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A Comparison of the Potential Radiological Impact of Recycle ^{233}U HTGR Fuel and LMFBR Plutonium Fuel Released to the Environment

John E. Till

Environmental Sciences Division Publication No. 666

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ORNL-TM-4768

Contract No. W-7405-eng-26

A COMPARISON OF THE POTENTIAL RADIOLOGICAL IMPACT OF RECYCLE ^{233}U HTGR FUEL AND LMFBR PLUTONIUM FUEL RELEASED TO THE ENVIRONMENT

John E. Till

ENVIRONMENTAL SCIENCES DIVISION

JANUARY 1975

Environmental Sciences Division
Publication No. 666

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ABSTRACT

The anticipated use of recycle uranium-233 fuels in High Temperature Gas-Cooled Reactors (HTGR) has prompted the need to review the radiological implications of this material. The recycle uranium is primarily ^{233}U, but it also contains up to 1200 ppm ^{232}U. The highly radiotoxic ^{232}U contributes from 50% to 90% of the internal dose to man from this recycle uranium. The INREM, BIORAD, TERMOD, and AIRDOSE codes developed by the ORNL Environmental Hazards Study Group are used to predict potential hazards to man and biota from hypothetical exposure to recycle ^{233}U fuel and LMFBR plutonium fuel.

From a radiological impact standpoint, LMFBR plutonium fuel is approximately 500 times more radiotoxic than ^{233}U fuel when inhalation is the exposure pathway. In terms of doses to man via ingestion and doses to biota the two fuels are comparable. It is concluded that if atmospheric release is the only source of effluent, LMFBR plutonium fuel is more hazardous than recycle ^{232}U fuel by a factor of approximately 500; however, if these fuels are predominantly present in the terrestrial environment, their radiological impact on man is similar.

INTRODUCTION

The purpose of this study is to compare the relative radiological hazards of LMFBR plutonium fuel and recycle ^{233}U HTGR fuel. A brief review of the physical characteristics of uranium and plutonium isotopes in the fuels is also included. Natural uranium and light water reactor uranium fuel are chemical toxicants; therefore the chemical vs radiological toxicity of ^{233}U HTGR fuel and Pu LMFBR fuel is discussed.

Equal amounts (by weight) of each fuel are assumed to be released to the environment or ingested by man directly. All calculated doses are hypothetical and are not representative of actual insult to man from a nuclear facility handling ^{233}U or Pu fuel. Instead, it is the relative magnitude of the doses from each type of fuel that is significant.

An attempt is made to compare the two types of fuel under normal release conditions and single quantity intake by man. No comparison is included that shows industrial containment requirements.

ISOTOPIC ACTIVITIES CONTAINED IN ONE GRAM OF RECYCLE ^{233}U HTGR FUEL AND LMFBR PLUTONIUM FUEL

The production and decay of ^{232}U is illustrated in Figure 1; Tables 1 and 2 show calculated activity per gram of fuel. The isotopic composition of plutonium is that given in the LMFBR Environmental Statement.[1] The isotopic composition of recycle ^{233}U was provided by the General Atomic Company.[2]

For the purpose of this study all doses are derived using equilibrium recycle fuel, an assumption which gives slightly higher ^{234}U, ^{235}U, and ^{236}U activities than in beginning recycle fuel. The doses attributed to these isotopes are small compared to the doses from ^{232}U and ^{233}U.

CHEMICAL TOXICITY VS RADIOLOGICAL TOXICITY OF URANIUM AND PLUTONIUM

The environmental impact of plutonium and uranium is influenced by chemical toxicity of the long-lived isotopes and radiological effects of the shorter-lived isotopes. Therefore, when one compares the biological effects of these elements, the type of injury (chemical or radiological) must be distinguished.

Known plutonium biological effects are primarily due to radiotoxicity. This element is a bone seeker and deposits on the surface of the bone rather than moving into the tissues. An alpha emitter, plutonium has a high relative biological effectiveness. Stannard[3] reports that the chemical toxicity of plutonium has not been thoroughly investigated because there are no stable isotopes; consequently, investigations of plutonium toxicity have been conducted with one isotope and extrapolated to other isotopes. Vaughn[4] suggests that until more information is available, considerable caution must be used before applying data obtained with one plutonium isotope to predict the biological behavior of other plutonium isotopes. For the purposes of this study, however, radiotoxicity is assumed to be the limiting hazard of plutonium fuel.

