873. *Effects of γ-Radiation. Part VI.* Action of γ-Radiation on Deaerated Solutions of Ethylene Glycol.*

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The non-volatile products formed by γ-irradiation of ethylene glycol in 0·1% aqueous solution have been determined quantitatively by isotope dilution analysis. The primary products are glycollaldehyde, erythritol, and threitol. Glycollic acid, glyoxylic acid, glyoxal, and oxalic acid are formed by secondary processes. The nature and quantities of the products indicate that dimerisation of the $HO{\cdot}CH_2{\cdot}CH(OH){\cdot}$ radical initially produced is less favoured than degradation involving species derived from the solvent. The overall degradation of ethylene glycol is small.

Although much information is available in the literature on the effects of ionising radiation on simple aliphatic alcohols, polyhydric alcohols do not appear to have been as fully investigated. The complex nature of the products formed on γ-irradiation of deaerated D-sorbitol solutions has been recently reported.[1] Oxidation of the hydroxymethyl groups of D-sorbitol occurs together with chain scission and dimerisation of radicals of the type ·CHR·OH, to produce a twelve-carbon alcohol. Dimerisation may be regarded as the initial step in polymer formation which occurs at high energy inputs. Difficulty here lies in identification and determination of the dimerised products. It was of interest therefore to examine the effects of γ-radiation on deaerated ethylene glycol solutions where the dimerised products (erythritol and threitol) can readily be identified and determined. This in turn might lead to a clearer understanding of the mechanism of polymer formation.

* Part V, *J.*, 1961, 4086.

[1] Phillips and Criddle, *J.*, 1961, 3763.

Results and Experimental

Preparation of [$^{14}C_2$]*Ethylene Glycol.*—Dimethyl [$^{14}C_2$]oxalate was prepared from [$^{14}C_2$]oxalic acid dihydrate (25·3 mg., 0·5 mc), diluted to 7·5 g. essentially by the method described by Chin and Adams [2] for ethyl [2-^{14}C]malonate.

Dimethyl [$^{14}C_2$]oxalate (8 g.) in dry ether (100 ml.) was added slowly to a stirred suspension of lithium aluminium hydride (8·2 g.) in dry ether (200 ml.). Then the solution was refluxed for 3 hr. and stirred overnight at room temperature. Water (300 ml.) was added dropwise to destroy the excess of reagent, the solution centrifuged, and the supernatant layer and the washings were concentrated to *ca.* 100 ml. Methanol (100 ml.) was added. Lithium carbonate was precipitated on addition of solid carbon dioxide. The supernatant layer, after centrifugation, was concentrated with intermediate filtration to remove deposited solids, and distilled at 190° with carrier ethylene glycol (0·5 ml.). The distillate (1·75 g.) was diluted to 4 g. and used in irradiations.

Irradiation Procedure.—Solutions (4 l.) were placed round a 200-c ^{60}Co γ-radiation source similar to that described by Gibson and Pearce.[3] The solutions were evacuated for 4 hr. at 0·3 mm. before irradiation, sealed, and stirred continuously during irradiation. The dose-rate throughout was $3·16 \times 10^{16}$ ev min.$^{-1}$ ml.$^{-1}$, determined by the ferrous ammonium sulphate dosimeter,[4] [$G(Fe^{2+} \longrightarrow Fe^{3+}) = 15·6$].

Chromatography of the Irradiated Solution.—A solution of ethylene glycol (4 g.) in water (4 l.) was evacuated and irradiated to a total energy input of $1·06 \times 10^{23}$ ev. The irradiated solution was freeze-dried and analysed by chromatography in butan-1-ol–ethanol–water (4 : 1 : 5); components were detected with alkaline silver nitrate,[5] Chlorophenol Red,[6] and 2,4-dinitrophenylhydrazine.[7] The chromatograms showed severe streaking but indicated the presence of glycollaldehyde, glycollic acid, and glyoxylic acid. Removal of aldehyde and acidic fragments by passage down Amberlite IRA-400 (OH^-) and Deacidite FF (CO_3^{2-} form) and electrophoresis of the concentrated eluates in molybdate [8] and arsenite buffers [9] revealed components indistinguishable from erythritol and threitol. Chromatography in butan-1-ol–acetic acid–water (4 : 1 : 5) revealed a component(s) of corresponding mobility to the tetritols.

