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RATES OF CO_2 PRODUCTION FROM THE MICROBIAL DEGRADATION OF TRANSURANIC WASTES UNDER SIMULATED GEOLOGIC ISOLATION CONDITIONS

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ABSTRACT

Transuranic wastes containing organic matter can serve as an energy source for microbial growth. The rates of microbial respiration during decomposition of several transuranic-contaminated waste materials were measured under environmental conditions representative of a geologic waste repository in bedded salt. The major observed effect of microbial activity on organic-matrix wastes was the generation of CO_2 gas. Experimental variables studied include: incubation temperature (25^o to 70^oC), atmosphere (aerobic and anaerobic), moisture content, brine content, and plutonium contamination level (0 to 40 microcuries of alpha activity per gram of waste). The maximum rate of CO_2 generation observed was 11 g/day per gram of waste. The addition of 300 μg (20 μCi) of defense-grade PuO_2 per gram of waste reduced the rate of CO_2 generation by approximately 70 %. Results indicate that microbial activity in existing drums of defense-related transuranic wastes has the potential to generate significant quantities of gas under both aerobic and anaerobic conditions. Carbon dioxide was the only gas detected in these studies. No evidence was found for the conversion of europium, thorium, or plutonium to volatile gas species via microbial alkylation reactions such as those known to alkylate mercury and lead.

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RATES OF CO_2 PRODUCTION FROM THE MICROBIAL DEGRADATION OF TRANSURANIC WASTES UNDER SIMULATED GEOLOGIC ISOLATION CONDITIONS

INTRODUCTION

Transuranic-contaminated (TRU) wastes to be stored in the WIPP facility can consist of many materials (matrices) including cellulosics, rubbers, plastics, as well as metals, glasses, sludges, and, quite possibly, residual chelating chemicals from prior waste decontamination operations. The majority of such wastes will be contained in 55 gallon (200 L) steel drums or in fiberglass-reinforced, polyester-coated plywood boxes. The TRU wastes are contaminated with small amounts of plutonium, americium, plus, to a smaller extent, other radionuclides. The presence of microorganisms in transuranic wastes has already been documented.[1] The bacteria and fungi in/on the waste materials can be derived from human and environmental contact, laboratory animals, air, moisture, and soil.

TRU wastes containing organic-matrix materials can serve as the energy source for microbial growth. Heterotrophic bacteria or fungi can utilize the organic content of TRU waste (matrices) as nutrients. Lithotropic microbes can synthesize organic matter for their needs from inorganic substances found in the waste container or near-field environment, e.g., oxidizable substances such as H_2, NH_4^+, SO_3^-, Fe^{2+}, or H_2S.[2] Such microbial activity could affect the containment of nuclear wastes through the degradation or weathering of waste containers[3] and through the generation of gases during the decomposition of organic materials in the wastes.

Existing organic, unprocessed, TRU wastes could contain an adequate number and diversity of bacteria and fungi to cause significant biological degradation. The studies described in this paper provide quantitative data on the kinetics of TRU waste degradation and the composition of the by-products. The consequences of microbial degradation as well as other modes of degradation (radiolytic, thermal, and chemical) under environmental conditions that could be credibly encountered during terminal isolation in a salt repository are described and assessed elsewhere.[2,4]

The primary objectives of this study were to measure gas production rates during microbial degradation of TRU waste and to determine the effects of several environmental variables on these rates. Results are presented for the effects of brine and water content (1% added water, or inundated with either water or concentrated NaCl brine), oxygen concentration (aerobic or anaerobic), temperature (25° to 70°C), and plutonium contamination level (0 to 40 microcuries of alpha activity per gram of waste) on the gas generation rates in simulated, organic-matrix TRU wastes. The possibility that europium or thorium (used as chemical simulants for the transuranic radionuclides) could be alkylated and released as a volatile gas during microbial waste decomposition was also investigated.

