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Comparison of the Radiological Impacts of Thorium and Uranium Nuclear Fuel Cycles

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J. P. McBride
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Prepared for
U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety and Safeguards
Division of Fuel Cycle and Material Safety
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ABSTRACT

A study is being performed for the Nuclear Regulatory Commission (NRC) to determine whether the existing regulations for the uranium fuel cycles require modification and/or additions in order to regulate thorium fuel cycles. This report was prepared during Phase 2 of the study and compares the radiological impacts of a fuel cycle in which only uranium is recycled, as presented in the Final Generic Environmental Statement on the *Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors (GESMO)*, with those of the light-water breeder reactor (LWBR) thorium/uranium fuel cycle in the *Final Environmental Statement, Light Water Breeder Reactor Program*. The significant offsite radiological impacts from routine operation of the fuel cycles result from the mining and milling of thorium and uranium ores, reprocessing spent fuel, and reactor operations. The major difference between the impacts from the two fuel cycles is the larger dose commitments associated with current uranium mining and milling operations as compared to thorium mining and milling. Estimated dose commitments from the reprocessing of either fuel type are small and show only moderate variations for specific doses. No significant differences in environmental radiological impact are anticipated for reactors using either of the fuel cycles. Radiological impacts associated with routine releases from the operation of either the thorium or uranium fuel cycles can be held to acceptably low levels by existing regulations.

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PREFACE

The Nuclear Regulatory Commission (NRC) requested that the Oak Ridge National Laboratory (ORNL) study the health, safety, and environmental aspects of thorium nuclear fuel cycles and assess how the differences with those of the uranium fuel cycles could impact on the regulatory process. The contribution of ORNL to the study is twofold:

Phase 1. review the literature on thorium fuel cycles and evaluate the health, safety, and environmental impacts that might result from them; and

Phase 2. compare the impacts delineated above with those from uranium fuel cycles and identify modifications or additions, if any, to the existing regulations that may be necessary for thorium fuel cycles.

The present report is part of Phase 2 of the study and compares the radiological impacts of the thorium and uranium fuel cycles.

COMPARISON OF THE RADIOLOGICAL IMPACTS OF THORIUM AND URANIUM NUCLEAR FUEL CYCLES

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1. INTRODUCTION

This report identifies the significant differences between the radiological impacts posed by nuclear fuel cycles using $^{232}Th/^{233}U$ (Th/U) vs $^{238}U/^{239}Pu$ (U/Pu) fuels. To optimize certain sets of interacting economic, engineering, and safeguards/nonproliferation considerations, practical fuel cycle systems using recycle fuels in power reactors may use combinations of thorium/uranium (Th/U) and uranium/plutonium (U/Pu) fuels. For example, the operational Fort St. Vrain high-temperature gas-cooled reactor utilizes a mix of ^{238}U-$^{235}U^{232}Th$ materials in its core and blanket in anticipation of ^{233}U, ^{235}U recycle. The following compares on a generic basis the significant radiological impacts associated with the implementation of either the thorium or uranium fuel cycle.

Recycle fuel systems involve complex networks of specific, often geographically independent, facilities, each of which contributes to the overall fuel cycle release of radioactive materials to the environment. To assess the relative radiological impacts of the Th/U and U/Pu fuel cycles, it is not necessary to analyze in depth the spectrum of radiological impacts associated with each part of the fuel cycle. We will identify those components of the fuel cycles which present a significant radiological impact and limit our comparison of the two fuel cycles to these components. This report compares the impacts associated with the routine operations of the two fuel cycles and does not consider the radiological impacts associated with accidental releases nor occupational hazards.

Table 1 lists the estimated whole body, bone, and lung person-rem 50-yr U.S. and world population dose commitments from the operation of various parts of the uranium nuclear fuel cycle normalized to a GW(e)-yr of energy production (see footnote a Table 1). The estimated radiological impacts in Table 1 are for a fuel cycle in which only uranium is recycled and are derived from data in the *Final Generic Environmental Statement on the Use of Recycle Plutonium in Light Water Cooled Reactors* (GESMO).[1] Table 2 shows analogous 70-yr population dose commitments for a light-water breeder reactor (LWBR) thorium/uranium fuel cycle taken from the *Final Environmental Statement Light Water Breeder Reactor Program.*[2] Because of

*Health and Safety Research Division.

Table 1. United States and world population 50-yr dose commitments from the uranium nuclear fuel cycle

Fuel cycle component	Person-rem per GW(e)-yr[a]		
	Whole body	Bone	Lung
Mining	660[b]	2170[b]	204[b]
Milling	130[b]	420[b]	39[b]
UF_6	9.7	23	0.22
Enrichment	0.032	0.24	0.11
UO_2 fuel fabrication	0.64	10	0.037
MOX fuel fabrication	0	0	0
Reactor operations	77	276	76
Irradiated fuel storage	0.004	0.004	0.008
Fuel reprocessing	270	660	290
Transportation	0.40	0.40	0.40
Waste management	0.001	0.011	0.001
Industry total (U.S.)	1150	3560	609
Foreign additional	230	830	316

[a]Values are for a fuel cycle in which only uranium is recycled. The numbers are normalized to a 26-yr period Jan. 1, 1975 - Dec. 31, 2000. The estimated electrical energy produced from nuclear reactors during this time corresponds to 3990 MW(e)-yr or 4990 1000-MW(e) reactors operating at a capacity factor of 0.8 for 1 year. The numbers were obtained by dividing the integrated (26-yr) population doses in the tables referenced below by 3990. Basis for the calculation was developed by W. Davis of ORNL.

