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Effects of Ionizing Radiation on Solid Rocket Motor Components

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EFFECTS OF RADIATION ON ROCKET MOTOR OPERATION

Richard E. Gardner

ABSTRACT

Problems which the solid propellant rocket engineer will encounter in designing for long-term storage in a radiation environment are discussed. A summary of present knowledge of the radiation environment is given. Mechanisms of radiation degradation and its effects on tensile properties of propellant binders are discussed qualitatively. Data from a program of irradiation of several propellants is presented. Properties of two of the propellants were changed significantly by doses of the order of 4×10^6 rads.

I. INTRODUCTION

Future missions in space will undoubtedly involve storage of motors in space for long periods of time. Missions using the Earth orbital rendezvous concept would involve storage of motors in an Earth orbit for periods of the order of several months. Effects of long time exposure in the Van Allen radiation belts must be estimated. Data on these zones is rather sparse. There is a very real need for an extensive, detailed census of particles trapped by the Earth's magnetic field, and also in interplanetary space. Early Ranger experiments are expected to provide some of this information. In the meantime, we must make educated guesses.

The purpose of this paper is to point out some of the problems which the solid-rocket engineer will encounter in designing for long-term storage in a radiation environment.

II. RADIATION DEGRADATION OF MOTOR COMPONENTS

The term radiation covers a wide variety of phenomena: electrons, protons, neutrons, alpha particles, and electromagnetic radiation. The effect on organic materials of all of them is the same: ionization, which produces chemically active molecules. As a result of this, two general types of chemical changes, crosslinking, and bond scission, are produced in polymers. In crosslinking, two active sites on different polymer chains react to form a new chemical bond. Crosslinking, up to a point, increases mechanical hardness and strength and reduces elastic deflection. Eventually it leads to an extremely brittle substance with very little mechanical strength. Scission is the decomposition of polymer chains into smaller fragments. Its effect is to increase deflection and decrease the strength of the material.

Both crosslinking and scission can occur at the same time. Usually, one or the other predominates, the extent of the reactions being dependent on the composition of the polymer in question. The presence of oxygen in the atmosphere tends to increase the amount of crosslinking and chain decomposition.

Ammonium perchlorate is also significantly affected by ionizing radiation (Ref. 1). Small amounts of ammonia, water vapor, hydrogen chloride, chlorine, and water vapor are evolved.

Table I is a presentation of estimates made by the Battelle Memorial Institute (Ref. 2) of radiation effects on some polymers of interest to solid propellant engineers. JPL experimental work reported in this paper indicates that polyurethane propellants cannot be ranked as high as Battelle has ranked the binder material.

The radiation dose unit which is being used (rad) is defined as the absorbed dose of any ionizing radiation which is accompanied by the liberation of 100 ergs per gram of absorbing material. The roentgen is a unit of exposure dose. The factor for converting from an exposure dose to an absorbed dose is a function of energy of the radiation and the absorbing properties of the material. The factor is of the order of slightly less than one. For order-of-magnitude discussions we can say that a roentgen is equivalent to a rad.

Metals are relatively unaffected by radiation. Plastic materials, such as those used as binders in motor nozzles and fibre-glass wound cases have degradation thresholds in the range of 10^5 - 10^9 rads, depending on what the particular plastic is.

III. THE RADIATION ENVIRONMENT

It is likely that, even before leaving the ground, future rocket motors may encounter a considerable amount of radiation. X-ray inspection of motors for quality control is now being used. Motor sterilization by use of radiation is being considered. As with x-ray inspection, penetrating power is an important parameter in the selection of the type of radiation to be used for sterilization. Either x-rays or gamma rays are used. JPL space biologists have specified that a dose of 10^7 rads of gamma rays or x-rays is necessary for satisfactory sterilization. X-ray motor inspection and sterilization could easily be combined in one operation to give an integrated dose of 10^7 rads. A potential problem in sterilization would be uneven irradiation causing variations in burning rate and mechanical properties.

Motor storage in an orbit in the Van Allen belts for a period of the order of several months to a year would most likely affect adversely the properties of the propellant and liner. The present concept of radiation intensity variation with distance from Earth, as portrayed by Van Allen (Ref. 3) is shown in Fig. 1.