Determination of Products by Isotope Dilution Analysis.—A solution (4 l.) of [$^{14}C_2$]ethylene-glycol (64·5 millimoles, spec. activity 0·79 μc/millimole) was irradiated *in vacuo* to a total energy input of $5·3 \times 10^{22}$ ev. The individual products were determined by applying the isotope dilution method directly to aliquot parts of the untreated irradiated solution.

In preliminary experiments the derivatives prepared from glycollic and glyoxylic acid were heavily contaminated with ethylene glycol and this resulted in abnormally high counts, but adsorption of the acids on Deacidite FF (CO_3^{2-} form) followed by elution with water removed the glycol. Thereafter the acids were recovered from the resin by elution with 2N-ammonium carbonate. Glyoxal and glycollaldehyde were both determined as glyoxal bisphenylhydrazone. The total amount of glycollaldehyde and glyoxal was obtained by formation of the bisphenylhydrazone at the b. p. The amount of glyoxal was then found by formation of the bisphenylhydrazone at room temperature, where glycollaldehyde does not react.

Materials containing carbon-14 were assayed by gas-counting, with a standard mixture of carbon dioxide and carbon disulphide as the filling for a Geiger counter.[10] Amounts sufficient to give about 44 mg. of carbon dioxide, were oxidised in a steam of oxygen in a standard dry combustion train. The gaseous products were passed through granulated manganese dioxide, to decompose oxides of nitrogen, and then through a trap cooled in liquid oxygen. The resulting carbon dioxide was then transferred to the vacuum-line used for filling of the counter. Oxides of nitrogen can interfere with the functioning of Geiger counters,[11] and so the carbon dioxide derived from specimens rich in nitrogen was treated with hot copper gauze on the vacuum-line.

[2] Chin and Adams, *Nuclear Sci. Abs.*, 1954, **8**, 1057.
[3] Gibson and Pearce, *Chem. and Ind.*, 1957, 613.
[4] Hardwick, *Canad. J. Chem.*, 1952, **30**, 17; Donaldson and Miller, *J. Chim. Phys.*, 1955, **52**, 578.
[5] Trevelyan, Procter, and Harrison, *Nature*, 1950, **166**, 444.
[6] Brown, *Nature*, 1951, **167**, 441.
[7] Forsyth, *Nature*, 1948, **161**, 239.
[8] Bourne, Hutson, and Weigel, *J.*, 1960, 4252.
[9] Frahn and Mills, *Austral. J. Chem.*, 1959, **12**, 65.
[10] Bevington, Guzman, and Melville, *Proc. Royal Soc.*, 1954, *A*, **221**, 437.
[11] Glascock, "Isotopic Gas Analysis for Biochemists," Academic Press Inc., New York, 1954, p. 109,

For each filling of the counter, the plateau was plotted, and routine counting was performed at a voltage corresponding to the middle of the plateau. Observed counting rates were corrected for lost counts and background. Standard ^{14}C-labelled substances were used to calibrate the counter; a specific activity of 1 μc per mg. of carbon dioxide corresponded to 2×10^5 counts per minute.

The results of a typical determination are next given.

(*a*) *Ethylene glycol.* To an aliquot part (380 ml.) of the irradiated solution was added redistilled ethylene glycol (20 g., 323 mmoles), and the solution was freeze-dried. A portion (0·5 g.) of the residue was refluxed for 10 min. with *p*-nitrobenzoyl chloride (3 g.) in pyridine (10 ml.), and the dinitrobenzoate was precipitated on addition of water to the cooled solution. The product was collected, washed with cold dilute sodium hydroxide solution and water, dried, and, after five recrystallisations from ethanol, had m. p. 140°, constant specific activity $1·53 \times 10^{-2}$ μc/mmole.

(*b*) *Erythritol.* The irradiated solution (380 ml.) with carrier erythritol (4·09 mmoles) was freeze-dried. The material remaining after six recrystallisations from ethanol had m. p. 120° and constant specific activity $7·04 \times 10^{-4}$ μc/mmole.

