General

JERG-2-143

# DESIGN STANDARD

# SPACE ENVIRONMENT EFFECTS MITIGATION

Sept. 3 , 2008

Japan Aerospace Exploration Agency

This is an English translation of JERG-2-143. Whenever there is anything ambiguous in this document, the original document (the Japanese version) shall be used to clarify the intent of the requirement.



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# 1 General Provisions

## 1.1 Purpose

This radiation resistance design standard specifies the basic design requirements for the radiation resistance design of spacecraft developed by Japan Aerospace Exploration Agency (hereinafter referred to as JAXA).

## 1.2 Scope

This radiation resistance design standard explains the basic conditions of the designs which cause deterioration or temporary malfunctions of devices and materials due to effects from radiation received in orbit. This radiation resistance design standard also outlines the effects on the components and materials from the cosmic radiation environment, and highlights procedures for radiation resistance designs and radiation countermeasures.

## 1.3 Related Documents

### 1.3.1 Applicable Documents

(1) ISO15390 Space environment (natural and artificial) - Galactic cosmic ray model

(2) CREME96 Cosmic Ray Effects on Microelectronics 96 https://creme96.nrl.navy.mil/

(3) JERG-2-141 Space Environment Standard

### 1.3.2 Related Documents

(1) N/A

## 1.4 Definitions of Terminology

### 1.4.1 Definitions of Terminology

The definitions of the terminology used in this design standard are as follows.

(1) Trapped Radiation Particles

A general term for charged particles trapped in the geomagnetic field.

(2) Galactic Cosmic Ray

Are fundamental particles of a high energy which fly from space, and fly from any direction towards the surface of the Earth. Most of these particles are protons, and also include a heavier nucleus than these particles.

(3) Flux

The intensity of radiation at any point is called flux or particle flux. The flux which passes through a minute flat surface of dS ($cm^2$) in unit time per unit area is called flat surface particle flux. The particle flux which traverses the surface of a sphere with a cross section of dS per unit time is called spherical surface particle flux. The unit of integration flux is expressed by $m^{-2}s^{-1}$. The unit of energy differential flux is expressed by $m^{-2}s^{-1}MeV^{-1}$. When including the direction, add $sr^{-1}$ (steradian).

(4) Fluence

Is a time quadrature of the flux. This is used to express the environment of the operation period of a spacecraft. The integration fluence unit is expressed by $m^{-2}$. The energy integral fluence unit is expressed by $m^{-2}MeV^{-1}$. When including the direction, add $sr^{-1}$ (steradian).

(5) Absorbed Dose

The absorbed dose is calculated by dividing the energy imparted into sufficiently small volume elements of a substance from ionizing radiation, by the mass of the volume elements. This is normally expressed in Gray or rad.

(6) Dose

This is an idiomatic term which expresses the radiation dose and the absorbed energy, and is used to express various meanings, such as the absorbed dose, exposure dose, etc.

(7) Total Dose

The total absorbed dose received by components or materials to a specific point.

(8) Rad

A unit of absorbed dose, and 1 rad equals 100erg/g = $10^{-2}$J/kg.

(9) Gray: Gy

This is the SI unit of the absorbed dose, and 1 Gy is equivalent to 1J/kg = 100 rad.

(10) Single Event Effect

Refers to effects, such as malfunctions of circuit elements (software errors), or latch up which are caused by the effect of a single high energy particle.

(11) Bremsstrahlung

Electromagnetic radiation produced when charged particles are slowed down by the behavior of the nucleus.

(12) Solar Flare

This is an explosion phenomenon which occurs on the surface of the sun, accompanied by the release of high energy particles.

(13) Spectrum

This generally refers to the items regarding the wave length of light. However, in this standard, the spectrum refers to the items which express the particle flux density of the radiation for each of the energies.

(14) L Value

This refers to the distance to a point where the magnetic lines of force intersect with the equatorial plane of the geomagnetic field from the earth's core, with RE (radius of earth) used as the unit.

(15) Anneal

This refers to the phenomenon where there is a recovery in performance recovers which previously deteriorated due to radiation.

(16) Linear Energy Transfer

This is the energy which the charged particles lose per unit length or unit surface density. This is expressed by MeV/μm or MeV/(g/cm$^2$). This is referred to as LET.

(17) Geomagnetic Effect

This phenomenon refers to when cosmic rays enter into the geomagnetic field, and are drawn into various orbits according to the energy and the incident direction, and certain particles move away again without touching the surface of the earth.

(18) Dose Rate

This refers to the dose per unit of time.

(19) Heavy Ion

These are ion particles with a large atomic number, and generally refer to particles of He or more.

(20) NIEL (Non-Ionizing Energy Loss)

Damage not caused by ionization of the incidence particles is called non-ionizing energy loss.

(21) DDD (Displacement Damage Dose) Method

A method of predicting the deterioration of solar cells using the NIEL value developed by NRL of the U.S. as a parameter.

(22) RDC (Relative Damage Coefficient) Method

A method of predicting deterioration of solar cells using the RDC developed by JPL of the U.S. as a parameter.

### 1.4.2 Abbreviations

The abbreviations used in this design standard are as follows.

(1) NASA: National Aeronautics and Space Administration

(2) JPL: Jet Propulsion Laboratory

(3) NRL: Naval Research Laboratory

(4) MOS: Metal Oxide Semiconductor

(5) CREME96: Cosmic Ray Effects on Microelectronics 96

(6) DDD: Displacement Damage Dose

(7) RDC: Relative Damage Coefficient

(8) NIEL: Non-Ionizing Energy Loss

(9) CFRP: Carbon Fiber Reinforced Plastics

(10) SEU: Single-Event Upset

(11) SET: Single-Event Transient

(12) SEL: Single-Event Latch up

(13) SEB: Single-Event Burnout

(14) SEGR: Single-Event Gate Rupture

(15) MCU: Multiple Cell Upset

(16) MBU: Multiple Bit Upset

(17) EDAC: Error Detection and Correction

(18) CTE: Charge Transfer Efficiency

(19) CTR: Current Transfer Ratio

(20) MSM: Metal-Semiconductor-Metal

### 1.4.3 System of Units

The units used in this design standard are SI units in principal, as specified in JIS Z 8203 'International System of Units (SI) and Method of Use', except for the following units.

| Used in this Design Standard | SI Unit |
|---|---|
| Absorbed dose (rad) | Gray: Gy (= 100 rad) |
| Energy (electron-volt: eV) | Joule: J (= $1/1.602\times10^{-19}$eV) |

# 2 Standards

## 2.1 Outline of Radiation Resistance Design

The damage which radiation causes to components and materials can be classified into cumulative effects of all incidental radiation is called the total dose effect. Damage which occurs due to an incident of one charged particle and the former is called the single event effect. The design procedures and items of the design evaluation for these two effects are as follows.

### 2.1.1 Design Procedures

The radiation resistance design procedures are indicated in Figure 2.1-1.

The details are described in item 2.2 and later, and the outline is indicated in the following.

(1) Cosmic radiation environment

The types and effects of the cosmic radiation are indicated in Table 2.1-1.

The effects from the trapped radiation particles and solar protons with an abundance of fluence dominate the total dose effect, and heavy ions and high energy protons with a large LET (heavy ions created by the nuclear reaction with the material atoms) are applicable to the single event effect.

(2) Prediction of radiation damage

As indicated in Figure 2.1-1, the prediction of the radiation damage must be performed by predicting the radiation dose which the components and materials receive and compared to the test results, in consideration of the value of the environmental conditions of the cosmic radiation received which declines according to the mass distribution in a spacecraft.

The total dose effect is a phenomenon where incidental radiation occurs to the material, doing damage proportional to the total amount of energy given, and semi-permanently deteriorating the characteristics of the material, and eventually destroying its function.

The deterioration of solar cells is a type of total dose effect. However, the displacement damage in the crystals of semi-conductors becomes a significant problem. Therefore, it is common to use the incidental number per unit area converted into 1 MeV electron (1 MeV equivalent fluence) as a radiation dose, not as a total dose. Recently, the method of using the displacement damage dose (DDD) was established, which converts to a capacity to generate the displacement damage using the electrons, protons and NIEL value of each of the energies. Since the occurrence of a single event effect depends on the LET of the heavy ions, it is necessary to consider the radiation environment as a function of LET. The fluence of the protons in which the energy is used as a function, is also necessary depending on the device and the orbit. Since optical semiconductor devices and bipolar devices deteriorate due to displacement damage resulting from protons, deterioration prediction using the NIEL value is performed.

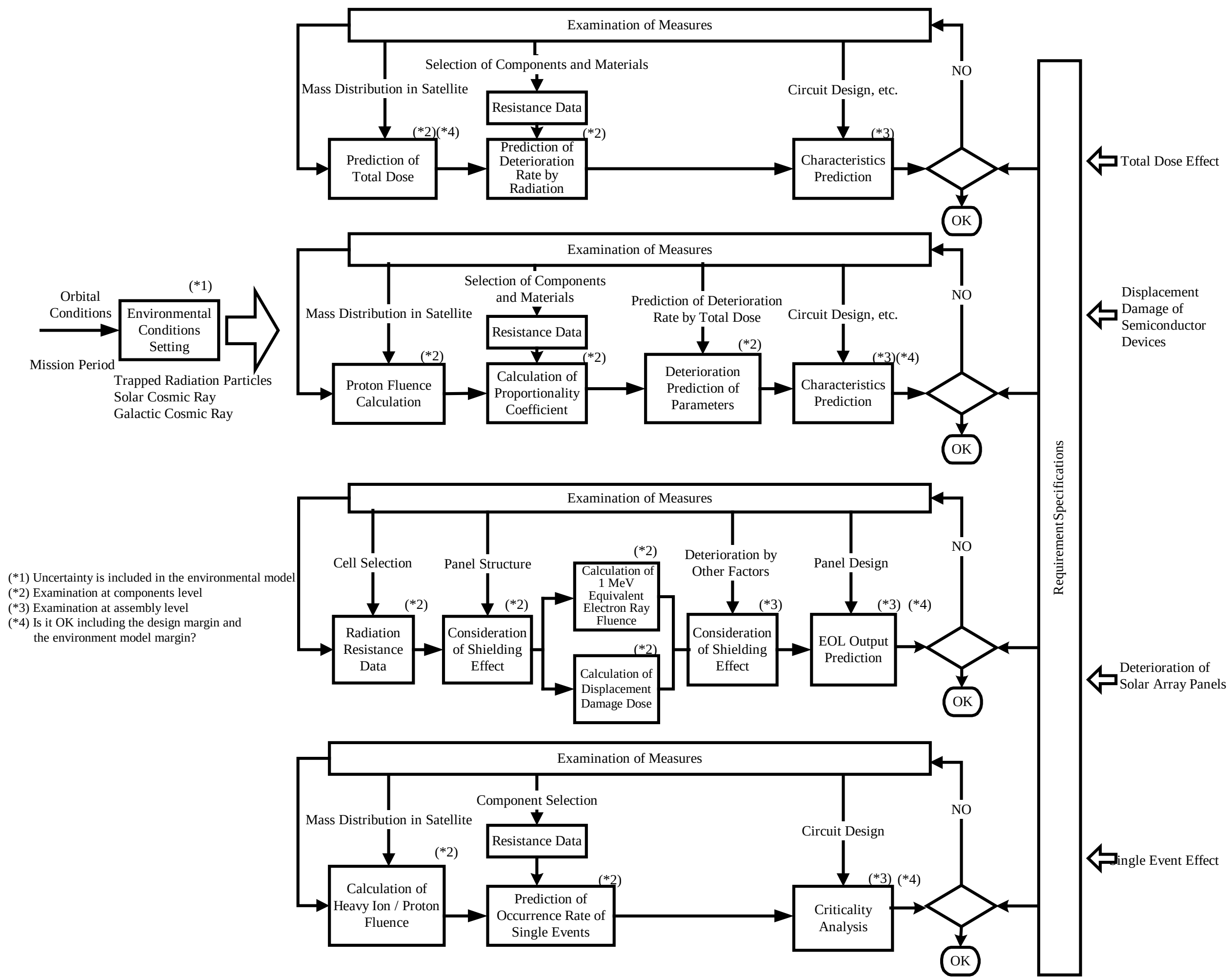



Figure 2.1-1 Radiation Resistance Design

(3) Measures against radiation

When the characteristics value is predicted to exceed the tolerance range due to the effects of radiation, it is necessary to take measures against radiation. The following three methods are measures against radiation.

