NUCLEAR WEAPON EFFECTS ON WARSHIP ELECTRONIC EQUIPMENT

BY

CAPTAIN J. C. G. FIELD, M.SC., F.I.E.E., R.N. (RET.), R.C.N.C.
(Ship Department, Electronics Section)

Introduction

It has long been a requirement that modern warships should have a capability for operating within a tactical nuclear scenario, and to this end their design is such as to minimize operational damage from blast and underwater shock. Measures to reduce contamination and protect the ship's company from nuclear fall-out are provided, and will be familiar to readers.

In addition to the blast wave and thermal flash, a nuclear weapon produces an intense pulse of nuclear and electromagnetic radiation at the instant of detonation. 'Old-fashioned' thermionic-valve electronic equipments were electrically robust and not greatly affected by these phenomena. Modern semiconductor electronic equipment, on the other hand, is both electrically fragile and inherently sensitive to nuclear radiation; in consequence, it is prone to damage or destruction from these nuclear weapon effects unless designed to 'live' with them.

The proliferation of solid-state electronic equipment in modern warships, and the recent extension of its application to vital areas, such as machinery control, electrical power generation and distribution, steering, etc., requires that careful consideration be given to the 'nuclear hardness' of such equipment. We could otherwise find ourselves in a battle situation where the ship had survived the blast and thermal effects of a nearby tactical nuclear explosion, but was nevertheless temporarily incapacitated (at a particularly inconvenient moment!) due to loss of electrical power or manoeuvring capability.

This article seeks to provide an elementary outline of the problem and of the design measures required to overcome it.

Characteristics of Nuclear Explosions

The energy produced by a fission weapon is generated in a time of the order of 50 nanoseconds (50 x 10^{-9} second). The subsequent distribution of this energy is roughly as follows:

Blast and shock:	50 per cent.
Thermal radiation:	35 per cent.
Radioactive energy of fission products:	10 per cent.
Prompt gamma and neutron radiation:	5 per cent.

For the purpose of this article, the prompt gamma and neutron radiation is of primary interest. The gamma rays are of high quantum energy — of the order of 10 MeV — and travel at the velocity of light. The neutrons are of similar energy and, being particles, travel somewhat more slowly than the velocity of light. Even for a weapon as small as 1 kiloton yield, the total energy radiated outwards by prompt gamma and neutron radiation is about 60 000 kilowatt-hours — which is appreciable by any standards!

Some of the nuclear (and thermal) radiation in the weapon vicinity produces intense ionization, so that high-speed electrons are emitted. This is equivalent to a very large outwardly-directed negative electric current with an initial rise-time of the order of 10 nanoseconds. If the explosion occurred in outer space, no *direct* electromagnetic radiation would be produced, since the current would be spherically symmetrical. A near-surface burst, however, introduces sufficient asymmetry for vertically-polarized electro-magnetic radiation to take place, just as if a vertical transmitting aerial existed at 'ground zero'. This electromagnetic radiation is very intense and produces field strengths of tens of kilovolts per metre at considerable distances from the explosion. It is known as the 'Electromagnetic Pulse', or EMP for short.

It was stated before that, under conditions of perfect spherical symmetry, no EMP would be directly radiated. However, some of the spherically-emitted electrons from an exo-atmospheric nuclear explosion will be 'trapped' by the Earth's magnetic field, and their spiral motion round the magnetic 'lines of force' will produce strong electromagnetic radiation. The result is an intense EMP which can reach amplitudes of 50 kilovolts per metre and may extend up to 1000 miles from 'ground zero'.

An underwater nuclear explosion, provided it does not vent through the surface, does not produce any nuclear or electromagnetic radiation at ranges of tactical interest. If it does vent, however, radiation will occur from the exposed fireball — though naturally at lower levels than from an air-burst weapon.

Effect of Distance and Weapon Yield

All nuclear weapon effects are attenuated by distance, but to different degrees; the detailed mechanisms are rather complicated and outside the scope of this article. As a broad generalization, however, it can be stated that rapidity of attenuation with distance is in the following order:

Neutrons (most rapidly attenuated)
Gamma Rays
Blast
EMP

There are certain 'scaling laws' which relate weapon yield to the distance at which a particular value of effect is produced. In the case of blast, for example, the distance at which a given peak static over-pressure is produced is proportional to the cube root of the weapon yield.

