[redacted]

[redacted] (6)

MonP-208

This document consists of 25 pages
Copy 4 of 10 copies. Series B (AVP)

Contract No. W 7405 - eng. 39

* * * * * * * * * * * * * *

Section V.

H. W. Newson, Section Chief

* * * * * * * * * * * * * *

EFFECTS OF RADIATIONS ON MATERIALS

F. C. Armistead

* * * * * * * * * * * *

November 11, 1946

T/D-INS
PC Hanse
Y-12 Technical Library
Document Reference Section

Series A. Issued; 11/29/46 Series A. Received: 11/29/46

[redacted]

[redacted]

[redacted]

1C

[redacted]

OUTLINE

I. General Description of the Irradiation- Induced Effects in Materials ..... Page 4.

II. Survey of Irradiation-Induced Effects in Specific Materials Classified According to their Applications ..... Page 7.

1. Fuel Materials
   - A. Uranium ..... Page 7.
   - B. Uranium Alloys ..... Page 7.

2. Moderator and Reflector Materials
   - A. Graphite ..... Page 8.
   - B. Beryllium ..... Page 13.
   - C. Beryllium Oxide ..... Page 13.
   - D. Water and Heavy Water ..... Page 13.

3. Coolants
   - A. Gases ..... Page 15.
   - B. Water ..... Page 15.
   - C. Liquid Metals ..... Page 15.

4. "Breeding" Materials
   - A. Thorium ..... Page 15.

5. Shielding Materials
   - A. Concrete ..... Page 15.
   - B. Cellulose-Base Materials ..... Page 15.
   - C. Heavy Elements ..... Page 16.
   - D. Water ..... Page 16.

6. Auxiliary Materials
   - A. Structural Materials ..... Page 16.
     - (a) Aluminum ..... Page 16.
     - (b) Iron and Steel ..... Page 16.
     - (c) Concrete ..... Page 16.
     - (d) Wood ..... Page 16.
   - B. Lubricants and Hydraulic Fluids ..... Page 16.
     - (a) Petroleum Products ..... Page 16.

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

[redacted]

C. Electrical Insulators ..... Page 17.
(a) Plastics..... Page 17.
(b) Glass and Quartz..... Page 19.
(c))Porcelain ..... Page 19.
(d) Mica ..... Page 19.

D. Miscellaneous Materials ..... Page 19.
(a) Elastomers and Plastics ..... Page 19.
(b) Optical Materials ..... Page 20.
(c) Permanent Magnets..... Page 20.
(d) Textiles ..... Page 20.
(e) λ- Detonation of $N_2H_3I_3$ ..... Page 20.

Acknowledgement ..... Page 20.

Appendix ..... Page 21.

References ..... Page 23.

[redacted]

[redacted]

[redacted]

EFFECTS OF RADIATIONS ON MATERIALS

I. General Description of the Irradiation-Induced Effects in Materials

1. Solids[1] Neutrons knock atoms out of crystal lattice points driving them into crystal interstices, whence many of them move ultimately out to the edge of the lattice. Properties change, and energy is stored. Some effects are due to the holes, some due to the displaced atoms. New elements may be created which do not fit into the crystal lattice. These effects are seen in non-metallic crystals, but have not been seen in metals, possibly because the stresses and disturbances due to the interstitially trapped atoms can more readily be relieved in metals, by recrystallization of the stray atoms or by yielding of the metal in a gradual low temperature annealing (i.e., a plastic flow). Neutrons cause chemical changes in compounds in some cases by actually breaking the chemical bonds (direct neutron impact); however, in the case of organic compounds and covalent inorganic compounds (where ionization energy is greater than bond energy) we have thousandfold greater chemical changes due to ionizing effects of the recoiling ion on its passage through the material. New substances are then formed, with attendant property changes in the original material, and frequently with gas evolution.

Ionizing irradiations[2] (fission fragments, alpha and beta particles, and gamma radiation) also effect changes in materials. Metals are not affected significantly. Chemical compounds are decomposed with similar property changes to those mentioned above as induced by neutrons; extent

[redacted]

of decomposition is dependent upon number of ion pairs produced and also upon the susceptibility of the substance to ion-induced changes. This susceptibility is expressed by the "ion-pair yield", defined as the number of new molecules formed per ion pair. Organic and covalent inorganic compounds are particularly susceptible to the ionization-induced effects and organic compounds show polymerization. Aromatics are thought[3] to be more stable than the aliphatics, yet may have other disadvantages in practice.

Fission fragments released in the body of a solid result in quantities of foreign substances, some gaseous, being trapped within the solid. These trapped substances are possibly the cause for observed changes in the fuel or fuel alloy material, such as embrittlement and surface blistering. Cohesion of the fuel material deteriorates after extensive fissioning; e.g., a uranium foil (50% U^{235}) was completely powdered after 7% fissioning. Fission fragments cause severe changes such as the fast neutrons cause by the same mechanism of knocking atoms out of their positions.