Uranium differs from plutonium in that it presents both a chemical and a radiological hazard to man. The biological effects (and critical organ) are determined by the specific isotope present. Chemical toxicity is the limiting criterion for the longer-lived isotopes of uranium (^{235}U and ^{238}U); the shorter-lived isotopes of uranium (^{230}U, ^{232}U, ^{233}U, ^{234}U, ^{236}U, and ^{240}U) are limited by radiological effect.[5] Most studies of uranium toxicity have used low enriched uranium or natural uranium. Little work has been done to investigate $^{233}U/^{232}U$ and their daughters. Thus, with the anticipated use of these isotopes in the thorium fuel cycle, more research is needed to evaluate their hazards to man and other biota.

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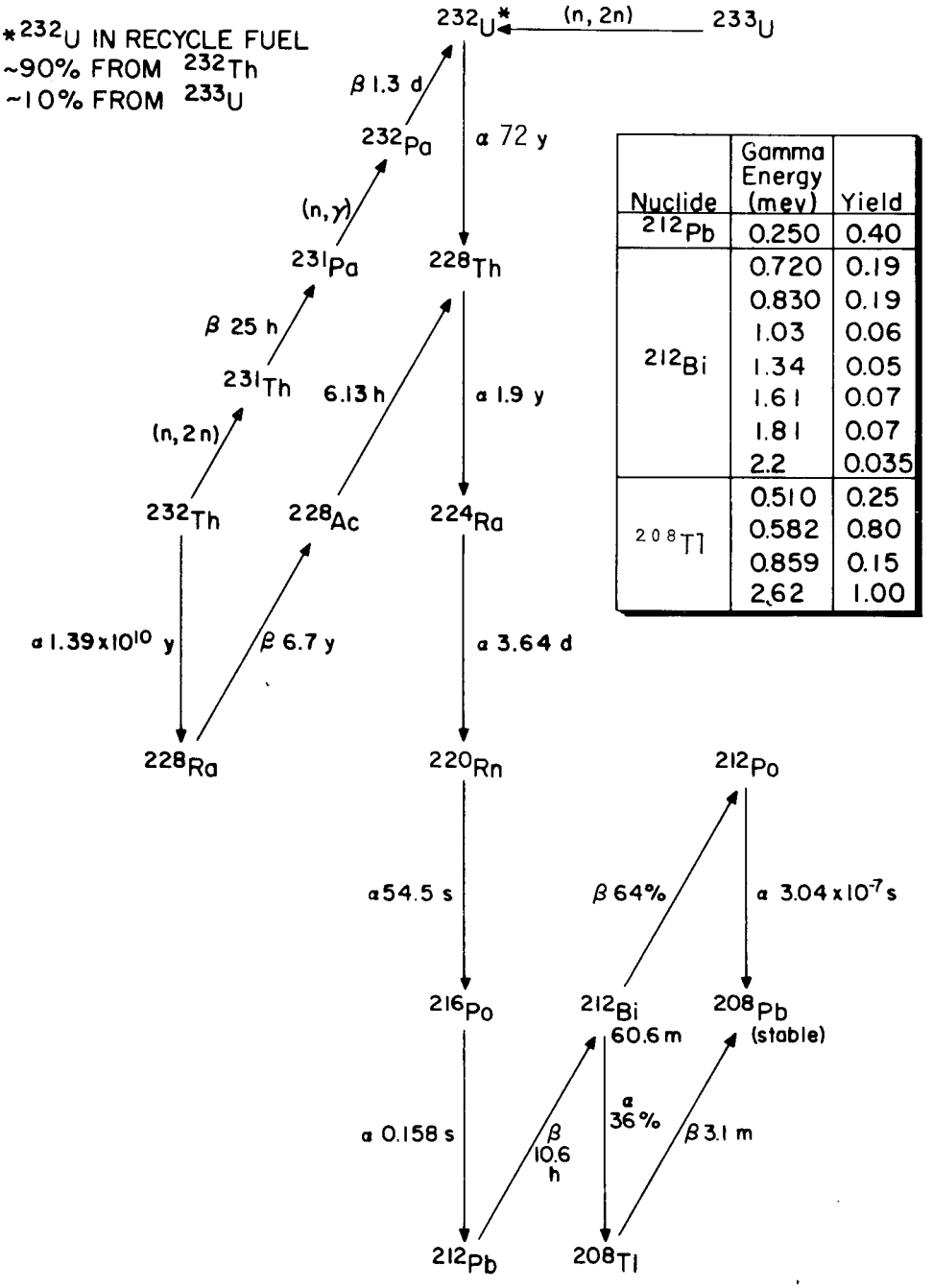

