Fuel Age Impacts on Gaseous Fission Product Capture during Separations

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Waste Management

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SUMMARY

As a result of fuel reprocessing, volatile radionuclides will be released from the facility stack if no processes are put in place to remove them. The radionuclides that are of concern in this document are ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. The question we attempt to answer is how efficient must this removal process be for each of these radionuclides? To answer this question, we examine the three regulations that may impact the degree to which these radionuclides must be reduced before process gases can be released from the facility. These regulations are 40 CFR 61 (EPA 2010a), 40 CFR 190(EPA 2010b), and 10 CFR 20 (NRC 2012), and they apply to the total radonuclide release and to the dose to a particular organ – the thyroid. Because these doses can be divided amongst all the radionuclides in different ways and even within the four radionuclides in question, several cases are studied. These cases consider for the four analyzed radionuclides inventories produced for three fuel types—pressurized water reactor uranium oxide (PWR UOX), pressurized water reactor mixed oxide (PWR MOX), and advanced high-temperature gas-cooled reactor (AHTGR)—several burnup values and time out of reactor extending to 200 y. Doses to the maximum exposed individual (MEI) are calculated with the EPA code CAP-88 (Rosnick 2007, 1992). Two dose cases are considered. The first case, perhaps unrealistic, assumes that all of the allowable dose is assigned to the volatile radionuclides. In lieu of this, for the second case a value of 10% of the allowable dose is arbitrarily selected to be assigned to the volatile radionuclides. The required decontamination factors (DFs) are calculated for both of these cases, including the case for the thyroid dose for which ^{14}C and ^{129}I are the main contributors. However, for completeness, for one fuel type and burnup, additional cases are provided, allowing 25% and 50% of the allowable dose to be assigned to the volatile radionuclides. Because ^{3}H and ^{85}Kr have relatively short half-lives, 12.3 y and 10.7 y, respectively, the dose decreases with the time from when the fuel is removed from the reactor and the time it is processed (herein "fuel age"). One possible strategy for limiting the discharges of these short half-life radionuclides is to allow the fuel to age to take advantage of radioactive decay. Therefore, the doses and required DFs are calculated as a function of fuel age. Here we calculate, given the above constraints and assumptions, the minimum ages for each fuel type that would not require additional effluent controls for the shorter half-life volatile radionuclides based on dose considerations. With respect to ^{129}I doses, we find that the highest dose is calculated with iodine as a fine particulate. The dose scales as the fraction of the total ^{129}I that is particulate. Therefore, we assume for all of our calculations that 100% of the ^{129}I is particulate and allow the user of the results given here to scale our calculated doses to their needs.

To summarize the data given in the body and appendices of this report, we find that the principal isotopes of concern are ^{3}H and ^{129}I, the latter requiring the highest DFs. The maximum DF value for ^{129}I is 8000 for the illustrated cases. The required DF for ^{3}H could be as high as 720, depending on the age of the fuel processed. The DF, depending on fuel age, for ^{85}Kr could be up to ~60. The DF for ^{14}C is in many cases 1 (no treatment required) but could be as high as 30. The DFs are within the range of DFs that are reported for the capture technologies for the volatile radionuclides. Achieving the required ^{129}I and ^{3}H DFs is more challenging. Variations in stack design and other design factors may also significantly impact the DF requirements.

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ACRONYMS

AHTGR	Advanced High Temperature Gas-Cooled Reactor
ALI	annual limit on intake
CFR	Code of Federal Register
Ci	curies
d	day
DAC	derived air concentration
DF	decontamination factor
DOE	U.S. Department of Energy
EAC	effluent air concentration
EPA	U.S. Environmental Protection Agency
GW	gigawatt (10^9 W)
GWd	gigawatt-days
GWy	gigawatt-y
GWd/t	gigawatt-day per tonne (metric ton)
h	hour
IHM	initial heavy metal (mass of heavy metals in fuel before irradiation)
LEU	low-enriched uranium (enrichment with respect to ^{235}U)
MEI	maximally exposed individual
MOX	mixed-oxide (a nuclear fuel that consists of both UO_2 and PuO_2)
mrem	millirem
mSv	millisieverts
MW	megawatt (10^6 W)
MWd	megawatt-days
NGNP	next-generation nuclear plant
NRC	U.S. Nuclear Regulatory Commission
PBR	pebble bed reactor
PWR	pressurized water reactor
rem	Röntgen equivalent man (mammal)

s	second
scfm	standard cubic feet per minute
t	tonne (metric ton or 1000 kg)
T	Tritium (^{3}H)
UNF	used nuclear fuel
UOX	uranium oxide fuel
WG	weapon-grade (reference to the source of plutonium)
y	year

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1. INTRODUCTION

Atmospheric releases of radionuclides during the reprocessing of used nuclear fuel (UNF) must be controlled to levels that comply with air emissions regulations. Radionuclides that tend to form gaseous species that evolve into reprocessing facility off-gas systems are more challenging to efficiently control compared to radionuclides that tend to stay in solid or liquid phases. Radionuclides that have been identified as "gaseous fission products" are noble gases (most notably isotopes of krypton and xenon); ^{3}H; ^{14}C; and ^{129}I. In aqueous reprocessing, these radionuclides are most commonly expected to evolve into off-gas streams in tritiated water [$^{3}H_2O$ (T_2O) and ^{3}HHO (THO)], radioactive CO_2, noble gases, and gaseous HI, I_2, or volatile organic iodides. The fate of these radionuclides from a non-aqueous fuel reprocessing facility is unknown at this time, but active investigations are taking place. Therefore, we have limited our scope to aqueous reprocessing of UNF.

Fuel aging prior to separations allows decay of the short-lived gaseous fission products ^{3}H, ^{85}Kr, ^{131}I, and the radioactive isotopes of xenon. In the context of this report, "fuel aging" refers to the time between removal from the reactor core and the processing of the UNF. The ^{131}I and radioactive isotopes of xenon have such short half-lives (< 37 d) that if the fuel ages up to a year after reactor discharge, then these isotopes are decayed to negligible levels in the UNF. Further aging of the fuel before reprocessing allows the remaining short-lived isotopes of the four radionuclides considered here to decay, hence reducing the overall dose impact. We determined the dose from the four isotopes over a 200-y time span. This showed the impact on the whole body dose and the thyroid by isotope so that the strategy of aging fuel to meet regulatory releases or provide more "head space" for required decontamination factors (DFs) could be assessed.

Krypton capture and storage has been discussed as a potentially very costly portion, up to 15–20% of the total costs for a separations facility.* Because it readily exchanges for hydrogen in water, the recovery of tritium is expensive as well. In this study, we assess the implications of fuel age and the need for capturing the short-lived fission products ^{3}H and ^{85}Kr. The results of this study can be used as input to broader systems analysis studies in which the implications of fuel age with respect to the fuel cycle as a whole are investigated. The results shown here should serve to inform future analyses of the impact of regulatory requirements of the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC).

Also included in this study are ^{14}C and ^{129}I. Although they do not significantly decay within reasonable fuel aging time periods, the potential need to control emissions of these radionuclides during UNF reprocessing can also affect the cost and complexity of the off-gas system and the cost and complexity of managing waste streams that are generated. An insignificant amount of ^{14}C comes from fission; however, significant quantities come from the activation of trace nitrogen in the fresh fuel. This is discussed in sufficient detail to justify including ^{14}C in this study.

As part of the advanced fuel cycle effort, reprocessing of UNF is being considered (DOE 2010). Since the last time fuel reprocessing was investigated, new regulations have been put in place to govern the release of radionuclides from a reprocessing plant and the rest of the fuel cycle. Within the scope of this

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study, the volatile radionuclides ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I are, in part, the nuclides that will need to be controlled to meet these regulations. We recognize, however, that other radionuclides are addressed in the regulations for allowable releases, for example, isotopes of plutonium. The scope of the study reported here covers only the four volatile radionuclides mentioned and is the reason that we have included different dose allocations for these radionuclides in this study. Thus, the impact of these regulations on the emissions control efficiencies needed for these radionuclides and the impact of fuel age on the required control efficiencies, expressed as DFs, are the subjects of this document.

Release of radionuclides from the entire fuel cycle is regulated by 40 CFR 190.10 (EPA 2010b). This regulation states that

> *The annual dose equivalent does not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public as the result of exposures to planned discharges of radioactive materials, radon and its daughters excepted, to the general environment from uranium fuel cycle operations and to radiation from these operations…*

and

> *The total quantity of radioactive materials entering the general environment from the entire uranium fuel cycle, per gigawatt-y of electrical energy produced by the fuel cycle, contains less than 50,000 curies of krypton-85, 5 millicuries of iodine-129, and 0.5 millicuries combined of plutonium-239 and other alpha-emitting transuranic radionuclides with half-lives greater than one year.*

The latter restriction has the greatest impact on the operation of a reprocessing plant, because it regulates the release of the volatile radionuclides, with iodine and krypton being mentioned explicitly. Additionally, 10 CFR 20 (NRC 2012) and 40 CFR 61(EPA 2010a) regulate the doses to the maximally exposed individual (MEI) near a reprocessing plant, primarily from stack releases. To meet these release restrictions for a plant, certain DFs are needed for the removal of these radionuclides from the gaseous effluent.

Part of meeting the regulations is fuel aging, in particular for the short-lived radionuclides ^{3}H ($t_{1/2}$ = 12.32 y) and ^{85}Kr ($t_{1/2}$ = 10.76 y). Letting the fuel age before it is reprocessed allows these radionuclides to decay to inventories that may be released without any removal or with removal efficiencies that are much easier to attain in an operating plant.

In a reprocessing plant where aqueous processing is used, volatile radionuclides come from the fuel during decladding and dissolution. In the facility, these nuclides are present in the cell ventilation, the dissolver, and the vessel off-gas systems. The amount of each radionuclide depends on the fuel burnup and the storage time (age) since its removal from the reactor. The concentration of these radionuclides in the various gas streams from which they must be removed depends on the fuel throughput and the process equipment designs, which ultimately determine the total flow rates of the off-gas streams.

Thus, the factors that play an important role in the required DFs for the volatile radionuclides are fuel age (time since end of irradiation), plant size (fuel throughput), and fuel burnup. These result in the amount of volatile radionuclide per unit mass of irradiated fuel and the volume of gas from which these radionuclides must be removed to meet the regulations. The pertinent regulations are set forth in 40 CFR 190 (EPA 2010b), 10 CFR 20 (NRC 2012), and 40 CFR 61(EPA 2010a). However, since the half-lives of ^{14}C and ^{129}I are very long relative to the likely fuel storage times, only the relatively short-lived radionuclides, ^{3}H and ^{85}Kr, are affected by storage times. The total inventory of these radionuclides

scales more or less linearly with fuel burnup. In general, the larger the plant throughput, the higher the gas flow rates and hence, the lower the concentrations of radionuclides. In this document, we analyze the effects of fuel type, fuel burnup, and plant size on the required DFs for the volatile radionuclides to make the plant compliant with regulations.

Recent studies have shown that the optimum storage time is 30 to 70 y (Collins et al. 2009; DelCul et al. 2003); we expand on these studies. We begin with a review of the applicable regulations and by calculating the radionuclide inventories for the radionuclides of concern for this study. These inventories are based on three reactor and fuel types and a range of fuel burnup of 20 to 100 GWd/tIHM. We then look at the effects of storing these fuels for up to 200 y. These sections are followed by sections on the CAP-88 code (Rosnick 2007, 1992) (an EPA code for calculating dose at locations from a emission stack), the input parameters to CAP-88, the required DFs for the radionuclides of concern to meet regulations, and a brief sensitivity study on the impact of the chemical and physical forms of ^{129}I.

2. REVIEW OF REGULATORY REQUIREMENTS

Volatile radionuclide emissions from a nuclear fuel recycle facility are addressed in several regulatory documents. The EPA has established, through 40 CFR 190, annual dose limits for nuclear fuel cycle facilities in the commercial sector (EPA 2010b). In 40 CFR 190.10, the dose limits for specific organs and for the whole body are provided. Specific release limits for ^{85}Kr, ^{129}I, and ^{239}Pu in curies (Ci) released per unit of electric power produced are also defined in 40 CFR 190 (EPA 2010b). Dose limits for workers and individual members of the public for facilities have been established in 10 CFR 20 and regulated by the NRC (NRC 2012). Dose limits at U.S. Department of Energy (DOE) facilities for workers and individual members have been established in 40 CFR 61.92 (EPA 2010a).

2.1 40 CFR 190

The provisions of this section are applicable to radiation doses received by members of the public in the general environment and to radioactive materials introduced into the general environment as the result of operations that are part of a nuclear fuel cycle. Section 40 CFR 190.10 provides the standards for normal operation and is quoted in Section 1 of this report.

For the purposes of this regulation, *organ* means any human organ exclusive of the dermis, the epidermis, or the cornea.

2.2 10 CFR 20

This regulation establishes "standards for protection against ionizing radiation resulting from activities conducted under licenses issued by the Nuclear Regulatory Commission. These regulations are issued under the Atomic Energy Act of 1954, as amended, and the Energy Reorganization Act of 1974, as amended" (NRC 2012).

Sections of 10 CFR 20 that apply to this analysis of compliance to dose regulations for the gaseous fission products (^{3}H, ^{14}C, ^{85}Kr, and ^{129}I) are excerpted below for reference in this report.

2.2.1 10 CFR 20.1301 Dose Limits for Individual Members of the Public

Section 10 CFR 20.1301 establishes the dose limits for individual members of the public and states the following.

(a) Each licensee shall conduct operations so that—

(1) The total effective dose equivalent to individual members of the public from the licensed operation does not exceed 0.1 rem (1 mSv) in a year, exclusive of the dose contributions from background radiation, from any medical administration the individual has received, from exposure to individuals administered radioactive material and released under § 35.75, from voluntary participation in medical research programs, and from the licensee's disposal of radioactive material into sanitary sewerage in accordance with § 20.2003, and

(2) The dose in any unrestricted area from external sources, exclusive of the dose contributions from patients administered radioactive material and released in accordance with § 35.75, does not exceed 0.002 rem (0.02 mSv) in any one hour.

….

(b) In addition to the requirements of this part, a licensee subject to the provisions of EPA's generally applicable environmental radiation standards in 40 CFR part 190 shall comply with those standards.

2.2.2 10 CFR 20.1302 Compliance with Dose Limits for Individual Members of the Public

(a) The licensee shall make or cause to be made, as appropriate, surveys of radiation levels in unrestricted and controlled areas and radioactive materials in effluents released to unrestricted and controlled areas to demonstrate compliance with the dose limits for individual members of the public in § 20.1301.

(b) A licensee shall show compliance with the annual dose limit in § 20.1301 by—

(1) Demonstrating by measurement or calculation that the total effective dose equivalent to the individual likely to receive the highest dose from the licensed operation does not exceed the annual dose limit; or

(2) Demonstrating that—

(i) *The annual average concentrations of radioactive material released in gaseous and liquid effluents at the boundary of the unrestricted area do not exceed the values specified in Table 2 of Appendix B to Part 20; and*

(ii) *If an individual were continuously present in an unrestricted area, the dose from external sources would not exceed 0.002 rem (0.02 mSv) in an hour and 0.05 rem (0.5 mSv) in a year.*

(c) Upon approval from the Commission, the licensee may adjust the effluent concentration values in appendix B to part 20, table 2, for members of the public, to take into account the actual physical and chemical characteristics of the effluents (e.g., aerosol size distribution, solubility, density, radioactive decay equilibrium, chemical form).

For the purposes of this study, we do not consider the short-term limit of 0.002 rem (0.02 mSv) in 20.1302(b)(2)(ii), since the lower annual limit is more restrictive.

Table 1 provides selected exposure and concentration limits for the radionuclides of interest for this study.

Table 1. Relevant exposure/concentration values for volatile radionuclides from Appendix B to Part 20 (NRC 2012)[a]

Atomic number	Radio-nuclide	Class	Table 1 Occupational values			Table 2 Effluent concentration		Table 3 releases to sewers
			Col 1	Col 2	Col 3	Col 1	Col 2	
			Oral	Inhalation				
			ALI, µCi	ALI, µCi	DAC, µCi/mL	Air, µCi/mL	Water, µCi/mL	Monthly average concentration, µCi/mL
1	^{3}H	Water, DAC includes skin adsorption Gas (HT or T_2) Submersion[a]: use above values as HT and T_2 oxidize in air and in the body to HTO[b]	8×10^{4}	8×10^{4}	2×10^{-5}	1×10^{-7}	1×10^{-3}	1×10^{-2}
6	^{14}C	Monoxide	-	2×10^{6}	7×10^{-4}	2×10^{-6}	-	-
		Dioxide	-	2×10^{5}	9×10^{-5}	3×10^{-7}	-	-
		Compounds	2×10^{3}	2×10^{3}	1×10^{-6}	3×10^{-9}	3×10^{-5}	3×10^{-4}
36	^{81}Kr	Submersion	-	-	7×10^{-4}	3×10^{-6}	-	-
	^{85}Kr	Submersion			1×10^{-4}	7×10^{-7}		
53	^{129}I	D,[c] all compounds	5 thyroid (20)	9 thyroid (30)	4×10^{-9} -	- 4×10^{-11}	- 2×10^{-7}	- 2×10^{-6}

[a]Submersion means that values given are for submersion in a hemispherical semi-infinite cloud of airborne material.
[b]H = hydrogen; T = tritium; O = oxygen
[c]For each radionuclide Table 1 indicates the chemical form which is to be used for selecting the appropriate ALI or DAC value. The ALIs and DACs for inhalation are given for an aerosol with an activity median aerodynamic diameter (AMAD) of 1 µm and for three classes (D,W,Y) of radioactive material, which refer to their retention (approximately days, weeks or years) in the pulmonary region of the lung. This classification applies to a range of clearance halftimes of less than 10 days for D, for W from 10 to 100 days, and for Y greater than 100 days. The class (D, W, or Y) given in the column headed ''Class'' applies only to the inhalation ALIs and DACs given in table 1, columns 2 and 3.

2.2.3 Definitions

Annual limit on intake (ALI) means the derived limit for the amount of radioactive material taken into the body of an adult worker by inhalation or ingestion in a year. The ALI is the smaller value for the intake of a given radionuclide in a year by the reference man that would result in a committed effective dose equivalent of 5 rem (0.05 Sv) or a committed dose equivalent of 50 rem (0.5 Sv) to any individual organ or tissue. The ALI values for intake by ingestion and inhalation of selected radionuclides are given in Table 1, Columns 1 and 2, of Appendix B to §§ 20.1001–20.2401.

Derived air concentration (DAC) means the concentration of a given radionuclide in air, which, if breathed by the reference man for a working year of 2000 hours under conditions of light work

(inhalation rate 1.2 cubic meters of air per hour), results in an intake of one ALI. The DAC values are given in Table 1, Column 3, of Appendix B to §§ 20.1001–20.2401.

2.2.4 How Compliance to 10 CFR 20 is Addressed in This Report

Table 2 of 10 CFR 20 Appendix B (NRC 2012) defines limits for annual average concentrations of radioactive material released in gaseous and liquid effluents at the boundary of an unrestricted area (the "fence line" that would surround a UNF reprocessing facility). These limits are based on an annual dose limit to an individual member of the public in the unrestricted area (just outside the fence line) of 0.05 rem (10 CFR 20.1302) (NRC 2012). For conservatism and simplicity in this study, we consider only these annual average concentrations because they are more conservatively restrictive than analyses in which the DACs are used to assess worker ALIs and analyses in which the basis is the short-duration 1-h exposure limits to the public.

For the purposes of this study we use the Effluent Concentrations given in Table 2 of Appendix B of 10 CFR 20 that are applicable to the exposure to the MEI at the site boundary. In the discussions provided in the following subsections of this report, we treat this using the same methodology as prescribed for the DACs.

2.2.4.1 Mixture rule

A stack gas from a reprocessing facility could contain any isotopes (or progeny of isotopes) in the UNF that is being processed. Off-gas control processes such as scrubbing and filtration would be designed to capture most isotopes with efficiencies high enough to comply with all emissions regulations including 10 CFR 20. The focus of this report is to determine what levels of control are needed for the gaseous fission products ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I.

The determination of capture efficiencies needed for the gaseous fission products is complicated by the potential for other radionuclides (some of which have very low effluent air concentrations [EAC]) to be present in the reprocessing facility off-gas. If the identity and concentration of each radionuclide in a mixture is known, the limiting value for each radionuclide is derived by the "sum of the fractions" rule. Following this rule, the maximum concentration of any radionuclide in a mixture is determined by dividing the concentration of the radionuclide by its single-component EAC from Table 2 of Appendix B (NRC 2012) and summing those fractions for all radionuclides in the mixture. The sum of these ratios for all of the radionuclides in the mixture may not exceed "1" (i.e., unity).

Example: If radionuclides A, B, and C are present in concentrations C_A, C_B, and C_C and if the applicable EACs are EAC_A, EAC_B, and EAC_C, respectively, then the concentration shall be limited so that the following relationship exists:

$$\frac{C_A}{EAC_A} + \frac{C_B}{EAC_B} + \frac{CC_CC}{EAC_C} < 1 \ .$$

2.2.4.2 When some or all radionuclides in a mixture are unknown

The notes to the tables of Appendix B (NRC 2012) indicate that for *any mixture for which identity of each of the radionuclides is known but the concentration of one or more of the radionuclides is not known, the DAC for the mixture shall be the most restrictive of the DAC for any of the radionuclides in the mixture.* However, if the identity of each radionuclide in the mixture is unknown, then the inhalation ALI, the DAC, and the effluent and sewage concentrations for the mixture are the lowest values specified in

Table 2 of Appendix B for any radionuclide that is not known to be absent from the mixture. Thus, if it cannot be shown that isotopes, such as ^{227}Ac, ^{229}Th, ^{232}Th, ^{231}Pa, ^{248}Cm, or ^{250}Cm, are not present, then the most restrictive effluent concentration limit would be 1×10^{-14} µCi/mL. Comparing this to the effluent concentration limits for the isotopes of interest, it is apparent that this would impose a requirement to reduce the dose from these isotopes by an additional factor of 10^3 to ~10^8 –significantly increasing the challenge of capturing these gaseous fission products.

For this study, we know that the stack effluent will contain a number of additional radionuclides, primarily as particulates. The bulk of these will be removed with HEPA filtration and scrubbers on the off-gas systems, but the potential for any (expectedly very small) amounts of these other radionuclides in the stack gas must be taken into account in the total exposure to the MEI. Accounting for the identity and concentration of every radionuclide in the effluent from the stack, besides the gaseous fission products, is outside the scope of this study. Also, for this study, it is overly restrictive to impose the most restrictive DAC to the four radionuclides of interest, because in an actual design for a reprocessing facility, the identities and concentrations of those other radionuclides would have to be taken into account.

The scope of this study is restricted to just the four gaseous fission products by restricting the potential dose from the gaseous fission products to a level that could cause an "insignificant" impact on how a reprocessing facility might comply with 10 CFR 20, considering the total dose from all the radionuclides that might be present in the stack gas. In this way, the dose from any single gaseous fission product, or the total dose from all the gaseous fission products, would not, by itself, cause the air emissions to be out of compliance. The largest reasonable "insignificant" amount might be 10% of the total. This approach allocates, to all other radionuclides that might be in the stack gas, 90% of the effective dose limit to the MEI.

With this approach, the dose to the public in §§ 20.1302 is reduced from the total of 50 mrem/y to 5 mrem/y for the amount of the dose that could be attributable to for the four volatile radionuclides, to make the potential total dose from these radionuclides "insignificant" compared to the total dose limit. As a result, we establish an effective effluent concentration limit for each of the four radionuclides of interest by reducing the effluent concentration limits DACs in Table 2, Appendix B, by a factor of 10. This approach reserves a majority of the allowable dose for other radionuclides.

2.2.4.3 Ranges of emissions control for other radionuclides

Some of the other radionuclides that could require emissions control for a reprocessing facility, such as ^{227}Ac, ^{229}Th, ^{232}Th, ^{231}Pa, ^{248}Cm, and ^{250}Cm, have very low effluent concentration limits, ranging as low as 1×10^{-15} µCi/mL. Detailed analyses of emissions of these other radionuclides are outside of the scope of this study. However, methodologies have been developed for use in estimating the uncontrolled emissions, required control efficiencies, and feasible control efficiencies (EPA 2010a; INEEL 1999). These low effluent concentration limits are more easily met for these solid and particulate-phase (nonvolatile or semi-volatile) radionuclides because they typically have different process release factors, control technologies, and control efficiencies, compared to those for the four volatile radionuclides evaluated in this study. Methods for estimating radionuclide emissions are provided in 40 CFR 61 Appendix D (EPA 2010a). Radionuclide emission factors are reported elsewhere (INEEL 1999; Soelberg et al. 2008). These authors indicate that the general decontamination factor ranges as shown in Table 2 for different forms of radionuclides.

Table 2 shows total DF values ranging from 10 to 100 for gaseous species with traditional scrubbing technologies, as long as the gaseous species are soluble in the scrubbing solution, and much higher DFs, ranging from 10^8 to 10^{14}, for radionuclides known to persist in liquid, particulate, and solid forms,

depending on assumed levels of conservatism and levels of redundancy (especially HEPA filtration). Trying to achieve such high DFs for the volatile radionuclides would be impractical at best, and unneeded to meet the emissions regulations in 10 CFR 20, 40 CFR 61, and 40 CFR 190.

Table 2. Ranges of decontamination factors to be expected for different radionuclide forms and different traditional control technologies

Control or process	Form	Decontamination factor			Comments
		From 40 CFR 61 App. D	From Abbot (1999)	Theoretical	
Aqueous separations processes	Gas	1	---	---	These factors indicate what fraction of gaseous, liquid, particulate, or solid-phase radionuclides evolve into reprocessing facility gas streams.
	Liquids and particulate solids	1000	---	1000	
	Solids	1×10^{6}	---	1×10^{6}	
Venturi scrubber	Gas	1	1	---	
	Particulate	20	2000	100	From Abbott (1999): Includes a calciner, cyclone, and venturi scrubber
Packed bed scrubber	Gas	10	---	100	For gases that are soluble in the scrubber solution; not applicable to particulates
Electrostatic precipitator	Particulate	20	---	---	
Fabric filters	Particulate	10		100	
Sintered metal filters	Particulate	---	---	100	Insufficient data on sintered metal filters data for EPA to include, but performance is similar to fabric filters
Each HEPA filter	Particulate	100	2.7×10^{5}	3000	From Abbott (1999): Total of four HEPAs in series – The first three have an assumed operating DF of 9E2 total; plus one final HEPA with DF of 3E2; DFs are de-rated for these from 3E3 each (1E14 total) for conservatism during operation.
Estimated cumulative DFs for a system that includes at least one scrubber, prefilter, and at least two HEPAs in series	Gas	10	---	100	Theoretical values are based on reasonably expected performance for a well-designed, maintained, and operated system, considering optimal performance; the cumulative theoretical values are de-rated by 1 or more orders of magnitude in conservative performance estimates. The cumulative DFs for gases only apply for gases that are soluble in scrub solutions.
	Liquids and particulate solids	2×10^{9}	5.4×10^{8}	1×10^{11}	
	Solids	2×10^{12}	---	1×10^{14}	

2.3 40 CFR 61

This part applies to operations at any facility owned or operated by DOE from which any radionuclide other than ^{222}Rn and ^{220}Rn is emitted into the air, except that this part does not apply to disposal at facilities subject to 40 CFR part 191 subpart B or 40 CFR part 192 (EPA 2010a).