[b]A recent U.S. government report estimates the total-body 100-yr dose equivalent from uranium mining and milling (normalized to dose and health effect factors associated with the body, bone, and lung and summed) could be as low as 210 person-rem per Reference Reactor Year (i.e., 0.8 GW(e)-yr): U.S. Nuclear Regulatory Commission, *Radon Releases from Uranium Mining and Milling and Their Calculated Health Effects*, USNRC Report NUREG-0757, p. 5-5, February 1981; see also Federal Register 46 (42), p. 15165, Mar. 4, 1981.

Source: U.S. Nuclear Regulatory Commission, *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors*, USNRC Report NUREG-0002, Vol. 3, Tables IV J(E)-1, -3, -7, August 1976.

Table 2. United States and world population 70-yr dose commitments from a light-water breeder reactor thorium/uranium fuel cycle

Fuel cycle component	Person-rem per reactor year[a]		
	Whole body	Bone	Lung
Mining	14 to 6.1	550 to 240	58 to 25
Milling	32 to 14	780 to 360	80 to 37
UF_6	0.003	0.06	0.02
Enrichment	0.003	0.04	0.02
Fuel fabrication	$<1 \times 10^{-5}$	$<1 \times 10^{-4}$	$<1 \times 10^{-4}$
Reactor operations	260 to 230	690 - 620	120 to 110
Irradiated fuel storage	$<1 \times 10^{-4}$	$<1 \times 10^{-3}$	$<1 \times 10^{-3}$
Fuel reprocessing	52 to 49	65 to 60	50 to 48
Transportation	1.1 to 1.5	1.1 to 1.5	1.1 to 1.5
Waste management	$<1 \times 10^{-5}$	$<1 \times 10^{-4}$	$<1 \times 10^{-5}$
Industry total	360 to 300	2090 to 1280	310 to 220

[a]For one 1000-MW(e) reactor operating for 1 yr at 0.7 load factor.

Source: Energy Research and Development Administration, *Final Environmental Statement Light-Water Breeder Reactor Program,* ERDA-1541, Vol. 3, pp. IX-178 to IX-187, June 1976.

the differences in the bases and parameters used in estimating the dose commitments, one cannot make a comparison of the relative impacts of the two fuel cycles from the data in the tables. However, it is clear that the dose commitments from mining and milling, reprocessing, and reactor operations dominate the radiological impacts from the operation of the fuel cycle. Minimal radiological impacts are associated with fuel fabrication, fuel refabrication, fuel storage, waste management, and transportation. The conversion to UF_6 contributes <1% to the total fuel cycle impact of the uranium fuel cycle and would have a lower relative impact in the Th/U fuel cycle. Hence, we will limit our comparison of the two fuel cycles to the following:

1. the mining and milling of thorium ore (Th/U cycles) vs uranium ore (U/Pu cycles);

2. the reprocessing of Th/U vs U/Pu fuels, and

3. the relative impacts of reactor operations in the two fuel cycles — reactors considered: light-water reactor (LWR) operating on recycle fuel; the light-water breeder reactor (LWBR); the high-temperature gas-cooled reactor (HTGR), and liquid-metal fast-breeder reactor (LMFBR).

2. MINING AND MILLING OF THORIUM AND URANIUM ORES

A comparison of the radiological impacts related to mining and milling of thorium and uranium should, ideally, proceed from a common base of data, models, and assumptions. However, the literature contains no examples of analyses allowing direct comparison of radiological doses between those operations of the two fuel cycles. Furthermore, because of variations in assumptions regarding population distributions, meteorological summaries, radiological dose conversion factors, and data bases for mining operations, it is not possible to make specific comparisons of the impact of facility operations. Nonetheless, enough similarities exist between two recent studies that, combined with information from GESMO and a recent report on the milling of uranium ores,[3] one can make some rather general conclusions regarding the relative impact of the facilities, particularly thorium vs uranium milling operations.

2.1 Radiological Impact During Operation

A study by Tennery et al.[4] analyzes the potential impacts resulting from the operation of a facility involving an open-pit thorium mine and a model thorium mill and refinery. The characteristics of the mine and mill are similar to those in the environmental statement for the Light-Water Breeder Reactor (LWBR) program.[5] The mine is an open-pit thorium mine producing 1600 metric tons (MT) of ore per day, containing an average thorium

content equivalent to 0.5 wt % of ThO_2. The thorium mill is hypothesized to process 1600 MT of ore per day, producing 4500 MT of $Th(NO_3)_4 \cdot 4H_2O$ per year. Radioactivity leaves the complex as ^{220}Rn (55.6-s half-life) from the mine, ore storage pile, mill refinery, and tailings beach, and as airborne dust from the mining and milling operations and the tailings. Besides ^{220}Rn, radionuclides of interest are ^{228}Ra, ^{232}Th, ^{228}Th, ^{224}Ra, ^{228}Ac, and daughters of ^{220}Rn, notably, ^{212}Pb. After facility shutdown, the drying thorium-tailings area is assumed to be stabilized by covering it with earth, reducing erosion processes. Because of the 55.6-s half-life of ^{220}Rn, however, only a thin covering of earth is necessary to reduce emanation rates of the gas to near zero. Since the ^{222}Rn in the uranium decay chain has a half-life of 3.82 days, the doses associated with the retired thorium tailings pile will be very low in contrast to the impact of retired uranium tailings treated similarly.

A study by Sears et al.[6] assesses the radiological dose commitments associated with the milling of uranium ores. The study was designed to assist the U.S. Nuclear Regulatory Commission (NRC) in defining the "as-low-as-practical," now "as-low-as-reasonably-achievable," guideline for the operation of nuclear facilities. The report estimates dose vs cost for a variety of radwaste treatment options. The "base case" model mills are representative of mills that will process a major fraction of U.S. uranium ore during the next decade or so. The "base case" acid leach-solvent extraction mill corresponds in many important ways to the model thorium mill hypothesized in the thorium study mentioned above, permitting an assessment of the relative radiological impacts.

