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Impact of Actinide Recycle on
Nuclear Fuel Cycle Health Risks

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CONTENTS

FIGURES	v
TABLES	v
EXECUTIVE SUMMARY	vii
1. INTRODUCTION	1
2. FUEL CYCLE RISK BASIS	3
2.1 REGULATORY BASIS	3
2.2 EXISTING U.S. FUEL CYCLE	6
3. FUEL CYCLE RISKS FOR ACTINIDE BURNING SCENARIOS	9
3.1 "NO RECYCLE" SCENARIO FOR LWR URANIUM	9
3.2 LWR URANIUM RECYCLE SCENARIO	13
3.3 DEPENDENCE ON ALMR DEPLOYMENT LEVEL	15
4. CONCLUSIONS	19
5. REFERENCES	21
Appendix A. BASIS FOR REPROCESSING PLANT SHORT-TERM HEALTH RISK ESTIMATES	23

FIGURES

Fig. 1. Actinide mass balance for an integrated LWR/ALMR-actinide-burning system with no uranium recycle.	10
Fig. 2. Actinide mass balance for an integrated LWR/ALMR-actinide-burning system with uranium recycle	14
Fig. 3. Nuclear fuel cycle health risk per gigawatt of electricity production as a function of the fraction of nuclear power that is produced by LMRs.	16

TABLES

Table 1. Summary of potential health risks among the total U.S. population per GW(e)-year for the regulatory-basis nuclear fuel cycle, assuming 1000-year dose commitments	5
Table 2. Summary of potential mortality health risks among the total U.S. population per GW(e)-year for the currently existing nuclear fuel cycle, assuming 1000-year dose commitments	7
Table 3. Summary of potential health risks in the total U.S. population (occupational and general) per GW(e)-year for several nuclear fuel cycles, assuming a 1000-year dose commitment	12
Table 4. Health effects (mortality only) in the U.S. general population resulting from normal operations of the standard reprocessing facility, 1000-year dose commitment	27
Table 5. Short-term reprocessing plant health risk to the general population	33

EXECUTIVE SUMMARY

The impact of actinide recycle on nuclear fuel cycle health risks was evaluated. The actinide recycle system, as defined for this study, refers to the selective removal of uranium and transuranium elements from spent fuel in a reprocessing facility and the subsequent recycling of these elements as fuel in Advanced Liquid Metal Reactors (ALMRs) and, as an option for the recovered uranium, in Light Water Reactors (LWRs).

The introduction of reprocessing into the nuclear fuel cycle is taken as reducing the relative dependence on uranium mining and milling. Mining and milling are shown to represent 70 to 85% of the entire health risk from the existing LWR once-through fuel cycle. The health risk of an actinide recycle fuel cycle is calculated and compared to the health risk from the LWR once-through system. The following major conclusions are reached:

- The deployment of an actinide recycle technology will reduce front-end fuel cycle health risks. The reduction in mining and milling health risks will be realized as actinide recycle technology is gradually phased in.
- If ALMR technology can be operated at the same hazard level as analogous LWR technology, then the overall fuel cycle risk will be significantly lower compared to a once-through LWR fuel cycle. Adoption of a complete ALMR economy is projected to reduce short-term nuclear fuel cycle health risks by more than 80%
- The beneficial effect of actinide recycle on short-term fuel cycle health risk appears to be much greater than the entire health risk attributed to the geologic repository.

The health risk attributable to reprocessing plants was examined as part of this study and is documented in Appendix A. The important conclusions from this analysis are:

- The major contributors to reprocessing plant health risk in standard environmental assessments are not the transuranic elements, but are tritium, ^{14}C and ^{85}Kr , all of which are assumed to be 100% released to the environment. The pyroprocessing facility for

ALMR fuel can be expected to have a considerably lower health risk due to the absence of a significant ^{14}C inventory in the ALMR metal fuel and the plans to recover and dispose of tritium and ^{85}Kr gases.

IMPACT OF ACTINIDE RECYCLE ON NUCLEAR FUEL CYCLE HEALTH RISKS

1. INTRODUCTION

The purpose of this background paper is to summarize what is presently known about potential impacts on the health risk of the nuclear fuel cycle from deployment of the Advanced Liquid Metal Reactor (ALMR)¹ and Integral Fast Reactor (IFR)² technology as an actinide burning system. In a companion paper by C. W. Forsberg,³ the impact on waste repository risk is addressed in some detail. Therefore, this paper focuses on the remainder of the fuel cycle.

In general, the introduction of new steps into the fuel cycle associated with generating a unit of electricity [herein taken to be 1 GW(e)-year] can be expected to have two types of impacts on the health risk. The first impact is to change the quantity of materials, and hence the quantity of radiological and hazardous effluents, involved in other fuel cycle operations. In the ALMR case, an important example of this kind of impact is the reduction of front-end uranium fuel cycle operations such as mining and milling. The second type of impact comes from the health risks posed by the new facilities that have been introduced into the fuel cycle themselves.

Only limited information is available to characterize this latter kind of health risk. Detailed studies of health risks for the actinide burning version of the ALMR, the IFR reprocessing plant, and associated facilities are not available at this time. However, by examination of the environmental releases from the standard aqueous reprocessing plant (for which detailed studies do exist) and performing appropriate scaling for technology differences, it is possible to make reasonable estimates of the health risks associated with the actinide recycle reprocessing plants.

In Sect. 2 of this paper, a fuel cycle risk basis is established assuming the light-water reactor (LWR) once-through system as the standard fuel cycle. In Sect. 3, two fuel cycles (with and without uranium recycle to LWRs) are defined and the impact of ALMR deployment on the front-end fuel cycle health risk is calculated. Appendix A explains the

rationale for the short-term health risk values that are assumed for the reprocessing plants in the Sect. 3 analysis.

2. FUEL CYCLE RISK BASIS

A regulatory basis for quantifying the health risks of the nuclear fuel cycle has been established by the Nuclear Regulatory Commission (NRC) and is given in 10 CFR 51.51, Table S-3.⁴ This table provides data on environmental considerations, including emissions, for a complete uranium fuel cycle. This regulatory standard is used in all environmental assessments submitted as part of the LWR licensing process as the basis for evaluating the environmental effects of each stage of the uranium fuel cycle.

