SECTION 14. TRANSDUCERS AND OTHER COMPONENTS

14.1. TRANSDUCERS

14.1.1. General

Electronic transducers can be described as devices which perform measurements. Space vehicles, remote scientific equipment and other forms of automated apparatus working in radiation are likely to require transducers. Transducer technology covers a very large variety of types and it is therefore difficult to predict the effects of radiation. Moreover, there is usually a close link between requirements for performance and individual measurement requirements.

Optical transducers have been dealt with under other headings. Further classes likely to be important for space vehicles include:

- mechanical sensors (strain gauges, displacement sensors, pressure gauges),
- temperature sensors (thermistors, thermocouples),
- particle sensors and
- magnetic sensors (including Hall devices).

The requirements for sensitivity are very variable but, clearly, radiation effects will have more impact on the high-sensitivity applications. Radiation-induced degradation is likely to cause inaccuracy and the associated high-gain instrumentation amplifiers and oscillators may be more vulnerable. Radiation-induced noise may be important at low levels of signal.

The science of transducers is growing and new designs appear frequently. Therefore, in project studies, each new design with its associated electronic preamplifiers etc. should be carefully examined for sensitivity to radiation before it is adopted for operation in radiation environments.

14.1.2. Previous transducer studies

No reports exist of previous studies of the impact of space radiation on transducers. However, in the nuclear field, Brucker (1977/78) wrote a useful report on his survey of piece parts used in diagnostic equipment on nuclear reactors. Its contents are mainly based on a search of the literature and followed by recommendations for choices wherever two device types are available. In Table 14(2), the sensors appear to fall into two classes, those which are useless at 10^{14} n.cm^{-2} (14 MeV) and those which still operate with little or no degradation. In the former group are opto-isolators (see Section 10 for further comment); charge-coupled devices (CCD) and a piezoelectric pressure transducer employing $BaTiO_3$ used in the shear mode. In the "resistant" class fall ZnS scintillators, InSb devices for sensing heat radiation, silicon thermistors and lead zirconate titanate pressure transducers used in the compression mode. At high particle fluences, germanium devices are not advisable.

Tables 14(3), (4) and (5) give some test data and basic information on the "corruption" of the signals from transducers by transient, radiation-induced ionisation or leakage effects. The two radiation sensors shown in Table 14(3), HgCdTe and a pyroelectric detector are the most sensitive to noise. The signal amplitude would have to be known for a proper noise evaluation to be made.

Table 14(5) records a calculation of current generation and Table 14(6) notes some measurements/calculations by the Princeton Fusion Experiment Group which may prove useful in defining background interference in X-ray detectors, including photomultipliers.

Two careful studies of space radiation effects in photovoltaic devices have some relevance to spaceborne sensors (Cooley and Janda, 1963; Tada et al, 1972). These studies explain damage in solar cells and give results for transparent materials.

TABLE 14(1) - RADIATION DAMAGE THRESHOLDS FOR DIAGNOSTIC SENSORS (After Brucker)

Director	Application	Threshold fluence $n.cm^{-2}$ (1 MeV eqt)	Threshold dose (rad (Si))
HgCdTe	Photovoltaic	5×10^{11}	10^{6}
InSnTe	Photovoltaic	5×10^{11}	10^{6}
GaAs	Photovoltaic	10^{12}	10^{6}
Si(Li) or Ge(Li) (1)	Reverse biased diode	10^{10}	3×10^{5}
Surface barrier diode	Reverse biased diode	10^{10}	10^{7}
Pyroelectric	Temperature change	10^{14}	10^{7}
Schottky diode (2)	Reverse biased diode	10^{14} to 10^{15}	5×10^{5} to 10^{8}
Crystal Ge (Cu or Hg-doped)	Photo-conductive	5×10^{13}	10^{6}
NaI	Scintillator	10^{14}	10^{5}

NOTES:

(1) Both these detectors can be annealed back to their initial state by high temperature.

(2) Depending on construction details, the minimum or maximum value applies.