Little information is available concerning mechanisms by which microorganisms might interact with transuranic radionuclides in radioactive wastes, although rates of movement between ecosystem compartments have been studied in great detail.[2,5-8] Experimental studies of the interactions of microorganisms and small (microgram) quantities of transuranic radionuclides have been limited to those conducted by Au[9-12] and by Francis.[1,13] A number of potential mechanisms can be postulated. Alkylation of transuranic radionuclides to form organic derivatives might result in volatile, tissue-soluble[14] or inhalable radioactive species. Although laboratory[15-20] and field data[21-24] on alkylation of lighter elements exist, none is available for the transuranic elements. Under conditions of low iron availability, many microorganisms produce siderochromes and other related compounds that chelate iron and that might also chelate TRU radionuclides. Conversely, the organic portion of radionuclide chelates may be degraded resulting in the precipitation of radionuclides from solution. As in the case of iron, the radionuclides could be biologically oxidized or reduced. Microbial activity is not necessarily limited by the absence of organic matter and could also occur where inorganic oxidants and reductants coexist. This phenomenon could potentially be of significance if oxygen were introduced into reducing environments in geological media during mining and waste handling or storage activities.

MATERIAL AND METHODS

Waste Simulations

Three types of organic-matrix wastes were investigated for this study: organic composite, sawdust (representative of plywood boxes), and asphalt (also referred to as bitumen, a potential waste encapsulant, widely used for low-level wastes, particularly in Europe). The composition of the organic composite waste material is given in Table 1. This material is typical of transuranic-contaminated (primarily plutonium-contaminated) organic wastes generated at the Los Alamos National Laboratories. Experimentally, the composite waste was cut into (about 0.3 cm x 0.3 cm) squares.

Plywood sawdust is representative of organic matter present in fiberglass-reinforced, polyester-covered plywood boxes used as containers for noncombustible transuranic wastes. Plywoods consist primarily of of cellulose and lignin. The decomposition of the cellulosic component can occur rapidly compared to the lignin fraction. This is due to the fact that cellulose is a homogeneous polymer of glucose monomers. Lignin, however, is a heterogeneous mixture of phenolic compounds.[25] As a result, there are numerous organisms capable of degrading cellulose using relatively few enzyme systems. A complex enzyme system is required for to degrade lignin. Cellulose can be degraded both aerobically and anaerobically (through a cellulose fermentation). It is normally degraded completely to CO_2 and H_2O.

Table 1. Composition of the Simulated Transuranic Waste Organic Composite

Waste Material	Percent by Weight
Kimwipes (cellulose)	17.0
Rags (cellulose)	17.0
Polyethylene	24.0
Polyvinyl chloride	12.0
Neoprene rubber	7.5
Hypalon rubber	7.5
Butyl rubber	7.5
Latex rubber	7.5

The asphalt (bitumen) used in this study is representative of that used for low-level waste volume-reduction systems, primarily in Europe. It has not been utilized to encapsulate TRU-contaminated wastes. Experimentally, the asphalt was coated onto 2-mm glass beads. The asphalt was supplied by the manufacturer, Industrial Fuel and Asphalt Co. of Indiana. The forms of plywood and asphalt used (sawdust, asphalt-coated beads) were selected to maximize observable degradation rates, in order to avoid underestimating potential gas production.

Simulated waste materials, either 1 g or 25 g samples, were placed in 15-mL serum vials (1 g) or 250-mL screw-cap flasks (25 g). Duplicate sample vials and blanks were sterilized using steam or ethylene oxide. A CO_2 trap containing either 1-mL of 0.1 N NaOH (for 1-g simulations) or 5-mL of 3 N NaOH (for 25-g simulations) was placed in each vial or flask. The vials were sealed with a laminated silicone-Teflon septum. The Teflon layer, which faced the outside of the containers, reduced the loss of gases by diffusion. The inner silicone layer provided a gas-tight seal that resealed even after repeated sampling of the CO_2 absorbant with a 22-gauge syringe needle. Anaerobic conditions were achieved in the 25-g simulations by flushing with oxygen-free nitrogen gas and adding 58 g of Fe_2S in a 50-mL aqueous slurry. The use of Fe_2S as a nontoxic reductant and redox indicator is described by Kucera and Wolfe[26] and by Brock and O'Dea.[27] Equimolar quantities of ferrous ammonium sulfate (39.17 g/L) and sodium sulfide (24.02 g/L of $Na_2S \cdot 9H_2O$) were brought to boiling in a fume hood and mixed. The mixture was allowed to stand overnight under nitrogen. The resulting precipitate was washed four times by centrifugation under nitrogen; water that had been purged with nitrogen for 10 minutes was used to wash the precipitate. The product was stored under nitrogen.