Therefore, this table of environmental data represents an appropriate starting point for an evaluation of the impact of ALMR deployment for actinide burning on environmental risk. However, this "basis" fuel cycle assumes uranium recycle; that is, it assumes that a reprocessing plant exists and that uranium is recovered from spent fuel and reenriched and recycled as LWR fuel. Plutonium recycle is not assumed because plutonium from LWR spent fuel is disposed of as high-level waste. Clearly, this regulatory basis is not consistent with either of the fuel cycles we wish to compare. The existing fuel cycle is a "straight-through" cycle that involves no reprocessing and recycle of uranium. The ALMR fuel cycle under study does involve LWR fuel reprocessing but is proposed to involve plutonium recycle, not uranium recycle.

In order to properly establish the basis for comparison, it is necessary to examine the regulatory basis case in more detail.

2.1 REGULATORY BASIS

The fuel cycle assumed as the regulatory basis for environmental impact assessments is defined in WASH-1248⁵ and contains the following components:

1. Mining uranium ore (including both open pit and below-ground mines).
2. Milling and refining ore to produce uranium concentrates (U_3O_8). A key environmental consideration is the radon gas emissions from the uranium mill tailings.
3. Conversion of U_3O_8 to uranium hexafluoride (UF_6) to provide feed for isotopic enrichment.

4. Isotopic enrichment of UF_6 to attain 3.2% ^{235}U assay. A ^{235}U tails assay of 0.3% is assumed.
5. Fabrication of nuclear reactor fuel (oxide).
6. Irradiation of fuel (33,000 MWd/t) in an LWR.
7. Reprocessing irradiated fuel in a plant utilizing the PUREX solvent extraction method. Recovered uranium is converted to UF_6 for recycle through the gaseous diffusion plant for reenrichment.
8. Long-term storage of high-level wastes in a geological (salt) repository.
9. Transportation activities associated with moving materials to and from each of the above operations.

As noted previously, the environmental effluents and considerations for this fuel cycle are given in 10 CFR 51.51, Table S-3.⁴ These effluents have been translated into potential health impacts and are presented in NUREG-0332, "Potential Health and Environmental Impacts Attributable to the Nuclear and Coal Fuel Cycle."⁶ These NUREG-0332 projections are summarized in Table 1.

The major radiological health effects to the general population in the front end of the fuel cycle result from airborne releases of ^{222}Rn and ^{226}Ra from uranium mines and from mill tailings and from liquid releases of ^{226}Ra from UF_6 conversion plants. For both mortalities and disease (latent cancer and genetic effects), the front-end fuel cycle facilities are the dominant sources of health risk.

This conclusion is not surprising. Uranium decay daughters such as ^{232}Th , ^{226}Ra , and ^{222}Rn are considered to be highly toxic. In fact, the EPA calculates that these nuclides are about twenty times more toxic than plutonium nuclides as measured on a basis of health impacts per curie released over land.⁷ Uranium ore bodies are distinguished by uranium elsewhere in the fuel cycle in that there has been ample time in the ore body for the thorium and radium nuclides 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.

Occupational radiation risks are also highest in the front end of the fuel cycle. In the case of uranium miners, the risks are predominately caused by deposition of ^{222}Rn and its

Table 1. Summary of potential health risks among the total U.S. population per GW(e)-year for the regulatory-basis nuclear 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	0.096	0.2	0.22	0.516	13	0.292	13.3
Uranium milling	0.076	<0.001	0.15	0.227	2.2	0.83	3.1
UF ₆ conversion	0.0005	<0.001	0.038	0.039	*	<0.001	0.001
Enrichment	0.0013	<0.001	<0.001	~0.001	*	0.001	0.001
Fuel fabrication	0.027	<0.001	<0.001	0.027	*	0.03	0.21
Power generation	0.046	0.01	0.014	0.070	5.0	0.05	5.0
Transportation	0.001	0.01	*	0.011	0.17	*	0.117
Reprocessing	0.0023	*	0.055	0.057	0.01	0.20	0.21
Waste management	*	*	0.004	0.004	*	*	0.008
Catastrophic accident	*	*	0.04	0.04	*	*	0.15
TOTALS	0.250	0.221	0.521	0.992	20.4	1.40	22.1

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

daughters in the lungs. 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 Table 1. These risks are large relative to radiological risks and are dominated by accidents in uranium mines.

In this paper, the analyses will focus on the mortality risk estimates for the fuel cycle rather than on the injury and disease risk estimates. It can be seen from Table 1 that there is little loss in generality by adopting this focus, that is, the fuel cycle facilities that dominate mortality risk also dominate the injury and disease risk.

2.2 EXISTING U.S. FUEL CYCLE

In the existing U.S. uranium fuel cycle (namely the LWR once-through system) the health risks from front-end facilities are actually greater than those assigned to it in the federal regulations due to the higher front-end throughput [per GW(e)-year] resulting from the absence of uranium recycle facilities. Additional mining, milling, and conversion activities must occur to compensate for the lack of a uranium recycle stream; however, these are the very activities that rank high as risk contributors.

For this analysis, we take the definition of the fuel cycle flows for the "no recycle" case in an NRC basis document⁸ as representative of the existing fuel cycle. A review of detailed environmental studies of the fuel cycle^{9,10} supports the simple view that environmental effluents and health risks may be assumed to scale linearly with the total uranium throughput in each front-end fuel cycle step.