Nuclide	Gamma Energy (mev)	Yield
^{212}Pb	0.250	0.40
^{212}Bi	0.720	0.19
	0.830	0.19
	1.03	0.06
	1.34	0.05
	1.61	0.07
	1.81	0.07
	2.2	0.035
^{208}Tl	0.510	0.25
	0.582	0.80
	0.859	0.15
	2.62	1.00

Figure 1. Production and decay of ^{232}U and ^{228}Th.

Table 1a. Assumed Activity of Uranium Isotopes in 1 Gram of ^{233}U Fuel

Isotope	Beginning Recycle Atom fraction	Equilibrium Recycle Atom fraction	Beginning Rec. Act. (Ci)	Equilibrium Recycle Act. (Ci)
		Uranium Fuel		
^{232}U	<0.001000	0.001000	$<2.14\times10^{-2}$	2.14×10^{-2}
^{233}U	0.919575	0.612800	8.74×10^{-3}	5.82×10^{-3}
^{234}U	0.073500	0.243000	4.55×10^{-4}	1.51×10^{-3}
^{235}U	0.005680	0.080200	1.22×10^{-8}	1.72×10^{-7}
^{236}U	0.000245	0.063000	1.56×10^{-8}	3.99×10^{-6}

Table 1b. Assumed Activity of ^{232}U Daughters in 1 Gram of ^{233}U Fuel

Isotope	Activity (Ci)
^{232}U	2.14×10^{-2}
^{228}Th	1.83×10^{-3}
^{224}Ra	1.73×10^{-3}
^{220}Rn	1.73×10^{-3}
^{216}Po	1.73×10^{-3}
^{212}Pb	1.73×10^{-3}
^{212}Bi	1.73×10^{-3}
^{212}Po	1.11×10^{-3}
^{208}Tl	6.62×10^{-4}

Table 2. Assumed Activity of Plutonium Isotopes in 1 Gram of LMFBR Fuel

Isotope	Atom fraction	Activity (Ci)
	Plutonium Fuel	
^{236}Pu	4.2×10^{-8}	2.24×10^{-5}
^{238}Pu	0.012	2.09×10^{-1}
^{239}Pu	0.647	3.97×10^{-2}
^{240}Pu	0.245	5.55×10^{-2}
^{241}Pu	0.058	6.52×10^{0}
^{242}Pu	0.038	1.48×10^{-4}
^{244}Pu	1.8×10^{-7}	3.48×10^{-12}

The radiotoxicity of both uranium and plutonium fuel allows a relative comparison of their respective dose potentials to man and other biota.

COMPARISON OF PHYSICAL PARAMETERS ASSOCIATED WITH ^{233}U AND PU FUEL

Tables 3 and 4 show the radioactive half lives and MPC_a values for isotopes in the uranium and plutonium fuel.[6] The most important property of uranium fuel is that ^{232}U has a very short half-life compared to the other uranium isotopes and hence a high specific activity. Even though ^{232}U is present as an impurity in small amounts by weight, it constitutes 52% of the total activity of the fuel.

The specific activities for several isotopes in uranium and plutonium fuel are shown in Table 5. Note that ^{232}U specific activity is about 100 times greater than ^{240}Pu. Dividing the specific activity by the MPC_a yields MPC/g/cc of material (shown in the third column of Table 5). In each case the most restrictive MPC_a is used. The MPC/g/cc of isotope is an index that demonstrates the relative radiological hazard assuming that only that isotope is present. It does not account for the isotopic distribution in the fuel. The data in Table 5 indicate that, on a gram per gram basis, ^{232}U is more hazardous than ^{239}Pu or ^{240}Pu.

