EFFECTS OF AN LMR-BASED PARTITIONING-TRANSMUTATION SYSTEM ON U.S. NUCLEAR FUEL CYCLE HEALTH RISK

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ABSTRACT

Health risks for the current U.S nuclear fuel cycle and for an illustrative partitioning and transmutation (P-T) fuel cycle based on LMR technology are calculated and compared. Health risks for the P-T fuel cycle are calculated for all non-reactor fuel cycle steps, including reprocessing, transportation and high-level waste disposal. Uranium mining and milling health risks have been updated to include recent occupational injury and death statistics, and the radiological health risk of the uranium mining overburden to the general public. In addition, the radiological health risks for transportation have been updated to include latenet cancer fatalities associated with both normal transport and accidents. Given the assumptions of the study, it is shown that the deployment of an LMR-based P-T system is expected to reduce overall nuclear fuel cycle health risk. An economic value is assigned to these health risk benefits based upon recent economics literature on the public's willingness to pay (WTP) to reduce the risk of morbidity and premature mortality.

INTRODUCTION

The projected impact of an advanced fuel cycle concept on the environment and on the public health is a major criterion by which. the concept will be judged Recent evaluations by Chang[1], Pigford,[2] Forsberg,[3] and Ramspott[4] have focused attention on the impact of partitioning-transmutation (P-T) fuel cycles on the health and environmental impacts of a high-level waste (HLW) repository. However, the implementation of P-T technology would alter much more than the characteristics of HLW reporting to a repository. Indeed, P-T fuel cycles involve the operation of reprocessing plants, different reactor systems, and different levels of tint-end fuel cycle operations, all of which can be expected to modify the health and environmental impacts of nuclear energy.

Recent work by Michaels[5] has addressed the issue of the impact of a specific P-T concept, the advanced liquid metal reactor (ALMR)/integral fast reactor (IFR) system, on nuclear fuel cycle health risks. The major conclusion of this study was that recycle of actinides based on these technologies has the potential to reduce the overall fuel cycle health risk, and that the magnitude of this beneficial impact appears to be much greater than the entire health risk attributed to the geologic repository.

This paper builds on this previous work and attempts to correct some of its limitations. A major limitation of the prior work was the absence of any consideration of transportation health risks to the general public. In this paper, we calculate *transportation* health risks for the current U.S. nuclear fuel cycle and present estimates of the modified health risk associated with a P-T fuel cycle. A second limitation was the outdated nature of some of the basis assumptions for the health impacts. This paper updates the following assumptions.

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- Radiation dose factors, which had been based *on* the values recommended by the 1980 report of the National Academy of Sciences (NAS) Committee on the Biological Effects of Ionizing Radiation (BEIR III)[6] values, are now based on the values recommended in the 1990 report by the same NAS Committee (BEIR V).[7]
- HLW repository health impacts now reflect recent performance assessment studies for the proposed Yucca Mountain site.
- The health effects of mining accidents have been updated to include recent U.S mining accident incidence data.
- Radioactive releases from the waste rock discarded from uranium mining operations have been recently estimated by the U.S. Environmental Protection Agency (EPA) and are now included.

FUEL CYCLE DEFINITIONS

The two fuel cycles to be studied are defined below.

1. **The LWR once-through fuel cycle.** This is the currently existing U.S. nuclear fuel cycle in which unprocessed spat fuel is emplaced in a geologic repository. No recycle of uranium or transuranic elements occurs. The light-water reactors (LWRs) in this fuel cycle and in the actinide burning fuel cycle are assumed to be loaded with 4-2% enriched $U0_2$ fuel and operated at fuel burnups of 50,000 MWd/MT.

2 **The ALMR fuel cycle** with uranium recycle. The ALMR deployment level is defined to be one that results in 21% of nuclear electricity production occurring in ALMRs and the remaining 79% of electricity production occurring in LWRs. This fuel cycle is illustrated in Fig. 1. Spent LWR fuel is removed from inventory and repressed as in a centralized LWR-actinide recycle (LWR-AR) plant. The separation technology used in the LWR-AR plant IS not defined, but it is assumed to have releases of radioactive effluents similar to a standard aqueous plant. The recovered uranium is assumed *to be converted to* UF_6, reenriched, and recycled as fuel to LWRs. The recovered transuranics are used as fuel in an ALMR, defined in refs. 8 and 9, with a colocated pyrochemical processing plant as described in refs. 10 and $1. The processing plant, called the IFR facility, includes cm-site facilities for fabrication and reprocessing of the ALMR metal fuel. The ALMR/IFR complex is assumed to continuously recycle its own spent fuel, with HLW streams bearing fission produets and trace quantities of transuranics reporting to the repository. The ALMR is assumed to operate as a "burner," with a breeding ratio of 0.85.