Based on these assumptions, we have scaled the regulatory case mortality risk values to develop a risk summary for the existing fuel cycle. This case is shown in Table 2. Risks due to mining, milling, and conversion operations are increased by 15.2% relative to the uranium recycle assumed in the federal regulations. A slight reduction (1%) in risks from gaseous diffusion plant operations occurs in the no-recycle case due to the slightly greater enrichment requirement associated with reprocessed uranium. No scaling of the risk estimates for the LWR operation, transportation, repository operation or catastrophic accidents categories is

Table 2. Summary of potential mortality health risks among the total U.S. population per GW(e)-year for the current existing nuclear fuel cycle, assuming 1000-year dose commitments

Source of risk	Occupational		General public (radiological)	Total mortality
	Radiological	Nonradiological		
Uranium mining	0.111	0.230	0.253	0.594
Uranium milling	0.088	0.001	0.173	0.262
UF ₆ conversion	0.0006	<0.001	0.044	0.045
Enrichment	0.0019	<0.001	<0.001	~0.001
Fuel fabrication	0.027	<0.001	<0.001	0.027
Power generation	0.046	0.01	0.014	0.070
Transportation	0.001	0.01	*	0.011
Reprocessing	^b	-	-	-
Waste management	*	*	0.004	0.004
Catastrophic accidents	*	*	0.04	0.04
TOTALS	0.275	0.251	0.528	1.054

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

^b- = Not applicable.

involved here. With the exception of the repository category, changes in potential health risk from these fuel cycle steps, relative to the uranium recycle case, are expected to be small.

The risk assessment given in Table 2 will be used as the basis for comparison with the ALMR actinide burner scenarios described in the subsequent two sections.

3. FUEL CYCLE RISKS FOR ACTINIDE BURNING SCENARIOS

Two different scenarios for ALMR actinide burning fuel cycles are considered. They are differentiated by their assumptions of the disposition of the reprocessed LWR uranium. In the first scenario, LWR fuel is reprocessed with the plutonium and other transuranic (TRU) nuclides being recovered and used as fuel in ALMRs, while the recovered uranium is placed in storage. In the second scenario, the recovered uranium is converted to UF_6 , reenriched in the gaseous diffusion plants, and recycled as LWR fuel.

A second assumption is required for scenario definition concerning the extent to which ALMR deployment is assumed to have occurred. Most advocates of ALMR technology envision that future nuclear power growth will eventually be aggressive and that new LWR deployment will be gradually phased out as ALMR deployment begins. Under such a plan, there will be no actual steady-state LWR/ALMR integrated fuel cycle, but rather a continuously changing set of fuel cycle flows as the ALMR systems become increasingly dominant.

For the purposes of this paper, we have adopted a scenario in which 21% of nuclear power production is attributed to ALMRs, and the remainder to LWRs as an illustrative case. It is at this deployment level that ALMRs (and their associated facilities) are consuming the LWR spent fuel inventory at twice the rate at which LWRs are contributing to it. This scenario is intended to represent a "snapshot in time" of what is expected to be an evolutionary fuel cycle. This assumption will be used in Sects. 3.1 and 3.2. In Sect. 3.3, the dependence of short-term fuel cycle risk on ALMR deployment level will be characterized.

3.1 "NO RECYCLE" SCENARIO FOR LWR URANIUM

Under this scenario, LWR spent fuel is assumed to be reprocessed, and the TRU elements are recovered and shipped to the ALMR site for fabrication as fuel elements. The initial ALMR cores are then recycled, and the recovered TRU are reused as fuel in future ALMR production campaigns.

The fuel cycle for this scenario is shown in Fig. 1. The fuel cycle flows shown have been normalized to a total of 1 GW(e)-year of nuclear power production, with 790 MW(e)-year

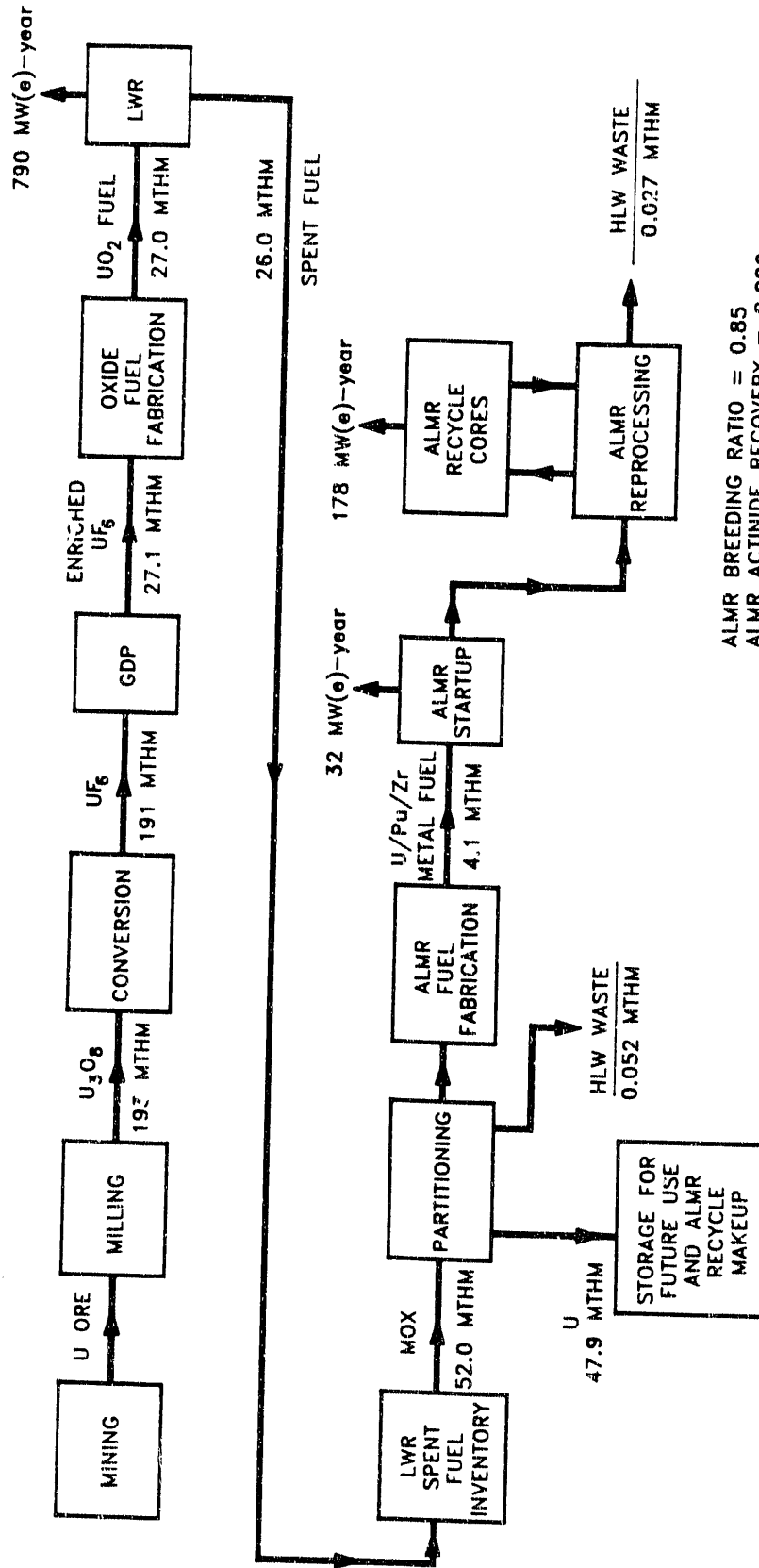


Fig. 1. Actinide mass balance for an integrated LWR/ALMR-actinide-burning system with no uranium recycle.

from LWR operations and 210 MW(e)-year of energy from the ALMR portion of the enterprise.