- Applying radiation shielding to reduce the cosmic radiation.
- Changing to components and materials with a higher radiation resistance.
- Margins in the circuits or structure should be in order to absorb deterioration by radiation.

Use of these measures must be carefully considered and selected based on suitability. .

(4) Important points in radiation resistance design

A high level of uncertainty is included in the prediction of radiation damage. Although regrettable, radiation damage cannot be determined with a high level of precision. Therefore, it is necessary to ensure an appropriate margin of radiation damage is incorporated into radiation resistance design. Even though it is difficult to determine this margin quantitatively, the important items must be sufficiently examined and evaluated in order to perform a complete and effective radiation resistance design.

As indicated in Figure 2.1-1, there are uncertainties in the cosmic radiation environment model, which must take into account potential errors in the evaluation of devices in the margin. The margins must be established as an individual project, and entered into the design standards of the project.

### 2.1.2 Design Evaluation Items

(1) Cosmic radiation environment

The environment model used for setting the environmental conditions of cosmic radiation is considered to have the greatest number of uncertainties. Therefore, the margin for the value of the environment model is particularly important for the radiation resistance design, including the impact to the spacecraft design.

(2) Prediction of total dose

There are many different materials arranged in complicated combinations in a spacecraft, and it is very difficult to accurately measure the total dose in the spacecraft. Usually, a simplification of calculation is performed and it is necessary to understand the relatively high likelihood of error.

(3) Prediction of the deterioration rate of solar cells

When predicting the deterioration rate of solar cells using a 1 MeV electronic conversion exposure dose as a parameter, which prevents inconsistencies by deriving the factors used for converting the radiation environment to the exposure dose (relative damage coefficient, and 10 MeV protons / 1 MeV electronic conversion factor) from the experimental results as much as possible. When predicting the deterioration rate of solar cells using the displacement damage dose as a parameter, the NIEL value can be acquired from the application data sheet, or using technical data.

(4) Prediction of the probability of an occurrence of single events

The design must be performed taking into consideration that there are uncertainties in the presumed accuracy of the induction area of the devices, including the environmental conditions in the occurrence rate of a single event. If the requirements cannot be satisfied at the device level, then necessary measures must be taken at the device level to satisfy the requirements.

(5) Deterioration by displacement damage of semiconductor devices (except for solar cells)

Since optical semiconductor devices and bipolar devices deteriorate in the displacement damage by protons, the deterioration prediction is performed using the NIEL value.

In particular, the radiation effect of the optical semiconductor devices greatly differs from the structure of the devices, and there are also great individual differences of select components. The radiation margins must be appropriately considered according to the mission requirements, while taking into account these differences.

(6) Radiation resistance of components and materials

The radiation resistance of components and materials is normally acquired from the results of radiation irradiation tests on the ground, and in conditions that are different than the conditions in space. Therefore, it is necessary to compare both conditions for the items indicated below, and it is necessary to predict the fluctuation of radiation resistance considering the differences in the conditions on Earth and in space.

- Types of rays
- Dose rate
- Operating conditions
- Surrounding environmental conditions
- Target characteristics

Table 2.1-1 Types and Effects of Cosmic Radiation

| Cosmic Radiation | | Total Dose Effect | Single Event Effect |
|---|---|---|---|
| Radiation source | Particles | | |
| Trapped radiation particles | Protons | ○ | ○ |
| | Electrons | ○ | × |
| Solar cosmic rays | Protons | ○ | ○ |
| | Electrons | △ | × |
| | Heavy ions / He particles | × | ○ |
| Galactic cosmic rays | Protons | △ | △ |
| | Electrons | × | × |
| | Heavy ions / He particles | × | ○ |

(Note 1) ○: Major effect △: Minor effect ×: No effect

### 2.1.3 Effects from sources other than Cosmic Radiation

Although not defined as cosmic radiation, atomic oxygen and ultraviolet rays are factors in the space environment which enter materials directly exposed to space, such as the thermal control materials, and may affect the life of the spacecraft. It is necessary to refer to the radiation resistance design procedures, and evaluate these affects.

## 2.2 Cosmic Radiation Environment

### 2.2.1 Cosmic Radiation Environment Model

Refer to Chapter 9 of JERG-2-141 for the cosmic radiation environment model.

(1) Margin of uncertainty of the cosmic radiation environment model

The cosmic radiation environment is under research even today, and the margin of uncertainty is included in the model.

It is necessary to include the margin using one of the following methods.

(a) Including a margin in the model.

(b) Calculating the parameters applicable for evaluation without including a margin in the model, and then comprehensively evaluating the results to include the model and other margins.

## 2.3 Total Dose Design Standard

One type of the radiation damage to components and materials is called the total dose effect, and is a lasting damage caused by the accumulation of total incidental radiation. The total dose effect can be classified into ionization damage and displacement damage. The energy loss from radiation in the material is pre-dominantly caused by an ionization phenomenon, and is characterized by the amount of energy (absorbed dose) absorbed by the material due to the passage of radiation. Using the absorbed dose concept, the radiation damage from different radiation sources can be evaluated at the same time. Optical devices ,CCD and solar cells tend be affected more easily by the displacement damage, and a deterioration of the output of the solar cells from radiation exposure is especially dominant due to this mechanism. Recently, the method of using the displacement damage dose (DDD) for converting to the ability to cause displacement damage using electrons, protons and the NIEL value of each energy, has been established for the predicted deterioration of solar cells. Refer to the items of the radiation deterioration prediction method of solar cells for details.

### 2.3.1 Total Dose Prediction Method

The types of radiation which must be considered to predict the total dose are trapped electrons, trapped protons and solar protons, as indicated in Table 2.1-1. When these types of radiation penetrate materials, the energy of the radiation will decrease due to the interaction and absorption of the radiation with the materials. In the case of electrons, the bremsstrahlung will be generated due to their interaction with the materials. Since the range of the bremsstrahlung is longer than electrons, it can become dominant when a thicker shield is used.

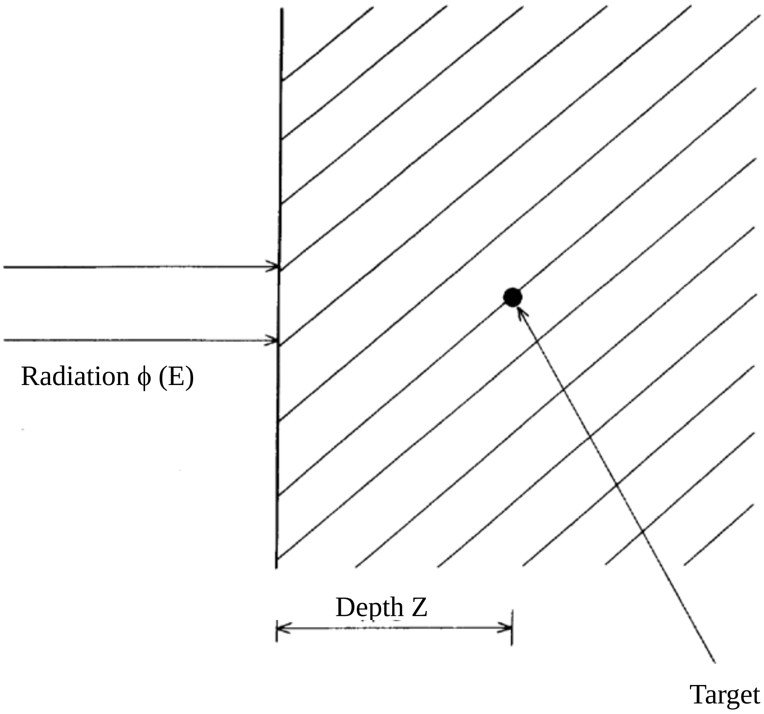
As indicated in Figure 2.3-1, the total dose is calculated for parallel incidence radiation. Accordingly, this is equivalent to the spherical shell model as indicated in item 2.3.2, when a shield of equal thickness is used for the isotropic radiation incidence from all directions.

The details of the total dose calculation method are indicated in JERG-2-143-HB001. The radiation absorbed dose and the generated amount of the bremsstrahlung differs according to the types of materials used for the shielding and the target components. However, the total dose is calculated by using aluminum as the shielding material, and is sufficient by converting the density into an equivalent aluminum thickness for shielding materials of other aluminum components. The results of the total dose calculation are generally provided by the relationship between the shield thickness (depth) and the absorbed dose, i.e., the Dose-Depth Curve. An example of a

Dose-Depth Curve is indicated in Figure 2.3-2.

2.3.2 Total Dose Prediction Model

The following two methods can be considered as the prediction models, to calculate the actual radiation dose which the components receive.




ϕ (E): Incidence Radiation Fluence (particles/$cm^2$)

Z: depth (g/$cm^2$)

Figure 2.3-1 Total Dose Calculation Model

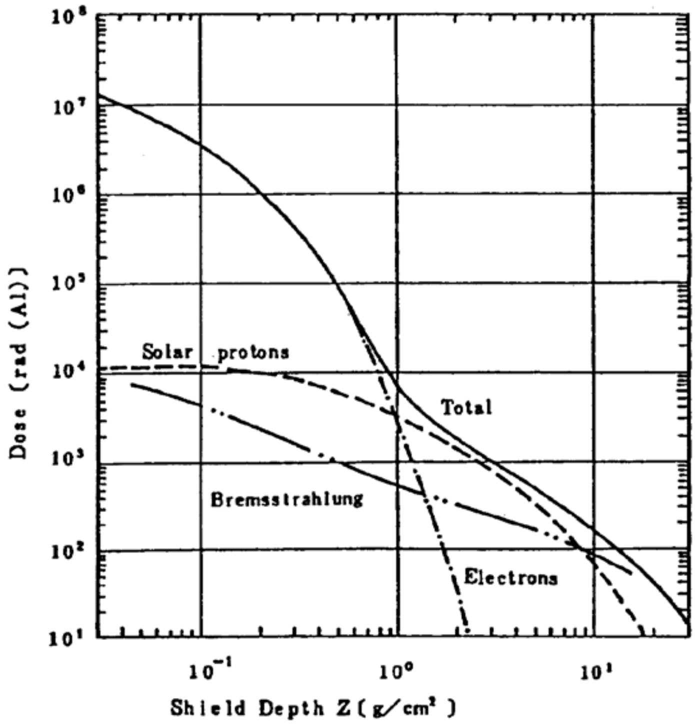



Figure 2.3-2 Dose-Depth Curve (Example)

- Simplified method

The purpose of this prediction model is to acquire the relationship between the shield thickness and the total dose (Dose-Depth Curve) assuming that the material and configuration of complex shielding is a simple shape, such as a spherical shell or a plate. Moreover, its purpose is also to acquire the total dose directly, calculated by using the shielding thickness and surface density.

- Three-dimensional model

The purpose of this prediction model is to acquire the distribution of the shielding thickness in each direction when viewed from the target (calculation point of the total dose), and to acquire the total dose using this calculated value.

(1) Simplified method

When calculating the Dose-Depth Curve, three types of shielding material configurations, such as spherical shell model, semi-infinite plate model and finite plate model will be used, in connection with the use of the shielding effect calculation code for space (SHIELDOSE-II).

(a) Spherical shell model

This model assumes that the model is covered with a shielding material of equal thickness for the isotropic radiation incidence. This model is the most basic model for performing the shielding calculation, and is acquired by the calculation method indicated in item 2.3.1. However, since the actual shielding configuration is close to the plate in many cases, the radiation dose calculated using this model may result in a larger value.