This regulation establishes that the

> *emissions of radionuclides to the ambient air from Department of Energy facilities shall not exceed those amounts that would cause any member of the public to receive in any y an effective dose equivalent of 10 mrem/y.*

It is also noted that

> *demonstration of compliance will be based on 10 CFR 20 methodology by reduction of DAC by appropriate factor of 5 (see notes on development of Table 2 (Appendix B to Part 20).*

So to summarize:

Under 40 CFR 190 (EPA 2010b), the total quantity of iodine and krypton that may be released to the environment from the entire fuel cycle is limited to 5 mCi of ^{129}I and 50,000 mCi of ^{85}Kr per gigawatt-year (GWy) of electrical energy produced throughout the fuel cycle. The most restrictive dose limit (10 mrem/y to the public) is established in 40 CFR 61 (EPA 2010a). In 10 CFR 20 (NRC 2012), the limit is set at 100 mrem/y, but a demonstration of compliance level of 50 mrem/y value is added. Two key values are set in 40 CFR 190 — a limit to the whole body of 25 mrem/y and to the thyroid of 75 mrem/y. Since the values specified in 40 CFR 190 are more restrictive than those set by the NRC in 10 CFR 20 (NRC 2012) and the most restrictive values of 10 mrem/y apply only to DOE facilities, we use the 25 mrem/y as the upper limit in this study. Further, an allocation factor of 0.1 is applied to the four volatile radionuclides, resulting in a 2.5-mrem/y and 7.5-mrem/y thyroid dose contribution from these radionuclides. While the use of only 10% of the allowable dose for these four radionuclides is arbitrary, it is just as unlikely that the full allowable dose can be assigned to these four radionuclides, especially in light of the very low DACs for some of the other radionuclides that are likely to be in the stack emissions from a reprocessing facility. Therefore, for all the fuel types and burnups considered, two main cases are shown in this study; for completeness, we also show 25% and 50% allocations for only one fuel type and burnup. In the first of the two main cases, the entire allowable dose (25-mrem/y whole body; 75-mrem/y thyroid) is assigned to these four radionuclides. In the second, only 10% of the allowable dose (2.5-mrem/y whole body; 7.5-mrem/y thyroid) is assigned to these four radionuclides.

3. ASSUMPTIONS USED IN THIS STUDY

The assumptions and working hypotheses that we used in this study are listed below.

(1) Recycle facility will be licensed by NRC
   i. 40 CFR 61 is not applicable
   ii. 40 CFR 190and 10 CFR 20 apply
(2) Dose limits will be derived from 40 CFR 190 based on lower limit.
(3) Allowable contribution by the four volatile radionuclides to total dose to MEI will be 10% of the total allowable dose.
(4) Same factor will apply to thyroid dose.
(5) No engineering margins will be applied.

(6) The entire calculated inventory for the four isotopes will be in the fuel meat, pellet-pellet gap, pellet-cladding gap, or that part of the fuel assembly that is processed. No migration will be taken into account (e.g., ^{3}H migration into the cladding), which will result in a decrease in the calculated maximum radionuclide inventory. (This was considered in one of the sensitivity analysis cases.)
(7) The chemical impurities in the starting UO_2 and PuO_2 material will be half of the maximum values shown in the standard specifications by ASTM (ASTM 2008, 2011).
(8) Plant size of 1000 t/y
(9) The site boundary will be at maximum plume concentrations as determined by CAP-88.
(10) Fuel age: 2, 5, 10, 20, 30, 50, 70, 100, and 200 y of cooling
(11) Fuel type: LWR uranium oxide (UOX), mixed oxide (MOX), and Advanced High-Temperature Gas-Cooled Reactor (AHTGR)
(12) Burnup: 20, 30, 60, and 100 GWd/tIHM
(13) The potential for release of ^{85}Kr or ^{129}I in other parts of the fuel cycle is not considered in this study. If discrete amounts of these radionuclides are released to the atmosphere in other parts of a fuel cycle (such as during reactor operations or during used fuel storage prior to reprocessing), then the control efficiencies estimated in this study for compliance to the fuel cycle limits in 40 CFR 190 would need to be proportionately higher.

4. SOURCE TERM CALCULATIONS

Radionuclide inventories representative of different spent nuclear fuel types have been calculated to provide source terms to be used for accident analyses and environmental impact studies. Three types of reactor/fuels configurations have been considered in this report: (1) pressurized water reactor (PWR) with low-enriched uranium (LEU) fuel; (2) PWR with MOX fuel; and (3) pebble bed reactor (PBR), as an example of an AHTGR with LEU fuel. Depletion simulations have been performed for configurations representative of the three considered reactors/fuels with the SCALE nuclear analysis code system (ORNL 2011). The depletion models and the analysis methodology are summarized in this section.

4.1 FUEL AND REACTOR DATA

A Westinghouse 17 × 17 fuel assembly was used in this study as representative of a PWR with UO_2 LEU fuel. The assembly data were taken from (ORNL 2011). For the purposes of this study, the LEU fuel had an enrichment of 4.0 mass% ^{235}U. The impurity content used in the fresh UO_2 fuel was based on data taken from ASTM C776-06 (ASTM 2011). This standard specifies maximum concentration limits for Al, C, Ca, Mg, Cl, Cr, Co, F, H, Fe, Ni, N, Si, and Th. The values used for impurities contents in the PWR LEU assembly model were taken as half of the maximum concentrations for this fuel (ASTM 2011).

A PWR 17 × 17 fuel assembly was used as representative of a PWR with MOX fuel. Fuel and assembly design specifications for the PWR MOX assembly model are based on data in a publicly available document prepared by FRAMATOME ANP for the DOE Office of Material Disposition (FRAMATOME 2001). In this MOX fuel, weapon-grade (WG) plutonium is used. The composition of this fuel is shown in Table 3. The UO_2 and PuO_2 mass fractions correspond to assembly-average values (Table 3). The model actually included three types of fuel pins with different PuO_2 weight fractions. The impurity content of the MOX fuel is based on data from ASTM C833-01 (ASTM 2008). In this standard, the maximum concentration limits for Al, C, Ca, Mg, Cl, Cr, Co, F, H, Fe, Ni, N, Si, and Th are specified. The values used for impurities contents in the PWR MOX assembly model are half of the provided maximum concentrations (FRAMATOME 2001).

Table 3. ICompositions for the MOX fuel used in this study

Parameter	Value, %
UO_2	95.63
PuO_2	4.37
U isotopes	
^{235}U	0.25
^{238}U	99.75
Pu isotopes	
^{238}Pu	0.0
^{239}Pu	93.6
^{240}Pu	5.9
^{241}Pu	0.4
^{242}Pu	0.1

The PBR fuel configuration used in this study is representative of the PBR design considered under the Next Generation Nuclear Plant (NGNP) program (MacDonald et al. 2003). The fuel material present in the TRISO kernels is $UC_{0.5}O_{1.5}$ at 10.5×10^3 kg/m^3 density and has an enrichment of 7.0 mass% ^{235}U. A simplified model representative of the PBR NGNP fuel was used (Ilas and Gauld 2011), which consists of a fuel pebble surrounded by a helium coolant region. The fuel material was assumed to have the same impurities contents as used for the UO_2 fuel (ASTM 2011). The impurities values used in the depletion models are listed in Table 4.

Table 4. Impurity content in LEU and MOX fuels

Element	Impurity content in fuel, µg/g	
	LEU	MOX
Al	125	125
C	50	50
Ca	50	50
Cl	12.5	12.5
Cr	125	125
Co	50	50
F	7.5	12.5
Fe	250	250
H	0.65	0.65
Mg	50	50
N	37.5	37.5
Ni	125	125
Si	250	125
Th	5	-

4.2 ANALYSIS METHODOLOGY

The fuel depletion methodology used in this study includes two main steps. In the first step, computational models are developed for each of the three considered configurations for use with the SCALE/TRITON (DeHart and Bowman 2011) depletion sequence. Two-dimensional (2-D) geometry models are used for the PWR LEU and MOX assemblies and a 1-D geometry model is used for the PBR model. The 2-D model for the PWR MOX assembly is illustrated in Figure 1. The use of different colors for fuel pin materials in this figure serves to indicate different plutonium contents in the MOX fuel. The TRITON depletion models are used to simulate the fuel depletion to reach a total burnup of 105 GWd/tIHM. Burnup-dependent cross-section libraries for use in standalone SCALE/ORIGEN (Gauld et al. 2011) simulations are produced with TRITON (DeHart and Bowman 2011).

In the second step, the cross-section libraries generated with TRITON are used in depletion and decay simulations with the ORIGEN code. The ORIGEN code is used to calculate the radionuclide inventory for a desired fuel burnup and resulting activities at desired cooling times.

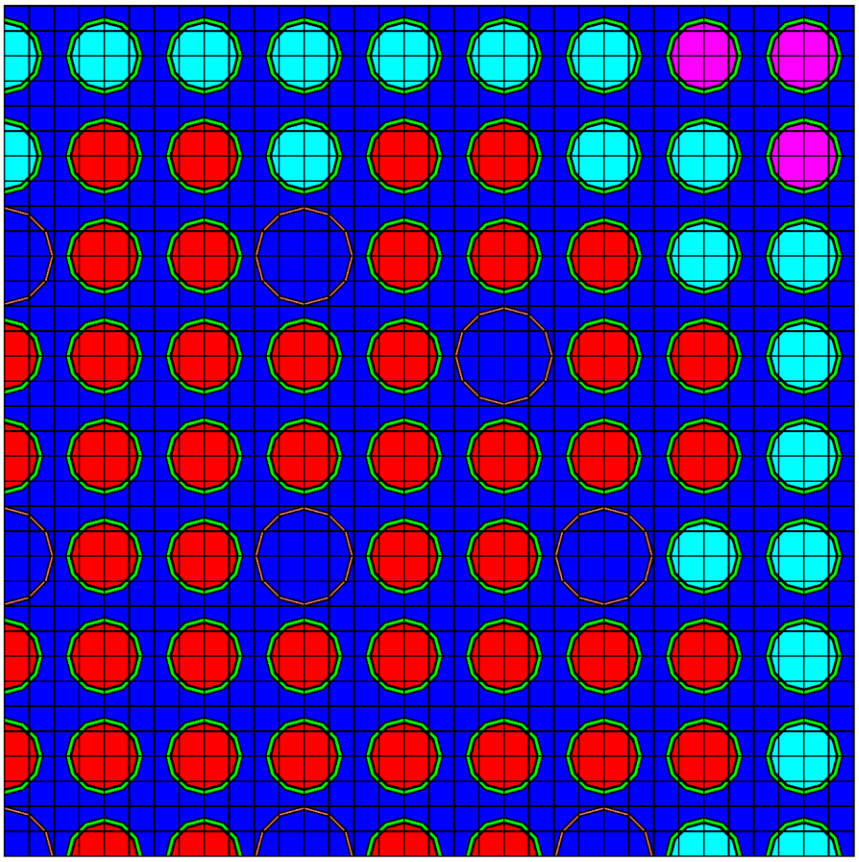

Figure 1. Illustration of PWR MOX assembly model (1/4 of the assembly is shown).

4.3 RESULTS

In the present study, ORIGEN-ARP simulations were carried out for each of the three considered fuels for total cumulative burnup values of 20, 30, 60, and 100 GWd/tIHM. For each of these burnup cases, radionuclide inventories and activities were generated for cooling times of 0 (discharge), 2, 5, 10, 30, 50, 70, 100, and 200 y.

The variation of the isotopic content of ^{3}H and ^{85}Kr, nuclides of importance to environmental impact studies, is illustrated in Figure 2 and Figure 3, respectively, as a function of cooling time for PWR LEU and PWR MOX fuels at 60-GWd/tIHM burnup. Extending the abscissae on these graphs to 200 y, the maximum cooling time in this study would not add to the information as these isotopes have already decayed to near-zero inventory (8 and 9 half-lives, respectively).

What is not indicated in these figures is any portion of the total ^{3}H that may migrate through the fuel meat and into, or through, the cladding. Once in Zircaloy cladding, the ^{3}H would be tightly held as a hydride. In either case, the ^{3}H would not contribute to the ^{3}H inventory in off-gas streams in a reprocessing facility, unless at the same facility the Zircaloy is processed to recover zirconium metal in such a way that the ^{3}H is released from the cladding. The UNF ^{3}H values reported in this section may overstate the amounts of ^{3}H that would be released to reprocessing facility off-gas systems.

The quantity of ^{129}I in MOX is significantly higher than in PWR/UOX because of the higher ^{129}I fission yield for ^{239}Pu fission (which is in a large quantity in WG MOX), compared to the ^{129}I fission yield from ^{235}U fission.

Most of the ^{14}C in the used UOX and MOX fuels is from activation of ^{14}N through the reaction ^{14}N (n, p) → ^{14}C, assumed to be present as an impurity in the fuels at a level that is half of the nitrogen impurity limit. Activation of oxygen in these fuels by the nuclear reaction ^{17}O (n, α) → ^{14}C also contributes to the generation of ^{14}C. Production of ^{14}C as fission product contributes very little to the total inventory of ^{14}C in these UNFs. For LWR UOX fuel, roughly 80% of the generated ^{14}C is produced by (n, p) reaction on ^{14}N and 20% is produced by (n, α) reaction on ^{17}O (there may be less ^{17}O in natural oxygen, but there is a lot of natural oxygen in the fuel. The natural abundance of ^{17}O is only 0.038 mol%.

In the AHTGR (PBR) there may be a significant increase in the quantity of ^{14}C from the ^{14}C produced as an activation product of ^{14}N (through the reaction ^{14}N (n, p) → ^{14}C) if N is assumed to be present as an impurity in the graphite (Bourdeloie and Marimbeau 2004; Yim and Caron 2006). The SiC and pyrolytic carbon are very pure and contain very little nitrogen. Therefore, ^{14}C generation in these materials is lower than in graphite and mainly from the activation of ^{13}C (Piet 2011). There is a natural abundance of ^{13}C in carbon of 1.11 mol%. It is activated to ^{14}C through neutron capture through the reaction ^{13}C(n, γ) → ^{14}C.

For the studies presented in this report, nitrogen was included as impurity only in the uranium of the TRISO kernels at 37.5 μg/g, but not in the graphite components of the fuel pebble. The "fuel," in this case, is considered to be the fuel pebble, which is made of two main regions: a pebble core with TRISO particles ($UC_{0.5}O_{1.5}$ kernels covered by graphite-based coatings) embedded in a graphite matrix and a pebble graphite shell (Figure 4). No nitrogen was included in any graphite, SiC, or pyrolitic carbon component of the fuel pebble. References specifying the amount of nitrogen content in the nuclear-grade graphite are scarce. Though three values are mentioned in Bourdeloie and Marimbeau (2004) – 10, 0, and 100 wt ppm for the nitrogen impurity level in graphite – the primary references from where these values were obtained are not provided. The pebble core radius is 25 mm, and the pebble outer radius is 30 mm; therefore, there is a significant amount of graphite. In addition, the fuel itself in the fuel kernels is $UC_{0.5}O_{1.5}$. Note also that the volume of the $UC_{0.5}O_{1.5}$ fuel kernels is ~1% of the pebble core volume. While based on cross-section data, the major production routes for ^{14}C are ^{14}N (n, p) and ^{17}O (n, α), contributions from neutron capture in ^{13}C become significant when significant quantities of graphite are present. Note that carbon in a natural isotopic composition includes 98.93 mass% ^{12}C and 1.07 mass% ^{13}C.

For the PBR fuel considered in this report, the microscopic cross sections for the production channels of ^{14}C are listed in Table 5, as obtained with ORIGEN.

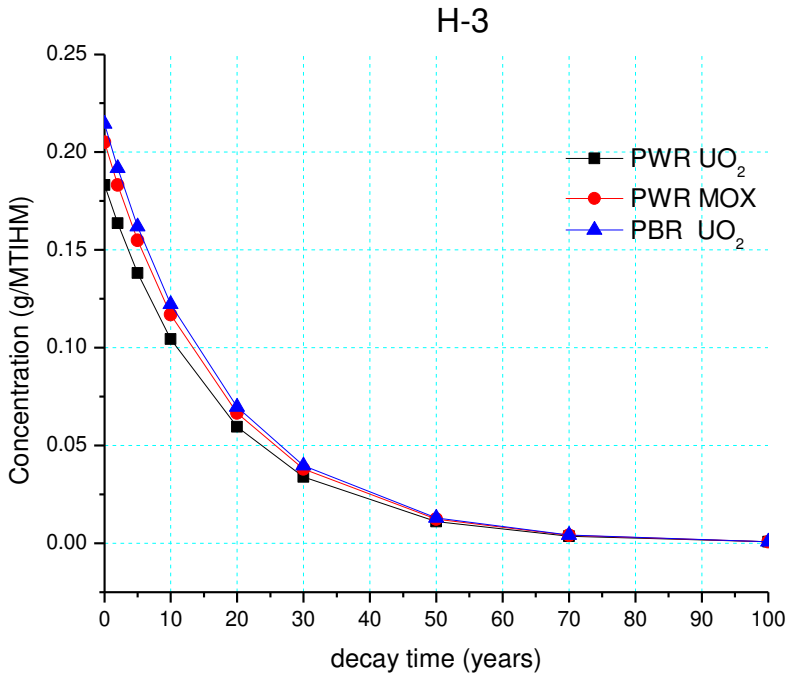

Figure 2. Variation of ^{3}H content with cooling time (60-GWd/tIHM burnup).

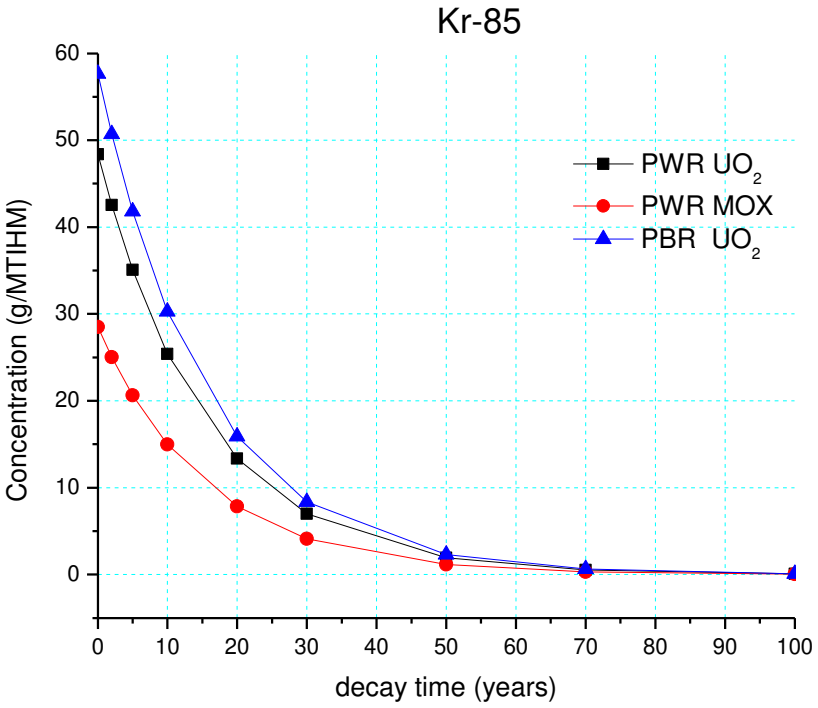

Figure 3. Variation of ^{85}Kr content with cooling time (60-GWd/tIHM burnup).

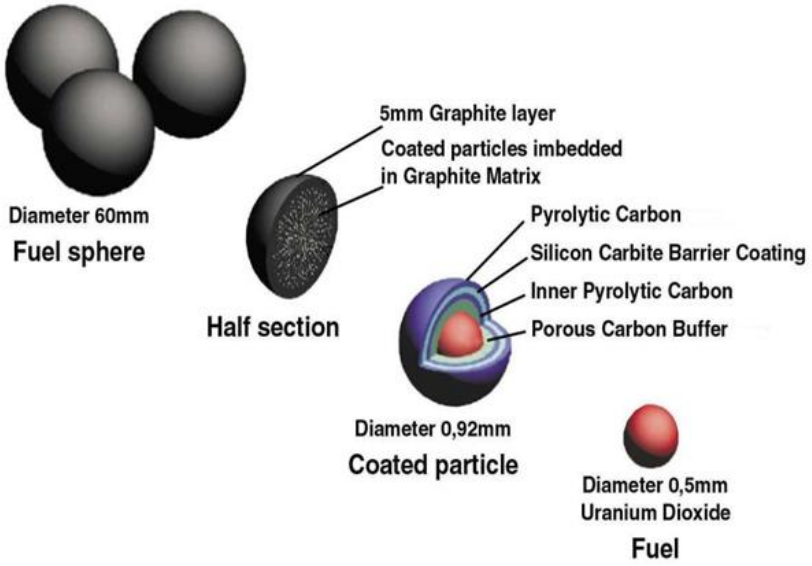

Figure 4. Pebbles constructed of TRISO-coated fuel particles, placed inside graphite pebbles (Peterson 2006).

Table 5. Microscopic cross sections for production of ^{14}C

Production channel	Target	Cross section (barns)
1	^{13}C	2.813×10^{-4}
2	^{14}N	0.2068
3	^{15}N	2.890×10^{-6}
4	^{16}O	2.638×10^{-9}
5	^{17}O	0.05094
6	^{18}O	2.465×10^{-6}

The effect of various production channels on the total amount of ^{14}C produced has been assessed for a 20-GWd/MTU PBR fuel by disabling one at a time one of the channels listed in Table 5. The results are presented in Table 6, which shows the total amount of ^{14}C generated in the original model (data as included in Table 9 of this report) and in alternate models in which one of the target nuclides listed in Table 5 has been removed from the initial fuel composition. In addition, case #5 in Table 6 considered the addition of 10 ppm (weight) nitrogen impurity in graphite; in this latter case, the amount of ^{14}C increases with 69% compared to the reference.

Data in Table 6 are consistent with data provided in Table 5 of (Yim and Caron 2006); in the paper, it is mentioned that these data are as taken from (Braun et al. 1983). The authors mentioned that over 60% of ^{14}C in gas-cooled reactor is produced by interaction with nitrogen impurities in graphite and ~40% by interaction with the ^{13}C in graphite. However, no details are available on the configuration for which data were provided in the above-mentioned reference, to make possible a consistent comparison with the data presented in this report.

Table 6. Effect of impurity levels on ^{14}C production for 20-GWd/MTU PBR fuel

Case #	Case description	^{14}C (g/MTU)	^{14}C ratio to reference	^{14}C change (%)
1	Reference	0.278	1.000	0
2	^{13}C removed from graphite	0.042	0.151	-85
3	Nitrogen removed from fuel	0.241	0.867	-13
4	^{17}O removed from fuel	0.272	0.978	-2
5	10 ppm (wt) nitrogen added to graphite	0.471	1.694	69

The other potential geometry for high-temperature gas reactor fuel is the prismatic core design, in which TRISO particles are encapsulated inside cylindrical graphite compacts that are placed inside graphite prismatic fuel elements. In this geometry, the analogy is similar – a significant amount of carbon is associated with the fuel meat, TRISO particles, the compacts, and the prismatic fuel elements. The carbon would contain ^{14}C as an activation product of ^{13}C, even if there is little nitrogen impurity. If even a portion of the graphite releases some of the ^{14}C, then this ^{14}C may require off-gas control to meet regulatory limits.

The amount of ^{14}C in AHTGR fuel is estimated to be higher than the amounts in the UOX and MOX fuels with similar burnup, but if the reprocessing process does not gasify the carbon in the coatings and pebble graphite matrix, then the ^{14}C in the AHTGR fuel coatings and graphite might not be released to the off-gas systems, and the levels of ^{14}C that would require off-gas control would be lower than indicated in this report.

Tables 7 to 9 provide the quantity of each of the four radionuclides of interest for each of the reactor types as a function of fuel age and burnup. For purposes of this report, the shortest fuel cooling time considered is 2 y. The terms “fuel age” and “cooling time” refers to the time since the fuel was discharged from the reactor. At very short cooling times, dose contributions from xenon would need to be considered. Also note that increased amount of ^{129}I in the 2-y cooled fuel and beyond is from the decay of ^{129}Te.

Table 7. Source terms, by isotope, for LWR reactor with UOX fuel with time since discharge

Isotopic mass (g/tIHM) – 20-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.052	0.047	0.040	0.030	0.017	0.010	0.003	0.001	0.000
^{14}C	0.105	0.105	0.105	0.105	0.105	0.105	0.104	0.104	0.104
^{85}Kr	22.41	19.71	16.24	11.77	6.18	3.24	0.894	0.246	0.036
^{129}I	84.97	85.04	85.04	85.04	85.04	85.04	85.04	85.04	85.04

Isotopic mass (g/tIHM) – 30-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.084	0.075	0.063	0.048	0.027	0.015	0.005	0.002	0.0003
^{14}C	0.163	0.163	0.163	0.163	0.163	0.163	0.162	0.162	0.161
^{85}Kr	30.79	27.08	22.32	16.17	8.49	4.46	1.23	0.338	0.049
^{129}I	134.3	134.4	134.4	134.4	134.4	134.4	134.4	134.4	134.4

Isotopic mass (g/tIHM) – 60-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.184	0.164	0.139	0.105	0.060	0.034	0.011	0.0036	0.0007
^{14}C	0.376	0.376	0.376	0.376	0.375	0.375	0.374	0.373	0.372
^{85}Kr	48.45	42.59	35.11	25.43	13.35	7.008	1.931	0.532	0.077
^{129}I	291.0	291.1	291.1	291.1	291.1	291.1	291.1	291.1	291.1

Table 8. Source terms, by isotope, for LWR reactor with MOX fuel with time since discharge

Isotopic mass (g/tIHM) – 20-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.184	0.164	0.139	0.105	0.060	0.034	0.011	0.0036	0.0007
^{14}C	0.376	0.376	0.376	0.376	0.375	0.375	0.374	0.373	0.372
^{85}Kr	48.45	42.59	35.11	25.43	13.35	7.008	1.931	0.532	0.077
^{129}I	291.0	291.1	291.1	291.1	291.1	291.1	291.1	291.1	291.1

Isotopic mass (g/tIHM) – 30-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.096	0.085	0.072	0.054	0.031	0.018	0.006	0.0019	0.0003
^{14}C	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.116	0.116
^{85}Kr	15.79	13.88	11.44	8.289	4.351	2.284	0.629	0.173	0.025
^{129}I	209.8	209.9	209.9	209.9	209.9	209.9	209.9	209.9	209.9

Isotopic mass (g/tIHM) – 60-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.205	0.183	0.155	0.117	0.067	0.038	0.012	0.0040	0.0007
^{14}C	0.272	0.272	0.271	0.271	0.271	0.271	0.270	0.269	0.268
^{85}Kr	28.49	25.04	20.64	14.96	7.851	4.121	1.136	0.313	0.045
^{129}I	391.8	391.9	391.9	391.9	391.9	391.9	391.9	391.9	391.9

Isotopic mass (g/tIHM) – 100-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.347	0.311	0.262	0.198	0.113	0.064	0.021	0.0068	0.0013
^{14}C	0.536	0.536	0.536	0.536	0.535	0.534	0.533	0.532	0.530
^{85}Kr	42.07	36.99	30.48	22.09	11.59	6.086	1.677	0.462	0.067
^{129}I	602.7	602.8	602.8	602.8	602.8	602.8	602.8	602.8	602.8

Table 9. Source terms, by isotope, for PBR reactor with UOX fuel with time since discharge

Isotopic mass (g/tIHM) – 20-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.086	0.077	0.065	0.049	0.028	0.016	0.0052	0.0017	0.0003
^{14}C	0.278	0.278	0.277	0.277	0.277	0.277	0.276	0.275	0.274
^{85}Kr	23.94	21.07	17.36	12.58	6.603	3.466	0.955	0.263	0.038
^{129}I	80.64	80.77	80.77	80.77	80.77	80.77	80.77	80.77	80.77

Isotopic mass (g/tIHM) – 30-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.118	0.106	0.089	0.067	0.038	0.022	0.0071	0.0023	0.0004
^{14}C	0.416	0.416	0.416	0.416	0.415	0.415	0.414	0.413	0.411
^{85}Kr	33.79	29.71	24.49	17.74	9.314	4.889	1.347	0.371	0.054
^{129}I	127.6	127.8	127.8	127.8	127.8	127.8	127.8	127.8	127.8

Isotopic mass (g/tIHM) – 60-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.215	0.192	0.162	0.122	0.070	0.040	0.013	0.0042	0.0008
^{14}C	0.853	0.853	0.852	0.852	0.851	0.850	0.848	0.845	0.842
^{85}Kr	57.67	50.71	41.79	30.28	15.89	8.343	2.299	0.634	0.092
^{129}I	278.9	279.0	279.0	279.0	279.0	279.0	279.0	279.0	279.0

Isotopic mass (g/tIHM) – 100-GWd/tIHM burnup

	Time since discharge (y)								
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**
^{3}H	0.350	0.313	0.264	0.199	0.114	0.065	0.021	0.0068	0.0013
^{14}C	1.502	1.501	1.501	1.500	1.498	1.496	1.493	1.489	1.483
^{85}Kr	80.32	70.61	58.20	42.17	22.13	11.62	3.202	0.882	0.128
^{129}I	490.7	490.9	490.9	490.9	490.9	490.9	490.9	490.9	490.9

5. AIR DISPERSION AND RADIONUCLIDE DOSE MODELING

The Clean Air Act Assessment Package (CAP88-PC Version 3.0) computer model (Rosnick 1992, 2007) is a set of computer programs, databases, and associated utility programs used to estimate dose and risk to members of the public from radionuclide emissions in the air. Version 3.0 of CAPP-88 incorporates dose and risk factors from Federal Guidance Report 13 (EPA 1999), which are based on the methods of the International Commission on Radiological Protection (ICRP 1995). Emission monitoring and compliance procedures for DOE facilities require the use of the CAP-88 model, or other approved methodologies, to estimate the effective dose to members of the public (Rosnick 1992, 2007).