In this flow sheet, the 790 MW(e)-year of LWR operation is assumed to result in 26 metric tons of heavy metal (MTHM), in the form of spent fuel, being placed into inventory. Fifty-two MTHM of LWR spent fuel are assumed to be removed from the spent fuel inventory and reprocessed, resulting in 4.1 MTHM of ternary metal fuel to be used for the startup of an ALMR. This quantity of ALMR startup fuel is equivalent to 32 MW(e)-year. Assuming a fissile plutonium "breeding ratio" of 0.85 for the ALMR and an actinide recovery factor of 0.999 for the ALMR metal fuel reprocessing, the original 4.1 MTHM of startup fuel is credited with producing an additional 178 MW(e)-year of energy in the form of ALMR recycle fuel. Overall, the ALMR portion of the enterprise contributes 210 MW(e)-year of energy.

It should be noted that the total amount of energy produced by the ALMR fuel is quite sensitive to the assumed value of the breeding ratio for the reactor. The value used in this study represents current design concepts for ALMRs that include, as a design objective the rapid and efficient transmutation of long-lived TRU nuclides.

Table 3 gives the projected short-term fuel-cycle health risks associated with this flow sheet. The environmental and health risk values for the ALMR operation were assumed to be nominally equivalent on a per GW(e)-year basis as the analogous values for the standard LWR system. The values of short-term health risk for the waste repository and transportation are small contributors to the overall risk and were assumed to have the same values as in the regulatory basis scenario.

The values of short-term health risk assumed for the LWR and metal fuel reprocessing plants were 0.042 and 0.0166 health effects/GW(e)-year respectively. These values are considerably less than the standard value of 0.057 health effects/GW(e)-year, and reflect current regulations with regard to radiation releases to the atmosphere as well as nuclide inventory differences between the standard regulatory-basis reprocessing plan and the reprocessing plants assumed in this flow sheet. The derivation of these lower health effect values is explained in detail in Appendix A.

The estimate of short-term mortality risk for this fuel-cycle scenario is about 10% lower than the current once-through LWR scenario. Front-end fuel cycle risk is reduced

Table 3. Summary of potential health risks in the total U.S. population (occupational and general) per GW(e)-year for several nuclear fuel cycles, assuming a 1000-year dose commitment

Source of risk	Current U.S. fuel cycle	LWR/ALMR-AB fuel cycle ^a	
		No U recycle	With U recycle
Uranium mining	0.594	0.470	0.352
Uranium milling	0.262	0.207	0.155
Conversion to UF ₆	0.045	0.036	0.036
Enrichment	~0.001	~0.001	~0.001
LWR fuel fabrication	0.027	0.022	0.022
Power generation	0.070	0.070	0.070
Transportation	0.011	0.011	0.011
LWR reprocessing	— ^b	0.067	0.067
ALMR reprocessing	—	0.004	0.004
Waste management	0.004	0.004	0.004
Catastrophic accidents	0.04	0.04	0.04
TOTALS	1.054	0.931	0.762

^aAssumed 21% of nuclear power generation is from ALMRs.

^b— = Not applicable.

substantially for the LWR/ALMR case because less uranium mining, milling, and conversion are required. However, this reduction is partially offset by the additional health risk posed by the introduction of reprocessing facilities for both LWR and ALMR fuel.

It should be noted that, in this scenario, uranium recovered from LWR spent fuel is assumed to be either stored or disposed as low-level waste. A small fraction could be used as makeup uranium in the ALMR cores. We have made no attempt to characterize health risks resulting from the storage or disposal of this stream due to the current lack of definition regarding the storage option.

3.2 LWR URANIUM RECYCLE SCENARIO

The fuel cycle for this scenario normalized to 1 GW(e)-year of total nuclear energy production, is shown in Fig. 2. In this scenario, the uranium recovered from LWR fuel reprocessing is converted to UF_6 and reenriched by the gaseous diffusion plants. As in the prior scenario, plutonium and minor actinides recovered from LWR fuel reprocessing are cycled through the ALMR complex as fuel.

The uranium flows in the front end of the fuel cycle are significantly reduced by the presence of the recycle uranium stream. Because mining and milling operations are major sources of short-term health risk, this fuel cycle will have a markedly reduced overall risk projection.

The steps involved in recycling LWR uranium in this scenario are not well defined. The chemical form of the recycle uranium stream is undetermined but may well require a distinct facility for conversion to UF_6 . In Fig. 2, this facility is shown as a distinct processing step.

The potential fuel cycle risks associated with this flow sheet are given in the third column of Table 3. Here again, we have assumed the health risk values derived in Appendix A for the ALMR reprocessing facilities. The facility for conversion of reprocessed uranium to UF_6 has nominally the same risks per MTHM throughput as its analogous LWR fuel cycle facility. Health risk values for the reactor, the waste repository, and transportation have been held constant.