Up to now, the discussion has dealt with the physical characteristics of the independent isotopes present in recycle ^{233}U and plutonium fuels. The following sections review the radiological implications of these fuels when isotopic composition is considered.

DOSE COMPARISON USING INREM COMPUTER CODE

A radiological assessment is made using the INREM computer code,[7] which calculates radiation dose to various organs of the body as a result of a given intake of radionuclides. In each case it is assumed that ingestion of the isotope is proportional to its content in the fuel and 1 μg of fuel is ingested.

This assessment does not account for environmental transport of the fuel before it reaches man. Application of the INREM code alone simulates a situation where the fuel is ingested or inhaled directly, as might be the case in an accident.

Table 6 shows estimated 50-year dose commitments for total body, bone, liver, and kidneys. The most important value is the total dose to each organ derived from the uranium or plutonium fuel present in the organ. Plutonium fuel contributes the maximum dose commitment to the bone, 0.315 rem. The uranium/plutonium dose ratio is 0.313; that is, uranium gives 31.3% as much dose as the plutonium. Total body doses for the two fuel types are very similar (U/Pu = 0.95).

Table 3. Radioactive Half Lives of Isotopes in ^{233}U Fuel and Plutonium Fuel

Isotopes	Radioactive Half Life
Uranium Fuel	
^{232}U	7.20×10^{1}y
^{233}U	1.62×10^{5}y
^{234}U	2.47×10^{5}y
^{235}U	7.10×10^{8}y
^{236}U	2.39×10^{7}y
Uranium-232 Daughters	
^{228}Th	1.91y
^{224}Ra	3.64d
^{220}Rn	55.30s
^{216}Po	0.15s
^{212}Pb	10.64h
^{212}Bi	60.60m
^{212}Po	3.04×10^{-7}s
^{208}Th	3.10m
Plutonium Fuel	
^{236}Pu	2.85y
^{238}Pu	86.40y
^{239}Pu	2.44×10^{4}y
^{240}Pu	6.58×10^{3}y
^{241}Pu	13.20y
^{242}Pu	3.79y
^{244}Pu	7.60×10^{7}y

Table 4. Selected Nonoccupational MPC_a Values[6]

Isotope	Critical Organ	168 hr/week MPC_a (μCi/cc)
^{232}U (soluble)	Bone	3×10^{-11}
^{233}U (soluble)	Bone	2×10^{-10}
^{239}Pu (soluble)	Bone	6×10^{-13}
^{240}Pu (soluble)	Bone	6×10^{-13}

Table 5. Specific Activity of Several Isotopes in ^{233}U and Plutonium Fuel and Resulting MPC_a/g/cc

Isotope	Specific Activity (Ci/g)	MPC_a /g/cc Isotope
^{232}U	2.1×10^{1}	2.4×10^{18}
^{233}U	9.5×10^{-3}	2.4×10^{14}
^{239}Pu	6.1×10^{-2}	1.0×10^{17}
^{240}Pu	2.3×10^{-1}	3.8×10^{17}

Table 6. Comparison of Estimated Doses from Ingestion of Recycled ^{233}U Fuel and LMFBR Plutonium Fuel Using INREM