TABLE 14(2) - THRESHOLD DAMAGE LEVELS: PERMANENT DAMAGE EFFECTS IN PARTS FOR DIAGNOSTICS (After Brucker)

Detector or device	Ionisation (rad)	Bulk damage (n/cm^2) (1 MeV eqt.)
Optical isolator (PD)	10^6	5×10^{10}
Optical isolator (PT)	5×10^4	10^{10}
Zinc sulfide	–	10^{14}
Indium antimonide (doped 10^{15} atoms/cm^3)	10^8	10^{14}
Germanium bolometer (doped 10^{15} atoms/cm^3)	10^7	2×10^{13}
Germanium (PV) (Gallium-doped)	3×10^6	10^{12}
Germanium (PC) (Gallium-doped)	6×10^7	5×10^{13}
Diamond	–	10^{14}
CCD (SC) (dark-current failure)	10^4	10^{11}
CCD (BC) (dark-current failure)	10^4	5×10^{10}
Silicon thermistor (Boron-doped)	–	10^{14}
RCA memory CDP 1821	5×10^3	10^{15}
Harris memory HMI 6508	10^3	10^{15}
RCA memory CD 4061	10^5	10^{15}
NMOS memory - 4 kilobit	10^3	10^{15}
Barium titanate	9.5×10^6	7.6×10^{10}
Lead zirconate titanate	4×10^{10}	3.6×10^{18}
Quartz crystal (X-ray diffraction effects)	–	10^{19}

NOTES:

Channeltron: temporary fatigue commences after 10^{10} counts; gain can be restored by a clean-up treatment.

PD = photodiode
PV = photovoltaic
PT = phototransistor
PC = photoconductive

TABLE 14(3) - DETECTOR RADIATION NOISE THRESHOLDS (After Brucker)

Material or detector	Threshold flux or dose rate
Hg Cd Te	10^{2} rad s^{-1}
Fibre optics	10^{10} rad s^{-1}
Pyroelectric	3×10^{-3} rad s^{-1}

TABLE 14(4) - THRESHOLD DAMAGE (DATA UPSET) LEVELS (after Brucker)

Detector or device	Dose rate (rad/s)	Neutron rate ($n.cm^{-2}.s^{-1}$)
Optical isolator	10^{4}	–
CCD (scramble of data in a register)	10^{5}	–
RCA memory CDP 1821	6×10^{10}	–
Harris memory HMI 6508	8×10^{7}	–
Intersil memory IM 6508	8×10^{7}	–
RCA memory CD 4061	10^{8}	–
Kilobit NMOS memory	5×10^{8}	–
Barium zirconate titanate	–	2.1×10^{14}
Lead zirconate titanate	–	1.2×10^{12}

TABLE 14(5) - CARRIER GENERATION RATES AND CURRENTS FOR EXPOSURE TO A UNIT DOSE RATE (rad/s) (after Brucker)

Detector or device	Generation (carrier/cm^3.s)	Current (A/cm^3)
Silicon	4×10^{13}	6.4×10^{-6}
Germanium	10^{14}	1.6×10^{-5}
In Sb	4×10^{14}	6.4×10^{-5}
Diamond	10^{13}	1.6×10^{-6}
Channeltron	6.4×10^{-5} $e.cm^{-2}.s^{-1}$	10^{-13} A

TABLE 14(6) - NEUTRON AND GAMMA RAY RESPONSE BY SOME DETECTORS (after K.W. Hill, quoted by Brucker, 1977)

Detector	Material	Radiation	Signal	Units
SPMT	ZnS	Reactor n	54	($eV.cm^2$) / n.mg
IC	Argon	Reactor n	8	n.mg
PMT	Glass	Reactor n	2.4	Electrons/n (*)
PMT	Quartz	Reactor n	.28	Electrons/n (*)
PMT	Glass	.662 meV	6×10^{-3}	Electrons/(*) photon
IC	Argon	2.5 meV n	2.8	($eV.cm^2$) / n.mg

(*) Photocathode electrons

PMT = Photomultiplier
IC = Ionisation chamber
SPMT = Scintillator optically coupled to PMT

14.1.3. Temperature sensors

ESA experience has shown that thermocouples are very insensitive to typical space radiation levels. Thermocouples can be used even inside nuclear reactors (say, fluences of 10^{20} n.cm^{-2}) as long as the wire insulation associated with them (e.g. glass and ceramic tube) does not become leaky (Ricketts, 1972). The same general statements apply to platinum resistance thermometers.