The model uranium mill in the Sears study processes 1800 MT of 0.2 wt % U_3O_8 ore per day, producing ~1000 MT of U_3O_8 per year. About 12.3 curies (Ci) of waste radioactivity leaves the mill per day as tailings waste. The radionuclides of interest are ^{238}U, ^{234}U, ^{226}Ra, ^{230}Th, ^{234}Th, ^{210}Pb, ^{210}Bi, ^{210}Po, and ^{222}Rn. Offsite releases of radioactive materials from milling operations consist of airborne ore dust, yellowcake dust, tailings dust, and radon gas during uranium mill life. After shutdown of the facility, the tailings are stabilized by covering them with earth topped by rock or vegetation. This procedure reduces wind and water erosion of the tailings but allows release of radon gas for thousands of years. No underground migration of radionuclides due to seepage is expected.

The Sears report does not discuss the radiological impact of uranium mining, but the radiological impacts below will include an assessment of the impact of uranium mining taken from the GESMO report.

2.1.1 Source terms

Table 3 lists estimated releases of radioactive materials, Ci/yr, for a hypothetical Montana-Idaho, thorium mine-mill complex, using an acid-leach-solvent extraction milling process, and Table 4 lists the releases from a hypothetical Wyoming uranium mill using similar technology. The source terms in Table 4 are reasonably representative of current uranium milling

Table 3. Airborne source terms for a model acid-leach — solvent extraction thorium mine-mill complex and active tailings area in Montana-Idaho

Source	Estimated radioactivity released, Ci/yr						
	^{232}Th	^{228}Ra	^{228}Ac	^{228}Th	^{224}Ra	^{212}Pb	^{220}Rn
Ore handling	4.4E-4[a]	4.4E-4	4.4E-4	4.4E-4	4.4E-4	4.4E-4	1.3E4[b]
Mill and refinery	1.6E-4	1.6E-4	1.6E-4	1.6E-4	1.6E-4	1.6E-4	3.1E4
Tailings beach and pond	3.2E-5	2.8E-4	2.8E-4	2.2E-4	2.2E-4	2.2E-4	1.0E4
Mine operation	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.6E-3	1.4E4

[a] 4.4E-4 = 4.4×10^{-4}.

[b] 1.3E4 - 1.3×10^{4}.

Source: V. J. Tennery et al., *Environmental Assessment of Alternate FBR Fuels: Radiological Assessment of Airborne Releases from Thorium Mining and Milling,* ORNL/TM-6474, Tables 4.1 and 4.2, October 1978.

Table 4. Airborne source terms for model acid-leach — solvent extraction uranium mill and active tailings area in Wyoming near end of 20-yr life of model mill

Source	Ci/yr					
	U_{nat}	^{226}Ra	^{230}Th	^{234}Th	^{210}Pb, ^{210}Po, and ^{210}Bi, each	^{222}Rn
Case 1						
Ore crusher and bins	4.5E-3[b]	4.5E-3	4.5E-3	4.5E-3	4.5E-3	3.7E1[b]
Yellowcake	8.5E-2	1.7E-4	4.7E-3	4.7E-3	-	3.1E2
Tailings pond	-	-	-	-	-	3.1E2
Tailings beach						
<10 μ	3.9E-4	4.2E-3	4.5E-3	3.9E-4	4.2E-3	8.7E2
10-80 μ	9.3E-4	1.0E-2	1.1E-2	9.3E-4	1.0E-2	
Total	9.1E-2	1.9E-2	2.4E-2	1.0E-2	1.9E-2	1.2E3

[a] 4.5E-3 = 4.5×10^{-3}.

[b] 3.7E1 = 3.7×10^{1}.

Source: M. B. Sears et al., *Correlation of Radioactive Waste Treatment Cost and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "as low as practicable" Guides - Milling of Uranium Ores*, ORNL/TM-4903, Vol. 1, Table 4.7, May 1975.

practice in older mills. It should be noted that the releases in Table 4 are for a facility producing about one-half the product (i.e., U_3O_8) tonnage per year when compared to the thorium facility production rate. Comparison of Tables 3 and 4 indicates that the quantities of radionuclides released to the environment from the two facilities are of similar magnitude. However, the radioactive daughters of ^{232}Th are relatively short-lived, while several of the daughters of ^{238}U are long-lived. Table 5 lists the radioactive half-lives of several isotopes from the two decay chains. Removal of 91% of the ^{232}Th parent from the thorium chain will greatly reduce the long-term radioactivity of thorium tailings, whereas removal of ^{238}U from the uranium tailings has little effect on the radioactivity levels for thousands of years.

Considering the mines themselves, the only significant radioactive release would be radon gas — ^{220}Rn in the case of thorium and ^{222}Rn in the case of uranium. It has been estimated that the ^{220}Rn release from the 12-acre open-pit model thorium mine would be ~37 Ci/day or ~1.35 x 10^4 Ci/yr.[7] Because of atmospheric dispersion and its rapid decay, the air concentration at a hypothetical site boundary of 800 m (0.5 miles) ($\frac{\chi}{Q}$ ca. 1 x 10^{-6}) would be ~8 x 10^{-12} μCi/ml. The ^{222}Rn release from a model uranium mine was estimated at 3 Ci/day or 1095 Ci/yr.[7] For similar conditions, the air concentration of ^{222}Rn at the site boundary would be ~4 x 10^{-10} μCi/ml or two orders of magnitude higher. All concentrations are orders of magnitude less than the limits for an unrestricted area in 10 CFR 20.

