SECTION 18. COMPUTER METHODS

18.1. INTRODUCTION

Earlier discussion indicates the complexity involved in estimating radiation effects within a spacecraft. Often, the designer will be provided with environment data in the form of orbit-averaged particle flux spectra for the project under consideration. However, such data can be generated by the use of the environment models described in Section 3 and their associated computer programs. The environment is also often specified in terms of the "dose-depth" curve giving the dose as a function of depth of shielding in a simple geometry (slab or sphere). The necessary end-point is most often the estimation of the radiation dose likely to be received by a particular device at a particular point within the spacecraft structure. "Manual" methods were described earlier, but powerful computer codes now serve as the main tools for the engineer. Some problems require an explicit computation of particle flux and this requires special computational techniques, in particular Monte-Carlo methods discussed in Section 18.3.2.

An overview of the radiation analysis problem is given in Figure 18.1. The steps necessary to provide the final dose can be summarised as:

(a) Prediction of orbital and mission particle fluxes,
(b) Generation of a spherical-geometry "dose-depth" curve from (a),
(c) Extrapolation of (b) to complex spacecraft geometries by means of sectoring, accounting for shielding afforded by various parts of the real spacecraft.

Simplifying assumptions are made in separating steps (b) and (c). A rigorous analysis would require that the geometry be explicitly considered as the dose is computed - such methods are usually of the "Monte Carlo" type described below.

Manual methods may be useful for a preliminary dose assessment, but the simplifications introduced may introduce undue error at the detailed design stage where highly detailed computer-based sector analysis of the spacecraft structure can be performed very efficiently.

A brief review is given here of the various computer programmes and their methods. Calculation of single-event upset rates is also described.

18.2. ENVIRONMENT CALCULATIONS

The environment models described in Section 3 are available on computer tape from the WDC-A-R&S (NSSDC) at NASA/GSFC and

can be used to produce the required particle flux spectra. To do this, they must be used in conjunction with an orbit generator, giving the spacecraft trajectory and a geomagnetic field program to provide the corresponding B-L coordinates of the trajectory. ESA/ESTEC have integrated these steps together in the UNIRAD system (Daly, 1988) which also includes programs for dose and equivalent fluence calculations. Recently a PC-based version has been marketed by Severn Communications Corporation in the U.S.

18.3. DOSE AND FLUX COMPUTATION

Over the last two decades, a number of computerised methods have been developed to handle the complete problem. Some of these are complex and require considerable computer capacity; some of them employ simplified approaches, making certain reasonable approximations. These methods are in wide use and are recommended especially when geometrical and material complexities of spacecraft are considered. Programs are available in Europe via the program library of the Nuclear Energy Agency (operated by the OECD). Some programs are also available from ESA and others from NASA via the COSMIC software agency. CERN have also developed the GEANT particle transport code.

It should be noted that many older programs are not designed for universal application, have poor documentation and/or are not clearly coded. These are important considerations when one is selecting codes, as the cost of circumventing such problems may be high.

18.3.1. Particle types to consider

18.3.1.1. Electrons

Problems to be dealt with in computing the transport of electrons through materials are electron scattering and the production of brehmsstrahlung (see below). Most interactions between energetic electrons and the electrons and atoms of the material through which they are moving involve small energy losses and trajectory deflections. This makes the computational treatment of electron transport difficult.

18.3.1.2. Protons

Because of their mass, protons do not undergo significant scattering in travelling through a medium. They slow down, losing energy quasi-continuously, in a straight line. Therefore, the well-known range-energy relation can be applied quite simply to their motion. Occasionally, protons produce secondary particles when they collide with atomic nuclei. Such "spallation products" are important in contributing to single-event-upset or radiobiological damage; computational treatment of these interactions is difficult.

18.3.1.3 Bremsstrahlung (photons)

As electrons slow down in material, they generate bremsstrahlung photons with a distribution of photon energies and directions. Photons subsequently interact through a number of processes (photoelectric, Compton, pair-production), resulting in loss or scattering. Photon transport calculations are therefore also difficult.

18.3.1.4 Other particles

The above three particle species are the main concern for total dose problems. A number of secondary particles can be produced in the interactions between protons or heavier ions and the spacecraft material, or in the residual atmosphere in low Earth orbit. These can include secondary protons, neutrons, spallation fragments and more exotic nuclear particles.

Continuous exposure to space radiation can also lead to "activation" of spacecraft material which then emits radiation.

Finally, on-board nuclear sources, e.g. thermoelectric generators, can be an important source of radiation.

These various "second-order" radiations must be considered in circumstances where there is a specific sensitivity to them, e.g. in manned flights and for interference with instrument detectors.

18.3.2. "Monte Carlo" techniques

Monte Carlo techniques numerically follow the trajectories of large numbers of particles and predict their interactions in the material through which they are travelling. Interactions usually have distributions of possible outcomes to which random sampling is applied. For electrons, successive individual interactions are too numerous to follow; instead, attention is given to a small section of the electron's path containing a large number of individual interactions. The net result of all the interactions can be expressed analytically and, at the end of each section, the electron energy loss is computed and its direction is altered by random sampling of a scattering distribution. The section length is chosen such that the energy loss in the section is a small fraction of the electron energy. This is the "condensed history" Monte Carlo technique (Berger, 1963).

Monte Carlo techniques can also be used to compute the transport and interactions of other particles and their secondaries, including bremsstrahlung, neutrons etc.