Moisture (deionized water or concentrated brine) was supplied to the test system as 1% (w/w) or 91% (w/w) mixtures of liquid and waste. The composition of the concentrated brine used (WIPP Brine B) in these studies is given in Table 2. It is representative of brine obtained by dissolving bedded rock salt cores from the site of the Waste Isolation Pilot Plant in southeastern New Mexico. For brine-effects experiments, 5 mL of brine were added to 1-g simulations, and 100 mL were added to 25-g simulations.

The transuranic contamination levels investigated in this study were 2, 20, and 40 microcuries (alpha activity) per gram of waste. This was accomplished by adding the equivalents of

Table 2. Ionic Composition of WIPP Brine B

Ion	Concentration (ppm)
Na^+	115,000
K^+	15
Mg^{+2}	10
Ca^{+2}	900
Sr^{+2}	15
Cl^-	175,000
SO_4^{-2}	3,500
I^-	10
HCO_3^-	10
Br^-	400
BO_3^{-3}	10
pH (adjusted)	6.5
Specific gravity	1.2

Molarity of Major Constituents

Na^+	5.0 M
Cl^-	5.0 M
Ca^{+2}	0.03 M
SO_4^{-2}	0.04 M

30, 300, or 600 μg of PuO_2 per gram of waste. The plutonium was defense-grade, primarily ^{239}Pu. All studies using this material were conducted at the Los Alamos National Laboratories. A slurry of powdered PuO_2 was used to prevent any potential inhalation of airborne particulates; all work was conducted in a fume hood. A double layer of rubber gloves and taped laboratory coat sleeves were used to prevent physical contamination. Room air was continuously monitored for radionuclide contamination, and all personnel were monitored for contamination throughout the manipulation of the simulations.

A microbial inoculant was prepared by adding the equivalent of 20 mg of soil inoculant to 1 g of waste material. The soil samples were originally collected at the Los Alamos National Laboratories TRU shallow burial site TA-54, Area C.[27] The techniques used for culturing and evaluating the microfloral populations of these soil samples, and for preparing soil inoculant, are described in detail elsewhere.[27] The inoculant was added to the waste samples as a portion of the liquid phase in most experiments.

Quantification of CO_2 Evolution

Carbon dioxide production was measured both by gas chromatography[29] and by alkaline solution absorption. In all cases, measurements of CO_2 gas production were higher when the alkaline absorption technique was used. The continuous absorption of CO_2 appears to reduce the loss of CO_2 by diffusion (caused by disequilibrium with atmospheric concentrations of

CO_2) over the 6- to 12-month incubation periods. Hence alkaline absorption was the method of choice for determination of CO_2. The measurement sensitivity of the simulations containing 1 and 25 g of waste material were 10 μg and 0.40 μg of CO_2 produced per gram of waste material, respectively.

In the 1-g and 25-g simulations, 0.1 M and 3 M NaOH were used to absorb the CO_2 evolved. At the end of the incubation, the sodium hydroxide solution was added to an equal volume of an equimolar solution of $BaCl_2$. This solution was promptly titrated to a phenophthalein (0.1 g phenophthalein per 100 mL 95% ethanol) end point with 0.1 M potassium hydrogen phthalate or 1.0 M HCl. The difference between the amount of acid required to titrate the sodium hydroxide CO_2 absorbant from the simulations and that required to titrate the absorbant from sterile controls was due to biological activity. At least 50 % of the NaOH remained in the CO_2-absorption solution before titration to ensure that each mL of acid titrant was equivalent to 1/2 mL of equimolar CO_2. The amount of CO_2 produced was calculated by use of the following equation:

$$\text{mg } CO_2 = (22 \text{ mg } CO_2)\begin{pmatrix}\text{molarity}\\ \text{of}\\ \text{titrant}\end{pmatrix}\begin{pmatrix}\text{mL's to} & & \text{mL's to}\\ \text{titrate} & - & \text{titrate}\\ \text{control flask} & & \text{soil flask}\end{pmatrix}$$

Gas chromatography was also used, to a lesser extent, to analyze for other gases of interest: CH_4, H_2S, H_2, CO, NH_3, O_2, SO_2, etc. Using a Varian 3700 gas chromatograph with a thermal conductivity detector, the detection sensitivity was 6×10^{-10} g/sec; the minimum detectable level for CO_2 was 2×10^{-8} moles/100 μL of sample.

