SECTION 5. THE RESPONSE OF MATERIALS AND DEVICES TO RADIATION - OVERALL SURVEY

5.1. INTRODUCTION

5.1.1. General

The effect of irradiating an electronic material and the consequent degradation in performance of devices made from such material can follow a number of courses. The final result will depend upon the type of radiation, its mode and rate of interaction with the material, the type of material and its particular contribution to the device function and the physical principles upon which the function of the device is based. Table 5.1 gives an impression of the variety of effects which radiation can have on devices.

This section provides a general introduction to radiation effects on materials and devices, describing first the two main types of interaction of radiation with materials (atomic displacement and ionisation) and, second, the consequences in general of these interactions for the individual parts of a device. The description is extended to a classification of about 60 varieties of electronic media or devices. This classification is given in greater detail in Holmes-Siedle (1974).

A more detailed discussion of the effects of various types of radiation on particular devices is given in later sections.

5.1.2. Dose rates

It is often necessary to specify the dose rate at which radiation is delivered. For example, a spacecraft orbiting in the Van Allen belts is said to be exposed to a low dose rate and a sample close to a reactor core to a high dose rate. A nuclear weapon pulse delivers an even higher rate. We can specify this rate in terms of the average energy absorbed per unit mass and time (e.g. rads per second). This method of specifying rates is adequate for high-energy electrons and photons. However, local ionisation effects on very dense electronic components exposed to certain particles may lead to strong transient electrical response. Special questions of dose rate effects such as these will be dealt with as required.

5.2. DEGRADATION PROCESSES

Energetic particles or photons passing through matter lose energy through a variety of interactions and scattering mechanisms. It is not within the scope of this study to discuss these complex mechanisms in detail; it is sufficient to note that we are concerned primarily with the two major consequences of energy transfer from radiation to electronic materials, namely ionisation and atomic displacement.

5.2.1. Atomic displacement

A small but significant fraction of the energy of particles passing through an absorber is dissipated in the transfer of momentum to the atoms of the absorber. Provided an atom subject to such a collision receives sufficient kinetic energy (displacement energy E), it will be removed from its position in the lattice and leave a vacancy or defect. The removed atom may meet another such vacancy and "recombine" or lodge in an interstitial position in the lattice. Persisting vacancies may be mobile and either combine with impurity atoms or cluster with other vacancies. The resulting vacancy complexes are usually electronically active in semiconductors, but the interstitial atoms are less active. The consequences of displacement in a solid are clearly complex; in addition, the incident particle must have a certain threshold energy before displacement occurs. The process is conventionally termed "bulk damage".

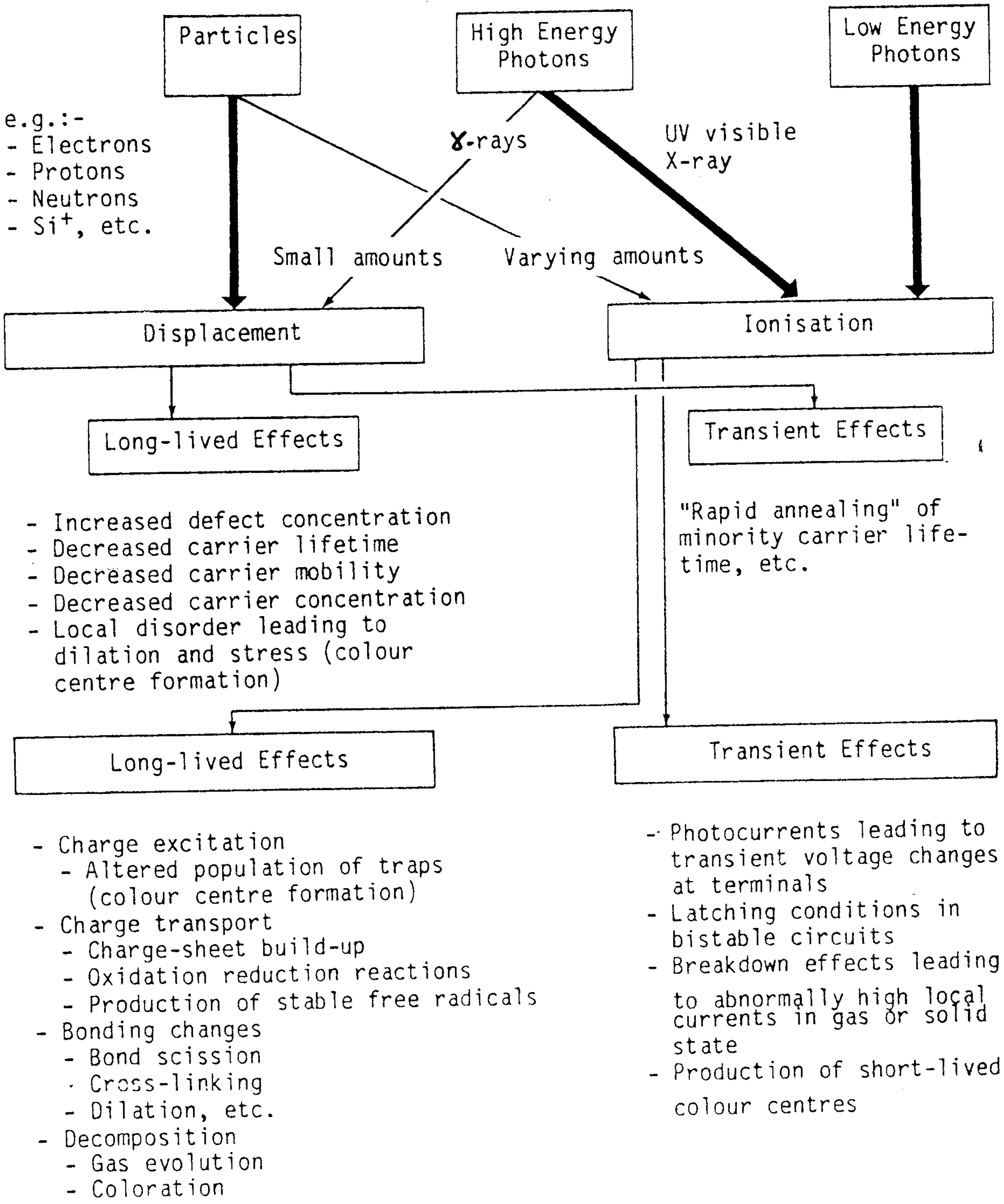
The effect of displacement damage on the minority carrier lifetime of silicon, caused by 1 MeV electron irradiation, is shown in Figure 5.1 (after Wertheim (1957). It can be seen that, over a wide range of electron fluence (ϕ), lifetime varies with fluence as follows:

$$\frac{1}{\tau} - \frac{1}{\tau_o} = K_\tau \phi\,.. \qquad ......\ 5(i)$$

where τ_o and τ are the values before and after irradiation. K_τ is known as the minority carrier lifetime damage constant; it expresses the "damage" (change in lifetime) per unit electron fluence.

TABLE 5(1) - RADIATION EFFECTS

A Summary of Radiation-induced Degradation Effects



Displacement – Long-lived Effects:

- Increased defect concentration
- Decreased carrier lifetime
- Decreased carrier mobility
- Decreased carrier concentration
- Local disorder leading to dilation and stress (colour centre formation)

Displacement / Ionisation – Transient Effects:

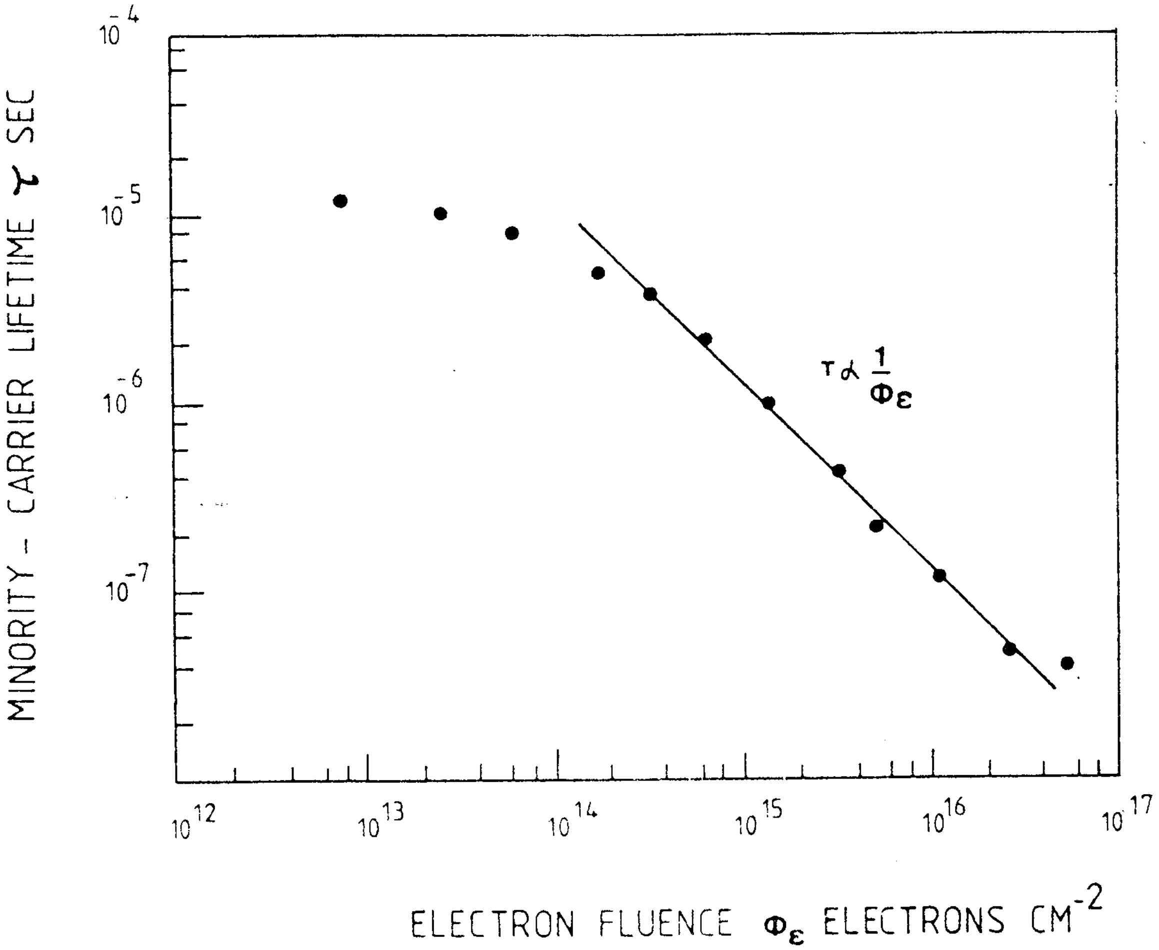
"Rapid annealing" of minority carrier lifetime, etc.