(*c*) *Threitol.* The irradiated solution (380 ml.) with carrier L-threitol (4·09 mmoles) was freeze-dried; the material remaining after six recrystallisations from ethanol had m. p. 88° and constant specific activity $4·42 \times 10^{-4}$ μc/mmole.

(*d*) *Glycollaldehyde.* The irradiated solution (380 ml.) was boiled with phenylhydrazine (5 ml.), acetic acid (3·2 ml.), and carrier glycollaldehyde (10·0 mmoles) for 45 min. The derivative was filtered off and after five recrystallisations from benzene gave glyoxal bisphenylhydrazone, having m. p. 170° and constant specific activity $1·96 \times 10^{-3}$ μc/mmole.

(*e*) *Glyoxal.* The irradiated solution (380 ml.) was treated with phenylhydrazine (2·5 ml.), acetic acid (1·7 ml.), and carrier glyoxal (8·62 mmoles) overnight at room temperature. The bisphenylhydrazone was filtered off and after four recrystallisations from benzene gave glyoxal bisphenylhydrazone, m. p. 170°, constant specific activity $3·18 \times 10^{-4}$ μc/mmole.

(*f*) *Glycollic acid.* The irradiated solution (380 ml.) with carrier glycollic acid (9·21 mmoles) was stirred with Deacidite FF (CO_3^{2-} form), packed into a column, and washed with water (100 ml.). The acid was eluted with 2N-ammonium carbonate (30 ml.), and the cations were removed by passage down Amberlite IR-120 (H^+). The eluate and washings were neutralised with 2N-sodium hydroxide, and the residue, after freeze-drying, was boiled with *o*-phenylenediamine (0·7 g.) in 4N-hydrochloric acid (8 ml.) for 15 min. The benzimidazole derivative that separated on treatment of the cooled solution with concentrated ammonia solution was filtered off and boiled with picric acid (0·7 g.) in ethanol (8 ml.). The picrate was filtered off and after three recrystallisations from ethanol had m. p. 214° and constant specific activity $4·67 \times 10^{-4}$ μc/mmole.

(*g*) *Glyoxylic acid.* The irradiated solution (380 ml.) with carrier glyoxylic acid hydrate (10·87 mmoles) was treated with Deacidite-FF (CO_3^{2-} form) and Amberlite IR-120 (H^+) as described for glycollic acid. The aqueous eluate was treated with a saturated solution of 2,4-dinitrophenylhydrazine in 2N-hydrochloric acid (1 l.) for 16 hr. at room temperature. The precipitate was filtered off and after four recrystallisations from ethanol had m. p. 195° and constant specific activity $2·13 \times 10^{-4}$ μc/mmole.

(*h*) *Oxalic acid.* The irradiated solution (380 ml.) with carrier oxalic acid dihydrate (7·93 mmoles) was neutralised with 2N-sodium hydroxide, and calcium oxalate was precipitated by addition of a saturated solution of calcium chloride. The dried precipitate was suspended in 2N-sulphuric acid (100 ml.) and continuously extracted with ether for 48 hr. The residue obtained on removal of the solvent was recrystallised three times from hot water and had m. p. 101° and constant specific activity $4·27 \times 10^{-5}$ μc/mmole.

The results of the isotope dilution analysis are tabulated.

Determination of Carbon Dioxide.—This was done by the method described by Grant and Ward.[12]

Determination of Formaldehyde.—Attempts to determine formaldehyde as described by Grant and Ward [12] by using chromotropic acid reagent were unsuccessful. The small amount of formaldehyde produced in our experiments did not lie on the linear portion of the calibration curve.

[12] Grant and Ward, *J.*, 1959, 2659.

Products from the irradiation of aqueous ethylene glycol *in vacuo*.

(*a*) Initial ethylene glycol 64·5 mmoles (spec. activity 0·794 μc/mmole). Energy input $5·3 \times 10^{22}$ ev (vol. 4 l.).