Thermistors are composed of semiconductors but, again, the wire insulation is usually the most sensitive element and most devices will withstand megarad doses (Ricketts, 1972). Modern fibre-optic temperature sensors will, of course, exhibit the optical darkening discussed elsewhere.

14.1.4. Hall-effect sensors

Hall-effect sensors are small "Hall bars" made of ferrite (e.g. type SBV 566). When a "control current" of about 50 mA is passed through the bar and a magnetic field, B, is applied perpendicular to the current, a Hall voltage, V_H , of a few mV appears across the voltage output arms at right angles to the current flow and field direction, which is proportional to current and field. An operational amplifier with feedback - frequently placed in the same package as the Hall bar - is used to amplify V_H to a few volts. Diverse transistors (e.g. 2N2222) can be added to act as relays or to give a TTL logic voltage.

The transport properties of ferrite (mobility, etc.) will not be greatly affected by neutrons in the 10^{15} n.cm^{-2} (1 MeV) range. Thus, the site of any degradation suffered is more likely to be in amplifier circuits. The latter is essential for read-out. The Hall bar can be connected remotely to the amplifier chip by means of a cable but, of course, the low value of the original Hall voltage means that - as the leads become longer - so the Hall effect sensitivity is reduced by noise, voltage drop, thermal EMFs etc.

14.1.5. Mechanical Sensors

14.1.5.1. General

Transducers of mechanical movement include sensors for displacement, pressure, acceleration, vibration, sound etc. The effect of radiation depends, of course, on the principle used to measure the movement. The earliest electrical types were moving coils. Later, strain gauges made of metal and silicon were developed. More recently, use has been made of optical fibres and piezoelectric effects in ceramics and polymers, and of silicon microstructures for the manufacture of accelerometers, pressure gauges, tactile sensors, oscillators etc.

In coil solenoid sensor structures, the effects of radiation will centre on the degradation of the coil insulation and the mechanical linkages (e.g. the polymeric parts). In optical types, darkening of glasses will be most important. Metallic and ceramic strain gauges are unlikely to be affected. The piezoelectric polymer film, PVF2 , has been shown to survive doses of more than 10^7 rads without loss of performance, but degrades at higher doses with evolution of HF (HolmesSiedle, 1985). Note that PVF2 appears much less sensitive to radiation than PTFE.

14.1.5.2. Silicon micromechanisms

As the mechanical properties of silicon are not affected by even large doses of electrons, protons, neutrons or gamma rays, it is probable that radiation-tolerant, silicon, micromechanical devices can be built. However, these often incorporate diffused junctions or even integrated transistors which, as discussed elsewhere, must of course be considered in the usual way. Discrete strain gauges, capacitive pressure sensors and accelerometers, however, should not be severely affected by typical space radiation levels.

14.2. OTHER ELECTRONIC COMPONENTS

14.2.1. General

Devices included in this section are those that either have a relatively high tolerance to radiation or cannot logically be categorised under any other section. Examples of the first category are non-semiconductor components such as resistors, inductors and electron tubes. To the second category belong connectors and various mechanical devices.

Table 14(7) shows a list of components and materials known to be sensititive to radiation. This section includes several of these, but more general information is given in Section 5. Information on reactor tests of miscellaneous components can be found in a number of handbooks on nuclear hardening (see e.g. Rudie (1976); Ricketts (1972) and references therein) as well as in the bibliography given in Appendix B to this handbook and the Data Bank compilations listed elsewhere.

TABLE 14(7) - MATERIALS AND DEVICES WITH GENERALLY POOR RADIATION TOLERANCE

Semiconductors
Optical lenses
Optical fibres
Optical windows (e.g. encoder plates)
Elastometers (e.g. plastic bellows)
Plastic bearings
Lubricants
Adhesives
Hydraulic fluids
Paints
Reflective coatings
Wood, paper, string and cloth
Thin insulators
Photosensitive materials
Gas sensors
Liquid-ion sensors
Surface-active reagents
Piezoelectric transducers
Micropositions

14.2.2. Capacitors

14.2.2.1. General

Capacitors consist of large areas of conductor separated by a thin insulator. It is usually desirable for the insulator to exhibit very low leakage (R(insulation) >$10^{13}\Omega$). Total dose permanently degrades the insulation resistance of organic insulators, but barely at all in the case of air or ceramic. On the other hand, if the dose rate is significant, the insulator can exhibit "transient photoconductivity". In solid capacitors, some charge becomes trapped during irradiation and may be released slowly some time later to produce a small, long-term conductivity after irradiation has ceased.