Ionisation – Long-lived Effects:

- Charge excitation
  - Altered population of traps (colour centre formation)
- Charge transport
  - Charge-sheet build-up
  - Oxidation reduction reactions
  - Production of stable free radicals
- Bonding changes
  - Bond scission
  - Cross-linking
  - Dilation, etc.
- Decomposition
  - Gas evolution
  - Coloration

Ionisation – Transient Effects:

- Photocurrents leading to transient voltage changes at terminals
- Latching conditions in bistable circuits
- Breakdown effects leading to abnormally high local currents in gas or solid state
- Production of short-lived colour centres



The effect of 1 MeV electron irradiation on the lifetime of holes in N-type silicon.

FIGURE 5.1 - ATOMIC DISPLACEMENT DAMAGE

The value of K_τ for 1 MeV electrons is often taken as the standard with which the effect of all other particles is compared. An electron of higher energy will displace more atoms per unit volume, whilst a proton of the same kinetic energy will displace over a thousand times more because it has far greater momentum and is more rapidly stopped.

As the damage caused - though not identical for all particles at all energies - is of the same general kind, it is possible to express the effect on silicon of all particles in terms of the damage equivalent fluence of a 1 MeV electron. This concept has been described by Brown, Gabbe and Rosenzweig (1963).

The question of damage equivalents extends into neutron damage physics (reactor and weapon effects), and Van Lint et al (1975) suggest 3 MeV electrons, 20 MeV protons and 1 MeV neutrons as standard particles for relating the effects of the three particle species.

Whilst developing design rules for the TELSTAR satellite, Brown, Gabbe and Rosenzweig expressed the variations of damage constants with electron and proton energy. Their sets of curves illustrating the relation between damage and particle energy and the effect of protective shielding are given later. The "no front shield" curve in these figures indicates the effect of omnidirectional particles on a bare "semi-infinite" silicon solar cell (i.e. with an infinite amount of absorber protecting the back of the wafer). This geometry is not representative of either internal electronics or the solar cell panels of today (which have limited absorber at the back), but the complex energy-dependence of proton damage and the threshold energy of electrons are suitably illustrated by these curves.

Van Lint et al reviewed minority carrier lifetime damage equivalents for electrons, protons and neutrons in silicon. Srour, Othmer and Chiu (1975) have also reported some improved measurements. In the light of this work, the figures produced by Brown and his colleagues - although calculated for silicon of relatively high resistivity (greater than 1 ohm/cm) and the solar cell mode of operation - would still seem to be generally correct.

For typical transistor designs, the damage constants are probably lower because lifetime is less affected when the concentration of injected minority carriers ("injection level") is high. However, the effect of the lower resistivity of the typical transistor base region may operate to counteract this reduction of the lifetime damage effect.

The possibility of damage caused by bremsstrahlung X-rays must also be considered. X-rays (or gamma rays of the same energy) are photons which possess negligibly small momentum. Therefore, they themselves cannot interact with, and displace, an atom in a crystal. They may, however, generate an appreciable quantity of high-energy Compton electrons which, in turn, can produce damage (1 rad of ^{60}Co gamma rays produces about 107 Compton electrons cm^{-2} of energies up to about 1.3 MeV in the steel cap of a transistor). Thus, high doses of electromagnetic radiation may produce displacement damage, the amount depending upon details of the component's shielding configuration; however, the effect in space is usually negligible.

5.2.2. Ionisation

The primary interactions between energetic radiation and the electronic structure of atoms are more complex and varied than the simple transfer of momentum to nuclei of atoms described earlier. Despite the initial variety of interaction (see Johns and Cunningham (1971) for example), much of this loss of energy to the electrons in semiconductors and inorganic insulators is ultimately converted to the form of electron hole pairs. In this process, known as ionisation, the valence band electrons in the solid are excited to the conduction band and are highly mobile if an electric field is applied.

Any solid - even an insulator - thus conducts for a time at a level higher than is normal. The positively charged holes are also mobile, but to a different degree because their motion is effectively that of valence band electrons in the opposite direction.

The production and subsequent trapping of these positive holes in oxide films, which cause serious degradation in MOS and bipolar devices, are the main subjects of later sections of this document. In polymers, the main result of electronic excitation may be instead the breaking of chemical bonds and the creation of new ones. In this case, conduction may also result, but other forms of physical breakdown may be more apparent.

It is worth noting that the net energy required to create an electron hole pair is relatively small (e.g. 18eV in SiO_2). Therefore, since no momentum transfer to atoms is involved, the energy of the radiation causing ionisation is not so critically important as in atomic displacement (of course, the number of pairs created depends upon the particle or photon energy). Thus, ionisation effects as produced by megavolt particles in space may often be simulated by much lower energy X-rays, electron beams or even ultraviolet light. For displacement damage, freedom of choice of simulation methods is more limited.