Super-cooled liquids such as glass and fused quartz have their electrical resistivity reduced and also show a coloration effect (which limits their usefulness in optical equipment). Electrical resistivity is reduced as a result of release of metallic (e.g., Na) ions which migrate through the substance and carry electric current. Coloration is due to "F-Centers"[4], i.e., electrons, freed by the irradiation, and trapped in chance-empty or bombardment-emptied lattice positions. These electrons absorb in the visible region of light and give color to the substance by subtraction of portions of the incident light. One instance of the coloration of glass under ultra-violet irradiation has been attributed[5] to a photo-induced

oxidation and reduction process which produces visible compounds within the material.

2. Liquids. Liquids are subject to the ionization-induced effects mentioned above for solids. Decomposition of the irradiated liquid, formation of new compounds, and release of gas, are all observed to result. Neutrons can cause these changes too, largely by ionizing action of the ion recoils from the atoms of the liquids. Regarding the mechanism involved in the chemical changes there are[6] conflicting theories: the ion cluster theory vs. the theory of free or excited atoms and free radicals. The latter theory[7] is given more credence now.

3. Gases. Compound gases are subject to the same chemical changes as those noted above for compound liquids and solids. Theories and conflicts are[6] the same as for liquids.

Note:[8] In solids, liquids, and gases the component elements are always subject to the induced radioactivity that is possible under neutron irradiations.

II. Survey of Irradiation-Induced Effects in Specific Materials Classified According to their Application

1. Fuel Materials

A. Uranium. Natural uranium slugs at Hanford[9] have shown effects (possibly of embrittlement[10] by fission gases) after about 7% fissioning of the U^{235} atoms; small surface blisters have been observed[11] after only about a 3% fissioning. A foil composed of equal parts of U^{235} was found[12] to be completely powdered after about 7% of the U^{235} had fissioned. It is expected that the effect of internal fissions can be reduced by operating the active material in a fluid or semi-fluid form. The Hanford slugs have shown[13] marked hardening and decrease in cross-breaking strength. Also the 1¼ inch O.D. slugs have been found to be 0.1 inch out of round after exposures.

B. Uranium Alloys, Compounds, and Mixtures. Samples of UO_2 - BeO mixtures, of high and low densities and also of high (10%) and low (2%) UO_2 content were exposed to W pile radiation for 24 and 63 day periods. The U was 30% U^{235}. The percent of all the U^{235} atoms which underwent fission was of the order of 0.1%. Thermal conductivity was reduced[14] to approximately 25% in 24 days and 20% in 63 days. Annealing in vacuo at 900° C removed only about 15% of the induced conductivity change. No annealing is thought worthwhile below 600° C. Elastic modulus (Young's) was reduced about 1 to 2% during the 24 and 63 day exposures. Crushing strength is approximately doubled[15] in 63 days. 80 to 90% of the change taking place in the first 24 days. An expansion of 0.5 to 1.0% was also observed, again with most of the change occurring in the first 24 days.

Uranium-aluminum alloy ... nothing to report.

[redacted]

2. Moderator and Reflector Materials

A. Graphite. Under intense pile radiation graphite has shown notable increases in the following five properties: Young's elastic modulus (E), thermal resistivity (1/K), electrical resistivity (R), stored energy (S), and breaking strength (B). These properties are changed at rates which decrease; i.e., the property changes saturate or approach saturation in various degrees[16]. See Figure 1. These changes are all healed to some extent by heating either concurrently or subsequent to the irradiation. Changes in R and S are recoverable (by heating) more completely than changes in E and K.

E increases under neutron irradiation, leveling off[17] at approximately three to four times its initial value after long exposure under pile conditions of temperature and irradiation. Heating, subsequent to the irradiation[18], reduces the induced excess in E; the higher the heating temperature, the less the residual excess E: residual of $\frac{1}{2}$ after one hour at 300° C and zero (complete recovery) after one hour at 800° C. Heating, concurrent with irradiation[19], leaves graphite with induced excess E of approximately the same magnitude as if the heating had been subsequent to the irradiation. Thus the hotter the graphite in the pile the less the net induced excess E. The initial rate of change of the property is given by $\Delta E/E_o = 0.25/L$-unit* at 35° C at the start of irradiation, by definition[20] of unit L.

Breaking strength, B, increases[21] for both compression and tension at gradually decreasing rate, with possible ultimate embrittlement and crumbling[22] of the graphite. B seems to level off[23] at 2 to 3

* For Units and Standards see Appendix A.

From CS-2745, p.13.