It follows that if a ship can withstand a certain maximum blast level, this will be accompanied by more severe nuclear radiation, with a higher proportion of neutrons, if the weapon is of low yield. For a sufficiently large weapon, the ship will have to be at such a large distance (in order to survive the blast) that nuclear radiation will become unimportant; nevertheless, EMP may well remain at a significant level.

Radiation Dose

The total radiation 'dose' received by a material body is defined in terms of energy absorption, the unit being the 'rad'. One rad corresponds to an energy absorption of 0·01 joule per kilogram of material. This energy manifests itself internally as micro-structural damage and ionization of constituent atoms.

The dose received by a sample of material at a given point in space depends on the material, as well as the energy spectrum of the nuclear radiation and the relative proportions of gamma rays and neutrons. It is customary to express the instantaneous intensity of gamma radiation at a point as so many 'rads (silicon) per second' — meaning that if 1 kilogram of silicon were placed at that point, 0·01 joule per second, or 0·01 watt, would be absorbed from the gamma radiation per rad/sec. The total gamma dose received is the time-integral of the dose rate.

A similar approach applies for neutrons, but it is often more convenient to work in terms of 'neutron fluence', which is defined as the total number of neutrons which have crossed an area of 1 mm^2 perpendicular to their direction of travel.

In the case of human tissue, potential total radiation doses are expressed in 'rads (tissue)', and figures are available which relate the incidence and severity of radiation sickness to total dose; this can in turn be estimated as a function of weapon yield and range.

Radiation Shielding

In a modern surface warship, the majority of electronic equipment is well inside the ship's structure and first thoughts are that this should provide a fair degree of shielding against nuclear radiation — as is indeed the case with nuclear fall-out. It might again be thought that additional local shielding could be provided to protect radiation-sensitive equipment.

Regrettably, these ideas would not be well-founded. Because of its high quantum energy, the direct nuclear radiation from a fission weapon is much more penetrating than fall-out radiation or the stray radiation from a nuclear reactor. In order to attenuate the prompt gamma radiation by a factor of 10, the following material thicknesses would be required:

Water:	1·2 metres
Aluminium:	0·5 metre
Steel:	0·15 metre (6")
Lead:	0·06 metre ($2\frac{1}{2}$")

In order to attenuate the prompt neutron radiation by a factor of 10, a material rich in light atoms (such as polythene) would be chosen, and the typical thickness required would be of the order of 0·25 metre (10 inches). Neutron absorption in such a shield would generate additional gamma rays, so the gamma-ray shielding would have to be placed inside the neutron shielding and also somewhat increased in thickness.

Even equipment (or men) well below the water-line, or with fuel/water tanks between them and the explosion, would not be protected to anything like the degree that might at first be imagined. The reason is that the neutron flux passing overhead, and interacting with air molecules or ship's structure, produces a secondary flux of gamma rays which is essentially omni-directional.

The general conclusion is that radiation shielding is of little practical value in the protection of either equipment or men from prompt nuclear radiation. From the design point of view, the assumption is made that the ship is transparent to prompt nuclear radiation.

Effect of Neutrons on Electronic Devices

Virtually all modern electronic devices (i.e. diodes, transistors, integrated circuits, etc.) are based on extremely pure silicon slices cut from carefully-grown single crystals. Their electrical properties depend on the regularity and uniformity of the basic silicon crystal lattice.

If an incident neutron collides with a lattice atom, this is knocked out of place and institutes a 'collision cascade' within which some hundreds of atoms are involved. As a result a small region is formed where the lattice damage is highly concentrated.

The initial total damage is proportional to the neutron fluence, but there is a subsequent annealing process during which there is some degree of recovery; apart from this, however, the damage is permanent (and cumulative if there is more than one nuclear event). It makes no difference whether the device is in a working equipment or in a spare unenergized unit in the storeroom — except that the annealing process takes longer in the latter case.

Some of the practical effects of lattice damage are as follows:

(*a*) *Bi-polar transistors:* The main effects are a reduction in current gain and an increase in collector-emitter saturation voltage. It is not difficult to design low-power circuits which can tolerate these effects, but the design problem becomes less easy in the case of high-power, high-voltage transistors.

(*b*) *Diodes:* With these, there is a permanent increase in the forward voltage drop, which requires the provision of additional heat-sinking in the case of high-power devices.

(*c*) *Thyristors:* These require higher gate-triggering power after neutron irradiation, and also suffer from an increase in forward voltage drop and hence increased heat dissipation.

(*d*) *Photo-diodes and photo-transistors:* These are relatively rather sensitive to damage by neutron radiation, and the latter may suffer a loss in optical sensitivity of up to 90 per cent.