14.2.2.2. Total-dose effects

The electrical effects of total dose become severe in capacitors until a dose of about 10^7 rads is reached. Plastic and paper capacitors are the most likely to exhibit radiation-induced changes in leakage and dielectric loss. Glass and ceramic capacitors may be unaffected up to 10^{10} rads. For reactor irradiation, damage thresholds are in the region of 10^{14} to 10^{16} n.cm^{-2} (E>10 keV) (Ricketts, 1972) and it is likely that the source of damage in this case is the accompanying gamma-ray dose.

14.2.2.3. Dose-rate effects

Electrolytic capacitors are subject to an unusual photovoltaic type of leakage (Rudie, 1978) but, in fact, leak less than plastic and paper ones (Ricketts, 1972).

Natural radiation dose rates in space are, normally, not high enough to yield significant radiation-induced conductivity (RIC) in capacitors' dielectrics. The order of magnitude for RIC was given in the section on "Polymers".

14.2.3. Resistors and conductors

Most of the effects of radiation on resistors were being observed during irradiations of very high intensities in nuclear reactors or flash X-ray machines. Most of the changes observed are due to the breakdown of encapsulating media such as silicone potting compounds. Only mild resistance changes take place at a fluence of 10^{13} fast neutrons in carbon resistors which are the most sensitive class. The dose rates required to give transient changes are of the order of 10^{10} rad.s^{-1}. Precision wire-wound resistors are many orders less sensitive.

Conduction in metals is not affected by gamma rays or space particles. In reactor irradiation, changes are observed in the ultra-high fluence range (10^{20} n.cm^{-2} and above) due to alterations in crystal lattice structures.

14.2.4. Radiofrequency devices

14.2.4.1. Oscillator crystals

The piezoelectric properties of quartz and most other single crystals are not catastrophically affected by neutrons, even at 10^{18} n. cm^{-2}. However, oscillator frequencies must often be accurate to extremely close limits (say 1 part in 10^{6}) and neutron damage to the lattice in the range 10^{12} n.cm^{-2}, and gamma doses in the 10^{5} rad range can produce permanent changes in oscillation frequency of about 1 part in 10^{7}. Thus, ultra-high-precision oscillators may experience inconvenient drifts, but predictable drift of this sort can probably be adjusted by recalibration.

High-grade synthetic quartz, suitable for oscillators and having a reproducible response to radiation, is now available commercially. King (1974), in a review of the effect of radiation on 5 MHz, 5th-overtone resonators, notes a negative change of 50 ppm in frequency for 10^{6} rads in natural quartz and one-fifth of this amount in Z-growth electronic-grade synthetic quartz, in the positive direction. Neutron damage produces positive shifts at rates which vary from 0.56 x 10^{-15} to 3 x 10^{-15} ppm/n/cm^{-2} for unpurified synthetic quartz. Many important literature references are given in King's review.

14.2.4.2. Vacuum tubes

Despite the large power drain and size of vacuum tubes, their use in very high neutron/gamma environments has proved to be useful. For amplifying tubes (valves), no known degradation mechanism (except outgassing in some cases) provides an upper fluence limit to operation. Imaging devices, of course, suffer optical-path and possibly photosensor degradation, but vidicons are used in reactors and have been tested for use in space missions.

14.2.4.3. Microwave devices

Both silicon and III-V semiconductors are used for microwave signal generation, switching and amplification. Amplifiers are dealt with in our discussion of transistors. The other two microwave device types employ the action of majority-carriers and fall into a different, lower class of radiation sensitivity.

The main effects of radiation on the above class of device are:

(a) Reduction of majority carrier concentration by bulk displacement damage and
(b) Transient increase in majority carriers produced by a burst of radiation.

In ESA's experience, the above effects have not produced significant problems in geostationary orbit. The effects of intense neutron and flash X-ray irradiation on Gunn diodes and silicon p.i.n. switches have been investigated by Berg and co-workers (1970, 1971) and Chaffin (1971).