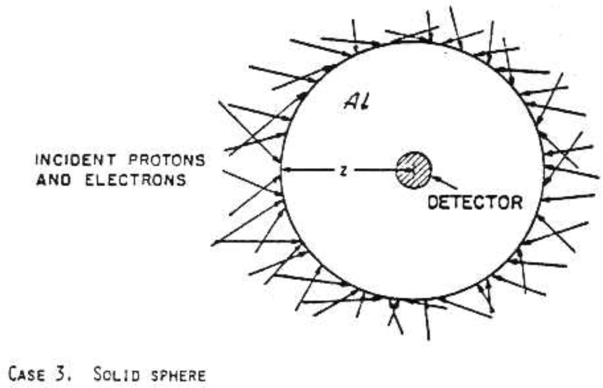
This model is used for the shielding calculations for shielding configurations close to spherical shell or semi-spherical shell, and the basic data for the semi-infinite plate model and the three-dimensional model indicated in the following diagram.

(b) Semi-infinite plate model

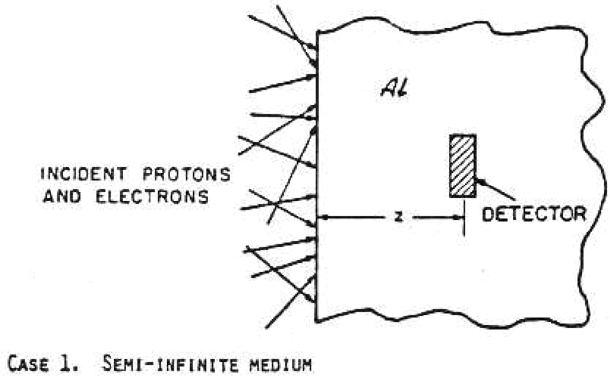
This model assumes that the model is covered with a shielding material of an infinite width with a uniform thickness, having an infinite plane surface shielding material, and a shielding material of infinite thickness in the opposite direction.

(c) Finite plate model

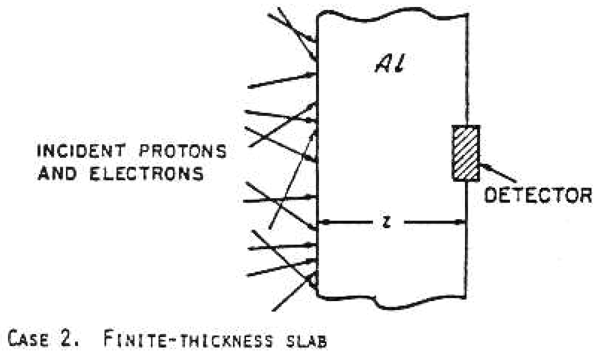
This model assumes that the model is covered with a shielding material of a finite thickness, having a semi-infinite plane surface shielding material, and a shielding material of a finite thickness in the opposite direction (radiation incidence from one surface of the plate).




(1) Spherical Shell Model




(2) Semi-infinite Plate Model




(3) Finite Plate Model

Figure 2.3-3 Model Configurations

(Note) These figures are typically presented in order to easily understand the models, with the back diffusion scattering taken into consideration in the actual calculation.

In the actual mounted devices, there are many cases where one direction of the shielding has a sufficiently large thickness compared to the other direction, when viewed from the component's position. There are also many cases where the configuration of the shielding material is a plate, or close to a plate. Therefore, when calculating the radiation absorbed dose in a simplified method, the semi-infinite plate model is effective.

(2) Three-dimensional model

This model is used for calculating the total dose of the components and materials more accurately. The spherical shell model and the semi-infinite plate model are simple. However, the total dose of the components and materials used in spacecraft changes according to the conditions of the surroundings, such as the mounting position, etc., and the actual configuration of the shield is complex and may not necessarily work in conjunction with them. Therefore, in order to calculate the total dose more accurately, it is necessary to acquire the mass distribution for each direction with the target as the center. This model converts the mass distribution into the shielding thickness of standard materials, calculates the absorbed dose in each direction using the Dose-Depth Curve of the spherical shell model, and integrates the values for all solid angles. The formulas are as follows.

$$D_T = \frac{1}{4\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_0^{2\pi} D(\ t\ (\theta, \varphi))\cos\theta\ d\varphi\ d\theta \qquad (2.3\text{-}2)$$

| | |
|---|---|
| $D_T$ | : Absorbed dose of the target |
| $D(x)$ | : Absorbed dose of the spherical shell model when assuming the shield thickness is x |
| $t(\theta,\varphi)$ | : Shield thickness of the $(\theta,\varphi)$ direction |
| $\varphi$ | : Longitude direction |
| $\theta$ | : Latitude direction |

A conceptual diagram of the mass distribution in space craft is indicated in Figure 2.3-4.

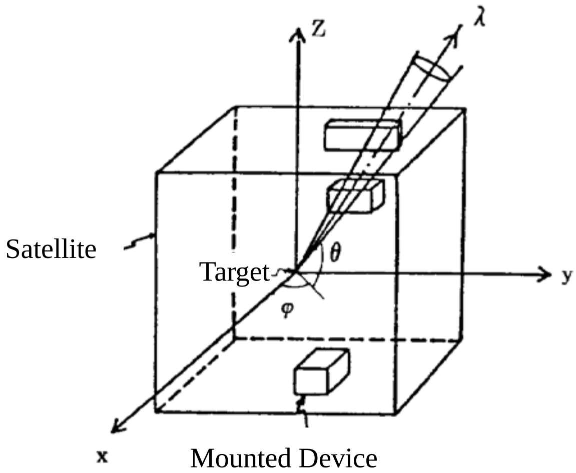



Figure 2.3-4 Mass Distribution in Space Craft

### 2.3.3 Radiation Deterioration of Electronic Components

(1) Semiconductor electronic components

(a) Outline of radiation deterioration

When there is constant radiation, the effect of a positive charge remains in the insulating layers, such as the $SiO_2$, and the occurrence of the interface state density on the insulating layer and interface of the silicon crystals are the largest issues with silicon semiconductors. These issues are expressed by a decrease in the current amplification factor, and an increase in the leakage current for bipolar transistors. In ICs, the circuit characteristics indicate a remarkable fluctuation due to the variations of these parameters. The main variable parameters and tendencies of various semiconductor devices for the total dose are indicated in Table 2.3-1. The parameters with the largest effect are indicated in the following.

i) Bipolar transistors

Deterioration in the current amplification factor hFE is the most remarkable in the low current range.

Recently, Enhanced Low Dose Rate Sensitivity (ELDRS) of linear bipolar components has been discovered in ground radiation tests, and with dose rates of 50 rads/sec or less, the deterioration of the gain was larger in some of the linear bipolar components in which radiation tests were performed at low dose rates.

ii) TTL

The output voltage ($V_{OL}$) and the propagation delay time ($t_{PHL}$) increases remarkably due to the decrease in the current amplification factor $h_{FE}$.

iii) CMOS

The input level $V_{IH}$ and $V_{IL}$ fluctuates, the output driving capability $I_{OH}$, $I_{OL}$ decreases, and the propagation delay time tpd increases remarkably. The power current $I_{DD}$ increases when static due to internal leakage. The refinement means that thinning of the gate oxide film and then total dose tolerance is improved in general. However, the leakage phenomenon is increased specifically by irradiation has also been confirmed in the oxide film of several nm order, it should be noted.

iv) Memory devices (SRAM, DRAM, etc.)

The same tendency as CMOS basically occurs. Particularly, there are many cases where a great fluctuation can be observed in the power current $I_{DD}$ and the input leakage current when static.

v) FPGA (anti-fuse type)

The input level $V_{IH}$ and $V_{IL}$ fluctuates, the output driving voltage $V_{OH}$ and $V_{OL}$ decreases, and the propagation delay time tpd increases remarkably. The power current $I_{DD}$ increases when static due to internal leakage.

(b) Notes for use

Generally, the radiation tolerated dose of the electronic components greatly depends on manufacturing process factors, device design factors, operating conditions (existence of a bias application, etc.), type or energy of the radiation and the dose rate. There are also cases where the radiation tolerated dose greatly changes according to the manufacturer, production lot etc. and therefore, it is necessary to understand the radiation tolerated dose data of each electronic component sufficiently when designing the circuitry. An important point for the design of the circuitry which can be predicted at the electronic component level is that it is necessary to consider the acceptable level of characteristic deterioration and how to use it, and examine whether to introduce a derating design. Examples of cautionary measures for the main variable parameters for the total dose are as follows.

i) Bipolar transistors

Since the current amplification factor $h_{FE}$ changes greatly when the collector current is smaller, it must be designed so that the collector current and the minimum necessary $h_{FE}$ after exposure are compatible in the actual circuit.

ii) TTL

In consideration of the deterioration of the low level output voltage ($V_{OL}$), it is necessary to take a derating of fan-out.

iii) CMOS, memory devices, FPGA

It is necessary to be cautious in terms of preventing a conflict between signals, even though there is a variation of the propagation delay time tpd from the early stages to the final stages of exposure.

Table 2.3-1 Deterioration Tendency of Semiconductor Devices by Radiation

| Semiconductor Device | Main Variable Parameters | | Change Tendency |
|---|---|---|---|
| | Items | Symbols | |
| Bipolar transistors | Current amplification factor | $h_{FE}$ | Decrease |
| | Leakage current | $I_{CEO}$<br>$I_{CBO}$ | Increase<br>Increase |
| | Saturation voltage | $V_{CE\ (SAT.)}$ | Increase |
| TTL | Input current | $I_{IH}$<br>$I_{IL}$ | Increase<br>Decrease |
| | Output voltage | $V_{OH}$<br>$V_{OL}$ | Decrease<br>Increase |
| | Power current | $I_{CC}$ | Decrease |
| | Propagation delay time | $t_{PHL}$<br>$t_{PLH}$ | Increase<br>Increase |
| CMOS, Memory devices | Input level | $V_{IH}$<br>$V_{IL}$ | Varies |
| | I/O leakage | $I_I$<br>$I_{OZ}$ | Increase |
| | Power current | $I_{DD}$ | Increase |
| | Drive capacity | $I_{OH}$<br>$I_{OL}$ | Decrease |
| | Propagation delay time | tpd | Increase |
| FPGA (anti-fuse type) | Input level | $V_{IH}$<br>$V_{IL}$ | Varies |
| | Power current | $I_{DD}$ | Increase |
| | Drive voltage | $V_{OH}$<br>$V_{OL}$ | Decrease |
| | Propagation delay time | tpd | Increase |

### 2.3.4 Radiation Deterioration of Material

The radiation changes the mechanical and physical characteristics of almost all materials, and generally leads to the deterioration them. Metals and ceramics among the components of a space structure excel in radiation resistance. Polymeric materials, such as plastics, elastomers etc., however, are inferior, and polymeric materials receive remarkable affects from radiation depending on the dose in the space environment.

The affects on the materials from radiation may change as a result of the type of radiation, energy and dose rate. Therefore, it is necessary to pay attention to the evaluation data.

(1) Metals

As one guide of the fluence which must take into consideration the radiation deterioration of metals, the values of $10^{17}$ - $10^{19}$ protons/cm$^2$ or more are mentioned for protons. However, since the values are several orders of magnitude smaller than that, even though the fluence of a spacecraft with missions that can last decades, the radiation deterioration of metals may be disregarded in the actual design.

(2) Polymeric materials

Polymeric materials are materials which are most affected by radiation, and the radiation resistance changes greatly according to its type and composition. Even though the same dose is exposed, the radiation resistance of the material changes according to temperature, the existence of air etc. (generally the radiation resistance deteriorates more in the air). Therefore, it is necessary to pay attention to the evaluation of the selection data of the material. The parameters which are affected by radiation exposure of materials are the density, tensile strength, elongation, Young's modulus, adhesive strength, impact strength, and thermal conductivity etc.

(a) Thermosetting resins

There are materials of resin elements which can be used with doses up to $10^7$ rads. However, if $10^7$ rads is exceeded, it is necessary to consider adopting fiber reinforced plastics which are strengthened with carbon fibers, glass fibers or using epoxy, as a material.

The tensile strength, density and elasticity modulus of fiber reinforced plastics which generally use thermosetting resin as a material increases due to radiation exposure, and tends to decrease in impact strength and elongation. However, the mechanical properties up to about $10^8$ rads do not change greatly. When about $10^8$ rads are exceeded, there are cases where the characteristics tend to change according to the type and composition of the matrix. As a result of NASA performing electron beam irradiation tests on CFRP (carbon fiber/epoxy),its employment as a material of space structures has demonstrated that CFRP has sufficient resistance for use up to $10^9$ rads. However, since the radiation resistance changes according to the composition of the material even with the same epoxy CFRP, it is necessary to sufficiently confirm the characteristics through experiments for high level doses.