Alkylation

Attempts were made to alkylate europium, thorium, and plutonium using procedures described for mercury.[15,18,22,30] Methylcobalamine (0.5 μM) was allowed to react with mercuric chloride (2.0 μM) at 37°C in 1 mL of 0.2 M KH_2PO_4, pH 7.0, in the dark. The amount of methylcobalamine that decomposed to aquacobalamine after release of the methyl group was monitored spectrophotometrically by following an increase in absorbance at 351 nm and a concomitant decrease at 380 nm. After a reaction time of about 4.5 h, the methyl group was released quantitatively. At 24 h, the reaction mixture was extracted with 1 mL of benzene, and the upper layer was removed and allowed to evaporate to 500 μL.

A 50-μL aliquot of the benzene extract was spotted on a silica gel thin-layer chromatography (TLC) plate. The solvent used to develop the chromatogram was hexane:acetone (90:10 v/v). A 20-μL aliquot of standard mercuric chloride (7 μg/μL) was spotted as a control. The chromatographs were developed for 1.5 h. The retardation factors (RFs) were 0.30 for monomethyl mercury and 0.75 for the dimethyl mercury. The $(CH_3)_2Hg$, because of its extreme volatility, was lost from the TLC plate within 24 h. Mercury was detected as a canary yellow spot by spraying with a 0.05% dithizonchloroform solution.

Methylation of thorium and plutonium was attempted under the same conditions as for europium and monitored spectrophotometrically, to observe the conversion of methylcobalamine to aquacobalamine. However, during the extent of this study, no methylation for either thorium or plutonium was detected. As such, no further discussion as to potential repository hazards from volatile transuranic species appears necessary.

RESULTS AND DISCUSSION

Inclusion of organic matter in waste repositories provides both an energy and water source for microbial activity. The presence of some water is essential for microbial growth and/or waste decomposition to occur. Only a small amount of water in or on the waste matrix waste, corresponding to approximately 60% relative humidity (water activity $A_w = 0.60$) <u>inside</u> of a container, is assumed to be necessary for decomposition to occur.[31] Indeed, certain microbial species found in highly arid soils have been found to be active with extremely low concentrations of water such as $A_w = 0.02$.[32,33] An adequate amount of water necessary to initiate microbial action is assumed to be present in existing, stored TRU wastes.[2] For example, when cellulosic-matrix TRU wastes at Los Alamos National Laboratories were heated through the range of 40° to 110°C, 2 to 3 weight % of sorbed water was evolved.[2,34]. This water originates from sorbed moisture or ambient humidity, sorbed (predominantly) prior to containerization. This range could possibly change (increase) appreciably if the wastes were stored in a more humid environment than that which exists at Los Alamos.[2] In summary, it must be assumed that (the majority of) TRU wastes have an adequate water content to support microbial degradation. The water is initially within the TRU waste container, it does not need to be supplied by the storage environment, i.e., by the external ambient humidity.

Gas is formed as organic matter is degraded to form CO_2 and H_2O (and possibly other) gases. Exclusion of organic matter would effectively prevent the microbial degradation of TRU wastes. The exposure of mineral-reducing environments to atmospheric oxygen during repository operational activities may permit microbial activity such as has been observed in natural caverns where oxidizing-reducing interfaces occur.[35,36] However, the activity of the chemosynthetic microorganisms that are responsible for the reactions must be supported by the presence of (assumed) sufficient water.

As shown in Tables 3, 4, and 5, the measured rates of CO_2 gas generation from waste materials were significantly influenced by the physical and chemical (test) environment imposed on the waste materials. Treatments were selected to determine the effects of matrix material and environmental variability on rates of gas production; this is indicated in Table 3. For the data in Table 4, tests on 25-g waste matrix specimens with selected (repository environmental) conditions likely to result in microbial degradation were replicated up to 10 times to

Table 3.

Rates of Microbial CO_2 Gas Generation (μg CO_2/day per gram)* in Nuclear Waste Simulations Containing 1 g of Waste Material. Treatments were selected to determine the effects of substrate and environmental variability on rates of gas production.

	Organic Composite	Sawdust	Asphalt
25°C	5.1 (3.9)[a]	9.4 (6.3)	2.3 (1.5)
40°C	6.5 (5.8)	8.2 (5.5)	0.88 (0.45)
70°C	8.6 (5.5)	10.4 (5.5)	4.9 (3.2)
Aerobic	4.8 (4.6)	7.3 (5.1)	3.4 (2.9)
Anaerobic[b]	7.4 (5.8)	11.4 (5.6)	2.0 (1.9)
1% H_2O	3.8 (4.7)	8.1 (4.7)	2.0 (2.5)
H_2O, 91%	4.4 (3.5)	10.8 (7.4)	1.0 (1.0)
Brine, 91%	2.9 (3.0)	11.4 (5.2)	2.9 (3.0)

[a] Standard deviations given in parentheses.