Jaffe and Rittenhouse (Ref. 4), of JPL, have compiled a summary of available data on the radiation environment in space. Table II shows pertinent information taken from Ref. 4. Data shows that the principal part of the radiation dose in the inner belt is due to protons. The outer belt is thought of as predominantly electrons. The doses due to solar flare particles, solar "wind", solar electromagnetic radiation, and cosmic rays are negligible.

IV. RADIATION DOSE DISTRIBUTION

Protons are difficult to shield against, due to their high energy levels. The dose rate depends mainly on the number of protons striking the material rather than their energies. The depth of penetration, however, does depend on the proton energy. Energy is deposited along the straight path of the proton, decreasing approximately linearly to zero at the maximum range of the proton. Calculations by R. D. Evans of MIT (Ref. 5) indicate a range of 7 cm by a 40-mev proton, in liquid oxygen shielded by a 30-mil-thick stainless steel container. Evans indicates that the range in most organic materials would be the same as the range in LOX. One must remember, of course, that since proton energies vary over a wide spectrum, the proton penetration will also vary. Thus, the integrated dose at a point will be a function of the distance of the point from the surface of the motor case.

In addition to the ionization caused by the proton impact with an atom of absorbing material, secondary radiation (x-rays) called bremsstrahlung is generated. The effective dose from the bremsstrahlung is of the same order of magnitude as the dose caused by the proton impact.

Because their mass is so small, compared with the mass of an atom of the absorbing material, electrons are deflected at large angles during impact. Consequently the path of the electron in the material is twisting and random. Approximately one half of the incident electrons will be reflected back into space. The depth of penetration of the remaining electrons is small, compared with the motor case thickness. In the process of particle collisions, bremsstrahlung is produced, and this secondary radiation is the significant portion of the outer belt dose. Being in the x-ray range of electromagnetic radiation, it has high penetrating capabilities. Bremsstrahlung production varies with the atomic number of the absorbing material, the intensity being about twice as large in stainless steel as in aluminum.

V. EXPERIMENTAL WORK ON PROPELLANT IRRADIATION

At JPL we have begun a program for testing several of the propellants which will be used in various space exploration programs. A PBAA-ammonium perchlorate-aluminum propellant, an aluminized double-base propellant, and a polyurethane-ammonium perchlorate-aluminum propellant were selected for preliminary irradiation tests. Dumbbell tensile specimens and burning-rate strands were exposed to cobalt-60 gamma radiation in the Hughes Aircraft Company's 500-curie radiation source in Culver City, Calif. Their facility gave a uniform exposure dose rate of 2.54 roentgens per hour. For cobalt-60 gamma rays, and for our propellants, it was estimated that this exposure dose could be translated into an absorbed dose of 2.29 rads/hr.

For each type of propellant three groups of samples were subjected to integrated total absorbed doses of 5.2×10^5, 3.8×10^6, and 1.48×10^7 rads. Each group consisted of three dumbbell specimens and four burning-rate strands. In addition, three dumbbell specimens of each of the composite propellants were subjected to a dose of 7.0×10^6 rads. The propellants were irradiated in air at atmospheric pressure. It is estimated that irradiation did not raise the specimen temperature more than a few degrees above room temperature. The strands were then restricted and burned in a nitrogen atmosphere at 1000 psi, 90°F. The dumbbell specimens were pulled in an Instron tester at 80°F, at a rate of .741 in./in./min.

It was not anticipated that the burning rates of the propellants would be changed significantly by irradiation. The experimental data (Fig. 2) shows some change. There is a definite increase in the polyurethane burning rate in the dose range between 4×10^6 and 1.5×10^7 rads. This increase might be attributed to the ammonium perchlorate in the propellant. Work done by Freeman and Anderson (Ref. 1) indicates that x-ray irradiation of ammonium perchlorate to a dose of 10^7 roentgens speeds up the thermal decomposition rate. However, the PBAA propellant, which also contains ammonium perchlorate, was not affected in the same manner. It would be interesting to explore further this range of dosages, in the two composite propellants. There was considerably more scatter in the double base data than in the composites. The trend in the double-base propellant seems to be an immediate drop in the burning rate for a small dose, but no significant change in rate with increased irradiation. In the three propellants, the amount of data scatter did not significantly change with increased dosage.

The effect of radiation on the PBAA propellant was significantly less than the effect on the other propellants, both in burning rate and in mechanical properties. In the double-base and polyurethane propellants, ultimate tensile strength drops rapidly for doses greater than 4×10^6 rads. Strain at maximum stress, secant modulus, and ultimate elongation also changed radically in this range. Figures 3, 4, and 5 show the tensile properties as functions of the total absorbed dose.