Some Monte Carlo programs include particle transport and interactions in complex geometries while others consider simple slab geometries. Some commonly used programs are:

GEANT3 (Brun et al., 1987, Alison et al., 1987).
GEANT has been developed at CERN for analysing problems in high-energy physics. Flexibility of problem definition is provided by the user writing a Fortran "main program" with calls to GEANT subroutines for geometry definition, initial particle properties and tracking and event data retention. The lower energy limit for most particles is 10 keV. GEANT is well supported by CERN, with many ancillary packages (graphics etc.) and network communications, and runs on a variety of computers.

ITS/Tiger (Halbleib et al., 1992)
The Integrated Tiger System, ITS provides three versions for analysing coupled electron-photon transport in 1, 2 and 3 dimensions and energies from 1 keV to 1 GeV. As a successor to the ETRAN codes, the electromagnetic shower physics is dealt with very rigorously.

HETC (Deitz, 1986)
The High-Energy Transport Code, HETC is a 3-dimensional code for full treatment of the transport of ions and associated secondaries (including protons, neutrons, pions and muons).

EGS4 (Neslon, Hirayama and Rogers, 1985, Nelson and Namito, 1990)
The Electron-Gamma Shower (EGS) code is a rigorous 3-dimensional code for simulating the electron-photon transport problem. Here again, the user writes elements of the analysis program, which call the EGS subroutines.

Typical outputs of the electron-bremsstrahlung codes are:

- Transmission and back-scatter of electrons and photons,
- Production of bremsstrahlung by electrons and its transport,
- Spectrum of energy deposition in a thick target by an electron beam,
- Flux spectra as a function of depth in the material and
- Deposition of dose as a function of depth of shielding (dose-depth).

18.3.3. Dose "look-up" table methods - SHIELDOSE

If one is always dealing with a simple (e.g. slab) geometry, then - for an incident particle of a single energy - the generated dose per unit fluence at a given depth of shielding will be the same. Seltzer (1979, 1980) has created a large data set containing the dose per unit of incident fluence as a function of depth of aluminium shielding and particle energy. The total dose at a given depth of shielding for a given incident particle spectrum is then found by summing the contributions from each particle energy, considering

the incident flux at that energy and the time duration. This method was presented in Section 16.6.

Seltzer's data set is created with the ETRAN Monte Carlo code (a forerunner of ITS) considering all the relevant physics, and his SHIELDOSE program can rapidly give the dose for any arbitrary input spectra. Protons are treated according to their range-energy relation with nuclear reactions neglected. Figure 18.2 shows the three simple geometries considered by SHIELDOSE. If one is not interested in performing a geometrical analysis, the appropriate geometry to choose will depend on the location of the particular dose point. However, the slab case may be too optimistic in practice since it represents a situation where there is relatively good shielding in most directions. The widespread use of the slab model stems from the fact that it is easier to compute doses with slabs than with spheres. The sphere case is more conservative because in a slab there are longer paths through the material in directions away from the normal. In subsequent sectoring, the sphere case should be used, since slant paths in a laterally infinite slab are meaningless when a small solid angle about a particular direction is considered.

This program is interfaced with the environment spectra and included in ESA's UNIRAD system.

18.3.4. Straight-ahead approximation methods

Simpler and shorter alternatives of full Monte Carlo codes exist where analytical methods have been developed for specific application to spacecraft. These include:

- CHARGE (Lilley and Yucker, 1969; available from NEA) and
- SHIELD (Davis and Jordan 1976; available from COSMIC).

These simpler codes assume in the first instance that particles travel in straight lines and, according to the basic range-energy relations, lose energy continuously. Corrections are applied to account for the angular effects and the "degraded" spectrum is computed at a number of depth intervals in the shielding. These methods have the advantage over SHIELDOSE that they can treat the effects due to material differences. They can consider laminations of materials in simple (slab, sphere) geometries. Differences between materials are not completely accounted for by normalising the thickness to density to give g/cm^2 (or by converting to the equivalent aluminium thickness).

18.3.5. The CHARGE program

In the case of electrons, an attempt is made to account for the effect of their angular scattering by applying "transmission coefficients" derived from Monte Carlo runs. For example, CHARGE uses the empirical relationships developed by Mar.

Bremsstrahlung is treated in CHARGE by using the Koch and Motz model for generation with transmission based on the exponential attenuation model of Goldstein. "Build-up" factors are applied to account for bremsstrahlung angular distribution effects.

As indicated above, proton-slowing can be treated well by straight-ahead methods.

The ability of CHARGE to treat laminations of different materials has been used in an ESTEC study (Daly and Adams, 1984), where the program was assessed and then applied to the problem of predicting the shielding efficiency of various laminations of high-Z and low-Z materials.

CHARGE can also optionally calculate the dose from secondary protons and neutrons. Typical dose-depth curves from CHARGE are shown in Figure 18.3. This shows the dose in water behind very large thicknesses of aluminium shielding (100 g/cm^2 is about 37 cm). At "normal" thicknesses (i.e. a few millimetres), the dose from secondary protons is almost two orders of magnitude lower than that due to primary protons. The incident proton spectrum in this example is "a typical trapped-proton spectrum". Other proton-

generated particles, e.g. muons, pions, electrons or positrons, are not treated by CHARGE owing to insufficiency of data. Alsmiller (1964) has shown that the doses due to muons and photons can be ignored if present understanding is reliable.

Given the appropriate fluence-to-response conversion functions, CHARGE can compute rad doses, rem doses for biological effects and activation response.

SHIELD, developed particularly for the analysis of the VOYAGER spacecraft, overcomes some of the deficiencies of the CHARGE program with electrons of energies greater than 10 MeV encountered in the Jovian environment. The Mar formula used by CHARGE was based on the lower electron energies found in Earth orbit.

