ANNEX A
GLOSSARY OF TERMS

ABSORBER

Any matter intervening in the path of a radiation beam which thus absorbs energy from that beam.

ABSORPTION COEFFICIENT (μ)

Electromagnetic radiation penetrating a material is absorbed according to Lambert's Law: $I = I_0 e^{-\mu t}$.

ACCELERATION FACTOR

The ratio between the dose rate of radiation used in simulation and the dose of the same type of radiation expected in the actual environment. When a radiation beam is scanned across a sample surface, a distinction must be made between the instantaneous and time-averaged dose rate.

ADD-ON ABSORBER

A material added to equipment for the specific purpose of stopping radiation (in contrast to "built-in" absorber).

APOGEE BOOST MOTOR

Solid fuel rocket often forming the central core of spacecraft, especially geostationary vehicles.

BAND-BENDING (ψ_S)

A uniform electric field in a material is associated with a linear variation of potential with distance. If, however, the material responds to the applied potential by producing a space charge, the field will not be uniform and the potential-versus-distance plot will be curved. This often occurs near the surface of silicon (as in a MOS device) and is called "band-bending". (According to this system, band-bending at zero applied potential results from work function differences between the silicon and gate electrodes.)

In terms of surface potential, the degree of bending can be expressed as $\psi_S = E_C$ (bulk) - E_C (surface).

The conductivity of the silicon at the interface is a function of ψ_S. The condition of zero band-bending ($\psi_S = 0$) is called the "flat band" condition.

BAND-EDGE

See BAND GAP.

BAND-GAP

In perfectly crystalline inorganic insulators and semiconductors, there are well-defined regions of the energy-state diagram which are "forbidden bands". In these regions, there are no quantum energy states which can accommodate electrons or holes. The lowest of these bands

is often referred to as the band-gap. The lower edge is defined by electron potential energy 'E_V' (the top edge of the valence band); the upper edge is defined by 'E_C' (the bottom edge of the lowest conduction band).
The band-gap energy 'E_G' is equal to $E_C - E_V$. Conduction in any inorganic solid involves the excitation of electrons from energy levels below 'E_V' to levels above 'E_C' and subsequent motion of the electron or the resulting hole.
The bands have a continuous overlap of quantum states which allow this. Very similar conditions occur even in non-crystalline but continuous networks such as the Si-O-Si-O network of an oxide thermally grown on silicon (see also CARRIER, FERMI LEVEL, TRAPPING and MOBILITY).

BGR CURVES
See DOSE TRANSMISSION.

BREMSSTRAHLUNG (BRAKE RADIATION)
X-rays produced when particles (mainly electrons, but also protons) are slowed down by interaction with matter. Sometimes also called "White Radiation" to distinguish it from the characteristic line spectra produced by each element.

BUILT-IN ABSORBER
Material forming part of the normal fabric of an equipment box or structure (in contrast with ADD-ON ABSORBER).

BULK DAMAGE
The disturbance of the lattice structure of matter by the displacement of atoms as frequently produced by energetic particles (term often used to distinguish between this type of damage and IONISATION EFFECTS or surface damage).

BULK DAMAGE FIGURE $(\Delta (1/\beta)_b$
Change in the reciprocal of the gain (β, h_{FE}) of a bipolar transistor under irradiation, as caused by the reduction of a minority carrier's lifetime (in contrast with SURFACE DAMAGE FIGURE).

CARRIERS
When electrons are excited across the BAND-GAP, both they and the resulting holes are mobile and will move if an electric field is applied (see MOBILITY). In inorganic oxides and semiconductors, electrons and holes are the main "carriers" of current. Ions usually contribute only to a very minor extent.
In n-type silicon, electrons are in the majority and holes in the minority (and vice versa in p-type silicon). Radiation or forward junction bias can produce "excess minority carriers". When the source of these is cut off, the excess will decay by recombination with majority carriers via DEEP

TRAPS. The time constant for this process, which is known as the minority carrier lifetime τ, is controlled by Shockley Hall-Read statistics.

CONDUCTION BAND
See BAND-GAP.

DAMAGE-EQUIVALENT FLUENCE
Bulk damage expressed in units of fluence of some standard energy of particle. The first unit developed was the Damage-Equivalent, Normally-Incident 1 MeV Electron cm^{-2}, sometimes abbreviated to "DENI". Other common unit: 1 MeV neutron cm^{-2}.

DEEP TRAP
A CHARGE TRAP is considered "deep" when it lies well away from the band-edges so that thermal excitation cannot depopulate it. In silicon, traps due to radiation-induced displacement damage lie deeper than 0.1 eV from the band-edges. Traps lying at the centre of the band-gap are the most efficient as recombination centres for minority carriers in semiconductors (see CARRIERS). Hole traps in silicon dioxide lie at depths greater than 2 eV. Thermal depopulation at room temperature is not significant for any trap lying deeper than 0.025 eV.

DEFECT
See TRAPPING.

DEPTH DOSE
Term used in medicine to indicate the total dose expected within a mass of tissue at a specified depth (see DOSE-DEPTH CURVE).

DOSE ('D')
Used broadly for any accumulated energy value, but strictly in dosimetry for the energy absorbed in a unit mass of material, usually by ionisation processes. Units are the "rad" and "gray" which are equivalent to respectively 100 $ergs.g^{-1}$ and 1 $J.kg^{-1}$ (1 Gy = 100 rad).

DOSE-DEPTH CURVE
Term used extensively in space engineering for a curve indicating the dose deposited in a given material behind various thicknesses of a separate absorber or array of absorbers.

DOSE RATE
The rate at which energy is transferred to a material by a radiation beam, e.g. $rad.s^{-1}$ (or $Gy.s^{-1}$).

DOSE TRANSMISSION CURVES
Term used for curves which indicate the effect of the thickness of a given slab of absorber on particles of a given energy, yielding the dose at a given depth in rads per unit fluence. An early set of these curves is referred to in this document as "BGR Curves", after the authors Brown, Gabbe and Rosenzweig.

ENERGY FLUX

The passage of energy in the form of penetrating particles, not necessarily stopped. Typical units: $erg.cm^{-2}$ and $W.m^{-2}$.

ENERGY TRANSMISSION COEFFICIENT (ETC)

The fraction of incident energy flux that emerges from an absorber slab.