(b) Thermoplastic resins

Since the tensile strength and hardness of thermoplastic resins (Teflon, etc.) which include fluorine generally decreases with high level doses, it cannot be used with doses which exceed $5x10^4$ rads. Other thermoplastic resins are thought to be safe for use up to about $10^6$ rads. However, radiation resistance for $10^6$ rads or more changes greatly according to the type of material.

(c) Adhesives

Deterioration of the tensile strength was not observed up to doses of $5x10^7$ rads for thermosetting resin type adhesives used for structures, and can be used safely. The strength deteriorates slightly at $3x10^8$ rads. However, the level of deterioration changes greatly according to the type and composition of the material with doses which exceed $3x10^8$ rads. As a result of performing electron beam irradiation ($10^5$ electrons/$cm^2$) on silicon type adhesives for solar cell coverings, which is a typical non-structure adhesive, it has been reported that there was almost no deterioration in the permeability.

(d) Elastomers

Elastomers are materials most affected by radiation among the polymeric materials, and the range for safe use from radiation is from $10^5$ to $5x10^6$ rads, and its stability changes according to its type.

Generally, the elongation decreases by radiation exposure, and the tensile strength decreases substantially after the initial increase or decrease, while the compression residual strain increases 50 to 100% in most elastomers. There is a tendency of the hardness to increase due to radiation exposure in most elastomers. However, butyl rubber and Thiokol rubber become softer. Natural rubber, urethane rubber and neoprene rubber among the elastomers excel in radiation resistance; however, caution is required regarding neoprene rubber, as the radiation resistance changes greatly according to its composition.

(3) Ceramic, graphite and glass

The physical characteristics of these materials, such as the density, mechanical properties, thermal characteristics, optical quality and electrical properties are all affected by radiation. The characteristics which are affected by radiation and the level of affect changes according to the type and composition of the materials and the type of radiation. Generally, their radiation resistance is higher as compared to organic materials. The items which should be taken into consideration in terms of design are indicated in the following.

(a) Ceramic

Generally, the physical characteristics of ceramic do not change significantly with ionizing radiation of $10^9$ rads, or neutron ray exposure at $10^{19}$n/cm$^2$ or less. When ceramic is exposed to a large dose of radiation, the density, elastic modulus, heat conductivity, optical quality and electrical properties will change. However, composites containing beryllium or boron will be affected by the thermal neutron fluence at the $10^{17}$n/cm$^2$ level.

(b) Graphite

Graphite is slightly more sensitive to radiation as compared to ceramic. The mechanical properties (size, intensity, elasticity), thermal characteristics, and electrical properties change with exposure to radiation, particularly fast neutron rays ($E > 1$keV). The fluence level in which remarkable changes occur is at about $10^{19}$n/cm$^2$.

(c) Glass

The optical quality of glass changes when exposed to radiation equivalent to neutron rays of $10^{15}$ to $10^{16}$n/cm$^2$ or more. Particularly, caution is required as the transparency deteriorates greatly with the color.

The radiation resistance of other physical characteristics excluding the optical quality is comparable to ceramic.

(4) Thermal control coating materials

The items which are affected the most among the damage of thermal control coating materials, is the deterioration of the optical properties, such as the solar absorption rate and thermal emissivity. The deterioration of the optical properties is also caused by ultraviolet rays and high vacuum environments, not only from radiation, particularly organic based thermal control coating materials, but also by ultraviolet rays. Generally, the radiation tolerated dose of metalbased thermal control coating materials is higher, compared to inorganic-based materials and organic-based materials, which have increasingly lower tolerance to radiation. The mechanism of deterioration of the optical properties is complicated by the complex behavior of the ultraviolet rays, radiation, and high vacuum environments. It is difficult to predict the deterioration quantitatively using laboratory data unless the testing equipment which is used can apply several of these space environments at the same time.

Therefore, it is preferable to use flight data of spacecraft in the thermal design. However, when laboratory data is used, adequate caution is required.

### 2.3.5 Design Procedure

The flow of the design for the total dose is indicated in Figure 2.3-5.

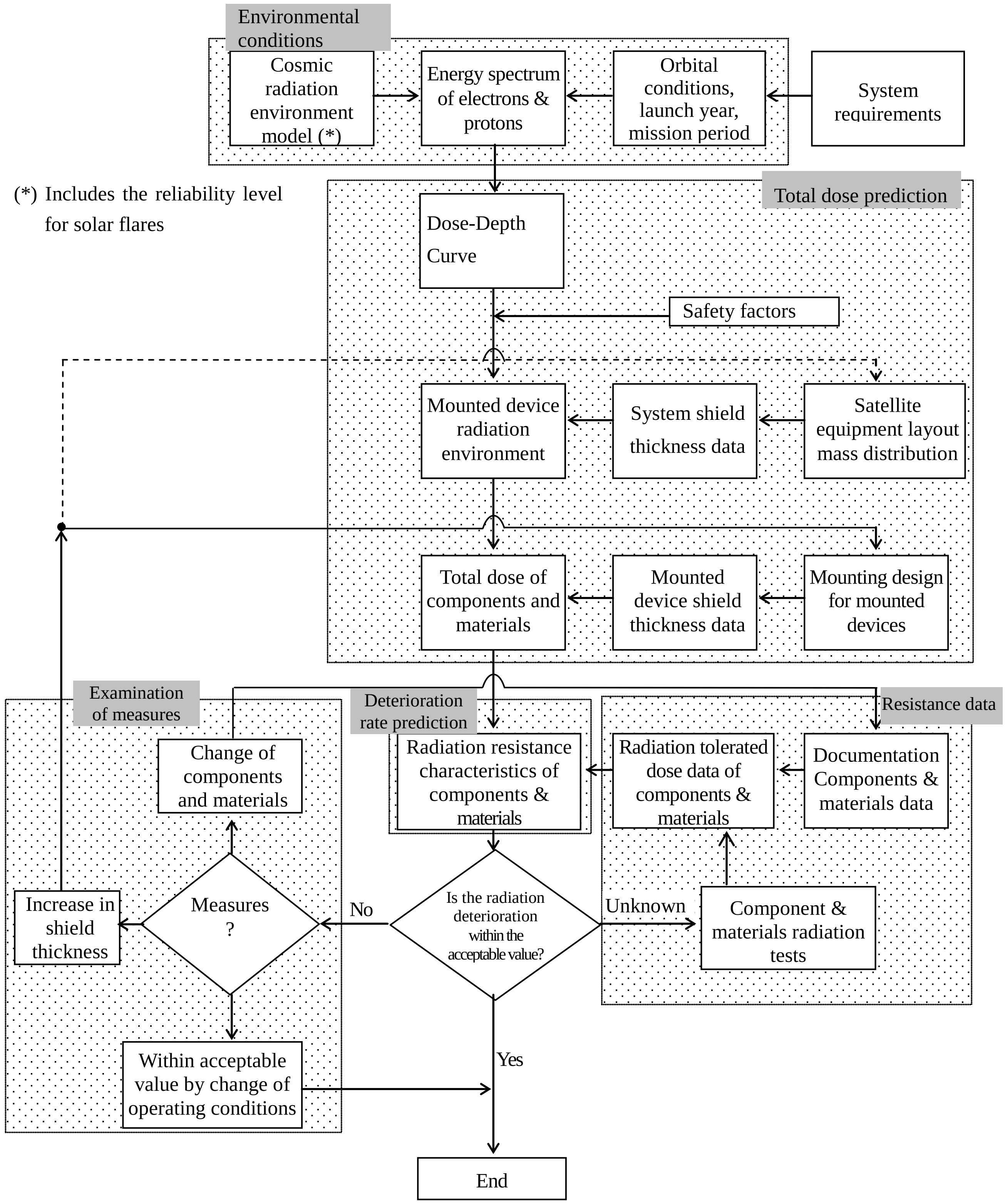



Figure 2.3-5 Design Flow for Total Dose

(1) Cosmic radiation environment

The energy spectrum of the electrons and the protons are calculated using orbital conditions, launch year and the mission period determined in the system requirements, based on item 2.2.

The calculated energy spectrum is described in the system specifications as one of the environmental conditions in orbit.

(2) Total dose calculation

Based on the energy spectrum, the Dose-Depth Curve is calculated based on item 2.3.1. Based on the shield data of this Dose-Depth Curve and the system, and the shield data of the mounted device, the absorbed dose of the components and materials is calculated based on item 2.3.2. Normally, it is efficient to perform this calculation by separating it into a system level analysis and a mounted device analysis.

The analysis of results at the system level are provided to the designer of the mounted device as shielding thickness data equivalent to the absorbed dose on surfaces other than the mounted device, or the shielding effect on the system. Based the mounting design, the total dose on the components and materials of the mounted device is calculated according to item 2.3.2.

(3) Comparison of tolerated dose of electronic components and materials

Based on the calculated total dose and the radiation resistance characteristics data of the components and materials indicated in item 2.3.3 and item 2.3.4, the radiation deterioration of the characteristics of the components and materials to be used is estimated. The deterioration of characteristics is considered within an acceptable value when viewed from the application of the components and materials, and the application is determined to be appropriate. When the deterioration of characteristics deterioration exceeds the acceptable value, it is necessary to take measures according to item (4). When the radiation resistance characteristics of the components and materials are unknown, it is necessary to acquire the deterioration data by performing radiation tests. Since the acceptable value of the radiation deterioration of the components and materials changes with individual application conditions, even though it can be used for one application for the same total dose, there are cases when it cannot be used for other applications.

When the radiation tolerable dose of the components and materials depends on the production lot, and is determined to be critical judging from the predicted total dose and the operating conditions, it is necessary to confirm radiation resistance characteristics by performing radiation tests on each production lot.

(4) Measures

When the deterioration of the components and materials in the calculated total dose exceeds the acceptable value, it is necessary to take the following measures.

- Change to components and materials with less radiation deterioration
- Decrease the total dose by increasing the shield
- Relax the acceptable value by changing the operating conditions

When it is necessary to increase the shielding, it must be considered that the increase in the mass be kept to a minimum. Increasing the thickness of the shielding at the system level will lead to a great increase in the mass.

When the radiation deterioration of a specific component only is critical, spot shielding is generally performed at the component level. However, by increasing the shielding thickness of the entire mounted device, an increase in the mass can be reduced. On the other hand, it is necessary to consider that there are cases where there is little affect according to the orbital conditions and the mounting position.

### 2.4 Radiation Resistance Design Standard for Solar Array Panels

Because of their function, solar cells are equipped on solar array panels or on the surface of spacecraft structures. Therefore, the solar cells are exposed to a more severe radiation environment compared with other semiconductor devices. The output of the solar cells deteriorates from radiation damage, which in turn deteriorates the power generation of the panels. Therefore, in order for the generation of power from the solar array panels to meet the power required for the spacecraft until the end of its mission, the amount of deterioration from the radiation must be predicted and reflected in the panel design (estimate the portion of deterioration, and consider an appropriate margin to determine the initial generation of power).

Normally, the solar array panels consist of a structure in which an aluminum honeycomb, which is called the substrate, is sandwiched between CFRP and hardened by a resin. Polymide (Kapton) film is attached to the surface for insulation (the surface where the solar cells are attached). Solar cells, cover glass, diodes, electrical wiring are held together with adhesives and silver evaporation coating. Teflon, which is a thermal control material, may be attached to the back side as required. Since this chapter indicates the design standard for radiation resistance regarding power generation, only the solar cells and cover glass are described here.

In the radiation deterioration of the output power of the solar array panels, there is radiation deterioration (color) from sunlight transmissivity of the cover glass or the adhesives, in addition to the solar cells. The amount of deterioration to the power generation due to the above must be predicted, and reflected in the panel design.