[b] Purged with N_2.

*1.0 μg CO_2/day per gram = 8.3×10^{-3} moles CO_2/year per kg of waste material.

obtain a narrow confidence interval. In Table 5, similarily obtained data[2] has been converted to units of moles of gas/ per year/ per container of TRU waste. The average, or nominal weights/container listed in Table 5 are as follow:[2] 51.4 kg for organic-composite waste; either 153 kg or 18 kg for a plywood (sawdust) box, corresponding to the calculated weight of plywood, 0.75 in.-thick, in a 4 ft x 4 ft x 7 ft DOT 7A fiberglass reinforced polyester box, or to a similar/scaled-down

Table 4.

Microbial CO_2 Generation in 25-g Organic-Composite Nuclear Waste Simulations, 24°C. Treatments were selected to narrow the confidence interval on conditions likely to result in microbial degradation.

Treatment	μg/g/day	95% Confid. Interval	Number of Replicates	Standard Deviation
Anaerobic, Brine[a]	0.22	0.14	10	0.16
Anaerobic, Water	10.03	2.7	7	2.7
Aerobic, 100% RH	3.56	0.37	10	0.53
Aerobic, Brine	2.24	0.26	9	0.32

[a] Anaerobic conditions maintained with FeS.

plywood box of 0.21 m^3 volume--for direct comparison to a 200 L drum, respectively; and, 153 Kg for asphalt (bitumen). Temperature, oxygen content (aerobic or anaerobic), moisture level, and salinity all affected rates of CO_2 production, as indicated. In situ microbial activity could also result in (localized) elevated temperatures that may increase these rates further. Gas generation was higher at 40° and 70°C than at 25°C (Table 3). The maximum rate of CO_2 production was 11 μg/day per gram of waste and was observed during the first 6 months of aerobic decomposition.

The presence of radionuclides (alpha radiation) slows the rate of gas generation. After 8 months of monitoring, the rate of CO_2 production was reduced approximately 70%, as shown in Figure 1. In this test, 300 μg PuO_2 was added per gram of

Table 5.

Net Microbial CO_2 Gas Generation From Organic Waste Matrices

(Moles/Year/Container)

Temperature: °C	25	40	70	25	40	70
Environment:		AEROBIC			ANAEROBIC	
			Organic Composite (51.4 kg/drum)			
Water, 1%	1.3	1.3	4.2	2.4	2.7	5.1
Water, 91%	1.6	1.8	3.1	4.2	6.4	3.4
Brine, 91%	N.D.	5.2	5.4	3.2	7.9	N.D.
			Sawdust-Plywood (153 kg/box)			
Water, 1%	3.0	6.5	6.4	11.2	17.3	17.3
Water, 91%	14.3	10.3	3.5	26.2	4.7	23.0
Brine, 91%	N.D.	11.6	18.5	11.8	23.8	6.9
			Sawdust-Plywood (18 kg)			
Water, 1%	0.4	1.1	0.3	1.3	2.0	2.0
Water, 91%	1.7	1.2	1.7	3.1	0.6	2.7
Brine, 91%	(0)	1.4	2.2	1.4	(3)	0.8
			Bitumen (135 kg/drum)			
Water, 1%	0.1	0.9	0.1	4.8	0.9	6.7
Water, 91%	3.4	N.D.	N.D.	0.6	1.9	1.9
Brine, 91%	2.6	N.D.	8.3	N.D.	0.9	1.6

N.D. = Not Detected.

simulated nuclear waste material; the test was conducted at 27°C, with a 1% added moisture content. However, this added amount of plutonium, the maximum concentration permitted in TRU-contaminated wastes, was not sufficient to prevent microbial decomposition entirely. The average amount of contamination found in existing organic-matrix TRU wastes is less than 1 μg of PuO_2 per gram of waste.[2]

Carbon dioxide was the only gas detected from the aerobic and anaerobic degradation of the three waste matrices studied. The absence of methane (detection) in the anaerobic tests was possibly due to the lack of FeS as a reductant, and/or the lack of adequate NO_3^- and SO_4^{-2} necessary for methanogenesis. The reductant FeS was added in later tests. However, due to termination of contract funding of this work in early 1980, the methanogenesis studies were not completed.