Three main pathways for exposure from an atmospheric release of radiological material are considered in CAP-88: ingestion, inhalation, and external exposure. Ingestion is from consumption of plants, animals, fish, or water contaminated with radionuclides. Inhalation occurs when a person is in the pathway of a gas plume containing radioactive materials. External exposure occurs for people who live or recreate in areas where the ground or water has been exposed to radiological materials. Assessments for collective populations or a MEI are possible. Dose and risk estimates from CAP-88 are applicable only to low-level chronic exposures, since the health effects and dosimetric data are based on low-level chronic intakes. The model cannot be used for either short-term or high-level radionuclide intakes.

5.1 INPUT PARAMETERS FOR CAP-88

To use the CAP88-PC model, various location-specific, design-specific, and operational parameters are required as input for the simulation. The following were used to form the base case.

Facility Data – This input is for general descriptive information of the facility; however, the only information actually used in calculations is the state in which the facility is located. The state parameter determines the appropriate agricultural data (cattle and crop production) to be used in the simulation. Data are available for all states.

Run Options – This input is for an individual or a collective population. The individual option was used in this study so the results could be applied to an assumed MEI.

Meteorological Data – The local average weather conditions are required and include wind characteristics (16 vector description), annual rainfall, average ambient temperature, humidity, and meteorological lid. Calculations performed for each site used meteorological data in the CAP-88 model local to those areas and considered representative of those local areas.

Source Data (Facility Design and Operation) – This input is for the source of the emission. A stack release is assumed for a reprocessing plant, and the data required includes the stack dimensions. The plume type is also required with choices of buoyant or momentum and Pasquill stability class categories for plume rise above stack. The values used for the base case are a stack height of 37 m (120 ft); a stack diameter of 1.5 m; and a momentum-type plume with a stack exit velocity of 18 m/s (corresponds to volumetric rate of 34 m^3/s or 72 000 scfm). This reference case was selected as it was the basis for a study at INL for the calciner processing facility (Soelberg 2008).

Agricultural Data – This input is used to estimate the uptake of nuclides into the food chain based on agricultural use in the area. Choices are urban, rural, local, regional, or imported. Although values are automatically selected based on the state (location) of the source, the agricultural data can be defined by the user if desired. The rural case was assumed for this study.

Radionuclide Data – This input identifies the nuclides emitted from the source, their emission rate in curies per year, the physical form for some radionuclides (particle, vapor, or organic), and chemical form for some species (tritium, carbon). The vapor form of ^{3}H in tritiated water was assumed; ^{85}Kr form was an unspecified gas; ^{129}I form was particulate (see Section 7.8 for more discussion); and ^{14}C form was gaseous CO_2.

6. DETERMINATION OF REQUIRED DECONTAMINATION FACTORS

6.1 APPROACH OUTLINE

For this analysis of DF requirements, we consider that the required ^{129}I and ^{14}C DFs are not a function of fuel age, since those have >5000-y half-lives, and the dose contributions of the long and short half-life radionuclides are controlled within allowable discharge limits. However, the ^{14}C and ^{129}I DF values must be high enough to provide sufficient "dose headroom" such that the DFs for ^{3}H and ^{85}Kr are practicable. Thus, we consider the potential impacts of processing relatively short-cooled fuel to determine those practicable limits. For each size facility and for each fuel age, the following approach was used to identify required DF values.

1. Total dose to MEI was determined with the CAP-88 code (Rosnick 1992, 2007) for a hypothetical reprocessing facility location in the United States. In this initial calculation, we assume there are no emission controls for the four radionuclides of interest. As a point of interest, we calculated the maximum plant size that would not require emission controls if dose to the MEI was the only criteria. This was evaluated for each fuel type and compared the impact of fuel age and burnup.

In the next steps, for each fuel type and burnup, we examine the degree of control needed to meet both the fuel cycle curie discharge limits and the dose limits, as a function of fuel age and specific isotope. In all of the following steps, we used a nominal plant throughput of 1000 t/y.

2. Calculated the uncontrolled dose to the MEI and dose contributions for each of the four radionuclides of interest for the 1000-t/y facility.
3. Applied the computed DF requirements imposed by 40 CFR 190 for ^{85}Kr and ^{129}I to meet the fuel cycle curie discharge limits, assuming the reprocessing facility was the only release point for these isotopes in the complete fuel cycle.
4. Applied additional recovery factors to reduce the dose to the MEI from all four radionuclides to the regulatory limits imposed by 40 CFR 190.
5. Determined the additional DF required assuming that the dose contribution from the four volatile radionuclides would be limited to 10%, 25%, and 50% of the dose limit.
6. Calculated the dose to the thyroid to determine if a higher DF would be required for the 10%, 25%, 50%, and 100% dose allocation cases.

6.2 EXAMPLE CASE (PWR UOX – 30 GWD/TIHM)

The following is an example case for one fuel type and one burnup. The details of the remaining fuel types and burnups can be found in Appendices A–C.

Step 1. Calculate whole body dose and maximum plant size requiring no dose-based controls for a fuel type (not yet considering the 40 CFR 190 fuel cycle limits for ^{85}Kr and ^{129}I). In the case of PWR UOX fuel, the maximum plant size for 30 GWd/tIHM fuel cooled 5 y is 37.6 t/y; if the fuel is cooled 100 y, the plant size is increased slightly to 45.2 t/y (Figure 5). If the allowable contribution of the

volatile components to the total dose is limited to 2.5 mrem/y (i.e., 10% of the total dose), the plant sizes drop to 3.8 t/y and 4.5 t/y for cooling times of 5 and 100 y, respectively. At 5 y cooling, ^{129}I contributes 82.7% of the total dose and tritium contributes 16.1% of the total dose. For a 100-y cooling period, ^{129}I contributes 99.4% of the total dose.

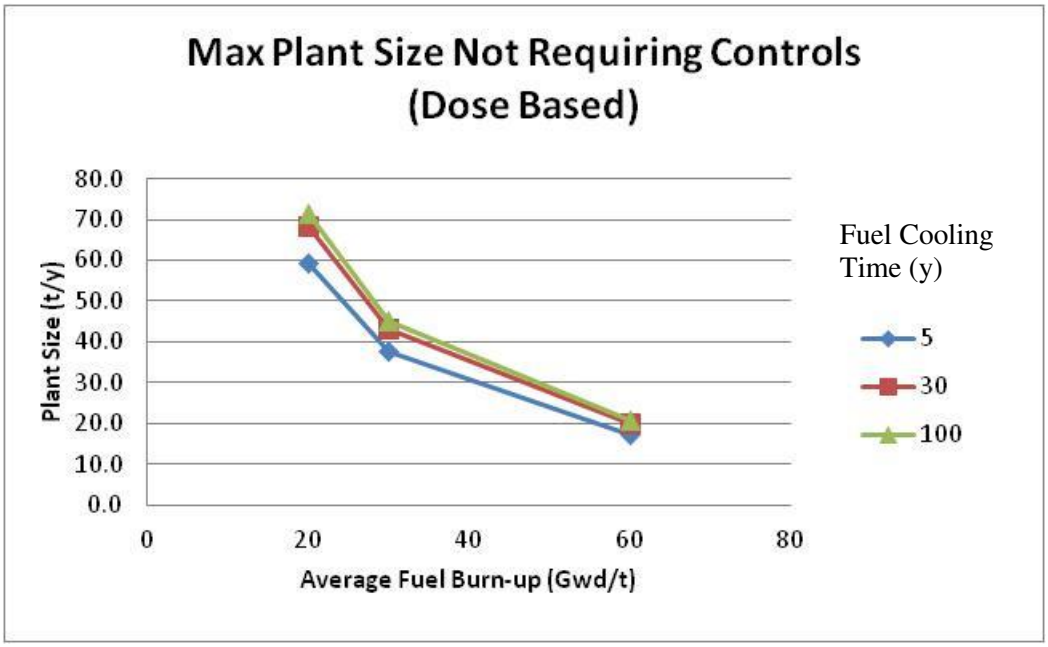

Figure 5. Maximum plant size for processing PWR UOX fuel that would not require controls to limit exposure to the MEI to ≤25 mrem/y.

In the second phase of the evaluation, the impact of time since discharge was evaluated in three steps for each fuel type and fuel burnup. Now, focusing only on the case of 30 GWd/tIHM burnup for the detailed calculations of DF requirements, the next steps are as follows.

Step 2. Calculate uncontrolled dose contributions. For the case of the 30-GWd/tIHM fuel and a plant size of 1000 t/y, the total dose to the MEI ranges from 686 mrem/y for 2-y-cooled fuel to 553 mrem/y for 100-y-cooled fuel (Figure 6). Iodine is the major contributor (550 mrem/y). At cooling times up to 30 y, tritium dose contributions exceed 25 mrem/y; ^{14}C contributes 2.6 mrem/y at all cooling times; and ^{85}Kr could contribute up to 6 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table 10.

Step 3. Apply 40 CFR 190 release limits. If the iodine and krypton release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 134 mrem/y at 2-y cooling and 6.24 mrem/y for 100-y-cooled fuel (Figure 7). The iodine contribution is reduced to 3.15 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 50 y. Carbon-14 again contributes 2.6 mrem/y, but ^{85}Kr contributions are reduced to less than 0.8 mrem/y. It is clear from Figure 7 that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit. Figure 8 shows that for a 2.5-mrem/y apportioned limit, additional controls (DF) for iodine and carbon would also be required (note that the allowable [2.5 mrem/y] and ^{14}C [2.6 mrem/y] lines are superimposed because of the scale of the graph).

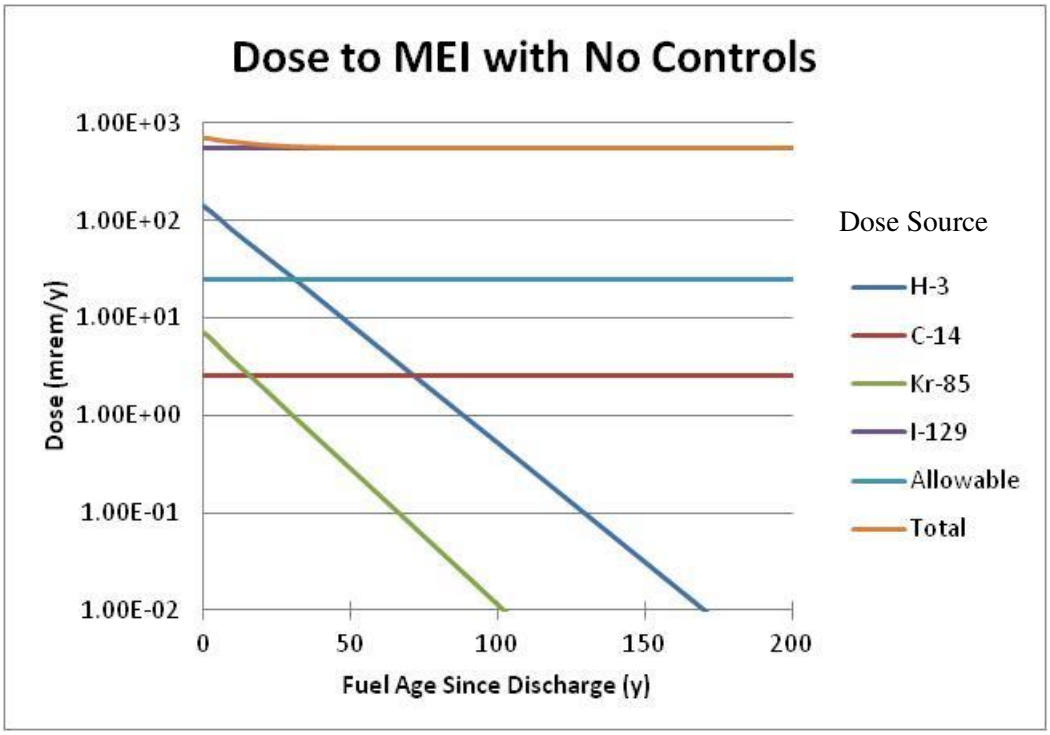

Figure 6. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000 t/y recycle plant processing 30-GW/tIHM PWR UOX fuel. Allowable dose limit is shown at the 25 mrem whole body dose level.

Table 10. Dose contributions by radionuclide based on 30-GWd/tIHM PWR UOX fuel cooled up to 200 y processed in 1000 t/y recycle plant without effluent controls

Isotope	Dose to the MEI, mrem/y									
	Fuel age, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	142	127	107	81.1	46.2	26.4	8.56	2.78	0.52	0.0019
^{14}C	2.60	2.60	2.60	2.60	2.59	2.59	2.58	2.58	2.57	2.54
^{85}Kr	7.19	6.32	5.20	3.77	1.97	1.03	0.28	0.078	0.011	0.000017
^{129}I	550	550	550	550	550	550	550	550	550	550
Allowable	25	25	25	25	25	25	25	25	25	25
Total	**702**	**686**	**666**	**638**	**601**	**580**	**562**	**556**	**553**	**553**

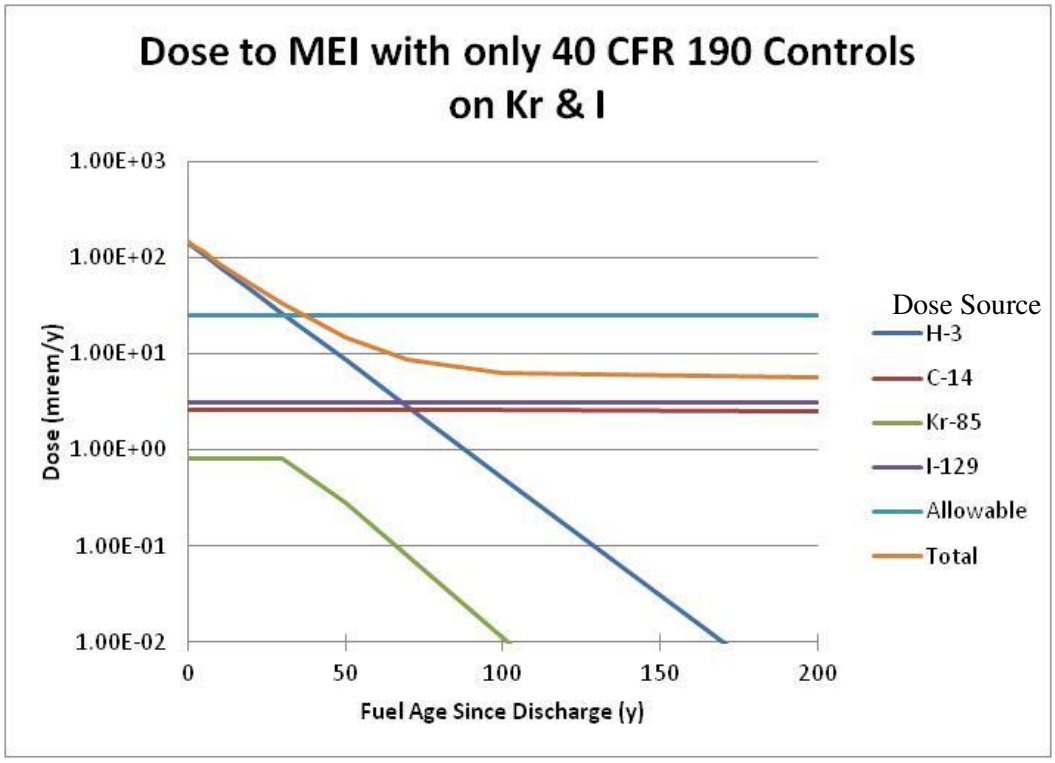

Figure 7. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem whole body dose level.

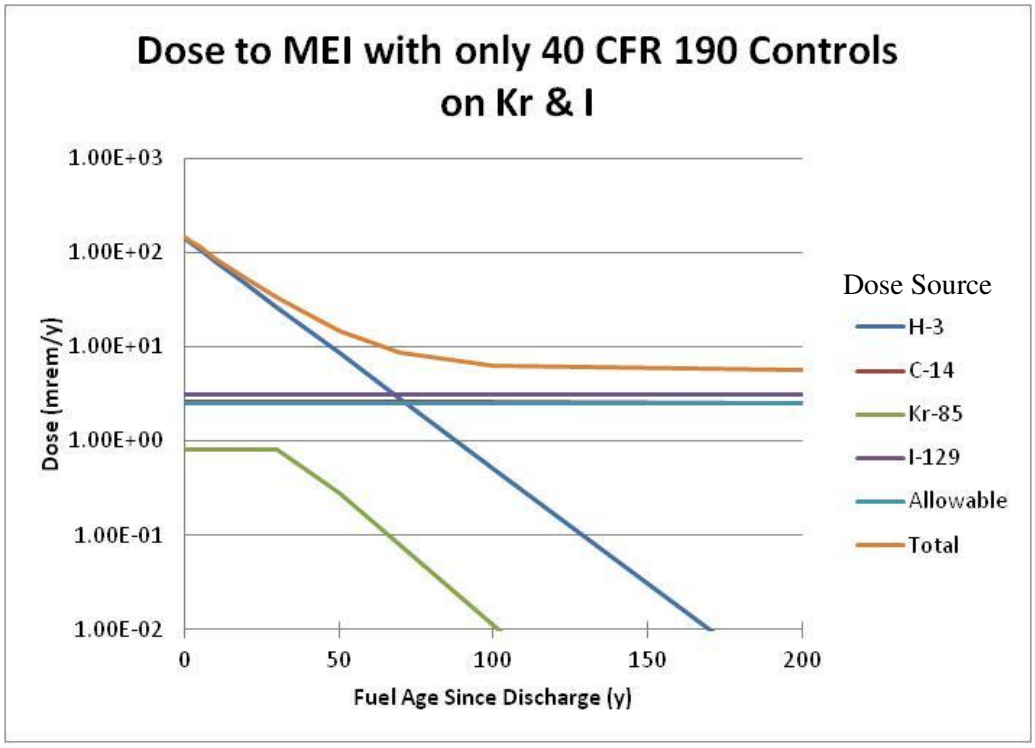

Figure 8. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem whole body dose level.

Steps 4 and 5. Apply additional DF requirements as needed to limit dose to MEI to regulatory limits. Additional controls were imposed as needed on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to the regulatory limit or to a portion of the regulatory limit. In general, we attempted to impose control on as few individual radionuclides as possible, since each would likely require a separate process to control and result in a separate waste stream that would need treatment. In selecting the required DF, there is no single correct answer, since the total dose is a sum of the individual contributions. The reduction in one allows more "headroom" for another. A nominal goal was to reduce the dose contribution from an individual radionuclide to somewhere in the range of 10–50% of the total allowable dose. Additional controls were applied first to species that exceeded the allowable limits. For ^{3}H and ^{85}Kr, these were typically applied over the periods of fuel age in which the dose contributions exceeded 30–50% of the allowable dose. Additional controls were typically added to ^{129}I before ^{14}C, since ^{129}I control would be required in all cases anyway.

For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 6.9 at 2-y cooling to 1.43 at 30-y cooling (Figure 9 and Table 11). Beyond ~35-y fuel cooling, no additional ^{3}H capture would be required if the total allowable dose to the MEI was considered to result from only ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. If these four radionuclides are apportioned 2.5 mrem/y or 10% of the allowable dose, then additional controls must be placed on ^{14}C and ^{129}I for all fuel ages, since these two radionuclides individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to ^{129}I for all fuel ages, raising the total ^{129}I DF to ~1200. A ^{14}C DF of 3 was applied to reduce its contribution to the total dose to ~0.8 mrem/y. Tritium DFs of 250 would be required for 2-y-cooled fuel. Beyond ~80 y, no ^{3}H recovery would be required. Figure 9 shows the resulting total dose to the MEI and the individual dose contributions as a function of time, for the 25 mrem/y allocation. Table 11 and Figure 10 depict the DF requirements for each isotope to meet the 25-mrem/y allocation as a function of cooling time. Figure 11 shows the resulting dose contributions for the 2.5-mrem/y allocation, while Table 12 and **Error! Reference source not found.** show the overall DF required to limit the dose to the MEI to 2.5 mrem/y; Table 13 shows the resulting dose contributions.

Table 11. Effective DFs required to achieve 25-mrem whole body dose to MEI for 30-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Effective decontamination factors										
Isotope	**Fuel age, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	7.72	6.90	5.83	4.40	2.50	1.43	1.00	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	8.91	7.83	6.45	4.67	2.44	1.28	1.00	1.00	1.00	1.00
^{129}I	175	175	175	175	175	175	175	175	175	175

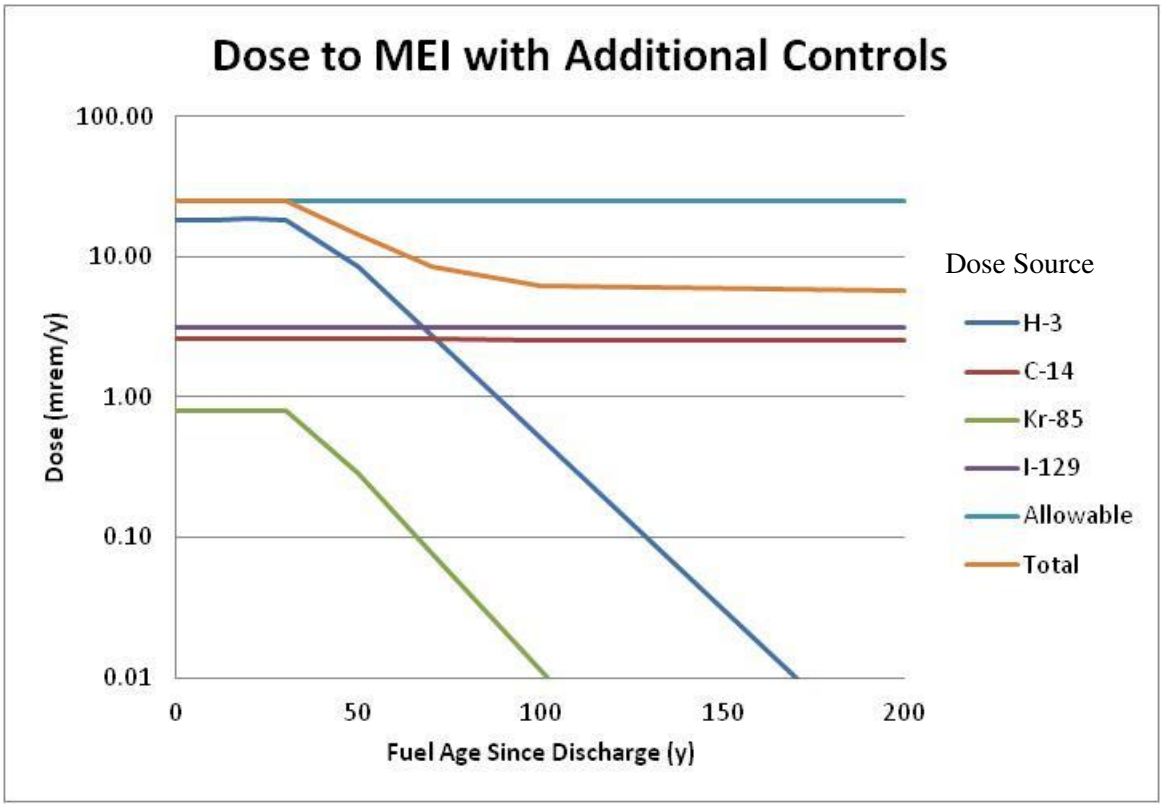

Figure 9. Dose to MEI total and dose contribution from each of the volatile radionuclides with fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem.

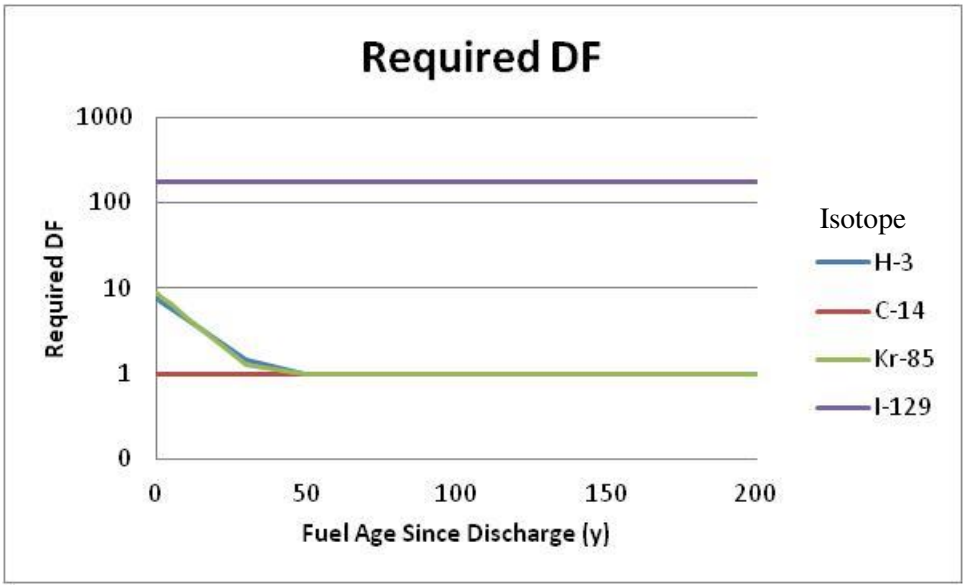

Figure 10. Required DFs for each of the volatile radionuclides with fuel age for a 1000 t/y recycle plant processing 30 GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem.

