RADIATION EFFECTS

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THE EFFECT OF RADIATION ON SOLID STATE MATERIALS AND DEVICES

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Introduction

The effect of radiation on solid state materials and devices is indeed a broad subject area to review, not that there is a lack of data but rather the opposite, there is a plethora. Specific data on specific devices taken under specific conditions has been tabulated, compiled (1), and filed, and is certainly available to all (2). However, there is more than a suspicion that the data, except for frozen electronic systems, is little used. There are many reasons for this: the obsolescence of the device itself by the time the test data is made available; the variation in the device characteristics caused by the vagaries of manufacture, or deliberate change of method or of contact materials or of potting compound; the use of the device in new combinations; the uncertainty of whether the conditions of test actually can be extrapolated to the presumed conditions of use of the device under consideration; and probably of least importance, ignorance of the existence of the test data in the first place.

The Air Force has, for some time, had to have knowledge of how off the shelf items and systems would function under various prescribed conditions. This has not been what might be called a research program but rather an engineering test program to determine the limits of utility of the various electronic systems upon which our defenses depend. Originally, this test approach was aimed at determining the effect of atomic weapons on existing and postulated weapon systems. Gradually— with the advent of nuclear power packages and then the discovery of the Van Allen Belts, the concern with whether the moon is radioactive to an appreciable degree, and even the possibility of the existence of other radiation belts around Jupiter — requirements of the Air Force have extended to a need for basic knowledge of the effects of radiation of all types on materials and devices from which they are made. This requirement should not be construed as an immediate need to set up test facilities to duplicate radiation environments either known or imagined but rather a need to develop in detail a fundamental knowledge of how radiation moves atoms about, the range of movement of secondaries, the energy levels produced, the energy-effect and dosage-effect relationships, the permanence or additivity of the changes, and the interaction between these changes in a given material and the other environmental factors involved. In short, there is a considerable need for basic research to establish more quantitatively the fundamental theory upon which extrapolation to practical situations can be based.

In the past, the testing program has been based principally on reactor data results. Because of the complex spectrum of neutron energies and gamma ray energies present in such reactors the data has been difficult to interpret in terms of fundamental events. An additional complication has been that the neutron energy spectra differ in the different reactors and in different locations in the same reactor, and variation in temperature too has led to additional complications. The tendency has seemed to be to lump the results under a series of generalizations which may be paraphrased thus: solid state devices are sensitive to radiation, and transistors are very sensitive to radiation. As with all generalizations, this is an oversimplification and indeed a harmful oversimplification since it stultifies further investigation. The reactor data is crude, but no more crude than the conditions under which the data was obtained. Unfortunately, in this paper there is no time for other than generalities but these may indicate some of the possibilities. The effects of radiation on certain classes of materials and devices may be examined through a brief review of how incident radiation interacts with materials. There are two types of occurrences, ionization and atomic displacement; the latter is accompanied by the former but ionization need not be accompanied by displacement. Gamma rays and electrons (beta rays) will produce ionization, but atomic displacement usually will not occur if the energy of the ray is less than some minimal amount. This minimal energy for atomic displacement, the threshold, is dependent upon the material in which the event takes place. The threshold is not truly a singly valued step function but rather a statistical function of lower energy. Gamma rays function in much the same way as electrons because the energy of the ray may be given up in Compton scatter to an electron on collision and then this energetic electron is, except for its origin, identical to a beta ray. The efficiency of conversion, by collision, of the gamma ray is quite low and is dependent on the electron density of the target material. For our purposes gamma nucleus interactions may be neglected.

Radiation Interactions

Our consideration will now be given to the behavior of neutrons, protons, and other particles during radiation. Uncharged neutrons will approach any target, but will not produce an effect on other particles except subsequent to a collision. Neutrons will usually collide with a nucleus rather than with an electron because of their relative sizes. After collision, the now charged energetic particle goes speeding off, collides with other nuclei, dislodging them as well as many electrons. In the same manner, protons impinging on a target will also collide with nuclei and dislodge electrons. Charged particles are more effective in freeing electrons from their bonds when they are moving slowly because of the longer time available for a reaction to take place. Neutrons will frequently displace 10^3 to 10^4 or more atoms; protons will displace somewhat fewer atoms than neutrons; electrons will displace 1 to 10 atoms; and gamma rays will displace one or a few atoms if there is conversion.