The deposition of energy in a material by means of ionisation is conventionally termed "dose" and measured in rads or Grays. One rad is equivalent to the deposition of 100 ergs in one gram of material; the SI unit (the "Gray") is equivalent to the deposition of one joule in one kilogram and therefore equal to 100 rad.

5.3. THE CONSEQUENCES OF DEGRADATION

5.3.1. General

To consider the degrading effects of radiation on electronic devices requires their classification according to the following three points:

1. Degradation may be caused by either ionisation or atomic displacement;
2. The effect may be long-lived or transient;
3. Degradation may be associated with particular active "sub-elements" which can be classified as dielectric, semiconductor or conductor.

It can be seen that there is scope for an extremely complex interaction of processes to be involved in the loss of function of any particular device, integrated circuit or electronics module. Fortunately, the field is often considerably narrowed. For instance, degradation of an MOS device, especially in the relatively low dose rate environment in space, is almost entirely due to the long-lived effects of ionisation in the dielectric subelement, i.e. in the gate insulator.

Many modern semiconductor devices make use of electronic processes that are seriously affected by the alterations produced in materials by high-energy radiation. A prime example is the bipolar transistor. Like many (but not all) p-n junction devices, the "key material parameter" is the minority carrier lifetime. The production of gain relies on the efficient transport of minority carriers across several hundred nanometres of silicon.

Displacement of atoms and the subsequent formation of vacancy-impurity complexes provide centres for recombination of those carriers and, the more sophisticated the device structure, the greater the possibility of loss of other minority carriers, e.g. at interfaces. It is probably a fair generalisation to say that the more complex the geometry and operational principle of a solid-state device becomes, the more vulnerable it is to radiation-induced changes. Further, as we move from the purely electronic type of device to the type in which light is used to produce electronic effects in the solid, or which itself generates light by such effects, the possibilities of interference or degradation of efficiency as a result of irradiation are even more varied.

The following pages describe the modes of degradation which are likely to be induced by ionisation and displacement of atoms in the various "subelement" materials. The types of device which are, in consequence, likely to be most affected are listed in Table 5(2) together with a summary of the more important effects.

The information in these tables has been derived from the results of a very large number of physical experiments and radiation tests performed on devices in the U.S. and Europe during the design of electronics for space vehicles, military equipment and reaction components. This concise summary is intended to introduce the reader to the range and variety of effects to be expected before the detailed discussion of particular cases in following paragraphs.

5.3.2. Degradation of conductors

Radiation effects on conductors in space applications are less important than on those in reactor technology. In some circumstances, the atomic displacement effect may cause changes in conductivity such as occur in carefully balanced resistive elements. Also, at extra high particle fluences, say, greater than 10^{20} neutrons.cm^{-2} (likely to be encountered, for example, in reactor cores), atom displacement may lead to serious changes in mechanical strength. Ionisation is not likely to create problems, except that photo-emission and charge-scattering may cause electrical currents that can affect sensitive circuits. No important example of degradation of a metal by radiation in space has yet been encountered.

5.3.3. Atomic displacement in semiconductors

Displacement effects in semiconductors are long-lived and usually result in the reduction of carrier mobility and lifetime or in the removal of carriers by trapping. We mentioned elsewhere the effects in bipolar transistors, where displacement-induced defects provide recombination centres. Besides bipolar transistors, the most sensitive devices in space technology are solar cells and silicon-controlled rectifiers, all of which require a high minority carrier lifetime for efficient operation. Field Effect Transistors (FETs) are less sensitive and would require particle fluences higher than normally experienced in a space mission before their performance was affected significantly.

A few types of devices are sensitive to the slow emptying of displacement-induced charge traps in the semiconductor sub-element. This effect may produce inconvenient "tails" on the otherwise sharply falling edge of electrical pulses (for example, this could increase the dark current of an imaging device). Only at higher fluences would "other properties" (e.g. the electro-mechanical constant of a transducer) be affected, but such effects are unlikely in the space environment. New high electron mobility transistors are sensitive to these effects.

5.3.4. Ionisation in semiconductors

In semiconductors, high-energy radiation produces electron hole pairs, leading to spurious photocurrents. The magnitude of this effect is clearly dependent upon dose rate rather than total dose and the photocurrents produced in the space environment will generally be insignificant. At worst, these currents may register as background "noise" in some extremely sensitive circuits. Galactic cosmic rays can produce local pulses of photocurrent and this is a problem in dense semiconductor devices using small geometries. Single-event upset and latchup due to cosmic rays are dealt with in detail in later sections. Logic upset and latchup in MOS and bipolar circuits require dose rates of at least 10^7 rad.s^{-1} of high-energy radiation, i.e. over a million times higher than those experienced by orbiting equipment.

5.3.5. Atomic displacement in dielectrics

This effect is well-known in optical materials and metal halide salts. The vacancies so produced are known as "colour centres". However, displacement defects in dielectrics rarely interfere with the function of electronic devices.

Dielectric materials do not require crystalline perfection in order to be good dielectrics. Many are glasses, with no crystalline structure at all. Consequently, the displacement of nuclei from their original sites has no significant effect on a dielectric material's dielectric properties. Thus, for example, capacitance and leakage currents are not sensitive to radiation-induced displacements in the dielectric of a capacitor, and the function of a stand-off insulator is not impaired by such displacement events.