Hardness was a function of the radiation dose in the case of the polyurethane propellant only. Figure 6 shows this variation.

One may conclude, then, that although mechanical properties of this PBAA propellant are much poorer in the unirradiated case, the PBAA is the better of the three propellants for use when radiation doses greater than 4×10^6 rads are expected. It is interesting to note that for this particular PBAA propellant, mechanical properties are insensitive to subjection to high temperatures for long periods of time, but that thermal sterilization increases the burning rate significantly.

The next step in the project will be to irradiate the propellants in an inert-gas atmosphere, to evaluate the extent that this will slow down the degradation process. In addition to this, NASA has a JPL monitored contract with Battelle Memorial Institute for an extensive investigation of space environment effects on motor components. Thermal, vacuum, and radiation effects on several propellants, liners, igniters, and motor case materials will be evaluated.

In summary, one may say that the maximum possible radiation dose a motor would encounter during quality control, sterilization, and one-year storage in an Earth orbit would be approximately 1.1×10^7 rads. The largest part of this (10^7 rads) would be due to sterilization. Some propellants in use today are capable of satisfactory performance after receiving this magnitude of dose.

The largest radiation dose would be received by the motor case and nozzle. Restriction to use of metals for motor cases is not warranted, however, as some glass reinforced plastics with very good radiation resistance have been developed. The most critical part of the motor would probably be the liner. No data is available on the effect of radiation on the adhesive properties of liner materials.

Table I

Material	Threshold dose[1] rads	Usable dose[2] rads
Polyurethane	10^6	8×10^8
Polyvinyl chloride	10^7	10^8
Polybutadiene-acrylic acid copolymer	10^6	10^7
Polysulfide rubber	5×10^5	5×10^6
Polysulfide rubber plus phenolic resins	10^6	5×10^7
Cellulose acetate	10^6	10^7

[1]Lowest dose at which change in some physical property has been noted.

[2]Maximum dose at which materials will still function for limited applications.

Table II

Radiation	Energy, ev	Range, gm/cm^2	Dose (Rads/Yr)		
			Extreme surface	Through 1 mg/cm^2	Through 1 gm/cm^2
Inner Radiation Belt					
Protons	$10^3 - 7 \times 10^8$	$10^{-6} - 10^3$	10^{10} (?)	10^9	10^5
Electrons	$< 2 \times 10^4 - 1 \times 10^6$	$10^{-3} - 10^0$	10^{12} (?)	10^{12}	0
Bremsstrahlung	$< 2 \times 10^4 - 1 \times 10^6$	$10^{-1} - 10^1$	10^5 (?)	10^5	$10^5 - 10^6$
Total			10^{12} (?)	10^{12}	$10^5 - 10^6$
Outer Radiation Belt					
Electrons	$2 \times 10^4 - 5 \times 10^6$	$10^{-3} - 10^0$	$10^{11} - 10^{13}$	$10^{11} - 10^{13}$	10^3
Bremsstrahlung	$2 \times 10^4 - 5 \times 10^6$	$10^{-1} - 10^1$	$10^5 - 10^7$	$10^5 - 10^7$	$10^4 - 10^6$
Total			$10^{11} - 10^{13}$	$10^{11} - 10^{13}$	$10^4 - 10^6$
Solar Flare High Energy Particles					
Protons	$2 \times 10^7 - 10^9$	$10^0 - 10^3$	$10^3 - 10^4$	$10^3 - 10^4$	$10^2 - 10^3$
Electrons	$\sim 5 \times 10^4$	10^{-2}	$10^5 - 10^7$ (?)	$10^5 - 10^7$ (?)	0
Bremsstrahlung	$\sim 5 \times 10^4$	$10^0 - 10^1$	$10^0 - 10^2$ (?)	$10^0 - 10^2$ (?)	$10^0 - 10^2$ (?)
Total			$10^5 - 10^7$ (?)	$10^5 - 10^7$ (?)	$10^2 - 10^3$
Cosmic Rays					
Protons	$10^8 - 10^{19}$	$>10^{-1}$	$10^0 - 10^1$	$10^0 - 10^1$	$10^0 - 10^1$