HEALTH RISK BASIS

A regulatory basis for quantifying the health risks of the nuclear fuel cycle has been established by the U.S. Nuclear Regulatory Commission (NRC), and is given in 10 CFR 51.52 Table S-3.[12] This table provides assumptions on environmental considerations, including releases for a uranium fuel cycle that includes spent fuel reprocessing and uranium recycle to LWRs. These emissions have been evaluated and translated into health impacts for the NRC by Gotchy.[13] Gotchy also provides estimates of occupational health risks, based upon a variety of other sources. The Gotchy results for the nuclear fuel cycle health risks are used in submissions to the NRC and are standard in the industry because of the detailed level of documentation and because of the breadth and depth of review that his study has received.

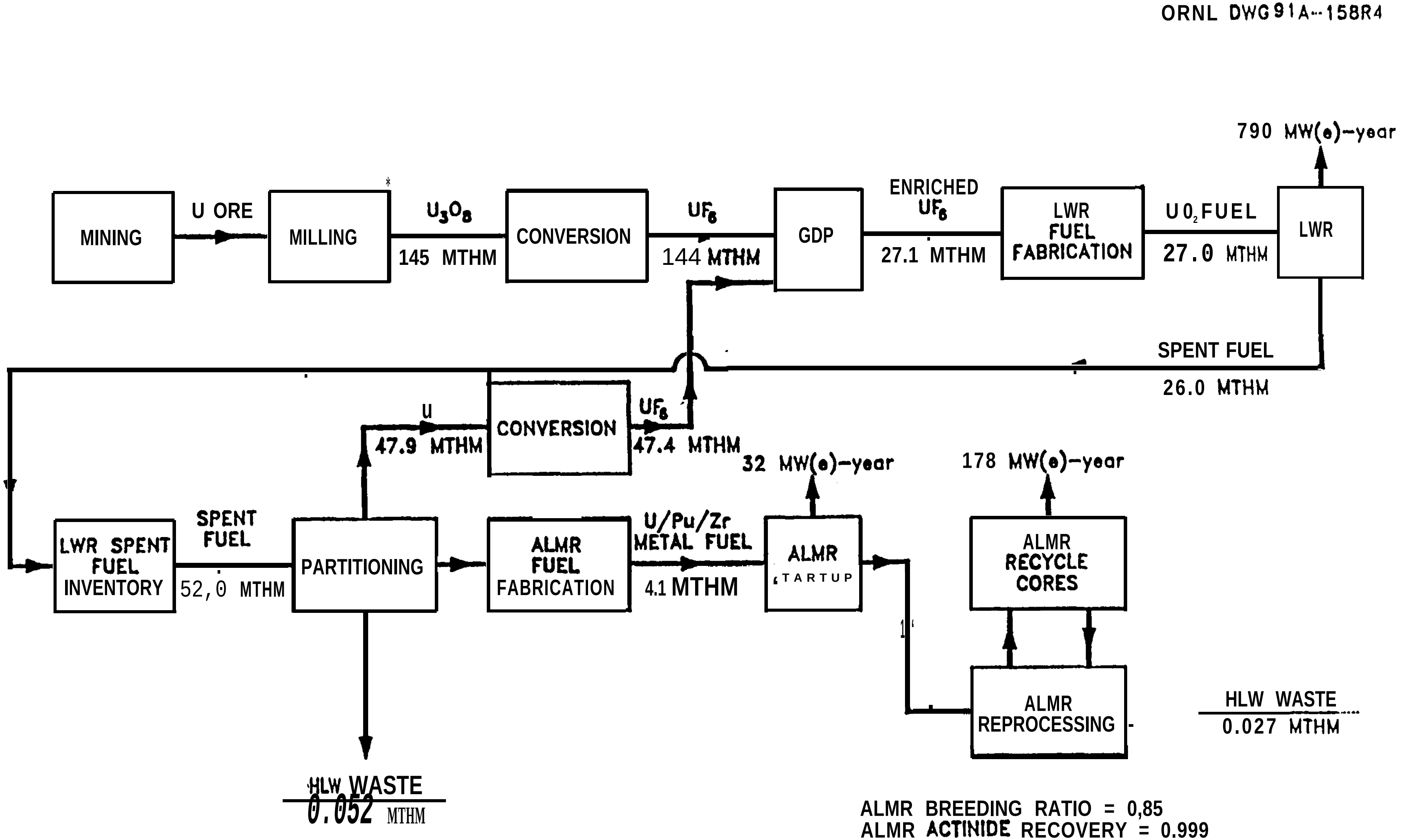

Fig. 1. Actinide mass balance for an integrated LWR/ALMR-actinide-burning system with uranium recycle.