Isotope	Assumed Intake (μCi)	50-Year Dose Commitment (rems)			
		Total Body	Bone	Liver	Kidneys
^{232}U	2.14×10^{-2}	6.27×10^{-3}	8.87×10^{-2}	6.27×10^{-3}*	9.49×10^{-3}
^{228}Th	1.83×10^{-3}	3.05×10^{-5}	9.02×10^{-4}	1.53×10^{-5}	8.49×10^{-5}
^{224}Ra	1.73×10^{-3}	3.50×10^{-4}	2.77×10^{-3}	3.50×10^{-4}*	3.50×10^{-4}*
^{216}Po	1.73×10^{-3}	No Data	No Data	No Data	No Data
^{212}Pb	1.73×10^{-3}	5.23×10^{-6}	6.54×10^{-5}	1.74×10^{-5}	1.51×10^{-4}
^{212}Bi	1.73×10^{-3}	6.31×10^{-8}	9.38×10^{-8}	3.90×10^{-7}	4.37×10^{-6}
^{212}Po	1.11×10^{-3}	No Data	No Data	No Data	No Data
^{208}Tl	6.62×10^{-4}	No Data	No Data	No Data	No Data
^{233}U	5.82×10^{-3}	3.05×10^{-4}	5.03×10^{-3}	3.05×10^{-9}*	1.17×10^{-3}
^{234}U	1.51×10^{-3}	7.75×10^{-5}	1.25×10^{-3}	7.75×10^{-5}*	2.98×10^{-4}
^{235}U	1.72×10^{-7}	8.27×10^{-9}	1.37×10^{-7}	8.27×10^{-9}*	3.19×10^{-8}
^{236}U	3.99×10^{-6}	1.96×10^{-7}	3.17×10^{-6}	1.96×10^{-7}*	7.56×10^{-7}
Total U		7.04×10^{-3}	9.87×10^{-2}	7.04×10^{-3}	1.11×10^{-2}
^{236}Pu	2.45×10^{-5}	2.68×10^{-7}	9.46×10^{-6}	8.12×10^{-7}	6.15×10^{-7}
^{238}Pu	2.09×10^{-1}	3.60×10^{-3}	1.43×10^{-1}	2.02×10^{-2}	1.53×10^{-2}
^{239}Pu	3.97×10^{-2}	7.59×10^{-4}	3.12×10^{-2}	4.21×10^{-3}	3.22×10^{-3}
^{240}Pu	5.55×10^{-2}	1.06×10^{-3}	4.36×10^{-2}	5.89×10^{-3}	4.50×10^{-3}
^{241}Pu	6.52×10^{0}	1.99×10^{-3}	9.70×10^{-2}	4.95×10^{-3}	9.54×10^{-3}
^{242}Pu	1.48×10^{-4}	2.72×10^{-6}	1.08×10^{-4}	1.51×10^{-5}	1.16×10^{-5}
^{244}Pu	3.48×10^{-12}	7.34×10^{-14}	2.97×10^{-12}	7.34×10^{-14}*	3.11×10^{-13}
Total Pu		7.41×10^{-3}	3.15×10^{-1}	3.53×10^{-2}	3.26×10^{-2}
Uranium / Plutonium	Dose Ratio	0.95	0.313	0.20	0.34

*Total body dose conversion factor is assumed since organ values are not presently included in INREM.

Dose conversion factors for several of the ^{232}U daughters are not yet incorporated into the INREM data base. Therefore, uranium fuel doses would be slightly higher than those indicated in Table 6. Uranium-232 contributes 90% or more of the dose to the total body, bone, and kidneys. The dose from plutonium fuel is more evenly distributed between several isotopes (^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu).

A comparison of ^{232}U and ^{239}Pu INREM parameters provides insight regarding the high radiotoxicity of ^{232}U.

	(Effective Absorbed Energy)	f_w (Fraction Absorbed from Ingestion)	T_e (Effective Half-Time in Bone)
^{232}U	1.2×10^3 MeV/dis	1.1×10^{-3}	3.0×10^2 d
^{239}Pu	2.7×10^2 MeV/dis	2.9×10^{-5}	7.2×10^4 d

The effective absorbed energy for ^{232}U is approximately 5 times higher than that of ^{239}Pu. The fraction absorbed from ingestion, f_w, is 46 times greater for uranium while the effective half time, T_e, is 240 times greater for plutonium. Applying these factors to the internal dose commitment equation gives a $^{232}U/^{239}Pu$ dose conversion ratio of approximately 5 for equal intakes of the two radionuclides.

DOSE COMPARISON USING BIORAD

The BIORAD[8] computer code estimates internal and external doses to aquatic plants, invertebrates, fish, and terrestrial animals dependent on aquatic food supplies. The aquatic environment is assumed to be contaminated by atmospheric fallout since no liquid effluent is considered in this study.

A comparison of uranium and plutonium fuel is made by assuming that radionuclide concentrations in the water are proportional to concentrations in the fuel. A fuel concentration in water of 1 μg/ml is assumed. Uranium-232 daughters other than ^{228}Th are not included in the total dose since these isotopes cannot be handled in the BIORAD code at the present time.