The chief contribution of radiation-induced displacement events to radiation effects in modern electronic devices is through the ionisation which accompanies the displacement, generated by interactions between the electric field of the displaced nucleus with the electrons of other nuclei as it passes by on its way to its resting place. Such ionisation contributes to charge trapping, as discussed in Section 5.3.6.

Radiation-induced displacement in dielectrics is therefore rarely a functional problem. Moreover, dielectrics used in electronic devices are seldom required to have quite the same degree of purity as semiconductors, so that the creation of new defects has proportionately less effect. (By contrast, the action of existing defects in trapping charge generated by ionisation is the main cause of the radiation problem in MOS devices and glasses.) Possible exceptions to this are certain phosphors and photochromic materials in which the device principle involves the exchange of charge between a controlled number of defect levels. An example of such an exception is thermoluminescence in lithium fluoride dosimeters.

5.3.6. Ionisation in dielectrics

In space technology at the present time, the ionising effect of radiation on dielectric subelements is of particular significance. This is especially true in large- and medium-scale MOS integrated-circuit devices. The effect of ionisation in a dielectric will be the production and transport of charge in media which are specifically designed to be nonconducting. This motion will persist only while excitation continues. However, the permanent effects resulting from the motion of radiation-induced charge can be drastic, particularly the charge-trapping (space-charge buildup) in MOS gate oxides and bipolar transistor passivation layers. They may also be accompanied by rearrangement of atomic bonds in the dielectric semiconductor interface (interface state production) and, just possibly, by chemical decomposition (mainly in organic dielectrics under the most severe exposure). Much of the following paragraphs will be concerned with these permanent effects.

The potentially harmful effects of ionisation in dielectrics are diverse for a number of reasons. First, the variety of dielectrics employed is much greater than the variety of semiconductors. Second, the gap between valence and conduction bands of a dielectric is large; additionally, dielectrics are usually covalent compounds often involving several chemical elements. Thus, a large variety of trapping levels and excitations is possible, while polarisation effects may be long-lived. Third, impurity concentrations tend to be higher because, unlike semiconductors, processes analogous to "doping" are not commonly used; this being so, the need for rigorous preliminary refinement, as is essential for semiconductor materials, is removed.

Devices incorporating dielectrics will often be sensitive to the fields produced by charge-trapping since charge transport and trapping, sensed by its field effect, is sometimes used as a device principle (e.g. the NMOS device).

Table 5.(3) summarises the long-lived effects of ionisation in the dielectric subelements of a number of devices. The table is divided

according to whether the dielectric has an active or a passive electrical or optical function. The number of 'X' symbols gives a preliminary idea of the degree of sensitivity of a device to ionisation induced in its dielectric subelement and indicates the problems which may arise when the device is used in a severe radiation environment. However, the magnitude of the effect is not indicated. For example, it is possible that electroluminescent phosphors withstand larger doses than a photochromatic device which, though having 'X' symbols in the same three columns, is probably much sooner affected in memory storage capability than most phosphors in respect of luminescent efficiency.

5.3.7. Induced radioactivity

Any material exposed to the space environment becomes radioactive. Protons, neutrons, nuclei and pions are capable of transforming stable nuclei of any spacecraft material into radioactive nuclei by the removal of nucleons or, in the case of low-energy neutrons, by neutron capture. A wide range of radioactive nuclei is produced and these decay at a later time according to their characteristic half-lives. The majority decay by emitting a positron (beta+) or by capture of an orbital electron, often accompanied by gamma-ray emission while, in a few cases - such as neutron capture - emission of an electron (beta–) occurs. Such products have typical energies in the range 0.01 to 10 MeV. In space, primary protons are the most abundant particles producing radioactivity, while in thick materials activation by secondary protons, pions and especially neutrons becomes increasingly important. The total interaction cross-section for protons increases monotonically with energy, reaching a peak at 30 MeV, after which it falls slightly to a constant level for energies greater than 200 MeV. While total cross-sections are known to within 5%, the spallation cross-sections for production of particular radionuclides are mostly unknown, but can be estimated to within a factor of 2 by means of semi-empirical formulas. For high-Z target materials, some 200 radionuclides contribute significantly to the induced radioactivity.

In space, the most intense proton fluxes are to be found in the heart of the inner radiation belt where radioactivity is induced by the energetic proton component in the energy range 30 to 400 MeV. At altitudes below or above this trapped proton regime, the more energetic (GeV) cosmic rays dominate the induced radioactivity and the precise flux and level of induced activity varies with the geomagnetic latitude. At high altitudes (e.g. GEO or interplanetary space), solar flare protons can penetrate and will typically provide the major component of activation for some 20 days per year at solar maximum.