14.2.5. Miscellaneous hardware

The term "miscellaneous hardware" includes connectors, cables, gaskets, O-rings, switches and so on.

In this range of hardware, an approach to prediction is to examine data of the plastic materials used in their construction. Normally, the mechanical properties of structural plastics show the onset of damage in the range 10^7 to 10^8 rads. Elastomers are more sensitive than rigid plastics, owing to the larger cross-linking changes in the former. Leakage effects in connectors and cables are dealt with by calculation of radiation-induced conductivity (see "Polymers" section).

REFERENCES

TRANSDUCERS

G.J. Brucker, "TFTR Diagnostic Engineering Report No. 2", Report No. PH-I-001, Princeton Physics Lab. (1977)

G.J. Brucker, ibid, No. 3, Report No. PH-I-004 (May 1979)

J.R. Carter and H.Y. Tada, "Solar Cell Radiation Handbook", JPL-NASA, Pasadena (1972)

W.C. Cooley and R.J. Janda, "Handbook of Radiation Effects in Solar Cell Power Systems", NASA SP-3003, Appendix A (1963)

R. Grube et al (on Pulse Shape in Proton-damaged Silicon Surface Detectors) Nucl.Instrum. & Methods 101, p. 92 (1972)

E.E. Haller et al (on Germanium Detectors), IEEE Trans.Nucl.Sci. NS-19(3), p. 271 (1972)

H.M. Heijne et al, "TSC Defect Levels in Silicon Produced by Irradiation with Muons of GeV Energy", Radiation Effects 29, p. 25 (1976)

A. Holmes-Siedle, "Radiation Effects in the Joint European Torus: Guidelines for Preliminary Design", Fulmer Report No. R 857/2, Fulmer Research Inst., Stoke Poges, England (Sept. 1980)

A. Holmes-Siedle, Unpublished work on irradiation of PVF2 (1985)

H.N. Norton (Member of JPL Techn. Staff),
(a) "Sensor and Analyser Handbook" (1982)
(b) "Biomedical Sensors" (1982)
(c) "Sensor Selection Guide" (1984)
Elsevier Sequoia, Lausanne

A. Stefanini (ed) "Miniaturisation of High-Energy Physics Detectors", Plenum, New York (1983)

OTHER COMPONENTS

L. Adams and A. Holmes-Siedle, "The Development of an MOS Dosimetry Unit for Use in Space", IEEE Trans.Nucl.Sci. NS-25(6), pp. 1607-1612 (Dec. 1978)

D.J. Allen, T.F. Wrobel, F.N. Coppage and G.L. Hash, "Gamma-induced Leakage in Junction Field-effect Transistors", IEEE Trans.Nucl.Sci. NS-31(6), (Dec. 1984)

C.E. Barnes and J.J. Wiczer, "Neutron Damage Effects in AlGaAs/GaAs Solar Cells", IEEE Trans.Nucl.Sci. NS-31(6), (Dec, 1984)

N. Berg and H. Dropkin, "Neutron Displacement Effects in Epilaxial Gunn Diodes", IEEE Trans.Nucl.Sci. NS-17(6), pp. 233-238 (Dec. 1970)

N. Berg and H. Dropkin, "The Effect of Ionising Radiation on Gunn Diode Oscillators", IEEE Trans.Nucl.Sci. NS-18(6), pp. 295-303 (Dec. 1971)

D.M. Binkley, "A Radiation-hardened Accelerometer Preamplifier for 2 x 10 Rads(Si) Total Dose", IEEE Trans.Nucl.Sci. NS-29(6), pp. 1500-1507 (Dec. 1982)

G. Brucker and A.D. Cope, IEEE Trans.Nucl.Sci. NS-19(6), p. 147 (Dec. 1972)

R.J. Chaffin, "Permanent Damage in PIN Microwave Diode Switches", IEEE Trans.Nucl.Sci. NS-18(6), (Dec. 1971)

S.C. Chen and J.R. Srour, "Ionising Radiation Effects on Indium Antimonide MIS Devices", IEEE Trans.Nucl.Sci. NS-26(6), pp. 4824-4827 (Dec. 1979)

W.R. Dawes Jr and J.R. Schwank, "An IC Compatible Ionising Radiation Detector", IEEE Trans.Nucl.Sci. NS-28(6), pp. 4152-4155 (Dec. 1981)