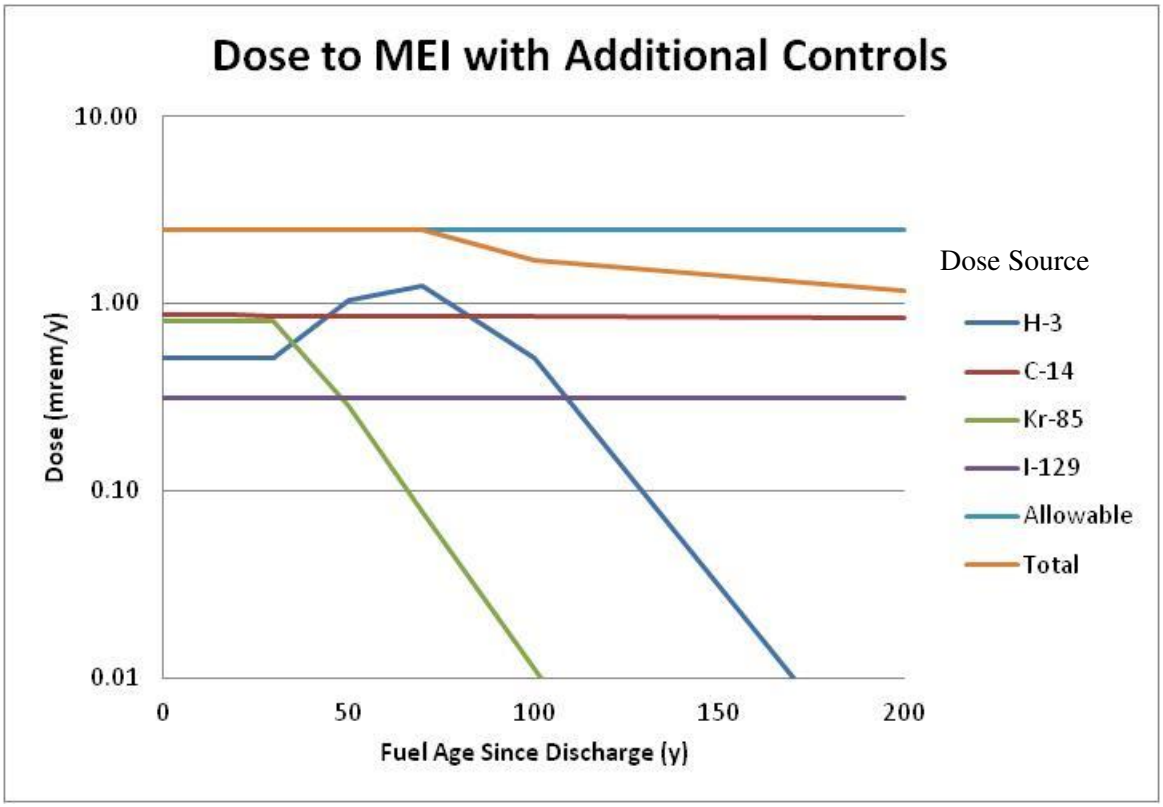

Figure 11. Dose to MEI total and dose contribution from each of the volatile radionuclides with fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem.

Table 12. Effective DFs required to achieve 2.5-mrem dose to MEI for 30-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	280	250	210	158	90.0	51.0	8.20	2.23	1.00	1.00
^{14}C	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
^{85}Kr	8.91	7.83	6.45	4.67	2.44	1.28	1.00	1.00	1.00	1.00
^{129}I	1749	1749	1749	1749	1749	1749	1749	1749	1749	1749

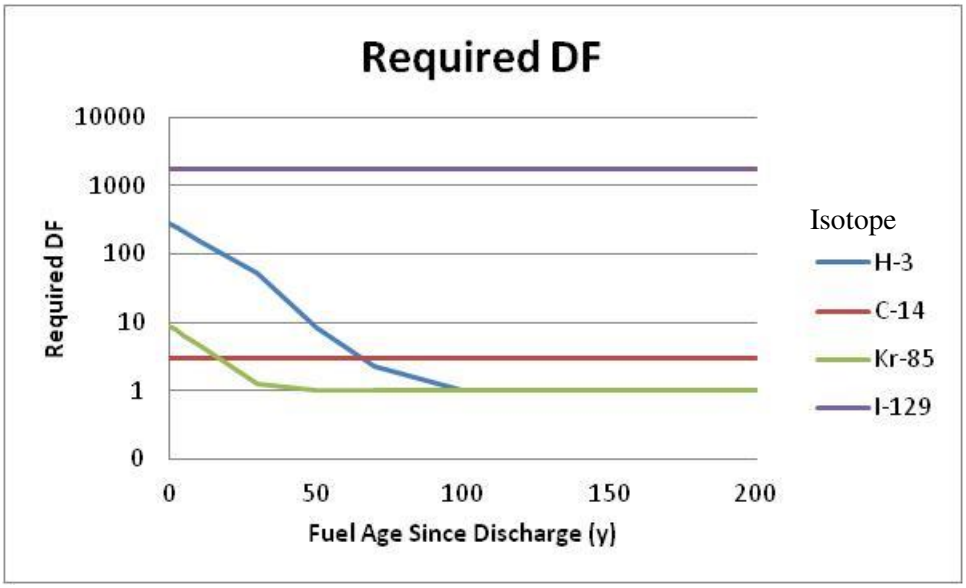

Figure 12. Required DFs for each of the volatile radionuclides with fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem.

Table 13. Dose contributions by radionuclide based on 30-GWd/tIHM PWR UOX fuel cooled up to 200 y with the effective DFs from Table 12

Isotope	Dose to the MEI, mrem/y									
	Fuel Age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.51	0.51	0.51	0.51	0.51	0.52	1.04	1.25	0.52	0.0019
^{14}C	0.87	0.87	0.87	0.87	0.87	0.86	0.86	0.86	0.86	0.85
^{85}Kr	0.81	0.81	0.81	0.81	0.81	0.81	0.28	0.078	0.011	0.000017
^{129}I	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.70	1.16

Step 6. Calculate thyroid dose. In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified in 40 CFR 190 as 75 mrem/y. Applying the same DFs previously used to meet the 40 CFR 190 discharge limits for only iodine and krypton reduces the thyroid dose to 129 mrem/y for the processing of 2-y-cooled fuel and to 65.6 mrem/y for the processing of 100-y-cooled fuel (
Figure 13). The two primary contributors to the dose are ^{3}H and ^{129}I in the case of short cooling times.

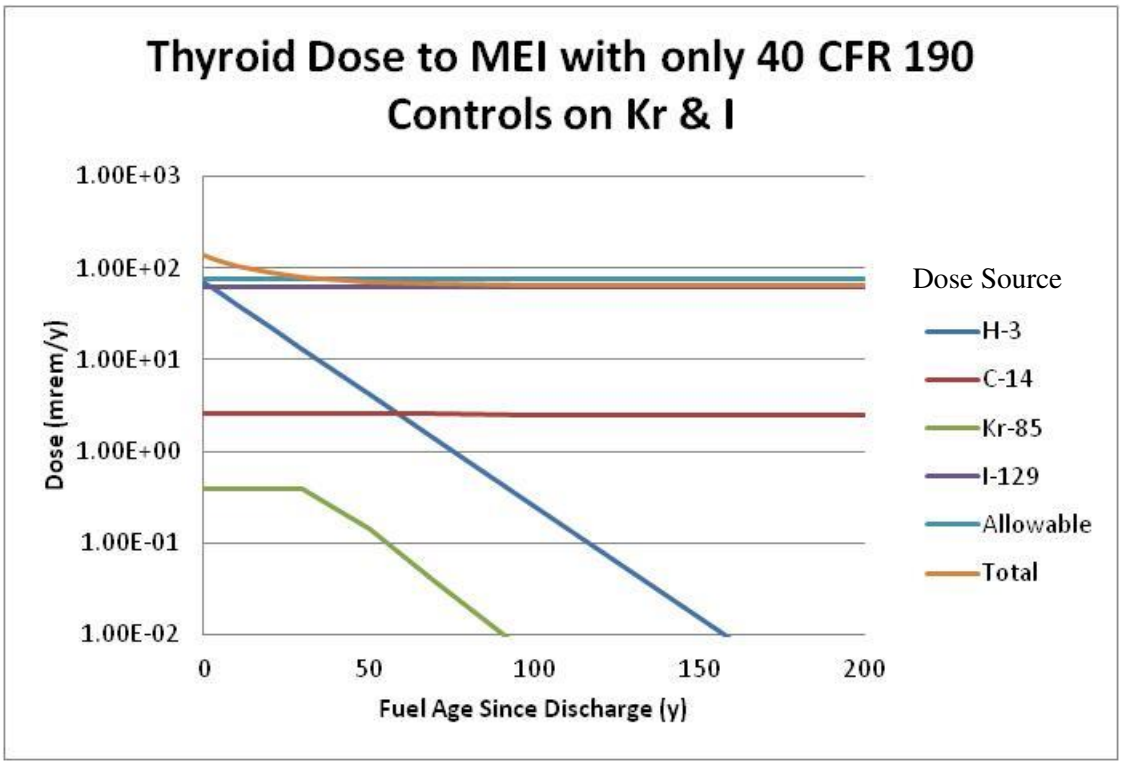

Figure 13. Dose to the thyroid and dose contribution from each of the volatile radionuclide with fuel age for a 1000-t/y recycle plant processing 30 GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem.

Now, applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 mrem/y, the thyroid dose calculations show that dose to the thyroid is reduced to 74.8 mrem/y. Thus, no no additional DF requirements would be needed beyond those needed to meet the 25-mrem/y whole body dose dose limit (

Figure 14).

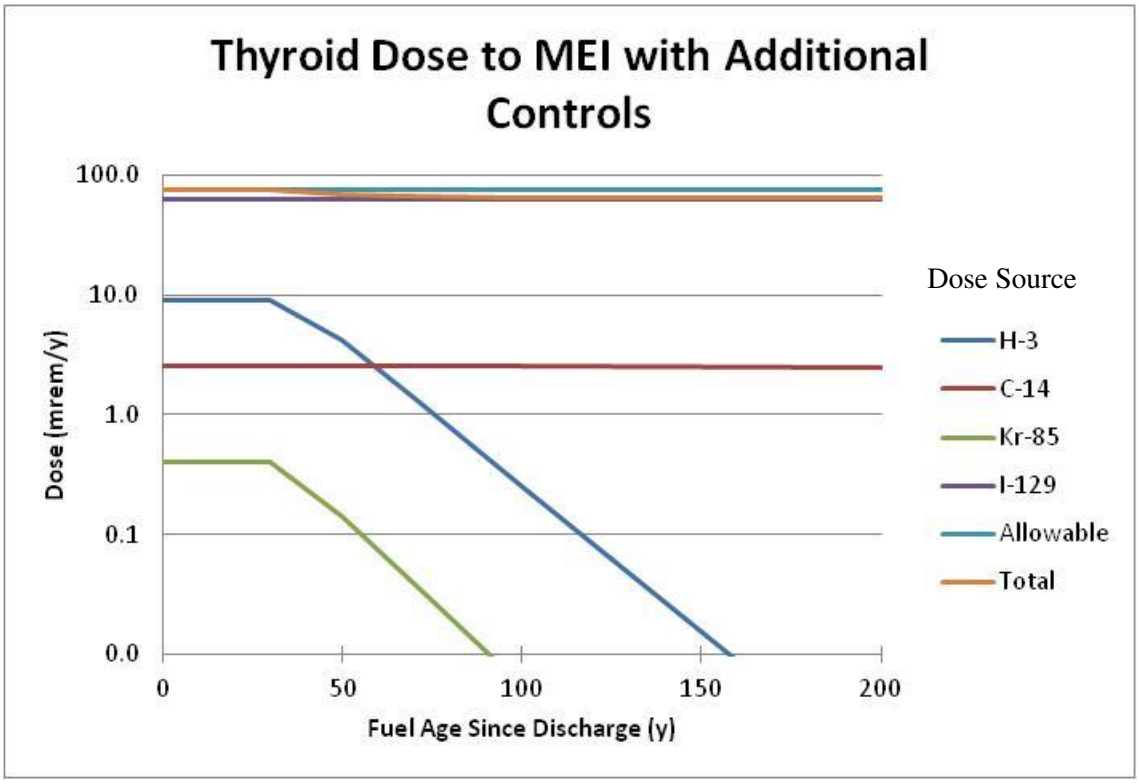

Figure 14. Dose to the thyroid and dose contribution from each of the volatile radionuclides with fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem whole body dose limit. Allowable thyroid dose shown is 75 mrem.

If the same apportionment of 10% is made for the thyroid dose from the four volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is 7.78–7.38 mrem/y (Figure 15). Iodine-129 accounts for approximately ~80% of this dose, with ^{14}C the major contributor to the remaining dose. A slight increase in the ^{129}I DF from ~1750 to 1850 is required to reduce the thyroid dose to <7.5 mrem/y, holding the DFs for the other isotopes as they were.

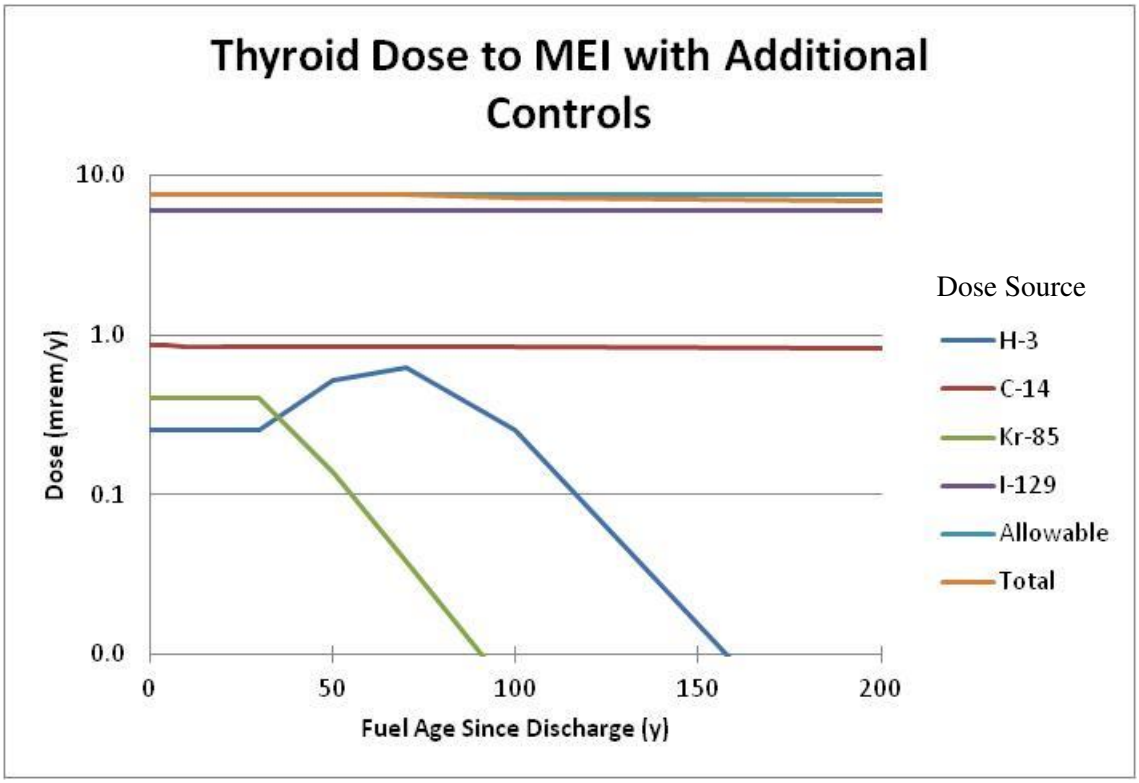

Figure 15. Dose to the thyroid and dose contribution from each of the volatile radionuclides with fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem whole body dose limit. Allowable thyroid dose shown is 7.5 mrem.

6.3 ADDITIONAL CASE STUDIES

For completeness, we investigate additional cases for the PWR UOX fuel at 30-GWd/tIHM burnup. We calculate the required DFs and doses to the MEI for 25% and 50% of the allowed dose allocation to the MEI (i.e., 6.25 and 12.5 mrem/y whole body; 18.75 and 37.5 mrem/y to the thyroid). In the second case study, we look at allocating 1% of the allowable dose to three of the volatile radionuclides and 9% to the remaining one; there are four cases in all. Finally, we look at the case of half of the ^{3}H inventory to simulate the possibility that half of the ^{3}H is in the Zircaloy and is not released at the reprocessing facility.

6.3.1 Alternate Allocations for the Volatile Radionuclides

This analysis provides intermediate cases to the ones given in the previous sections; namely, 25% and 50% of the dose allocation are assigned to the four volatile radionuclides. Rather than show graphs of these results, they are summarized in Tables 14 to 17; both effective DFs and doses to the MEI are shown. These tables are followed by Tables 18 to 21 that contain the information for the required DFs and doses to the thyroid.

Table 14. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 25% of the allowable dose allocation

Isotope	Effective decontamination factor

	Fuel age, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	112	100	85	64	36.3	20.6	4.7	1.4	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	8.9	7.8	6.4	4.7	2.4	1.3	1.0	1.0	1.0	1.0
^{129}I	350	350	350	350	350	350	350	350	350	350

Table 15. Dose contributions by radionuclide based on 30-GWd/tIHM PWR UOX fuel cooled up to 200 y and 25% of the allowable dose allocation (effective DFs from Table 14)

Isotope	**Dose to the MEI, mrem/y**									
	Fuel age, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	1.27	1.27	1.27	1.28	1.27	1.28	1.81	2.02	0.52	0.002
^{14}C	2.60	2.60	2.60	2.60	2.59	2.59	2.58	2.58	2.57	2.54
^{85}Kr	0.81	0.81	0.81	0.81	0.81	0.81	0.28	0.08	0.01	1.74×10^{-5}
^{129}I	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
Allowable	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
Total	6.25	6.25	6.25	6.25	6.25	6.25	6.24	6.22	4.53	3.99

Table 16. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 50% of the allowable dose allocation

Isotope	**Effective decontamination factor**									
	Fuel age, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	24	21	18	14	7.8	4.4	1.3	1.0	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	8.9	7.8	6.4	4.7	2.4	1.3	1.0	1.0	1.0	1.0
^{129}I	175	175	175	175	175	175	175	175	175	175

Table 17. Dose contributions by radionuclide based on 30-GWd/tIHM PWR UOX fuel cooled up to 200 y and 50% of the allowable dose allocation (effective DFs from Table 16)

Isotope	Dose to the MEI, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	5.95	5.95	5.95	5.95	5.95	5.96	6.49	2.78	0.52	0.002
^{14}C	2.60	2.60	2.60	2.60	2.59	2.59	2.58	2.58	2.57	2.54
^{85}Kr	0.81	0.81	0.81	0.81	0.81	0.81	0.28	0.08	0.01	1.74×10^{-5}
^{129}I	1.40	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
Allowable	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Total	12.5	12.5	12.5	12.5	12.5	12.5	12.5	8.6	6.2	5.7

The required DFs and resulting doses to the MEI thyroid are show below (Tables 18 to 21).

Table 18. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 25% of the allowable thyroid dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	112.0	100.0	84.5	63.5	36.3	20.6	4.7	1.4	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	8.9	7.8	6.4	4.7	2.4	1.3	1.0	1.0	1.0	1.0
^{129}I	724	724	724	724	724	724	724	724	724	724

Table 19. Dose contributions by radionuclide based on 30-GWd/tIHM PWR UOX fuel cooled up to 200 y and 25% of the allowable thyroid dose allocation (effective DFs from Table 19)

Isotope	Thyroid dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.6	0.6	0.6	0.6	0.6	0.6	0.9	1.0	0.25	9.2E-04
^{14}C	2.56	2.56	2.55	2.55	2.55	2.55	2.54	2.53	2.53	2.50
^{85}Kr	0.40	0.40	0.40	0.40	0.40	0.40	0.14	0.04	0.01	8.6E-06
^{129}I	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
Allowable	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75	18.75
Total	18.75	18.7	18.7	18.7	18.7	18.7	18.7	18.7	18.0	17.7

Table 20. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 50% of the allowable thyroid dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	23.9	21.4	18.1	13.6	7.8	4.4	1.3	1.0	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	8.9	7.8	6.4	4.7	2.4	1.3	1.0	1.0	1.0	1.0
^{129}I	347	347	347	347	347	347	347	347	347	347

Table 21. Dose contributions by radionuclide based on 30-GWd/tIHM PWR UOX Fuel cooled up to 200 y and 50% of the allowable dose allocation (effective DFs fromTable 20)

Isotope	Thyroid dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	2.9	2.9	2.9	2.9	2.9	2.9	3.2	1.4	0.25	9.2E-04
^{14}C	2.56	2.56	2.55	2.55	2.55	2.55	2.54	2.53	2.53	2.50
^{85}Kr	0.40	0.40	0.40	0.40	0.40	0.40	0.14	0.04	0.01	8.6E-06
^{129}I	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
Allowable	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5
Total	37.50	37.5	37.5	37.5	37.5	37.5	37.5	35.6	34.4	34.1

Table 22 provides a comparison of the DF requirements for the PWR UOX 30 GWd/tIHM fuel as the dose allocations are varied from 10% to 100%. Note that in both the 25% and 50% dose allocation the thyroid dose is the controlling case.

Table 22. Impact of dose allocation on DF requirements for PWR UOX 30-GWd/tIHM fuel case

Dose allocation to volatile radionuclides	Most restrictive dose limit (25-mrem/y whole body; 75-mrem/y thyroid)	Required DF to meet dose limit			
		$^{3}H^{a}$	^{14}C	$^{85}Kr^{a,b}$	^{129}I
10%	Thyroid	250 – 1	3	7.83 – 1	1850
25%	Thyroid	100 – 1	1	7.83 – 1	724
50%	Thyroid	21.4 – 1	1	7.83 – 1	347
100%	Whole body	6.9 – 1	1	7.83 – 1	175

[a]These are ranges depending on the fuel burnup (i.e., 3.85 – 1 is the range from 3.85 to 1).
[b]The DFs for ^{85}Kr and ^{129}I are required based on the 40 CFR 190 fuel cycle limits, but also help to reduce the doses from ^{85}Kr and ^{129}I.

6.3.2 Dose Allocation of 1% to Three Radionuclides

In the following tables, we show the results for the case in which 1% of the allowable dose is allocated to three of the volatile radionuclides (i.e., 0.25 mrem/y for whole body; 0.75 mrem/y for the thyroid) while allowing the fourth to take the remaining 97% (i.e., 24.25 mrem/y for whole body; 72.75 mrem/y for the thyroid). This is for the overall case where 100% of the allowable dose to the MEI is reserved for the volatile radionuclides. In most cases, the 40 CFR 190 restrictions had be relaxed, since imposing these limits caused the dose for a particular isotope to fall below the 0.25-mrem/y or 0.75-mrem/y dose limits. In these cases, we set the required dose to meet 40 CFR 190 to 1.0 and, if needed, adjusted the effective DF to achieve the 0.25-mrem/y whole body and 0.75-mrem/y thyroid doses.

In the first of these cases, the dose allocation for ^{3}H = ^{14}C = ^{85}Kr = 0.25 mrem/y (Tables 23 and 24)

Table 23. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{3}H, ^{14}C, and ^{85}Kr and 24.25 mrem/y for ^{129}I for a total of 100% of the allowable dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	569	509	430	324	185	105	34.3	11.1	2.1	1.0
^{14}C	10.4	10.4	10.4	10.4	10.4	10.4	10.3	10.3	10.3	10.2
^{85}Kr	28.7	25.3	20.8	15.1	7.9	4.1	1.1	1.0	1.0	1.0
^{129}I	23	23	23	23	23	23	23	23	22	22

Table 24. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{3}H, ^{14}C, and ^{85}Kr and 24.25 mrem/y for ^{129}I for a total of 100% of the allowable dose allocation
(the DF values are shown in Table 23)

Isotope	Dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.002
^{14}C	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
^{85}Kr	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.08	0.01	1.74×10^{-5}
^{129}I	24.2	24.2	24.2	24.2	24.2	24.2	24.2	24.4	24.5	24.7
Allowable	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Total	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0

For the thyroid, this case (dose from ^{3}H = ^{14}C = ^{85}Kr = 0.75 mrem/y) yields the results shown in Tables 25 and 26. Since the ^{85}Kr activity contributes very little to the thyroid dose, there is no increase in the ^{85}Kr DF required to meet 40 CFR 190. Thus, in this case, the ^{85}Kr dose falls below the allowed 0.75 mrem/y (Table 26); ^{129}I takes up more than 7% of the allowable dose.

This case shows that if the 40 CFR 190 fuel cycle limit ^{129}I is ignored, and the other three radionuclides were controlled so that ^{129}I could be controlled the least to meet total the total body and thyroid dose limits, ^{129}I would still need a DF of at least about 150 regardless of fuel age.

Table 25. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{3}H, ^{14}C, and ^{85}Kr and 72.75 mrem/y for ^{129}I for a total of 100% of the allowable thyroid dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	93.7	83.7	70.7	53.4	30.4	17.4	5.6	1.8	1.0	1.0
^{14}C	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.3
^{85}Kr	4.7	4.1	3.4	2.5	1.3	1.0	1.0	1.0	1.0	1.0
^{129}I	151	151	151	151	151	150	150	150	148	148

Table 26. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{3}H, ^{14}C, and ^{85}Kr and 72.75 mrem/y for ^{129}I for a total of 100% of the allowable thyroid dose allocation
(the DF values are shown in Table 25)

Isotope	Thyroid dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.25	9.2×10^{-4}
^{14}C	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
^{85}Kr	0.75	0.75	0.75	0.75	0.75	0.51	0.14	0.04	0.01	8.6E-06
^{129}I	72.8	72.8	72.8	72.8	72.7	73.0	73.4	73.5	74.0	74.2
Allowable	75	75	75	75	75	75	75	75	75	75
Total	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0

In the second of these cases, the dose from ^{3}H = ^{14}C = ^{129}I = 0.25 mrem/y. However, no additional DF is required over the existing DF to meet 40 CFR 190 for ^{85}Kr; that is, the additional required DF is 1.0. Thus, by assigning 0.25 mrem/y to ^{3}H, ^{14}C, and ^{129}I, the total dose to the MEI is less than 2.5 mrem/y (Tables 27 and 28).