Doses due to induced radioactivity are small compared with the dose produced directly by the inducing radiation (Fishman, 1976). However, it is a major source of background in the performance of highly sensitive X-ray and gamma-radiation astronomy and remote-sensing spectroscopy. Induced radioactivity was first observed directly in a scintillation spectrometer carried on board the OSO-1 spacecraft following passages through the trapped radiation belt in the South Atlantic Anomaly region (Peterson, 1965). More detailed observations of induced radioactivity resulting from trapped protons were made possible by spectrometers carried on OSO's 3, 5, 7 and 8, HEAO's 1 and 3, the Solar Maximum Mission and DOD spacecraft 1972-076B and P78-1. Activity dominated by cosmic rays has been observed on APOLLO's 15, 16 and 17 operating in interplanetary space and on APOLLO- SOYUZ operating in LEO below the trapped radiation belts (Dyer et al, 1980). Packages have been returned to earth in order to monitor the radioactivity from APOLLO 17, APOLLO-SOYUZ (Dyer et al, 1980) and SKYLAB (Fishman, 1976).

Calculations of induced radioactivity in thin homogeneous materials can be made with the aid of methods and formulas given by Dyer et al, 1980 and Barbier, 1969, and based either on semi-empirical cross-sections or on ground-based irradiations using representative particle beams. To a first approximation, 1 radioactive decay results from each proton interaction so that a saturated activity of some 4 to 6 decays per second per kilogram of material is attained in a cosmic-ray flux of 1 particle $cm^2.s.^{-1}$ Trapped protons can be stopped by ionisation without interacting and, in general, are at least a factor of 3 less efficient in inducing a decay even under minimal shielding. The detailed decay behaviour and spectrum of emissions is a complex superposition of many radionuclides and required methods such as those described by Dyer et al, 1980. For heavy spacecraft, activation by secondary neutrons becomes important and particle transport calculations must be performed. Activation by neutron capture is very dependent on the spectrum of neutrons and the detailed cross-section of the material of interest, the former varying considerably with location as evidenced by results (Fishman, 1976; Dyer et al, 1980). For heavy detector systems, activation by secondary neutrons generated within the detector volume may dominate (Dyer and Hammond, 1985).

5.4. CONCLUSIONS - AN OVERALL VIEW OF DEVICE DEGRADATION

The complex nature of degradation effects induced by radiation has been indicated. Table 5(3) will serve as a useful summary of physical, chemical and functional effects, both long-lived and transient, caused by atomic displacement and ionisation in electronic device materials.

The reader may also refer to Figure 5.2 to obtain an indication of the general dose range at which the effects that have been described begin to degrade the function of various types of device and material. The information shown has been derived from tests in nuclear reactors on mass-produced devices and degradation results from neutron and gamma radiation. It is "general" in the sense that several mechanisms may combine to cause the general degradation of "utility" indicated by the bars. The fact that the bar indicating, say, "mild to moderate" degradation extends over perhaps six decades of radiation fluence is because one member of a class may degrade much more rapidly than another. For instance, a capacitor employing an organic dielectric (such as Mylar) may degrade more quickly than one employing an inorganic dielectric (such as mica). Even the mechanisms can be different and multiple; the Mylar device may develop leakage via the degraded dielectric, change capacitance owing to dimensional change, or rupture owing to gas release, while the mica would probably not suffer from any of these effects.

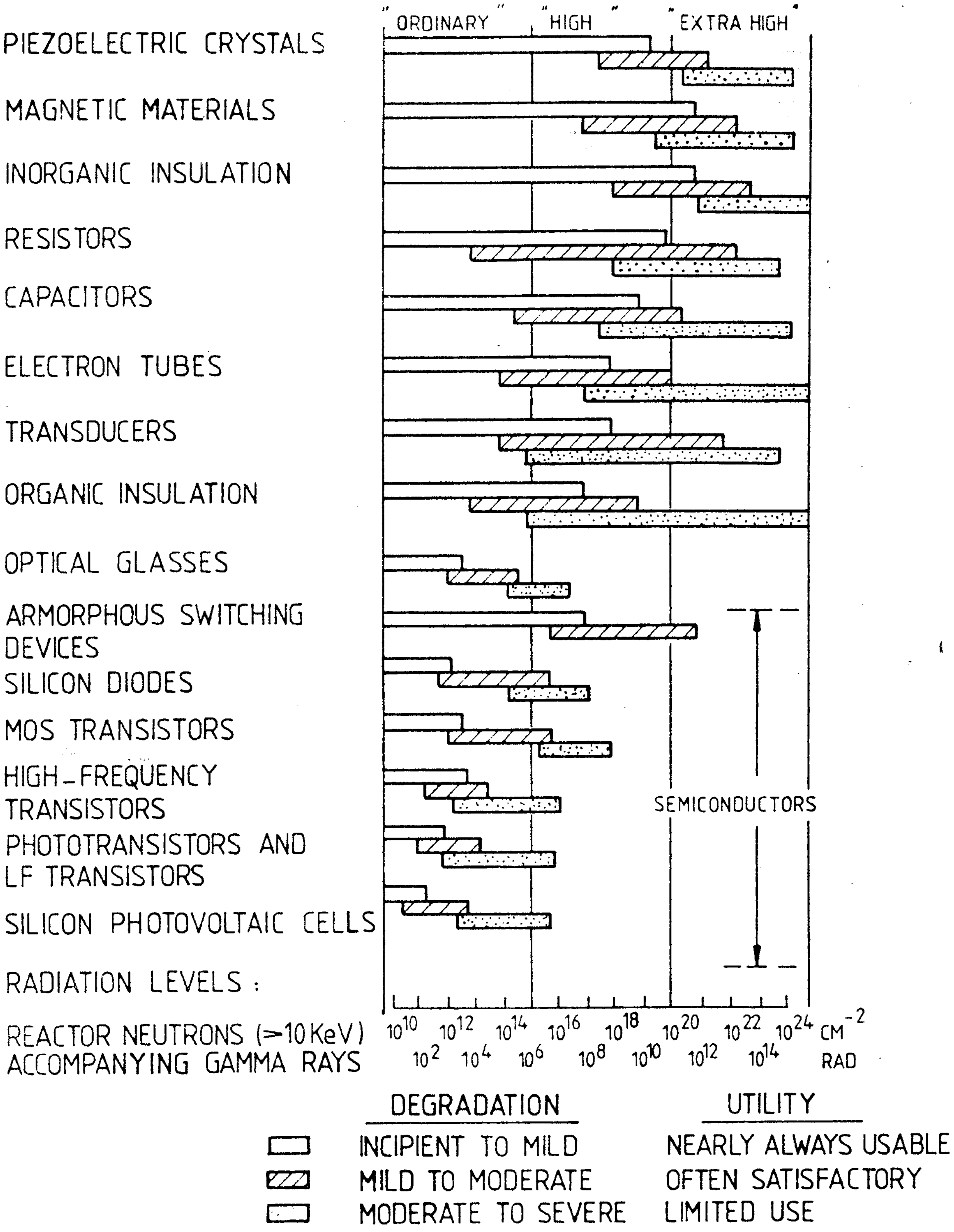
Two interesting points arise from the comparative data in Figure 5.2. First, the compilers found that, in general, the same positions of the bars resulted no matter whether reactor neutrons or 3 MeV electrons had been used for irradiation. This suggests that tests performed with one radiation environment in mind may also provide useful data for other environments (see Section 19 on radiation testing). Second, the radiation sensitivity of the semiconductor group is markedly apparent; few such devices survive far into the "high" range of radiation fluence.

