SECTION 17. EQUIPMENT DESIGN PRACTICE

17.1. INTRODUCTION

The most common starting-point for equipment radiation effects and shielding analysis is the dose-depth curve for the particular mission. A first-cut at the shielding analysis can be made by determining the dose corresponding to the most lightly shielded part of the subsystem under evaluation. If the dose is tolerable then clearly no further analysis is necessary. Tolerability is obviously determined on the basis of device testing which is crucial. It must be borne in mind that, apart from dose, an evaluation of single-event upset and latchup, and possibly displacement damage effects, may need special consideration. A device-and-location combination which appears satisfactory from a total dose perspective is not necessarily immune from all radiation effects. If a problem is identified, more extensive analysis of shielding will be necessary, possibly including a detailed sector-analysis of the whole or a part of the spacecraft.

17.1.1. Materials

Among the large variety of synthetic materials which go into a spacecraft, there is a wide spread of radiation tolerance. Materials with high tolerance include all metals, many ceramics and inert gases. Tolerance in the semiconductor, optics and polymer fields ranges from "fair" to "very poor". To the former class belong bipolar ICs, rectifying diodes and "hardened" MOS circuits; to the latter, devices such as commercial MOS circuits, analogue devices, power transistors and solar cells. At the present time, the degradation of materials other than semiconductor devices, optics and polymers is, where typical space missions are concerned, generally considered as a secondary problem.

It is certain, however that degradation will present a major problem in future missions involving, for example, high-performace electronics and sensors, spaceborne nuclear power sources and particle accelerators.

17.1.2. The importance of layout

In previous sections, we have predicted the likely amount of degradation for various types of semiconductor devices in a spacecraft, where they usually lie behind a structure which attenuates the radiation. It is clear that the designer must always attempt to put equipment boxes containing the more sensitive devices in protected locations; to surround them with structures containing less sensitive materials.

This implies that equipment layout and system sensitivity to space radiation are intimately connected. Layout, packaging and circuit design all contribute to the radiation tolerance of a spacecraft and, hence, its life expectancy in space. Thus, if a high-radiation mission is planned, a complex "radiation effects engineering" process has to be brought into equipment design practice. The aim of this discipline is to produce a space vehicle of maximum capability (for example with the maximum number of communication channels or scientific experiments) which will survive for a maximum period of time at minimum penalty (attributable to the radiation environment) in cost and launch weight. This section introduces some design rules which may be applied and gives also some examples of current practice in analysing existing spacecraft.

17.1.3. Built-in versus add-on shielding

To avoid confusion, a strict distinction is made here between the "built-in" and "add-on" protection of components. Although all mass surrounding a specific component can be regarded as "shielding" or protection, much of that mass serves some other primary, usually structural, purpose. We will describe this type of protection as "built-in" as opposed to "add-on" shielding. In this context, a neutral term used here for radiation-stopping material is "absorber". (Owing to its ambiguity, the term "screening" is not recommended.)

The ultimate aim of the design practice described in this section is to use "built-in" shielding such that the need for "add-on" shielding is minimised. In other words, layout has a fundamental importance in the design of a radiation-tolerant spacecraft.

17.2. TYPICAL SPACECRAFT CONFIGURATIONS AND MATERIALS

17.2.1. General

The detailed layout of a spacecraft may have quite a strong influence on the radiation dose reaching the silicon chips which are the focus of our interest. For example, if the system designers opt for a spinning satellite, the solar array will be drum-shaped and act as shielding.

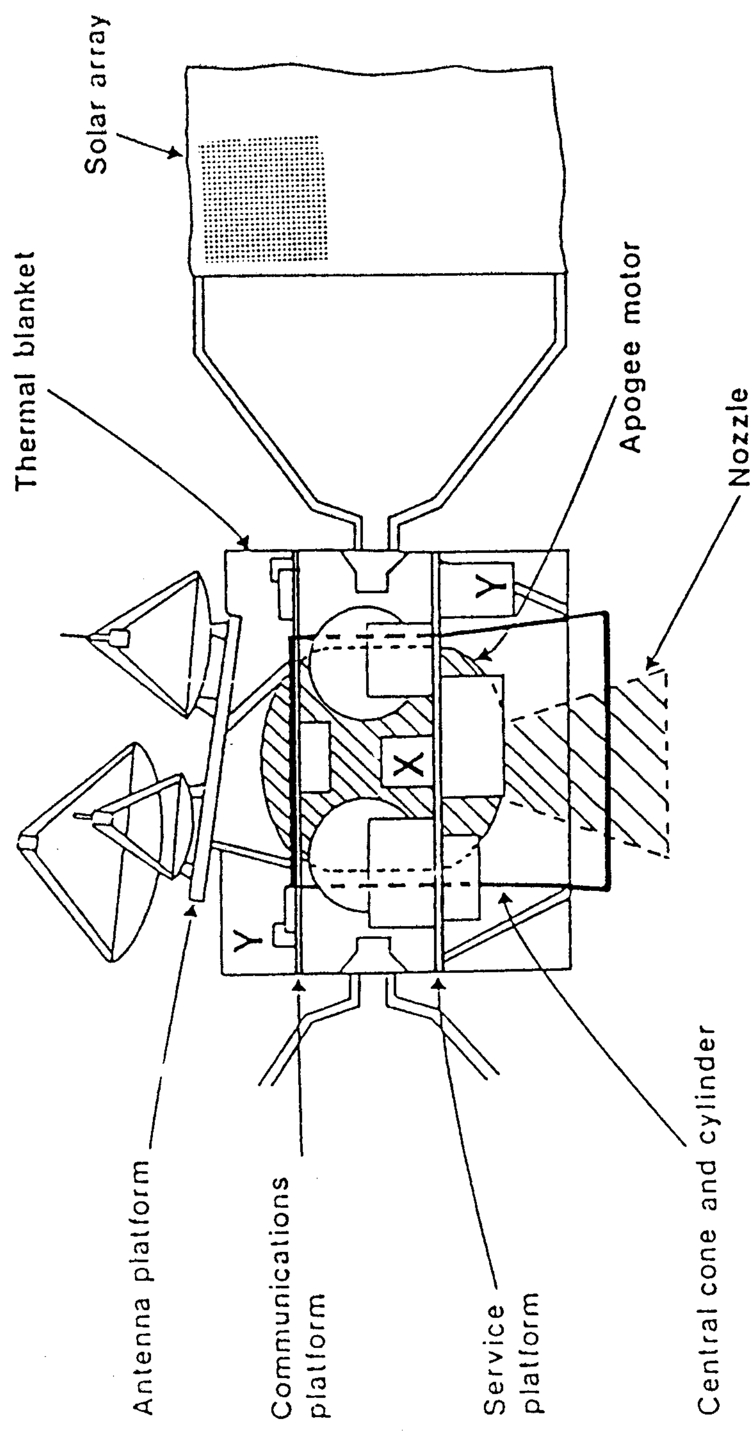
The shielding effect of a wrap-around solar array will be the equivalent of 3 to 4 mm of aluminium. As we shall see later, this is a significant addition (possibly 30 kg) to the built-in shielding provided by platforms, box covers and circuit boards. To give another example: an integrated circuit in the centre of a stack of printed circuit boards may be exposed to only one-tenth of the dose received by the same circuits on the uppermost board of a stack. Similarly, equipment boxes near the edge of a platform receive more dose than those near the centre. As an example, Figure 17.1 shows the lay-out of the OTS satellite, the forerunner of the Olympus series, which operates in a geostationary orbit. The equipment is secured to two parallel platforms attached to a central cylinder which, in turn, is jointed to the launcher via a conical transition section.