The results of this NRC health risk study are used as a starting point for our calculations. Incremental modifications to these results are performed to supply missing entries (as in the case of transportation health impacts on the general public) and to update bases in those instances where more recent information is available.

NRC/Gotchy Study Basis. The fuel cycle steps assumed by Gotchy for the NRC are summarized below.

- Uranium mining production was assumed to be two-thirds below-ground mines and one-third open-pit mining. Mining accident incidence data were based on a 1977 National Academy of Sciences report.[14]
- Uranium milling and ore refining to produce uranium oxide. A key environmental consideration is the persistent release of radon gas from the uranium mill tailings piles.
- Conversion of uranium oxide, U_3O_8, to uranium hexafluoride, UF_6, to provide feed for uranium isotopic enrichment.
- Isotopic enrichment of UF_6 to attain 3.2% ^{235}U assay. A ^{235}U tails assay of 03% is assumed.
- Fabrication of nuclear reactor fuel as UO_2
- Irradiation of fuel in an LWR to a burnup of 33,000 MWd/t.
- Repmessing irradiated fuel in a plant utilizing the PUREX solvent extraction method. This plant is assumed to release 100% of the tritium, ^{85}Kr, and ^{14}C in the reprocessed spent fuel. Recovered uranium is converted to UF_6 for refeeding through the gaseous diffusion plant for re.enrichment and recycle to LWRs.
- Disposal of HLW in a geological (salt) repository.
- Transportation activities associated with moving materials to and from each of the above operations. Only occupational health effects associated with radiation exposures and accidents were considered No health effects to the general public were considered.

Modifications to the NRC/Gotchy Study Basis An important modification to the NRC/Gotchy results is the addition of transportation health risks to the general public, as well as the recalculation of transportation health risks to the occupational work force. Because of the complexity of these calculations, they will be discussed in a separate section of the paper, immediately following this one. Listed below are the other modifications to the study.

- Nonradiological occupational mortality and injury data for mining and milling in the NRC/Gotchy report are based upon industrial experience dating from the mid-1970s. However, significant revisions to uranium mining practice have been implemented since that time. We have reviewed uranium mining and milling accident incidence data as compiled for the Department of Labor[15-19] for the years 1985-1989 (data for 1990 and later years are not yet available). Combining this with published reports of the quantities of U_3O_8 produced during those years, we have arrived at the following mortality and injury incidence rates per 100 MT U_3O_8 produced.

	Mining	Milling
Nonradiological occupational deaths (per 100 MT U_3O_8)	0.0068	0
Nonradiological occupational morbidity (per 100 MT U_3O_8)	0.936	0.722

These values are almost an order of magnitude lower than the values used in the NRC study.

- Radiation releases associated with the uranium mining overburden are not included in the NRC/Gotchy study, but have recently been estimated by the EPA.[20] These releases, mostly

Table 1. Short-term reprocessing plant health risk to the general population'

	Standard plant health risk [mortality/ GW(e)-year]	LWR-AR plant		IFR plant	
		Nuclide inventory relative to standard plant	Health risk [mortality/ GW(e)-year]	Nuclide inventory relative to standard plant	Health risk [mortality/ GW(e)-year]
^{3}H	0.0552	().59	0.0322	1.15	0,0126
" c	0.0414	1,0	().0414	<0.(X)1	<().()001
^{85}Kr	0.0068	0.54	0.(XX)6	0.72	0.0(X)8
^{134}Cs	0.0024	0.04	<0.0001	1.04	0S)024
^{137}Cs	0.0036	().85	0.003	1.25	(),()()44
TR Us	().()006	1.0	().(X)3	15.0	().()(182
Other FPs	0.0002	1,()	0.002	1.0	0.0002
Total risk	0.110		0,078		0.0286

'Cooling times: standard plant = 160 d, LWR-AR plant = 10 year, IFR plant = 2,25 year. Kr-85 fractional release is 0.15 in LWR-AR, IFR cases, 1.0 In standard case. Tritium release fraction is 0.20 in IFR case, otherwise, it is 1.0.

radium and radon, will persist over a period >1000 years because of the long-half lives of the thorium and uranium parent nuclides. Adjusting the EPA estimates to a 1000-year integrated dose, the latent cancer mortality rate due to the mining overburden is estimated to be 0.006 per 100 MT U_3O_8.