EXPOSURE

An important term in dosimetry which expresses fluence in terms of its effect on a dosimetric medium (nearly always air at STP) and the number of air ions produced per unit mass. An exposure of 1 röntgen = exposure to that fluence of a given radiation which, in air, would generate 2.58×10^{-4} coulombs of ionic charge per kilogramme (term used in contrast with DOSE which varies from absorber to absorber).

FAST STATES

See INTERFACE STATES.

FERMI LEVEL (E_F)

An important mathematical concept of Fermi statistics which defines the electron population of the conduction band, whether populated by thermal or radiation-induced excitations. In the latter case, the term quasi-Fermi level is used. In undoped (intrinsic) silicon, E_F lies at the centre of the band-gap E_i.

In n- and p-type silicon, it lies respectively above and below E_i. Temperature and high doping move E_F towards the band-edges. BAND BENDING at the $Si\text{-}SiO_2$ interface changes the relation between E_F and E_C, hence the alterations of conductivity which accompany band bending (for E_C, see BAND GAP).

FLAT-BAND VOLTAGE (V_{FB})

In MOS devices, an important parameter which indicates the amount of charge in oxide. Gate voltage at which no surface band-bending is present. V_{FB} shifts under irradiation.

FLUENCE

Time-integrated flux. Unit: $e.cm^{-2}$. It is useful to add the symbol for the particle, e.g. "$e.cm^{-2}$" or even "1 MeV $e.cm^{-2}$" (the unit "m^{-2}" is not often used in relation to radiation).

FLUX

Number of particles passing through a specific zone per unit time. For parallel beams, this will be a unit area; for omnidirectional radiation, the zone chosen is usually a sphere with cross-section 1 cm . In both cases, the unit is $cm^{-2}.s^{-1}$ (the unit $m^{-2}.s^{-1}$ is not often used in relation to radiation).

GRAY (Gy)

New radiation dose unit of the Système Internationale. Its value is 1 $J.kg^{-1}$ = 100 rad.

GROWTH CURVE
Plot of change in threshold voltage or flat-band voltage (ΔV_T or ΔV_{FB}) against radiation dose 'D'. Important analytical tool in MOS testing and circuit design.

HARDENING, HARDENED
Terms used to describe improvement in the tolerance of a device or system to a radiation environment. Originally used by the military for sites invulnerable to attack.

HARDNESS ENGINEERING
A new term proposed here to describe briefly the whole process of introducing tolerance to radiation into a system, involving interaction with the design process at many points.

INITIAL TRAPPING PROBABILITY (A)
See TRAPPING.

INTERFACE INSTABILITY
See INTERFACE STATE.

INTERFACE STATE
At the interface between two dissimilar media, wave functions in any periodic solids must be disturbed. The quantum states at an Si-vacuum interface are called "surface states" or "Tamm states". At the interface between silicon and an oxide film thermally grown upon it, the opportunities for unique quantum states are numerous owing to the presence of lattice mismatch, non-stoichiometric conditions and impurities, especially hydrogen.
Those states which are observed in electrical measurements of MOS systems to accept or donate charge to the silicon are lumped under the operational term "interface states". If the exchange of charge is rapid (1 microsecond), the states are termed "fast".
In other quantum states, "slow" charge exchange may occur over many hours, leading to an INTERFACE INSTABILITY. Concentration of interface states may be plotted versus potential at the silicon surface. Local concentration D_{it} is usually expressed in units $cm^{-2}.eV^{-1}$.
Charge in these states in a given equilibrium condition Q_{it} is usually expressed in units of cm^{-2}.

IONISATION EFFECTS
A large class of radiation effects which involve the removal of an electron from a valence level, or below, in an atom and its escape beyond the excitation levels of that atom (for semiconductors, used in contrast with "bulk damage").

IRRADIATION BIAS
The electrical stress voltage placed on a device during irradiation. Some authors use the term "bombardment bias".

LARGE-SCALE INTEGRATION (LSI)

The integration of several hundred or more device elements on a single semiconductor chip.

LATCHUP

The onset of a self-sustaining conduction mechanism in a junction structure with four regions such as p-n-p-n in series and closely spaced. The mechanism is otherwise known as being of the SCR or thyristor type. Latchup can be triggered in certain complementary MOS integrated circuit designs and also in many junction-isolated bipolar integrated circuits by a pulse of radiation of dose rate greater than about 10^6 rad.s^{-1}.

LOGIC UPSET

Pulses of radiation of dose rate higher than about 10^6 rad s^{-1} generate photocurrents of significant magnitude in semiconductor junctions. They can so alter the voltages at circuit nodes that logic circuits can interpret the disturbance as a logic signal and change state. The proper signals passing through are thus "corrupted" by spurious data.

MAJORITY CARRIER

See CARRIERS.

MAXIMUM ACCEPTABLE DOSE D_A (MAX)

Term proposed here for the dose at which some specified degradation phenomenon reaches intolerable proportions for a given purpose of the device.

MODIFIED PROCESS (M1, M2)

Terms proposed here for a MOS ranking scheme. Used to describe only minor process modifications of MOS processing, e.g. modification of oxide growth temperatures or ambients, but not including the modification of layout, gate electrodes or any property.

MEDIUM-SCALE INTEGRATION (MSI)

The integration of 10 to 100 device elements in a single semiconductor chip.

MeV

Mega-electronvolt. Value: 1.6018 x 10^{-13} joules.

MISSION DOSE

The radiation dose acquired by a given component behind a given amount of absorber over the time specified for survival in orbit of a space vehicle.

MINORITY CARRIER

See CARRIERS.

MINORITY CARRIER LIFETIME ( )

The decay time constant for excess minority carriers (see CARRIERS).

MIS

Metal-Insulator-Semiconductor device of which MOS is an example.

MOBILITY (μ)

The velocity achieved by MAJORITY CARRIERS in a medium under unit electric field. Units: $cm^2\ V^{-1}\ s^{-1}$. In solids, mobility is controlled by TRAPPING and the scattering of carriers from charged DEFECTS.

MONTO CARLO TECHNIQUE

Calculation method involving the insertion of random numbers to simulate a phenomenon such as the random scattering experienced by electrons passing through an absorber.