2.1.2 Dose commitments

The source terms in Tables 3 and 4 were used to estimate 50-yr radiological dose commitments, using similar dispersion and uptake computer codes, thus enabling a comparison of the relative impacts of the operation of the thorium and uranium facilities. The 50-yr dose commitment as used in the above reports is the total dose accrued in an individual over a 50-yr period following the intake of radioactivity during 1 yr of exposure to the radioactive effluents from the facilities.

Tables 6 and 7 list dose commitments resulting from the operation of the thorium and uranium facilities. The doses are calculated for a maximally exposed individual residing near the facility, subsiding on foods grown locally, and living in a wind direction maximizing the dose. Doses from the uranium mill are calculated for an individual residing 800 m (0.5 mile) from the facility center and doses from the thorium mine-mill complex to an individual 1600 m (1 mile) distant. This increased distance from the thorium facility will reduce the estimated dose by a factor of ~2.6 over that which would have been received at 800 m (0.5 mile).[3] However, the increased through-put of the thorium over the uranium mill (2200 vs 1000 MT of oxide product per year) approximately compensates for this reduction, allowing rough comparison of the data.

The doses from the thorium operation (Table 6) include dose commitments resulting from the mining of thorium, while corresponding uranium mining doses are not included in Table 7. Doses are estimated for two sets

Table 5. Radioactive half-lives for selected isotopes in the ^{232}Th and ^{238}U decay chains

^{238}U		^{232}Th	
	T 1/2		T 1/2
^{238}U	4.5×10^{9} yr	^{232}Th	1.39×10^{10} yr
^{234}Th	24.1 d	^{228}Ra	5.75 yr
^{234}U	2.47×10^{5} yr	^{228}Th	1.9 yr
^{230}Th	7.7×10^{4} yr	^{224}Ra	3.64 d
^{226}Ra	1.6×10^{3} yr	^{212}Pb	10.6 h
^{210}Pb	22.3 yr	^{212}Bi	60.6 m
^{210}Po	138 d		
^{222}Rn	3.82 d	^{220}Rn	55.6 s

Table 6. Maximum individual 50-yr dose commitments from airborne effluents during 1 yr of model thorium mining and milling complex operation[a]

Meteorology	Dose commitment (mrem)						
	Total body	GI tract	Bone	Thyroid	Lungs	Kidneys	Liver
				Lemhi Pass site			
Butte, Montana	2.4	4.1	9.5	2.4	35.3	4.3	2.9
Mullan Pass, Idaho	2.4	3.7	9.4	2.4	32.0	3.9	2.7

[a]Dose commitments assume that 100% of the food consumed is produced locally.

Source: V. J. Tennery et al., *Environmental Assessment of Alternate FBR Fuels: Radiological Assessment of Airborne Releases from Thorium Mining and Milling,* ORNL/TM-6474, Table 6.1, October 1978.

Table 7. Maximum individual 50-yr dose commitments from airborne effluents during 1 yr of model uranium mill operations in Wyoming[a]

	Dose commitment (mrem)		
	Mill	Tailings	Total
Total body	16.4	44.4	60.9
Bone	189.4	447.9	637.3
Liver	19.1	51.7	70.8
Kidney	32.5	71.9	104.4
Spleen	19.3	57.7	77.0
Lung	23.6	44.1	67.7

[a]Twentieth year of operation when tailings cover maximum area. Dose commitments assume that 100% of the food consumed is produced locally.

Source: M. B. Sears et al., *Correlation of Radioactive Waste Treatment Cost and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "as low as practicable" Guides -Milling of Uranium Ores*, ORNL/TM-4903, Vol. 1, May 1975. The doses are the sum of the doses from airborne particulates and ^{222}Rn gas from the operating mill and active tailings area listed in Tables 7.7c, 4.12, and 7.13.

of meteorological data in Table 6 (Butte and Mullan Pass) because of the lack of site-specific data. Dose commitments from the operation of the thorium facility are 2.4 mrem total body, 9.5 mrem bone, and 35 mrem lung. Daughters of ^{220}Rn are largely responsible for these doses, although ^{228}Ra also contributes significantly to all but lung doses.

Table 7 lists dose commitments resulting from uranium operations. Doses are seen to be large, particularly from tailings pile emissions, and the need for increased control of effluents for this base case facility is apparent.

Table 8 lists the estimated annual maximum individual dose commitments resulting from the operation of a model open-pit uranium mine described in GESMO, producing annually 2.0×10^5 MT of ore containing 0.1 wt % U_3O_8.[8] It was assumed that ^{222}Rn was the only significant radioactive material released from the mine, that the maximally exposed individual lived 500 m (~0.3 mile) from the facility, and that all of his food was produced at this location. The annual dose commitment to the closest theoretical resident ranged from <1 mrem to whole body and a number of organs such as the skin, thyroid, and GI tract to as much as 8.7 mrem to the lung and 4.7 mrem to the kidney. In the unlikely event of an individual living 500 m (~0.3 mile) from a 20,000-ton-per-yr underground mine, it is estimated that the dose commitments would be about one-tenth of the tabulated values.[8]

While direct comparison of doses resulting from the operation of the thorium vs uranium facilities is not possible because of differences in data bases, it appears that the milling of thorium poses a reduced radiological hazard when compared to uranium milling. While no direct comparison of the impact of thorium vs uranium mining is possible from the above, it also appears that thorium mining poses a lower radiological impact than does uranium mining. The milling operations as opposed to mining result in the larger radiological impact in the immediate vicinity of the facilities. However, the continental impact of the uranium mining and milling industry operations are apparently comparable.[9] In any case, amelioration procedures available to the milling industry allow reduction of doses from either uranium or thorium operations to any level required by the regulations.