GRAPHITE

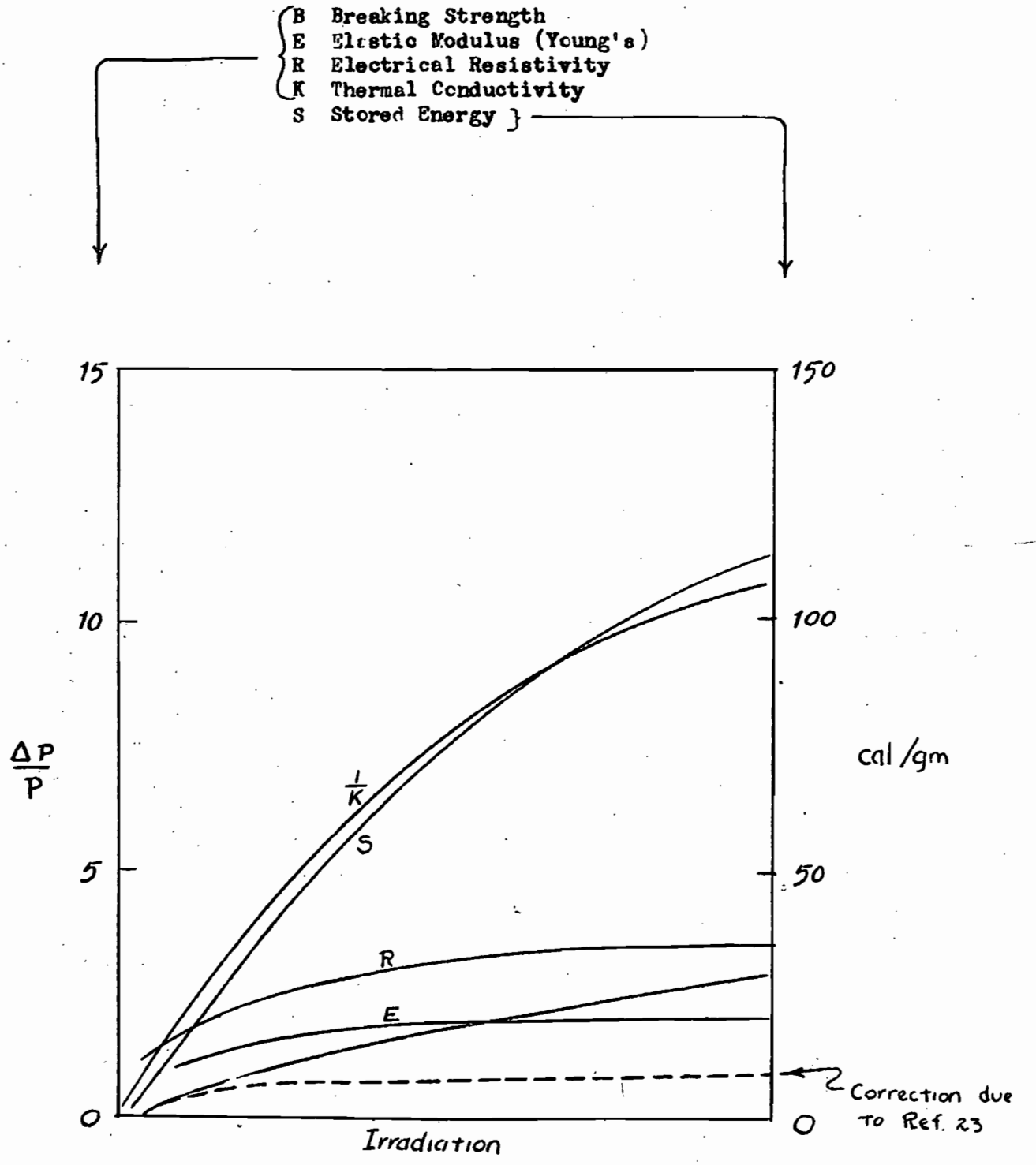

Figure 1

[redacted]

times its initial value. At start of irradiation[24], $\Delta B/B_o \simeq 0.05/L$.

The energy (S) stored in graphite, as a result of neutron collisions causing dislocation of carbon atoms from their crystal lattice positions, has been measured both by the increased heat of combustion and by the reduced apparent specific heat (Sykes method). The apparent specific heat is reduced by the releasing of stored energy in the sample as it is heated. The heat of combustion method gives the upper limit of energy releasable, and the specific heat method gives for various temperatures the amounts of heat which can be released during temperature rises in a graphite pile. As with other properties, heating also reduces the energy stored; e.g., 1000° C heating leaves 15% residual[25], yet minimum residuals attainable became greater[7] with longer exposures. Therefore it is feared that a sudden rise in pile graphite temperature might release large quantities of heat with a thermal explosion. The relative specific heat and the combustion methods show that samples irradiated at Hanford have had stored energies respectively as high as 400 cal/gm[26] and 150 cal/gm[27] (excess over the normal 7900 cal/gm heat of combustion for graphite); if the 400 cal/gm were released completely and adiabatically there could result a 1200° C temperature rise. Seitz and Wheeler have considered this problem of instability theoretically and conclude[28] that such a thermal explosion is highly improbable. Attempts to initiate[29,30,31] a self-propagating thermal wave in high S graphite have not been successful.