The apogee boost motor provides good built-in protection from at least one sector.

17.2.2. Box covers

Many equipment boxes designed by European industry are made up of sections milled out of solid aluminium with certain parts milled very thin as a weight-saving measure. As will be explained later, such an absorber array gives less protection than the uniform sheet-metal enclosures more common in the USA. This is a case of the general rule that good built-in protection from radiation is a matter of total mass as well as efficient mass distribution. This same rule applies not only to box structures, but also to the arrangement of masses around a box containing sensitive devices. Clearly, some point such as 'X' in Figure 17.1 is a suitable one for the placing of radiation-sensitive equipment while points such as those marked 'Y' are not suitable because they do not make good use of the built-in spacecraft mass.

To calculate the dose levels at a given point within a given box, all radiation-absorbing masses present in the satellite have to be taken into account. These, of course, constitute an extremely complex array of masses, but we must calculate as closely as possible how they contribute to radiation-stopping. This is done by "sector analysis" - calculating the solid angle subtended at a given point of interest ("dose point") by a given mass. Computer programs to perform this task are widely available and are described in Section 18.



The central core of the satellite, by which it is attached to the launch vehicle, carries parallel platforms to which electronic equipment is secured.

FIGURE 17.1 - LAYOUT OF THE OTS SATELLITE

17.2.3. Radiation-absorbing properties of a spacecraft structure

17.2.3.1. A light weight structure (SMOP)

Figure 17.2 shows the dimensions of a typical spacecraft core structure (platforms, central cylinder and thrust cone with struts) which was designed by Contraves to give optimum structural mass for a 720 kg, Thor-Delta launched, spacecraft. This design, named SMOP, provides for a mass of 20.6 kg, distributed as follows:

- centre cylinder + core: 7.3 kg,
- lower platform: 7.1 kg,
- upper platform: 5.4 kg,
- struts : 0.8 kg.

The average mass density of the platform appears to be between 0.22 and 0.28 g.cm^{-2}, equivalent to between 0.8 and 1.0 mm of Al. In fact, the platform deck itself will contain even less absorber than this since much mass will be concentrated in attachment points, mechanical connectors and stiffeners. The facings ("shims") of the carbon fibre honeycomb used were only 0.15 mm thick; those on OTS were of similar thickness, but made of aluminium foil (2). Thus, the shielding capability of a platform is very low, probably less than 0.5 mm Al equivalent. The core of the SMOP design was made of aluminium sheet of less than half the thickness used for OTS (e.g. 0.15 versus 0.4 mm for the cylinder; 0.2 versus 0.6 mm for the core).

17.2.3.2. The apogee motor as an absorber

The spent apogee-kick motor within the central structural cylinder of a space vehicle forms a large part of a geostationary spacecraft mass. A description of the OTS motor and its treatment as an absorber of radiation is given here for guidance in future projects.

The "total inert" material in the OTS motor (Aerojet SVM-7A) has a mass of 32.237 kg, approximately 3% of the total system weight. The fuel compartment can be represented as a fibre-reinforced plastic cylinder (780 mm in diameter and 682 mm in length) which is, in fact, rounded at the ends. The nozzle, composed of carbon felt and reinforced plastic, is a cone extending about 700 mm at one end. The fuel compartment fits within the central cylinder and thrust cone of the space vehicle.