Recently, efficient deterministic one-dimensional alternatives to Monte Carlo analysis have been developed for space application. These are the CEPX/ONELD discrete ordinate code for electron-photon transport (Beulter et al., 1991), the BRYNTRN code for nucleon transport (Wilson et al., 1989) and the HZETRN code for heavy-ion transport (Shinn and Wilson, 1992).

18.3.6. Sectoring analyses

Application of one of the simple-geometry techniques can produce the dose-versus-depth relationship which can be combined with solid-angle sectoring to produce an approximate dose at a point in a representative model of the spacecraft geometry. Often, the engineer is provided with this dose-depth curve as a specification of the environment. Sectoring is only an approximation since the angular scattering of electrons and angular distributions of bremsstrahlung are not explicitly treated. Used independently of the dose-depth curve, sectoring is useful for computing the distribution of spacecraft shielding about a particular point.

Manual methods for sectoring calculations were described previously, but computer programmes are available for the task:

- ESABASE/Radiation, an ESABASE analysis module (Daly, 1988; available from ESA),
- SIGMA II, developed for JPL (Davis and Jordan, 1976; available from COSMIC) and developed from SIGMA I/B (Jordan and Yucker, available from NEA),
- MEVDP, AFWL (Lilley and Hamilton, available from NEA).

As an ESABASE module, ESABASE/Radiation has the advantage of the use of the ESABASE "pre- and post-processing" visualisation utilities for geometry checking and 3-D display of results. The spacecraft geometry is defined in terms of simple shapes and the dose-depth curve taken automatically from the SHIELDOSE

program in the UNIRAD system which is fully integrated into ESABASE. ESABASE/Radiation, in common with other sectoring methods, employs ray-tracing where a large number of rays are followed out through the geometry; intersections with structure materials are found and the total shielding thickness along each ray computed. The elemental solid angles around the rays are used to "weight" the interpolated dose values from the the (4.pi) dose-depth curve at the appropriate depth values and an integration performed over all rays and solid angles. Thus, a highly detailed sectoring of complex spacecraft geometries is possible. ESABASE/Radiation is well documented and is being continually developed. Figure 18.4 shows the constituent part of ESABASE/Radiation and the data-flow between them.

SIGMA operates on basically the same principle. Multiple attenuation curves can be input, for example individual radiation species doses and ion fluences. Dependence on material of the attenuation of the various input radiation species can be partially accounted for by specifying different thickness-normalising factors for each material and radiation type. The usual tracing of the rays, accounting for their slant paths through materials, is augmented by a "minimum path" estimation to give the minimum shielding a multiply scattered electron would encounter. Parametric shielding calculations are possible where the sensitivity of the dose to additional "spot" shielding is computed. The COSMIC package containing SIGMA II also contains the shield optimisation programme SOCODE and the SHIELD program described above.

However, in common with other older programs, SIGMA with its limited documentation is quite difficult to use. The original SIGMA, still available through the NEA, was extremely difficult to use for the definition of complex geometries since it was necessary to define the shield structure in terms of bounding surface quadratic equations, and voids also had to be explicitly defined. The SIGMA II program available through COSMIC, has improved geometry definition facilities and no longer requires void specification.

18.3.7. Comparisons

While it is not the objective of this brief review of computer methods to make rigorous comparisons between the various approaches, a number of specific instances where comparison has been possible are given.

18.3.7.1. Charge validation examples

The CHARGE documentation contains a number of comparisons made by way of validation of the code. Agreement with other calculations of primary proton dose is good. Secondary nucleon doses are reasonable when compared with Monte Carlo results. Electron doses computed by CHARGE were found to be higher

than with other Monte Carlo methods, the disagreement being within a factor of 2 at normal shield thicknesses.

18.3.7.2. Bremsstrahlung dose - CHARGE and "manual" methods

The CHARGE documentation includes tabulated data for dose in water behind aluminium shielding in an elliptical polar orbit for which a trapped-electron spectrum is given. The bremsstrahlung dose calculated by the manual approximation is 0.6 rad (H_2O)/ month. The dose calculated by CHARGE is between 0.4 and 0.5 rad (H_2O)/month, depending on shield thickness. This correlation is considered to be reasonable.

18.3.7.3. Electron dose - CHARGE, SHIELD and BETA

Davis and Jordan (1976) compared the two "simplified" programs and the BETA Monte Carlo program in the calculation of an electron depth-dose curve for the Jupiter environment. The flux is isotropic upon a spherical aluminium shield with the dose point at the centre. Excellent agreement is obtained for shield thicknesses of up to 4 g/cm^2 (15 mm). Divergence thereafter is probably due to the weakness in CHARGE with electrons greater than 10 MeV energy.

18.3.7.4. Electron transmission - BETA, ETRAN and experiment

The BETA documentation contains a number of comparisons between experimental electron and bremsstrahlung transmission data which show very good agreement. ETRAN results have also been reported (Berger, 1968) and these too agree very closely with experimental data.

18.3.7.5. Comparisons between CHARGE and SHIELDOSE

The results of the ESTEC study mentioned in Section 18.3.3.1 showed that:

- In spherical geometry, there is good agreement between proton and bremsstrahlung doses;
- In slab geometry, the CHARGE bremsstrahlung dose is 2 to 3 times higher;
- SHIELDOSE predicts electron doses 2 to 3 times higher than CHARGE in spherical geometry, but agrees well in slab geometry. This is probably due to the solid sphere geometry of SHIELDOSE with account taken of back-scattered electrons;
- SHIELDOSE should be used as a tool for routine analysis with CHARGE available for situations where materials are important.