Table 27. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{3}H, ^{14}C, and ^{129}I and 24.25 mrem/y for ^{85}Kr for a total of 100% of the allowable dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	569	509	430	324	185.0	105.4	34.3	11.1	2.1	1.0
^{14}C	10.4	10.4	10.4	10.4	10.4	10.4	10.3	10.3	10.3	10.2
^{85}Kr	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{129}I	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200

Table 28. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{3}H, ^{14}C, and ^{129}I and 24.25 mrem/y for ^{85}Kr for a total of 100% of the allowable dose allocation
(the DF values are shown in Table 27)

Isotope	Dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.002
^{14}C	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
^{85}Kr	0.81	0.81	0.81	0.81	0.81	0.81	0.28	0.08	0.01	1.74×10^{-6}
^{129}I	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0

For the thyroid, this case (dose from ^{3}H = ^{14}C = ^{129}I = 0.75 mrem/y) yields the results shown in Table 29 and Table 30. Here again, the ^{85}Kr dose falls below the 0.75-mrem/y value imposed in this scenario.

This case shows that if ^{85}Kr is controlled to meet the 40 CFR 190 fuel cycle limit, and the other three radionuclides were controlled so that ^{85}Kr could be controlled the least to meet total the total body and thyroid dose limits, then ^{85}Kr would require no additional control regardless of fuel age. To meet the 0.75-mrem/y thyroid dose allocation, a very high ^{129}I DF is needed.

Table 29. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{3}H, ^{14}C, and ^{129}I and 72.75 mrem/y for ^{85}Kr for a total of 100% of the allowable thyroid dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	93.7	83.7	70.7	53.4	30.4	17.4	5.6	1.8	1.0	1.0
^{14}C	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.3
^{85}Kr	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{129}I	14600	14600	14600	14600	14600	14600	14600	14600	14600	14600

Table 30. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{3}H, ^{14}C, and ^{85}Kr and 72.75 mrem/y for ^{129}I for a total of 100% of the allowable thyroid dose allocation
(the DF values are shown Table 29)

Isotope	Thyroid dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.25	9.2×10^{-4}
^{14}C	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
^{85}Kr	3.54	3.11	2.56	1.85	0.97	0.51	0.14	0.04	0.01	8.6E-06
^{129}I	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Allowable	75	75	75	75	75	75	75	75	75	75
Total	5.8	5.4	4.8	4.1	3.2	2.8	2.4	2.3	1.8	1.5

In the third case, the dose from ^{3}H = ^{85}Kr = ^{129}I = 0.25 mrem/y (Tables 31 and 32).

Table 31. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{3}H, ^{85}Kr, and ^{129}I and 24.25 mrem/y for ^{14}C for a total of 100% of the allowable dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	569	509	430	324	185	105	34.3	11.1	2.1	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	28.7	25.3	20.8	15.1	7.9	4.1	1.1	1.0	1.0	1.0
^{129}I	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200

Table 32. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{3}H, ^{85}Kr, and ^{129}I and 24.25 mrem/y for ^{14}C for a total of 100% of the allowable dose allocation
(the DF values are shown in Table 31)

Isotope	Dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.002
^{14}C	2.60	2.60	2.60	2.60	2.59	2.59	2.58	2.58	2.57	2.54
^{85}Kr	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.08	0.01	1.74×10^{-6}
^{129}I	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Allowable	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Total	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.2	3.1	2.8

This case (dose from ^{3}H = ^{85}Kr = ^{129}I = 0.75 mrem/y) yields the results shown in Tables 33 and 34 for the dose to the thyroid.

This case shows that if the other three radionuclides were controlled so that ^{14}C could be controlled the least to meet total the total body and thyroid dose limits, then ^{14}C would require no control regardless of fuel age. The high required DF for ^{129}I is because of the low thyroid dose allocation (0.75 mrem/y).

Table 33. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{3}H, ^{85}Kr, and ^{129}I and 72.75 mrem/y for ^{14}C for a total of 100% of the allowable thyroid dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	93.7	83.7	70.7	53.4	30.4	17.4	5.6	1.8	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	4.7	4.1	3.4	2.5	1.3	1.0	1.0	1.0	1.0	1.0
^{129}I	14600	14600	14600	14600	14600	14600	14600	14600	14600	14600

Table 34. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{3}H, ^{85}Kr, and ^{129}I and 72.75 mrem/y for ^{14}C for a total of 100% of the allowable thyroid dose allocation
(the DF values are shown in Table 33)

Isotope	Thyroid dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.25	9.2×10^{-4}
^{14}C	2.56	2.56	2.55	2.55	2.55	2.55	2.54	2.53	2.53	2.50
^{85}Kr	0.40	0.40	0.40	0.40	0.40	0.40	0.14	0.04	0.01	8.6×10^{-6}
^{129}I	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Allowable	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Total	4.5	4.5	4.5	4.5	4.4	4.4	4.2	4.1	3.5	3.2

In the last case, the dose from ^{14}C = ^{85}Kr = ^{129}I = 0.25 mrem/y (Tables 35 and 36).

Table 35. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{14}C, ^{85}Kr, and ^{129}I and 24.25 mrem/y for ^{3}H for a total of 100% of the allowable dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	5.9	5.2	4.4	3.3	1.9	1.1	1.0	1.0	1.0	1.0
^{14}C	10.4	10.4	10.4	10.4	10.4	10.4	10.3	10.3	10.3	10.2
^{85}Kr	28.7	25.3	20.8	15.1	7.9	4.1	1.1	1.0	1.0	1.0
^{129}I	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200

Table 36. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.25 mrem/y for ^{14}C, ^{85}Kr, and ^{129}I and 24.25 mrem/y for ^{3}H for a total of 100% of the allowable dose allocation
(the DF values are shown in Table 35)

Isotope	Dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	24.25	24.25	24.25	24.25	24.25	24.25	8.56	2.78	0.52	0.002
^{14}C	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
^{85}Kr	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.08	0.01	1.74×10^{-5}
^{129}I	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Allowable	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Total	25.0	25.0	25.0	25.0	25.0	25.0	9.3	3.4	1.0	0.5

For the thyroid dose part of this case (dose from ^{14}C = ^{85}Kr = ^{129}I = 0.75 mrem/y), results are shown in Tables 37 and 38.

This case shows that if the other three radionuclides were controlled so that ^{3}H could be controlled the least to meet total the total body and thyroid dose limits, then ^{3}H would require a DF of up to 5.9 for fresh used fuel, decreasing to a DF of 1 (no control) for used fuel cooled at least 30 years. The high required DF for ^{129}I is because of the low thyroid dose allocation (0.75 mrem/y).

Table 37. Effective decontamination factors by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{14}C, ^{85}Kr, and ^{129}I and 72.75 mrem/y for ^{3}H for a total of 100% of the allowable thyroid dose allocation

Isotope	Effective decontamination factor									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{14}C	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.3
^{85}Kr	4.7	4.1	3.4	2.5	1.3	1.0	1.0	1.0	1.0	1.0
^{129}I	14600	14600	14600	14600	14600	14600	14600	14600	14600	14600

Table 38. Doses to the MEI by radionuclide based on 30 GWd/tIHM to achieve 0.75 mrem/y for ^{14}C, ^{85}Kr, and ^{129}I and 72.75 mrem/y for ^{3}H for a total of 100% of the allowable thyroid dose allocation
(the DF values are shown in Table 37)

Isotope	Thyroid dose, mrem/y									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	70.26	62.79	53.04	40.05	22.83	13.01	4.23	1.37	0.25	9.2×10^{-4}
^{14}C	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
^{85}Kr	0.75	0.75	0.75	0.75	0.75	0.51	0.14	0.04	0.01	8.6×10^{-6}
^{129}I	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Allowable	75	75	75	75	75	75	75	75	75	75
Total	72.5	65.0	55.3	42.3	25.1	15.0	5.9	2.9	1.8	1.5

From this part of the study, we can determine the maximum and minimum DF values needed to achieve the case where 1% of the total allowable dose is assigned to each of three isotopes while the remaining 97% is assigned to the remaining isotope. These are shown in Tables 39 to 42.

Table 39. A summary of the maximum DF values to meet the whole body dose when 0.25 mrem/y is assigned to isotope listed

Isotope	Maximum effective decontamination factor for whole body dose									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	569	509	430	324	185	105	34.3	11.1	2.1	1.0
^{14}C	10.4	10.4	10.4	10.4	10.4	10.4	10.3	10.3	10.3	10.2
^{85}Kr	28.7	25.3	20.8	15.1	7.9	4.1	1.1	1.0	1.0	1.0
^{129}I	2200	2200	2200	2200	2200	2200	2200	2200	2200	2200

Table 40 A summary of the minimum DF values to meet the whole body dose when 0.25 mrem/y is assigned to three isotopes and 24.75 mrem/y to the isotope listed

Isotope	Minimum effective decontamination factor for whole body dose									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	5.9	5.2	4.4	3.3	1.9	1.1	1.0	1.0	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{129}I	23	23	23	23	23	23	23	23	22	22

Table 41. A summary of the maximum DF values to meet the thyroid dose when 0.75 mrem/y is assigned to isotope listed

Isotope	Maximum effective decontamination factor for thyroid dose									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	93.7	83.7	70.7	53.4	30.4	17.4	5.6	1.8	1.0	1.0
^{14}C	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.3
^{85}Kr	4.7	4.1	3.4	2.5	1.3	1.0	1.0	1.0	1.0	1.0
^{129}I	14600	14600	14600	14600	14600	14600	14600	14600	14600	14600

Table 42. A summary of the minimum DF values to meet the thyroid dose when 0.75 mrem/y is assigned to three isotopes and 72.75 mrem/y to the isotope listed

Isotope	Minimum effective decontamination factor for thyroid dose									
	Fuel age, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{14}C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{85}Kr	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
^{129}I	151	151	151	151	151	150	150	150	148	148

6.3.3 Zircaloy Sequestering of 50% ^{3}H

In this last case, we illustrate the impact on DFs needed if 50% of the ^{3}H is sequestered in the Zircaloy or otherwise lost so that ^{3}H inventory available to enter the gas streams is reduced. In the case of the 30-GWd/tIHM fuel, the ^{3}H evolved to the off-gas streams is reduced from 0.084 g/tIHM to 0.042 g/tIHM. These results show that the early dose from ^{3}H decreases from 20% of the total allowable to 10%— half the inventory yields half the dose. While this is the expected result, it does allow some headroom for the other isotopes. For example, at the same DF for the other isotopes (Table 12), the ^{3}H effective DF can be relaxed from 280 to 139.

6.4 SUMMARY OF RESULTS FOR PWR UOX FUEL

Tables 43 and 44 summarize the DF requirements for the capture of volatile radionuclides from the processing of PWR UOX fuel with burnups ranging from 20 to 60 GWd/tIHM and fuel cooling times from 2 y to 200 y. This assumes the nominal plant throughput of 1000 t/y. The details supporting these tables are in Appendix A and in Sections 4 and 6.2. The results shown in Table 43 consider the case where the dose to the MEI only is attributable to the volatile radionuclides. This provides the smallest DF that would be required, based on the assumptions and inputs to the CAP-88 air dispersion and dose model. (Again, note that no engineering margins are included in these values.) For low-burnup fuel the dose to the whole body is the limiting dose factor, but as the burnup increases, the thyroid dose becomes limiting. Controls for ^{3}H and ^{85}Kr are required for shorter-cooled fuels, up to ~60-y cooling. No controls are required on ^{14}C. Iodine DFs ranging from 166 to 380, depending on fuel burnup, would be required for any fuel cooling time.

Results shown in Table 44 are based on the allocation of 10% of the dose limit being attributed to the volatile radionuclides. For only the lowest burnup fuel (20 GWd/tIHM) is the dose to the whole body the limiting dose factor. For higher fuel burnups the thyroid dose is the limiting case. Iodine DF values range from 1660 to 3800, depending on fuel burnup, for all cooling times. Iodine DF increases with fuel burnup. For this case, increasing ^{14}C DF values (Table 41) are needed with increasing fuel burnup for all cooling times with the exception of very low-burnup fuels (20 GWd/tIHM). These ^{14}C DF values range from 1 to 10. Controls on ^{85}Kr are only needed for fuels cooled less than ~50 y, but ^{3}H controls are needed for cooling times up to ~90 y. Maximum ^{3}H DFs range from 225 to 600. While these values are associated with relatively short fuel cooling time, even for a 30-y cooled fuel the ^{3}H DF values are >100.

Table 43. A summary of DF requirements for the processing of PWR UOX in a 1000-t/y facility. For these data, 100% of the dose to the MEI is allocated to volatile radionuclides

Burnup (GWd/tIHM)	Most restrictive dose limit	Required DF to meet dose limit				Max age of fuel requiring control (y)			
	25 mrem whole body/ 75 mrem thyroid	^{3}H[a]	^{14}C	^{85}Kr[a]	^{129}I	^{3}H	^{14}C	^{85}Kr	^{129}I
20	Whole body	3.85 – 1	1	8.84 – 1	166	~25	NR	~35	All
30	Whole body	6.9 – 1	1	7.83 – 1	175	~35	NR	~35	All
60	Thyroid	25 –1	1	6.16 – 1	380	~60	NR	~30	All

[a] These are ranges depending on the fuel cooling time (i.e., 3.85 – 1 is the range from 3.85 to 1).

Table 44. A summary of DF requirements for the processing of PWR UOX in a 1000-t/y facility.
For these data, 10% of the dose to the MEI allocated to volatile radionuclides

Burnup (GWd/tIHM)	Most restrictive dose limit	Required DF to meet dose limit				Max age of fuel requiring control (y)			
	2.5 mrem whole body/ 7.5 mrem thyroid	$^{3}H^{a}$	^{14}C	$^{85}Kr^{a}$	^{129}I	^{3}H	^{14}C	^{85}Kr	^{129}I
20	Whole body	225 – 1	1	17.9 – 1	1660	~85	NR	~45	All
30	thyroid	250 – 1	3	7.83[b] – 1	1850	~85	All	~35	All
60	thyroid	600 –1	10	12.32 – 1	3800	~90	All	~40	All

[a]These are ranges depending on the fuel cooling time (i.e., 3.85 – 1 is the range from 3.85 to 1).
[b]The DF for ^{85}Kr decreased here compared to the 20 GWd/tIHM case because of the addition of ^{14}C control and higher controls for the other radionuclides.

6.5 SUMMARY OF RESULTS FOR PWR MOX FUEL

Tables 45 and 46 summarize the DF requirements for the capture of the volatile radionuclides from processing PWR MOX fuel with burnups ranging from 20 to 100 GWd/tIHM and fuel cooling times from 2 y to 200 y. This assumes the nominal plant throughput of 1000 t/y. The details supporting these tables can be found in Appendix B. Results shown in Table 45 are for the case where the dose to the MEI only is attributable to the volatile radionuclides. This provides the smallest DF that would be required. (Again, note that there are no engineering margins included in these values.) For low-burnup fuel the dose to the whole body is the limiting dose factor, but as the burnup increases, the thyroid dose becomes limiting. No controls are required for ^{14}C and, for fuels cooled longer than ~25 y, no controls are required on ^{85}Kr. The period of time for which ^{3}H controls are required increase with fuel burnup; ~25 y for 20 GWd/tIHM fuel increases to ~80 y for 100 GWd/tIHM fuel. Iodine DFs ranging from 279 to 630, depending on fuel burnup, would be required for any fuel cooling time.

Results in Table 46 are based on the allocation of 10% of the dose limit being attributed to the volatile radionuclides. For only the lowest burnup fuel (20 GWd/tIHM), the dose to the whole body is the limiting dose factor. For higher fuel burnups, the thyroid dose is the limiting case. Iodine DFs range from 2800 to 8000, depending on fuel burnup, for all cooling times. Iodine DFs increase with fuel burnup. For this case, large ^{14}C DFs are needed as fuel burnup increases for all cooling times with the exception of very low-burnup fuels (20 GWd/tIHM). The ^{14}C DFs range from 1 to 15. Controls for ^{85}Kr are only needed for fuels cooled less than ~40 y, but ^{3}H controls are needed for cooling times up to ~110 y. Maximum ^{3}H DF ranges from 158 to 720. While these values are associated with relatively short fuel cooling time, even with a 30-y fuel cooling time, ^{3}H DFs are still significant.

Table 45. A summary of DF requirements for the processing of PWR MOX in a 1000 t/y facility
For these data, 100% of the dose to the MEI is allocated to volatile radionuclides

Burnup (GWd/tIHM)	Most restrictive dose limit	Required DF to meet dose limit				Max age of fuel requiring control (y)			
	25 mrem whole body/ 75 mrem thyroid	$^{3}H^{a}$	^{14}C	$^{85}Kr^{a}$	^{129}I	^{3}H	^{14}C	^{85}Kr	^{129}I
20	Whole body	4.25 – 1	1	4.15 – 1	279	~25	NR[b]	~25	All
30	Whole body	7.55 – 1	1	4.01 – 1	273	~35	NR	~25	All
60	Thyroid	24.3 – 1	1	3.62 – 1	510	~60	NR	~25	All
100	Thyroid	160 – 1	1	3.21 – 1	630	~80	NR	~20	All

[a]These are ranges depending on the fuel burnup (i.e., 3.85 – 1 is the range from 3.85 to 1).
[b]NR = not required.

Table 46. A summary of DF requirements for the processing of PWR MOX in a 1000 t/y facility.
For these data, 10% of the dose to the MEI is allocated to volatile radionuclides

Burnup (GWd/tIHM)	Most restrictive dose limit	Required DF to meet dose limit				Max age of fuel requiring control (y)			
	2.5 mrem whole body/ 7.5 mrem thyroid	$^{3}H^{a}$	^{14}C	$^{85}Kr^{a}$	^{129}I	^{3}H	^{14}C	^{85}Kr	^{129}I
20	Whole body	158 – 1	1	4.15 – 1	2792	~80	NR[b]	~25	All
30	Thyroid	193 – 1	3	4.01 –1	2800	~85	All	~35	All
60	Thyroid	490 – 1	10	8.24 – 1	5100	~90	All	~30	All
100	Thyroid	720 –1	15	12.83 – 1	8000	~110	All	~40	All

[a]These are ranges depending on the fuel burnup (i.e., 3.85 – 1 is the range from 3.85 to 1).

[b]NR = not required.

6.6 SUMMARY OF RESULTS FOR AHTGRS (PBR DESIGN)

Tables 47 and 48 summarize the DF requirements for the capture of the volatile radionuclides for AHTGR UOX (PBR) fuel with burnups ranging from 20 to 100 GWd/tIHM and fuel cooling times from 2 y to 200 y. This assumes the nominal plant throughput of 1000 t/y. The details supporting these tables can be found in Appendix C. Table 47 considers the case where the dose to the MEI only is attributable to the volatile radionuclides. This provides the absolute smallest DF that would be required. (Again, note that there are no engineering margins included in these values.) For only the lowest burnup fuel (20 GWd/tIHM), the dose to the whole body is the limiting dose factor. For higher fuel burnup, the thyroid dose is the limiting case. No controls are required on ^{14}C except for very high-burnup fuels. For fuels cooled longer than ~35 y, no controls are required on ^{85}Kr. The time for which ^{3}H controls are required increases with fuel burnup; ~35 y for 20 GWd/tIHM fuel increases to ~80 y for 60 GWd/tIHM fuel. The decrease in ^{3}H DF and fuel age requiring treatment for the 100 GWd/tIHM comes from the need to add controls for ^{14}C. This increase in ^{14}C arises from the TRISO pebble coating, as discussed in Section 4.3. Iodine DFs ranging from 158 to 653, depending on fuel burnup, would be required for any fuel cooling time.

The data shown in Table 48 come from an allocation of 10% of the dose limit being attributed to the volatile radionuclides. For all fuel burnup cases, the dose to the thyroid is the controlling limit. Iodine DFs range from 1580 to 6540, depending on fuel burnup, for all cooling times. Iodine DF increases with fuel burnup. Because of the higher level ^{14}C in the fuel, there is a need to control its release for all cooling times and for all fuel burnups. The ^{14}C DF values range from 5 to 30. Controls on ^{85}Kr are only needed for fuels cooled less than ~50 y, but ^{3}H controls are needed for cooling times up to ~115 y. Maximum ^{3}H DF values range from 151 to 585. While these values are associated with relatively short fuel cooling time, even with a 30-y cooling time ^{3}H DF values for processing this fuel are still significant.

Table 47. A summary of DF requirements for the processing of AHTGR UOX in 1000 t/y facility
For these data, 100% of the dose to the MEI is allocated to volatile radionuclides

Burnup (GWd/tIHM)	Most restrictive dose limit	Required DF to meet dose limit				Max age of fuel requiring control (y)			
	25 mrem whole body/ 75 mrem thyroid	$^{3}H^{a}$	^{14}C	$^{85}Kr^{a}$	^{129}I	^{3}H	^{14}C	^{85}Kr	^{129}I
20	Whole body	7.30 – 1	1	9.13 – 1	158	~35	NR[b]	~35	All
30	Thyroid	12.4 – 1	1	8.59 – 1	189	~50	NR	~35	All
60	Thyroid	91 – 1	1	7.33 – 1	390	~80	NR	~35	All
100	Thyroid	41.4 –1	4	6.12 – 1	653	~70	All	~30	All

[a]These are ranges depending on the fuel burnup (i.e., 3.85 – 1 is the range from 3.85 to 1).
[b]NR = not required.

Table 48. A summary of DF requirements for the processing of AHTGR UOX in 1000 t/y facility.
For these data, 10% of the dose to the MEI is allocated to volatile radionuclides

Burnup (GWd/tIHM)	Most restrictive dose limit	Required DF to meet dose limit				Max age of fuel requiring control (y)			
	2.5 mrem whole body/ 7.5 mrem thyroid	$^{3}H^{a}$	^{14}C	$^{85}Kr^{a}$	^{129}I	^{3}H	^{14}C	^{85}Kr	^{129}I
20	Whole body	151 – 1	5	9.13 – 1	1577	~85	All	~40	All
30	Thyroid	251 – 1	10	8.59 – 1	1714	~90	All	~40	All
60	Thyroid	500 – 1	20	22.0 – 1	3650	~115	All	~50	All
100	Thyroid	585 – 1	30	61.25 – 1	6545	~115	All	~50	All

[a] These are ranges depending on the fuel burnup (i.e., 3.85 – 1 is the range from 3.85 to 1).

7. SENSITIVITY ANALYSIS

Many factors can affect the dose impacts to a MEI from radionuclide emissions from a reprocessing facility. The results of this study are constrained by the parameters in the CAP-88 dispersion model. Many of the parameters in the CAP-88 model can be user specified, with the intent that this model can be used to evaluate ambient air concentrations and dose impacts for specific sites and facilities. Without site-specific parameters for a specific fuel cycle and reprocessing facility, we have chosen hypothetical

parameters as model inputs and conditions to create several illustrative examples of dose impacts from uncontrolled emissions of gaseous radionuclides in UNF reprocessed in a hypothetical reprocessing facility. These results are only valid for the hypothetical input conditions. We have also performed various sensitivity studies to evaluate how variations in certain key input conditions can affect the hypothetical cases. These sensitivity studies and their results are summarized below.

7.1 RADIONUCLIDE INPUT RATE

The mass input rate of a radionuclide depends on the UNF composition, which is defined by the fuel cycle, the fuel burnup in the reactor, and the age of the UNF after reactor discharge prior to reprocessing. Analysis of Transmutation Library (Piet et al. 2011b) data for UNF compositions has shown that the amounts of the gaseous fission products that could be formed as daughters of the decay of other radionuclides are negligible compared to the amounts of those radionuclides in the UNF at the time of reactor discharge. Furthermore, the decay of the gaseous fission products results in nonradioactive progeny that have no dose impacts.

The CAP-88 dose results for a radionuclide are proportional to the radionuclide input rate. Similarly, as long as other parameters are unchanged, the following is true.

- For a specific UNF, the CAP-88 dose results are proportional to the amounts of radionuclides in the UNF as the UNF ages after reactor discharge prior to reprocessing.
- The CAP-88 dose results are proportional to the amounts of radionuclides in UNF that vary as a function of fuel burnup in the reactor.
- The CAP-88 dose results are proportional to the amounts of radionuclides in different UNFs from different fuel cycles or that have different ages or burnups.
- The CAP-88 dose results are proportional to the UNF processing rate in the reprocessing facility.

7.2 STACK GAS HEIGHT

The stack is normally used to elevate the off-gas emission well above ground level and the heights of nearby structures, which aids in dispersing the plume. The higher the stack, the higher the plume begins; the point downwind at which the dispersed plume "hits" the ground increases, and so does the dilution of the stack gas, which results in lower ambient air concentrations and lower doses to the MEI.

Table 49 shows the effect of changing the stack height from the reference used for the calculations done in this study. The orientation of the MEI from the stack does not change, but the distance to the MEI reaches a maximum within the range of heights in this study. At 37 m, the maximum dose is 600 m north (800 m north for the higher stacks).

These data indicate that doubling that stack height from 37 m to 74 m could decrease the dose for the gaseous radionuclides by approximately a factor of ~4. Further doubling the stack height from 74 m to 150 m could decrease the dose by an additional factor of ~4 (a ~75% reduction). The total impact of varying stack height by a factor of 4 between 37–150 m (a reasonable range of full-scale stack heights) on dose is about a factor of 16–25 (a reduction of 94–96%).

These results are sensitive to the site for which the calculation is done. For example, the results for another site indicate that doubling the stack height from the 37 m to 74 m decreases the dose of gaseous species (^{3}H, ^{14}C, and ^{85}Kr) by a factor of 3.2 (a reduction of 69%) and the dose from particulate-phase ^{129}I by only a factor of 1.8 (a reduction of only 45%). To completely analyze the effects of stack height on

the MEI would require a much more in-depth study or a selection of a particular site, an activity that is outside the scope of this study.

Table 49. Impact on dose to the MEI from a change in stack height relative to a 37-m high stack

Radionuclide	Stack height, m		
	74	100[a]	150[b]
	Change, %		
^{3}H	-74	-86	-96
^{14}C	-74	-87	-96
^{85}Kr	-73	-86	-95
^{129}I[c]	-72	-85	-94

[a] Stack height at La Hague, France
[b] Stack height at Rokkasho, Japan
[c] Particulate form 100%

7.3 STACK EXIT GAS VELOCITY AND RADIONUCLIDE CONCENTRATION

The CAP-88 model allows the user to assume that the rise, if any, of a plume of off-gas leaving the stack is either momentum dominated or buoyancy dominated. The momentum is provided by the stack gas exit velocity. The higher the exit velocity, the higher the plume rises as it disperses in the atmosphere, and so (a) the distance at which the plume reaches ground level increases, and (b) the concentration at the point where the plume reaches the ground decreases because of increased dispersion. These factors combine to reduce the dose to the MEI.

Table 50 shows the results from CAP-88 calculations when the stack gas velocity is varied between 9 and 36 m^3/s by varying the flow rate of stack gas without changing the radionuclide input rate. In this case, two parameters change: the stack gas velocity and the radionuclide concentration in the stack gas. When the nominal 18-m/s stack gas velocity is reduced to half its nominal value and the stack gas radionuclide concentration is increased to twice its nominal concentration, then the total dose increases by 21%. When the nominal 18-m/s stack gas velocity is doubled (and the stack gas radionuclide concentration is decreased to half its nominal value), then the total dose decreases by 29%.

