by the gamma fraction alone results in the generation of electron-hole pairs in reverse-biased junctions. This is a transient effect. (ii) Ionisation arising out of the total dose received with contributions from both gamma and neutrons results in charge build up leading to increased leakage current and decreased gain at low current. This is a permanent effect. (iii) Displacement damage solely from neutrons is also a total dose effect which results in increased resistivity due to removal of carriers. It is responsible for failure of p-n diodes. This damage is also responsible for reduced minority carrier life time resulting in reduced gain and is the main cause for failure of bipolar transistors. This also is a permanent effect.

The prompt y pulse, typically about 10 to 100 ns duration, responsible for the creation of free electron-hole pairs across reverse-biased junctions, leads to upset of or latch up or burn out in semiconductor circuits[5]. The upset condition may also result in permanent loss of data in a digitally-controlled system-necessitating the delivery of programming material from another unit[8]. Many deleterious effects, such as voltage kick back from an inductor load, lock-up in balanced circuits, unacceptable restart conditions. etc. can occur in circuits. Operational amplifiers are extremely sensitive to neutron environment as evinced by the reduced input impedance and decreased open loop gain[5]. Special attention is needed in circuits employing matched pairs of transistors/diodes since the matched parameters will not necessarily track in the same direction and by the same magnitude. Signal and power diodes will show changes in forward and reverse voltages and also reverse leakage current as a result of displacement damage. Assessment of these effects must be based on individual applications. Zener diodes exhibit permanent shifts in Zener voltages. Digital integrated circuits will undergo permanent changes in fanout and input current.

The techniques that are used to mitigate the above effects and to harden electronic systems are : (i) using shields for sensitive parts, (ii) selecting parts with high cut-off frequencies (> 50 MHz) (iii) avoiding MOS devices in high total dose environments because these devices exhibit a change in gate voltage at low dose levels. Since light nuclei are very effective in degrading the neutron energy, hydrogenous materials such as polyethylene or paraffin are the most effective materials. To slow down fast neutrons inelastic scatterers such as iron are effective but they become sources of secondary gammas and hence are not recommended.

2.4 Damage from EMP and its Mitigation

The EMP arises as a result of an assymmetry in the distribution of the compton electron current (this assymmetry can be achieved by an asymmetric shield in the weapon design) produced by ionisation of the air molecules by a small fraction of gammas produced in the explosion. The number of γ s from a weapon of yield[9] Y kilotons is 7.5 x 10^{21} Y. The region constituting the outward moving electrons and the relatively immobile positive ions is called the SOURCE REGION. The asymmetry in the source region gives rise to a RADIATED FIELD. The size of the source region and the area of earth illuminated by the radiated field are dependent on HOB. Table[10] 1 illustrates the extent of EMP coverage for an exoatmospheric (HOB above 35-40 km) burst.

Table 1. EMP coverage

HOB (km)	Target distance along the surface from GZ (km)
100	1250
200	1760
300	2150

For an endo-atmospheric burst (HOB upto 30 km), the source regipn and the region covered by the radiated field are smaller. The frequency spectrum of the EMP has components upto 100 MHz for an exo-atmospheric burst and upto 1 MHz for a near surface or endo-atmospheric burst[11]. The rise time for the EMP is ~ 10 ns whereas for lighting[12] it is ~ 6 μ s. Any conductor in the path of the EMP can efficiently couple wirh the radiated EMP. The induced voltage can. be easily fed into a neighbouring conductor as a spark or as a current if there is an electrical continuity, The electric fields for a near surface burst are ~ 10^5 V/m and the EMP in this case has an azimuthal magnetic field. For a high altitude burst, the electric field is about an order of magnitude lower but the radiated field does not attenuate that rapidly as in a near-surface burst.

Fig. 1 illustrates how an EMP can interact with an aircraft[12]. The degradation of or damage to a system by the EMP arises due to the following mechanisms : (i) incident EMP causes current and charge on the external surface, (ii) surface currents and charges excite inadvertent penetrations, (iii) the penetrations couple to internal cables, and (iv) the cable systems couple to critical subsystems.

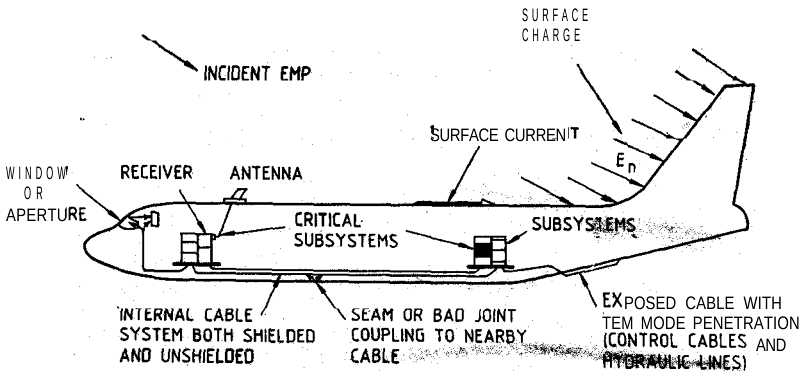

Figure 1. System EMP interaction.