The most noticeable effects of these interactions during radiation are the resultant crystalline defects and the energy released from the increased number of electrons free to move about until trapped. The first named, atomic displacement, produces the permanent effects while the latter generates only temporary effects. Nuclear transmutations and its delayed effects are considered, for our present discussion, to be only minor.

Ionization events, resulting from the released energy, have a relaxation period during which the electrons in the conduction band revert to a more stable energy level. The number of electrons placed in the conduction band is a function of the kind of radiation causing the ionization and the number of incident quanta or particles (dose).

Radiation Effects

The defect density is a function of the kind of particle while the number of defects reflects the amount of dosage.

The transient effects produced in electronic devices may cause other effects at a considerable distance from the particular radiation sensitive device since all parts of an electronic circuit are interrelated. The immediate effect of transient radiation pulses is revealed by the presence of conduction electrons which may provide leakage paths and/or alternate conduction loops. The result may be a noise signal induced in the circuit where a pulse would not normally be or an alteration of signal normally present. The duration of the transient effect itself normally does not last much longer than the radiation pulse and the extent of the alteration is somehow related to the pulse intensity (dose rate).

Permanent effects, residual after the occurrence of the pulse, are dependent on the type of material in which the radiation-induced event occurs and result in such phenomena as increased resistivity (e.g., when n-type germanium is converted to p-type), increased brittleness in conductors, variation in the frequency of oscillation of quartz crystals, induced voltages, and chemical changes. Permanent effects are cumulative and present data indicates that they are largely independent of dose rate.

The devastating effects of radiation are so great that it is not possible to develop materials which will not be affected by radiation. This point is well illustrated by consideration of the fact that electronic binding energies are measured in no more than tens of electron volts and that the energy required to move an atom by collision with an electron, in hundreds of kilovolts, but the energies of ray particles are described in millions of volts.

Protection From Radiation

Protection from radiation may be accomplished in more than one way; shielding and design are two which have been studied. In general, the cheapest and lightest shield is supplied by distance from the source because radiation intensity decreases with the square of the distance between source and target (except for beamed particulate radiation). In addition to distance, mass is the radiation shield protection most frequently used, and may be attained by simply supplying an inactive mass.

Devices and circuits can be designed to accommodate the effects of radiation up to certain stated limits without excessive deterioration in functional performance. This can be done by again using the protection of distance by locating less radiation-sensitive components on the outside of the circuitry. It can also be done by incorporating redundancy or parallelism into the design or by such tricks as blocking out, during pulses, portions of the system by radiation sensors.

A combination of materials knowledge, circuit design, and shielding design can be parlayed into circuitry which will meet requirements not only of function in atom bomb radiation fields but in Van Allen Belt type radiation or in proton flares and the other radiation fields which may be encountered. Even with the relatively simple types of radiation environments which we now know exist there are considerable complications.

Radiation Environments

We will start our discussion of specific radiation environments with a discussion of perhaps the simplest and most easily shielded against, the recently described Van Allen Belt. (Its characteristics are summarized in table 1.) The protons of this belt constitute a hazard to solar cells which do not have a protective layer above their active surfaces. Electron bombardment in the Van Allen Belt reduces the short circuit current in p-n solar cells. Expected lifetime of a solar cell in a circular orbit at an altitude of 2000 miles would be about 2 months unshielded and 5 months if shielded. The protons in the Van Allen Belt are relatively easily stopped, however: a sheet of aluminum with a thickness of 0.062 cm (.167 gms/cm^2) is sufficient to stop protons of 10 Mev energy, and a shield of 0.21 cm stops protons of 20 Mev energy. The principle effect of the protons is to eject electrons by inelastic collisions. Some of these would in turn attack atoms. But, consideration of the electron range in aluminum as a function of energy reveals that 0.21 cm of aluminum would stop virtually all electrons of energy below 1.5 Mev (4). However, the damage threshold for silicon is about 145 Kev, which accounts for the present trend to consider the shielding of the solar cells by a quartz plate if appreciable time is to be spent in the Van Allen Belt.