Up to irradiations of 400 Mwd/ct* at Hanford empirical formulas for S show[26] a saturating rise up to 300-400 cal/gm (by the relative

---

* For Units and Standards see Appendix A.

specific heat method) with a "time constant" in the exponential term of 100 Mwd/ct. For irradiations over 400 Mwd/ct there is evidence of a slight decrease in the Sykes stored energy, and X-ray evidence of the graphite becoming more amorphous. Despite this behavior the total stored energy (by heat of combustion) continues to increase. Continued pressure on high S graphite was not observed[32] to release stored energy.

Electrical resistivity, R, behaves very like E on neutron irradiation, starting off[20,23] with $\Delta R/R_o \simeq 0.25/L$. It levels off at approximately 5 to 6 times its original value[17,11,34]. It differs from E, however, in that the longer the exposure the less recovery is possible by heating to 1000° C, even though the un-heat-treated graphite levels off[35] to constant R in continued exposure. Its temperature rate of recovery is faster than that of E at the lower temperatures of annealing, yet it doesn't recover[7,29] nearly so completely as E. Like E, heating during irradiation is equally as effective[19,36] as subsequent heating in reducing the induced excess R. An irradiated sample heated to 2000° C shows the usual reduction in excess R, levels off at about 1.5 times its normal value from 500 to 1200° C, rises[37] to 2 times normal at 1400° C and drops to about 1.01 times normal at 1800° C. This is interpreted as due to the migrating of lattice "holes" to form extensive networks of holes or "micro-cracks" (causing the high resistivity at 1400° C) followed by elimination of these "micro-cracks" at higher temperatures. This effect was observed in a slightly irradiated sample, but not in highly irradiated samples[7].

Thermal resistivity, 1/K, starts rising under irradiation approximately twice as fast as R[20,33]. Hence $\Delta 1/K//1/K_o \simeq 0.50/L$. It changes more than R under irradiation, and yet it recovers more completely[37,29,38] under heating up to 1000° C. Heating concurrent with irradiation

makes[36] the induced change smaller. No test is reported of restoring thermal resistivity by heating up to 2000° C as with R, yet a similar hump in the curve may be expected. Unlike R, 1/K continues to rise with exposure, with only slight tendency to level off. Its rise is represented by an empirical formula showing the superposition of a linear component, increasing by the original resistivity every 50 Mwd/ct, and a saturating component leveling off at about 13 times the original resistivity with a "time constant" of about 100 Mwd/ct. Highest increase in thermal resistivity reported[11,34,39] is 30 to 35.

It is seen from the above that some of the effects are considered relatively "curable" by heat (such as E or K); perhaps these effects are due to the trapped atoms, which can be removed by heating. Some effects are considered relatively "incurable" (such as S or R, when the heat-treating is limited to 1000° C or less), and perhaps these are due to the holes themselves, which are not removed by heating. It is interesting in this connection that intense α- radiation was found[40] to cause internal "carbon spots" in diamonds which are visible to the naked eye and located deeper in the diamond than the range of the alphas. They are removable by heating and cooling cycles. Perhaps the C-atoms in diamonds are knocked out of position by fast alphas and migrate in to form such "spots", later to be removed by migrating to the surface under heating.

X-ray studies of the exposed graphite have revealed that 1250° C is required to remove all trapped C-atoms from between the layers of the highest-exposed graphite "available"[41]; 1000° C is not sufficient. Also it is found that lattice distortion has resulted from exposure, and remains[42] even after 1000° C. The number of trapped C-atoms was observed to be 2.8% in such a sample. A crystal phase change upon irradiation has

been looked for and thought not to take place, and no detectable change took place[43] in the crystal periodicity, or lack of it. However, the following were observed: a substantial increase in one period, A_3, a smaller decrease in another, and blistering of the C-layers, yet there was no rupture nor large scale dislocation[44] in the crystallites. In connection with the increase in the A_3 period[45] it is significant that expansion[11,30,31,32,38,46,47] of the graphite under irradiation has been found as large as 2.5%[31] perpendicular to the axis of extrusion, and less than 0.025%[46] parallel the axis; furthermore, this expansion is linear with exposure as far as it has been observed. The roof of a Hanford pile rises approximately 0.1 inch per month, and the expansion is greatest in the vertical central plane, thus causing bulging of the graphite cube. Heating the graphite at 1000° C leaves a residual of only 6% of the change. Prolonged high temperature annealing of irradiated graphite produced[36] a crumbling specimen, whereas unirradiated graphite remained stable.