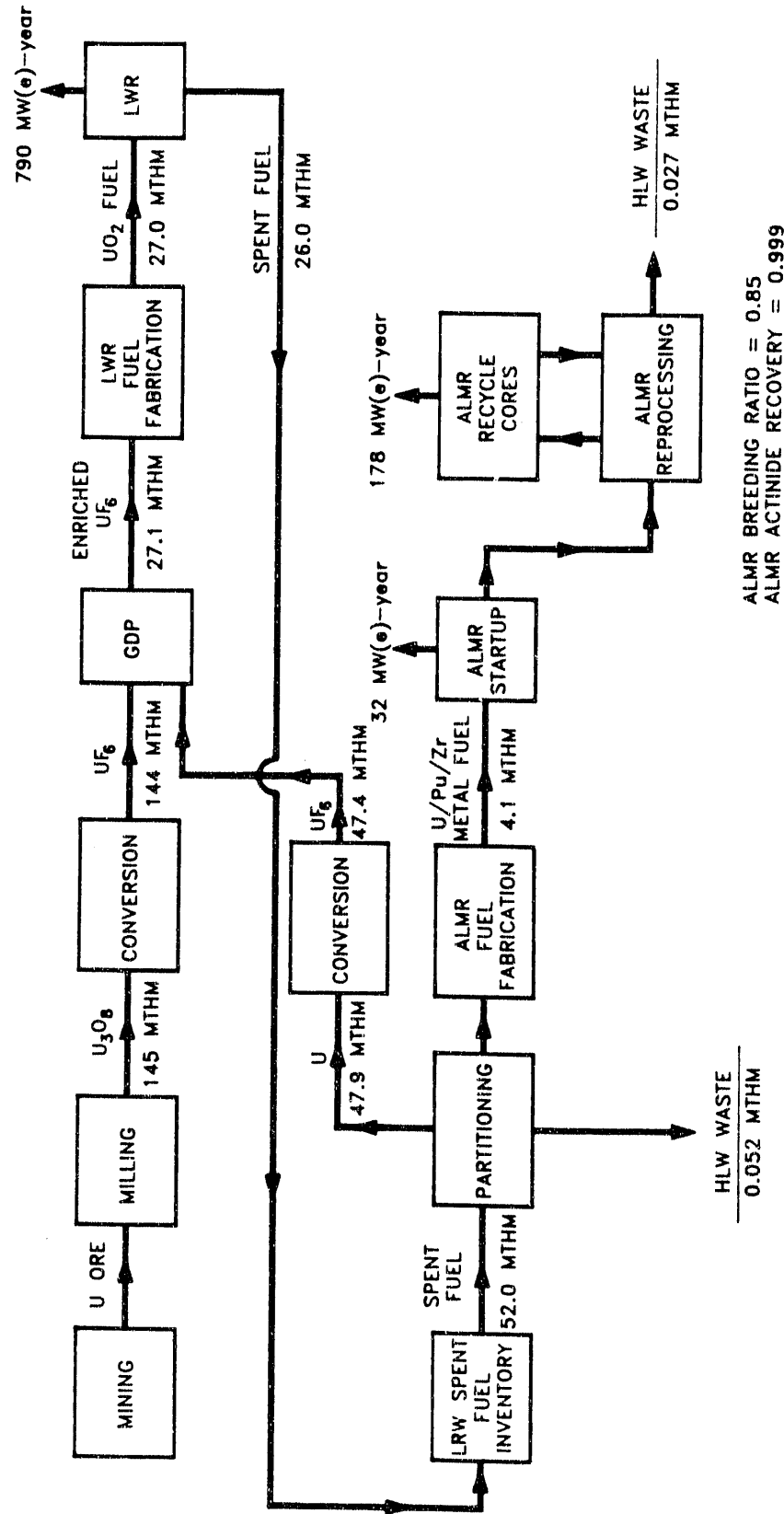


Fig. 2. Actinide mass balance for an integrated LWR/ALMR-actinide-burning system with uranium recycle.

The values of risk for this fuel cycle estimate are reduced about 28% relative to the current LWR once-through fuel cycle. This effect is due to the lower level of releases associated with mining and milling facilities.

3.3 DEPENDENCE ON ALMR DEPLOYMENT LEVEL

A key assumption in the results of the previous sections is that the ALMR component of the nuclear power complex comprises 21% of U.S. nuclear power capacity. This value of deployment level for the ALMR is a purely nominal one, and as such, it is appropriate to consider the parametric dependence of short-term fuel-cycle risk on the fraction of U.S. nuclear capacity generated by ALMRs.

A series of calculations were performed to characterize fuel cycle flows and health risk for the two scenarios shown in Figs. 1 and 2 as a function of the deployment level of ALMRs. Key assumptions in this study concerning the ALMR breeding ratio are listed below.

- The ALMR breeding ratio was assumed to be 0.85 for those calculations in which the ALMR nuclear power capacity is less than 21% of the overall U.S. nuclear power complex.
- For those cases in which the ALMR capacity exceeds 21% (up to 100%) of the overall U.S. nuclear capacity, it was assumed that the LWR spent fuel inventory would be depleted at twice the rate at which new LWR spent fuel is being generated, and that the fissile plutonium breeding ratio would be adjusted so as to meet this criteria. The net result of this assumption is that as the ALMR component of the nuclear fuel cycle becomes increasingly dominant, the ALMR breeding ratio is assumed to rise above the minimum value of 0.85, and ultimately approaches 1.0 as the ALMR fraction of the nuclear fuel cycle approaches 100%.

The results of this parametric study are shown in Fig. 3. The endpoint corresponding to zero deployment of ALMRs represents the current once-through LWR fuel cycle. The values of health risk at about the 21% deployment level correspond to the cases shown in Figs. 1 and 2 and delineated in Table 3. The scenario of 100% ALMR deployment, with complete phaseout of the LWR technology, corresponds to the other endpoint on the curves.