Product	$(CH_2·OH)_2$	Erythritol	L-Threitol	$HO·CH_2·CHO$
Carrier (mmoles)	323	4·09	4·09	10·0
Spec. activity (μc/mmole)	$1·53 \times 10^{-2}$	$7·04 \times 10^{-4}$	$4·42 \times 10^{-4}$	$1·96 \times 10^{-3}$
Yield (mmole)	63·8	0·0186	0·0117	0·253

Product	$HO·CH_2·CO_2H$	$(CHO)_2$	$OHC·CO_2H$	$(CO_2H)_2$
Carrier (mmoles)	9·21	8·62	10·87	7·93
Spec. activity (μc/mmole)	$4·67 \times 10^{-4}$	$3·18 \times 10^{-4}$	$2·13 \times 10^{-4}$	$4·27 \times 10^{-5}$
Yield (mmoles)	0·058	0·035	0·030	0·0044

CO_2, determined titrimetrically, 0·005 mmole.

(*b*) Initial ethylene glycol 64·5 mmoles (spec. activity 2·02 μc/mmole). Energy input $1·06 \times 10^{23}$ ev (vol. 4 l.).

Product	$(CH_2·OH)_2$	Erythritol	L-Threitol [a]	$HO·CH_2·CHO$
Carrier (mmoles)	323	4·92	4·92	10·0
Spec. activity (μc/mmole)	$3·62 \times 10^{-2}$	$1·87 \times 10^{-3}$	$5·33 \times 10^{-3}$	$7·63 \times 10^{-3}$
Yield (mmoles)	59·2	0·0237	0·066	0·331

Product	$(CHO)_2$	$OHC·CO_2H$ [b]	$(CO_2H)_2$
Carrier (mmoles)	8·62	10·87	7·93
Spec. activity (μc/mmole)	$1·12 \times 10^{-3}$	$6·17 \times 10^{-4}$	$2·13 \times 10^{-4}$
Yield (mmoles)	0·049	0·052	0·0087

[a] Did not attain constant specific activity. [b] Determined in 250 ml. portion. CO_2, determined titrimetrically, 0·01 mmole.

(*c*) Initial ethylene glycol 64·5 mmoles (spec. activity 0·8 μc/mmole). Energy input $1·59 \times 10^{23}$ ev (vol. 4 l.).

Product	$(CH_2·OH)_2$	Erythritol	L-Threitol	$HO·CH_2·CHO$
Carrier (mmoles)	323	4·92	4·92	10·0
Spec. activity (μc/mmole)	$1·43 \times 10^{-2}$	$1·04 \times 10^{-3}$	$6·70 \times 10^{-4}$	$3·45 \times 10^{-3}$
Yield (mmoles)	58·4	0·0328	0·021	0·374

Product	$HO·CH_2·CO_2H$	$(CHO)_2$	$OHC·CO_2H$	$(CO_2H)_2$
Carrier (mmoles)	9·21	8·62	10·87	7·93
Spec. activity (μc/mmole)	$1·40 \times 10^{-3}$	$5·6 \times 10^{-4}$	$6·3 \times 10^{-4}$	$6·25 \times 10^{-5}$
Yield (mmoles)	0·162	0·061	0·086	0·0069

Discussion

Information in the literature on the radiolysis of dilute aqueous solutions suggests that chemical changes are very largely initiated by the reactive species produced during primary radiolysis of water. The nature of the products obtained on the irradiation of solutions of aliphatic alcohols,[13] sorbitol,[1] and hexoses [14] indicates that the $CH_2·OH$ grouping is susceptible to attack by hydrogen atoms and hydroxyl radicals. Primary abstraction of hydrogen from ethylene glycol by these reactive species would furnish the radical $·CH(OH)·CH_2·OH$, which would undergo degradation.