NIR

See NOISE IMMUNITY.

NOISE IMMUNITY (V_{NIL} OR V_{NIH})

That voltage which, when applied to the input node of a logic device in either the high 'H' or low 'L' condition, will cause a spurious change of logic state. "Noise Immunity Reduction (NIR) is the term used for a degradation mode in logic circuits.

NUMBER TRANSMISSION COEFFICIENT (NTC)

The number fraction of incident particle flux that emerges from an absorber slab. The equivalent term for energy flux is the ENERGY TRANSMISSION COEFFICIENT.

PROTECTION

Collective term used to indicate a piece or whole arrays of absorbers without specifying whether they are "add-on" or "built-in".

RAD

Most commonly used unit of dose; equal to 100 erg g^{-1}.

RANGE

The depth to which a particle is likely to penetrate an absorber. Since stopping is a statistical process, several ranges ("practicable", maximum", "extrapolated", etc.) have to be defined.

RECIPROCITY

The condition which obtains when, irrespective of the dose rate, the damage or other effect produced depends on the total dose.

RÖNTGEN

Unit of EXPOSURE equivalent to the generation of 2.68 x 10^{-4} coulombs of air ion per kilogramme.

SECTOR ANALYSIS

Analytical process required for assessment of total protection of a given point within a spacecraft ("dose point"). Involves dividing the spacecraft into sectors of roughly uniform thickness and calculating the dose transmission through each.

SHIELD

General term; as for PROTECTION.

SURFACE EFFECT

In MOS devices and bipolar transistors, the various effects which occur in the passivating layer at the top surface of the active chip.

SWITCHING SPEED

In a logic circuit, the time taken for a logic swing at an input node to be registered as a voltage swing at the output node of a logic gate is termed the "delay time" of that gate. Within that delay, we can consider the shape of the output voltage waveform and define a "rise time" for that wave-form. Both times may be altered by irradiation.
"Switching Speed Reduction" (SSR) is the term used for a degradation mode which can define the MAXIMUM ACCEPTABLE DOSE, D_A (max) of a logic circuit.

SWITCHING SPEED REDUCTION (SSR)

See SWITCHING SPEED.

SURFACE DAMAGE FIGURE ($\Delta(1/\beta)_S$

Change in the reciprocal of the gain (β, h_{FE}) of a bipolar transistor under irradiation, as caused by one of the "surface effects" (in contrast to BULK DAMAGE FIGURE).

SURFACE STATES

See INTERFACE STATES.

THRESHOLD VOLTAGE (V_T)

In MOS devices, the gate voltage at which the source-drain current reaches a specified value, commonly 10 μA.
"V_{TN}" is often used to denote V_T of the n-channel element of a CMOS device.
"V_{TP} " is often used to denote V_T of the p-channel element of a CMOS device.

THRESHOLD VOLTAGE SHIFT (ΔV_T)

One of the most important parameters in the analysis of radiation-induced degradation of CMOS devices. The difference in V_T values before and after irradiation or other treatment.

TRANSCONDUCTANCE (g_m)

The term for "gain" of a MOS device, i.e. the slope of the I_D -VG curve at a particular V_G and supply voltage.

TRAPPING

A local disturbance of the atomic network in a semiconductor or insulator; e.g. an impurity atom or the absence of an atom (vacancy) is termed a DEFECT and produces a local disturbance in the BAND-GAP. A quantum level of potential energy 'E_T' is found in the normally forbidden gap region.
Trapping occurs when a hole or electron falls into this potential well and is held there. If 'E_T' lies near 'E_C' or 'E_V', then the trap can be emptied by thermal excitation and be termed "shallow".
If 'E_T' is far from 'E_C' or 'E_V' (DEEP TRAPPING), then only recombination effects or high-energy excitation can empty the trap. Holes are very deeply trapped in SiO_2 near the interface (E_T-E_V> 2eV).

TRAPPING PROBABILITY (A)

The probability that a trap will capture an electron or hole for unit flux of holes is equal to N_TS, where 'N_T' is the density of empty traps per unit area and 'S' is the trapping cross-section. The term INITIAL TRAPPING PROBABILITY is used to express the probability of capture of holes in a MOS device early in the charge build-up process, i.e. when most of the existing traps are unfilled. This 'A' value is in the form of a fraction and used operationally to define the performance in space of a MOS device.

VACANCY

See TRAP.

VTNZ

Term proposed here to describe a form of degradation in an MOS device when radiation-induced shift brings 'V_{TN}' to zero.

VALANCE BAND

See BAND GAP.

WATER PHANTOM

A mass of absorber used to surround a detector for measuring radiation dose. Used, during calibration of a radiation beam, to establish a state of secondary electron equilibrium almost similar to that found in tissue or water under the same radiation. Certain plastics ("water- equivalent phantoms") can be used in place of a tank of water.

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ANNEX B.
RADIATION HANDBOOKS, TEXTBOOKS AND REVIEWS

The publications in this section either give a comprehensive treatment of the engineering problems of radiation effects or contain extensive compilations of radiation test data. A list is given below in chronological order.

1963

- W.C. Cooley and R.J. Janda, "Handbook of Space Radiation Effects on Solar-Cell Power Systems". NASA SP-3003, U.S. Dept. of Commerce, Washington DC (1963).

1964

- J. Kircher and R. Bowman, "Effects of Radiation on Materials and Components", Reinhold (1964).

1965

- C.J. Goetzel, J.B. Rittenhouse and J.B. Singletary, "Space Materials Handbook", Pt. I, Addison-Wesley, Reading, Mass., USA (1965).

1966

- H. Oleson, "Radiation Effects on Electronic Systems", Plenum Press (1966).

1970

- N.W. Holm and R.J. Berry, "Manual on Radiation Dosimetry", Dekker, USA (1970).

1972

- L.W. Ricketts, "Fundamentals of Nuclear Hardening of Electronic Equipment", New York, Wiley (1972).
- M.H. Van de Voorde and C. Restat, "Selection Guide to Organic Materials for Nuclear Engineering" (July 1972).