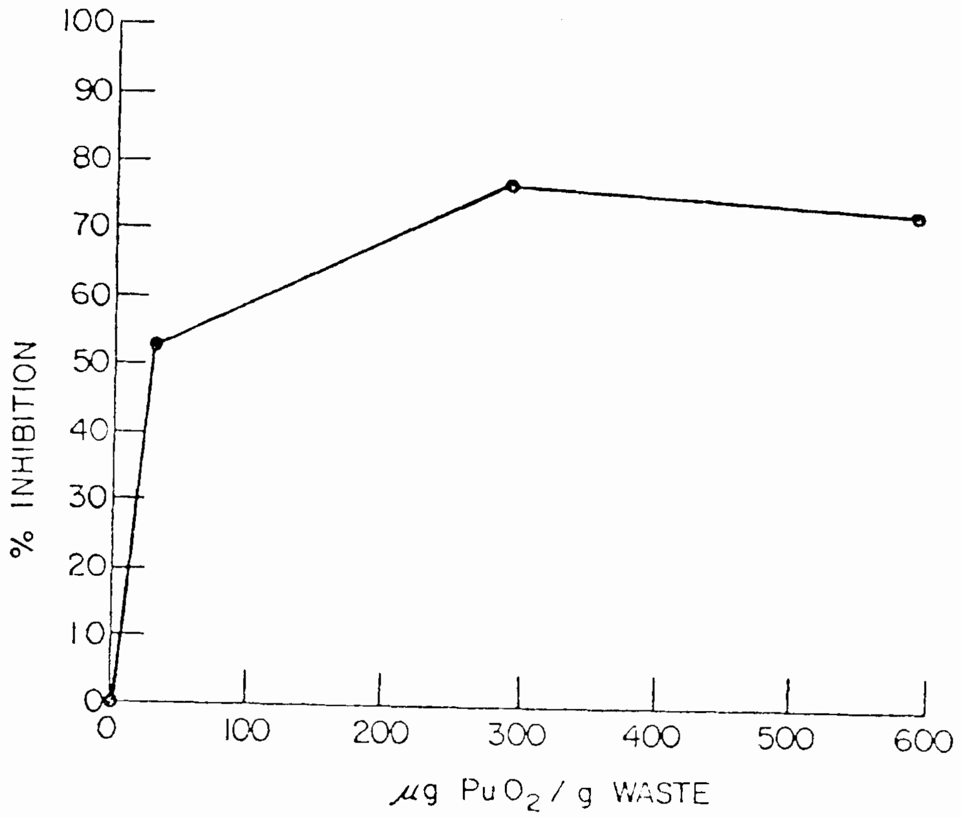

Figure 1. Effect of PuO_2 on Microbial Production of CO_2 in Nuclear Waste Simulations. Percent inhibition of CO_2 generation after an incubation period of 8 months. Incubation of the organic-composite was at 27°C, aerobically, with 1% moisture content. Data shown are averages of three replicates.

Generation and quantification of both methane and hydrogen sulfide gases may be important factors for waste isolation. Potentially significant concentrations of flammable (methane) and toxic (hydrogen sulfide) gases in an operational waste repository should be considered. In the event that the wastes decompose anaerobically rather than aerobically, carbon dioxide and methane will be the primary gases formed.[37] Hydrogen sulfide may also be produced anaerobically because high concentrations of sulfate may be present (6.2 g/L) in brines that could form if fresh water is introduced to salt bed formations. Formation of hydrogen sulfide, mercaptans, and related sulfur gases[38] during waste decomposition would be minor where the sulfur content was low. However, production of hydrogen sulfide through sulfate reduction is possible[39,40] when brine is present. The presence of sulfate may inhibit methanogenesis,[39] however, until all of the available sulfate is converted to hydrogen sulfide. Under these conditions, hydrogen sulfide and carbon dioxide would be the major products of decomposition. This conclusion is supported by the presence of biogenic sulfide pools in nearby salt formations[41] and Laguna-Grande de la Sal, a salt lake near the WIPP facility in southeastern New Mexico. Rates of CO_2, CH_4, and H_2S gas production under specific repository conditions are not known but are assumed to be bounded by the values measured in this study. However, persistence of hydrogen sulfide might be prevented by including ferric chloride as a backfill material in salt mines, thus scavenging hydrogen sulfide through the formation of ferrous sulfide.