- The NRC/Gotchy study uses radiation dose factors that have since been superseded by further analysis. The NAS report,[7] commonly called the BEIR V report, gives statistics on the number of cancer deaths and genetic effects expected to occur from a continuous exposure of 1 rem per year from age 18 through 65. This value results in a risk factor of 4.0x 10^{-4} latent cancer fatalities (LCFs) per person-rem that is most applicable to occupational exposures. The BEIR V report also considers the number of cancer deaths expected to occur from a continuous lifetime exposure of 0.1 rem/year, which results in a risk factor of 5.0 x 10^{-4} LCFs per person-rem that is most applicable to exposures to the general public. Both of these risk factors were used in this study depending upon whether the exposure was to workers or the general population.

- Definitions of reprocessing plant health effects are needed for both the LWR-AR and IFR reprocessing plants. Our methodology for defining reprocessing plant health effects follows the methodology described in Appendix A of ref. 5. The value of the health effects used by the NRC/Gotchy for the "standard" reprocessing plant does not apply to the IFR reprocessing plant for several reasons. First, the ALMR fuel will have different inventories of the key radionuclides than was assumed for the LWR fuel in the standard reprocessing plant. Secondly, the pyrometallurgical processes used in the IFR plant make collection of tritium, ^{85}Kr, and ^{14}C relatively straightforward; thus, release fractions for these nuclides can be expected to be lower than in the standard plant case where they are 1.0. The LWR-AR plant may be either aqueous or nonaqueous technology, but its health effects will also be different than the standard plant defined in the NRC study for two reasons.

1. The standard plant assumes radionuclide inventories consistent with LWR fuel burnup values of 33,000 MWd/MT and 160-d preprocessing time whereas the LWR-AR plant basis is assumed to be 50,000 MWd/MT fuel burnup and 10 years preprocessing time’

2. The EPA has promulgated a regulation, 40 CFR 190 Subpart B,[21] that effectively limits the ^{85}Kr releases to about 15% of the ^{85}Kr inventory in a reprocessing plant. Thus, it appears unreasonable to assume 100% releases. Our evaluation assumes the maximum ^{85}Kr release fraction of 1 5%. The reprocessing plant assumptions are given in Table 1

- The NRC/Gotchy study bases on the HLW repository are outdated. Since the disk. of the NRC/Gotchy report, the Yucca Mountain site in Nevada has been selected as the potential repository site, and an extensive literature has appeared on repository performance. Based on the recent studies at Sandia National Laboratory,[22] it appears that health effects from LWR spent fuel emplaced in a Yucca Mountain repository are expected to be dominated by releases of ^{14}C as gaseous CO and CO_2. The releases of ^{14}C are given in ref. 22 as probability curves in units of the fractional total repository release limit. These probabilistic release curves have been integrated and converted into estimates of released curies by using the defined values of the EPA attainment release limits.[23] These projected releases were then converted into long-term health effects using the EPA conversion factors[24] and BEIR V[7] dose factors. The result of these calculations is a mortality risk of 0.008 per GWe-year for the LWR once-through fuel cycle. HLW from reprocessing plants is expected to contain ^{14}C in an immobilized form and, thus, this gaseous release mode will not apply. A mortality risk value of <0.001 is assumed for reprocessing plant HLW based upon inspection of the magnitude of other projected repository releases in the Sandia performance assessment.

TRANSPORTATION RISK ASSESSMENT

A significant omission from the NRC basis study is the lack of estimates of health risk to the general public due to nuclear fuel cycle transportation operations. To correct this omission, we have performed a transportation risk assessment for both subject fuel cycles, amounting for radiation exposures to the public from incident-ke transportation and from transportation accidents. Occupational radiation exposures to the transportation crew are also calculated.

The radionuclide inventories were calculated using the ORIGEN2[25] code, and radiation dose rates external to shipping packages were estimated for each type of shipment in the fuel cycle. Locations for the fuel cycle facilities were defied. Actual sites for existing production facilities were assumed for front-end facilities such as mines, mills, conversion plants, enrichment plants, and UO_2 fuel fabrication facilities. The LWR site was defined to be Wilmington, Ohio, which was chosen because it is close to the geographic center of U.S. nuclear facilities. The LWR reprocessing plant was assumed to be at Barnwell, South Carolina, and the ALMR facilities, including the colocated IFR reprocessing facility, were assumed to be sited at Columbia, South Carolina. The HLW repository site was taken to be Yucca Mountain, Nevada.