1977

- N.J. Rudie, "Principles and Technique of Radiation Hardening", 3 Volumes, Western Periodicals Co., 13000 Raymer St., N. Hollywood, Cal. 91605 (1977).
- H.Y. Tada and J.R. Carter, "Solar Cell Radiation Handbook", 2nd Edition, JPL Publication 77-56, Jet Propulsion Laboratory, Pasadena, Cal. (Nov. 1977).
- D. Bräunig, W. Gaebler, W.R. Fahrner and H.G. Wagemann, "GfW Handbook for Data Compilation of Irradiation Tested Electronic Components", 1st Edition,

Report No. HMI-B248 (TN 53/08), DFVLR/BPT and Hahn-Meitner Institut für Kernforschung, Berlin, W.Germany (Nov. 1977). (Note: 2nd Edition 1981).

1978

- G. Holmes-Siedle and R.F.A. Freeman, "Radiation Effects Engineering Handbook (Methods of Improving the Radiation Tolerance of Electronics in Space Vehicles)", European Space Agency Report No. CR(P)-1067, (Fulmer Research Institute, Stoke Poges, Slough, England, Report No. R730/8, April 1978).

1979

- H. Schonbacher and A. Stolarz-Izycka, "Compilation of Radiation Damage Test Data, Part I: Cable Insulating Materials" (April 1979).

1980

- V.A.J. van Lint, T.M. Flanagan, R.E. Leadon, J.A. Naber and V.C. Rogers, "Mechanisms of Radiation Effects in Electronic Materials", Vol. I, Wiley, New York (1980).

1983

- The European Space Agency, "The particle and ultraviolet (UV) radiation testing of space materials". ESA PSS-01-706 Issue 1 (March 1983).

1989

- T.P. Ma, P.V. Dressendorfer, "Ionizing Radiation Effects in MOS Devices and Circuits". Wiley Interscience (1989).
- G.F. Knoll, "Radiation Detection and Measurement". Second edition. Wiley International (1989).

1991

- G.C. Messenger, M.S. Ash,"The Effects of Radiation on Electronic Systems". Second edition. Van Nostrand Reinhold (1991).

1992

- A.G. Holmes-Siedle, L. Adams, "Handbook of Radiation Effects". Oxford University Press. (1992).

ANNEX C
USEFUL DATA ON MATERIALS

C.1 DENSITIES AND CHEMICAL FORMULAS OF COMMERCIAL PLASTICS (IN ORDER OF INCREASING DENSITY)

Name	Density (*) (g/cm^{-3})	Typical formula	Example of trade name and properties
POLYPROPYLENE	0.90	$(CH_2)_n$	Grace
POLYETHYLENE		$(CH_2)_n$	Xylonite H.F.D.4201
- High density	0.941-0.965		
- Medium density	0.926-0.941		
- Low density	0.910-0.925		
POLYSTYRENE	1.04-1.08	$(C_7H_8)_n$	Grace
POLYURETHANE	1.088	$(C_{10}H_{10}N_2O_4)_n$	Thiokol Solithane 113 (d = 1.073)
ACRYLONITRILE-BUTA-DIENE-STYRENE (ABS)	1.06-1.08	$(C_{15}H_{19}N)_n$	Genco
EPOXY	1.12	$(C_{18}H_{24}O_3N_2)_n$	Shell Epikote 828 (d = 1.165)
NYLON	1.13-1.15	$(C_{12}H_{24}O_3H_2)_n$	Nylon 6.6 (d = 1.13)
POLYVINYLIDENE CHLORIDE	1.15-1.80	$(C_2H_3Cl)_n$	3M
POLYMETHYL METH-ACRYLATE (PMMA)	1.18-1.20	$(C_5H_8O_{22})_n$	Perspex, Lucite
PHENOL-FORMALDEHYDE	1.3-1.6	$(C_7H_7O)_n$	Bakelite
POLYSULPHONE	1.41	$(C_{27}H_{22}SO_4)_n$	Union Carbide P1700
POLYESTER	1.5-2.1	$(C_{24}H_{12}O_{12})_n$	Mylar
SILICON	1.08-2.8	$(C_2H_6SiO)_n$	Dow corning 93-500 (d = 1.08)
POLYTETRAFLUOR-ETHYLENE (PTFE)	2.1-2.3	$(CF_2)_n$	Teflon
EPOXY-GLASS-FIBRE COMPOSITE	2.2	Composite	Fortin FR4

See next page.

(*) Tabulated densities from:

R.C. Weast, 'CRC Handbook of Chemistry and Physics' (1972-3), pp. C 764-774;
J. Brandrup and E.H. Immergut (Eds.), 'Polymer Handbook', Interscience 1966, tables IX-5;
N.A. Waterman (Ed.), 'Fulmer Materials Optimiser', Fulmer Research Institute, 1977.
(1 g/cm^{-3} = 1000 kg/m^{-3})

C.2 PROPERTIES OF SEMICONDUCTORS AND OXIDES (a)

Name	Band-gap E_G(300K) (eV)	Density (kg m^{-3}) (d)	Dielectric constant (k)	Carrier mobility electrons ($m^2V^{-1}s^{-1}$) (μ)	holes
Si	1.12	2330	11.8	0.15	0.06
Ge	0.80	5330	16	0.39	0.19
GaAs	1.43	5320	10.9	0.85	0.04
CdS	2.42	2530	10.0	0.03	0.005
SiO_2					
- quartz	8.9(c)	2660	4.5	10^{-5}	-
- amorphous (Suprasil)	8.9	2200	3.8	0.002	-
- thermally grown on Si				0.017(b) -0.0034	$2x10^{-9}$
$A_{12}O_3$					
- sapphire	9.8	3870	9.4	-	-
- ceramic	9.8	3500	8.5	-	-

(a) Mainly from:
- A. Grove, 'Physics and Technology of Semiconductor Devices', (Wiley 1967.
- T.H. Laby, 'Tables of Physical and Chemical Constants', (Longmans 1973).