#### 2.4.1 Radiation Deterioration Prediction Method of Solar Cells

As a method to predict the radiation deterioration quantity of solar cells, there are currently two types of methods, the relative damage coefficient (RDC) method by JPL, and the displacement damage dose (DDD) method by NRL. Generally, until now, the former method is most often used. However, a considerable number of ground radiation irradiation tests must be performed in order to acquire the RDC which is a parameter required for prediction. The latter method is a relatively new method, and there are still few application results. However, this method has an advantage where only 3 ground radiation irradiation tests are required in principal (any 2 types of electron ray energies, and 1 type of proton ray energy), if the parameter called the NIEL value is acquired by calculations and used in this type of prediction. Therefore, it is suitable to use the RDC method when sufficient ground radiation test data is available, such as JAXA space authorized solar cells, or the RDC has already been acquired, and use the DDD method when sufficient ground radiation test data has not yet been acquired for new solar cells, or when the three types of irradiation tests could not be implemented.

When either of the methods is used, it is necessary to estimate the exposure dose of the radiation for the spacecraft mission period which is applicable for design. Use the radiation environment codes, such as the JAXA model, NASA AP8 or AE8 and acquire the energy spectrum of the total exposure dose (fluence) for electron rays and proton rays, from the orbit and mission period. The number of other existing particles (ions), i.e. the collision frequency, is extremely low in space when compared to electrons and protons, and even though radiation incidences occur, it will be mitigated by the cover glass and will not reach the solar cells. Therefore, it is not necessary to consider this as a deterioration factor.

Next, it is necessary to acquire the deterioration curve (fluence dependency data of the remaining factors), by 1 MeV electron rays and 10 MeV proton rays of the solar cells to be adopted, or when there is no data, it is necessary to acquire the data by implementing irradiation tests. The remaining factors refer to the ratio of the performance data before radiation exposure and after the deterioration of the initial performance value.

Use either the RDC method or the DDD method mentioned above for the radiation deterioration prediction of the solar cells to be adopted. Two types of deterioration prediction methods are described in the following. Refer to this description when selecting the deterioration prediction method. Refer to the description in JERG-2-143-HB001 for the detailed deterioration prediction calculation method by the RDC method and the DDD method.

**(1) Relative damage coefficient (RDC) method**

In the case of the RDC method, first prepare the RDC (using no shielding material, with one directional radiation incidence) for the electrons and protons of the solar cells to be adopted, and the output deterioration curve by 1 MeV electron rays from the tests or data sheet. On the other hand, it is necessary to calculate the energy distribution of the fluence of the electrons and protons during the mission period from the radiation environment code.

Once the RDC is acquired from ground radiation tests with no shielding material and a one directional radiation incidence, it is necessary to convert the value taking into account the conditions with the isotropic incidence and shielding material (considering the cover glass, adhesives and thickness). Using the converted RDC value and the particle energy distribution of the fluence of the electrons and protons, then calculate and derive the equivalent fluence of 1 MeV electron rays for electrons, and the equivalent fluence of 10 MeV proton rays for the protons. Then convert the equivalent 10 MeV proton ray fluence to a 1 MeV electron ray fluence using a 10 MeV protons/1 MeV electron conversion factor, and add to the previous equivalent 1 MeV electron ray fluence of the electron rays. In this way, the entire radiation exposure dose is converted as an equivalent 1 MeV electron ray fluence. Then, it is necessary to acquire the deterioration quantity (remaining factor) of the solar cell output from the equivalent 1 MeV electron ray fluence acquired from the deterioration curve by 1 MeV electron rays which were acquired, or acquired by these tests. This is the deterioration prediction amount (rate) of the solar cells for the mission concerned. The prediction procedure is indicated in Figure 2.4-1.

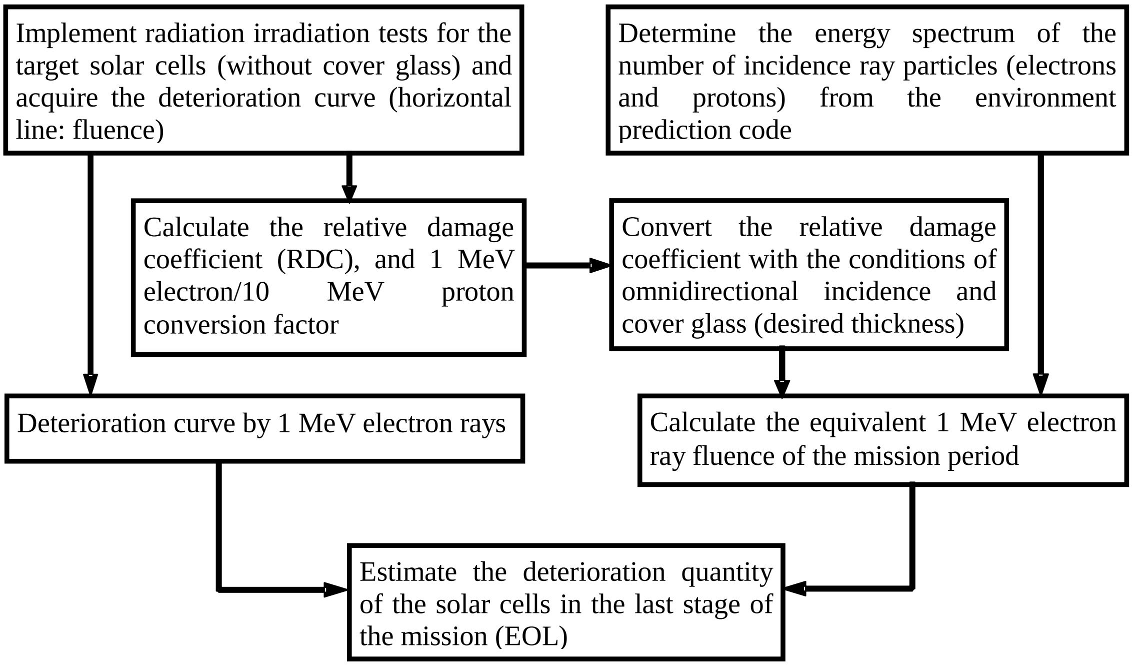



Figure 2.4-1 Prediction Procedure of Solar Cell Deterioration Quantity by Relative Damage Coefficient (RDC) Method

**(2) Displacement damage dose (DDD) method**

In the case of the DDD method, first prepare the NIEL value of each element which consists of semiconductor materials of the solar cells to be adopted based on documentation or calculations. Then it is necessary to calculate the energy distribution of the fluence of the electrons and protons during the mission period from the radiation environment code. Since these distributions are the conditions without shielding material, this is converted in consideration of the effect of the shielding material (considering the cover glass, adhesives and thickness). Use the energy distribution of the fluence of the electrons and protons after this conversion and the NIEL value mentioned above, and then calculate and derive the DDD value during the mission period. On the other hand, it may be necessary to convert the horizontal axis of the deterioration curve data acquired by ground radiation irradiation tests into the DDD value using the NIEL value of the electron or proton fluence, to acquire the new deterioration curve (horizontal axis is the DDD value). In this case, it is necessary to acquire the deterioration quantity (remaining factors) of the solar cell output from the DDD value during the mission period, which was acquired from this deterioration curve. This is the predicted deterioration amount (rate) of the solar cells for the concerned mission. The prediction procedure is indicated in Figure 2.4-2.

When the deterioration rate of the solar cells acquired by the above two methods is larger than the deterioration rate of the solar cells which is required for the panels/power supply design, it is necessary to change the solar cells or enhance the shielding material (such as increasing the cover glass thickness).

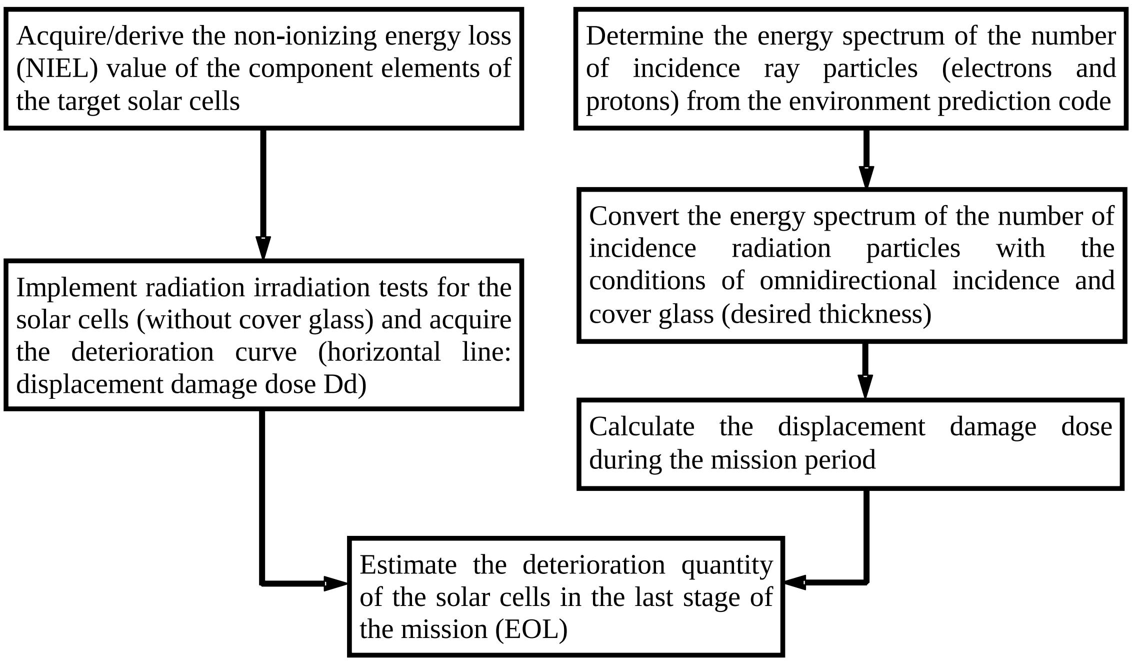



Figure 2.4-2 Prediction Procedure of Solar Cell Deterioration Quantity by Displacement Damage Dose (DDD) Method

### 2.4.2 Radiation Resistance Design of Solar Cells (Cell Selection)

Basically, there are two types of solar cells currently authorized by JAXA as components for use in space: highly efficient silicon cells and 3 junction solar cells. When radiation resistance is the only consideration for the materials and structure, the 3 junction solar cells are superior (the details of their radiation resistance capabilities are outlined in JERG-2-143-HB001). However, the silicon cells provide superior weight, price, and ease of handling. Determination of the type of solar cell to be used must consider the above.

The 3 junction solar cells provide superior radiation resistance. However, since the cells are made of a laminated structure, the amount of radiation damage changes according to the amount of penetration from the surface, which is determined by the energy - particularly in proton rays (refer to JERG-2-143-HB001 for details). For this reason, the radiation deterioration of the 3 junction solar cells indicates a complex behavior. Therefore, it is necessary to consider the radiation environment and the shielding materials before adopting the 3 junction solar cells.

The measures for radiation deterioration in the structural design of the above two types of solar cells are described in the following. Refer to this description when selecting the type of solar cells.

**(1) Silicon solar cells**

The minority carrier diffusion length of silicon (Si), which is the most important property value of solar cells, is larger than other solar cell materials, by approximately several 100 μm or more. On the other hand, the property value which deteriorates greatly due to the effects of significant radiation damage is also the minority carrier diffusion length. Therefore, in order to control radiation deterioration, the thickness of the solar cells should be designed for between 50-100 μm to prevent the emergence of an effect of the deterioration of the minority carrier diffusion length, to improve the radiation resistance. By this design, the initial output is sacrificed to some extent.

Each of the remaining factors of the open circuit voltage (Voc), short circuit current (Isc) and the maximum power (Pmax) is about 85%, 80% and 67%, when a 1 MeV electron ray of a space Si solar cell #109 (NRS/BSF type 100 μm), which is authorized by JAXA, is exposed at a fluence of $1x10^{15}$ $cm^{-2}$.