Glycol formation resulting from dimerisation of radicals of the type ·CHR·OH has been observed on irradiation of primary aliphatic alcohols.[13] Dimerisation of $·CH(OH)·CH_2·OH$ similarly yields a mixture of erythritol and DL-threitol. From stereochemical considerations erythritol and threitol would be expected to be formed in approximately equal amounts. L-Threitol only was used as inert carrier in our experiments and this accounts for the differences observed between the yields of the two tetritols (Table). The small amounts of erythritol and threitol produced in our experiments confirm the view that radicals ·CHR·OH can dimerise under suitable conditions. However, the total yield of dimerised product is considerably less than those reported for

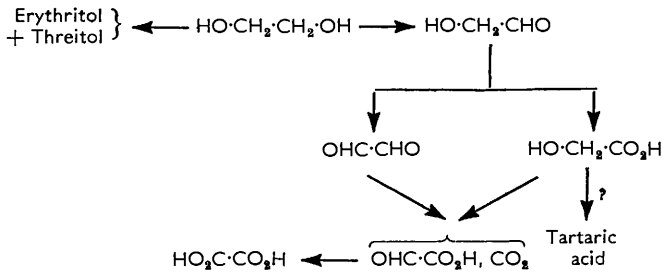
[13] Garrison, *Ann. Rev. Phys. Chem.*, 1957, **8**, 129; Jayson, Scholes, and Weiss, *J.*, 1957, 1358.
[14] Grant and Ward, *J.*, 1959, 2871; Phillips, *Nature*, 1954, **173**, 1044; Phillips, Moody, and Mattok, *J.*, 1958, 3522; Phillips and Criddle, *J.*, 1960, 3404.

the dimerisation of similar radicals. Under comparable conditions glycollic acid [12,15] is principally degraded by dimerisation of the initial radical $\cdot CH(OH)\cdot CO_2H$ to tartaric acid. Primary aliphatic alcohols also yield glycols in substantial amounts.[13] Phillips and Criddle [1] recently suggested that radicals $\cdot CHR\cdot OH$ derived from D-sorbitol dimerise to yield the twelve-carbon alcohol. The higher yield of dimerised product obtained by these workers may be due in part to the higher concentration of solute used.

Degradation processes involving $\cdot CH(OH)\cdot CH_2\cdot OH$ radicals, rather than dimerisation, appear to predominate under our conditions and probably involve the action of the organic radicals with molecular hydrogen peroxide originating from water. Glycollaldehyde is formed with initial $G \sim 0{\cdot}3$. This value is again somewhat lower than those reported for the transformation $R\cdot CH_2\cdot OH \longrightarrow R\cdot CHO$ in irradiated solutions of D-sorbitol [1] (G 1·4) and primary aliphatic alcohols.[13] Glycollic acid, glyoxal, glyoxylic acid, and oxalic acid are then formed by secondary degradation of glycollaldehyde. The higher yield of glycollic acid than of glyoxal (Table) is also to be expected, since on irradiation *in vacuo*, D-glucose is oxidised preferentially at the reducing end and to a smaller degree at the hydroxyl group adjacent to the reducing end group.[14] The conversion $R\cdot CH_2\cdot OH \longrightarrow R\cdot CO_2H$ has not been observed to any appreciable extent in evacuated solutions,[1] so that direct conversion of ethylene glycol into glycollic acid is unlikely. Thus glycollic acid must arise indirectly through glycollaldehyde.

Glyoxylic and oxalic acid were also detected by isotope dilution analysis and probably result from further degradation involving glyoxal and glycollic acid. Grant and Ward [12,15] have shown that glycollic acid is degraded in deaerated solutions to glyoxylic acid and oxalic acid; tartaric acid is also formed from glycollic acid under these conditions but was not sought by us. Phillips and Criddle [1] attribute the presence of oxalic acid in γ-irradiated D-sorbitol solutions to oxidation of the two-carbon aldehyde fragments (principally glycollaldehyde and glyoxal) produced by chain fission.

The above observations are compatible with the mechanism illustrated.



The amount of degradation caused by γ-irradiation of deaerated ethylene glycol solutions is less than that observed for glycollic acid,[12,15] carbohydrates,[14] and D-sorbitol solutions.[1] Approximately 10% of the glycol is destroyed after total energy inputs of $1{\cdot}59 \times 10^{23}$ ev. Certain reservations must be placed on this figure since some ethylene glycol may be lost during evacuation procedures and thus result in reduced recovery of ethylene glycol in isotope dilution assay.

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[15] Grant and Ward, *J.*, 1959, 2654.