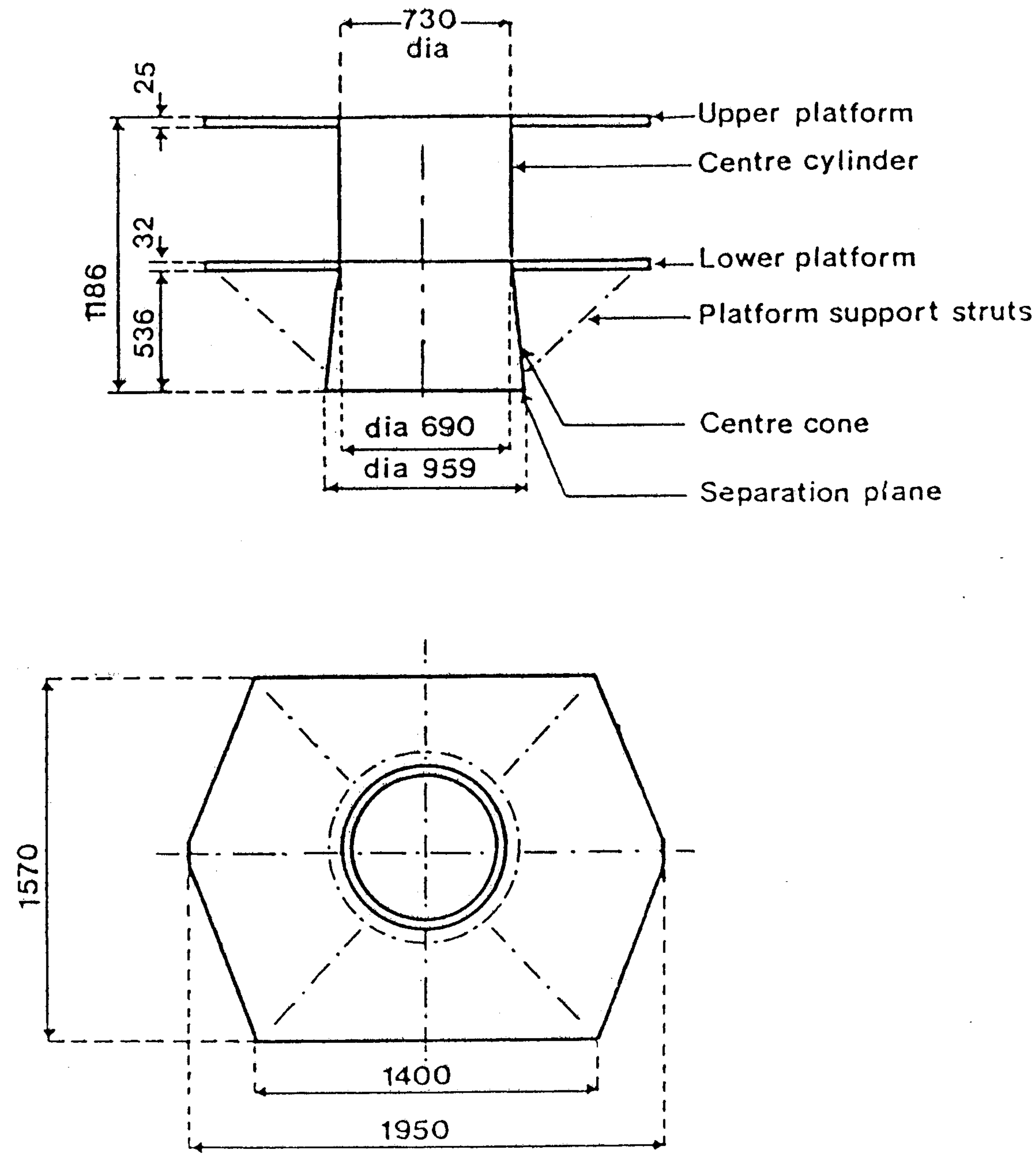


FIGURE 17.2 - A TYPICAL SPACECRAFT (SMOP STUDY)

The central cylinder and thrust cone are made of aluminium honeycomb and corrugated aluminium sheet. The cylinder has an outer diameter of 816 mm and a length of 770 mm, and the cone flares from the same diameter to one of 972 mm in a length of 457 mm.

In a normal sector analysis, the radiation-absorbing mass of the fuel chamber is represented by a cylinder of aluminium sheet of about 2 mm thickness and the nozzle by a cone of about 3 mm thick aluminium sheet. The central structural cylinder and cone can be represented as being of 0.6 thick aluminium sheet. Thus, a particle passing radially through the central part of the space vehicle will have traversed an amount of absorber equivalent to at least 5-6 mm of aluminium. For a box on one of the equipment platforms, especially one of those on the inner faces of the platforms, the central column may subtend more than π steradians (i.e. more than a quarter of the whole sphere). Clearly, the excellent protection given by this large absorber of radiation should be assessed carefully and included in sector analysis calculations. When designing add-on shields, considerable weight can be saved by reducing added mass on the side of the box protected by the motor and column.

17.2.3.3. Antennae as absorbers

On OTS, the six communication antennae are very light dish structures, their thickness being equivalent to about 0.2 mm discs of aluminium, covering less than 50% of the top platform area. The antennae platform is also of light honeycomb of total thickness equivalent to about 0.3 mm aluminium and covering only the centre portion of the top platform.

17.2.4. Typical spacecraft materials

A space vehicle is composed of a large number of small components of widely varying materials. Annex C lists the materials used by one spacecraft contractor and likely to be included in the electronic subsystems and a table of polymers likely to be used in spacecraft. It will be impossible to assign a solid angle to every component in the spacecraft and some form of "homogenisation" of the small parts into an equivalent solid sector of representative atomic number will be necessary for a "manual" calculation of dose.

17.2.5. Conclusions

The analysis of typical designs of geostationary spacecraft shows that:

a) Shielding power often resides mainly in the central structure and not in the equipment platform, and

b) Refinements in mechanical design reduce the built-in protection from some quarters.

The reason why it is difficult to assess the true protection given by the built-in mass is the fact that the mass is divided between a few large structures and a large number of small components.

17.3. SECTOR ANALYSIS

As stressed previously, the application of "single material" dose-depth curves, while useful for preliminary estimation, is not entirely adequate for the detailed design of engineering models. With this limitation in mind, the manual estimation of doses received by devices within sectored structures will now be considered, so that rules for reliable predictions of operating lifetime may be developed. Considering that each part of the spacecraft acts as a radiation shield, even though this may not be its prime function, the need for "sector analysis" is obvious.

A device in operation will clearly not be surrounded by a uniform thickness of material, but by a complex array of spacecraft components and structures as well as the material associated with the mounting of the device itself. It will be necessary to divide the complete structure into a number of sectors, each subtending a solid angle at the device or "dose point". Within each of these sectors, the shielding should be roughly uniform. The dose at the "dose point" arising from radiation through each sector is derived from the appropriate dose depth curve, taking into account the characteristic thickness and, if possible, atomic number of absorber in that sector. The sector dose will be the appropriate fraction of the dose arising from uniform "all-round" shielding and the "total dose" will be the sum of all sector doses.

Obviously, there is scope for considerable variation in the degree of sophistication with which this technique is applied, but some such sectoring method must be used if the life of a component in space use is to be estimated. The choice between the "single layer" approximation as described here and the more complex "multilayer" calculation has been discussed earlier.