For each fuel cycle transportation step, mileages were estimated and divided into rural freeway, rural non-freeway, suburban, and urban categories using the HIGHWAY computer model.[26] The RADTRAN IV computer model[27] was used to model both the incident-free radiological exposure and the consequences of radiological releases due to severe accidents The incident-free risks are dependent on the radiation dose rate from the shipment, number of shipments, package dimensions, route distance, vehicle velocity, and population densities along the travel routes. The accident risks are dependent upon the radiological inventory, accident severity, probability of occurrence for each accident category, and the amount of inventory released, aerosolized, and inhaled, as well as the dispersibility of the waste form. Table 2 shows the health effect results of these calculations for the ALMR actinide burning fuel cycle. The incident-free general public radiation doses arise in the calculations mostly during periods when the transportation vehicle is parked at rest stops.

Summary results of statistical deaths attributable to nuclear transportation operations are shown for the two fuel cycles in Table 3. Note that transportation risk is dominated by the transport of LWR spent fuel Spent fuel is highly radioactive and accidents involving spent fuel include scenarios in which volatile fission products are assumed to be released. Transportation operations involving HLW involve radioactivity inventories that are comparable to spent fuel but are estimated to pose less health risk because the radionuclides are immobilized in the waste matrix, thus, resulting in low releases in all accident scenarios.

Table 3 shows a lower overall health risk associated with the actinide recycle system as compared to the LWR once-through system. This result is caused by the fact that LWR fuel shipments to the HLW repository are assumed to involve more mileage than LWR shipments to a reprocessing plant. Although not necessarily true, this assumption is felt to be reasonable. The repository by its nature is located in a remote section of the United States, whereas a reprocessing plant might be heated at relatively shorter distances from the majority of the operating LWRs.

Table 2. Summary of the transportation risk assessment for the LWR/ALMR fuel cycle with uranium recycle[a]

Fuel cycle stage	Radiological latent cancer fatalities per GW(e)-year[b]			Maximum individual, radiation dose[e] (rem)
	Incident-free risk		Accident risk	
	Crew[c]	Total population[d]	Total population	
Milling → U_3O_8 conversion	233 x 10^{-5}	2.03 x 10^{-4}	3,98 x 10^{-9}	4,68 x 10'
U_3O_8 conversion → enrichment	5.49 x 10^{-6}	4.78 X 10^{-5}	2.01 x 10^{-5}	2,77 x 10'
Enrichment → LWR fuel fabrication	3.90 x 10^{-6}	3.39 x 10^{s}	3.97 x 10^{-6}	2.21 x 10”7
LWR fuel fabrication → LWR	1.07 x 10^{4}	‘9.31 x 10-’	1.51 x 10¹’	4.83 x 10^{-8}
LWR → repository				
LWR → LWR reprocessing	1.20 x 10-’	1.05 x 10^{3}	1.74 x 10^{-2}	4,83 x 10^{-6}
LWR reprocessing → repository	3.36 x 10^{-4}	2.93 X 10^{-3}	3.68 x 10^{-4}	3.48 X 10^{-6}
LWR reprocessing → ALMR facilities	8.84 x 10^{-7}	7.70 x 10^{-6}	4,87 x 10^{-5}	2,95 X 10”7
LWR reprocessing → U-metal conversion	4.84 x 10^{-6}	4.23 x 10^{s}	2.90 x 10’0	2.08 X 10”’
U-metal conversion → enrichment	1.94 x 10^{4}	1.69 X 10^{-5}	6.55 x 10^{-6}	9.82 X 10^{-8}
ALMR facilities → repository	3.36 x 10^{-4}	293 x 10^{-3}	9.25 x 10^{-4}	3.48 x 10^{-6}

[a] Transportation risks were calculated using RADTRAN version 4,0.13 dated October 27, 1992. Access to RADTRAN IV was furnished on the TRANSNET MicroVAX computer by the DOE’s Transportation Technology Center at Sandia National Laboratories.

[b] The number of radiological LCFS statistically expected to occur from the calculated exposures was estimated using a conversion factor of 4.0x 10^{4} LCFS per person-rem for occupational exposures and 5.0 x 10^{-4} LCFs per person-rem for exposures of the general public.[7]

[c] The crew size was assumed to be two persons.

[d] The incident-free risk to the total population does not include the risk to the crew.

[e] The maximum individual radiation dose assumes a hypothetical individual located 30 m adjacent to the roadway during the shipment of the entire radiological inventory.