18.3.7.6. Comparisons between ITS and related codes and experiment

Lockwood et al. (1976) found very good agreement between the energy deposit in various multilayer geometries computed by an

early version of the TIGER code and experimental measurements. Sanford et al. (1985) reported on comparisons of measured doses of bremsstrahlung produced by 0.75 MeV electrons incident on Ta/C targets with doses calculated with the CYLTRAN Monte Carlo code. Again, close agreement over a wide range of Ta target thicknesses and angles was found. Kensek (1992) reported several other comparisons between experiment and the predictions of ITS and CEPXS/ONELD codes wich resulted in very good agreement.

18.4. SINGLE-EVENT UPSET PREDICTION

18.4.1. Ion-induced SEU

Pickel and Blandford (1980) first reported the basic method for single-event-upset-rate computation ("CRIER" - Cosmic-Ray Induced Error Rate). Cosmic-ray environments have since been comprehensively modelled by Adams and co-workers at NRL (Adams et al., 1981), on the basis of satellite data for cosmic-ray and flare ion fluxes. They developed the CREME suite of programs (Adams, 1986) which include these models, together with upset-rate computation which is functionally equivalent to Pickel and Blandford's method. The environment available from CREME include solar-cycle modulated GCR fluxes for most ions, 10% worst-case GCR fluxes, anomalous component fluxes and anomalous, worst-case and ordinary flare fluxes including mean or worst-case composition. Earth shadowing and transport through shielding material are also considered. For treating geomagnetic shielding, CREME computes an orbital attenuation function on the basis of Shea and Smart's world map of vertical cut-off rigidities. Energy and LET spectra are produced, the latter being composites of the fluxes of all ions as functions of ion stopping-powers (dE/dx) in silicon. CREME has data files of stopping-powers and ranges of cosmic-ray ions in aluminium and silicon for computing shielding effects and particles LETs.

To compute an upset or hit rate for an electronic device or a detector from the predicted fluxes, device characteristics must be specified, particularly the size of the sensitive volume and the critical charge, or equivalent, critical energy E_C, in the volume which results in upset (bit-flip) or registers as a "count'. The rate is found by integrating over the composite differential LET spectrum, $\phi(L)$, and the path-length distribution for the sensitive volume, p(l):

$$U = S/4 \int_{E_c/L_{max}}^{l_{max}} p(l) \int_{E_c/l}^{L_{max}} \phi(L)\, dL\, dl$$

where S is the total surface area of the sensitive volume. Integration limits are set by the sensitive volume dimensions and the critical energy E_C; E_C/L_{max} is the shortest path capable of supporting

upset, l_{max} is the maximum path length, E_C/l is the minimum particle LET necessary to cause upset on a path length l and L_{max} is the maximum LET of the spectrum. Figure 18.5 shows an overview of CREME.

Ion-beam tests can establish the threshold LET, defining the critical charge ($E_C = L_C$ x depth), and saturation cross-section, giving information about the sensitive volume. However, all the upsetting "bits" may not be the same, and often no sharp threshold in LET is apparent. In these cases, an integral over the measured response curve may be performed (Harboe-Sorensen et al., 1986). The upset-rate computation is sensitive to the value chosen for this critical charge, and derived from the LET threshold, because whereas particle fluxes fall rapidly with increasing LET, the sensitivity increases rapidly. Sensitive volume dimensions may be deducible from device technology data which is best obtained from the manufacturer, since to obtain the necessary information by "reverse engineering" is quite an extensive task.

The CREME program is used by ESA for evaluations of critical devices in various environments (Daly, 1988).

18.4.2. Proton-induced upsets

In Section 16.11.1, the phenomenon of proton-induced single-event effects was described. As with the computation of ion-induced SEU described above, proton-induced SEU rate prediction depends heavily on testing. Bendel and Peterson (1983) have described a method for making predictions of in-orbit proton-induced error-rate which is simple, provided the upset cross-section of a device as a function of proton energy is available from ground-tests.

The CREME programs include the BENDEL program, which implements the above model. This program requires an input proton spectrum which must be derived either from the AP8 trapped proton models or a solar proton model. The test data are characterised by the 'A' parameter which is chosen so that the standard model cross-section versus proton energy upset curve follows the test results most closely. A is the "apparent threshold" of the device.

It is often difficult to fit a unique A parameter to the test results. Recently Shimano et al. (1989) reported a two parameter modification which performed better. Stapor et al. (1990) gave a slightly different variant of this model and reported on the importance of a two-parameter model for newer devices with small feature sizes.

18.5. CONCLUSIONS

This section has provided a brief review of the many computer methods which are now available for performing analyses of particle fluxes and radiation doses in simple and complex models of spacecraft structures.

When one is using simple geometries for routine dose computation, the sphere case is preferable to the slab case unless the use of the latter can be justified by the location of a specific component in the spacecraft. Shielding in a single slab model is relatively good in most directions.

The use of the programs described in this section enables one to assess the environment and doses in spacecraft, considering the mission and structural materials and geometry. Their use is recommended as an integral part of the detailed spacecraft design phase.

The ESABASE/RADIATION module is designed as an easy-to-use tool for calculating mission radiation environments. The sectoring method makes it possible to use the UNIRAD suite of programs and the resulting dose in a complex model of the spacecraft geometry. It is recommended that this be used when necessary and where possible.

Figure 18.4 shows the constituents and data flow in the ESABASE/RADIATION module.

Alternatively CHARGE or SHIELD can be combined with SIGMA to compute doses in complex geometries.

If a high degree of accuracy is required, especially for problems where particle fluxes and interactions need explicit analysis, the Monte Carlo methods of Section 18.3.2. should be employed.

Single-event upset sensitivity should be assessed with the CREME program together with device data.