The estimated internal doses to biota from uranium and plutonium fuel are listed in Tables 7 and 8. The uranium dose is 25% to 65% of the plutonium dose even though plutonium fuel is present in much higher concentrations. The most significant contributor to the uranium dose is ^{232}U, which gives from 49.5% to 90.0% of the total dose. Table 9 lists the U fuel/Pu fuel dose ratios and clearly shows that these two fuels are similar to each other when dose potentials to biota other than man are compared.

Table 7. Estimated Internal Doses to Biota from ^{233}U Fuel

Isotope	Concentration (μCi/ml)	Aquatic Plants	Invertebrates	Fish	Muskrats
		(mrads/year)			
		Uranium Fuel Internal Dose			
^{232}U	2.1×10^{-2}	1.1×10^{11}	1.1×10^{10}	1.1×10^{9}	1.2×10^{8}
^{228}Th	1.8×10^{-3}	1.2×10^{10}	3.9×10^{9}	2.4×10^{8}	1.2×10^{8}
^{233}U	5.8×10^{-3}	5.4×10^{9}	5.4×10^{8}	5.4×10^{7}	7.6×10^{6}
^{234}U	1.5×10^{-3}	1.4×10^{9}	1.4×10^{8}	1.4×10^{7}	1.9×10^{6}
^{235}U	1.7×10^{-7}	1.5×10^{5}	1.5×10^{4}	1.5×10^{3}	2.1×10^{2}
^{236}U	4.0×10^{-6}	3.5×10^{6}	3.5×10^{5}	3.5×10^{4}	4.9×10^{3}
Total	3.0×10^{-2}	1.2×10^{11}	1.5×10^{10}	1.4×10^{9}	2.4×10^{8}
Percent of Dose from ^{232}U		90.0	73.0	81.5	49.5

Table 8. Estimated Internal Doses to Biota from Plutonium Fuel

Isotope	Concentration (μCi/ml)	Aquatic Plants	Invertebrates	Fish	Muskrats
		(mrads/year)			
		Plutonium Fuel Internal Doses			
^{236}Pu	2.2×10^{-5}	5.0×10^{7}	1.4×10^{7}	5.0×10^{5}	1.1×10^{5}
^{238}Pu	2.1×10^{-1}	7.8×10^{10}	2.2×10^{10}	7.8×10^{8}	3.3×10^{8}
^{239}Pu	4.0×10^{-2}	1.4×10^{10}	3.9×10^{9}	1.4×10^{8}	5.9×10^{7}
^{240}Pu	5.6×10^{-2}	1.9×10^{10}	5.5×10^{9}	1.9×10^{8}	8.3×10^{7}
^{241}Pu	6.5×10^{0}	9.8×10^{10}	2.8×10^{10}	9.8×10^{8}	4.2×10^{8}
^{242}Pu	1.5×10^{-4}	4.9×10^{7}	1.4×10^{7}	4.9×10^{5}	2.1×10^{5}
^{244}Pu	3.5×10^{-12}	No Data	No Data	No Data	No Data
Total	6.8×10^{0}	2.1×10^{11}	5.9×10^{10}	2.1×10^{9}	8.9×10^{8}

Table 9. Uranium/Plutonium Dose Ratios from BIORAD Computations

	Aquatic Plants	Invertebrates	Fish	Muskrats
Internal Dose (U/Pu)	0.59	0.25	0.65	0.27

DOSE COMPARISON BASED ON ATMOSPHERIC RELEASES

Table 10 shows hypothetical release rates of isotopes from HTGR uranium fuel and LMFBR plutonium fuel, assuming that 1 μg/sec of each fuel escapes. Atmospheric concentration is calculated with a dispersion coefficient of 2×10^{-7} sec-m^{-3} used in the HTGR Fuel Refabrication Pilot Plant Draft Environmental Statement.[9] A deposition velocity of 10^{-2} m/sec is used for all isotopes.

Estimated doses resulting from these atmospheric concentrations are listed in Table 11 for submersion in air, ground exposure, and various body organs for inhalation and ingestion. The highest doses are from inhalation of plutonium fuel. The U/Pu inhalation dose ratio for the bone is 1.8×10^{-3}.

The ingestion pathway results from consumption of food products contaminated with uranium or plutonium originally deposited on the terrestrial surface. These doses are comparable for uranium and plutonium fuel. Both fuel types contribute the highest dose to the bone. The total body dose from uranium fuel is higher than that from plutonium fuel. The respective U/Pu dose ratios for bone and total body are 0.4 and 1.18.