A somewhat better known type of radiation environment yet none the less difficult to describe accurately or to reproduce in test facilities is that which may be expected from a nuclear power package. Most of the testing work to date has been performed at reactors such as the two in table 2 whose results we will discuss as a "rule of thumb." Fundamentally, the observed phenomena are not varied in kind but in degree and the difficulties of interpretation lie as much in the complexities of the materials and devices as in the physical phenomena. Since the data on specific devices is available in the requisite detail from reports on file at the Radiation Effects Information Center at Battelle, we will restrict ourselves to a brief description of this phenomena as it appears in certain types of devices.

Resistors

Carbon composition resistors are extremely variable in manufacture and it is indeed a problem to determine whether changes are due to radiation, interfacial contact changes, humidity, or to some other cause. The resistors exhibit a decrease in resistivity of some 3 to 10 percent during irradiation under fast neutron flux of the order of 10^{15}, an integrated thermal flux of 10^{16}, or a gamma dose of 10^{11} ergs/gm (C). The cause of these changes may be the decomposition and carbonization of the epoxy binder. Also, the variation of effect with resistance value is related to the relative quantity of binder.

Pulsed radiation, which is available from Triga or Godiva (see table 3), produces an instantaneous decrease in resistivity as high as 86 percent for high value resistors. This large and instantaneous decrease may be due to the setting up of surface leakage paths rather than to variation of binder or bulk materials.

Deposited carbon film resistors are even more complex in manufacture and composition. Usually, the thickness of the film is within the range of the recoil of a displaced carbon atom — the higher the value, the thinner the film. It may be that the atomic displacements actually tear out chunks to decrease effective film thickness and thus increase resistivity, or that displacements actually increase the difficulty of movement of electrons in the film. (This is only an excuse for observed data not an explanation.)

Negative resistance changes are noted in resistors which are coated with methacrylate. This is excused by postulating the existence of ionization and thus alternate leakage paths.

Metal film resistors show an increase in resistivity, as expected, because atomic displacements would increase electron scatter. (A decrease would be expected, and has been observed, if coating materials other than metal are used.)

Wire wound resistors are least sensitive to radiation since they present a continuous path for the flow of electrons. As expected, an increase in resistivity results from increased electron scatter. Pulsed radiation for some reason results in a considerable resistivity increase which may be related to the induced electromagnetic field in the wire coil and the back EMF generated. This phenomena is illustrated for several types of resistors in figure 1. Unfortunately, very little is really known about fundamental processes in resistor materials.

Varistors

Nonlinear voltage sensitive devices such as copper or selenium oxide rectifiers are also sensitive to radiation. The character of the oxide film changes easily due to collisions with particles and the secondary products of such collisions. Dosages as low as 10^{13} n/cm^2 produce appreciable change. The symmetrical varistors however, such as compacted silicon carbide powders have considerably greater radiation accommodation.

Capacitors

The myriad types of capacitors preclude individual consideration but some generalizations are possible. The metal film aluminum in capacitors is essentially not damaged by radiation; dielectrics and supports are. Organic dielectrics change chemically by decomposition, carbonization or polymerization. Inorganic dielectrics are much more stable. Electrolytic capacitors containing boron, which has a high neutron-capture cross section, have low radiation tolerance. Solid dielectrics of aluminum oxide, magnesium oxide, and boron nitride undergo little change in a static radiation flux. A decrease in leakage resistance accompanies a pulse because of the ionization in the dielectric.

Transformers

Transformers are capable of withstanding neutron doses in the order of 10^{17}/cm^2 without marked change in characteristics, provided no mechanical change takes place. Potting compounds, usually organic, undergo chemical changes and become gassy. The organic insulation resistance between windings suffer similarly; hence short circuits could occur.

Infrared Detectors

Infrared detectors of the semiconductor type such as PbS, PbSe, In Sb, and thermistors have been studied both in pulsed and continuous radiation fields. The signal to noise ratio decreases after about 10^{13} neutrons/cm^2, decreasing essentially to zero at doses of 10^{16}. Bolometer thermistor types have the best radiation accommodation. Irradiation results in a decrease in dark resistance. Window materials such as CaF_2 tend to become less transparent but this transmission loss which can be annealed out is minor compared to the signal to noise ratio change of the detector itself.