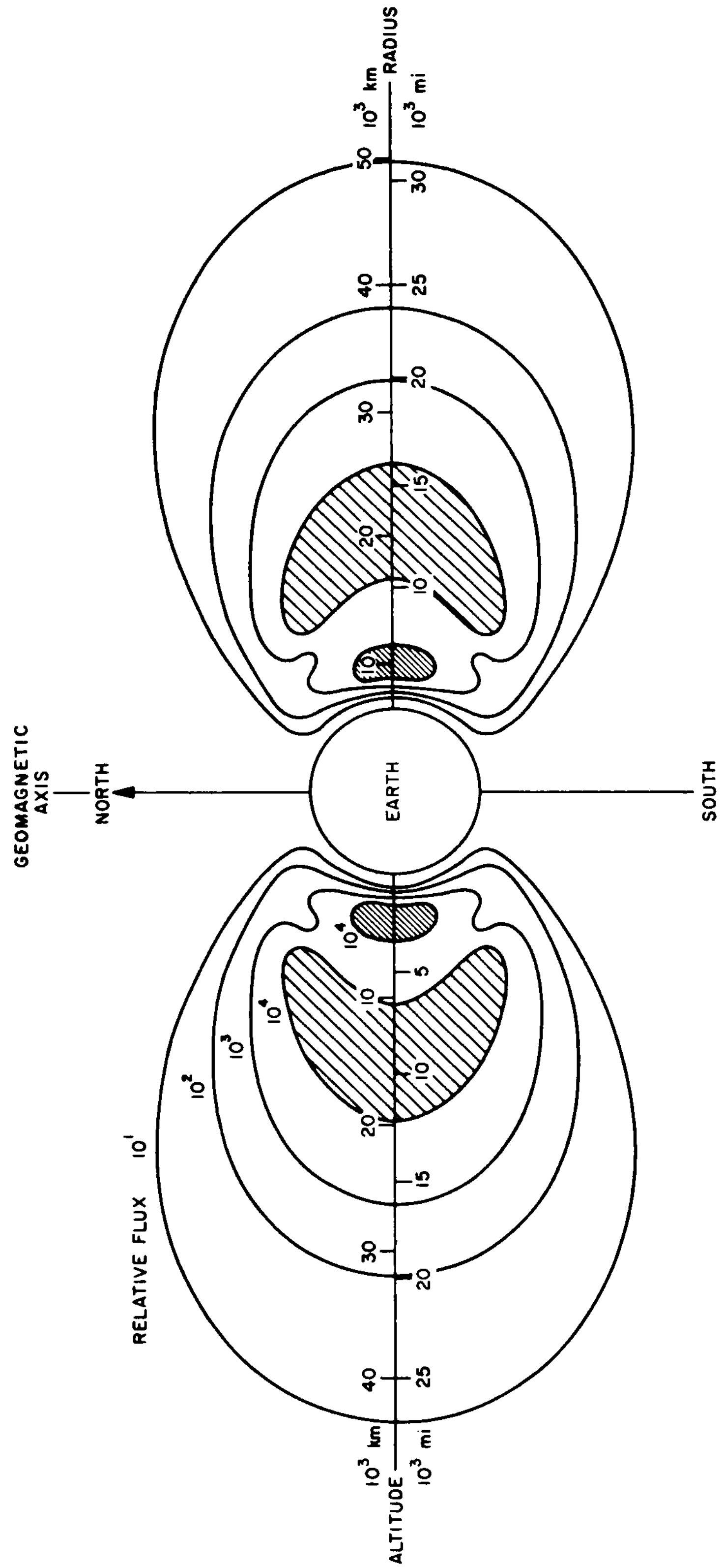

Fig. 1. Radiation Belts

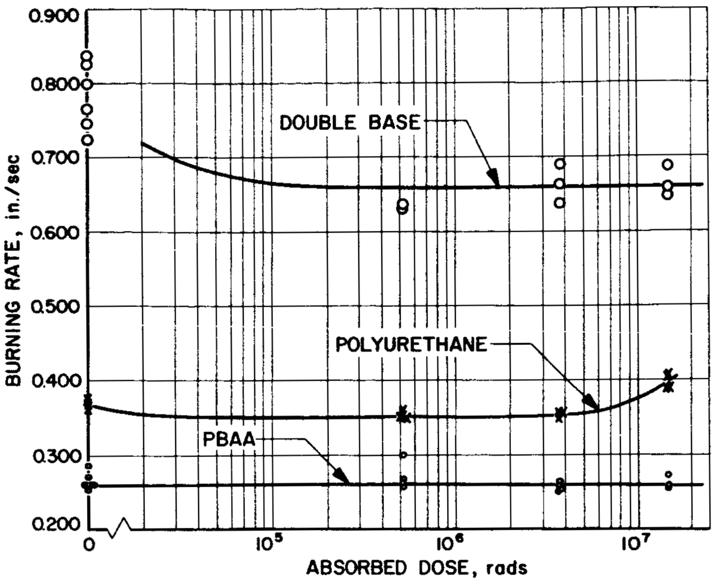

Fig. 2. Effect of radiation on burning rate

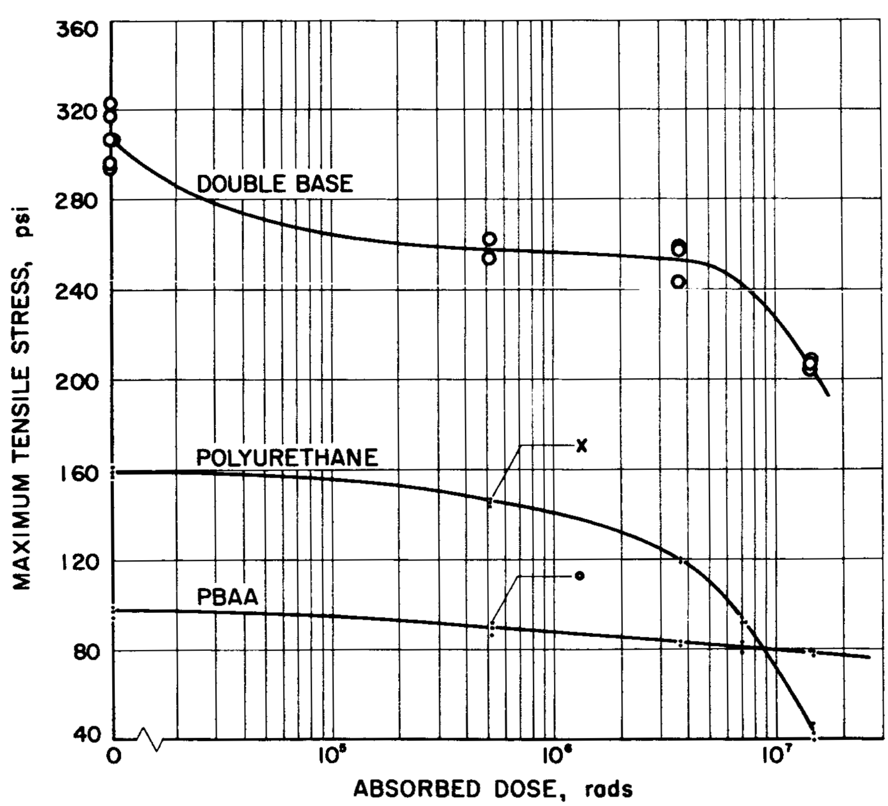