A simplified sector analysis which has been used in preliminary design studies is described here as an illustration. In this case, the solid angle subtended by each sector has been estimated as a simple fraction of 4 π. A more rigorous calculation of solid angle may be made, for example, by using the following trigonometric expression:

$$\text{solid angle } \Omega = 4 \arctan \pi \; \frac{ab}{c(a^2 + b^2 + c^2)} \qquad \ldots\ldots 17(\text{i})$$

where the solid angle is subtended at the dose point by a rectangle 2a x 2b. The dose point is at a perpendicular distance c from the centre of the rectangle. For small sectors, this expression approximates to:

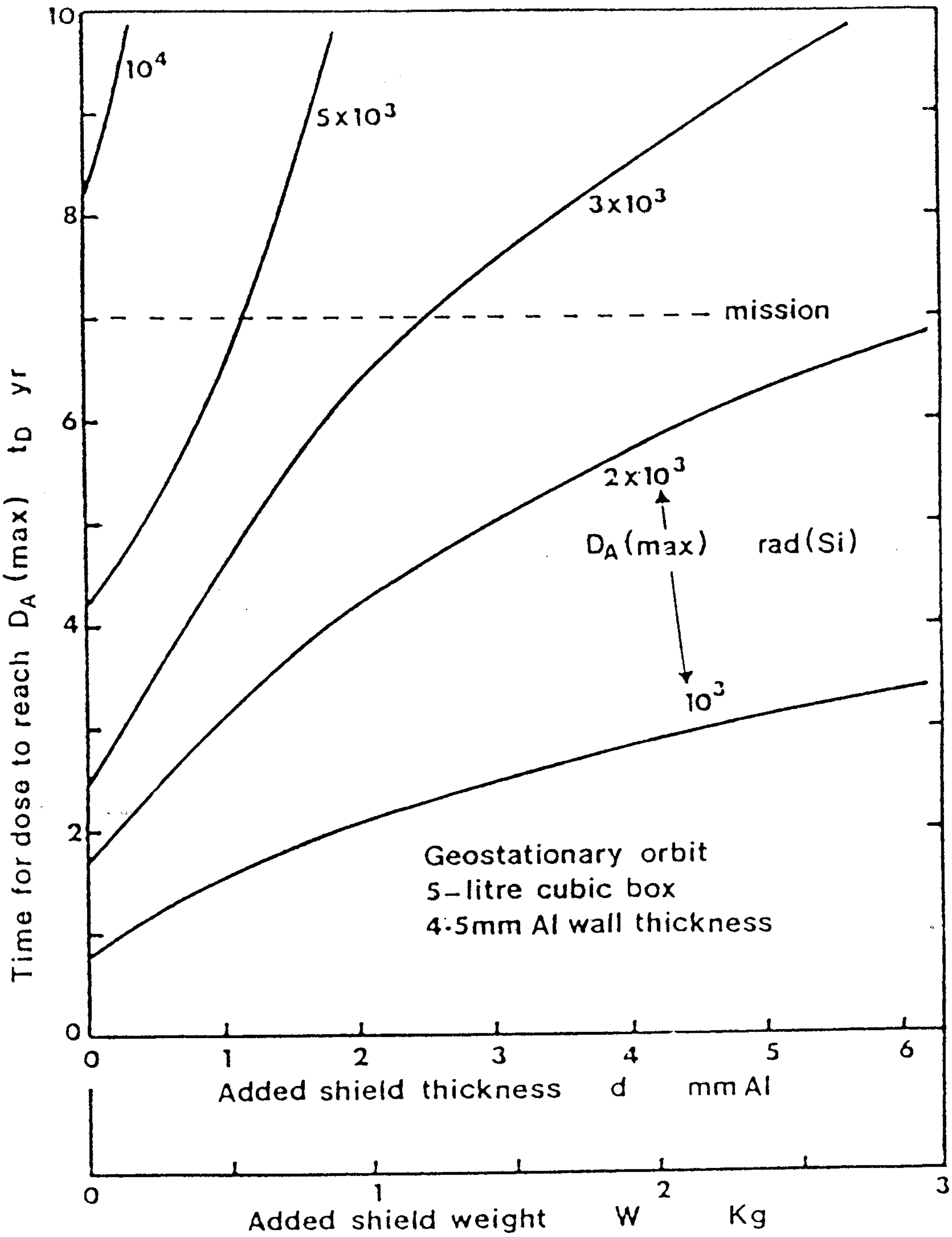
$$\Omega = 4ab/c^2 . \qquad ......17(ii)$$

Employing a computer to perform detailed sector analysis is obviously easier than calculating by 'hand'. Various methods are described in Section 18. An important prerequisite for such an analysis is the mass breakdown and dimensions of the spacecraft elements. Once these are available, the computerised geometrical model can be established, the mass values being used to ensure correct allocation of shielding.

The ideal situation is where the prime contractor's layout of the spacecraft is available in computerised form for subcontractors, experimenters or others to perform a detailed computerised sector-analysis. The most important detail in a sector-analysis is the region close to the point of concern. Therefore the subsystem engineer or experimenter can take the 'global' satellite model, including the masses of all the elements, and introduce the detailed description of the contents of his "box" and its immediate surroundings. This was been done for Cluster by Dornier, using ESABASE (see Section 18) to establish the model which was then communicated by ESTEC to experimenters via computer network.

Once a model is established, various parametric analyses are possible, including optimisation of orbit and design of special shielding elements. This was done during the process of orbit selection for XMM (Daly et al., 1992). Apart from predicting dose (or flux) levels at a point, computerised sector analysis can give graphical information on directions which are poorly shielded, and indeed a full distribution of shielding thicknesses.

An important point to bear in mind when performing sector analysis is that it may not always be appropriate to consider the external environment to be isotropic (uniform in all directions). This was discussed in detail in Section 3. This is a particular problem at low altitudes where there are very strong east-west and pitch-angle anisotropies. Gravity-gradient stabilisation on LDEF, for example, and a similar attitude control on the Space Station mean that different parts of these spacecraft are exposed to very different environments. Therefore it must be emphasised that it makes almost no sense to perform a sectoring shielding analysis unless the anisotropy is accounted for at the same time.