Table 3. Summary of the transportation risk assessment for two fuel cycles’

Fuel cycle stage	Radiological latent cancer fatalities for both incident-free and accident risk per GW(e)-year Once-through	 Actinide-burning with U-recycle
Milling → U_3O_8 conversion	3.01 x 10^{4}	**226 x 10^{-4}**
U_3O_8 conversion → enrichment	9.73 x 10-^{5}	734 **x 10^{-5}**
Enrichment → LWR fuel fabrication	**4.18** x **10-s**	**4.18** x 10-s
LWR fuel fabrication → LWR	**1.04 x 10^{-5}**	1.04 x **10^{-5}**
LWR → **repository**	**6.08 x** 10-^{2}	
LWR → LWR **reprocessing**[b]		1.86 x 1O-*
LWR reprocessing_ repository		3.63 x **10^{-3}**
LWR reprocessing → ALMR facilities’		5.73 x **10^{-5}**
LWR reprocessing_ U-metal conversion		***4.71 x*** 10-^{s}
U-metal conversion → enrichment		2.s4 x **10^{-5}**
ALMR facilities → repository		**4.19 x 10^{-3}**
TOTAL RISK FOR EACH FUEL **CYCLE:**	6.13 x **10^{-2}**	**2.69** x **10^{-2}**

[a] **Shipment** quantities are for a fuel **cycle** that produces 1,000 **MW** of electrical power.

‘Assumes that **LWR fuel storage is provided for at the reactor site and/or the LWR reprocessing plant with no separate storage facility.**

[c] **ALMR facilities include the ALMR reactor, ALMR reprocessing plant, and the ALMR fuel fabrication facility, which are located at the same geographic location.**

Another key assumption that underlies the health risk differences between the LWR once-through and actinide burning fuel cycles is the assumption that the ALMR fuel reprocessing and fabrication facilities will be colocated with the reactors. The reasonableness of this assumption is debatable. Future work is planned to examine the transportation risks associated with actinide burning systems which involve centralized metal fuel reprocessing/fabrication plants.

RESULTS AND DISCUSSION

The calculated health impacts for the LWR once-through fuel cycle and for the actinide burning fuel cycle are shown in Tables 4 and 5. As can be seen in these tables, both radiological and nonradiological health effects to the general population are dominated by the front-end fuel cycle facilities. The major radiological risks result from releases of radon gas and radium-bearing airborne particulate from uranium mines, liquid releases of ^{226}Ra from milling operations and persistent releases of radon gas from mill tailings piles.

This conclusion is not surprising. Uranium decay daughters such as ^{230}Th, ^{226}Ra, and ^{222}Rn are known to be highly toxic. In fact, the EPA calculates that these nuclides are about 20 times more toxic than plutonium nuclides as measured on a basis of health impacts per curie released over land.[24] This toxicity arises from the fact that radium is water soluble, which allows it to migrate through the biosphere. Upon ingestion, radium is a bone-seeker. Radium in the environment decays to radioactive radon which, as a heavy gas, is mobile and poses an ingestion hazard. By contrast, plutonium and most other transuranics, are relatively insoluble and, thus, have limited mobility in the biosphere Uranium ore bodies are distinguished from uranium elsewhere in the fuel cycle in that there has been ample time in the ore body for the thorium and radium decay daughters to build up to their secular equilibrium values. These large levels of toxic decay daughters cause the handling and refining of uranium during the mining and milling steps to be relatively more hazardous than any other fuel cycle operation.

This observation is central to the results of thii paper. Currently, there are two sources of fissile inventory that maybe exploited for nuclear fuel: (1) uranium ore bodies, and (2) spent fuel inventories. Mining of uranium ore bodies occurs out in the environment; "mining" (or reprocessing) of spent fuel inventories occurs in well-shielded engineered structures. Radioactive wastes from uranium ore processing, such as the mining overburden and mill tailings, are left at the surface; radioactive wastes from reprocessing are more compact and, thus, can be more easily immobilized and buried in engineered waste forms.

Occupational radiation health effects are also highest in the front-end of the fuel cycle. In the case of uranium miners, the risks are predominately caused by the inhalation of gaseous ^{222}Rn. In uranium milling, most of the occupational dose results from whole-body exposures to external radiation sources.

Nonradiological occupational health risks from accidents are also reported in Tables 4 and 5. The mortality risk is dominated by mining accidents. Nonradiological occupational morbidity is dominated by mining and milling injuries, usually involving damage to extremities, and by chronic mining and milling diseases relating to noise (auditory loss), mechanical vibrations (osteoarthritis), and dust inhalation. With the sole exception of external radiation exposures, none of these occupational mortality and morbidity sources are expected to be found in a reprocessing plant.