We are speaking here only of the radiological impact to off-site individuals. It may very well be that occupational radiological hazards of the operation of the thorium and uranium facilities may be comparable. It may also be that, independent of the radiological inhalation hazards, the operation of thorium facilities may require more stringent measures to protect workers because of the more serious health risks associated with thorium ingestion as opposed to uranium.

2.2 Post-Shutdown Radiological Impact

The above discussion applies to doses from the operation of the milling facilities. It is also important to consider differences in impact between Th/U vs U/Pu activities in terms of post-operational effects.

Table 8. Maximum individual 50-yr dose commitments from airborne effluents of a model uranium mine

Organ dose (mrem/yr)[a]						
Whole body	Bone	Lung	GI Tract	Liver	Kidney	Thyroid
0.29	2.1	8.7	0.27	1.5	4.7	0.0006

[a]Based on estimated ^{222}Rn effluent from open-pit mine producing 200,000 tons per year of 0.1 % U_3O_8 ore. $\chi/Q = 5.4 \times 10^{-6}$ s/m^3 at 500 m (~0.3 miles) for release at ground level.

Source: U.S. Nuclear Regulatory Commission, *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors,* USNRC Report NUREG-0002, Vol. 3, p. IV F-20, August 1976.

Management of uranium tailings piles is complicated by the presence of long-lived precursors of ^{222}Rn (see Table 5), leading to radiological doses from both the emanation of radon gas from the tailings and windblown dusts suspended from the piles. Extraction of 91% of ^{232}Th from the thorium milling wastes reduces the activity of thorium tailings by a factor of 10, and the remaining radionuclides decay in equilibrium with ^{228}Rn ($T_{1/2}$ = 5.75 yr). Removal of ^{238}U from the uranium chain has little effect on tailings radioactivity levels for thousands of years. Radon-220 gas created in the thorium tailings is much less mobile than is ^{222}Rn in the uranium tailings because of the short half-life of ^{220}Rn. A few feet of compacted earth is estimated to reduce the ^{220}Rn source term to near-zero.

Both the reports by Tennery et al.[4] and Sears et al.[6] consider the question of postoperational maintenance of tailings piles in detail, and it is apparent that, for a given level of control, the radiological hazard encountered following plant shutdown is significantly lower for the thorium facility. Extensive stabilization and sealing procedures are expected to be necessary to provide sufficient isolation of uranium tailings from the environment, and Sears et al. discuss a number of ongoing projects involving coverage and reseeding of existing tailings piles. No such extensive procedures are anticipated to be necessary for thorium tailings, although Tennery et al. caution that site-specific evaluations of western U.S. thorium mills (if these are ever constructed) will be necessary to confirm these conclusions.

3. REPROCESSING OF Th/U AND U/Pu FUELS

No commercial reprocessing facility is currently in operation in the United States. A number of detailed studies of hypothetical facilities are available, however (see refs. 4, 5, and 10 through 19), and several are sufficiently similar in terms of data and methodologies applied that meaningful comparisons may be made between the thorium and uranium operations. Two of these studies[12,17] are particularly useful in this comparison. Both develop flow sheets, radionuclide characterizations via the ORIGEN computer code, and radionuclide release rates and dose commitments for facilities reprocessing LMFBR spent fuels. One of the reports (1976) considers (U,Pu) carbide fuel containing 150 ppm nitrogen, a ^{14}C precursor.[12] The other (1978) considers (Th/^{233}U) carbide fuel containing 300 ppm nitrogen.[17] The higher nitrogen content of the (Th,U) fuel somewhat increases ^{14}C production by neutron capture in the LMFBR. The studies consider inputs from a quantity of spent fuel from the generation of 50 GW(e)-yr of energy and utilize similar confinement factors in the hypothetical reprocessing plants.

Table 9 lists estimated release rates in μCi/yr for radionuclides of interest. Gaseous radionuclides dominate the source terms. Variations in the spectra of fission products for ^{239}Pu vs ^{233}U account for the variations seen in production and release rates for several radionuclides listed. Figure 1 displays the shift to lower mass number thermal fission products for Th/^{233}U vs U/^{239}Pu fuels. Increased ^{14}C production in the

Table 9. Comparison of radioactive airborne effluents from chemical plants reprocessing 1-yr-decayed spent LMFBR fuel equivalent to 50 GW(e)-yr of generated energy

Radionuclide	U/Pu[a] (150 ppm N) (μCi/yr)	Th/U[b] (300 ppm N) (μCi/yr)
^{3}H	9.2E10[c]	8.3E10
^{14}C	2.0E7	3.8E7
^{85}Kr	7.5E10	3.3E11
^{129}I	5.8E3	8.2E3
^{106}Ru	7.7E5	7.9E4
^{90}Sr	1.1E4	3.8E4
^{137}Cs	2.8E4	3.5E4
^{228}Th	-	5.3E3
^{232}U	-	8.4E3
^{238}Pu	5.4E3	4.7E1
^{239}Pu	2.7E3	2.2E-3
^{241}Am	1.4E2	-
^{244}Cm	2.0E1	-

[a]Data obtained from V. J. Tennery et al., *Environmental Assessment of LMFBR Advanced Fuels: A Radiological Analysis of Fuel Reprocessing, Refabrication and Transportation*, ORNL-5230, p. 17, November 1976.

[b]Data obtained from V. J. Tennery et al., *Environmental Assessment of Alternate FBR Fuels: Radiological Assessment of Reprocessing and Refabrication of Thorium/ Uranium Carbide Fuel*, ORNL/TM-6493, p. 26, August 1978.