Transistors

For purposes of study, the transistor is most satisfactory since it is composed of material of known structure, known chemical composition, and the results of irradiation are relatively easy to measure. It seems to be rather frequently rediscovered that narrow base transistors can best accommodate radiation changes. From a simple geometric viewpoint, a narrow base presents the least mass target. Electrically the narrow base transistor permits radiation injected minority carriers to pass through without recombination. Lifetime changes are a function of the recombination cross section of the defects. The data indicates that fast neutron generated defects in silicon have a larger recombination cross section than in germanium. Silicon transistors will tolerate some 10^{15} neutrons.

Conclusion

Air Force needs of the next decade are difficult to predict, but in view of the environments to which they will undoubtedly be subjected, electronic devices of all types will need to possess all of the attributes of the most highly developed present-day equipment, reliability, power conservation, compactness, as well as the added requirement of radiation compatability. The radiation compatability of these new devices shall evolve from a basic knowledge of the effects of radiation on materials and a revelation of their inherent characteristics by exposure to radiation. These, in turn, will project from planned programs of research and testing coordination of physicists, chemists, engineers, and military strategists.

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TABLE 1
VAN ALLEN BELT RADIATION[3]

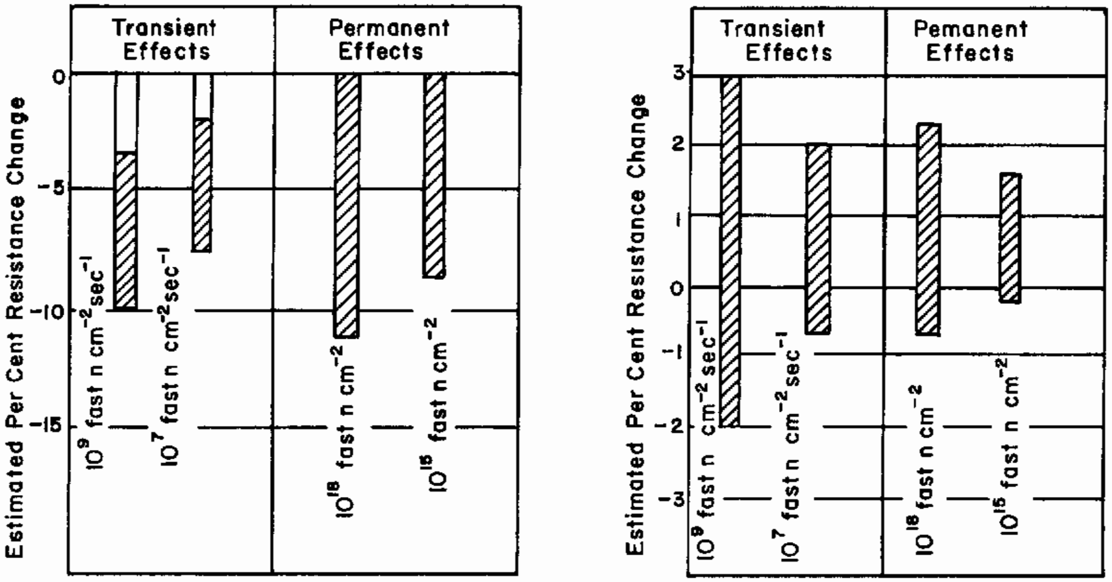
ALTITUDE	1400 – 3400 KM	8000 – 12000 KM
GEOMAGNETIC LATITUDE	± 15°	± 60°
PROTON FLUX	2×10^{4} p/cm^{2}-sec > 40 mev	
ELECTRON FLUX	$\sim 10^{10}$ e/cm^{2}-sec > 20 kev	$\sim 10^{11}$ e/cm^{2}-sec 40 kev
	$\sim 10^{7}$ e/cm^{2}-sec > 600 kev	$< 10^{8}$ e/cm^{2}-sec > 200 kev
		$< 10^{6}$ e/cm^{2}-sec > 2.5 mev