Fig. 3. Effect of radiation on strength

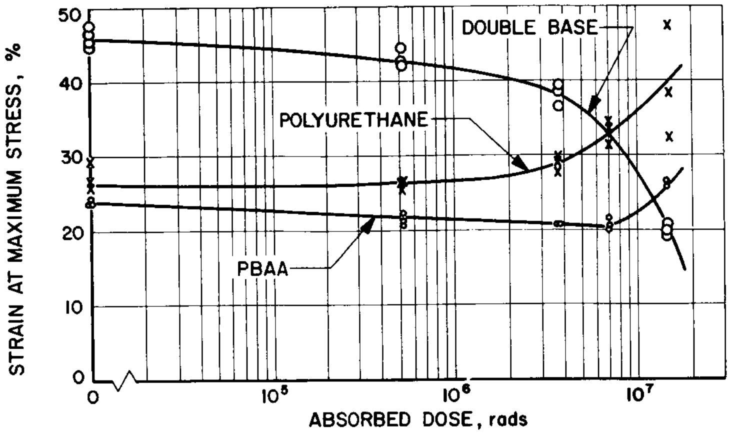

Fig. 4. Effect of radiation on elongation

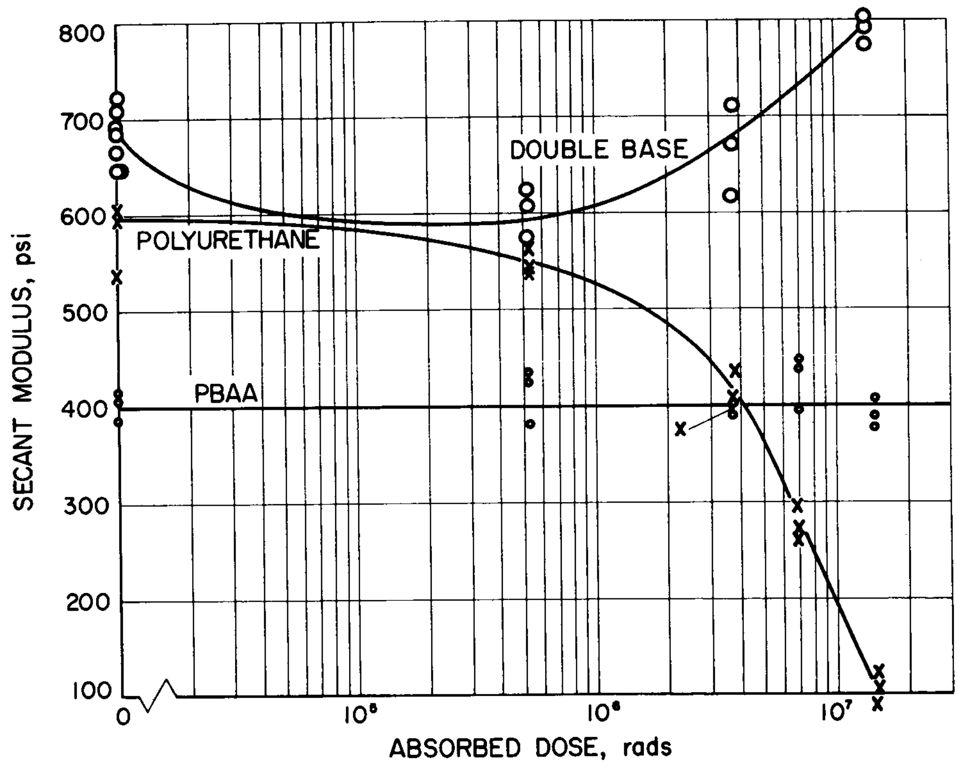