Other properties which have been observed after exposure are: the energy decrement (measure of internal friction), which was found[18] to have decreased, though it is recoverable by heating; the specific heat[48], which was practically unchanged (less than 3%), except around 20° K where it may increase slightly (in the direction of amorphous carbon); the Hall effect coefficient, which is found[49] to be more positive, though it too is recoverable by heating. Graphite hardens[50] under irradiation, but there is no change in the coefficient of friction on aluminum.

[redacted]

B. Beryllium. No significant change in electrical conductivity[51] has been observed under fast neutron bombardment.

C. Beryllium Oxide. Beryllium oxide samples have been exposed to W pile radiation for 24 day and 63 day periods. Cracking was apparent in the samples and thermal conductivity was reduced[14] to 80% after 24 days and 70% after 63 days. Annealing in vacuo at 900° C restored the original conductivity. Crushing strength was doubled[15] after 24 days and no further change was found up to 63 days.

D. Water and Heavy Water[52]. Hydrogen gas (or deuterium gas), and peroxide are produced[53] in water under intensely ionizing radiations.

A considerable amount of work was done on the subject of radiation effects upon chromate ion added[54] to Hanford cooling water. The aluminum tubes and slug jackets at Hanford needed protection from excessive film formation under the action of the cooling water. Sodium silicate and sodium dichromate were added to the water as inhibitors; yet it was known[55] that Cr^{VI} is reduced to the film-forming Cr^{III} under ionizing radiation, and therefore the exact behavior of the treated water under simulated pile conditions was investigated. The chromate reduction is retarded by high pH, high temperature, and high radiation intensity (perhaps[56] because of the higher intensity accelerating the oxidation of Cr^{III} back to Cr^{VI}). The effect was finally[57] not serious in the Hanford piles, and it was permissible to control the pH at as low a level as 6.5, which level is the best from the point of view of retarding Al corrosion.

Peroxide was thought at one time to accelerate corrosion of metals, but this has not been clearly established[7,58]. The rate of production of peroxide has been studied[59] in a low power pile (100 to 1500 KW) and

found to be linear within that range. Extrapolation of the results to a W pile (250,000 KW) gives 1.2×10^{-5} mols/liter, and if the water is deaerated first, the figure is half as large. The W pile water in question is the cooling water which flows continuously through the cooling tubes, and the peroxide concentration is that which would be measured in the exit flow.

D_2 gas evolution[60] from P-9 has been measured at Argonne at 300 KW. It was 16.8 std cm^3/sec at 20° C. The total amount of P-9 is approximately $4\frac{1}{2}$ tons. Water sealed in ampoules and irradiated in the X pile has shown[61] a gassing and peroxide forming characteristic that approaches equilibrium at a few mm Hg pressure. This equilibrium pressure increases rapidly with impurities and dissolved salts.

Palladium and palladium coated carbon have been tried[62] with some success as catalysts for the back reaction which would limit gassing and peroxide formation. This was done with Pu and U salts in solution in the X-pile at intensities of ~ 0.2 watt/cm^3. Loss of effectiveness of the catalyst by coagulation and sedimentation are notable obstacles to success.

P-9 taken from shipping drums and deaerated showed less decomposition[61] than the best purified water.

Nitrogen fixation is believed to take place[63] with a resulting slight acidity of the water which could be troublesome in corrosible pipes.

The pH of the P-9 moderator at Argonne was measured[64] as low as 4.52 after several months of operation. Acidity is reported[65] to be due to nitric acid.

Activity induced in water for a homogeneous pile has been studied[8].

[redacted]

3. Coolants

A. Gases. Under intense ionization gases have shown[66] chemical combination and decomposition, and in the case of the hydrocarbons there has been marked polymerization. Irradiation-induced chemical changes have been catalyzed by inert gases. The effects are generally proportional to the total amount of ionization.

B. Water. See 2. D. above.

C. Liquid Metals. Nothing to report. Perhaps nothing has been done. Little trouble is expected.

4. "Breeding" Materials.

A. Thorium. Nothing to report. Perhaps nothing has been done. Probably similar to uranium metal.

5. Shielding Materials.

A. Concrete. Not a great deal has been reported on concrete. Slight effects have been observed[67] after intense X-ray, electron, or neutron bombardment; water vapor is evolved, and the modulus of rupture is decreased approximately 20% (thought not serious in pile applications) by 10^{16} neutrons/cm^2 (maximum energy 18 Mev). This would be 10^8 nv for 10^8 sec or 3 years.

B. Cellulose-Base Materials[68]. Wood and wood products[69] (e.g. masonite) have relatively low ion pair yield ~0.2 gas molecules formed per ion pair.

Masonite (HD 128) samples exposed to pile radiation equivalent to normal intensity in the Hanford shield for 20 years suffered[70] the following changes:

(a) Gas liberated at the rate of 2.55 std cm^3/gm-day for 3 days, largely H_2, CO_2, and CO.

(b) Weight changed - (minus) 5%.