B.D. Evans, G.H. Sigel Jr., J.B. Langworthy and B.J. Fararday, "The Fiber Optic Dosimeter on the Navigational Technology Satellite 2", IEEE Trans.Nucl.Sci. NS-25(6), pp. 1619-1624 (Dec. 1978)

J.E. Ferl and E.R. Long Jr, "Infrared Spectroscopic Analysis of the Effects of Simulated Space Radiation on a Polymide", IEEE Trans.Nucl.Sci. NS-28(6), pp. 4119-4124 (Dec. 1981)

R.G. Fraas and R.W. Tallon, "Use of a Metal-Nitride-Oxide Semiconductor as the Detector for a Radiation Dosimeter", IEEE Trans.Nucl.Sci. NS-25(6), pp. 1613-1618 (Dec. 1978)

A.R. Fredrickson and S. Woolf, "Electric Fields in KeV Electron Irradiated Polymers", IEEE Trans.Nucl.Sci. NS-29(6), pp. 2004-2011 (Dec. 1982)

L.E. Halliburton, M. Markes, J.J. Martin, S.P. Doherty, N. Koumvakalis, W.A. Sibley, A.F. Armington and R.N. Brown, "Radiation Effects in Synthetic Quartz: The Role of Electrodiffusion and Radiation-induced Mobility of Interstitial Ions", IEEE Trans.Nucl.Sci. NS-26(6), pp. 4851-4857 (Dec. 1979)

A.H. Kalma and M.A. Hopkins, "Ionising Radiation Effects in HgCdTe MIS Capacitors", IEEE Trans.Nucl.Sci. NS-28(6), pp. 4083-4087 (Dec. 1981)

A.H. Kalma, R.A. Hartmann and B.K. Kanousek, "Ionising Radiation Effects in HgCdTe MIS Capacitors Containing a Photochemically Deposited SiO 2 Layer", IEEE Trans.Nucl.Sci. NS-30(6), pp. 4146-4150 (Dec. 1983)

J.C. King, "Hardening Quartz Resonators to Ionising Radiation - A Review", Report No. SAND 74-0136, Sandia Labs, Albuquerque, NM 87115, USA (Sept. 1974) and Proc.Intl. Conf. on Evaluation of Space Environ- ment on Materials, June 17-21, 1974, CNES, Toulouse, France

G.H. Marcus and H. Bruemmer, "Radiation Damage in GaAs Gunn Diodes", IEEE Trans.Nucl.Sci. NS-17(6), pp. 230-232 (Dec. 1970)

D.K. Meyers and W. Herzog, "Feasibility Study on the Design and Radiation Testing of Complex Functions for 2 x 10 Rads(Si)", IEEE Trans.Nucl.Sci. NS-29(6), pp. 1508-1511 (Dec. 1982)

J.R. Norton, J.M. Cloeren and J.J. Suter, "Gamma Ray and Proton Beam Radiation Testing of Quartz Resonators", IEEE Trans.Nucl.Sci. NS-31(6), (Dec. 1984)

P. Pellegrini, F. Euler, A. Kahan, T.M. Flanagan and T.F. Wrobel, IEEE Trans.Nucl.Sci. NS-25(6), pp. 1267-1273 (Dec. 1978)

W. Poch and A. Holmes-Siedle, TOS Radiation Program Report NAS 5-9034, RCA Astro-Electronics, Princeton, N.J. 08540 (Sept. 1965)

RCA, "Nuvistor" Application Notes (1965)

W.F. Rees Ltd., Woking, U.K., Private communication

L.W. Ricketts, "Fundamentals of Nuclear Hardening of Electronic Equipment", Wiley (1972)

L. Varnell and D.E. Langford, "Radiation Effects in IRAS Extrinsic Infrared Detectors", IEEE Trans.Nucl.Sci. NS-29(6), pp. 1551-1554 (Dec. 1982)

J.J. Wiczer, T.A. Fischer, L.R. Dawson, G.C. Osbourn, T.E. Zipperian and C.E. Barnes, "Pulsed Irradiation of Optimized, MBE Grown AlGaAs/GaAs Radiation hardened Photodiode", IEEE Trans.Nucl.Sci. NS-31(6), (Dec. 1984)