Table 50. Impact of stack gas exit velocity and radionuclide concentration on dose[a]

Stack velocity, m/s	9	18 (base case)	36
Location of MEI, m	600 ENE	600 ENE	700 ENE
	Change, %		
^{3}H	20	---	-29
^{14}C	21	---	-29
^{85}Kr	19	---	-26
^{129}I	21	---	-29
Total	21	---	-29

[a] Base conditions = 18 m/s; constant input radionuclide rate; constant stack diameter (1.5 m); dose values are for a hypothetical facility in the northwest United States.

The individual doses from each of the gaseous fission products vary by nearly identical amounts (slightly less ^{85}Kr, perhaps because of its inertness, which may dominate the dose conversion more significantly than for the other radionuclides that would play more active roles in the biosphere). The total dose tracks very close to the dose from ^{129}I because, when the form of the ^{129}I is particulate (as in this case), then the dose from ^{129}I is large compared to the other doses from the other radionuclides (see Section 7.8), and so dominates the total dose. But regardless of gaseous phase, particulate phase, or chemical inertness, the differences in the change in dose between the different radionuclides is less than 10% of the change in the dose.

Table 51 shows how the dose changes when only the stack gas exit velocity is changed. The exit gas velocity is changed, while the stack gas flow rate and concentrations of radionuclides are held constant, by varying the stack inside diameter (ID).

Table 51. Impact of stack gas exit velocity on dose[a]

Stack velocity, m/s	9	18 (base case)	36
Stack diameter, m	2.12	1.5	1.06
Location of MEI, m	600 ENE	600 ENE	700 ENE
	Change, %		
^{3}H	11	–	-13
^{14}C	12	–	-13
^{85}Kr	11	–	-12
^{129}I	12	–	-14
Total	12	–	-13

[a]Base conditions = 18 m/s; constant input radionuclide rate, varying stack ID; dose values are for a hypothetical facility in the northwest United States.

The percent change in dose is less in this case because the impact on dose from changing the radionuclide concentration in the stack gas is eliminated. The change in dose from changing the exit gas velocity is about half the change in dose caused by the combined change in exit gas velocity and radionuclide concentration in the stack gas.

These results show that increasing the stack gas exit velocity by a factor of 4 from 9 to 36 m/s (by reducing the stack diameter) could decrease the dose to the MEI by about 30%. If the stack gas exit velocity is increased by 4 over this range by quadrupling the stack gas flow rate, which also dilutes the radionuclide concentrations in the stack gas by a factor of 4, then the dose could be decreased by about 60%.

7.4 STACK GAS BUOYANCY

The CAP-88 user can specify if a plume of gas leaving the stack is either momentum dominated or buoyancy dominated. If the stack gas is buoyancy dominated, then the density of the plume, relative to the density of the atmosphere, determines plume rise as the plume disperses. The model accounts for density change by allowing the user to input the difference in enthalpy of the stack gas compared to the enthalpy of the atmosphere. By considering the enthalpy of the stack gas, the differences in both the temperature and the molecular weight between the stack gas and the atmosphere are taken into account.

Table 52 shows how, for a stack gas that has constant average molecular weight, the dose changes for different stack gas temperatures compared to the ambient atmospheric temperature. Compared to a nominal differential temperature of 5°C, increases in the differential temperature by up to 5 (up to 25°C) decrease the dose by up to about 55%. This change in dose, when normalized to percent change in the input parameter, is about four times larger than the changes in dose caused by either changes in stack gas momentum (velocity) or stack gas radionuclide concentration.

Table 52. Impact of stack gas density difference compared to the atmosphere relative to the case of ΔT = 5°C on dose[a]

Heat emission rate, kJ/s	**214.2**	**428.3**	**857.0**	**1071**
Temperature difference, °C	**5**	**10**	**20**	**25**
Location of MEI, m	800 ENE	900 ENE	1000 ENE	1000 ENE
	Dose change, %			
^{3}H	–	-16	-38	-54
^{14}C	–	-16	-39	-55
^{85}Kr	–	-15	-35	-49
^{129}I	–	-16	-38	-55
Total	–	-16	-38	-55

[a]The volumetric stack gas flow rate is 33.6 m^3/s (71,200 scfm); the stack gas has an average molecular weight and heat capacity equivalent to air.

This change in dose could also occur if the density decreased by 6.8% from a lower average molecular weight (assuming that the temperature stays constant). Such a change in density might occur, for example, if the stack gas moisture content significantly increased, although that might have other impacts on the dose of ^{3}H if the larger amount of moisture significantly condensed into droplets.

7.5 REPROCESSING FACILITY LOCATION IN THE UNITED STATES

The CAP-88 cases in this study unavoidably use specific meteorological data (wind history, average ambient temperature, annual precipitation, and average humidity) to perform the air dispersion calculations. We have used generic meteorological data to illustrate the changes that take place if the same facility is located in four geographical areas in the United States.

Table 53 shows how gaseous radionuclide dose can vary for four representative U.S. locations. These generic locations are the Northwest, Southwest, Central Southeast, and Southeast. This selection also covers a range of wind history, ambient temperature, precipitation, and humidity. The dose variations shown in this table arise from multiple factors. Areas with higher wind velocities or directions that vary significantly reduce dose because there is more air dispersion. Areas with higher precipitation result in more rapid deposition of especially ^{14}C and ^{129}I, which can cause higher dose rates for these radionuclides. Areas with higher humidity result in isotopic dilution of ^{3}H, reducing the dose. Results from the CAP-88 studies with meteorology from these few selected locations indicate that, depending on location in the United States,

- dose from ^{3}H can vary by more than a factor of 2, depending on the humidity;
- dose from ^{14}C and ^{129}I may increase by more than 10% in areas with higher precipitation; and
- dose from any of the radionuclides can vary by more than 20% from wind velocity.

These values will vary for other locations in the country.

Table 53. Impact of facility location in the United States on dose relative to the base case of the northwest United States[a]

	Northwest	Southeast	Central Southeast	Southwest
Meteorological conditions				
Average temperature, °C	6.77	17.81	13.1	11
Annual precipitation, m	0.194	1.14	1.35	0.391
Average humidity, $\times 10^3$ kg/m^3	3.6	12	8.9	8.0
Location of MEI from stack (m)	600	500	500	400
Wind direction	ENE	S	NE	NE
	Dose change, %			
^{3}H	–	-58	-43	-50
^{14}C	–	15	23	0
^{85}Kr	–	8	20	2
^{129}I	–	27	37	1

[a] The assumed form of ^{129}I in these studies was particulate.

7.6 LID HEIGHT

One of the inputs required by the CAP-88 simulation is the "height of lid" under the meteorological data tab. This term refers to the average height of the tropospheric mixing layer, or the atmospheric boundary layer, at the site. Within this layer there is active transport and mixing of gases, vapors, and aerosols from convection caused, or influenced, by temperature variations, wind velocity, and surface structures. The actual mixing height varies during a typical day, with the height being lower during calm morning and evening hours and higher in the afternoon. The default value in CAP-88 is set for 1000 m. This value was used in the calculations reported here. In past studies, the INL Applied Geosciences department recommended 800 m (Staley et al. 2004), while at Los Alamos a value of 1525 m was used (Jacobson 1997).

A set of runs was conducted with the base case with the "height of lid" varied between runs. From 100 to 10,000 m (largest value used), the lid height had no effect on the dose or location of an MEI. However, for a lid height of 50 m, the dose to an MEI increased 24% (from 1.35 to 1.67 mrem/y), and the location was moved from 600 to 500 m with a slightly different compass position for the MEI.

If the lid height becomes less than about twice the stack height (for the conditions in the sensitivity study), then lid height starts to cause the dose to increase by reducing mixing.

7.7 AGRICULTURAL DATA

The CAP-88 model (Rosnick 1992) includes as part of the calculation the dose to the MEI through ingestion with user-selected food sources. These cases determine the fraction, if any, of vegetables, milk, and meat that are consumed, are home produced, come from the area impacted by the assessment area, or are imported from outside the assessment area. The user can select among several cases (urban, rural, local, regional, or imported) or may manually enter specific choices for those fractions.

Table 54 shows how the dose is impacted by choosing rural versus urban food sources. This table shows that in the rural scenario, most of the vegetables and some of the milk and meat are home produced; the remainder comes from the assessment area, and none is imported. In the urban scenario, none or almost none of the vegetables, milk, or meat is home produced; nearly all of the food is from the assessment area, and none is imported. When the majority of the food is not home produced by the MEI, but is still from the assessment area, then the dose for the radionuclides that are incorporated into the food cycle is decreased by about 30% to 40%. The dose from ^{85}Kr remains unchanged because it does not play a role in the food cycle.

Table 54. The impact of urban and rural food sources on dose[a]

Source	Rural			Urban		
	Vegetable	**Milk**	**Meat**	**Vegetable**	**Milk**	**Meat**
Fraction home produced	0.7	0.40	0.44	0.076	0	0.008
Fraction from assessment area	0.3	0.60	0.56	0.92	1	0.99
Fraction imported	0	0	0	0	0	0
Total	**1**	**1**	**1**	**1**	**1**	**1**
Change (%)						
^{3}H	–			-28		
^{14}C	–			-39		
^{85}Kr	–			0		
^{129}I	–			-38		

[a]This sensitivity study was done for the humid Southeast facility location.

7.8 DOSE SENSITIVITY TO THE CHEMICAL AND PHYSICAL FORM OF ^{129}I

The chemical and physical form of ^{129}I plays an important role in the dose the MEI receives from a given amount of ^{129}I.

7.8.1 Chemical and Physical Form of ^{129}I

Iodine released from the exhaust stack of a processing facility may exist in several different chemical species including elemental iodine (I_2), hydrogen iodide (HI), hypoiodous acid (HOI), and organic iodine (methyl iodide [CH_3I] is typically used as a surrogate). The chemical and physical form of ^{129}I in the atmosphere may have a significant impact on the estimated dose to an individual as calculated with the CAP-88 code. The user of CAP-88 may enter inorganic iodine as either a particulate or vapor, while methyl iodide defaults to a gas. The choice of speciation and form can have a huge impact on the calculated dose. In several base cases, the estimated dose varied by three orders of magnitude with the particulate form delivering the largest dose to an exposed individual, while the gas and vapor forms delivered much smaller and similar doses.

The speciation and behavior of iodine released to the atmosphere is not easily determined, but all forms are of considerable interest since they all may enter inhalation and ingestion pathways as described by the IAEA (IAEA 1973):

> *Iodine isotopes may be discharged to the atmosphere as molecular iodine or as inorganic or organic iodides, depending upon their origin and the conditions prevailing in the system. Molecular iodine may become adsorbed on submicron particles during or after discharge to atmosphere. All forms are subject to dispersion in the atmosphere by natural processes of turbulence, convection due to solar and other heating, movement by the wind, etc., and usually do not deposit under the influence of gravity. They are, however, deposited on the ground and other surfaces such as pasture grass, at*

rates which depend upon such variables as the physical and chemical form of the iodine and weather conditions, including wind speed and rainfall rates.

Information from reprocessing plants indicates a significant variation in major release points for iodine. At the Idaho reprocessing plant, only about 5% of iodine entering in the fuel was released to the dissolver off-gas. The remaining iodine inventory was carried downstream where thermal processing of waste effluents resulted in as much as 87% being driven off at the calciner.* The balance of iodine was retained in the solid calcine product (~1%) and in the liquid from an evaporator associated with the process. The speciation of iodine in the off-gas from the calciner and released (after filtration through HEPA filters and sorption on silica gel) to the stack was estimated to be 15% I_2, 21% HOI, and 64 % organic iodine (McManus et al. 1982). By comparison, at the Karlsruhe Reprocessing Plant (WAK) in Karlsruhe, Germany, as much as 99% of the iodine was released from the dissolver, where the practice of fumeless dissolution† was used. Atmospheric iodine sampling around the WAK was performed over two time periods, as shown in Table 55 (Wershofen and Aumann 1989). The sampling procedure separated the iodine into three fractions: iodine associated with aerosol particles, inorganic gases, and organic gases.

Table 55. Atmospheric iodine speciation in the vicinity of the WAK

	Sampling period	
	Oct. to Dec. 1986	June to Sept. 1987
	Composition, %	
Aerosol particles	5.3 to 30.8	1.7 to 9.7
Gaseous inorganic ^{129}I	26.8 to 35.2	17.2 to 27.3
Gaseous organic ^{129}I	34.0 to 65.9	62.9 to 88.8

The information presented in Table 55 is significant in that the reprocessing plants at Idaho and Karlsruhe had similar emissions (primarily organic iodine) even though the major release points were from different unit operations. The sampling near the WAK plant indicates that particulate iodine is a small, but significant, fraction of the inventory. The implications of these data are that the iodine specified in the CAP-88 simulation could be apportioned between the organic (as methyl iodide vapor), inorganic (gas), and particulate forms. In doing so, the estimated dose for uncontrolled release would be reduced from that estimated assuming all particulate (the most conservative approach) release. The consequent DF required for emission compliance could also be reduced.

7.8.2 Sensitivity Results from CAP-88 Calculations

In CAP-88 (Rosnick 1992), the dose to the MEI depends strongly on the chemical form (particulate or gas) of the radionuclide of interest. For this report, we performed all of the ^{129}I dose calculations assuming the iodine to be in particulate form, recognizing that this assumption results in conservatively high ^{129}I dose results.

We also performed a sensitivity study where the chemical and physical forms of the iodine were varied. Of the isotopes ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I, only iodine has options that include particulate. Since the other

* The calciner was a thermal treatment process that converted liquid waste to a solid granular form.

† Fumeless dissolution involves adding oxygen to the dissolver slightly in excess of that required for complete NO_x recombination.

three are normally gaseous (^{14}C as CO_2 and ^{85}Kr) and water vapor is the likely form in which ^{3}H appears, the sensitivity on the chemical form was determined only for ^{129}I. In CAP88 (Rosnick 1992), there are three options for iodine—particulate, vapor, and organic. A single case serves to illustrate the salient factor for iodine. For ^{129}I, we considered the case for 0.0482 mCi emitted from a processing facility located in Northwest. The prevailing winds and temperature conditions led to the maximum dose being deposited at 700 m northeast from the stack. The results for four cases of chemical form distribution are shown in Table 56.

These results show that the dose to the MEI scales with the fraction of emitted ^{129}I that is classified as particulate. The dose calculated when assuming the 100% particulate form was on the order of 10^3 times higher for both the whole body and thyroid, compared to when the iodine form was assumed to be 50% vapor and 50% organic. In cases where only ~30% to ~70% of the total iodine is in particulate form (as indicated by results from the Karlsruhe Reprocessing Plant [Table 55]), then the dose-based ^{129}I DFs estimated in this report could be reduced by 30 to 70%. Since the dose values scale with the amount of particulate and since studies performed have yielded reliable estimates of the distribution in a typical emission from a reprocessing facility stack, the doses from ^{129}I can easily be scaled to that fraction, because the contributions from the vapor and organic are about a factor of 100 less. The same can be concluded for the dose to the thyroid (Table 56).

Table 56. Results of the sensitivity study on the distribution of dose from 0.00482 mCi of ^{129}I in different chemical forms to the MEI located 700 m from the stack of a reprocessing plant hypothetically located in the northwest United States

Chemical form, %			Dose contributions, mrem/y				
			Whole body			Total	Thyroid
Particulate	Vapor	Organic	Particulate	Vapor	Organic		
100			1.5			1.5	30.2
50	50		0.75	0.0019		0.76	15.1
30	30	40	0.45	0.0012	0.0012	0.46	9.1
0	50	50	0	0.0019	0.0015	0.0034	0.069

8. CONCLUSIONS

As a result of fuel reprocessing, volatile radionuclides may be released from the facility stack if no processes are put in place to remove them. The radionuclides that are of concern in this document are ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. The question we attempted to answer is how efficient must this removal process be for each of these radionuclides? To answer this question, we examined the three regulations that may impact the degree to which these radionuclides must be reduced before process gases can be released from the facility. These regulations are 40 CFR 61 (EPA 2010a), 40 CFR 190 (EPA 2010b), and 10 CFR 20 (NRC 2012). These regulations apply to the total radonuclide release and to a particular organ – the thyroid.

Because these doses can be divided amongst all the radionuclides in different ways and even within the four radionuclides in question, we provided several cases. We first looked at the inventories for these radionuclides for three fuel types (PWR UOX, PWR MOX, and AHTGR), several burnup values, and time out of reactor extending to 200 y. We calculated doses to the maximum exposed individual (MEI) with the EPA code CAP-88 (Rosnick 2007, 1992) using a set of reference assumptions.

Finally, we looked at several dose allocation cases to calculate a range of possible decontamination factors (DFs). Allowing all of the allowable dose to be used by the volatile radionuclides is one bounding

case. Subsets of this bounding case that were evaluated for select cases were (a) allowing the allowable dose to be partitioned somewhat evenly between the four volatile radionuclides and (b) allowing each volatile radionuclide to have up to 97% of the allowable dose, while the other three radionuclides were allocated only 1% of the allowable dose. We also evaluated cases that only allocated 10%, 25%, and 50% of the total allowable dose to the four volatile radionuclides, allowing up 90%, 75%, and 50% of the total allowable dose for other radionuclides that may be in the stack gas in small amounts. For all systems the 100% and 10% allocation to the volatile radionuclides were evaluated.

We calculated the required DF values based on the whole body dose limiting case and thyroid dose limiting cases and used the more restrictive of the two.

We found that the highest dose was calculated when this iodine is assumed to be discharged as a fine particulate. The dose scaled as the fraction of the total ^{129}I that was particulate. Therefore, we assumed for all of our calculations that 100% of the ^{129}I was particulate and allowed the user of the results given here to scale our calculated doses for different ^{129}I partitioning values if needed.

To summarize the data given in the body and appendices of this report, we present the data for the maximum DF values required to meet regulations in Table 57. Figures 16 to 19 show the minimum required DF values for ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I respectively. These figures are based on the reference PWR UOX cases evaluated assuming that the full dose allocation is assigned to the four volatile radionuclides. The DF values shown in this table and the figures contain no engineering margin and could vary by a factor of 2 or more if different site-specific or reprocessing-facility-specific assumptions are used. In terms of establishing practicable target DF values for the capture processes under development, we believe that these should be on the order of three to ten times the values that result from a 25% to 50% dose allocation, that is, values that fall between those shown in the two major columns in Table 57, recognizing that if the fuel is cooled is long enough, then ^{85}Kr or ^{3}H control should be signigicantly reduced. These DF values are within the range of DFs that are reported for the capture technologies for the volatile radionuclides (Gombert 2007). Achieving the required iodine and tritium DFs will be the more challenging. While it can be argued that the 10% dose allocation was selected arbitrarily, and it was, the full dose allocation is certainly too optimistic as other radionuclides will contribute to the total dose. The anticipated range is expected to be from 5% to 50%. Further analysis into how potential emissions of other radionuclides in a used fuel can be controlled would be required to refine this value.

Table 57. Maximum DFs required for the volatile radionuclides of concern in this report

	Full dose allocation to volatile radionuclides			**10% dose allocation to volatile radionuclides**		
	PWR/UOX	**PWR/MOX**	**AHTGR**	**PWR/UOX**	**PWR/MOX**	**AHTGR**
^{3}H	25 (1 after 57 y)	160 (1 after 90 y)	42 (1 after 66 y)	600 (1 after 114 y)	720 (1 after 117 y)	585 (1 after 113 y)
^{14}C	1	1	4	10	15	30
^{85}Kr	9 (1 after 34 y)	4.2 (1 after 22 y)	9.2 (1 after 34 y)	18 (1 after 45 y)	13 (1 after 40 y)	62 (1 after 64 y)
^{129}I	380	630	650	3800	8000	6550

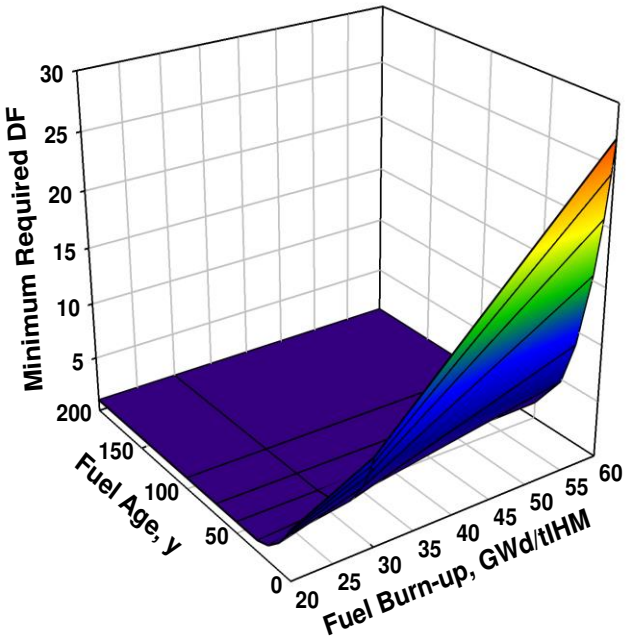

Figure 16. Minimum DF required for ^{3}H as a function of fuel age and burnup for a 1000-t/y recycle plant processing PWR UOX fuel.

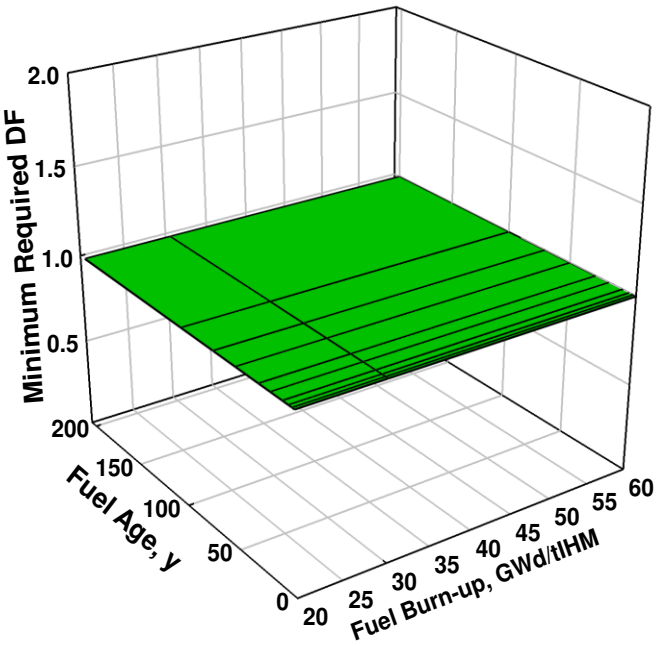

Figure 17. Minimum DF required for ^{14}C as a function of fuel age and burnup for a 1000-t/y recycle plant processing PWR UOX fuel.

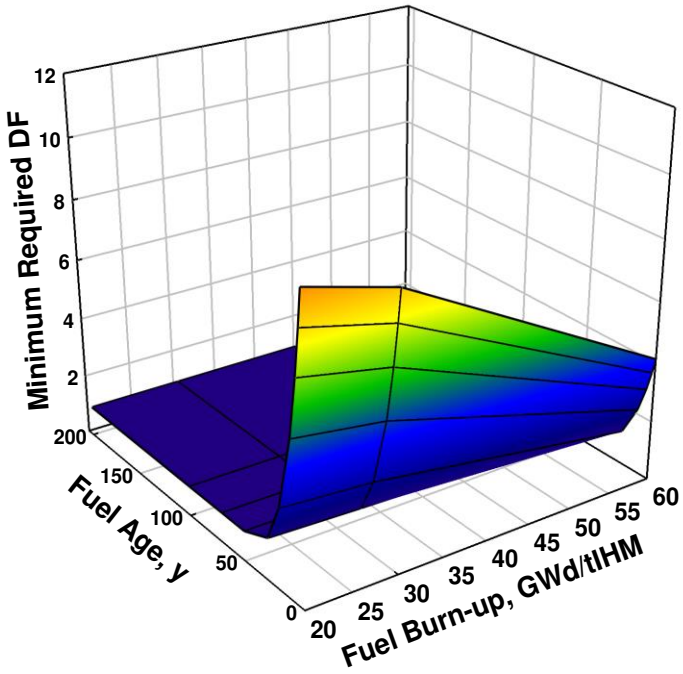

Figure 18. Minimum DF required for ^{85}Kr as a function of fuel age and burnup for a 1000-t/y recycle plant processing PWR UOX fuel.

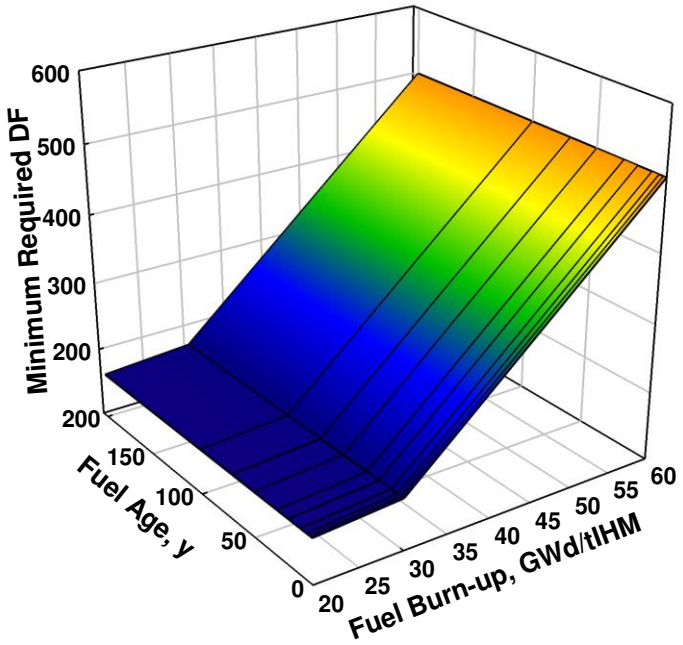

Figure 19. Minimum DF required for ^{129}I as a function of fuel age and burnup for a 1000-t/y recycle plant processing PWR UOX fuel.

It should also be evident from the discussions in Sections 4.2 and 6.2 and in Appendixes A–C that it is possible to decrease the DF for one volatile radionuclide and increase the DF for one of the others and still maintain the same dose to the MEI. With this in mind, it is not possible to arrive at a single target DF for one volatile radionuclide without taking into account the DFs for the other volatile radionuclides. The DF values required to limit the dose to the MEI are a function of the fuel age at the time of processing.

The sensitivity studies show that several reprocessing facility design, operation, and location parameters can cause variations in the DF values calculated in this analysis.

- Varying stack height by a factor of 4 (from 37m to 150 m) results in a factor of ~16 reduction in the dose to the MEI. (The dose is decreased by the square of the stack height increase.)

- Changing the speciation of the ^{129}I from 100% particulate form used in the calculations of this study to 30% to 70% particulate form (a range consistent with measurements from the Karlsruhe Reprocessing Plant) would reduce the ^{129}I dose to 30% to 70% of the original value.

- Changing the stack gas velocity and temperature can affect the dose to the MEI by up to a factor of 2, depending on if the plume is momentum or buoyancy dominated, and if the stack gas velocity is varied by changing the stack diameter or the stack gas flow rate.

- Site-specific meteorologic parameters can (a) cause the ^{3}H dose to vary by a factor of 2 depending on the humidity, (b) increase the dose from ^{14}C and ^{129}I by more than 10% in areas with higher precipitation, and (c) cause the dose from any of the volatile radionuclides to vary by more than 20% for different wind velocities.