Time taken to reach "maximum acceptable dose" as a function of added shielding. The sensitive component is within a 5 litre cube of initial wall thickness 4.5 mm aluminium. Additional thickness is added uniformly.

FIGURE 17.3 - TRADE-OFF CURVES - GEOSTATIONARY MISSION

17.4. ADD-ON SHIELDING

17.4.1. Introduction

If built-in mass on the spacecraft cannot be arranged so as to protect all sensitive components, then - as a last resort - some "add-on" absorber may have to be judiciously added. The choices that have to be made include:

(a) The elemental composition,
(b) The location,
(c) The method of attachment.

The question of elemental composition has been discussed earlier. Here, the possibilities for add-on shielding are classified by its location and method of attachment. Added shielding can be considered as either "local" or "whole box". Figure 17.3 shows a reasonable scheme for subdividing types of protection. It should be noted that "efficient use of "built-in (existing) mass" is put first. The use of add-on shielding should be regarded as a last resort after the former approaches have been exhausted, essentially because of the high price of payload per kg and the high "revenue" which useful payload can earn. The saving in deadweight can thus be equated to the increase in "revenue", whether this be cash from telecommunications traffic or scientific returns from experiment packages.

The first aim of add-on shielding is to interpose a few millimetres of any suitable material between the device of interest and the external environment. If the array of devices to be shielded is small, we can save weight by enclosing the array in a compact shield rather than build the same thickness onto the outside of the equipment. This is the idea of "local" shielding: simply to obtain a given dose reduction in a given volume for the minimum weight penalty. For instance, a single integrated circuit would best be protected by a blob of filled plastic applied directly to the package or by using thicker Kovar for the covers. We will call this type of shield a "spot shield".

The particle-scattering property of materials has some dependence on the atomic weight. This is weak in the case of protons and strong in the case of electrons. Thus, the choices of atomic weight for an add-on shield in a proton-dominated orbit such as that of Exosat might differ from that for an electron-dominated orbit such as the geostationary case where high-Z materials can dramatically attenuate electron and bremsstrahlung doses (see Section 16).

17.4.2. On-PCB Shielding

17.4.2.1. Spot-shielding

The simplest type of shield is one totally surrounding the device and lying close to it. Alumina-filled plastic would have the insulating power needed and could be given suitable mechanical strength to resist vibration. With ICs, the shield might have to be in two parts: one above and one below the board. Screw-on fins have been designed for ICs, so screw-on shields could also be designed. The USAF has successfully procured CMOS devices with Kovar lids about twice the usual thickness.

A new design of package incorporating radiation shielding has been developed for the USAF (Schmid et al, 1985); for the U.K. AMPTE satellite, tantalum spot-shielding was applied to the lids of certain CMOS circuits. Calculations of layered shield have shown that the dose in geosynchronous orbit can be reduced to 200 rads for 10 years.

17.4.2.2. Edge of board

Under the heading of "Efficient Use of Built-in Mass" comes the use of other active components on the same board. These, if arranged properly, can supply absorber mass in exactly the most critical direction - the line of view through the thin box walls. However, only the middle area of the board gets full benefit of this mode of shielding. On the other hand, if we put add-on mass around the edge of the device area, the whole of the board gains full benefit.

17.4.2.3. Internal slabs

The types of shield so far described protect only one plane of a single component. If a whole plane or several planes are sensitive to radiation, then the region involved can be sandwiched between two slabs of material. Such a slab would be bolted onto the lower frame element where the clearance with respect to the next board allows this. In certain cases, foam sheets could be inserted or potting compound could be poured into the module after fabrication. In extreme cases, an empty module - carrying only the add-on absorber - could be inserted.

17.4.3. Whole box shielding

17.4.3.1. Bolt-on slabs

The simplest way of adding mass to a box might appear to be by bolting a slab of plastic or metal to the outside. In fact, this is rarely convenient because:

a) Suitable bolting may not be available on the outside of the box and

b) The shield may foul other boxes or cables lying close to the sensitive box.

The latter difficulty may sometimes be dealt with by using a very dense material such as lead, tungsten or tantalum, but these may generate excessive bremsstrahlung if the low-energy electron fluxes from space impinge directly. High-Z materials perform best once an initial 1-2 mm aluminium shielding has removed these electrons so that fresh bremsstrahlung generation is minimised.

17.4.3.2. Thickened walls

If the precise amount of shielding needed is known at the beginning of the design, then box walls can be designed to the required thickness over and above that needed for mechanical strength. Many boxes are milled out of solid metal and hence this need not present mechanical difficulties. It has already been noted that, for radiation-sensitive boxes, thin areas of box wall are to be avoided. Such thin areas are sometimes produced when mechanically unnecessary material is milled away. As discussed, the thickening of a whole box is likely to be uneconomical in weight unless every component in the box requires shielding.

17.4.4. The quantitative effect of add-on shielding

Table 17(1) shows the range of doses for typical locations in a geostationary satellite.

For Exosat, the mission dose for a component within the Star Tracker electronics box was calculated as 4.4 krad. This dose was equivalent to an even thickness of 3.3 mm aluminium completely surrounding the component. It is instructive to calculate the effect on total dose of adding "whole box" shielding to this component. Table 17(2) shows the result of adding such aluminium shielding in successive 1 mm steps.

It is clear from the table that successive additions of shielding results in smaller reductions in accumulated dose. This is due to the bremsstrahlung background. The addition of further shielding in excess of 4 mm will have an insignificant effect on dose. The added weight will, of course, continue to penalise performance. It is therefore recommended that always a comparison be made between the penalties and benefits of added shield weight.

17.4.5. Conclusions

Shield types can be classified as "local", "whole-board" and "whole-box"; each may be needed at different times. Modularity in these shields is useful, but not essential. The shields used must be simple and easily applied. There is a strong incentive to apply the shielding only to the volume which really requires it (e.g. only one area of a printed circuit board); this arises from the cubic relationship between weight and linear dimension. In different cases, the shield may be poured or moulded plastic, aluminium or a very dense metal. Attachment to the device lid by adhesive has been found acceptable for some spacecraft. Complex layered shields have been designed.