**(2) 3 junction solar cells**

The 3 junction solar cells have a laminated structure laminated comprising types of solar cells (sub cells): InGaP on the euphotic surface, GaAs in the middle and Ge on the back side. Each of the sub cells are called the top cell, middle cell and bottom cell respectively. These 3 cells are electrically connected in a series, and tunnel junctions are inserted between the cells for current flow. InGaP and GaAs are III-V group compound semiconductor materials, and generally excel in radiation resistance more than the IV group semiconductor materials, such as Si or germanium. Particularly, InGaP provides excellent radiation resistance, and its output deterioration is the lowest among the 3 sub cells. For this reason, a thinner InGaP top cell is designed into the 3 junction solar cells as a current limiting cell to reduce light absorption, i.e. the current output. Since the 3 sub cells are connected in a series, the sub cell with the lowest output current determines the output current of the 3 junction cell. By this design, the current output of the 3 junction solar cells provides extremely high radiation resistance. On the other hand, the voltage output becomes the total of the 3 cells due to the series connection. There have been no specific measures taken to improve the radiation resistance.

Each of the remaining factors of the open circuit voltage (Voc), short circuit current (Isc) and the maximum power (Pmax) is about 90%, 97% and 87% respectively, when a 1 MeV electron ray of space 3 junction solar cells #502 (Epi wafer A), which is authorized by JAXA, is exposed at a fluence of $1x10^{15}$ $cm^{-2}$.

### 2.4.3 Radiation Shielding (Panel Structure)

When actually mounting the solar cells to the substrate of the solar cell panels of a satellite, glass (cover glass, usually with a thickness of about 50-100 μm), is attached to the euphotic surface as a shielding material, to control deterioration caused by radiation damage. The radiation, especially the proton energy which comes from space, can be reduced with this glass and adhesives (usually with a thickness of about 20-30 μm), and low energy protons, will stop in the glass or adhesives, and will not reach the core of the solar cells.

The panel substrate on the back side of the solar cells also has a shielding effect. As mentioned previously, the typical structure of a substrate consists of a sandwiched aluminum honeycomb with CFRP, with a polyimide film attached on the cell attachment surface. There are cases where a thermal control material is attached to the opposite side. These materials have a shielding effect against radiation.

As mentioned in the items of the deterioration prediction method, the effect of these shields must be considered in the radiation deterioration prediction of solar cells. The shielding effect is proportional to the surface density ($g/cm^2$) of the shielding material.

Therefore, the shielding thickness on the surface and the back side must be acquired based on the surface density before performing the deterioration prediction calculation. It is necessary to use the value considering the portion for the shielding effect in the RDC of the RDC method, and the radiation fluence in orbit for the DDD method. Then, it is necessary to consider the shielding effect for each of the radiation incidences from the surface and back side, acquire the equivalent 1 MeV electron fluence from the RDC or the DDD value from the fluence in orbit, total the values of the surface and back side, and determine the deterioration prediction calculations.

There are cases where the acceptable deterioration rate of the solar cells is determined by the constraints, such as the area, size and weight of the solar array panels. When this is the case, it is necessary to calculate the amount of deterioration using the thickness of the shielding material, such as the cover glass as a parameter, to derive the required shielding thickness and then adopt a shielding material of that thickness.

#### 2.4.4 Other Deterioration Factors

There is the possibility of deterioration from the sunlight transmissivity of the cover glass (there are many cases where an antireflection film coating of MgF is used on the surface of the phosphate glass) attached to the euphotic side of the solar cells, and the adhesive (silicon adhesives, typically Dow Corning DC93-500) used to attach the cover glass deteriorate (color) from radiation and UV rays. Therefore, it is also necessary to consider the deterioration in the power generation of the solar cells due to this kind of deterioration. However, the resistance to normal radiation and UV ray environments (mission of about 5 to 10 years in a low orbit or geostationary orbit), have been sufficiently secured for the cover glass and adhesives which are currently used. In this case, it would not be necessary to take deterioration into consideration. For missions with particularly severe radiation and UV ray environments other than the above, it is necessary to perform radiation/UV ray irradiation tests under suitable conditions, evaluate the deterioration of transmissivity, and reflect any necessary changes in the panel design.

## 2.5 Single Event Design Standard

### 2.5.1 Outline of Single Event Effect

When charged particles, such as high energy protons, He ions, or heavy ions are exposed to electronic components, the particles will ionize along the trajectory of the particles and an electron hole pair will be generated. When a portion of a generated charge flows into the circuit of a device, malfunctions, over current will occur due to a noise current. Such an effect can be generated with just one incidence particle, and is called a single event effect (SEE). Single event effects can be classified into a number of types due to the differences in the types of devices and the generating mechanism.

(1) SEU

SEU is a phenomenon which occurs in memory devices, microprocessors, etc., in which a charge occurs from the incidence of high energy charged particle flowing into the memory circuit, causes malfunctions and reverses information in the memory. There are cases where adjoining multiple cells are upset by an incidence of one ion in recently-made components with microstructures, which is called MCU. MCU is used differently from MBU, in which multiple bits are upset in one phase.

(2) SET

SET is a non-destructive behavior which is generated in linear ICs, and logic circuits , such as optical semiconductor devices, OP amplifiers and comparators. The noise pulse generated from the charged particles which entered at the input stage is retained in the latch circuitry, or transmitted to the output stage, where malfunctions occur in the circuitry.

(3) SEL

SEL is mainly generated in devices of a CMOS structure. The thyristor structure is specifically included in CMOS structures. The thyristor changes to the ON state according to the noise current generated by incidences of high energy charged particles, and a large current continues to flow. Becausee a large current continues to flow locally unless the power supply is turned OFF, it is necessary to turn OFF this particular thyristor before there are malfunctions caused by electrodes fusing within the device and a voltage drop within the same power supply system.

(4) SEB

SEB is mainly generated in power MOSFET. The particular transistor is triggered by an incidence of high energy charged particles to the particular transistor which is included in the structure of a power MOSFET, and a large current flows into the device and destroys the device.

(5) SEGR

SEGR is a phenomenon which is generated in power MOSFET, which destroys the gate oxide.

Other new single event effects have been discovered accompanying the miniaturization of devices. However, the mechanism has not yet been completely clarified, and there are names of events which have not yet been standardized.

### 2.5.2 Design Procedure

The design flow for SEE is indicated in Figure 2.5-1. First, orbital conditions and the mission period are determined according to the mission requirements, and the fluence of the heavy ions and protons on the conditions is calculated from the space environment model. , When the radiation resistance data on the components selected based on the system requirements is confirmed, (an irradiation test is performed), The SEE rate of incidence in orbit is calculated from the data, with the spectrum of the heavy ions and protons, and a criticality analysis is performed on the device. If the results are not acceptable for the system, it is necessary to re-select the components, or take measures to protect the device.

### 2.5.3 Prediction Method of Single Event Probability of Occurrence

Charged particles originating in galactic cosmic rays and solar cosmic rays (protons and heavy ions) and protons trapped in the geomagnetic field contribute to single events in cosmic radiation environments. CREME96, which was developed by NRL, can be used for the prediction of the probability of a single occurrence. When the information of the target semiconductor devices, such as the resistance data of a single event, the space environment, orbit, and shielding thickness are input into the program, the probability of occurrence in orbit will be output. If data on the heavy ions does not exist, it is necessary to perform irradiation tests on the heavy ions to acquire the occurrence cross section - LET curve, and calculate the probability of occurrence. However, the devices in which the $LET_{th}$ exceeds the maximum LET (119 (MeV/(mg/cm$^2$))) of uranium which is the heaviest atom in space, it can be handled as a device in which a single event is not generated. The $LET_{th}$ is calculated from the test results by the Weibull fitting, or simply use the LET of the reverse cross section will be 1/100 of the saturated reverse cross section. In the case where $LET_{th}$ < 10 (MeV/(mg/cm$^2$)), the calculation for the probability of a single event occurrence by protons is also performed. When there is no data on the protons, it is necessary to acquire the data of the occurrence cross section for the energy of the protons using irradiation tests, and calculating the probability of occurrence.

In the case of a single event in a destructive mode, since a large number of test pieces are required to determine the occurrence cross section - LET curve, there are cases where the tests are performed only to confirm that no event is occurring in the provided LET. In such a case, the maximum occurrence cross section is calculated assuming that a destructive event occurred once at maximum LET, where a destructive event did not occur, and the probability of occurrence is calculated.

### 2.5.4 Measures for Single Events of Electronic Components

As basic measures at the component level, it is necessary to give priority for the use of devices with a larger resistance to a single event, devices in which the level of resistance has been clarified, or actually measure the resistance of the devices in which the resistance is unknown and can be mentioned using basic measurements. The target devices for each single event are indicated in Table 2.5-1. Be sure to perform an examination, an SET can be generated in all analog ICs.

#### (1) IC

Numerous tests on the single event of ICs have been conducted worldwide, and data has been accumulated. It is necessary to collect information while referring to the data base for selection, and compare it to the requirements of the mission determine its appropriateness.

The error detection correction (EDAC) circuit is effective for the SEU. The resistance of the SEL changes greatly according to the structure of the device. However, since a parasitic thyristor does not exist in a device with an SOI structure, the SEL will not occur. The collected charge can also be suppressed, and is also effective for improvement in the SEU resistance.

The effect of SET, which is generated in linear ICs such as operational amplifiers and comparators, changes greatly with the operating conditions of the device. For example, it is said that it is easier for the comparator to be affected by SET when the difference between the input voltage and reference voltage is smaller, and when the degree of amplification is larger for the operational amplifier. Therefore, when referring to the existing SET data, it is necessary to confirm whether the data was taken under the worst possible conditions. When actually evaluating the resistance, it is necessary to perform the evaluation in the worst possible conditions, or at least in the actual operating conditions if it is difficult to determine the worst possible conditions. For the selection of the components, it is necessary to examine the selection of the components which can be used in the operating conditions where the effect from SET is as low as possible.

(2) Electronic components other than ICs

Since the power MOSFET is mainly used as a switching element of the power system, it is necessary to take precautionary measures as there is a high possibility of an immediate loss of functions occurring when SEB or SEGR occur. It is preferable to select a power MOSFET which has single event resistance as much as possible. SEB occurs in n channel type MOSFET with a vertical mold structure. Since SEB does not occur in p channel type MOSFET, one of the methods is to adopt the p channel type depending on application. SEB will also not occur if used at a voltage sufficiently lower than the rated voltage. There is a possibility of SEGR occurring in both the p channel type and the n channel type. When reverse bias is applied to gate voltage, SEGR tends to occur. Therefore, it is necessary to be careful not to apply a large reverse bias during operation. In order to adopt a power MOSFET, it is necessary to verify the safe operating area (SOA) for a single event, and set an appropriate derating according to the system requirements.

Over currents can be prevented by the load even when SEB occurs in bipolar transistors if there is a resistance load. There are many cases where damage of the devices can be avoided. However, if used for a switching application, it is necessary to take the same measures as the power MOSFET.

### 2.5.5 Measures for Single Events of Devices

Measures for devices are not required if electronic components free of single events can be adopted. However, if there is no electronic component with SEE resistance which meets the requirements, it is necessary to take measures at the device level. In this case, it is necessary to select components in consideration of the mission and probability of occurrence . from the view point to the system. In addition, since the single event effect occurs due to high energy particles, it is necessary to keep in mind that a reduction in the probability of occurrence cannot be expected by increasing the shield thickness.

(a) SEU measures

- Correct the errors caused by SEU by an error correcting code or the EDAC circuit. If there is a possibility of MBU occurring due to the structure of the devices, consider distributing the data bits over multiple devices to prevent MBU, or using a code which will possibly correct the errors of multiple bits.
- Prevent errors by having 3 or more of the same circuits as a redundant system, to handle the majority of the output.
- Provide a watchdog timer. This is a measure to prevent the CPU running from out of control, and the system is reset when a specific address is not accessed for each fixed time.

(b) SET measures

- Provide the same multiple circuits, and send the signals through a delay circuit with different time delays, to handle the majority of the output.
- Provide a filter circuit to remove false pulses.
- Use circuit parameters which will reduce the affect of SET.
- Take the same measures as SEU.

(c) SEL measures

- Provide a current limiting circuit to prevent the ICs from being destroyed due to an over current. The threshold value at constant and when abnormal, must be set in consideration of an increase in the power current due to the total dose of the concerned IC.
- Use two or more of the same circuits as a redundant system.