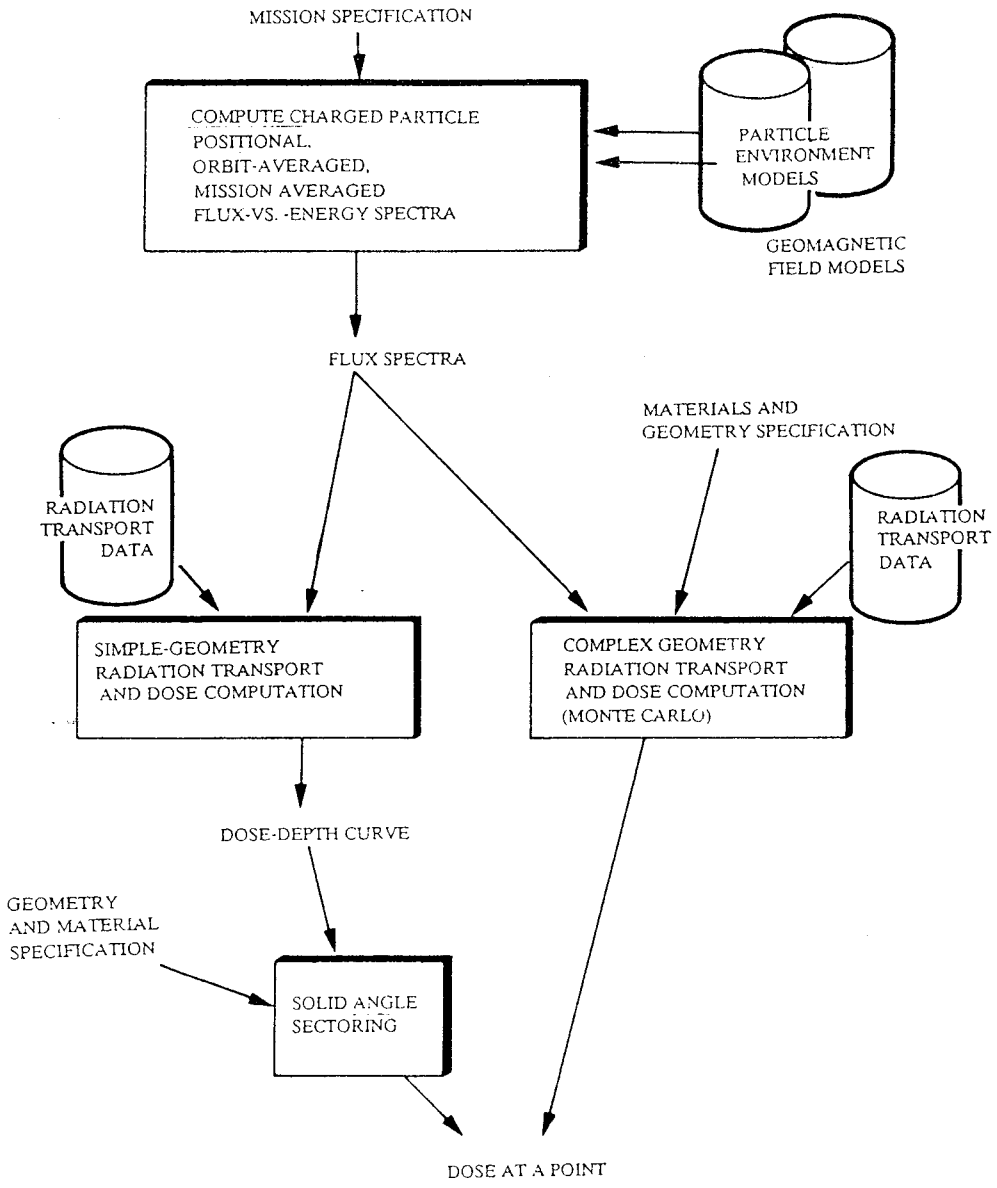
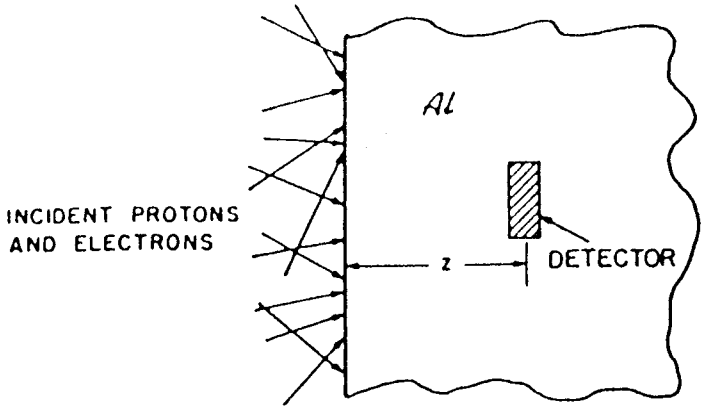
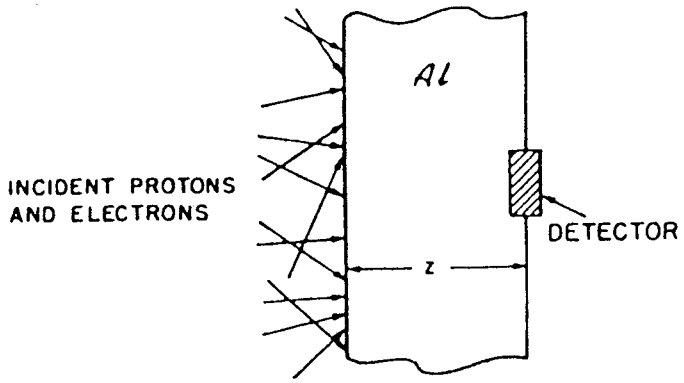