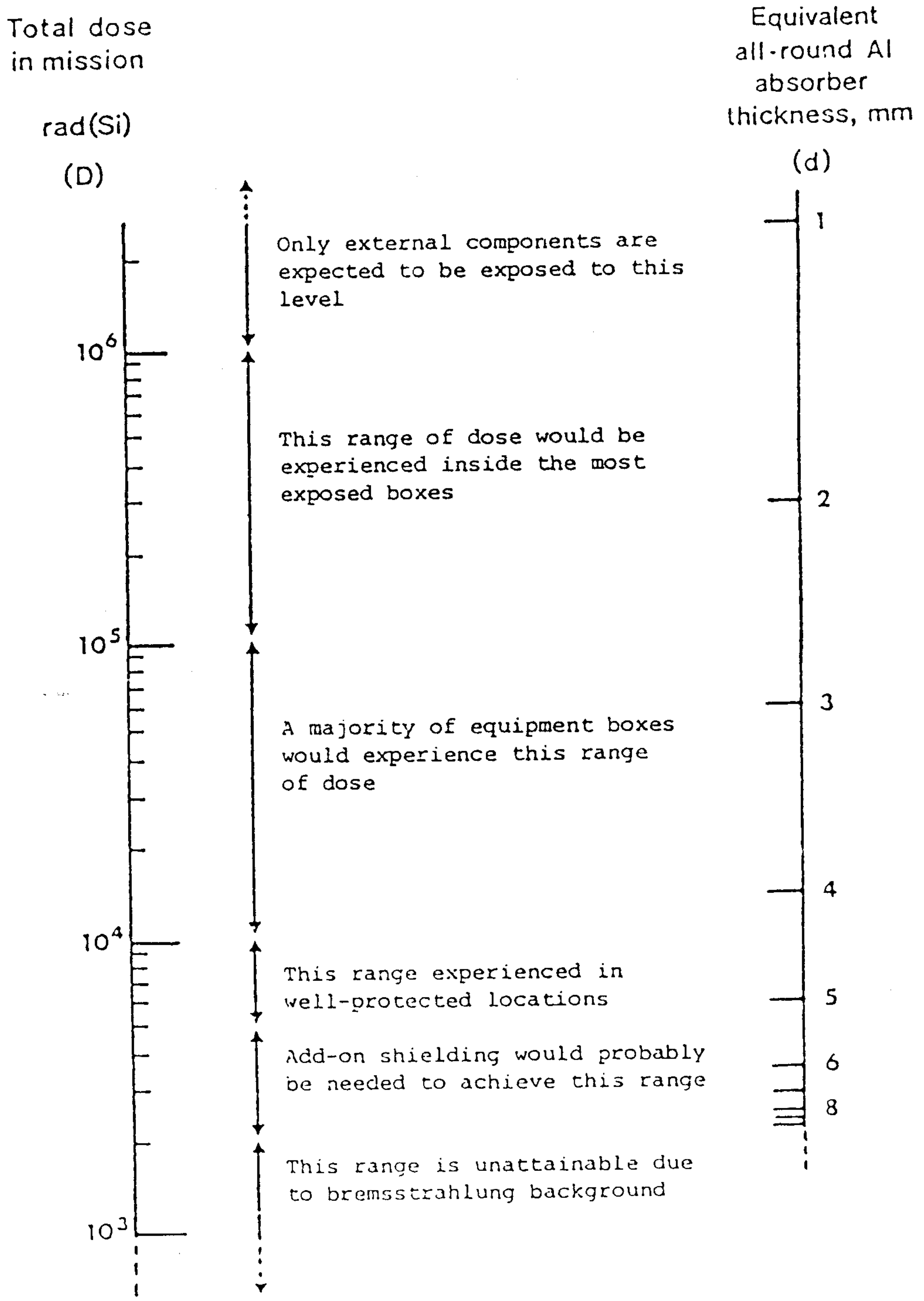
17.5. TRADING-OFF SHIELD WEIGHT AGAINST DEVICE ALTERATION

For long-term geostationary missions, as shown in Figure 17.4, the control of radiation tolerance of devices is critical. In the example illustrated, a sensitive component is placed inside a 5 litre cubic aluminium box with a 4.5 mm wall thickness. The time required for the maximum acceptable dose, D_A (max), to be reached is shown as a function of added shielding. For a device with a D_A (max) value of 10^3 rads, it is impossible to add sufficient shielding to make the device survive the desirable 7-year mission. Even with thick shields (3 kg), it will barely survive half the mission. Raising D_A (max) to 3×10^3 rads allows 7-year survival by applying less than 1.5 kg of shielding; when D_A (max) is raised to 5×10^3 rads, only about 0.5 kg will be necessary. The "hardening" has occurred at the best point in the system, namely in the device. The cost penalty of "hardening" to this rather low level may only amount to that incurred by the radiation testing involved. The cost saving in weight reduction or life enhancement may be many times the cost of a well-designed series of laboratory tests.

Figure 17.5 shows similar curves for a hypothetical, exposed Exosat box. Here, unlike the geostationary case, the most sensitive device can survive the mission with 2 kg of shielding while, with D_A (max) of 10^4 rad, scarcely any special absorber is necessary.

The curves shown are, of course, only examples and specific to one particular component location on one space vehicle. However, they present the combined information on sector analysis, testing results (including recovery), physics theory and circuit analysis in a concise form that the system engineer will find useful.