(c) Length changed - 1.7%.

(d) Rupture modulus (parallel the laminations) changed - 97.%.

(e) Tensile strength (parallel the laminations) changed - 88.%.

C. Heavy Elements. Pure elements are not affected in any way to cause gross property changes. Compounds will suffer the decomposition which strong ionization causes. There is no evidence that iron, lead, bismuth, or barium (to name a few) are susceptible to neutron, beta, and gamma induced ills.

D. Water. See 2.D. above.

6. Auxiliary Materials

A. Structural Materials.

(a) Aluminum - 2S Aluminum has been tested[71] for change in tensile and crushing strengths, hardness, elastic modulus (Young's), ductility, and electrical resistivity upon exposures to pile radiation, and there were no detectable changes.

(b) Iron and Steel - Iron is reported[72] as being "one of the few materials which corrode (in contact with water) more under radiation conditions than under ordinary corrosive conditions". There is no report of any thoroughgoing test of iron and the steels, yet, as with other metals, there is little reason to expect serious effects.

(c) Concrete - See 5.A. above.

(d) Wood - See 5.B. above.

B. Lubricants and Hydraulic Fluids.

(a) Petroleum Products - Deuteron, beta, and gamma radiation effects on lube oils have been observed[73]. All have the same general effect of increasing:

[redacted]

 [redacted]

i Viscosity
ii Iodine Number
iii Acid Content
iv Refractive Index
v Density

For instance, deuterons on Phillips SAE 20W lube oil (at 8.8 watt hrs/cm^3, the equivalent of approximately 55. years in the application of this oil at W) changed the viscosity from 1.380 to 4.253 poise and the iodine number from 0.0 to 17.46 (gms I_2 required to react completely with unsaturated compounds in 100 gm oil). Density and viscosity increases under gamma radiation have been observed(74) in hydraulic fluids also.

C. Electrical Insulators.

(a) Plastics(75) - Under approximately 10^7 roentgens of x-rays or electrons resistivity may be decreased(76) by several orders of magnitude. The effect is only temporary, however, and the original resistivity is restored almost completely upon standing clear of radiation. The temporary loss of resistivity, however, condemns many plastics for use as insulators. The following table shows the specific materials which have been tested under intense x-radiation and also indicates the relatively good materials.

The rate as well as the total amount of radiation determines the resultant changes in the properties. In general, those plastics which can be used over a wide thermal range are more stable under irradiation. The more the impurities added (filler, plasticizer, etc.) in making a plastic the greater the loss in resistivity under radiation.

[redacted]

TABLE I.

TABLE OF COMMON PLASTICS TESTED UNDER RADIATION.

		A-3201	(polyethylene)
		HF-41	(polyethylene)
*		Amphenol	(polystyrene)
		D-29	(poly TFE)
		Various Koroseals	(polyvinyl chloride)
		Lucite	(polymethylmethacrylate)
*		Halowax V5901	(polychlorinated naphthalenes)
*	#	Neoprene	
*	#	Natural Rubber	
		Saran	(copolymer of vinyl chloride and vinylidene chloride)
*	#	Vinylite Red	
		Vinylite V5900 and other vinylites	(copolymers of vinyl chloride and vinyl acetate)

* Means resistivity changed very little under intense radiation by x-rays.

\# Means tensile strength changed very little under intense radiation by x-rays.

Note:

Silicone impregnated glass fibre, cloth, and tape, also Sprague's inorganic CEROC have been tested at Argonne, and incomplete results were that they were good insulation under continued radiation.(48)

[redacted]

(b) Glass and Quartz - Under intensely ionizing radiations these usually excellent insulators lose[78] resistivity. Heating restores the loss. This loss is well-known to x-ray workers. Glass strength changes[79] slightly under radiation. Glass or quartz in a high electric field will actually break down internally and make a direct short after extended irradiation. However, this deterioration is slow, and glass and fused quartz still remain among the best practical insulators for use in intense radiations. Under intense ionizing irradiation fused quartz was found[80] to become brittle and crack; glass devitrified, and became brittle and difficult to work.

(c) Porcelain - Nothing reported as to its electrical properties. Coloration, as in glass, under ionizing radiations is reported[81]. Seems likely to be good, perhaps not as good as glass or fused quartz.

(d) Mica - Mica sheets under strong ionizing radiations were found[80] bent, and similar effects were observed in the crystal.

Note: Sulfur has been suggested as a likely-to-be-stable and good insulator.

D. Miscellaneous Materials.

(a) Elastomers and Plastics[82] - Under intense and prolonged x-radiation (10^7 r) elastomers and plastics suffer changes[83]:

i Tensile strength is decreased somewhat, but in most cases not enough to limit the use of the material. See the table above in Section 6.C. for listing -- see #

ii Hardness is increased and elasticity of elastomers is decreased noticeably. The magnitudes of these changes are large enough to be serious.

iii The transparent resins suffer coloration; thus their use in optical equipment is limited. Lucite CR-39 (an allyl resin) and 3830 (a methacrylate resin) were almost completely opaque after 10^7 r, x- or electron-radiation.