(*e*) *Light-emitting diodes (LEDs):* These can suffer degradation in optical output by some 10–20 per cent. Optically-coupled isolators, consisting of a LED and a photo-transistor, can therefore suffer a severe reduction in current-transfer ratio which has to be allowed for in circuit design.

(*f*) *Integrated circuits:* MOS integrated circuits (CMOS, PMOS, NMOS, etc.) are virtually immune to neutron radiation damage at levels of tactical interest, as are most bi-polar digital integrated circuits. Bi-polar linear integrated circuits, such as operational amplifiers, are affected in various ways which must be taken into account during equipment design.

Effect of Gamma Rays on Electronic Devices

Gamma rays produce ionization within all types of material at a rate proportional to the gamma dose rate. After the gamma pulse, the level of ionization decays and in many cases the material recovers completely for all practical purposes. In some cases, however, trapped electric charges persist in insulating regions and result in permanent changes in electrical characteristics.

In the case of junction diodes and bi-polar transistors, ionization takes the form of hole-electron pair production within the crystal lattice, with the result that electric currents are generated at reverse-biassed p-n junctions. This is in fact the photo-electric effect — i.e. essentially the same mechanism as is exploited in photo-diodes and photo-transistors. From the circuit designer's point of view, every reverse-biassed p-n junction has to be regarded as a current generator which injects a current pulse into the circuit, of amplitude proportional to the instantaneous gamma dose rate. These currents can be very large unless the circuit has sufficient impedance to limit them, and could be destructive unless precautions are taken.

Thyristors are triggered by these internally-generated photo-currents at quite low levels of gamma dose rate, and in this sense are exceptionally vulnerable to gamma radiation. Whether such false triggering actually matters depends on the details of the circuit application, but if it results in the blowing of fuses the operational consequences are probably unacceptable.

MOS transistors, since they are majority-carrier devices, are in themselves scarcely affected by the additional mobile charge carriers generated by gamma rays. However, trapped charges are produced in the insulating gate layer which result in a permanent shift in operating characteristics; this has to be allowed for in circuit design.

MOS integrated circuits incorporate a number of reverse-biassed p-n junctions which provide electrical isolation between various parts of the circuit. All these junctions generate photo-currents when they are 'hit' by the gamma pulse, and these cause temporary spurious operation. It is possible for such circuits to 'latch up' and subsequently remain inoperative until switched off and on again.

In general, all solid-state electronic devices produce spurious outputs of some sort during the gamma pulse; whether they subsequently recover, or remain in an incorrect operating state, depends on the circuit details. There will be no permanent damage provided the photo-currents are limited by circuit impedances.

The general term used to embrace all the above neutron and gamma phenomena is 'Transient-Radiation Effect on Electronics' or 'T.R.E.E.' for short.

Effect of EMP on Electronic Devices

When the electromagnetic pulse reaches the ship, it induces very large currents and voltages on the outer skin of the structure and on all exposed cables and conductors of every type — including pipework, ventilation trunks, etc. In this respect it is similar to a lightning strike, but of much greater amplitude, if of shorter duration. Despite the very high instantaneous level, it has no effect whatsoever on men.

The metal hull and superstructure provide a fair degree of electromagnetic screening, but nevertheless some of the EMP energy gets inside the ship through cable and pipework penetrations, openings such as bridge windows, and electrical discontinuities such as doors and hatches. As a result, steep-fronted pulses are induced on all internal electrical cables and thereby reach the interior of equipments.

Owing to their electrical fragility, most types of transistor and integrated circuits can be destroyed by electrical transients with energies in the micro-joule order; it is therefore important to ensure that they are adequately protected by avoiding direct coupling to the external electromagnetic environment. This is largely a matter of good electromagnetic compatibility (EMC) practice which should in any case be a normal feature of all electronic equipment designed for naval service.

While it is not difficult in the majority of cases to avoid permanent damage from EMP, it is not so easy to ensure that there will be no temporary mal-operation. This is a particular problem with digital circuits, particularly if they employ fast-switching TTL logic. In fact all 'one-shot' or triggerable devices (including thyristors) are at risk of false operation from stray pulses, and the existence of EMP simply means that the normal precautions require application with even more care and rigour.