(b) SiO_2 Mobility data (see later table).
(c) H. Ibach and J.E. Rowe, Phys. Rev. 10, pp. 710-718 (1974)

C. 3 SILICON DIOXIDE IN VARIOUS FORMS: DRIFT MOBILITIES OF CARRIERS (*) AT ROOM TEMPERATURE (300K)

Name	Type	Electron mobility		Hole mobility		Ref.
		($cm^2V^{-1}s^{-1}$)	($m^2V^{-1}s^{-1}$)	($cm^2V^{-1}s^{-1}$)	($m^2V^{-1}s^{-1}$)	
Amersil Suprasil (2)						
- Fused Silica 200 m foil		20 ± 3	$2x10^{-3}$	-	-	1
Valpey natural	Natural x-cut Synthetic	10^{-1}	10^{-5}	-	-	2
Thermal oxide on silicon, 0.370 m	Dry O_2 (1000°C)	-	-	$2x10^{-5}$	$2x10^{-9}$	3
Thermal oxide on silicon, 0.862 m	Steam (1100°C)	-	-	$1x10^{-8}$	$1x10^{-12}$	4
Thermal oxide on silicon	Steam/air (1050°C)	17-34	-	-	-	5

1. R.C. Hughes, Physical Review Letter 30, pp. 1333-1336 (1973).
2. R.C. Hughes, Sandia Internal Report SC-RR 1720863 (Dec. 1972).
3. R.C. Hughes, Physical Review B15 2012 (1977) and private communication.
4. R.C. Hughes, Applied Physics Letter 26, pp. 436-438 (1975)
5. R. Williams, Physical Review 140, A 569-575 (1965)

(*) Ionic mobility in all forms is approximately $10^{-7}cm^2. V^{-1}. s^{-1}$ ($10^{-11}m^2. V^{-1}. s^{-1}$)

$1\ m^2. V^{-1}. s^{-1} = 10^{-4}cm^2. V^{-1}. s^{-1}$.

C. 4 RADIATION ABSORPTION EFFECTIVENESS OF VARIOUS MATERIALS USED IN SPACE VEHICLE EQUIPMENT BOXES

Material	Commercial name or Type number	Function	Typical thickness (mm)	Typical density (g cm^{-3})
ORGANIC				
Polyurethane	Thiokol solithane 113	Coating	0.1 - 1.0	1.073
Silicone	Dow Corning 93-500	Encapsulant gasketing	0.1 - 5	1.08
Epoxy	Shell Epon 828	Adhesive, coating or PCB	0.1 - 5	1.1
PTFE	BS 2848	Cable sleeving	0.1 - 5	2.1
Nylon	Nylon 6, 6	Bushings, spacers	0.5 - 5	1.13
Polysulfone	Union Carbide P1700	Connector mouldings	0.5 - 5	1.24
PVC	3M	Adhesive tape, cable sleeving	0.1 - 5	1.4
PVF	Kedlar	Cable sleeving	0.1 - 5	-
Polyester	Du Pont Mylar	Dielectric	0.025-0.1	-
Phenolic	Bakelite	Connector	0.5 - 5	1.6
DAP	Type 10256	Transistor pads	1 - 2	-
Neoprene	Neoprene	Gasketing	0.1 - 5	1.25
INORGANIC NON-METAL				
Beryllia	Nat. Beryllia Corp.	Heat-sink	0.1 - 3	3
Fibreglass	Fortin FR4 epoxy-glass laminate	PC board		2.1 - 2.5
Borosilicate glass	Corning 7740	Encapsulant	0.1 - 5	2.23
Mica	EAC 699	Isolation shim	0.1 - 1	2.6 - 3.2

C. 4 RADIATION ABSORPTION EFFECTIVENESS OF VARIOUS MATERIALS USED IN SPACE VEHICLE EQUIPMENT BOXES (CONTINUED)

Material	Commercial name or Type number	Function	Typical thickness (mm)	Typical density (g cm^{-3})
INORGANIC (Continued)				
Alumina	Various ceramics, Linde Sapphire	IC Header and Lid, epitaxial substrate	0.1 - 1 0.1 - 1	3.9 to 3.97
Silicon	Monsanto	Electronic chip	0.2 - 2.0	2.33
Silica	GEC crystal or Spectrosil B	Electronic crystal substrate, optical window	0.1 - 5	2.65
Gallium arsenide	Monsanto or Metals research	Electronic chip	0.1 - 1	5.32
Molybdenum disulphide	Moly-ITC-Bond	Lubricant	0.01 - 0.1	4.80
Zinc oxide		Pigment	0.01 - 0.1	5.6
ELEMENTAL METALS				
Beryllium		Structure	1 - 10	1.848
Magnesium		"	1 - 10	1.738
Aluminium		"	1 - 10	2.699
Iron		Bolts, sheets	0.1 - 5	7.87
Chromium		Plating	1.01 - 0.1	7.20
Tin		"	-	7.31
Nickel		Structure	1 - 10	8.90
Copper		Cladding, cable, structure,heat-sink	0.01 - 10	8.93
Silver		Plating	.001 - .05	10.50
Lead		Solder	0.1 - 1	11.34
Gold		Plating, wire, thick film	.001 - 5	19.32
Tantalum		Shield	0.1 - 5	16.65
Platinum		Plating, wire	.001 - .01	21.45

C. 4 RADIATION ABSORPTION EFFECTIVENESS OF VARIOUS MATERIALS USED IN SPACE VEHICLE EQUIPMENT BOXES (CONTINUED)

Material	Commercial name or Type number	Function	Typical thickness (mm)	Typical density (g cm^{-3})
ALLOYS				
Brass	Cu70 Zn30	Structures	1 - 10	8.5
Kovar	Fe54 Ni29 Co17	IC Lids, connectors, wires	0.25 - 1.0	8.2
Solder	Pb64 Sn36	Solder joints	0.1 - 2.0	9.43
Stainless st.	Fe63 Cr25 Ni12(e.g.)	Bolts, vessels	1 - 10	7.5
Monel	Ni67 Cu28 Fe (etc.)	RF gaskets	0.1 - 1	8.8
Mu-metal	Fe18 Ni75 Cu5 Cr2	Magnetic shields, coil cores	0.1 - 5	8.58
COMPOSITES				
Fibre-board	Micaply 3M Cu-clad	PCB, box wall	0.1 - 5	2.2 (not incl. Cu)

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ANNEX D.
USEFUL RADIATION DATA

D.1 RADIATION UNITS

ABSORBED DOSE

1 rad	= 100 erg g	= 6.25 x 10^{13} eV g^{-1} = 10^{-2} Gy	
1 Mrad	=	6.25 x 10^{19} eV g^{-1} = 10 kGy	
1 Gy	= 1 J.kg	= 100 rad	
10^{20} eV g		= 1.6 Mrad	= 16 kGy

1 röntgen (R) = 86.9 erg.g (air) = 2.58 x 10^{-4} C.kg^{-1} (air)
1 röntgen of 1 MeV photons = 1.95 x 10 photons.cm^{-2}

This fluence deposits: 0.869 rads in air,
0.965 rads in water,
0.865 rads in silicon,
0.995 rads in polyethylene,
0.804 rads in LiF,
0.862 rads in Pyrex glass (80% SiO).