Table 4. Summary of potential health dsks among the total U.S. population per GW(e)-year for the once-through LWR fuel cycle, assuming 1000-year dose commitments

Source of risk	Occupational mortality		General public mortalities (radiological)	Total mortality	Injury and disease		Total injury and disease
	Radiological	Nonradiological			Occupational	General public	
Uranium mining	0.222	0.017	0.44	0.679	23	0.58	2.9
Uranium milling	0.176	<0.001	0.30	0.476	108	1.66	3.4
UF_6 conversion	0.001	<0.001	0.076	0.077	•	<0.001	0.001
Enrichment	0.002	<0.001	<0.001	-0.002	•	0.002	0,002
Fuel fabrication	0.054	<0.001	<0.001	0,054	•	0,06	.
Power generation	0.092	0.01	0.028	0.130	5.0	0.10	5.1
Transportation	0.001	0.01	0,061	0.072	0.17	•	0.17
Reprocessing	.	•	.	.	•	•	.
Waste management	•	•	0,008	0.008	•	0.016	0.016
Catastrophic accident	•	•	0.04	0,04	•	•	0.15
TOTALS	**0.548**	0.037	0.953	1.54	9.2	242	11.7

•These values are not currently available, but they are expected to be small relative to three presented.

Table 5. Summary of potential health risks among the total U.S. population per GW(e)-year for the ALMR fuel cycle with uranium recycle, assuming 1000-year dose commitments

Source of risk	Occupational mortality		General public mortalities (radiological)	Total mortality	Injury and disease		Total injury and disease
	Radiological	Nonradiological			Occupational	General public	
Uranium mining	0.132	0.010	0.261	0.402	**1.4**	0.34	1.74
Uranium milling	0.104	<0.001	0.178	0,282	1.07	0,98	2.05
UF_6 conversion	0.001	**<0.001**	0.061	0.062	[a]	<0.001	0.001
Enrichment	0.002	<0.001	<0,001	0.002	[a]	0.002	0s)02
Fuel fabrication	0.044	<0,001	**<0.001**	0.044	[a]	0.05	·
Power generation	0.092	0.01	**0.028**	**0.130**	**5.0**	0.10,	**5.1**
Transportation	0.001	**0.01**	0.027	0.038	0.17	[a]	**0.17**
Reprocessing	0.002	[a]	0.068	0.109	0.01	0.12	0.13
Waste management	[a]	[a]	<0.001	<0.001	[a]	<0.001	<0.001
Catastrophic accident	[a]	[a]	0.04	0.04	[a]	[a]	0,15
TOTALS	0,378	0.03	0.663	1.07	7.6S	159	9.24

[a] These values are not currently available, but they are expected to be small relative to those presented,

Comparison of the results of Tables 4 and 5 show that the deployment of actinide burning systems results in reduced levels of operation of uranium front-end fuel cycle facilities. The net impact is an overall reduction in fuel cycle deaths of about 31% and in fuel cycle morbidity of about 21%.

Another key assumption affecting the fuel cycle risk reduction is the extent to which actinide burning systems are deployed. Figure 2 shows the total fuel cycle mortality risk associated with ALMR deployment level. The endpoint corresponding to zero deployment of ALMRs represents the current LWR on-through fuel cycle. The scenario of 100% deployment, with complete phaseout of the LWR technology, corresponds to the other endpoint of the curves. In this last scenario, the short-term fuel cycle risk is reduced by 60% from the current LWR once-through scenario.

It should be noted that at deployment levels above 21%, it is assumed that the ALMR breeding ratio is increased above 0.85, reaching a value of LO (break-en) at the 100% deployment level. **This assumption accounts for some of the nonlinearity in the curve shown in Fig. 2.**

CONCLUSIONS

The **following** conclusions are made.