- Site-specific agricultural parameters, which vary for different locations in the United States, affect dose from ingestion. Changing from the rural food scenario used in the calculations of this study to an urban food scenario decreases the doses from those volatile radionuclides that play a role in the food cycle (^{3}H, ^{14}C, and ^{129}I) by 30–40%. The dose from ^{85}Kr is unchanged because it does not play a role in the food cycle.

Allowing the fuel to age before reprocessing allows a decrease in the volatile radionuclide inventory, but only for the relatively short-lived isotopes – ^{3}H ($t_{1/2}$ = 12.3 y) and ^{85}Kr ($t_{1/2}$ = 10.73 y). However, to be an effective method to limit the release of the volatile radionuclides to the point that little or no control would be required, these storage times are on the order of 30 to 100 y. We calculated the required DF values and doses to the MEI for storage times extending to 200 y so that the user of the calculations provided here can assess this strategy. The cost benefit of long storage of fuel as a strategy for reducing reprocessing costs by reducing or eliminating the need to control emissions of short-lived volatile radionuclides must be evaluated against the costs of long-term fuel storage and other impacts such as on the recycle fuel value. Such a cost-benefit analysis is outside the scope of the work presented here.

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PREFACE TO THE APPENDICES

These appendices contain much of the same information that is given in the main body of the text. It is by its nature repetitive of the main text and between the appendices. In our view, there was no alternative than repetitiveness and, therefore, we relegated this information to these appendices to unload the burden on the main text. There is important information in these appendices; we have attempted to summarize the important information into the main text. It is also important to note that these appendices can stand on their own.

APPENDIX A. UOX FUEL

A.1. PWR / UOX / 20 GWD/TIHM

For the case of PWR and UOX fuel with a burnup of 20 GWd/tIHM, the second-phase analysis results are as follows: For a plant size of 1000 t/y, the total dose to the MEI ranges from 434 mrem/y at 2-y-cooled fuel to 350 mrem/y at 100-y cooled (Figure A.1-1). Iodine is the major contributor (348 mrem/y); at cooling times up to ~25 y, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 1.67 mrem/y, and ^{85}Kr could contribute up to ~4.6 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table A.1-1.

If the iodine and krypton release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 83.8 mrem/y at 2-y cooling and 4.08 mrem/y for 100-y-cooled fuel (Figure A.1-2). The iodine contribution is reduced to 2.10 mrem/y, and tritium becomes the major contributor at cooling times less than ~60 y. Carbon-14 again contributes 1.67 mrem/y, but ^{85}Kr contributions are reduced to less than 0.54 mrem/y. It is clear from Figure A.1-2 that additional controls at least on tritium would be required to meet a 25-mrem/y limit at cooling times less than ~25 y and that from Figure A.1-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for iodine and/or ^{14}C would also be required since the sum of these alone exceeds 2.5 mrem/y.

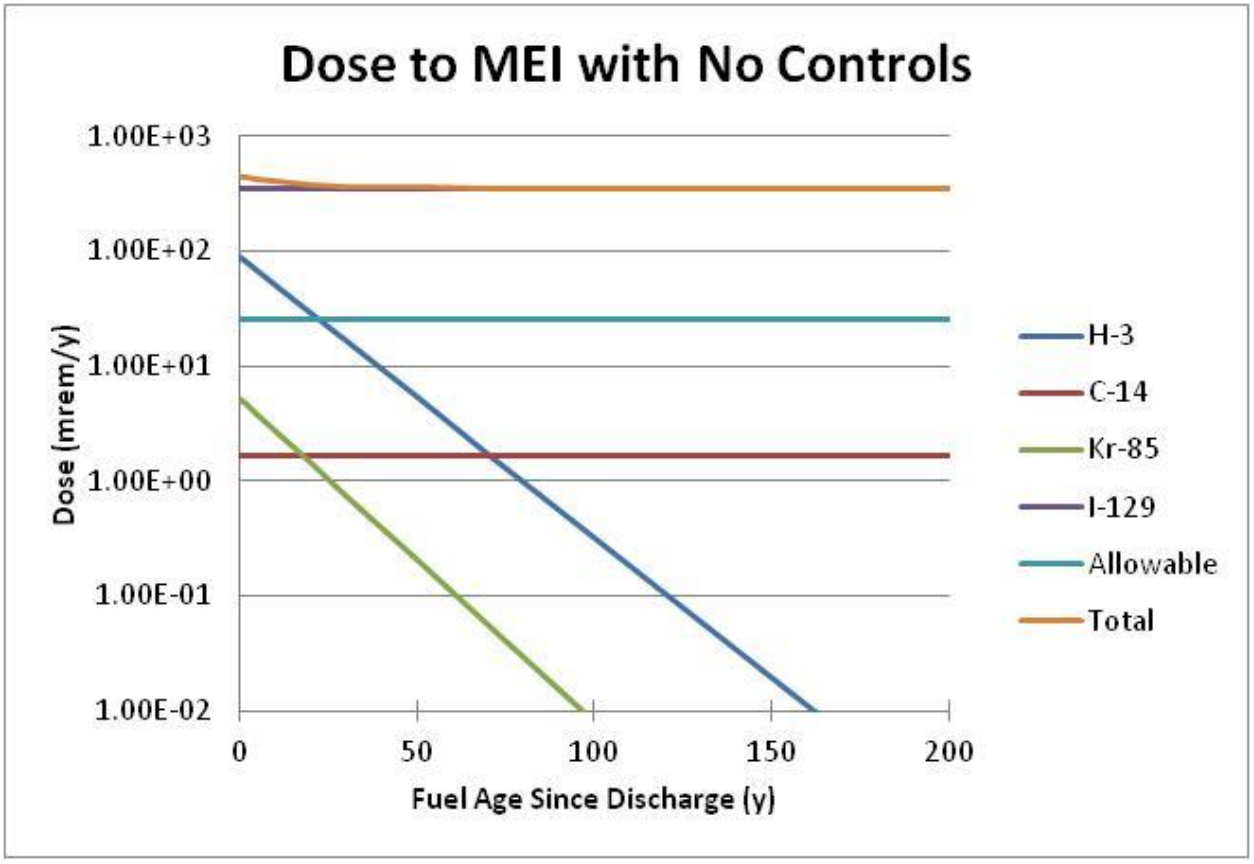


Figure A.1-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table A.1-1. Dose contributions by radionuclide based on 20-GWd/tIHM PWR UOX fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	89.0	79.5	67.2	50.7	28.9	16.5	5.35	1.74	0.32	0.0012
^{14}C	1.67	1.67	1.67	1.67	1.67	1.66	1.66	1.66	1.65	1.63
^{85}Kr	5.23	4.60	3.79	2.74	1.44	0.75	0.21	0.057	0.0081	1.27×10^{-5}
^{129}I	348	348	348	348	348	348	348	348	348	348
Allowable	25	25	25	25	25	25	25	25	25	25
Total	444	434	421	403	380	367	355	352	350	350

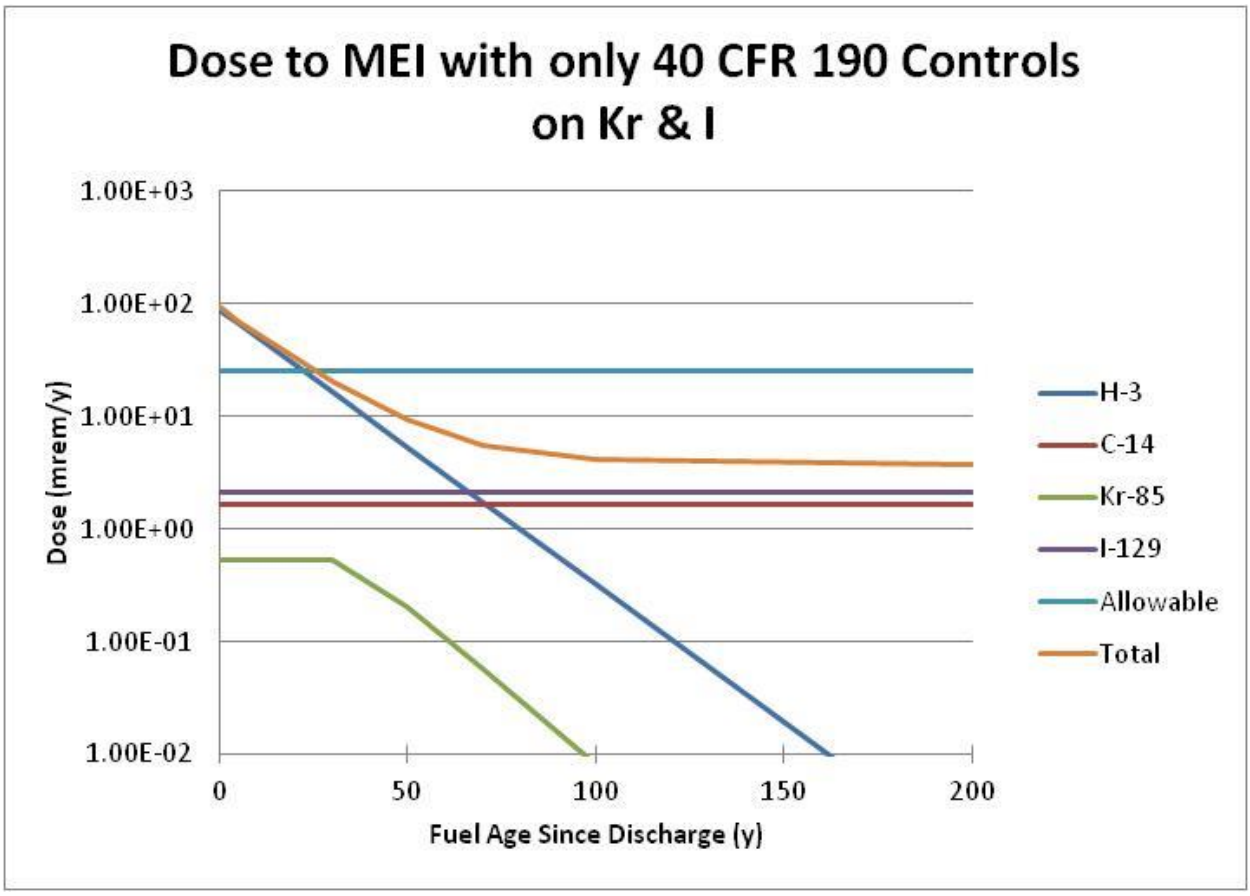


Figure A.1-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

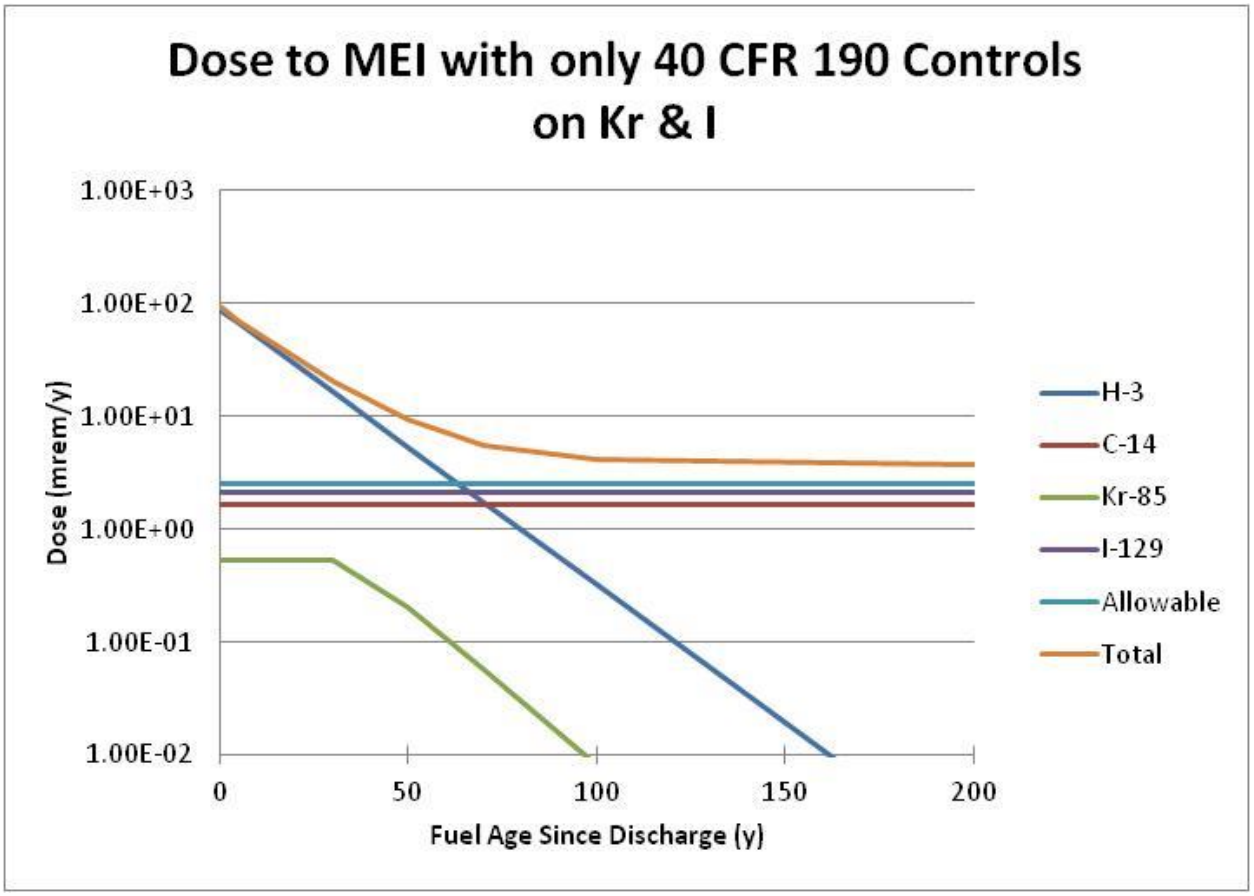


Figure A.1-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 3.85 at 2-y cooling to 1.4 at 20-y cooling (Figure A.1-4 and Table A.1-2). Beyond ~25 y fuel cooling no additional ^{3}H capture would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to iodine at all times, raising the total DF to ~1700. Since at short times krypton must be recovered, additional ^{85}Kr-DF requirements were also imposed during the time frame that treatment would be required (up to 30-y cooling). Tritium DF values range from 225 for 2-y-cooled fuel to ~3 at 70-y-cooled fuel. Beyond 100 y, no ^{3}H recovery would be required. Figure A.1-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of time. Figure A.1-6 depicts the DF requirements for each individual isotope as a function of cooling time. Table A.1-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table A.1-4 shows the resulting dose contributions.

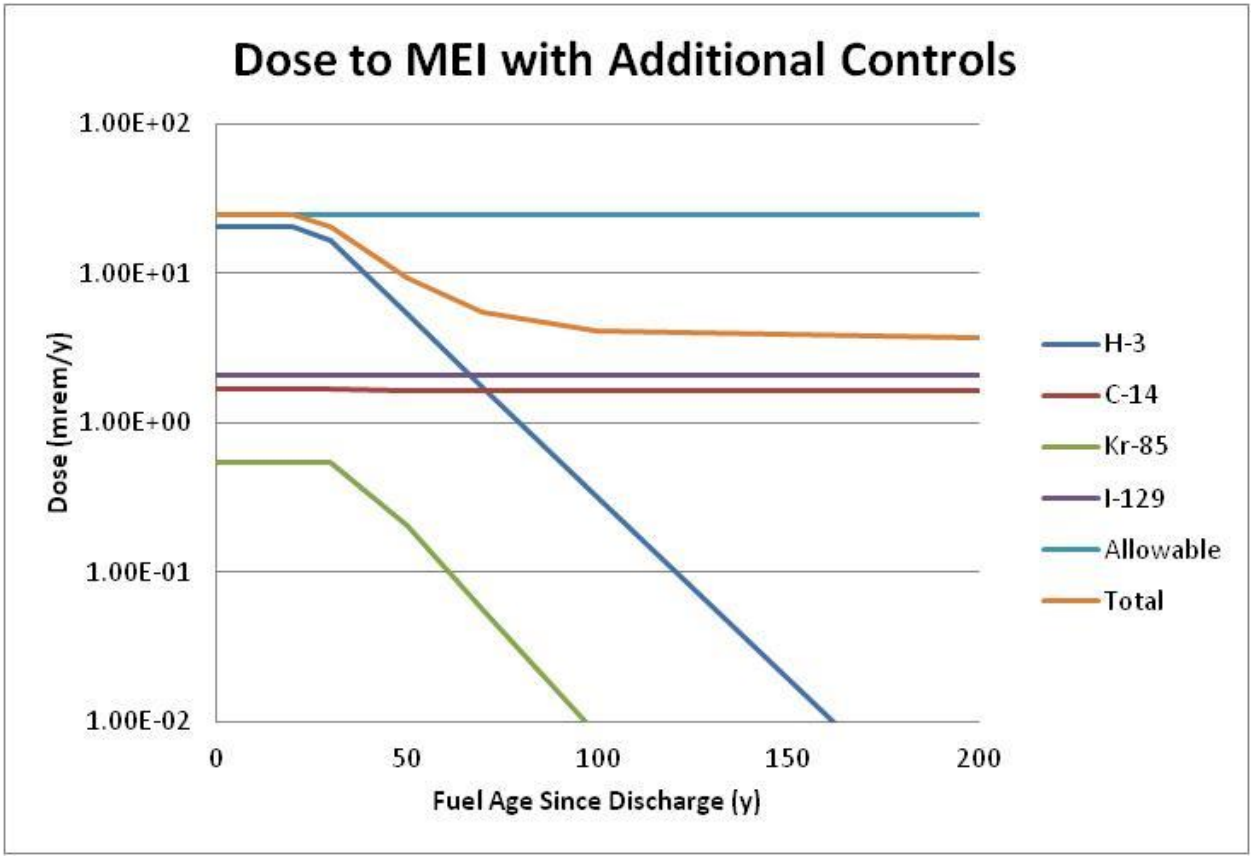


Figure A.1-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table A.1-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 20-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	Fuel cooling, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	4.30	3.85	3.25	2.45	1.40	1.00	1.00	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	9.72	8.54	7.04	5.09	2.67	1.40	1.00	1.00	1.00	1.00
^{129}I	166	166	166	166	166	166	166	166	166	166

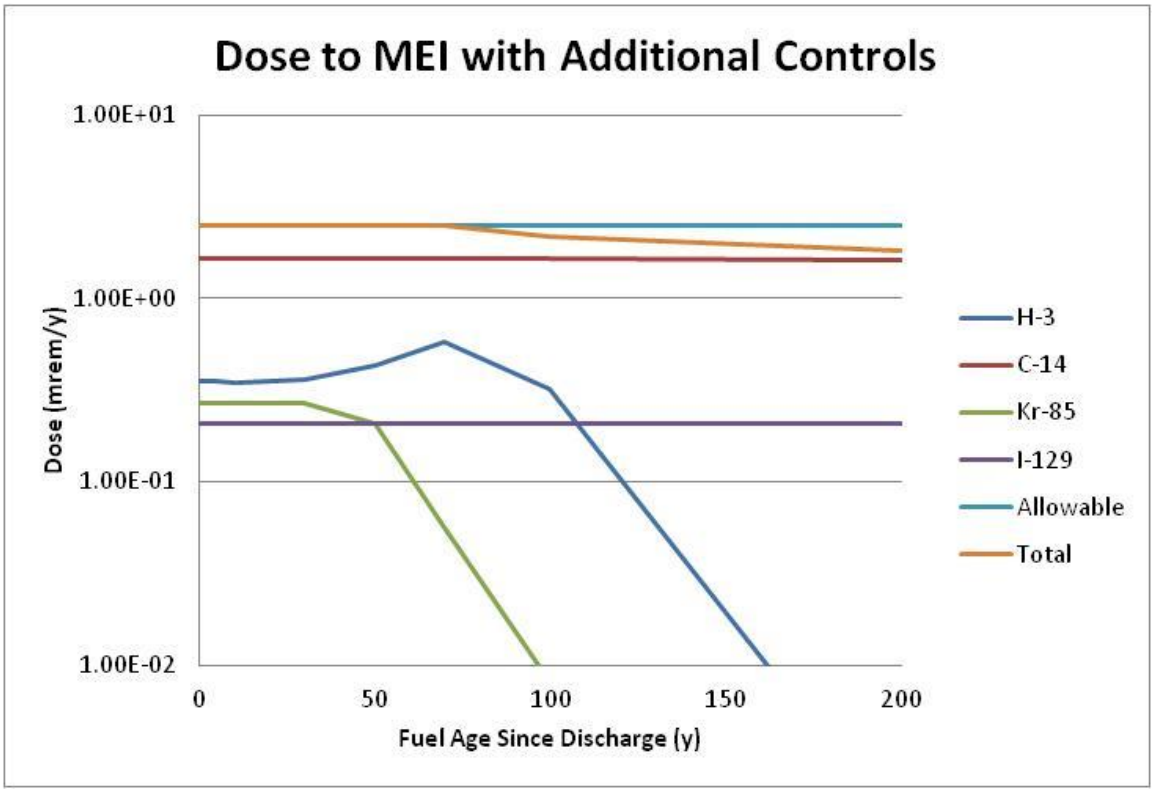


Figure A.1-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

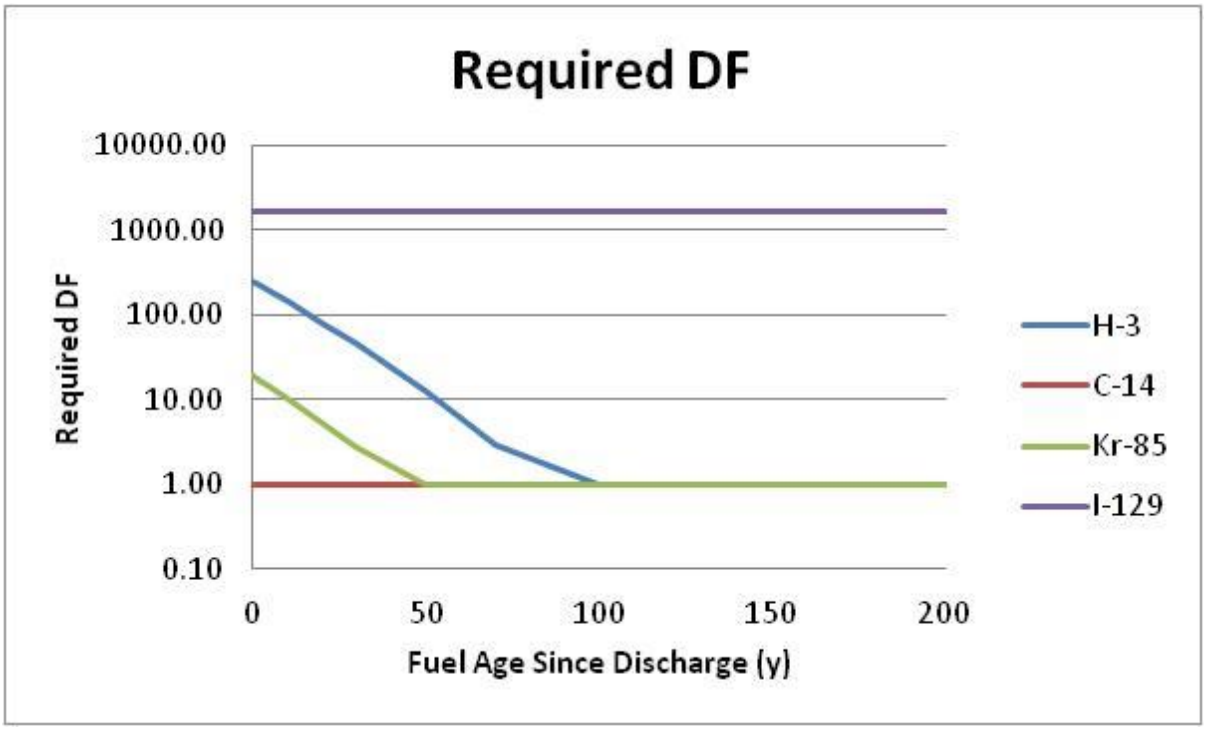


Figure A.1-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table A.1-3. Effective DFs required to achieve 2.5-mrem/y whole body dose to MEI for 20-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	Fuel cooling, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	250	225	190	145	82	46	12.5	3.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	19.4	17.1	14.1	10.2	5.34	2.80	1.00	1.00	1.00	1.00
^{129}I	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660

Table A.1-4. Dose contributions by radionuclide based on 20-GWd/tIHM, PWR UOX fuel cooled up to 200 y with effective DFs from Table A.1-3

Dose, mrem/y										
Isotope	Fuel cooling, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	0.36	0.35	0.35	0.35	0.35	0.36	0.43	0.58	0.32	0.0012
^{14}C	1.67	1.67	1.67	1.67	1.67	1.66	1.66	1.66	1.65	1.63
^{85}Kr	0.27	0.27	0.27	0.27	0.27	0.27	0.21	0.57	0.0082	1.27×10^{-5}
^{129}I	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.2	1.8

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for iodine and krypton only results in a thyroid dose of 83 mrem/y for the processing of 2-y-cooled fuel decreasing to 43.6 mrem/y at 100-y cooled (Figure A.1-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that does to the thyroid is reduced to 54 mrem/y; thus, no additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure A.1-8).

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is 6.1–5.8 mrem/y (Figure A.1-9). Iodine-129 accounts for approximately 70–75% of this dose, with ^{14}C the bulk of the remaining dose.