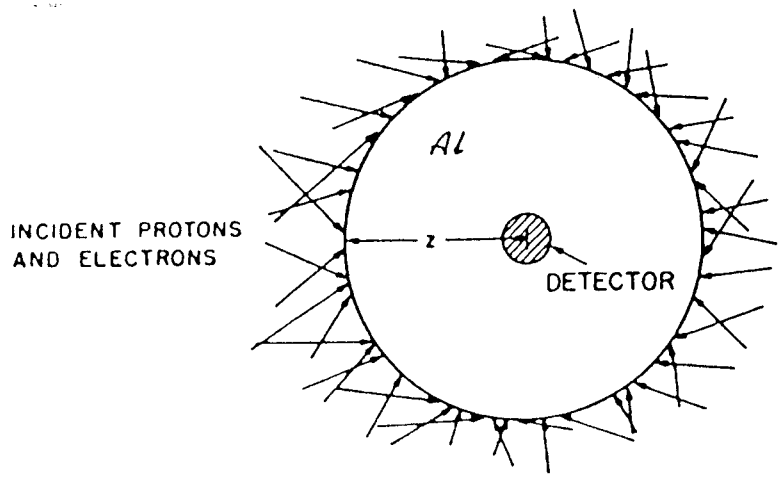
FIGURE 18.1 - RADIATION ANALYSIS OVERVIEW



CASE 1. SEMI-INFINITE MEDIUM; ABSORBED DOSE IN DETECTOR DENOTED AS $\mathcal{D}_{-}^{det}(z)$



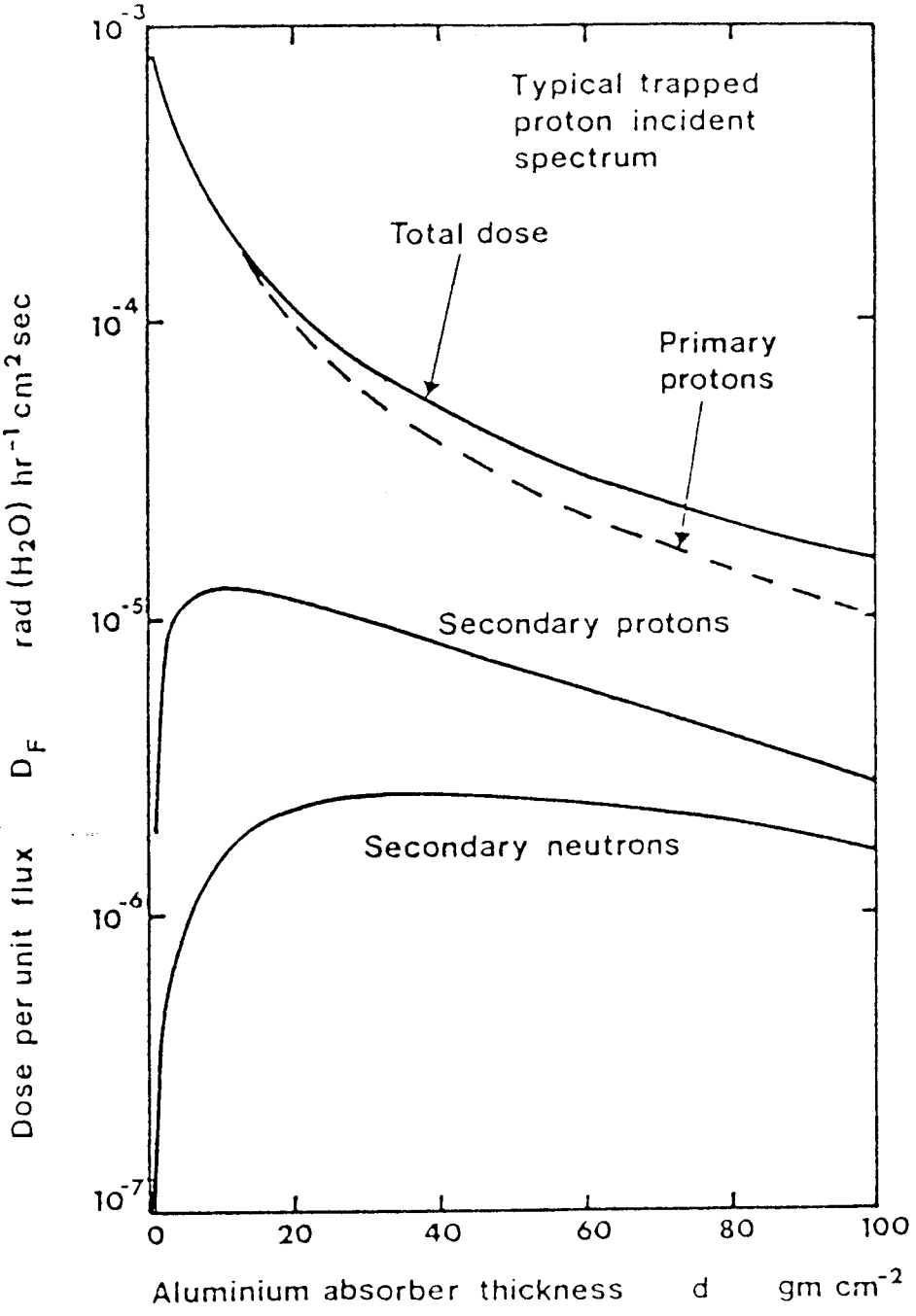
CASE 2. FINITE-THICKNESS SLAB; ABSORBED DOSE IN DETECTOR DENOTED AS $\mathcal{D}_{-}^{det}(z)$



CASE 3. SOLID SPHERE; ABSORBED DOSE IN DETECTOR DENOTED AS $\mathcal{D}_{\bullet}^{det}(z)$

Isotropic, broad-beam fluxes of protons and electrons are assumed incident on aluminium targets; absorbed dose is calculated for small volumes of detector materials Al, H_2O, Si and SiO^2.