TABLE 17(1) - SUMMARY OF DOSES WITHIN SPACECRAFT STRUCTURES



7-year Geostationary Mission

TABLE 17(2) - THE EFFECT OF ADDITIONAL SHIELDING ON THE EXOSAT STAR-TRACKER ELECTRONICS BOX

Total protection	2-Year dose krad (Si)	Dose reduction effected by added shielding
As designed	4.4	–
+ 1 mm Al*	2.4	45%
+ 2 mm Al	1.6	64%
+ 3 mm Al	1.15	74%
+ 4 mm Al	0.92	79%
+ 5 mm Al	0.89	80%

(*) all-round protection

17.6. ON-BOARD RADIATION MONITORING

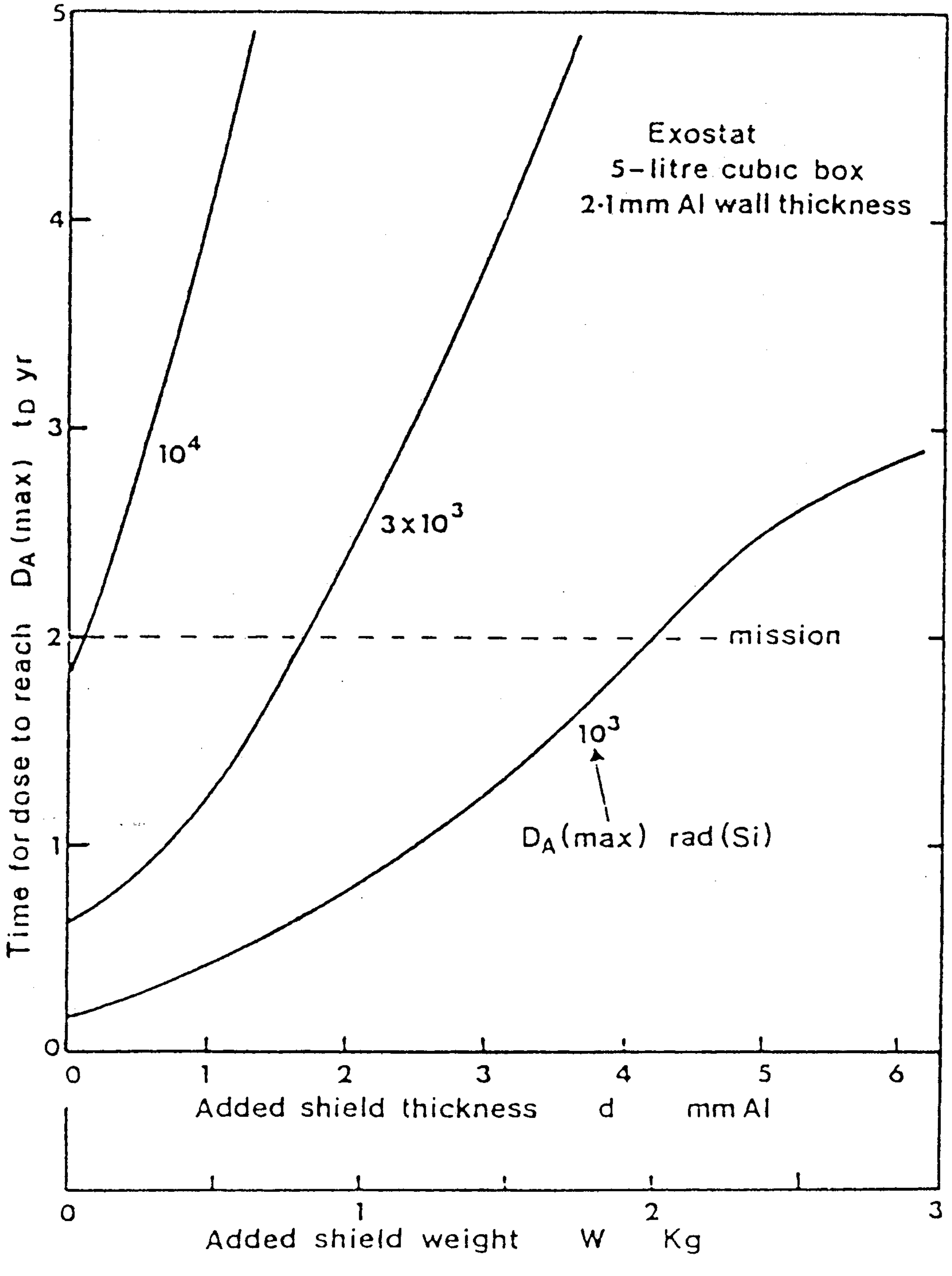
17.6.1. The need for monitoring

The extensive analytical methods described in this handbook inevitably involve a large number of approximations and may thus be subject to quite large percentage errors in the prediction of radiation exposure at a given dose point and the resulting device degradation. Just as thermal-control calculations are ultimately verified by the installation of thermocouples in space vehicles and telemetry of temperatures in orbit, it is desirable to install small radiation monitors in equipment boxes both to check predictions for future reference and to provide operations staff with guidance on stressing and life of equipment during the mission. Until now, only bulky power-consuming particle pulse detectors such as nuclear diodes and geiger counters have been used and then only as special payload on scientific satellites.

17.6.2. The development of a radiation monitoring unit (RMU)

A concept for such a sensor has only recently become available. ESTEC has designed a trial RMU which may be installed on several spacecraft as a non-interfering "passenger". Figure 17.6 illustrates the principle of a device which was installed on the GEOS-2 spacecraft. The RMU contained five MOS transistors especially processed for high sensitivity to radiation (Holmes-Siedle, Adams, Pauly & Marsden, 1985). Different devices are shielded by different thicknesses of aluminium. Power, mass and data requirements of such devices are very low.

Information from these RMUs was telemetered periodically and served to verify the basic dose-depth curves for the mission. A more accurate adjustment of shielding mass can be made in future missions and possibly also a cost-saving relaxation of radiation specifications on devices. Future versions placed inside operating boxes near key MOS LSI devices will give evidence of the precise operating conditions of these crucial control circuits and indicate when control should be switched to back-up units (e.g. if radiation-induced functional failure appears imminent).



Time taken to reach "maximum acceptable dose" as a function of added shielding. The sensitive component is within a 5 litre cube of initial wall thickness 2.1 mm aluminium. Additional thickness is added uniformly.

FIGURE 17.4 - TRADE-OFF CURVES – EXOSAT MISSION

17.6.3. Particle counting monitors

Small semiconductor counting detectors are useful when temporal data are required, or when particle species or energy discrimination is required. Charge pulses generated by particles passing through the semiconductor material are pulse-height analysed and counted (see e.g. Knoll, 1989). An example of this type of monitor is the Radiation Environment Monitor (REM) built by CIR and PSI for ESA (Daly et al., 1992). The price paid for the flexibility and more comprehensive data return of such devices is the requirement for power (~2W) and mass (~1kg) to accommodate them.