Having provided a general review of the problem of radiation-induced degradation in devices and materials, this document will now concentrate on electronic components used in spacecraft technology.

TABLE 5(2) - ATOMIC DISPLACEMENT EFFECTS IN SEMICONDUCTOR DEVICES

XX - Primary failure mode
X - Secondary failure mode

Device	Carrier life-time reduction	Carrier removal by trapping	Carrier mobility decrease	Slow emptying of traps	Other
P-N JUNCTION DEVICES					
(a) Low reverse fields					
Bipolar transistor & SCRs	XX	X			
MIS (MOS) Field effect transist.		XX	X		
Variable-threshold MIS ,,	XX	X			
Junction FETs		XX	X		
Rectifying/blocking diodes	XX	X			
Tunnel diodes					X
Schottky barrier diodes	XX	X			
Junction photosensors	XX	X		X	
Opto-isolators	XX	X		X	
Junction electroluminescent diodes		X		XX	
MIS electrolumininescent diodes		X		XX	
Solar cells	XX	X			
(b) Avalanche devices					
Zener and IMPATT diodes	X	XX			
Surface-controlled Aval.diodes		XX			X
(c) Other					
Charge-coupled devices		XX		X	
Hall-effect devices		X	XX		
OTHER DEVICES					
Transferred electron devices		X		XX	
Photoconductive photosensors			X	X	
Storage photosensors			X	X	
Mechanical transducers		XX	X		
Ovonic threshold switches				X	XX
Ovonic memory cells				X	XX
Amorphous tunnel triodes				X	XX
Photostructural switches				X	XX
Cold cathode electron emitters	X	X	XX		



A comparison of the tolerance of various materials and devices to reactor irradiation.

FIGURE 5.2 - RADIATION EFFECTS

TABLE 5(3) - ORBITAL ENVIRONMENT

Typical ESA specification of Orbit-integrated trapped particle environments 2-year EXOSAT mission; Apogee: 200.000 km; Perigee: 200 km; Inclination: 80° (PT-PR-040 000, 1976)

Electrons		Protons	
Energy E MeV	Flux ϕ (E) cm^{-2} (2 yr)$^{-1}$	Energy Ep MeV	Flux ϕ (Ep) cm^{-2} (2 yr)$^{-1}$
0.1	0.782 E 14	0.1	0.112 E 15
0.125	0.434 E 14	0.5	0.394 E 14
0.25	0.149 E 14	1.0	0.133 E 14
0.375	0.912 E 13	2.0	0.245 E 13
0.5	0.775 E 13	3.0	0.762 E 12
0.625	0.544 E 14	4.0	0.355 E 12
0.75	0.393 E 13	5.0	0.219 E 12
1.0	0.220 E 13	6.0	0.138 E 12
1.25	0.137 E 13	7.0	0.867 E 11
1.5	0.861 E 12	8.0	0.549 E 11
1.75	0.550 E 12	9.0	0.436 E 11
2.0	0.353 E 12	10.0	0.346 E 11
2.5	0.143 E 12	11.0	0.275 E 11
3.0	0.525 E 11	12.0	0.219 E 11
3.125	0.375 E 11	13.0	0.175 E 11
3.25	0.268 E 11	14.0	0.139 E 11
3.375	0.192 E 11	15.0	0.111 E 11
3.5	0.138 E 11	16.0	0.890 E 10
3.625	0.788 E 10	18.0	0.729 E 10
3.75	0.450 E 10	20.0	0.600 E 10
3.875	0.258 E 10	25.0	0.374 E 10
4.0	0.148 E 10	30.0	0.238 E 10
4.125	0.665 E 9	35.0	0.156 E 10
4.25	0.264 E 9	40.0	0.104 E 10
4.375	0.984 E 8	45.0	0.717 E 9
4.5	0.317 E 8	50.0	0.507 E 9
4.625	0.126 E 8	55.0	0.473 E 9
4.74	0.398 E 7	60.0	0.444 E 9
4.875	0.102 E 7	80.0	0.346 E 9
5.0	0.233 E 6	100.0	0.272 E 9