[c]9.2E10 = 9.2×10^{10}.

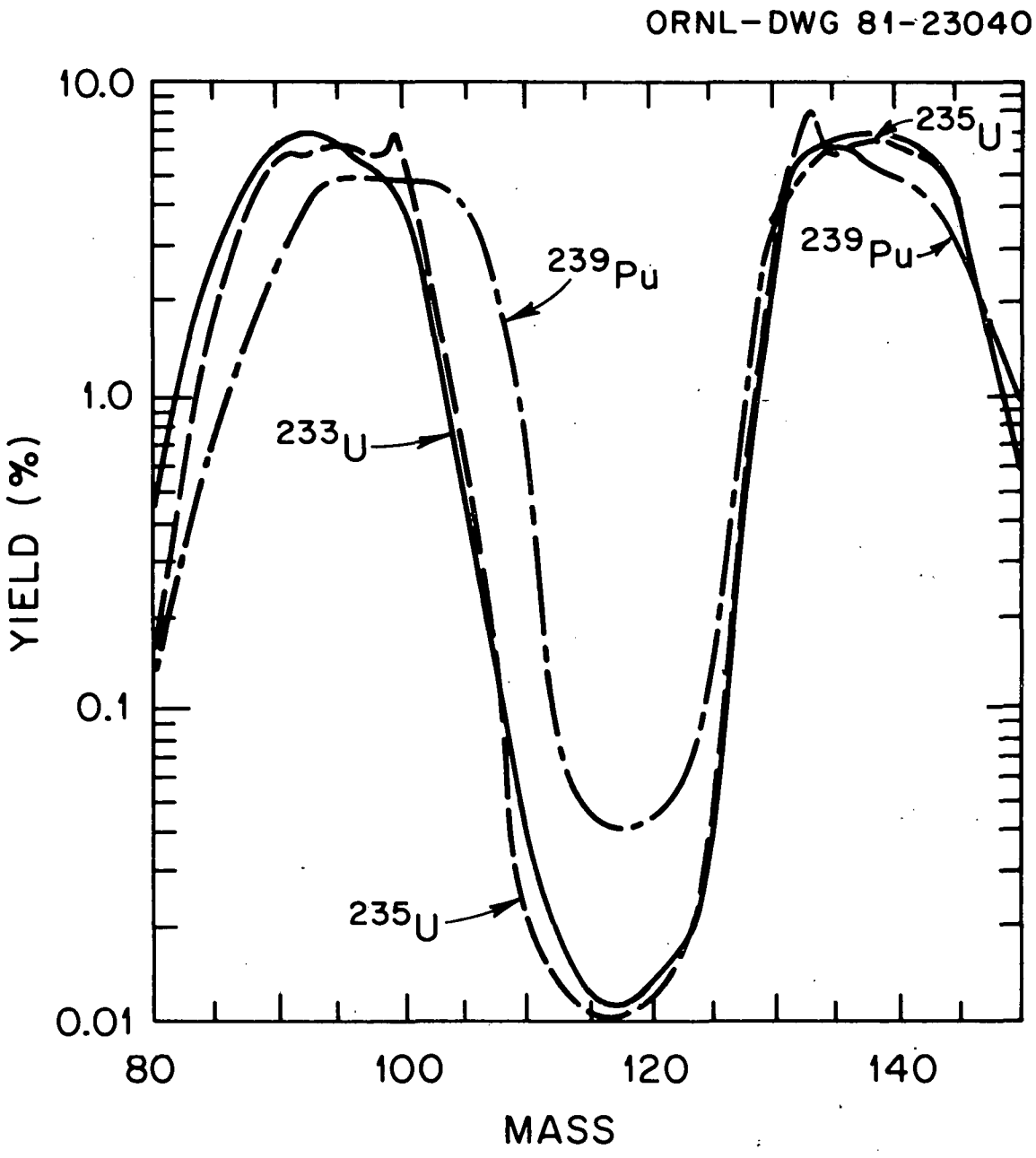

Fig. 1. Mass-yield curves for thermal-neutron fission of ^{233}U, ^{235}U, and ^{239}Pu. Source: U.S. Nuclear Regulatory Commission, *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors*, USNRC Report NUREG-0002, Vol. 3, p. IV. C-59, August 1976.

Th/U fuel (Table 9) is largely due to higher nitrogen content of that fuel, a feature not necessarily characteristic of thorium fuels in general. Decreased heavy actinide production in the thorium fuels results from the lack of precursor ^{238}U. Uranium-232 production in thorium fuels results from transmutation of ^{232}Th and ^{230}Th. In general, however, there are few significant differences in the radionuclide source terms from the reprocessing of the two generic fuels.

Dose commitments were calculated in the two assessments for both (1) a maximally exposed individual located 1000 m (~0.6 miles) from the plants, and (2) a general population of 10^6 individuals distributed uniformly within an 80.5-km (50-mile) radius. Meteorological data used in the two studies were identical.

Table 10 summarizes the estimated dose commitments from the operation of the two facilities. Doses to both the maximally exposed individual and to the general population are seen to be similar for the two fuel types, although some variation in doses to individual organs is apparent. Differences in doses calculated are not seen to be sufficient to exclude either fuel type from any proposed implementation scheme, since the estimated doses are low and the assumptions used in the estimating procedures were conservative. Radionuclides found to contribute significantly to the doses are ^{3}H, ^{137}Cs, ^{14}C, ^{232}U (Th/U only), and ^{106}Ru.