17.7. SUMMARY OF DESIGN RULES

17.7.1. General rules

(a) Device degradation predictions must be prepared in time to influence lay-out and circuit design;

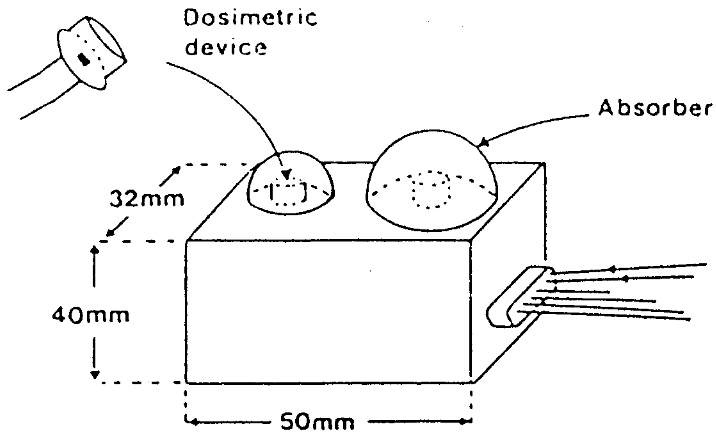
(b) Device selection can increase spacecraft life for no increase in weight.

17.7.2. Measures at device level

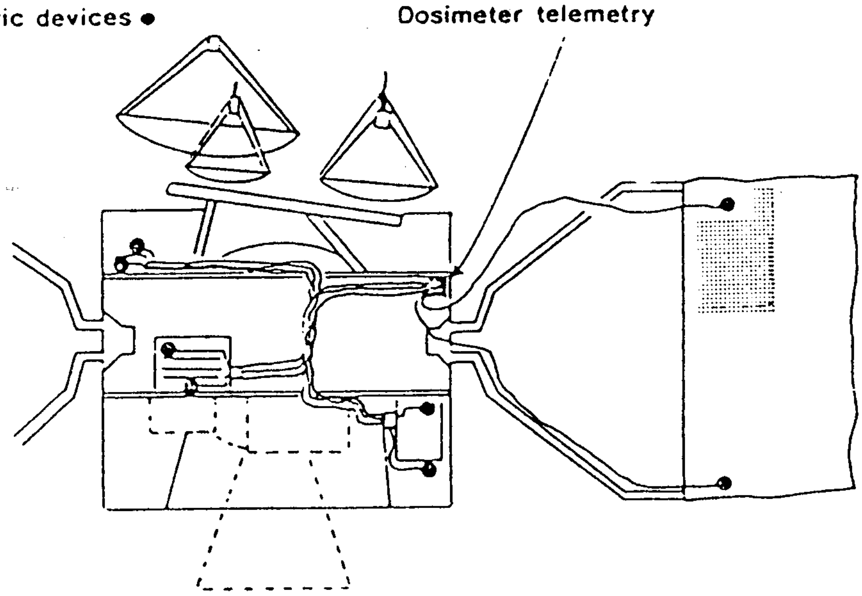
(a) Introduce redundancy as widely as possible: this can be "on-chip" (gate functions reassigned periodically) or "standby redundancy" of whole subsystems. The object is to allow "time off" for active recovery of charge build-up.

(b) Favour LSI where reasonable. This allows larger numbers of functions to be shielded with a small mass. However, note that LSI technology is sometimes less tolerant to radiation than the corresponding SSI.

(c) Avoid a mixture of logic technologies (e.g. TTL, CMOS and PMOS) as compatibility may be degraded by radiation. Also, the supply voltages may have to be higher than strictly necessary.



a) ESA self-contained radiation measurement unit (RMU, ESA, 1977)



b) Distributed dosimeters (Future)

Design and distribution of on-board dosimetry:
(a) Current version,
(b) Future distribution of miniature-head version.

FIGURE 17.5 - RADIATION MONITORING UNIT

17.7.3. Circuit design rules

(a) Discrete bipolar transistors

1. Predict and prescribe allowances for degradation of gain, increase of junction leakages, etc.
2. Select by manufacturer and lot.

(b) Bipolar digital circuits

1. Prescribe decreased fan-out.
2. Prescribe minimum collector current (especially with I^2L).

(c) MOS circuits

1. Classify devices by the values of parameters A and $\Delta VT(sat)$.
2. Predict device life and trade shielding against cost, etc.
3. Minimise electrical stress (V_{DD}, "Time On", etc.).
4. Decrease speed and output drive requirements.

(d) Bipolar analogue circuits

1. Prescribe allowances for:
   (i) decrease in open loop gain,
   (ii) input offset currents and voltages,
   (iii) output drive and maximum slow rate.
2. Make trade-offs as for MOS.

(e) CCDs and image sensors

1. Decrease storage times.
2. Allow for an increased dark current.
3. Trade off as for MOS.

(f) Other components - assessment

Perform radiation tests on:

- Voltage regulators,
- Diodes,
- Thyristors,
- Optoisolators,
- Other photosensors and LEDs,
- Glass optical components,
- Other classes of device deemed to be of dubious tolerance to radiation.

17.7.4. Layout for optimisation of built-in protection

(a) Avoid placing sensitive components on top of boards.

(b) Assemble as many sensitive components together as possible for mutual protection and site the box containing them near massive structural elements. Co-planar arrays of IC packages provide especially good edge-on protection for each other.

17.7.5. Add-on shielding

(a) The minimum weight of add-on shielding is obtained by small dense local shields (i.e. large solid angle subtended by small mass). For trade-off purposes, a figure of merit for shielding in units such as "rads per gram" should be utilised.

(b) Even small solid angles can admit large amounts of radiation if the absorber in the path of that radiation is thin (say, less than 1 mm).

17.8. CONCLUSIONS

Cost-effectiveness in performance of satellites operating in a space radiation environment is achieved only if a coherent engineering approach to radiation effects is adopted. The approach summarised here requires some advanced physical techniques in device selection and the calculation of shielding. The use of these hardness engineering techniques in a space project should therefore be assigned a priority measured by both the orbital environment and the requirement of that project for MOS LSI devices and other radiation-sensitive technologies.

It should be emphasised that each part of a spacecraft acts as a radiation shield.

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