(d) SEB measures

- The probability of a SEB occurrence increases as the operating voltage approaches the rated voltage. Therefore, adopt a circuit configuration which is set with an appropriate derating value according to the mission requirements in consideration of the SEB resistance of each device.

(e) SEGR measures

- In consideration of the SEGR resistance of each device, adopt a circuit configuration set with an appropriate derating value according to the mission requirements within the specified range of the safe operating area.

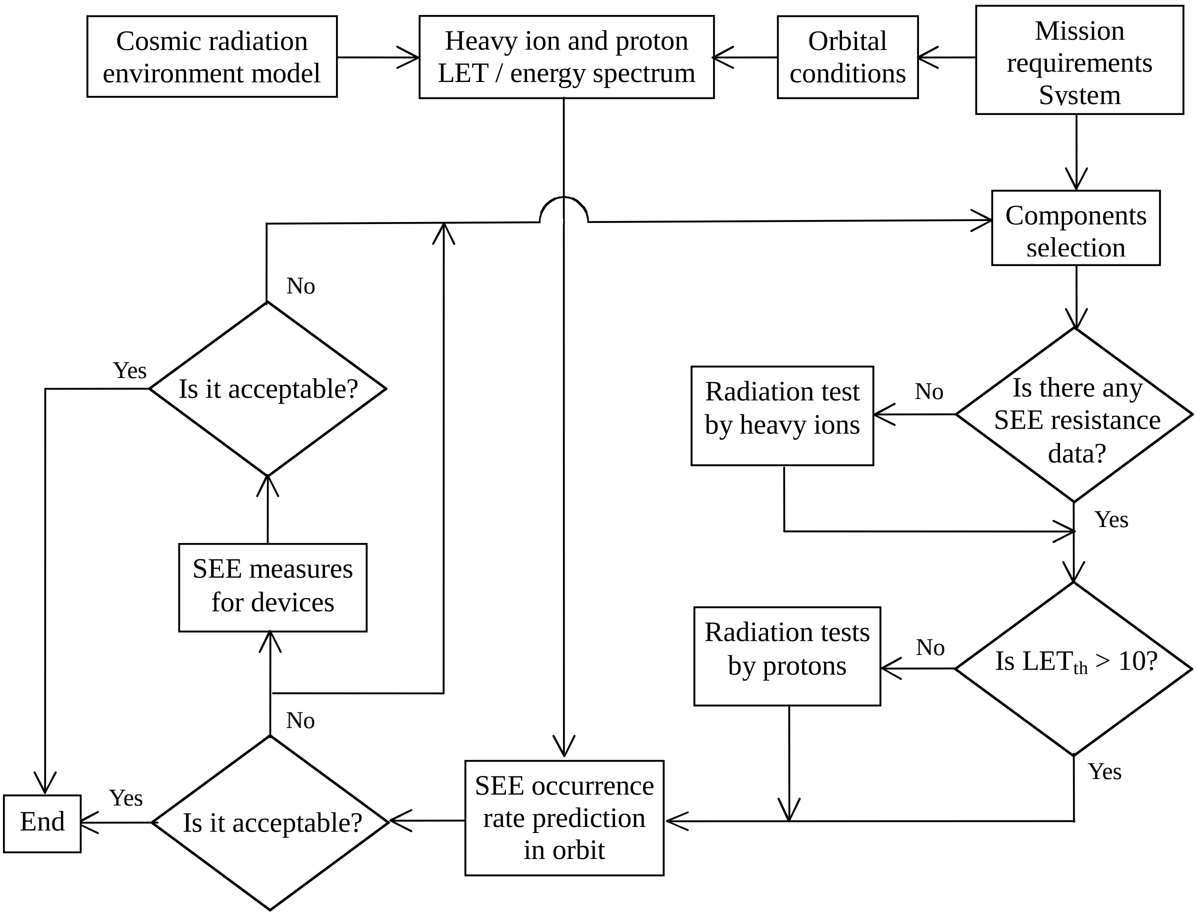



Figure 2.5-1 Design Flow for Single Events

Table 2.5-1 Target Device for each Single Event

| Type | Target Device |
|---|---|
| SEU | Memory devices, microprocessors |
| SET | Analog IC (comparators, operational amplifiers, regulators, driver ICs, ADC, DAC, etc.), logic circuits, high-speed photo couplers, high-speed MPUs, high speed memory devices, etc. |
| SEL | CMOS devices |
| SEB | N channel power MOSFET, NPN bipolar transistors |
| SEGR | Power MOSFET |

## 2.6 Design Standard for Displacement Damage of Semiconductor Devices

### 2.6.1 Overview

When a semiconductor is exposed to particles, such as electrons, protons and ions, most of the kinetic energy is lost due to ionization of the materials. The remaining small amount of energy drives out the nucleus in the semiconductor from the original position in the lattice, and causes permanent damage. This is called displacement damage (DDD), which is the cause of deterioration of the characteristics in optical semiconductor devices . In semiconductor devices covered with a thick shielding, the deterioration by displacement damage of electrons is less than the deterioration by the displacement damage of the total dose or protons. Therefore, it is not an issue for semiconductor devices, except for solar cells, which normally have a very thin shielding. Since an abundance of high energy protons exist in a space environment, the displacement damage by protons is an issue for semiconductor devices. The susceptibility for displacement damage changes greatly according to the application or method of use of the device. (Refer to item 2.4 for the deterioration by the displacement damage of solar cells, which is excluded from this section.)

When electrons, protons, and ions enter semiconductors and the nucleus is driven out, the driven out atom becomes an interstitial atom, and a hole will be generated in the original position. The re-coupling of this interstitial atom and hole is unstable, and most return to the original condition through recombination without leaving any damage. However, some holes move inside the lattice avoiding recombination, and become a stable defect by bonding with the impurities in the semiconductor. The level of this defect is formed in the band gap of the semiconductor, and generates electron hole pairs, recombination, capture of the carrier, compensation and tunneling at that level. For that reason, effects, such as an increase in the dark current, a decrease of the carrier, an increase in the leakage current at the time of the reverse bias, will occur. Since the minority carrier lifetime and the lifetime of the generated carrier among the characteristics of semiconductor devices are the most easily affected, the semiconductor devices utilizing these characteristics have the greatest susceptibility to displacement damage.

### 2.6.2 Prediction Method of Displacement Damage

The energy used to cause displacement damage to materials is expressed as NIEL. When semiconductor devices receive displacement damage, the parameters of the devices will deteriorate, and it is known that the degree of deterioration and NIEL are proportionally related.

Therefore, it is necessary to acquire the proportional coefficient K from past data or by irradiation tests of the protons first. Next, it is necessary to calculate the NIEL value in an actual proton environment and by multiplying the proportional coefficient K by the NIEL value, where the degree of deterioration in orbit of the parameters of the device concerned can be calculated. For example, in the case of a CCD, the charge transport efficiency (CTE) drops by the displacement damage. However, the change ΔCTE (E) of the CTE for the proton energy is expressed by the following formula using the proportional coefficient K.

$$\Delta CTE(E)=K \cdot NIEL(E) \cdot \Phi(E) \tag{2.6-1}$$

Φ(E) is the fluence of the protons. Therefore, ΔCTE in orbit is calculated by the following formula.

$$\Delta CTE = K\int_0^\infty NIEL(E)\frac{d\Phi(E)}{dE}dE \tag{2.6-2}$$

The prediction flow for displacement damage based on the above is indicated in Figure 2.6-1.

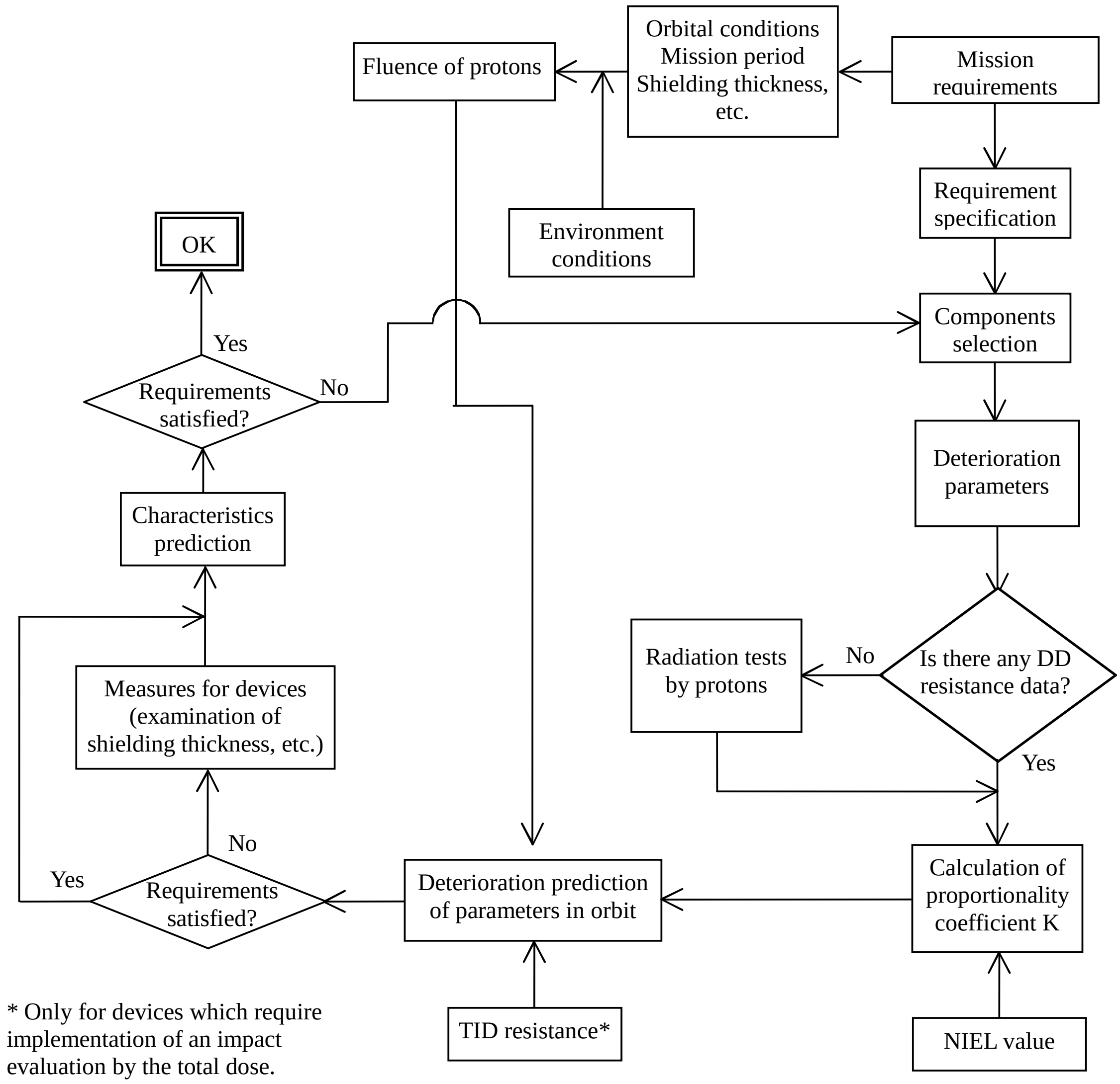



Figure 2.6-1 Deterioration Prediction Method by Displacement Damage to Devices in Orbit

### 2.6.3 Resistance for Displacement Damage of each Device

The semiconductor devices which will be affected by displacement damage are summarized in Table 2.6-1. It is necessary to perform evaluations on the resistance for displacement damage in advance, and perform a deterioration prediction in orbit for devices which may be greatly affected by displacement damage. It is also necessary to perform an evaluation on the affects of a single event or total dose as required. There are cases where an evaluation on the effects of both the total dose and displacement damage are required depending on the device. Generally, the devices in which the minority carrier lifetime and the generation carrier lifetime, or the devices in which extremely high performance is required in specific parameters, have low resistance to displacement damage.