For comparative purposes, the experimental data available on gas generation from the degradation of organic-matrix TRU wastes is summarized in Table 6 (from reference[42]). This is mostly ambient, room temperature data, with many data observations lumped together. It is apparent that microbial action has the greatest potential to yield significant amounts of gas than all the other mechanisms. However, because of the variable, uncertain environment imposed on TRU-contaminated wastes (within containers), and of the uncertainty on the presence or absence of viable bacteria or fungi necessary to initiate the degradation, microbial degradation also has the greatest inherent variability in measured gas-generation rates. This is indicated by the large estimated uncertainties in Table 6.

The microbial gas generation and alkylation studies described so far were a sub-set of the overall program to assess the potential microbial impacts on transuranic wastes to be disposed of in the WIPP facility. Other segments of the overall program include:[28]

1. Enumeration and identification of microflora in Los Alamos TRU burial site soil and in metallic and wood containers of actual TRU wastes.
2. Radiobiology of Los Alamos TRU waste microflora and their radiation-resistance. Study indicated that populations of microorganisms coexist quite well with radionuclides, including defense-grade plutonium.[28]

Table 6. Summary of TRU Waste Degradation Rates[42]

MECHANISM/Matrix	GAS GENERATION RATE** (moles/year/drum*)	COMMENTS
MICROBIAL		
Composite, Aerobic	0-(1.3-5.4)-8	
Composite, Anaerobic	1-(2.4-7.9)-12	
Plywood Box*, Aerobic	0-(0.5-2.9)-4	
Plywood Box*, Anaerobic	0.4-(0.8-4.2)-6	
Bitumen, Aerobic	0-(0.1-3.4)-8	
Bitumen, Anaerobic	0-(0.6-4.8)-7	
THERMAL DECOMPOSITION		
Cellulosic (Paper)	0.7-(1.3)-2	(70°C)
Organic Composite	0-(0.02-0.2)-0.4	(40°C, calculated)
ALPHA RADIOLYSIS		
Cellulosics	0.005-(0.0075)-0.011	(39 m Ci)
Composite	0.004-(0.0055)-0.007	(39 m Ci)
Bitumen	0.8-(1.1)-1.4	(7.7 Ci, 100g Pu)
Concrete-TRU Ash	0.03-(0.046-0.93)-1	(15 Ci, poured)
	0.0004-(0.0005-0.034)-0.044	(15 Ci, heated)
Plutonium Contaminant	0.00002 He	(15 Ci, 200g Pu)
CORROSION		
Mild Steel		
dry salt	0	0 micrometer/year
brine, deaerated	0-(2)-2	3 micrometer/year
brine, aerated	0	50 micrometer/year
salt, 100% humidity	0	5 micrometer/year

*volume = 0.21 m^3
**lower limit - (most probable range)-upper limit; limits include estimated uncertainties

3. Solubilization of plutonium by a chelate of microbial origin (uncompleted study; negative results to date).
4. Microbial degradation of various chelates (citrate, ethylenediamine tetraacetate, and nitrilo tetraacetate) study, using europium as a chemical simulant of plutonium.
5. Identification and enumeration of potential microorganism in WIPP salt beds (negative results).

The existing results of the above studies are summarized separately.[28] The experimentally measured rates of gas generation resulting from the microbial decomposition of organic TRU wastes, and the effects of environmental variables on such rates, have been described in detail in this document. Although the body of existing data is not definitive and could be expanded by further study, it has allowed realistic bounds or credible limits to be placed on the rates and amounts of gases that might be generated under realistic repository environments. Assessments of the consequences of such gas generation have been made elsewhere.[4]

All of the above results indicate that the potential effects of microbial interactions with radioactive wastes are not limited to laboratory situations, but must be considered in designing long-term radioactive waste storage capabilities.[28] Although microbial gas generation measurements were only a small but important segment of previous consequence assessments,[4] there appear to be no technical reasons why organic-matrix TRU wastes could not be safely isolated in a radioactive waste repository in bedded salt. Further gas monitoring studies and performance assessments will be conducted in the future for in situ validations (of waste isolation safety) in the Waste Isolation Pilot Plant.

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