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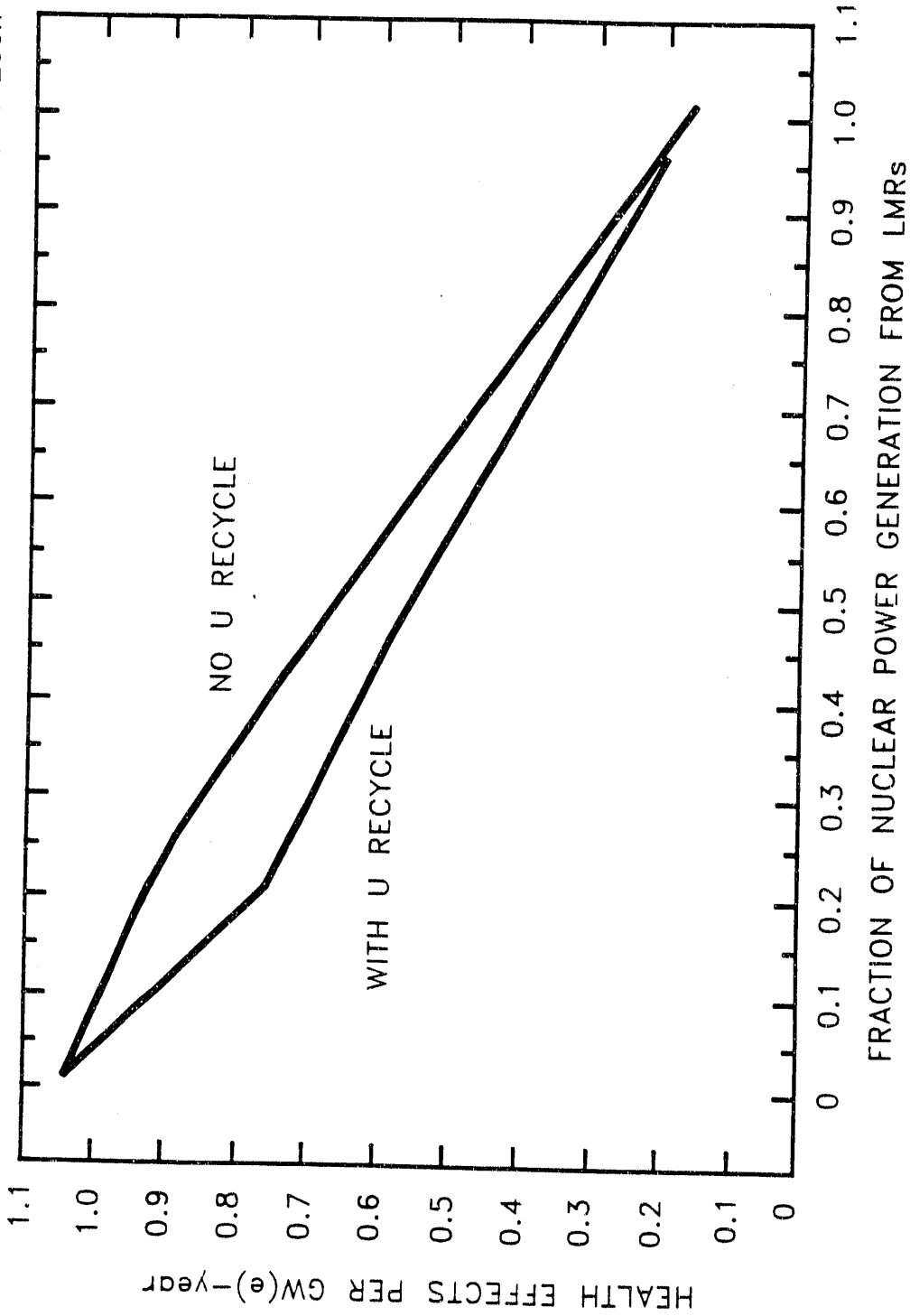


Fig. 3. Nuclear fuel cycle health risk per gigawatt of electricity production as a function of the fraction of nuclear power that is produced by LMRs.

In this last scenario, the short-term fuel cycle risk is reduced by 60% from the current once-through LWR fuel scenario.

4. CONCLUSIONS

Any breakdown of health impacts represents an unusual mixture of items in which many judgments must be made and for which the results will depend strongly upon the ground rules. We have tried to minimize the number of judgments in this study by scaling our results from a standard regulatory basis for estimating ALMR and reprocessing plant health risks, both for normal operations and accident scenarios. However, several conclusions can be made.

- The deployment of the ALMR/pyroprocessing technology as an actinide burner will reduce front-end fuel cycle health risks.
 - Uranium mining, milling, and fuel conversion, which comprise 75% to 85% of the current fuel cycle health risk, would be gradually phased down as ALMRs are deployed.
 - Implementation of uranium recycle in the integrated LWR/ALMR enterprise would further reduce health risk significantly during the early phases of ALMR deployment.
- If ALMR technology can be operated at about the same hazard level as analogous LWR technology, then the overall fuel cycle risk will be significantly lower compared to a once-through LWR fuel cycle.
 - Adoption of a complete ALMR fuel economy is projected to reduce short-term nuclear fuel cycle health risk by more than 80%.
- The major contributors to reprocessing plant risk in standard environmental assessments are tritium, ^{14}C , and ^{85}Kr , all of which are assumed to be 100% released to the environment (see Appendix A).

- The ALMR reprocessing facility is expected to have a lower health risk due to the absence of a significant ^{14}C inventory in the ALMR metal fuel and the plans to recover and dispose of tritium and ^{85}Kr gases.
- The beneficial impact of ALMR deployment on short-term fuel cycle health risk appears to be much greater than the entire health risk attributed to the geologic repository.

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**Appendix A. BASIS FOR REPROCESSING PLANT SHORT-TERM
HEALTH RISK ESTIMATES**

APPENDIX A

BASIS FOR REPROCESSING PLANT SHORT-TERM HEALTH RISK ESTIMATES

There are two distinct reprocessing facilities included in the actinide recycle flow sheets (Sect. 3, Figs. 1 and 2). An LWR-Actinide Recycle (LWR-AR) facility reprocesses uranium oxide fuel from the LWR spent fuel inventory and produces a TRU-rich stream that is subsequently converted into metal fuel for the ALMR. The reprocessing technology to be employed in the LWR-AR plant has not yet been chosen, so for the purposes of this discussion, it is assumed that there are no technology differences between the LWR-AR plant and the standard reprocessing plant assumed in the NRC environmental assessments.¹ The second reprocessing facility, the IFR plant, is defined as reprocessing the metal fuel of the ALMR and recycling the recovered uranium and transuranium (TRU) elements back into that reactor. This latter plant is assumed to employ pyrometallurgical technology that is under development at Argonne National Laboratory.²

This appendix explains the derivation of the short-term health risk values that are assumed for these two reprocessing plants in the Sect. 3 analyses.