(b) Optical Materials - See 6. D. (a) iii above. Glass and quartz suffer[78,80] coloration gradually under γ and x-irradiation, turning a dark reddish brown, yellow, violet, or black, depending on composition and impurities.

(c) Permanent Magnets - Intense (10^8 r) gamma radiation did not appreciably affect[84] an Alnico V permanent magnet. Effect was less than 1% in the field strength.

(d) Textiles - A canvas tarpaulin removed from the X-pile where it had been exposed for several months to a flux of approximately 10^8 nv (thermal) was found to have suffered marked deterioration of fibre strength

(e) α - Detonation of $N_2H_3I_3$ - $N_2H_3I_3$ was exploded[80] when a strong source of α rays was brought near it. The effect was sought but not found with several common explosives.

* * * * * * * * * * * * * * * * *

Acknowledgment

The assistance of Drs. F. Seitz and A. O. Allen, who read the manuscript and contributed towards the clarification of some of the results reported, is gratefully acknowledged.

APPENDIX

UNITS AND STANDARDS OF IRRADIATION

Units and standards of irradiation are in an unsatisfactory state. The ionizing radiations can perhaps be satisfactorily measured in terms of r-units, but a really significant unit of neutron radiation (or more generally "pile radiation") has not been established in the field of radiation-induced effects in materials. In the literature two units are encountered. One is the L (or "Loki", presumably for the Norse god of discord and mischief). One L is defined[20] as the "amount of exposure required to produce at 35° C a 25% increase in the elastic modulus (generally understood to be the Young's modulus) of previously unexposed average AGOT-F graphite." One L corresponds to approximately 1.2 Mwd in the maximum position in the thimble at Argonne, 6 Mwd in the X-pile doughnuts, hole 1867, or 40 Mwd in the W-pile, at the center of the pile adjacent to the tube. This unit is not generally acceptable since it has not been shown nor is it necessarily true that the amounts of "pile radiation" in two different piles, for instance, would cause equal changes in another property; i.e., there is likely to be an energy-spectrum dependence, and all piles have different spectra. This unit does have the attractive feature of relatively easy standardization by a simple test at any pile-site.

The other unit is the Hanford Mwd/ct (megawatt-day per central ton). Since we know that for any thermal pile the power per unit mass of fissionable material per unit thermal flux is a constant (approximately 5×10^{-11} watts/gm(25) /nv_{th}), the unit Mwd/ct is seen to be proportional to the time integral of the flux, or the total number of thermal neutrons

[redacted]

APPENDIX

which passed through unit area during the exposure. The unit is significant at Hanford exclusively, and therefore it is of practically no use generally. One Mwd/ct at Hanford is effectively somewhere between 0 and 10 L-units; perhaps 3 L-units*; yet the correlation of these units is not found in the literature.

A good unit can best be established by an experimental study of the physical factors involved in producing the property changes. The dependence of any property change upon the physical factors responsible could then be formulated in an empirical equation. Perhaps, for example, the fractional change in any property could be expressed as a function of a characteristic constant for that property and the temperature, exposure time, and neutron flux as measured at a few measurable neutron energies. Then the unit to choose would be the neutron flux itself. If this should prove possible, the necessity of inventing a new unit would be obviated by acquiring a more complete knowledge of the phenomenon.

---

* Note:

$$1\left(\frac{\text{mwd}}{\text{ct}}\right)_w = 1\left(\frac{\text{mwd}}{\text{ct}}\right)_w \times \frac{250 \text{ tons total}}{2.2 \text{ tons total}/(\text{ct})_w} = \frac{250}{2.2}(\text{mwd})_w$$