External body exposure from air and ground surface contaminated with uranium fuel was found to be approximately 100 times less than inhalation exposure. Thalium-208, which emits several very energetic gammas at high intensities contributes 77% of the external dose.

Several aspects of the data in Table 11 are important.

1. When all pathways are considered, the plutonium fuel presents the highest dose when inhaled. Bone is the critical organ for both types of fuel and U/Pu inhalation dose ratio for bone is 1.8×10^{-3}.

2. If the ingestion pathway is most important (which would be the case after the plant shuts down), uranium fuel has almost the same radiotoxicity as plutonium fuel. Bone is still the critical organ.

3. ^{232}U is the primary contributor to the total dose from uranium fuel for each organ.

INTAKE RATE BY MAN COMPUTED WITH TERMOD

The TERMOD computer code[10] calculates radionuclide intake to man based on a multicompartment model that considers consumption of milk, beef, and crops. Assuming a deposition rate for each isotope based on

Table 10. Hypothetical Release Rates and Atmospheric Concentrations of Uranium-233 and Plutonium Fuel Assuming a Dispersion Coefficient of 2×10^{-7} sec-m^3

Isotope	Release Rate (μCi/sec)	Release Rate (μCi/day)	Concentration (μCi/m^3)	Deposition Rate (μCi/m^2/day)
^{232}U	2.14×10^{-2}	1.85×10^{3}	4.28×10^{-9}	3.70×10^{-6}
^{233}U	5.82×10^{-3}	5.03×10^{2}	1.16×10^{-9}	1.01×10^{-6}
^{234}U	1.51×10^{-3}	1.30×10^{2}	3.01×10^{-10}	2.60×10^{-7}
^{235}U	1.72×10^{-7}	1.49×10^{-2}	3.45×10^{-14}	2.98×10^{-11}
^{236}U	3.99×10^{-6}	3.45×10^{-5}	7.99×10^{-13}	6.91×10^{-14}
^{228}Th	1.83×10^{-3}	1.58×10^{2}	3.66×10^{-10}	3.16×10^{-7}
^{236}Pu	2.23×10^{-5}	1.93×10^{0}	4.47×10^{-12}	3.86×10^{-9}
^{238}Pu	2.09×10^{-1}	1.80×10^{4}	4.18×10^{-8}	3.61×10^{-5}
^{239}Pu	3.97×10^{-2}	3.43×10^{3}	7.94×10^{-9}	6.86×10^{-6}
^{240}Pu	5.55×10^{-2}	4.80×10^{3}	1.11×10^{-8}	9.59×10^{-6}
^{241}Pu	6.52×10^{0}	5.64×10^{5}	1.31×10^{-6}	1.13×10^{-3}
^{242}Pu	1.48×10^{-4}	1.28×10^{1}	2.96×10^{-11}	2.56×10^{-8}
^{244}Pu	3.48×10^{-12}	3.01×10^{-7}	6.96×10^{-19}	6.01×10^{-16}

Table 11. Comparison of Estimated Doses to Man From ^{233}U Fuel vs Pu Fuel Assuming 1 μg/sec Release Rate and 1 μg/m^2 Deposition

Exposure Pathway or Organ	^{233}U Fuel Dose (mrem/year)	Percent of Dose from ^{232}U	Pu Fuel Dose (mrem/year)	U/Pu Dose Ratio
Submersion in Air	1.51×10^{2}	92	7.26×10^{-1}	2.08×10^{2}
Ground Exposure	1.98×10^{3}	92	1.16×10^{2}	1.71×10^{1}
Inhalation				
Total Body	3.55×10^{5}	65	9.19×10^{7}	3.86×10^{-3}
Bone	6.91×10^{6}	48	3.83×10^{9}	1.80×10^{-3}
Liver	2.89×10^{5}	79	4.35×10^{8}	6.64×10^{-4}
Kidney	6.55×10^{5}	54	3.96×10^{8}	1.65×10^{-3}
GI (Sol.)	1.94×10^{3}	69	2.55×10^{4}	7.61×10^{-2}
Lung (Insol.)	8.37×10^{6}	86	8.38×10^{7}	9.99×10^{-2}
Ingestion				
Total Body	6.73×10^{5}	94	5.69×10^{5}	1.18×10^{0}
Bone	9.68×10^{6}	93	2.42×10^{7}	4.00×10^{-1}
Liver	6.72×10^{5}	94	2.71×10^{6}	2.48×10^{-1}
Kidney	1.11×10^{6}	86	2.50×10^{6}	4.44×10^{-1}
GI (Sol.)	2.11×10^{5}	66	2.48×10^{6}	8.51×10^{-2}
GI (Insol.)	2.11×10^{5}	66	2.48×10^{6}	8.51×10^{-2}