FIGURE 18.2 - GEOMETRIES CONSIDERED IN "SHIELDOSE" CALCULATIONS



Dose-depth curves calculated by "CHARGE", showing effect of secondary particles generated by the passage of typical trapped protons through thick aluminium shielding.

FIGURE 18.3 - SECONDARY PARTICLE GENERATION

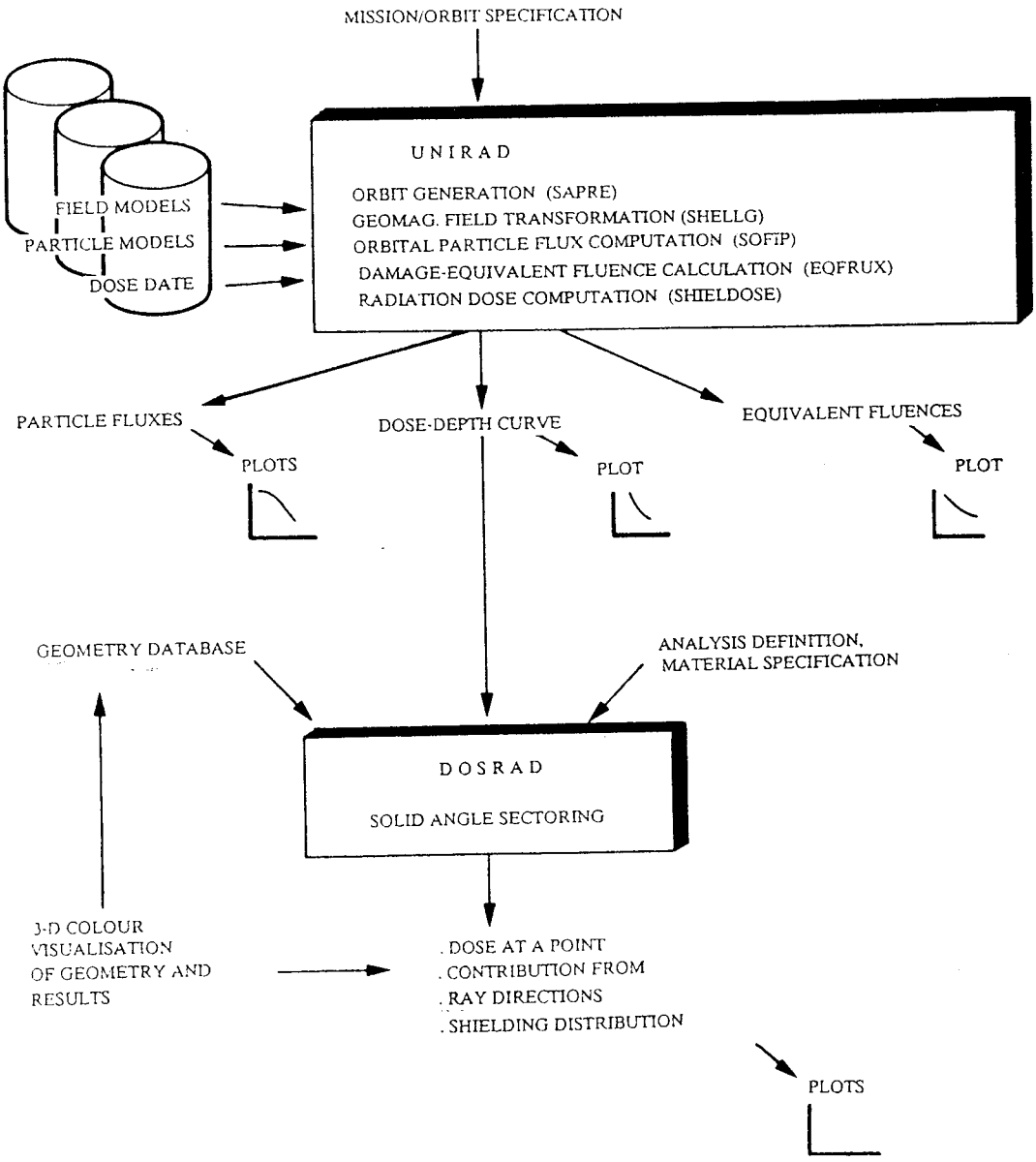


FIGURE 18.4 ARCHITECTURE OF THE ESABASE/RADIATION APPLICATION

REFERENCE

J.H. Adams, "Cosmic Ray Effects in Microelectronics Part IV", NRL Memorandum Report 5901 1986

J. Allison, R. Brun, F. Bruyant, F.W. Bullock, C.Y. Chang, J.J. Dumont, P. Hattersley, R.J. Hemingway, P.R. Hobson, et al., 'An Application of the GEANT-3 Geometry Package to the Description of the OPAL Detector', Comput. Phys. Commun. 47, 1, 55 (1987)

R.G. Alsmiller et al, ORNL-3714, Oak Ridge National Laboratory (1964)

R.G. Alsmiller, R.G., Nucl.Sci.Eng. 27, p. 158 (1967)

W.L. Bendel and E.L. Petersen, "Proton Upsets in Orbit", IEEE Trans. Nucl. Sci. NS-30, 6, 4481 (1983)