A.1 SHORT-TERM HEALTH RISK FOR THE STANDARD REPROCESSING PLANT

As shown in Sect. 2, Table 1, the three components of the health effects (mortality only) for the standard reprocessing plant are:

1. the radiological health effect on the general population, which is projected to be 0.055 mortalities/Gw(e)-year;
2. the radiological health effect on the reprocessing plant work force which is projected to be 0.0023 mortalities/GW(e)-year; and
3. the nonradiological health effect on the reprocessing plant work force, which is expected to be small, but for which no value is available.

In this discussion, we will examine only the health effects on the general population, which constitutes 96% of the total health effects. Occupational health effects for the actinide recycle facilities are assumed to be the same as the standard case values.

The contribution of individual nuclides to short-term reprocessing plant health risk is given in Table 4. The values in this table are from Gotchy,³ with the exception of the explicit value for actinides which was derived from NUREG-0002.¹

The standard plant is defined as releasing to the air 100% of the total inventory of tritium, ^{14}C and ^{85}Kr in the reprocessed fuel.¹ The result, as seen in Table 4, is that tritium and ^{14}C are the radiation source terms responsible for about 89% of the plant's effect on the general population, and ^{85}Kr is the third most important nuclide—accounting for another 6% of the total health effect.

The standard plant is also assumed to be reprocessing fuel that has been subject to a cooling period of 160 d. This assumption maximizes the inventory of short-lived nuclides available for release, such as ^{131}I , ^{134}Cs , ^{85}Kr , and tritium, and maximizes the overall health effect calculated for the standard plant.

It should also be noted that uranium and TRU elements only comprise about 0.5% of the standard plant's health effect on the general population.

A.2 CURRENT REGULATIONS AFFECTING ALLOWABLE RELEASES FROM A REPROCESSING PLANT

In the current regulatory environment, the assumption that normal operations for a reprocessing plant will involve releases of 100% of the inventory of tritium, ^{14}C and ^{85}Kr appears to be contradicted by other standards.

The most restrictive standard concerning ^{85}Kr releases is probably the U.S. Environmental Protection Agency (EPA) regulation 40CFR190, Subpart B,⁴ which states:

Operations . . . shall be conducted in such a manner as to provide reasonable assurance that . . . the total quantity of radioactive materials entering the general environment from the entire uranium fuel cycle, per gigawatt-year of electrical energy produced by the fuel cycle, contains less than 50,000 curies of krypton-85

Table 4. Health effects (mortality only) in the U.S. general population resulting from normal operations of the standard reprocessing facility, 1000-year dose commitment

Nuclide	Potential health impacts [per GW(e)-year]
^3H	0.0276
^{14}C	0.0207
^{85}Kr	0.0034
^{131}I	<0.0001
^{134}Cs	0.0012
^{137}Cs	0.0018
U and TRU	0.0003
Other fission products	<u>0.0001</u>
Total	0.0550

This regulation has the effect of limiting the reprocessing plants under consideration to releases that amount to less than ~15% of the plant ^{85}Kr inventory.

The standards that would be applicable to airborne releases of ^{14}C and tritium from reprocessing facilities include the following:

- limits on concentrations in air at the boundary of unrestricted areas, as given in Appendix B, Table 2, Column 1 of the NRC's 10 CFR Part 20,⁵ or a limit on annual effective dose equivalent to members of the public of 10 mrem, as given in Subpart I of EPA's 40 CFR Part 61,⁶ whichever is the more restrictive; and
- requirement in Subpart B of NRC's 10 CFR Part 20 that doses to members of the public should be as low as reasonably achievable (ALARA).⁵

Without a detailed site-specific assessment, it is difficult to tell whether the first set of standards will be limiting on either ^{14}C or ^3H releases. Given that technology is available to recover ^{14}C and convert it to a suitable waste form, it is likely that the latter standard (ALARA) will limit the releases of ^{14}C in a reprocessing facility to considerably less than 100%.

Tritium is a difficult nuclide to recover and immobilize, particularly in a reprocessing plant that utilizes aqueous processes. However, in the IFR (which processes metal fuel) all chemical operations are performed in an inert atmosphere, such as argon, with an extremely low oxygen background pressure. Given this type of environment, recovery of tritium from the reprocessed fuel is vastly simpler than in the standard (aqueous) plant, and the standard which stipulates that emissions must be ALARA might be interpreted in this instance as requiring tritium recovery. Indeed, this requirement is anticipated in the preconceptual design of the facility, which calls for tritium to be converted to water in the cell gas purification system, collected on molecular sieve beds, and eventually to be desorbed, stored in tanks, and disposed as low-level waste.

For this assessment, the following assumptions are made:

- LWR-AR (oxide fuel) plant release fractions are 0.15 for ^{85}Kr , 1.0 for ^{14}C , and 1.0 for tritium. These are very conservative values and are intended to represent the maximum credible releases for normal operations.
- IFR (metal fuel) facility release fractions are 0.15 for ^{85}Kr , 1.0 for ^{14}C , and 0.2 for tritium. Again, these are very conservative values and are intended to represent the reasonable upper bounds for normal operational releases.

A.3 NUCLIDE INVENTORY SCALING OF HEALTH RISK

There are several significant differences between nuclide inventories in the standard reprocessing plant and the two actinide recycle plants. These differences represent straightforward corrections on the health risk. Clearly if a given plant has more (or less) of a given nuclide in this inventory than the standard plant, then, all other assumptions being fixed, that plant will have more (or less) of a radiation source term for health risk to the general population.

In the following discussion, we will quantify inventory and health risk in terms of units per GW(e)-year. Because of the nature of some of the ALMR designs, which call for heterogeneous cores with differing core residence times, it is awkward to discuss the nuclide inventory in units of MTHM-processed. The following discussions are based on ORIGEN2 simulations of LWR and ALMR fuel which, in the case of the ALMR/IFR plant simulation, account for all reprocessed heavy metal streams and aggregate the nuclide inventories as units per GW(e)-year.