isotopic content in the fuel, TERMOD determines the subsequent intake by man. Once input values are obtained, the resulting dose rates are calculated separately with INREM (TERMOD does not predict dose rates). The use of TERMOD provides a relative comparison of terrestrial environmental transport of each fuel.

Table 12 compares intakes of uranium fuel and plutonium fuel by man, assuming surface deposition rates listed in Table 9. The total activity intake of plutonium by man is 1.73×10^2 greater than that of uranium because more plutonium activity is initially deposited on the soil. Transport of uranium through different compartments of the model is greater by a factor of about 1.3 (1.61/1.22).

CONCLUSIONS

A comparison of the potential radiological hazards associated with recycle ^{233}U HTGR fuel and LMFBR plutonium fuel yields several conclusions:

1. Although the chemical toxicity of plutonium is unknown, both ^{233}U fuel and LMFBR plutonium fuel are considered to be radiological hazards.

2. Based on MPC_a values and specific activity, pure ^{232}U is about 15 times more hazardous than ^{239}Pu.

3. If equal amounts are ingested, ^{233}U and LMFBR plutonium fuel give similar doses to the bone and total body. More than 90% of the uranium fuel dose results from ^{232}U, which is accounted for by a high effective absorbed energy and fraction absorbed from ingestion.

4. Doses to biota are approximately the same from ^{233}U fuel and plutonium fuel. Again the most significant contributor to the uranium fuel dose is ^{232}U which gives from 50% to 90% of the total.

5. When atmospheric transport of recycle ^{233}U HTGR fuel and plutonium LMFBR fuel is considered, plutonium gives higher doses from inhalation than uranium by a factor of about 500. Ingestion of contaminated foods gives comparable doses for uranium and plutonium.

If atmospheric release is the only source of effluent, plutonium fuel is about 500 times more hazardous than ^{233}U HTGR fuel; inhalation is the critical pathway and bone is the critical organ. When fuels are released in liquid or gaseous effluents, the concentration of fuel present determines which is the most hazardous to man. Doses to aquatic biota are similar regardless of the method of entry into the environment.

Table 12. Comparison of TERMOD Values for ^{233}U and Pu Fuel

Isotopes	Deposition Rate ($\mu Ci/m^2/day$)	TERMOD Intake Rate ($\mu Ci/day$)/ ($\mu Ci/m^2$ deposition)	Calculated Daily Intake Rate ($\mu Ci/day$)
	A	B	C=AxB
^{232}U	3.70×10^{-6}	1.60	5.92×10^{-6}
^{233}U	1.01×10^{-6}	1.61	1.63×10^{-6}
^{234}U	2.60×10^{-7}	1.61	4.19×10^{-7}
^{235}U	2.98×10^{-11}	1.61	4.80×10^{-11}
^{236}U	6.91×10^{-14}	1.61	1.11×10^{-13}
^{228}Th	3.16×10^{-7}	1.22	3.86×10^{-7}
Total			8.35×10^{-6}
^{236}Pu	3.86×10^{-9}	1.20	4.63×10^{-9}
^{238}Pu	3.61×10^{-5}	1.22	4.40×10^{-5}
^{239}Pu	6.86×10^{-6}	1.22	8.37×10^{-6}
^{240}Pu	9.59×10^{-6}	1.22	1.17×10^{-5}
^{241}Pu	1.13×10^{-3}	1.22	1.38×10^{-3}
^{242}Pu	2.56×10^{-8}	1.22	3.12×10^{-8}
^{244}Pu	6.01×10^{-16}	No Data	No Data
Total			1.44×10^{-3}

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