DOSE EQUIVALENT:
1 rem = rad x quality factor
1 sievert = gray x quality factor

QUALITY FACTOR:

X Ray, Gamma, Beta	1
Fast neutrons	10 upwards
Alpha particles	20

RADIOACTIVITY

1 Curie (Ci) of radioactive material produces: 3.700 x 10^{10} disintegrations per second (or becquerels).

A 1 Ci point source emitting one 1MeV photon per disintegration gives an exposure of .... 0.54 R.hr^{-1} at 1 metre;

A 1 Ci ^{60}Co source gives .... 1.29 R.hr^{-1} at 1 metre.

Photon fluence at 1 metre from a 1 Ci point source = 1.059 x 10^{9} cm^{-2} (assuming 1 gamma ray per disintegration).

SI Units recommended by the International Commission on Radiation Units and Measurements (ICRU) (Brit. J. Radiology No. 49, p.476 (1976):

- Absorbed dose: the gray (Gy) = 100 rad = 1 J/kg,
- Exposure: the coulomb per kg (no name given) = 1 C/kg,
- Quantity activity: the Becquerel (Bq) = 1 s^{-1} = 2.703 x 10^{-11} Ci.

Old units to be abandoned over ten years.

D. 2 ENERGY ABSORPTION VERSUS PHOTON ENERGY FOR AIR

Energy (MeV)	Mass energy absorption coefficient (μ_{en}/ρ) air ($cm^2 . g^{-1}$)	Photon fluence per röntgen ($cm^{-2} . R^{-1}$)
0.01	4.61	11.8×10^{-8}
0.05	0.0406	267×10^{-8}
0.10	0.0234	232×10^{-8}
0.50	0.0296	36.7×10^{-8}
1.0	0.0278	19.5×10^{-8}
5.0	0.0174	6.24×10^{-8}
8.0	0.0152	4.47×10^{-8}
10.0	0.0145	3.75×10^{-8}

From H.E. Johns and J.R. Cunningham, 'The Physics of Radiology', Table A3 (C.C. Thomas, Illinois 1969)

D. 3 TYPICAL PERFORMANCE FIGURES FOR HIGH ENERGY RADIATION SOURCES

Source	Beam current	Typical energy deposition
ULTRAVIOLET 250 W mercury arc	-	10^7erg. cm^2. s^{-1} over 2 cm spot (5.2 $h\upsilon$ 3.4 eV)
100 W hydrogen arc	-	10^4erg. cm^{-2}. s^{-1} over 2 cm spot (12 $h\upsilon$ eV)
X-RAY 40 keV	20 mA	10^6 rads. hr^{-1} over 1 cm spot
GAMMA RAYS Cobalt 60 cells	-	10^5 rads. hr^{-1} over 10^3 cm^3
Spent fuel rig	-	10^6 rads. hr^{-1} over 10^3 cm^3
ELECTRONICS 4 MeV Linac	20μA	5 x 10^8 rads. hr^{-1} in 5 cm spot
0.5 MeV VdG	10μA	5 x 10^9 rads. hr^{-1} in 2.5 cm spot
100 keV TEM	20μA	10^8 rads. s^{-1} over 2 cm spot or 10^{12} rads. s^{-1} over 20 μm spot
30 keV SEM	0.1nA	10^2 rads. s^{-1} over 10^{-1} cm^2 or 10^8 rads. s^{-1} over 10^{-6} cm^2
3-15 keV Betaprobe	0.5μA	10^9 rads. s^{-1} in 1 mm spot
FAST NEUTRONS Dido reactor	-	10^{14} cm^{-2}. s^{-1} over 100 cm^{-3}
IONS 3 MeV protons	2μA	10^{13} cm^{-2}. s^{-1} over 1 cm spot
0.4 MeV protons		10^{12} cm^{-2}. s^{-1} over 1 cm spot
0.005 - 3 MeV ions		10^{13} cm-2. s^{-1} over 1 cm spot

D. 4 TYPICAL PHOTON ENERGIES AND WAVELENGTHS

	Energy $h\upsilon$, (eV)	Wavelength, λ (nm)
GAMMA RAYS		
Co-60 gamma (average)	1.173×10^{6} and 1.33×10^{6}	10^{-3} approx.
1 MeV photon	1.00×10^{6}	1.2398541×10^{-3}
X-RAYS		
100 keV photon	10^{5}	0.012398541
Tungsten K α_1 , 59 keV	5.9312824×10^{4}	0.0209017 (*)
HYDROGEN LINES		
Lyman α line	10.198785	121.56681
H_2 160.8 nm line	7.7105	160.8
MERCURY LINES		
Hg 253.7 nm	4.8871	253.7
Hg 312 nm	3.9739	312
Hg 365 nm	3.3969	365
Hg 436 nm	2.8437	436
VISIBLE LIGHT		
Violet	3.10 - 2.92	400 - 424
Blue	2.92 - 2.52	424 - 491
Green	2.52 - 2.16	491 - 575
Yellow	2.16 - 2.12	575 - 585
Orange	2.12 - 1.92	585 - 647
Red	1.92 - 1.77	647 - 700
	2.046706	606.7802106
KRYPTON LINE (primary wavelength standard		
NEAR INFRARED		
1 eV photon	1.0	1 239.8591 (1.24μm)
1μm photon	1.2398541	1 000.00 (1μm)
CO_2 line	0.116967	10 600.00 (10.6μm)
Thermal energy	0.025	45 594.16 (49.6μm)
FAR INFRARED		
100 μm photon	0.012398541	100 000.00 (100μm)
HCN line (44.859 cm^{-1})	0.0055764	222 292.07 (222.292μm)

(*) Value given by American Institute of Physics Handbook (McGraw-Hill), 1972) is 0.02090100 nm.