Age of Reprocessed Fuel. The standard plant assumes the fuel has been cooled 160 d from discharge prior to being reprocessed. This short cooling time translates into conservatively large inventories of short-lived fission products such as ^{131}I , ^{134}Cs , ^{85}Kr , and tritium within the reprocessing plant. The Actinide Recycle Program has adopted a baseline cooling time of 10 years for the oxide fuel reprocessing plant. This longer cooling time, which is consistent with current reprocessing practice in

Europe, results in a reduction in health risk for the oxide fuel reprocessing plant of about 25%—from 0.0558 to 0.0412 health effects per GW(e)-year.

The baseline average cooling time for the metal fuel reprocessing plant is usually assumed to be 2.25 years (this shorter time is made possible by the high-temperature nature of the reprocessing operations). This short cooling time is still much longer than that assumed in the standard case, but translates into only a modest reduction in fission product inventory and health risk.

TRU Content of Spent ALMR Fuel. The inventory of TRU elements in reprocessed ALMR fuel can be expected to be 4 to 15 times larger, per GW(e)-year, than in the reprocessed LWR fuel assumed in the standard plant environmental assessment. For this study, it will be assumed that the ALMR spent fuel TRU inventory is 15 times that of the LWR, and that the total health effect of the uranium and TRU elements is subject to multiplication by this factor of 15 (for the metal fuel reprocessing plant).

Carbon-14 Content of Spent ALMR Fuel. Based on ORIGEN2 calculations, the ALMR inventory of ^{14}C is expected to be lower than the analogous LWR inventory by about a factor of 2000. The reasons for the lower ^{14}C inventory in an ALMR are as follows.

- There is virtually no nitrogen or carbon in the heavy metal fuel of the ALMR, due to the fact that the fuel is processed and fabricated in an inert (argon) atmosphere. Indeed, it is an aspect of the reprocessing technology that any nitrogen or carbon present will tend to form nitride or carbide compounds that become separated from the heavy metal streams. Nitrogen and carbon are the primary precursors of ^{14}C in an LWR system.⁷
- The other precursor nuclide for ^{14}C creation is ^{17}O . This nuclide is present in significant quantities in the oxide fuel form used in LWRs, but is not present in the ALMR metal fuel.

- The fast neutron flux employed in the ALMR results in very low cross-sections for generation of ^{14}C from any nitrogen or carbon impurities that are present in zirconium or other structural materials.

Results of General Electric calculations, reported in an Electric Power Research Institute (EPRI) assessment,⁸ also predict that the ^{14}C levels in the ALMR will be reduced by more than a factor of 1000 as compared to an LWR.

This relatively low level of ^{14}C inventory in the ALMR fuel will obviously result in a significant reduction in the IFR plant health risk attributable to the release of this nuclide. This reduction is important, as ^{14}C represents the source of about 37% of the standard plant's health risk to the general population.

Tritium Content of Spent ALMR Fuel. The inventory of tritium in ALMR fuel can be expected to be significantly higher than in the standard case LWR fuel, thus creating the potential for larger tritium releases and additional increments of health risk. The two major pathways for tritium production in reactor fuel are as a fission product from the relatively rare ternary fission event, and by activation of lithium that is present as an impurity in the fuel. The ternary fission event occurs more frequently during ^{239}Pu fission than for ^{235}U fission, and is more frequent in a fast flux system. The net effect is that the tritium inventory, at discharge, in spent ALMR fuel is calculated to be 30% higher than for discharged LWR fuel. Factoring in the cooling time of the fuel prior to reprocessing, the IFR plant tritium inventory is 15% larger, on a GW(e)-year basis, than the inventory assumed for the standard reprocessing plant.

Fission Product Content of Spent ALMR Fuel. The fission product inventories in spent ALMR fuel will be different than the standard case, because the dominant fissionable nuclide in ALMR fuel is ^{239}Pu , which has a different fission product yield spectrum than ^{235}U . This effect causes a small reduction in ^{85}Kr inventory and a slight increase in cesium nuclide inventory.

A.4 ESTIMATED SHORT-TERM RISK FOR ACTINIDE RECYCLE REPROCESSING PLANTS

Table 5 integrates the various effects discussed in the prior sections and presents the estimated short-term health risk effect on the general population for normal operations for the oxide and metal fuels reprocessing plants. These values have been derived from the standard regulatory case with scaling introduced to account for nuclide inventory differences and for revised practices in regards to releasing radioactive gases to the atmosphere.

The LWR-AR plant is projected to have a short-health risk to the general population of 0.039 mortalities/GW(e)-year, which is 30% lower than the standard case. Together with the occupational health impacts, the overall risk value is 0.041 mortalities/GW(e)-year.

The IFR plant is projected to have a general population health risk of 0.0143 mortalities/GW(e)-year; including the occupational risk, the value is 0.0166 mortalities/GW(e)-year. This value is almost a factor of four lower than the standard. This reduction is principally due to the reduced fractional releases of tritium and the reduction, by a factor of more than 1000, of the ^{14}C inventory. The increased level of TRU elements in the spent ALMR fuel is reflected in the fact that TRU releases are the second major radiation source in the health risk to the general public.

It is recognized that definitive estimates can only be produced by a formal environmental assessment activity. In the absence of such an activity, however, we believe that the values of health risk as applied to the actinide recycle case shown here are more correct than the use of the standard reprocessing plant values, and, thus, are adopted for use in this study.

Table 5. Short-term reprocessing plant health risk to the general population^a

	LWR-AR plant			IFR plant		
	Standard plant health risk [mortality/GW(e)-year]	Nuclide inventory relative to standard plant	Health risk [mortality/GW(e)-year]	Nuclide inventory relative to standard plant	Health risk [mortality/GW(e)-year]	Total risk
³ H	0.0276	0.59	0.0161	1.15	0.0063	
¹⁴ C	0.0207	1.0	0.0207	<0.001	<0.0001	
⁸⁵ Kr	0.0034	0.54	0.0003	0.72	0.0004	
¹³⁴ Cs	0.0012	0.04	<0.0001	1.04	0.0012	
¹³⁷ Cs	0.0018	0.85	0.0015	1.25	0.0022	
TRUs	0.0003	1.0	0.003	15.0	0.0041	
Other FFs	<u>0.0001</u>	1.0	<u>0.001</u>	1.0	<u>0.0001</u>	
Total risk	0.0550		0.039		0.0143	

^aCooling 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.

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