$$= \frac{6.2}{2.2}(40 \text{ mwd})_w \simeq 3 \text{ L.}$$

References

(1) CC-446.
(2) Lind, S.C.,"The Chemical Effects of Alpha Particles and Electrons", ACS Monograph Series, The Chemical Catalog Company (1928).
(3) CC-418; CL-606.
(4) Seitz, F., Rev. Mod. Phys. 18, 384 (1946) "Color Centers in Alkali Halide Crystals".
(5) Collin and Badger, Phys. Rev. 70, 437 (1946)
(6) Lind, S.C., Joun. Chem. Phys. 7, 790 (1939), which paper reviews and discusses the conflict in theories; Eyring, Hirschfelder, Taylor, Jour. Chem. Phys. 4, 479 (1936).
(7) Allen, A. O., Clinton Laboratories
(8) CP-1851; CP-1355; Mon E-64.
(9) HEW Technical Progress Letters.
(10) CP-1598; CP-1592 pp 44-47; CP-1661; CC-1925; CC-3069; CC-258 p.12; LAMS-167, Seitz in CP-2611.
(11) HEW Technical Progress Letters #82, 85, 83, 84, 81, 78, 76, 71.
(12) MUC-GTS - 1882.
(13) Seitz, F.
(14) Karp, J. at General Information Meeting, Clinton Laboratories, October 14-16, 1946.
(15) Gaarder , S. at General Information Meeting, Clinton Laboratories, October 14-16, 1946.
(16) CS-2745 (graph p. 13).
(17) CS-2745.
(18) CC-3162; CC-1668.
(19) CC-2758; CC-1669.
(20) CC-2320; CC-1667.
(21) CC-3193; CC-2656.
(22) CC-1925.
(23) HEW Technical Progress Letters #71, 72, 79.
(24) CC-2320; CC-3193.
(25) CS-3025.
(26) HEW Technical Progress Letters #69, 80, 84.
(27) CS-3072.
(28) CP-2704; Hanford report by J. A. Wheeler, fall of 1945.
(29) HEW Technical Progress Letter #105.
(30) HEW Technical Progress Letter #107.
(31) HEW Technical Progress Letter #106.
(32) HEW Technical Progress Letter #89.
(33) HEW Technical Progress Letter #93.
(34) HEW Technical Progress Letter #100.
(35) CS-2886, HEW Technical Progress Letter #103.
(36) HEW Technical Progress Letter #90.
(37) CC-2931, p.24.
(38) HEW Technical Progress Letter #99.
(39) HEW Technical Progress Letter #103.
(40) Lind, "The Chemical Effects of Alpha Particles and Electrons", (1928) p. 63.

[redacted]

(41) CP-3497.
(42) CP-3344.
(43) CC-3109.
(44) CP-3010.
(45) HEW Technical Progress Letters #79, 84, 85, 87, 103.
(46) HEW Technical Progress Letter #81.
(47) HEW Technical Progress Letter #92.
(48) CC-3161, HEW Technical Progress Letter #65.
(49) CP-2890.
(50) HEW Technical Progress Letter #80.
(51) CC-2319.
(52) In addition to references 33 through 40, see Mon-N Reports #161, 111, 103, 84, 72, 57, 45, 31, 15, 6, 2; Lind, especially pp. 100-103; and p.111; CC-2233.
(53) CS-3072; CS-2672; Mon-N 26, p.22; Mon-S 124, p.35.
(54) CC-2233; CC-2127; CC-2099; CC-1966; CS-1836; CC-1746.
(55) Fricke, J. Am. Chem. Soc. 55, 2358 (1933); CN-467.
(56) CC-1966.
(57) HEW Technical Manual, p.1016.
(58) CC-1677; CC-1321.
(59) CC-1310, p.2.
(60) CC-2613.
(61) Mon-N 131.
(62) CN-2819, p.20; Mon-N 27.
(63) Mon-N 150; Mon-N 131.
(64) CS-2793.
(65) CC-3412.
(66) Lind, pp. 100-103; Eyring, Hirschfelder, Taylor, Jour. Chem. Phys. 4, 570 (1936); Hirschfelder, Taylor, Jour. Chem. Phys. 6, 783 (1938).
(67) CC-1666, p.7; Rough Draft PPR, XA, Chap. X (A. Miller).
(68) In addition to references 43 through 44, see CC-648, CC-784, CC-733, CC-841, CC-967, CC-1195; Rough Draft PPR, XA, Chap. X (A. Miller).
(69) CL-606; CC-1925.
(70) HEW Technical Progress Letter #64.
(71) HEW Technical Progress Letter #73; CC-1925; CC-841; CT-750; CC-2319.
(72) CC-1925; CC-1677.
(73) CC-1139; CC-784; CC-520; CC-418; CC-389; CA-265; Rough Draft PPR, XB, 4.1 (A. Miller).
(74) CC-1139.
(75) Rough Draft PPR, XA, Chap. X (A. Miller).
(76) Farmer, F. T., Nature 150, 521 (1942); CC-648; CC-577; CC-520; CC-1097.
(77) Verbal report by K. O. Donelian (Kellex).
(78) CC-1925; CC-1139; CC-1109.
(79) CC-1320.
(80) Rutherford, Chadwick and Ellis "Radiations from Radioactive Substances", (1930), p.186.
(81) Lind, S.C., "The Chemical Effects of Alpha Particles and Electrons", (1928) p.51.
(82) Rough Draft PPR, XA, Chap. X (A. Miller).
(83) CC-1097; CC-1925; CC-1139; CC-841; CC-733; CC-648; CC-577; CC-520.
(84) CS-1658.

[redacted]

[redacted]

3012

ATOMIC ENERGY COMMISSION
RECEIVED
MAY 14 1946
DOCUMENT ROOM
WASHINGTON, D. C.