The way the EMP energy is collected is quite complex because it is dependent on the shape and size of the collector, its orientation with respect to the pulse source and on its frequency spectrum. It is worth mentioning here that the EMI and EMC communities have evolved over the past 40 years whereas concern for EMP and development of protection concepts are about 10 years old[12].

Protection against EMP is similar to protection against EMI/Lightning. Recent experience with F-16 aircraft has shown that the implementation of a stringent EMI/ Jightnjng protection programme can result in adequate EMP protection[12]. Particular techniques include : (i) installing the most sensitive equipment in the area of maximum EM attenuation known as ZONING, (ii) avoidance of circuit and system layouts with loops, (iii) use of-screened cables, (iv) keeping all cables as short as possible, and (v) making all interconnections through a screen at a common point.

3. Necessity to Establish Criteria

The foregoing account has shown how various effects accompanying a nuclear explosion can degrade weapon systems and equipment. Because new equipment costs are very high, it may not be possible to carry out real trials as were done a few years ago. Incorporating nuclear hardening into a new design should be an integral part of the design process. This necessitates a strong interaction between the designers of equipment and nuclear hardening group since the latter has to interpret the nuclear environment and its impact on the proposed design of the equipment/weapon system. The hardness analysis group will analyse the performance of equipment/system for each of the nuclear environments-thermal, blast, nuclear radiation and EMP. To perform this analysis, detailed data on parts and material responses is needed,

Literature shows that these analyses are performed using sophisticated computer programmes that model the item and predict its response. These analyses are performed at higher threat level than specified to establish what are known as design margins[13] (DM). The design margin is the ratio of the level at which failure of a part/component/system occurs to the anticipated level in a nuclear environment and is always greater than unity. Currently followed design margins for a hardened weapon system for the various nuclear environments are :

(i) NEUTRONS $DM \; \frac{\text{neutron flux at failure}}{\text{criteria flux}} > 10$

(ii) THERMAL $DM \; \frac{\text{temperature at failure}}{\text{criteria temperature}} , 2$

(iii) OVERPRESSURE $DM \; \frac{\text{overpressure causing failure}}{\text{overpressure criteria}} > 3$

(iv) EMP $DM \; 20 \log \left(\frac{\text{Induced current flow for damage}}{\text{Induced current}} \right) > 10 \text{ dB}$

(v) TOTAL DOSE $DM \; \frac{\text{Dose causing failure}}{\text{Criteria dose}} > 1$

i.e if we consider the neutron environment, the component/system should exhibit degradation at 10 times the neutron flux expected in real conditions and so on.

The requirements for each nuclear environment vary because for blast and thermal radiation, structural response is important, whereas for EMP and transient radiation, primary considerations are electronics survival and circuit response.

For neutron environment, components/systems are tested in a reactor test facility; testing of components for specified gamma dose can be carried out in spent fuel store of a nuclear reactor[8,13]. Linear accelerator facilities are used for testing of components for both gamma dose rate and total gamma dose effects[8]. Validation testing for thermal effects are carried out with solar furnaces and flash arrays[13]. Testing for blast effect is done using blast load generators and for dynamic pressure effects shock tubes and wind tunnels are used[13]. The Foulness blast tunnel (probably the only shock, tube of its size in the world) can test equipment upto a main battle tank head-on*. Validation testing of components systems for EMP is carried out with specialized equipment capable of delivering the required pulse in a specified time[8]. For EMP, the largest threat level simulator in the world is the Air Force Weapons Laboratory in Albuquerque, New Mexico, where the strategic B-52 bombers or the large C-5A cargo aircraft can be tested[12].

4. Conclusion

The hardening procedure demands a knowledge of the following parameters : (a) the peak static overpressure, peak dynamic pressure (kN/m^2), the positive phase duration and impulses from both these components, (b) the total thermal flux (MJ/m^2) and the time in seconds required for this flux to be delivered and also the maximum irradiance (MW/m^2) (c) total γ and n, the peak γ dose rate, maximum neutron flux (neutrons/mm^2) and the maximum neutron dose, and (d) EMP arising out of exo- and/or endo-atmospheric bursts.

Thus, in the operation and maintenance of nuclear hardened equipment/system, the importance of segregating the hardened spares or sub-units from the unhardened spares cannot be overstressed. A hardness qualified transistor from one supplier may have the same characteristics as a transistor from another supplier that has not been hardened[13]. Replacement in a hardened system by an unhardened component would thus result ‘in overall degradation of the complete system.