- **Nuclear fuel cycle health risks are currently dominated by tint-end uranium facilities. Deployment of an ALMR/pyroreprocessing P-T fuel cycle will reduce dependence on uranium mines and mills as a source of fissile material and, thus, reduce the overall nuclear fuel cycle health risk.**
- In standard environmental assessments, reprocessing plant health risk is predominately due **to tritium, ^{14}C, and ^{85}Kr, all of which are assumed to be 100% released to the environment. Very little risk is** attributed to the presence of transuranic elements in the reprocessing plant. The ALMR reprocessing plant health risk is expected to be lower due to the plans to recover radioactive gases, and due to the absence of significant quantities of ^{14}C in the metal fuel.
- Health risk from transportation operations is significant as compared to other fuel cycle steps and should be considered in health risk estimates. The P-T systems that were examined had transportation risks that were comparable to (and slightly lower than) the LWR once-through system. **Transportation risk is dominated by spent fuel shipments because of the quantities of volatile fission product compounds involved. Shipments of HLW involve comparable radioactivity levels, but pose health risks that are orders of magnitude lower because the HLW form effectively immobilizes the fission products, thus minimiig releases in accident scenarios.**

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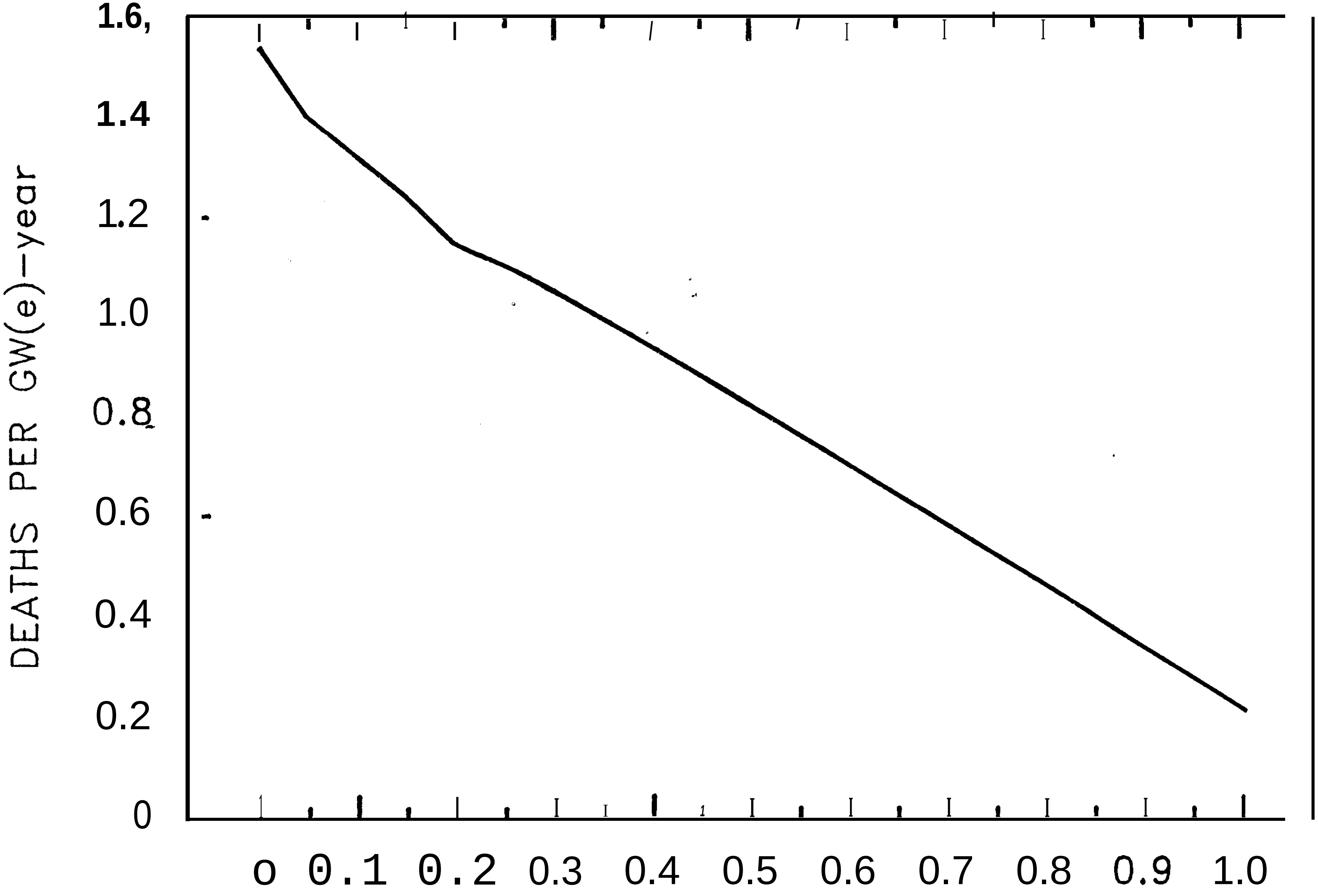

Fig, 2. Nuclear fuel cycle health risk as a function of LMR deployment levels.

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