M.J. Berger, "Monte Carlo Calculation of the Penetration and Diffusion of Fast Charged Particles", Methods in Computational Physics, Vol. 1: Statistical Physics, p. 135 Academic Press (1963)

M.J. Berger & S.M. Seltzer, "Penetration of Electrons and Associated Bremsstrahlung through "Aluminium Targets", NASA SP-169 (1968)

D.E. Beulter, L.J. Lorence and D.B. Brown, " Dosimetry in Linac Electron-Beam Environments", IEEE Trans. Nucl. Sci., NS-38, 6, 1171 (1991)

R. Brun, F. Bruyant, M. Marie, A.C. McPherson and P. Zanarinin, 'GEANT3', CERN DD/EE/84-1, Revised 1987 and subsequently. To be revised CERN/CN-AS Group, 1993

E.J. Daly, "The Evaluation of Space Radiation Environments for ESA Projects", ESA Journal 12, 229 (1988)

E.J. Daly and L. Adams, "Radiation Doses in Spacecraft Assessment of Computer Programs", ESTEC EWP 1389 (May 1984)

H.S. Davis and T.M. Jordan, "Improved Space Radiation Shielding Methods", NASA-CR-146581 / JPL-TM-33-765 NASA/JPL (1976)

D. Dietz, 'The HETC/LHI/SGS Radiation Transport Code System', IEEE Trans. Nucl. Sci. NS-33, 5, 1131 (1986)

C.S. Dyer, P.R. Truscott, A.J. Sims, C. Comber and N.D.A. Hammond, "Particle Transport Simulation for Spaceborne, NaI Gamma-ray Spectrometers", IEEE Trans. Nucl. Sci. NS-35, 6, 1407 (1988)

J.G. Ferrante, P. Coffinier, B. Aube and J. de Kruyf, "Spacecraft Systems Engineering and Geometry Modelling: The ESABASE-MATVIEW Approach", ESA Journal 84/4, p. 381 (1984)

J.A. Halblieb, R.P. Kensek, T.A. Mehlhorn, G.D. Valdez, S.M. Seltzer and M.J. Berger, 'ITS Version 3.0: The Integrated TIGER Series of Coupled Electron/Photon Monte-Carlo Transport Codes', Report SAND91-1634 UC-405, March 1992. Code and documentation also available from NEA, Saclay, France.

R.P. Kensek, presentation on ITS at ESTEC, May 1992.
Comparison references included:
- G.J. Lockwood et al., Report SAND-79-0414, January 1980;
- J.R. Marbach, Ph.D. Diss., U. Texas Health Sci. Center, 1978;
- T.A. Mehlhorn and J.A. Halbleib, ISBN 0-89448-111-8, p. 608, (1983)
- A.R. Frederickson and S. Woolf, IEEE Trans. Nucl. Sci. 28, 6, 4186 1981.

H.W. Koch,and Motz, J.W., Rev.Mod.Phys. 31 920 (1959)

J.R. Lilley and W.R. Yucker, "CHARGE Code for Space Radiation Shielding Analysis", McDonnell-Douglas Report DAC-62231, McDonnell-Douglas Astronautics Co., Santa Monica, CA. USA (1969). Available as NEA package CC-0070/01, NEA, Gif-sur-Yvette, France.

G.J. Lockwood, G.H. Miller and J.A. Halbleib, "Electron Energy Deposition in Multilayer Geometries", IEEE Trans. Nucl. Sci. NS-23, 6, 1862 (1976)

W.R. Nelson, H. Hirayama and D.W.O. Rogers,'The EGS4 Code System', Report SLAC-265 UC-32 (E/I/A), Stanford Linear Accelerator, 1985

W.R. Nelson and Y. Namito, 'The EGS-4 Code System: Solution of Gamma-ray and Electron Transport Problems', Report SU-SLAC-PUB-5193, Stanford Linear Accelerator, 1990

J.C. Pickel, and Blandford, J.T., "Cosmic Ray Induced Errors in MOS Devices" IEEE Trans.Nucl.Sci. NS-27 (2), pp. 1006-1015 (April 1980)

T.W.L. Sanford, J.A. Halbleib and W. Beezhold,"Experimental Check of Bremsstrahlung Dosimetry Predictions for 0.75 MeV Electrons", IEEE Trans. Nucl. Sci. NS-32, 6, 4410 (1985)

S.M. Seltzer, "SHIELDOSE: A Computer Code for Space Shielding Radiation Dose Calculations" NBS Techn. Note 1116 (May 1980) (Also available through RSIC & NEA Library, CCC-379)

S.M. Seltzer, "Electron, Electron-Bremsstrahlung and Proton Depth-Dose Data for Space Shielding Applications" IEEE Trans.Nucl.Sci. NS-26, p. 4896 (Dec. 1979)

Y. Shimano, T. Goka, S. Kyboyama, K. Kawachi and T. Kanai, "The Measurement and Prediction of Proton Upset", IEEE Trans Nucl. Sci. NS-36, 6, 2344 (1989)

J.L. Shinn and J.W. Wilson, "An Efficient HZETRN (A Galactic Cosmic Ray Transport Code)", NASA-TP-3147 (1992)

W.J. Stapor, J.P. Meyers, J.B. Langworthy, E.L. Petersen, "Two Parameter Bendel Model Calculations for Predicting Proton Induced Upset", IEEE Trans. Nucl. Sci., NS-37, 6, 1966, (1990)

J.W. Wilson, L.W. Townsend, J.E. Nealy, S.Y. Chung, B.S. Hong, W.W. Buck, S.L. Lamkin, B.D. Ganapol, F. Khan and F.A. Cucinotta, "BRYNTRN: A Baryon Transport Model", NASA-TP-2887 (1989)