D. 5 RADIO ISOTOPES USEFUL IN IRRADIATION EXPERIMENTS, LIST OF MAIN EMISSION ENERGIES

Nuclide	Half life (yrs.)	Type of decay	PHOTONS Energy (MeV)	PHOTONS Percent emitted (%)	PARTICLES Energy (MeV)	PARTICLES Transition probability (%)
Co-60	5.27		1.173 1.333 (av. 1.25)	99.86 99.98	0.318 1.491	99.9 0.1
Ir-192	0.526 (192 d)		0.296 0.308 0.316 0.468 0.604 0.612	29.6 30.7 82.7 47.0 8.2 5.3	0.530 0.670	42.6 47.2
Cs-137	30		0.662 0.032 -0.038	85.1 8	0.512 1.174	94.6 5.4
Sr-90 + daughter Y-90	28 0.176		0.54 2.27	100 100	- -	- -
Kr-85	10.6		0.15 0.67	0.7 99.3	0.51 -	0.7 -
Cf-252	2.65	Spontaneous fission			Neutrons: 2 MeV Alphas: 5.9-6.1 MeV Fission: 80 and 104 MeV fragments	

(*) The Radiochemical Centre, Amersham, U.K. (1977)

D. 6 PRACTICAL RANGES (R_p) OF ELECTRONS IN ALUMINIUM

Particle energy (MeV)	Practical range		Particle energy (MeV)	Practical range	
	(g.cm^{-2})	(mm)		(g.cm^{-2})	(mm)
0.001	0.000012	4.446×10^{-5}	1.0	0.42	1.56
0.003	0.000038	1.408×10^{-4}	1.25	0.52	1.92
0.005	0.000080	2.964×10^{-4}	1.40	0.60	2.22
0.010	0.00017	6.299×10^{-4}	1.50	0.65	2.41
0.030	0.0015	0.0056	1.75	0.80	2.96
0.050	0.0041	0.015	2.0	0.95	3.52
0.100	0.0135	0.050	2.15	1.00	3.705
0.125	0.020	0.074	2.5	1.20	4.45
0.250	0.058	0.214	3.0	1.45	5.37
0.300	0.078	0.289	3.5	1.75	6.48
0.375	0.110	0.408	4.0	1.9	7.04
0.500	0.165	0.611	4.5	2.3	8.52
0.540	0.20	0.741	5.0	2.6	9.63
0.625	0.22	0.815	5.5	2.8	10.37
0.750	0.25	0.926	6.0	3.2	11.86
0.78	0.2969	1.000	7.0	3.7	13.70
0.97	0.40	1.48	8.0	4.2	15.56
1.0	0.42	1.56	9.0	4.7	17.41
			10.0	5.2	19.27

D. 7 SOME SELECTED VALUES OF THE RANGE OF PROTONS IN ALUMINIUM

Energy		Range	Energy		Range
(MeV)	(g. cm)	(mm)	(MeV)	(g. cm)	(mm)
0.1	0.00019	0.0007	4	0.034	0.126
0.3	0.00073	0.0027	10	0.163	0.604
0.5	0.00143	0.0053	13.1	0.270	1.00
			15	0.340	1.26
1	0.0039	0.0145	19.3	0.539	2.00
3	0.021	0.078	25	0.809	3.00
5	0.049	0.0182	29	1.080	4.00
10	0.163	0.604	30	1.130	4.2
30	1.13	4.187	37	1.619	6
50	2.80	10.37			
100	9.20	34.09	40	1.888	7
			43	2.159	8
			46	2.429	9
			48	2.699	10
			65	4.048	15
			74	5.397	20
			100	9.200	34.1

Collected from curves by:

- V. Linnenbom, NRL Report 588 (1962) and
- C.J. Calbick, Phys. thin films 2, pp. 63-145 (1964).

D. 8 MASS ATTENUATION COEFFICIENTS (μ/ρ) OF SELECTED MATERIALS OF PHOTONS OF ENERGIES 0.01 TO 100 MeV SUITABLE FOR CALCULATIONS ACCORDING TO LAMBERT'S LAW FOR NARROW GEOMETRY
(coherent scattering included; density g cm^{-3} in brackets)
after Hubbell (*)

TOTAL MASS ATTENUATION COEFFICIENTS
μ/ρ (cm^2. g^{-1}); (g. cm^{-3}) in brackets

Photon energy (MeV)	H_2 (8.988 x10^{-5})	Be (1.85)	C (2.25)	N_2 (1.250 x10^{-3})	O_2 (1.429 x10^{-3})	Mg (1.74)	A1 (2.6989)
0.01	0.385	0.593	2,28	3.57	5.78	20.8	26.3
0.05	0.335	0.156	0.187	0.187	0.213	0.329	0.369
0.10	0.294	0.133	0.150	0.150	0.156	0.169	0.171
0.50	0.173	0.0773	0.0871	0.0871	0.0873	0.0864	0.0844
1.0	0.126	0.0565	0.0636	0.0636	0.0637	0.0628	0.0613
5.0	0.0505	0.0235	0.0274	0.0274	0.0278	0.0287	0.0284
0.10	0.0325	0.0163	0.0196	0.0292	0.0269	0.0231	0.0231
50.0	0.0141	0.0102	0.0156	0.0156	0.0169	0.0222	0.0231
100.0	0.0116	0.00992	0.0163	0.0163	0.0179	0.0241	0.0251
	Si (2.42)	Fe (7.86)	Cu (8.93)	Sn (-7.29)	W (17.1)	Pb (11.34)	U (18.7)
0.01	34.2	173.0	224.2	141.6	95.5	133.0	178.0
0.05	0.437	1.94	2.62	10.70	5.91	7.81	1.11
0.10	0.184	0.37	0.461	1.68	4.43	5.40	1.91
0.50	0.0875	0.084	0.0836	0.0946	0.136	0.161	0.193
1.0	0.635	0.0599	0.0589	0.0578	0.0654	0.0708	0.0776
5.0	0.0297	0.0314	0.0318	0.0354	0.0407	0.0424	0.0445
10.0	0.0246	0.0298	0.0308	0.0385	0.0464	0.0484	0.0506
50.0	0.0252	0.0382	0.0410	0.0588	0.0760	0.0804	0.0850
100.0	0.0275	0.0432	0.0465	0.0677	0.0881	0.0934	0.0984