General Equipment Design for Nuclear Hardness

When considering the design of a new electronic equipment, the first question to ask oneself is 'does it matter if this equipment is permanently damaged and rendered inoperable by EMP or TREE?' There will certainly be cases where it does not — bearing in mind that we do not expect to be narrowly surviving nuclear attack every day of the week. Equipments in this category would include such things as S.R.E., laundry equipment and cathodic protection. However, in the majority of cases it *will* matter — even if subsequent repair is within ships' staff capability. Assuming that we are dealing with an equipment of operational importance, which must therefore survive with substantially unimpaired performance, the next question is 'can a temporary malfunction be tolerated?'. This depends very much on the nature of the temporary malfunction and its affect on the associated system. For example, the following could presumably be accepted:

(*a*) Disconnection of a telephone call by the automatic electronic telephone exchange.

(*b*) Short transient swing of a few per cent. in the ship's power supply voltage.

(*c*) Short break in speech transmission via an intercom.

(*d*) Brief transient excursion in propeller pitch demand.

(*e*) Transient error in EM log speed indication.

The following, however, are examples of temporary malfunctions that certainly could not be tolerated:

(*a*) Spurious operation of over-voltage trips on main generators, leading to a total black-out.

(*b*) Blowing of fuses in static frequency-changers, causing loss of supplies to, say, steering or gyro-compasses.

(*c*) Spurious tripping of motor starters.

(*d*) False operation of certain propulsion machinery control and interlock circuits.

(*e*) Spurious operation of fire alarms.

In practice, it is not too difficult to design low-power analogue-type electronic equipment which can survive without damage and whose temporary malfunction does not lead to unacceptable consequences. In fact, it has been found that for equipment of this type, the normal application of sound electronic-engineering design principles tends to result in a nuclear-hardened design without any additional special features or increased production cost.

High-power electronic equipment requires rather more care and the employment of higher factors-of-safety and the avoidance from the outset of certain particularly vulnerable circuit approaches. For example, thyristors should not be used unless they are naturally-commutated to the 'off' condition every half-cycle of the a.c. waveform, so that at most only one half-cycle is 'let through' by gamma triggering.

Digital and 'one-shot' circuits present by far the greatest difficulty; the various gates, flip-flops, registers, counters, etc. will be set to random states by the gamma photo-currents, even if they are adequately screened from EMP. The most general method of attacking this problem is to arrange for the circuit to be periodically forced to its 'reset' condition and made to go through the sequence again, in such a manner that it only produces a valid output if the input signals persist for two or more iterations. If the digital system relies on a stored program rather than 'hard-wiring' (e.g. if it is a digital computer or programmed logic array) it is essential to use a read-only-memory (ROM) which cannot be corrupted. This rules out many types of dynamic and charge-storage memory devices.

Balanced Hardening

In order to undertake the design of a nuclear-hardened equipment in an intelligent and cost-effective manner, it is of course necessary to have figures for the peak gamma dose rate, neutron fluence, total gamma dose, and EMP amplitude which the equipment must withstand. These figures are arrived at by considering the maximum radiation dose that a man can withstand, and also the maximum blast over-pressure the ship can withstand, and plotting a composite survival boundary as a function of weapon yield and range. At low yields, the minimum distance from the explosion is set by the biological limit, and at high yields by blast.

A decision is then made on the *lowest* weapon yield which is tactically likely, and from this the closest permissible range to the explosion is read off from the graph. It is then possible to ascertain the maximum gamma dose rate, neutron fluence, and total gamma dose which the equipment must withstand. This is the 'balanced hardening' level, so-called because it has been balanced against the other survivability criteria and is a level above which there is nothing to be gained by attempting to 'harden' equipment against TREE and EMP.

Summary and Conclusion

In addition to its more spectacular effects such as blast and thermal flash, a tactical nuclear weapon produces an intense burst of nuclear and electromagnetic radiation at the instant of explosion. These radiations can affect electronic equipment at ranges well beyond those at which the ship or the ship's company could survive.

Trends in modern electronics are such that equipment has tended to become more vulnerable than hitherto, and in consequence designers have to be aware of the ways in which TREE and EMP can affect devices and circuits, so that these effects can be 'designed out'. In effect, these phenomena amount to extra environmental factors that have to be considered in addition to shock, vibration, temperature, humidity, electrical interference, etc.

It turns out that in most cases, all that is required is the proper application of good circuit design and electromagnetic compatibility practice, combined with electrical and thermal safety factors which would in any case be prudent on reliability grounds. At 'balanced-hardening' levels, there need be little or no increase in cost or complexity if the design is right.

Both digital and high-power equipment give the designer somewhat more trouble, but the techniques are known and their application is entirely practicable at 'balanced-hardening' levels if the necessary design effort is applied.