TABLE 5(4) - IONISATION IN DIELECTRICS: LONG-LIVED EFFECTS CHARACTERISED

Device	Charge excitation		Structural change	
	Re-trapped locally	Charge transport	Bonding changes only	Decom-position
SUBELEMENT HAS ACTIVE ELECTRICAL FUNCTION				
Charge storage				
Variable threshold transistors	–	–	–	–
Storage photosensors	–	X	–	X
Special MIS systems (e.g. Everhart EB-addressed MOS arrays, MOS dosimeters, FAMOS memories)	–	X	–	–
Charge emission				
Photo-emitters/multipliers, photo-tubes/channes/multipliers, etc.	–	X	–	–
Charge transport				
Tunnel emission cathodes	–	–	–	–
Filamentary switches	–	–	X	–
Other transduction				
Pyroelectric detectors	–	–	–	X
Acoustic surface wave devices	–	–	–	–

TABLE 5(4) - IONISATION IN DIELECTRICS: LONG-LIVED EFFECTS CHARACTERISED (Continued)

Device	Charge excitation		Structural change	
	Re-trapped locally	Charge transport	Bonding changes only	Decom-position
PASSIVE ELECTRICAL FUNCTION				
Bipolar, MOS and CCD devices	–	X	–	–
Josephson devices	–	–	–	–
Spacers in IC's				
- Metallisation separators	–	X	X	–
- Surface encapsulation layers	–	X	X	–
- Dielectric substrates	–	X	–	–
Capacitor insulators	–	X	X	X
Stand-off insulators	X	X	–	X
ACTIVE OPTICAL FUNCTION				
Light-beam modulators	X	–	–	X
Light-beam deflectors	X	–	–	X
Storage medium				
Photostructural switches	–	–	X	–
Photochromic memories	X	X	X	–
Thermoplastic memories	–	–	X	X

TABLE 5(4) - IONISATION IN DIELECTRICS: LONG-LIVED EFFECTS CHARACTERISED (Continued)

Device	Charge excitation		Structural change	
	Re-trapped locally	Charge transport	Bonding changes only	Decom-position
Phosphors and display media				
Laser media	X	–	X	–
Cathodoluminescent phosphors	X	–	X	–
Electroluminescent phosphors	X	X	X	–
Thermoluminescent phosphors	X	X	–	–
Scintillator	X	–	X	X
Dark-field displays	X	–	X	–
PASSIVE OPTICAL FUNCTION				
Lenses and filters	X	–	X	–
Interference coatings	X	–	X	–
Light guides	X	–	X	X
Thermal-control coatings	X	–	X	X
Glass dosimeters	X	–	X	–
PASSIVE MECHANICAL OR THERMAL FUNCTION				
Corrosion-protection coatings	–	X	X	X
Refractory layers	–	–	X	X
Nuclear-fuel encapsulants	–		X	X
Thermal inlsulators	X	X	X	X
Solid-lubricant systems	–	–	X	X

REFERENCES

M. Barbier, "Induced Radioactivity", Amsterdam, London, North Holland Publ. Co. (1969).

W.L. Brown, J.D. Gabbe and W. Rosenzweig Bell System Technical Journal 42 (4) 1505-1559 (1963).

C.S. Dyer, J.I. Trombka, S.M. Seltzer, L.G. Evans, "Calculation of Radioactivity Induced Gamma Ray Spectrometers During Spaceflight", Nuclear Instruments and Methods, Vol. 173, p. 585 (1980).

C.S. Dyer and N.D.A. Hammond, "Neutron Capture Induced Radioactive Background in Spaceborne, Large Volume, NaI Gamma Ray Spectrometers", IEEE Trans. Nucl. Sci. NS-32 (6), p. 4421 (1985).

A.G. Holmes-Siedle, Reports on Progress in Physics, 37, pp. 699-769 (1974).

H.E. Johns and J.R. Cunningham, "The Physics of Radiology", C.C. Thomas, Illinois (1971).

L.E. Peterson, "Radioactivity Induced in Sodium Iodide by Trapped Protons", J. Geophys. Res., Vol. 70, p. 1762 (1965).

J.R. Srour, S. Othmer and K.Y. Chiu, ibid, pp. 2656-2662 (1975).

V.A.J. Van Lint, G. Gigas and J. Barengoltz, IEEE Trans. Nucl. Sci. NS-22 (6) 2663-2668 (Dec. 1975).

G.K. Wertheim, Phys. Rev. 105 1730 (1975).