D. 8 MASS ATTENUATION COEFFICIENTS (μ/ρ) OF SELECTED MATERIALS OF PHOTONS OF ENERGIES 0.01 TO 100 MeV SUITABLE FOR CALCULATIONS ACCORDING TO LAMBERT'S LAW FOR NARROW GEOMETRY

(coherent scattering included; density g cm^{-3} in brackets)
after Hubbell (*)

TOTAL MASS ATTENUATION COEFFICIENTS
μ/p (cm^2. g^{-1}); (g. cm^{-3}) in brackets

Photon energy (MeV)	Air (1.205 x10-3)	H_2O (1.00)	SiO_2 (2.20-2.32)	Perspex PMMA (1.19)	Poly-ethylene	Bakelite (2.23)	Pyrex glass (2.23)
0.01	4.99	5.18	1.90	3.25	2.01	2.76	1.71
0.05	0.208	0.227	0.318	0.208	0.209	0.200	0.302
0.10	0.154	0.171	0.169	0.164	0.172	0.161	0.166
0.50	0.0870	0.0968	0.0874	0.0941	0.0995	0.0921	0.0870
1.0	0.0636	0.0707	0.0636	0.0687	0.0727	0.0673	0.0633
5.0	0.0275	0.0303	0.0287	0.0292	0.0305	0.0286	0.0284
10.0	0.0204	0.0222	0.0226	0.0211	0.0215	0.0206	0.0222
50.0	0.0161	0.0167	0.02028	0.0151	0.0142	0.0147	0.0201
100.0	0.0168	0.0172	0.0224	0.0154	0.0142	0.0150	0.0215

(*) Adapted from J.H. Hubbell, U.S. Nat. Bureau of Standards, Report NSDR-NBS-29 (U.S. Dept. of commerce, Washington D.C., Aug. 1969), Tables 3-1 to 3-36, columns 9 and 10, and Table 1-1, column 5.

ANNEX E. USEFUL GENERAL AND GEOPHYSICAL DATA

E. 1 GENERAL CONSTANTS

7 years	= 3.682 x 10^6 minutes = 2.209032 x 10^8 seconds
1 year	= 5.25960 x 10^5 minutes = 3.155760 x 10^7 seconds
1 day	= 1.440 x 10^3 minutes = 8.6400 x 10^4 seconds
1000 Å	= 0.1 µm = 100 nm
1 mm	= 0.03937 inch ~ 40 thou.
0.001 inch	= 25.4 µm
1 m^3	= 10^6 cm^3
1000 cm^3	= 10^{-3} m^3
1 litre	= 1000.028 cm^3 = 0.219 976 gallon
1 gm cm^{-3}	= 1000 kg.m^{-3}
1 eV	= 1.602 192 x 10^{-19} joules
1 MeV	= 1.602 192 x 10^{-13} joules
1 joule	= 10^7 erg
1 calorie	= 4.187 joules
1 eV/molecule	= 23.1 kcal/molecule
Permittivity of free space (ε_o)	= 8.86 x 10^{-14} F.cm^{-1}
	= 8.86 x 10^{-12} F.cm^{-1}
	= 55.4 electronic charges V.μ^{-1}
Permeability of free space (μ_o)	= 1.26 x 10^{-6} H.m^{-1}
Electronic charge (q)	= 1.602 192 x 10^{-19} coulomb
1 coulomb/cm^{-2}	= 6.241 459 x 10^{18} electrons/cm^{-2}
1 µA/cm^{-2}	= 6.24 x 10^{12} electrons/cm^{-2} .s^{-1}
Velocity of light (c)	= 2.997 925 x 10^8 m/s.
1 newton	= 10^5 dynes
1 mm Hg	= 133.3224 Nm^{-2}
Boltzmann's constant (k)	= 1.38062x10^{23} J.K^{-1} , 6.62 x 10^{-5} eV K^{-1}
kT at room temperature	= 0.0259 eV
Planck's constant (h)	= 6.63 x 10^{-34} J.s
Avogadro's number	= 6.022 x 10^{23} $mole^{-1}$
Electron Rest Mass (m_e)	= 9.11 x 10^{-31} kg
Proton Rest Mass (m_p)	= 1.67 x 10^{-27} kg

E. 2 FREQUENCY, WAVELENGTH AND ENERGY

Energy x wavelength ($E \lambda$)	$= 1.239854 \times 10^{-6}$ eV.m
Energy Wave-number (E/υ)	$= 1.98648 \times 10^{-25}$ J.m
Wave-number energy (υ/E)	$= 8.06546 \times 10s$ eV^{-1} $.m^{-1}$
Frequency energy $\frac{(f)}{E}$	$= 2.417966 \times 10^{14}$ $Hz.eV^{-1}$

Wavelength of photon of energy:

- 1 eV (infrared) = 1.239854 nm;
- 10.2 eV (Lyman α) = 121.55431 nm.

Energy of photon of:

- wavelength 1 μm (infrared) = 1.239854 eV;
- wavenumber 50 000 cm^{-1} = 6.19927 eV.

Wavelength of photon of wave-number:

- 50 000 cm^{-1} = 200 nm;
- 10 000 cm^{-1} = 1 μm;
- 50 cm^{-1} = 200 μm.

Wavenumber of photon of energy 1 eV = 8065.46 cm^{-1};
= 806 546 m^{-1}

E. 3 USEFUL GEOPHYSICAL AND ORBITAL PARAMETERS

Average radius of the Earth = { 6 371.315 ± 0.437 km; 3 959 statute miles; 3.438 nautical miles }

Altitude of geostationary orbit = { 35 863 km; 22 284 statute miles; 19 360 nautical miles }

Geocentric distance of geostationary orbit = { 42 234.314 km; 6.629 R_E }

Being circular and equatorial, the geostationary orbit is a special case of the geosynchronous orbit (period 24 hours).

1 statute mile	= 1.609344 km = 0.869 n mile
1 nautical mile	= 1.852 km = 1.151 statute mile
1 astronomical unit	= 1.496×10^{11} m
Gravitational acceleration	= 0.980665 m s^{-2} = 32.1741 ft s^{-2}