Table 2.6-1 Semiconductor Devices Affected by Displacement Damage

| Device | Effect of Displacement Damage | Resistance to Displacement Damage |
|---|---|---|
| CCD | Deterioration of charge transport efficiency (CTE), increase in the dark current | Easily affected by displacement damage<br>Linear CCD are highly resistant |
| Photo detectors | Deterioration in speed of response<br>Increase in dark current | Resistance changes with applications<br>Photo-transistors tend to be affected easily by displacement damage<br>MSM photo diodes are highly resistant |
| Light emitting devices (LED, laser diodes) | Deterioration of optical output<br>Increase in current threshold value (laser diodes) | Affect by displacement damage is relatively low<br>LED have less resistance than laser diodes<br>Amphoterically doped LED are less resistant |
| Photo couplers | Deterioration of current transfer ratio (CTR) | Response to radiation is complex<br>Resistance changes greatly with purpose & applications<br>Photo couplers which use photo diodes have the highest resistance<br>Photo couplers which use photo transistors have less resistance<br>* Photo couplers with a high speed operation of 1 MHz or more require an examination on SET |
| Si bipolar transistors, linear ICs | Deterioration of gain | Less resistance with horizontal type pnp transistors<br>High resistance heterojunctions |

(1) CCD

When a CCD receives displacement damage, deterioration of CTE increases in the average dark current with an extremely large dark current in each pixel, resulting in an increase of noise in the output amplifier.

The CTE is the most important parameter for a CCD. However, when the signal charge captured by the defective level formed by the radiation of the protons, and by the release of the signal charge after the clock cycle ends at the time of capture, the signal will appear in the image of the cycle when the signal is released. This does not produce an image of the original cycle and the quality of the image deteriorates. Therefore, the affect from the displacement damage to the CTE will be determined by the read method or clock frequency of the device. Since the clock frequency of linear CCD is as fast as 1 MHz or more, and the signal is transmitted without being captured by the defective level, it is not easily affected by displacement damage. The measures for CTE deterioration are currently under research. However, the deterioration of CTE can be slightly reduced by cooling the device to reduce the capture of the carrier. When additional measures are required, a thicker shielding should be used. However, the effect from the displacement damage by secondary particles which occurred due to collisions between the protons and shielding material becomes larger.

There is an average dark current and an extremely large dark current (spike) which appears in each pixel, and the signal to noise ratio (S/N) can be improved by using large area pixels.

The following items can be considered as measures for displacement damage of CCD. It is necessary to consider the effect on the devices which are easily affected by the total dose as well.

- Shielding of the devices
- Cooling of CCD
- Selection of devices which are highly resistant to displacement damage
- Selection of operating conditions which can not be easily affected by displacement damage, and signal processing
- Use of CCD with the large area pixel

(2) Photo detectors

There are PN junction photodiodes, PIN diodes, and photo-transistors. in photo detectors, and an increase in the dark current by the carrier generated in the depletion layer, as well as deterioration of the response due to the deterioration of the minority carrier lifetime which are mentioned as effects due to displacement damage. Since the gain of photo transistors is greatly affected by the lifetime of the minority carrier, it is easily affected by displacement damage. However, the MSM photo diode is the majority carrier component, and has a high resistance to displacement damage. The resistance to displacement damage changes greatly by the application of each device.

Photo diodes specific to various applications must be provided, and the effect from radiation changes greatly according to the design. In addition to the permanent damage by displacement damage, there may be an effect from a temporary increase in the output current due to ionization depending on the application.

(3) Light emitting devices

The resistance of laser diodes to displacement damage is relatively high. However, there is a possibility of the output deteriorating when the current threshold value changes greatly.

Even though LEDs are inferior to laser diodes, there are many LED which have a high resistance to displacement damage. However, the resistance changes according to the applications, such as a large output, and use at high speeds. As an exception, it is known that amphoterically doped LED tends to be affected by displacement damage.

(4) Photo couplers

Photo couplers are hybrid modules which consist of LED (light sources), photo detectors and optical couplings, and are extensively used for the purpose of separating circuits electrically. An important parameter of photo couplers is the current transfer ratio (CTR), and is expressed in a ratio for the LED forward direction (drive) current of the collector current of photo detectors. There are various designs of photo couplers, and the applications can also be largely divided into digital photo couplers and linear photo couplers. The response of photo couplers to radiation greatly depends on the design and the application. Photo couplers are also affected by the total dose or single events. In addition to displacement damage, it is necessary to consider the effects of SET in photo couplers which are used at high speeds of 1 MHz or more. Amphoterically doped AlGaAs LED tend to be affected by displacement damage the most among the LED. Current photo couplers have less resistance than the earlier photo couplers.

The response of photo couplers to radiation becomes complex for the following reasons.

(a) Since a photo coupler is a hybrid module, the individual difference in the radiation resistance is too large.

(The origin of the configured components cannot be clarified.)

(b) The deterioration which can be observed is a combination of the total dose and displacement damage, and the impact is dependent upon the design or application of the photo coupler.

(c) When a photo coupler is a part of a much larger hybrid module, such as a DC-DC converter, there is a possibility where the photo coupler may receive an effect from other components in the module as well.

CTR deterioration of photo couplers is mainly determined by the displacement damage resistance of the LED. When photo transistors are used for the photo detector, an effect from deterioration of the optical response may also be received. Photo couplers using photo diodes are the most resistant to displacement damage overall.

When performing an evaluation of the CTR, it is necessary to consider it according to the application. For digital photo couplers, it is necessary to evaluate the CTR across the entire wave range, and an evaluation on the CTR in the specific wave range to be used is required for linear photo couplers.

(5) Bipolar transistors

Bipolar transistors themselves have a relatively high resistance to displacement damage. However, analog bipolar ICs tend to receive displacement damage. Even though the resistance of linear ICs changes greatly according to the process and device design, it is known that linear ICs which include horizontal type pnp transistors tend to receive the most displacement damage, and there is a possibility of linear ICs which use horizontal type pnp transistors at low currents on the input portion having less resistance. In devices where high performance is demanded, such as extremely small input offset, bias current and low noise also tend to be affected by displacement damage. On the other hand, bipolar transistors with heterojunctions, such as SiGe, have a high resistance to displacement damage.

## 2.7 Affects from other than Cosmic Radiation

### 2.7.1 Measures for Atomic Oxygen

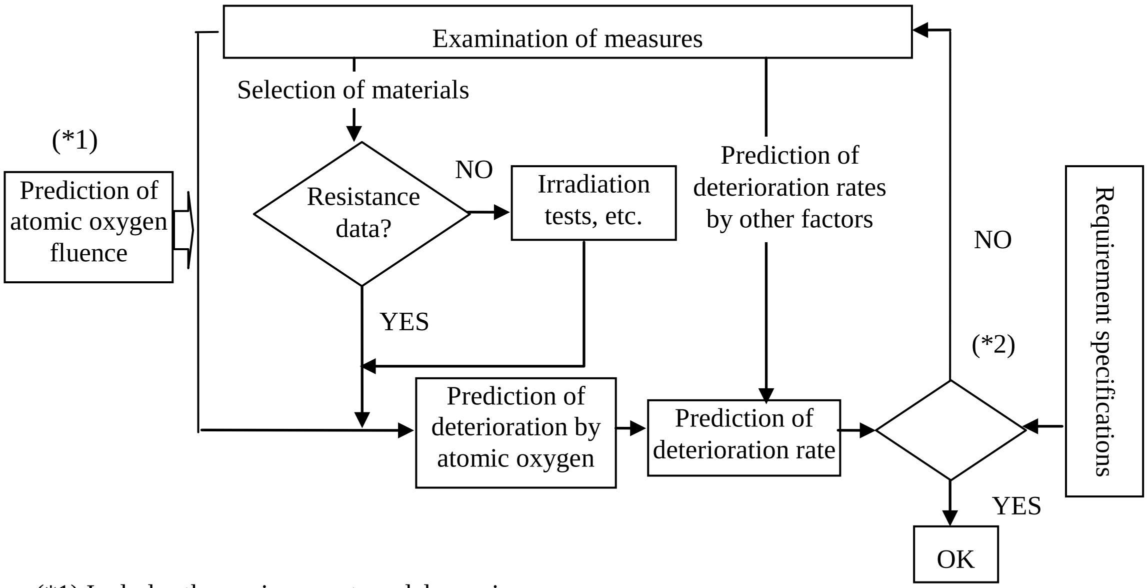
(1) Materials which have a resistance to atomic oxygen must be used, especially on the outer surfaces of spacecraft which travel at, or pass through, altitudes of 1,000 km or less.

(2) Even though a location is not directly exposed, if there is a possibility of atomic oxygen penetrating an opening, avoid using materials with notable reactions to atomic oxygen.

(3) When it is unavoidable to use such materials, use the appropriate coverings or coatings.

(4) Calculate and specify the fluence of the atomic oxygen for each mission, to predict whether the deterioration by atomic oxygen is acceptable for the mission period, based on the existing data. When no data exists, perform verifications as much as possible through testing..

The design flow regarding the measures for atomic oxygen is indicated in Figure 2.7-1. Refer to JERG-2-143-HB001 for details.




(*1) Includes the environment model margin

(*2) Is it OK to include the design margin and the environment model margin?

Figure 2.7-1 Design Flow Regarding Measures for Atomic Oxygen

2.7.2 Measures for Ultraviolet Rays

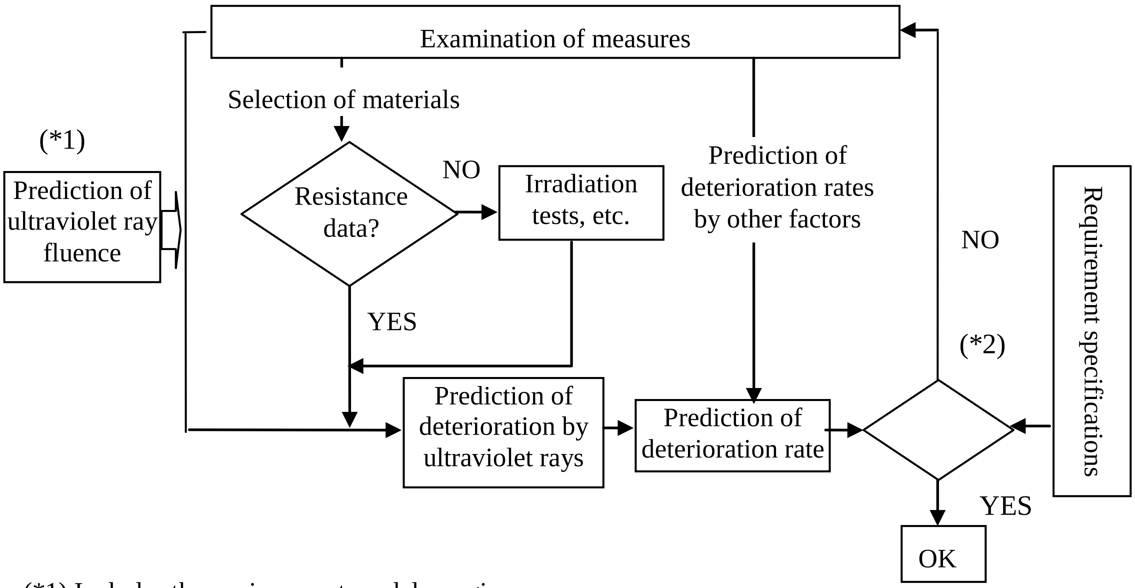
(1) Do not use materials which are notably affected by ultraviolet rays (wave length of about 400 nm or less), in locations directly exposed to space.

(2) Calculate and specify the fluence of the ultraviolet rays for each mission and location used, and predict whether the deterioration by ultraviolet rays is acceptable for the mission period based on the existing data. When no data exists, perform verifications through testing as much as possible. Confirm the wave length range of the irradiation light source in the resistance to ultraviolet ray data of noncommercial use materials.

(3) Consider that the materials will be affected by reflected lighting or concentrated lighting, and that the ultraviolet ray fluence will increase depending on the location where the materials are used.

The design flow regarding the measures for ultraviolet rays is indicated in Figure 2.7-2. Refer to

JERG-2-143-HB001 for details.




(*1) Includes the environment model margin

(*2) Is it OK to include the design margin and the environment model margin?

Figure 2.7-2 Design Flow Regarding Measures for Ultraviolet Rays