The most restrictive set of regulations currently applicable to the uranium (U/Pu) fuel cycle is in the *Code of Federal Regulations*, Title 40, Part 190 (10 CFR 190), "Environmental Radiation Protection Standards for Nuclear Power Operations." promulgated by the U.S. Environmental Protection Agency (EPA).[20] The EPA standard limits doses to any member of the public from planned releases from any uranium fuel cycle operations to 25 mrem to total body and other organs except the thyroid; the thyroid dose is limited to 75 mrem. The regulations also limit total quantities of specific radionuclides released to the general environment (per GW(e)-yr generated) to 50,000 Ci of ^{85}Kr, 5 mCi of ^{129}I, and 0.5 mCi of alpha-emitting transuranics with half-lives >1 yr (this latter group includes $^{238,239}Pu$). Mining operations, and radon and daughters generated during milling operations are specifically excluded from the EPA regulations. No equivalently restrictive code is applicable to the Th/U cycle, although one would anticipate equivalent regulation by EPA if the thorium cycles were to be implemented. However, the differences encountered in the radiological impacts associated with reprocessing either of the two fuel types are small and not significant in the context of other factors entering into the choice of fuel cycle systems.

While the above analysis is specific to U/Pu, Th/U LMFBR fuels, extensive review of the literature pertaining to HTGR and LWR reprocessing facilities and related releases appears to support extension of the above conclusions to these systems. Production of increased levels of ^{14}C during the burning of HTGR fuels in reprocessing is not a necessary characteristic of all Th/U fuels. Releases of ^{239}Pu, ^{232}U, or ^{233}U and other heavy actinides from a Th/U or U/Pu reprocessing facility would not be expected to significantly modify doses related to the operation of that facility in a

Table 10. Comparison of the annual 50-yr dose commitment from the reprocessing of 1-yr-decayed spent U/Pu and Th/U carbide fuels equivalent to 50 GW(e)-yr of generated energy

	Maximally individual dose at 1000 m (mrem/yr)		80-km-radius population dose, 10^6 persons (man-rem/yr)	
	U/Pu[a]	Th/U[b]	U/Pu[a]	Th/U[b]
Total body	2.9	3.1	33	39
GI tract	14	4.6	126	51
Bone	6.9	4.1	68	48
Thyroid	4.1	6.8	40	60
Lungs	2.8	3.3	32	40
Kidneys	3.3	2.9	36	37

Radionuclide contribution to maximum individual total-body dose, %

Radionuclide	U/Pu[a]	Th/U[b]
^{3}H	75	64
^{14}C	4.7	8
^{85}Kr		1
^{90}Cr		1
^{106}Ru	4.6	1
^{137}Cs	10	13
^{228}Th		1
^{232}U		9
^{238}Pu	1	

[a]Data obtained from V. J. Tennery et al., *Environmental Assessment of LMFBR Advanced Fuels: A Radiological Analysis of Fuel Reprocessing, Refabrication and Transportation*, ORNL-5230, pp. 27, 29, November 1976; (U,Pu) Carbide Fuel, 150 ppm N.

[b]Data obtained from V. J. Tennery et al., *Environmental Assessment of Alternate FBR Fuels: Radiological Assessment of Reprocessing and Refabrication of Thorium/Uranium Carbide Fuel*, ORNL/TM-6493, p. 73, August 1978; (Th,U) Carbide Fuel, 300 ppm N.

non-breeding, uranium cycle. Additional levels of confinement are possible for reprocessing facilities as technology becomes available and cost-effective, with a possible further reduction in doses related to reprocessing operations.

4. REACTOR OPERATIONS

Analysis of the rate of release of radioactive effluents at the site of an operating reactor indicates few significant differences related directly to the choice of either (Th, ^{233}U) or (U, ^{239}Pu) fuel in these reactors. Liquid releases and airborne releases of particulate fission and activation products are anticipated to be very low for all reactors considered here.

For LWR, HTGR, and LMFBR systems, most of the radioactive material generated during reactor operation remains in the spent fuel and is collected at reprocessing facilities. Only a minor fraction of the total radioactivity is released during routine operations at a reactor site. Several sources contribute to the radioactive material available for reactor site release:

1. nuclear activation of structural materials and chemical reagents used in the reactors;

2. fission or activation of "tramp" uranium or thorium on the fuel cladding; and

3. failure of the fuel pin cladding.

Radioactive effluents are released to the environment through either the stack or cooling tower.

Significant variations in the quantities of gaseous radionuclides released occur between reactor types. Carbon-14 and ^{41}Ar result from the neutron activation of isotopes in water, air, and structural materials (e.g., ^{14}C from activation of graphite in the HTGR) and are thus not directly related to the fuel cycle. Tritium production in GESMO mixed uranium-plutonium oxide (MOX) fueled reactor is estimated to be slightly higher than that for a comparable LWR, as indicated in Table 11. Table 11 also lists estimated release rates of other gaseous effluents for MOX vs uranium-fueled reactors.

No studies are available allowing direct comparison of source terms or estimated dose commitments for (Th, ^{233}U)- vs (U, ^{239}Pu)-fueled reactors. Tables 12 and 13, listing gaseous effluents for the (Th, ^{233}U)-fueled LWBR and the (U, ^{239}Pu)-fueled LMFBR, display significant differences in release rates for the two reactor types. However, the decreased release noted for ^{85}Kr in Table 13 is largely the result of the assumption of effective containment procedures for this gas upon implementation of the LMFBR system. Such a containment system should also be available for

Table 11. Estimated radioactivities in airborne effluents from 1000-MW(e) PWRs with U-tube steam generators, Ci/yr

Nuclide	GESMO model 1.15 SGR mixed-oxide[a] fuel	Uranium only fuel
Noble gases		
^{41}Ar	25	25
^{83m}Kr	1	1
^{85m}Kr	13	16
^{85}Kr	340	470
^{87}Kr	3	3
^{88}Kr	17	23
^{89}Kr	b	b
^{131m}Xe	87	82
^{133m}Xe	120	120
^{133}Xe	12,000	12,000
^{135m}Xe	b	b
^{135}Xe	90	86
^{137}Xe	b	b
^{138}Xe	b	b
Total	13,000	13,000
Others		
^{131}I	0.027	0.025
^{133}I	0.023	0.023
^{14}C	8	8
^{3}H	1200	1100
Particulates	0.06	0.06

[a]Equilibrium Pu recycle; $(U,Pu)O_2$ fuel.