TABLE 2
TEST REACTORS[5]

	G.E. TEST	PENN. STATE UNIV.
FAST NEUTRON FLUX (MAX)	1×10^{15} n/cm^{2}-sec	10^{12} n/cm^{2}-sec
THERMAL NEUTRON FLUX (MAX)	2×10^{14} nv	10^{12} nv
GAMMA INTENSITY (MAX IN FACILITIES)	3.6×10^{11} ergs/g-hr (c)	6.5×10^{8} ergs/g-hr (c)
MODERATOR	WATER AND BERYLLIUM	WATER
COOLANT	WATER	WATER
POWER AND TYPE	30 MW TANK TYPE	100 kw, POOL

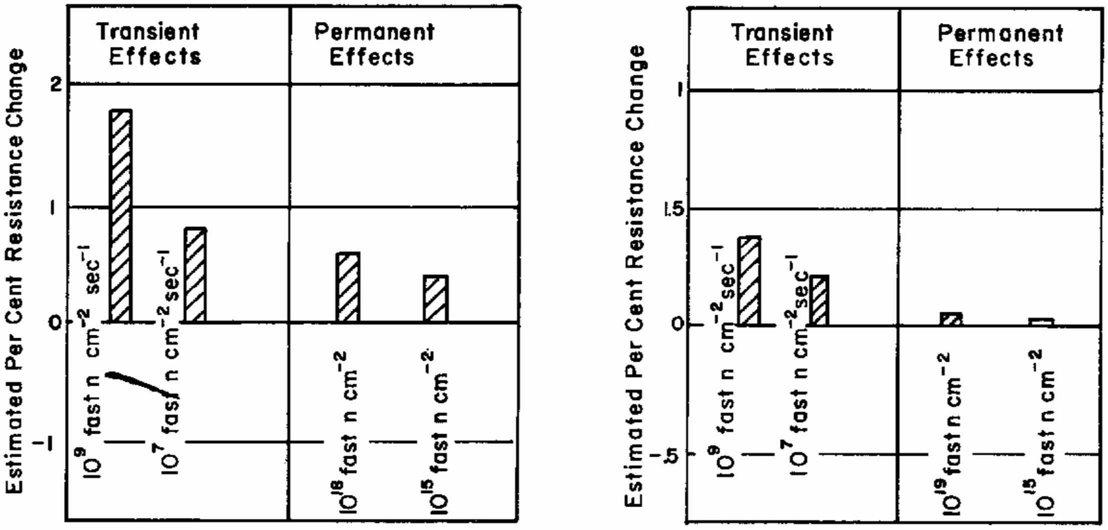
TABLE 3
PULSED REACTORS[5]

	Triga (Gen. Atom)	
FAST NEUTRON FLUX (AVG.)	4×10^{11} n/cm^2-sec	
THERMAL NEUTRON FLUX (AVG.)	1.6×10^{12} nv	
GAMMA INTENSITY		
MODERATOR		
COOLANT	WATER	
POWER AND TYPE	100 kw, POOL	
PULSE	40 millisecond	15 millisecond
	FAST NEUTRON FLUX 5×10^{13} nv	7×10^{13} nv/cm^2
	THERMAL NEUTRON FLUX 2×10^{14} nv	3×10^{14} nv/cm^2
	GODIVA II (LOS ALAMOS)	
PULSE WIDTH: APPROXIMATELY 80 MICROSECONDS AT HALF HEIGHT.		
YIELD: 10^{16} FISSIONS/BURST		
LEAKAGE SPECTRUN: SIMILAR TO U-235 FISSION MAX. AT 0.4 mev		
LEAKAGE NEUTRONS: 1.4 10^{16}/BURST.		
DOSE AT 1 METER: 30 RADS GAMMA, 370 RADS NEUTRON.		



a. Carbon Composition Resistors

b. Deposited Carbon-Film Resistors



c. Deposited Metal-Film Resistors

d. Precision Wire-Wound Resistors

Figure 1. Estimated Effects of Nuclear Radiation on Carbon-Composition Deposited-Carbon- and Metal-Film, and Precision Wire-Wound Resistors