Fig. 5. Effect of radiation on modulus

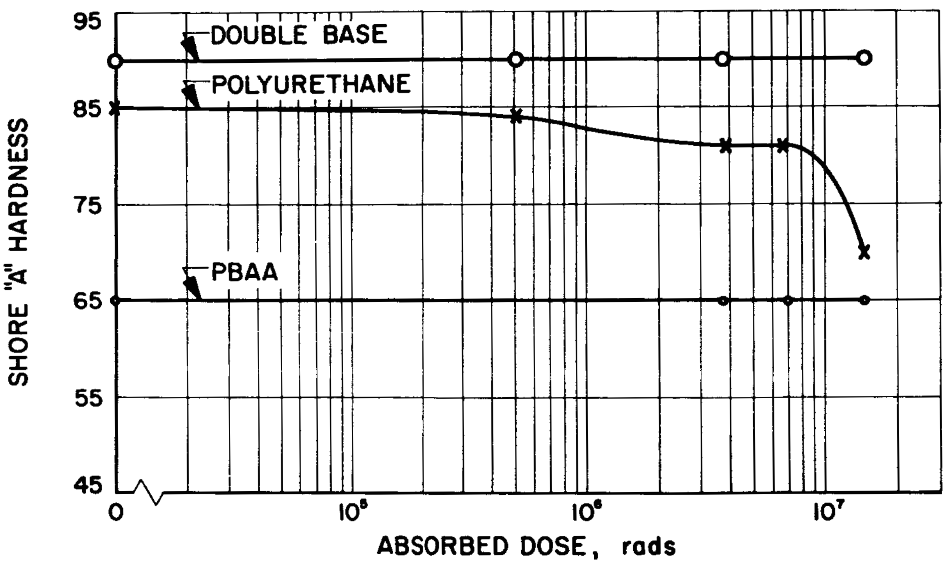

Fig. 6. Effect of radiation on hardness

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