[b]Annual release <1 Ci.

Source: U.S. Nuclear Regulatory Commission, *Final Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors*, USNRC Report NUREG-0002, Vol. 3, p. IV.C-106, August 1976.

Table 12. Estimated radioactivities in airborne effluents from a 1000-MW(e) LWBR operating for 1 yr at a 0.7 load factor

Nuclide	Reactor release (Ci/reactor-yr)
Noble gases	
^{83m}Kr	5.5 to 6.2
^{85}Kr	1100 to 1200
^{85m}Kr	25 to 32
^{87}Kr	15 to 17
^{88}Kr	44 to 48
^{131m}Xe	76 to 79
^{133}Xe	2800 to 2800
^{133m}Xe	6.0 to 7.6
^{135}Xe	100 to 110
^{135m}Xe	1.4 to 1.3
Total	4172.9 to 4301.1
Others	
^{129}I	1.7×10^{-9} to 2.2×10^{-9}
^{130}I	1.9×10^{-4} to 2.5×10^{-4}
^{131}I	0.053 to 0.055
^{132}I	0.0026 to 0.0027
^{133}I	0.036 to 0.035
^{135}I	0.0023 to 0.0022
^{135}I	0.010 to 0.010
^{3}H	1100 to 1000
^{14}C	3.4 to 3.0

Source: Energy Research and Development Administration, *Final Environmental Statement, Light-Water Breeder Reactor Program*, ERDA-1541, Vol. 3, p. IX-176, June 1976.

Table 13. Estimated radioactivities in airborne effluents from a 1000-MW(e) LMFBR operating for 1 yr at a 0.8 load factor

Nuclide	Atmospheric release Ci/yr
^{3}H	60.0
^{39}Ar	80.0
^{85m}Kr	0.3
^{85}Kr	0.4
^{87}Kr	0.4
^{88}Kr	0.5
^{133}Xe	0.03

Carbon-14 generation rates, Ci/GW(e)-yr

	LMFBR	PWR	BWR	HTGR
Fuel	5	13	15	2
Cladding	6	4	5	158
Coolant	-	6[a,b]	16[c]	-
Total	11	23	36	160[d]

[a]This value is taken from a paper by C. Kunz et al., "C-14 Gaseous Effluent from Pressurized Water Reactors," pp. 229-34 in *Proceedings of the Eighth Midyear Topical Symposium of the Health Physics Society*, Oct. 21-24, 1974, CONF-741018, 1975.

[b]Another estimate, 14 Ci/GW(e)-yr, has been made by the U.S. Atomic Energy Commission "Report on Releases of Radioactivity in Effluents and Solid Wastes from Nuclear Power Plants for 1972," Directorate of Regulatory Operations, 1973 — Yankee Rowe.

[c]Data taken from C. Kunz et al., "^{14}C Gaseous Effluents from Boiling Water Reactors," Trans. Am. Nucl. Soc. 21:91 (1975).

[d]Data taken from the report by L. H. Brooks et al., *Carbon-14 in the HTGR Fuel Cycle*, GA-A13174, November 29, 1974.

Source: *Proposed Final Environmental Statement, Liquid-Metal Fast Breeder Reactor Program*, U.S. Atomic Energy Commission, WASH-1535, Vol. II, Sect. 4.2, December 1974; *Final Environmental Statement, Liquid-Metal Fast Breeder Reactor Program*, U.S. Energy Research and Development Administration, ERDA-1535, December 1975.

thorium fuel cycle systems. The low tritium releases from LMFBR are at least partly due to the smaller production of ^{3}H in the LMFBR. LMFBR, PWR, and LWBR produce roughly comparable quantities of ^{3}H by ternary fission, but the major quantity of PWR and LWBR ^{3}H is formed in the primary coolant.

A direct comparison of Th/U and U/Pu fuel substitution in comparable reactors is not currently available in the literature. Indirect comparison, however, through estimated fission and activation product inventories indicates that no significant differences in terms of routine environmental radiological impact should be anticipated for reactors using either of the two cycles.

5. SUMMARY

Based on a review of the available literature and participation in related studies, it is our opinion that radiological impacts to the general public associated with routine releases of radionuclides from both thorium/uranium and uranium/plutonium recycle systems will be acceptably low. Technology to meet existing or anticipated radiological standards arise. The larger dose commitments associated with current uranium mine/mill facilities compared to hypothetical thorium facilities are clearly the major significant difference in radiological impact of the Th/U and U/Pu fuel cycles. Advanced release-abatement procedures for uranium mines and mill tailings are available for active and inactive sites. Only moderate variations in production and release rates of radioactive gases are seen for reactors and reprocessing facilities of either fuel cycle. Other components of the fuel cycles (fuel fabrication, fuel refabricatiion, fuel or waste storage, and transportation) result in relatively low dose commitments and need not enter into this comparison. Occupational doses, an area of study specifically excluded from the environmental analysis reported here, could vary significantly from one generic fuel cycle to another.

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