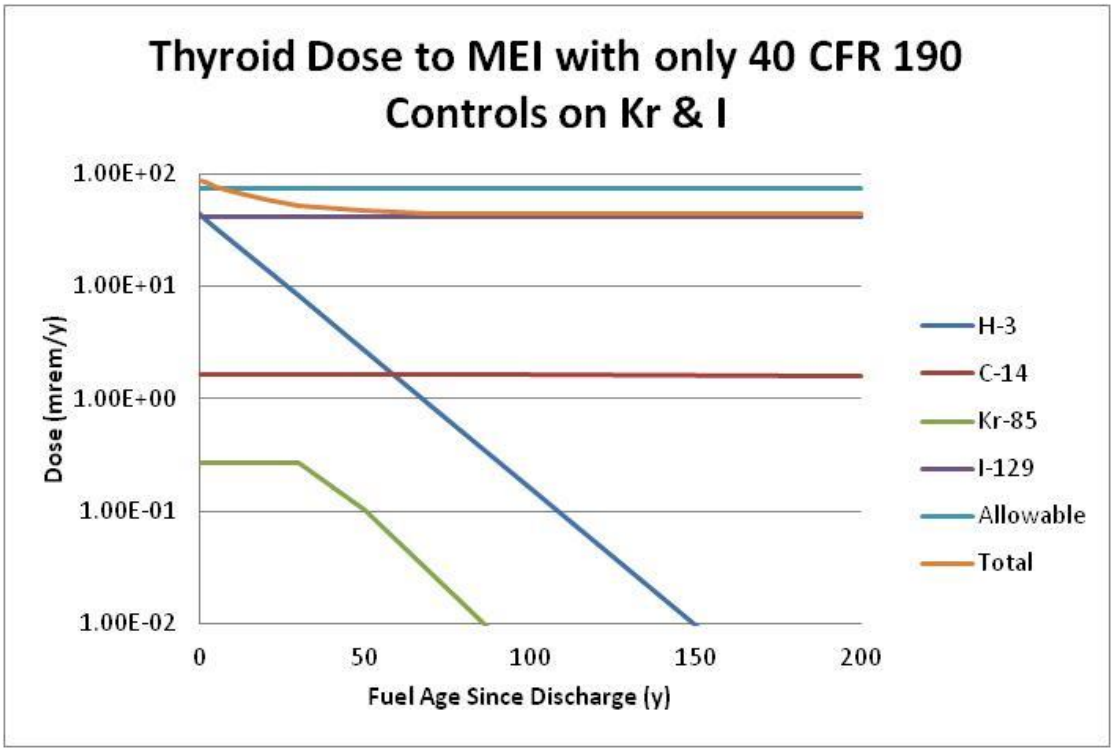


Figure A.1-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

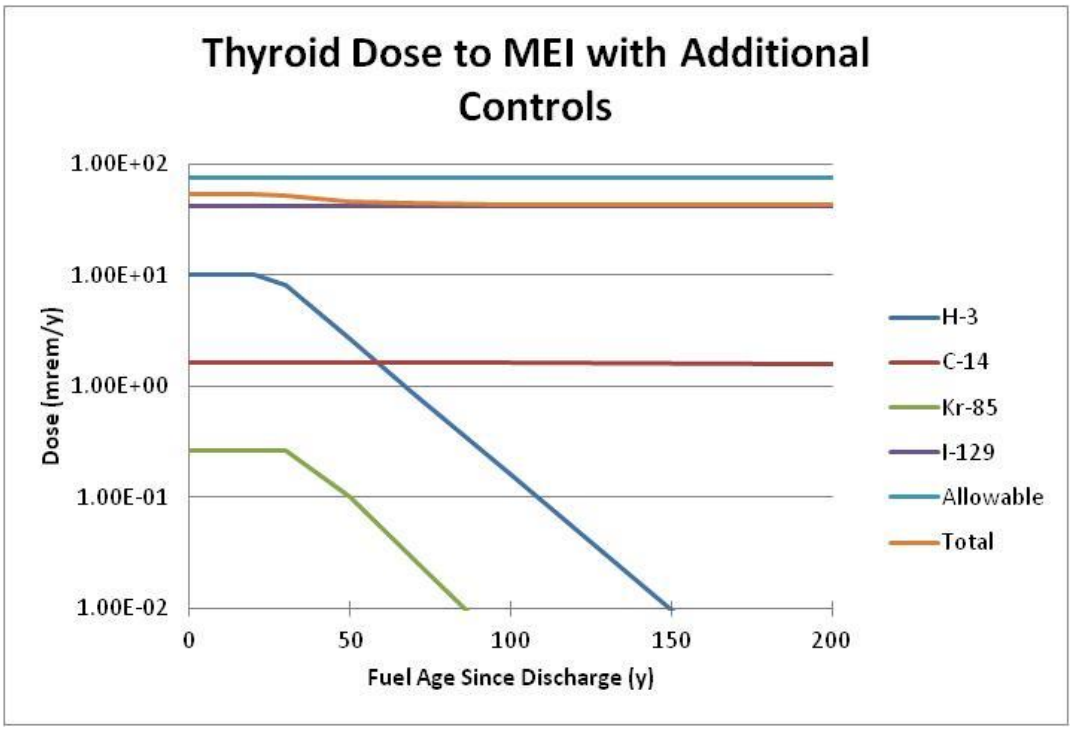


Figure A.1-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

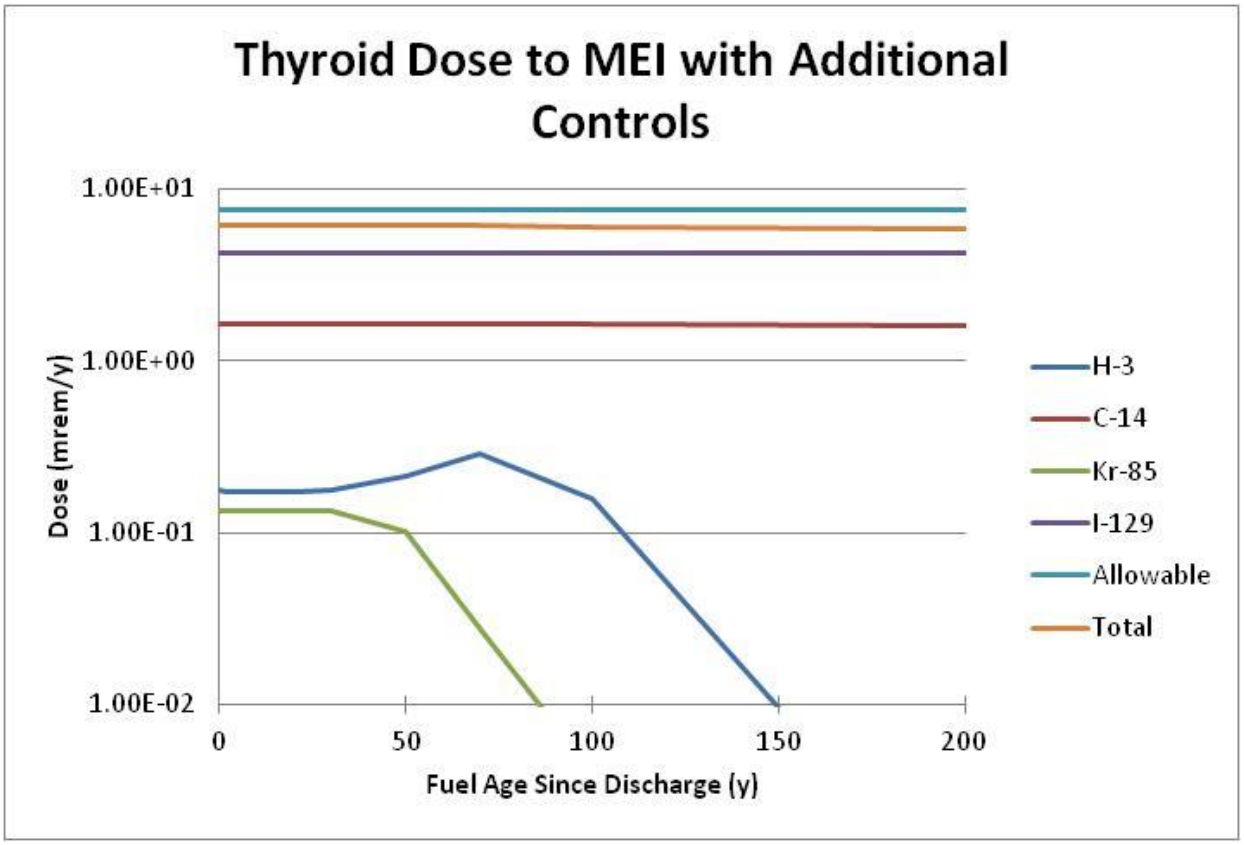


Figure A.1-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

A.2. PWR / UOX / 60 GWD/TIHM

For the same PWR/UOX fuel/reactor but at a burnup of 60 GWd/tIHM, the second-phase analysis results are as follows: For a plant size of 1000 t/y, the total dose to the MEI ranges from 1490 mrem/y at 2-y-cooled fuel to 1200 mrem/y at 100-y cooled (Figure A.2-1). Iodine is the major contributor (1190 mrem/y); at cooling times up to ~40 y ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 5.97 mrem/y, and ^{85}Kr could contribute up to ~10 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table A.2-1.

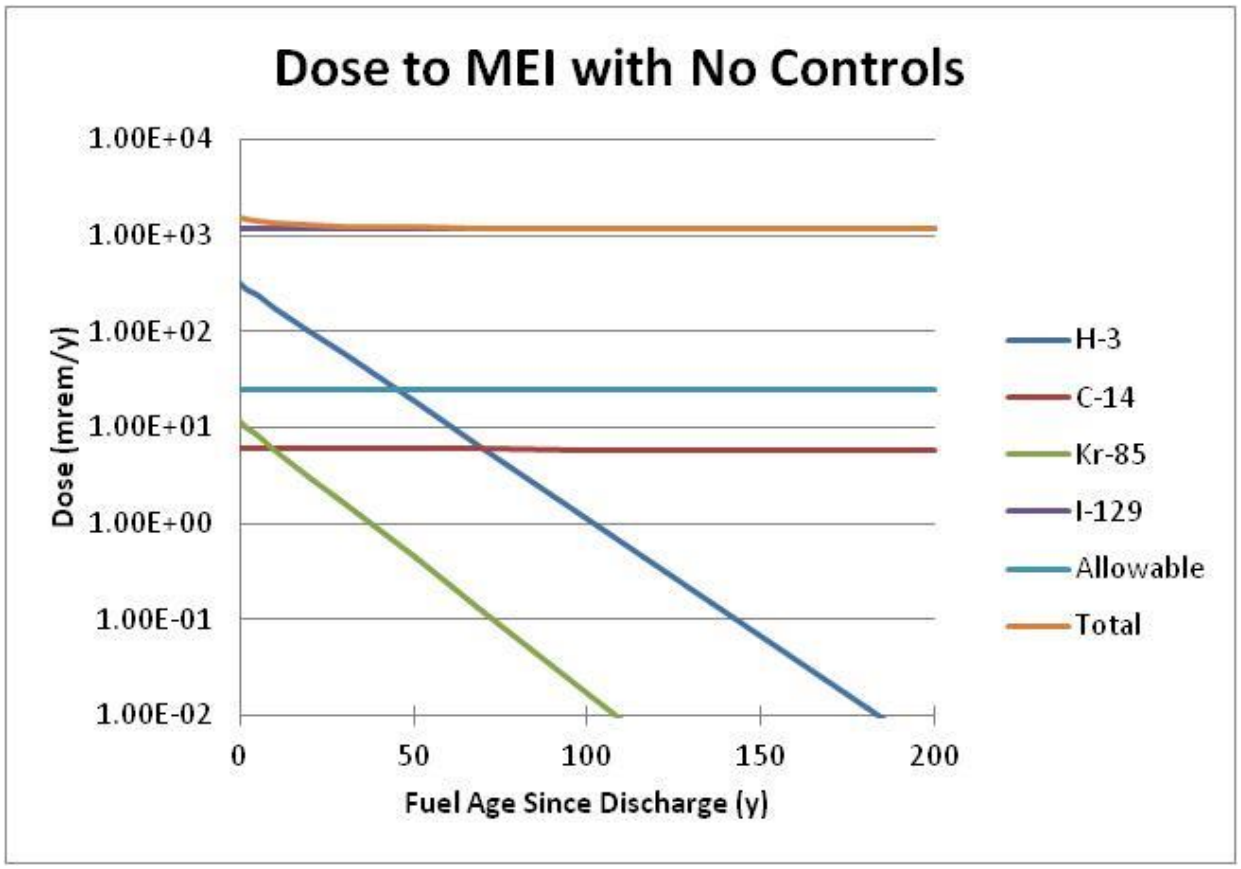


Figure A.2-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

If the ^{129}I and ^{85}Kr release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 293 mrem/y at 2-y cooling and 13.4 mrem/y for 100-y-cooled fuel (Figure A.2-2). The ^{129}I contribution is reduced to 6.29 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 70 y. Carbon-14 again contributes 5.99 mrem/y, but ^{85}Kr contributions are reduced to less than 1.61 mrem/y. It is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit and that from Figure A.2-3 for a 2.5-mrem/y apportioned limit additional controls (DF) for ^{129}I and ^{14}C would also be required.

Table A.2-1 Dose contributions by radionuclide based on 60-GWd/tIHM, PWR UOX fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	312	279	236	178	101	57.8	18.8	6.10	1.13	0.0041
^{14}C	5.99	5.99	5.98	5.98	5.97	5.97	5.95	5.94	5.92	5.84
^{85}Kr	11.3	9.94	8.19	5.92	3.1	1.63	0.45	0.12	0.018	2.74×10^{-5}
^{129}I	1190	1190	1190	1190	1190	1190	1190	1190	1190	1190
Allowable	25	25	25	25	25	25	25	25	25	25
Total	1520	1490	1440	1380	1300	1260	1220	1200	1200	1200

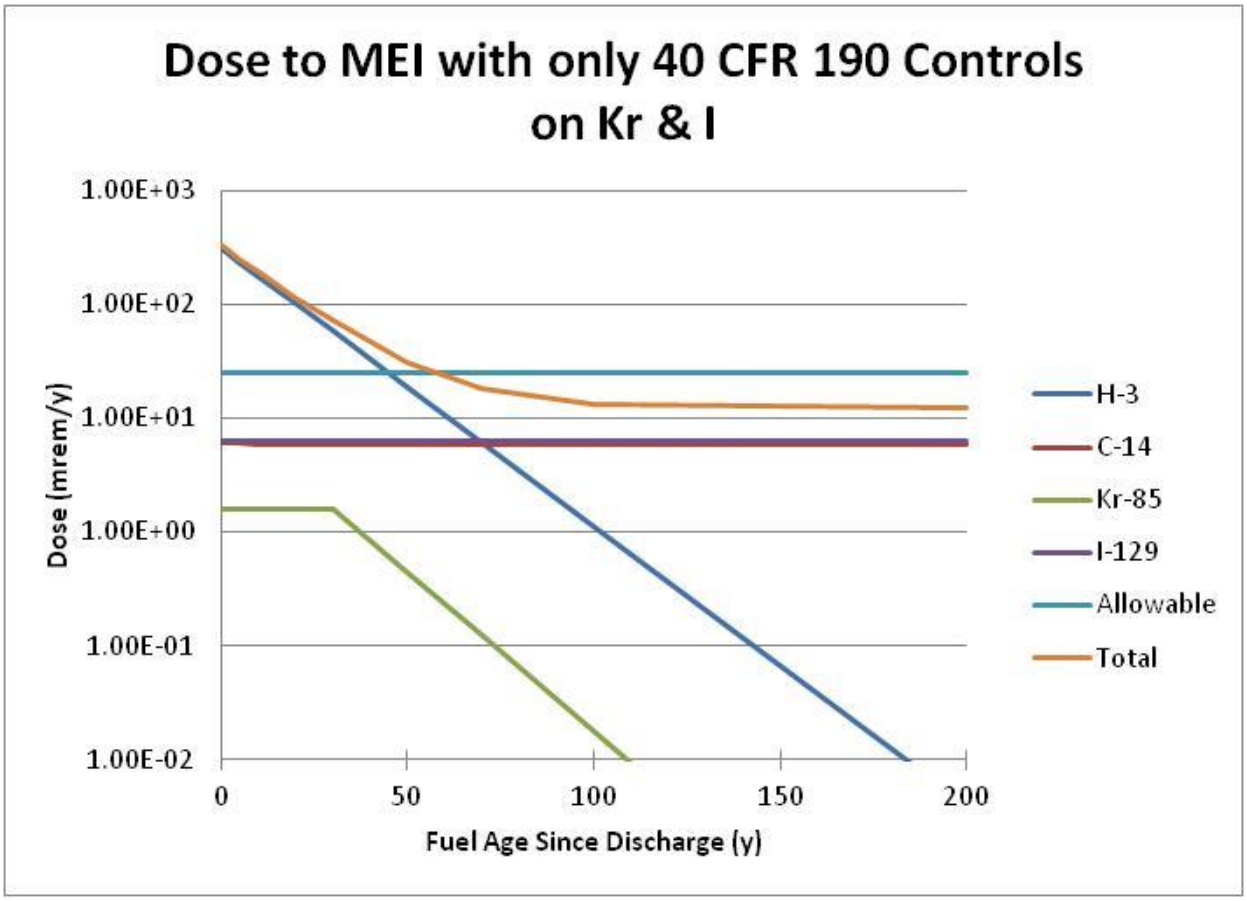


Figure A.2-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

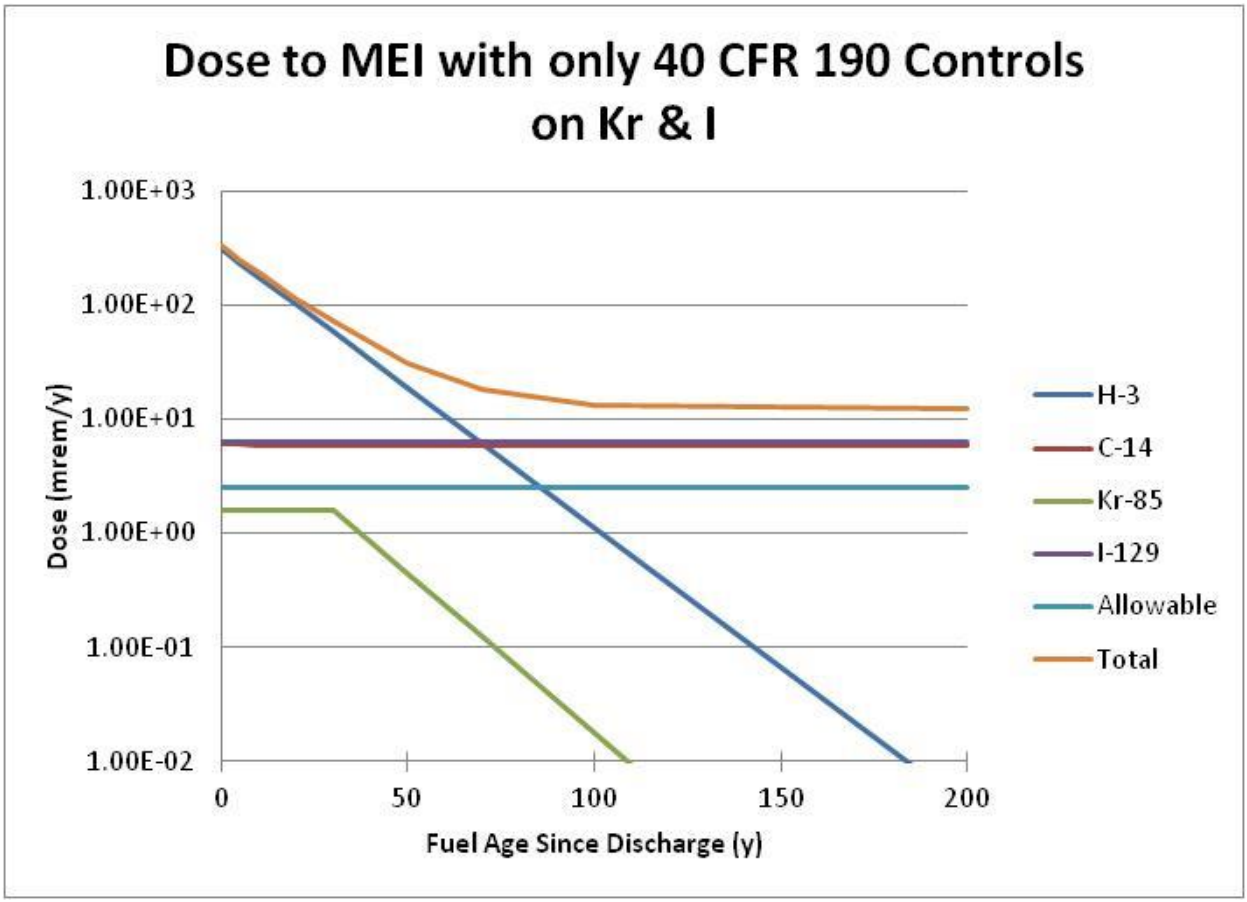


Figure A.2-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for tritium. Tritium DF requirements ranged from 25 at 2-y cooling to 1.52 at 50-y cooling (Figure A.2-4 and Table A.2-2). Beyond ~60-y fuel cooling, no additional tritium capture would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and tritium contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to iodine at all times, raising the total DF to ~1900. A ^{14}C DF of 10 for times up to 200 y was arbitrarily applied to reduce its contribution to the total dose to ~0.6 mrem/y. Additional ^{85}Kr DF requirements were also imposed up to 30-y cooling due to the relatively large contribution of ^{85}Kr (1.6 mrem/y out of 2.5 mrem/y). Tritium DFs range from 600 for 2-y-cooled fuel to ~5 at 70-y-cooled fuel. Beyond 100 y no tritium recover would be required. Figure A.2-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure A.2-6 depicts the DF requirements for each isotope as a function of cooling time. Table A.2-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table A.2-4 shows the resulting dose contributions.

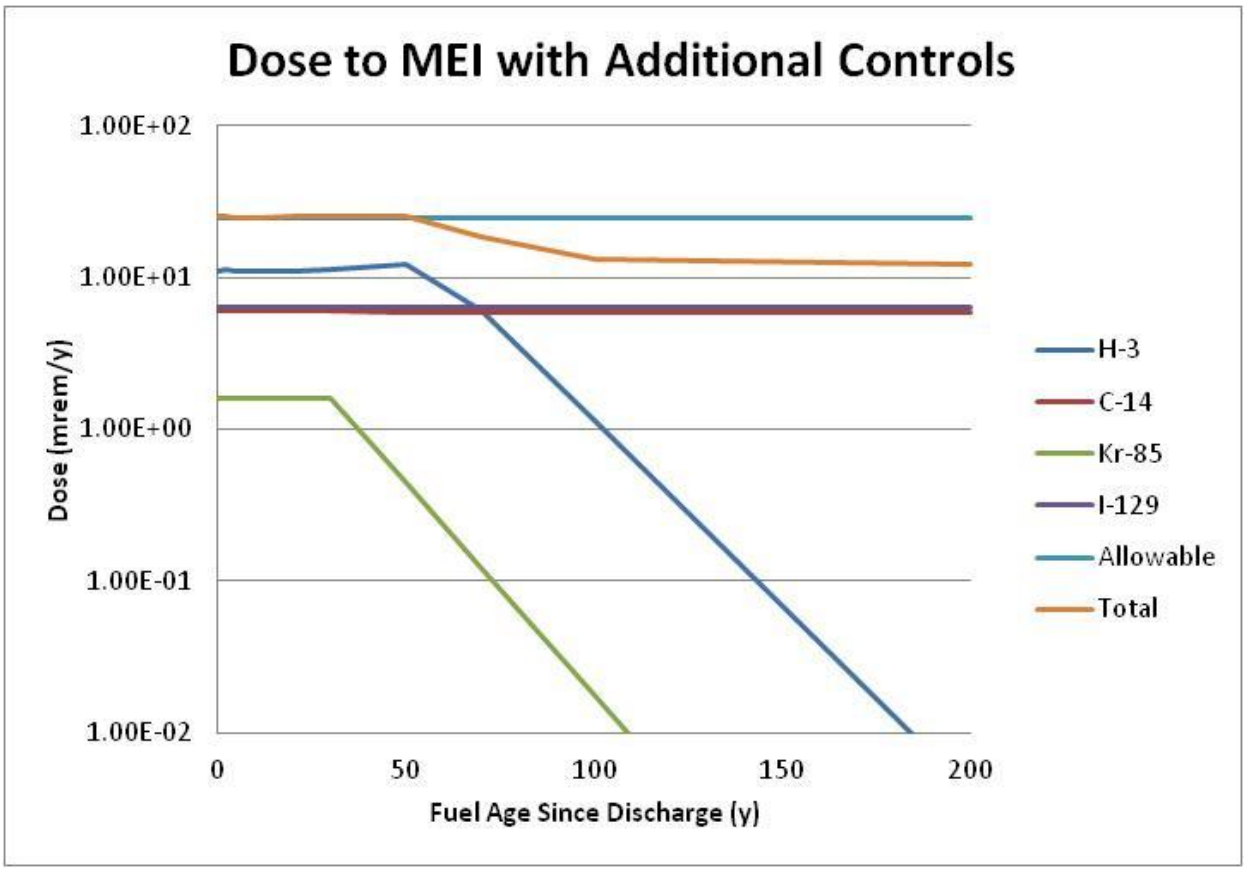


Figure A.2-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table A.2-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 60-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	28.0	25.0	21.2	16.0	9.10	5.18	1.52	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	7.01	6.16	5.07	3.67	1.92	1.01	1.00	1.00	1.00	1.00
^{129}I	189	189	189	189	189	189	189	189	189	189

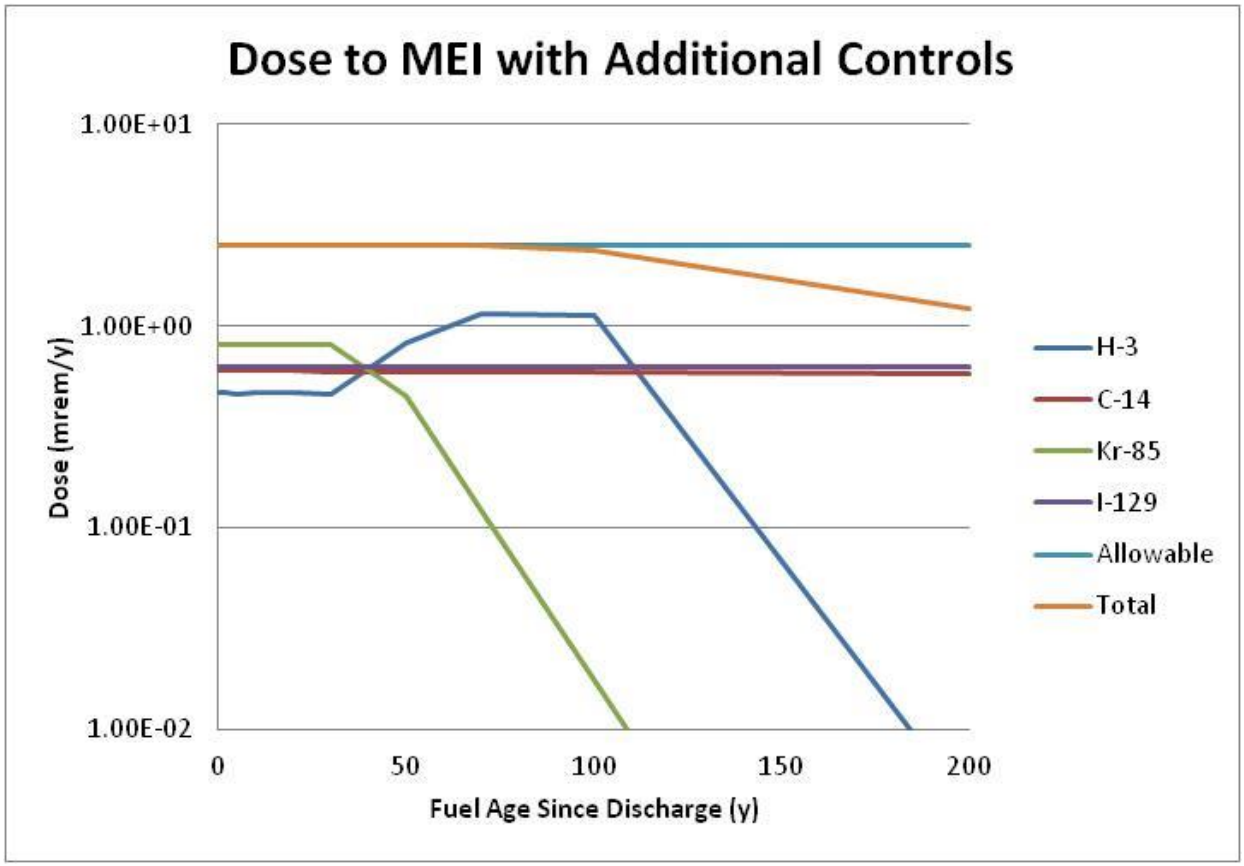


Figure A.2-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table A.2-3. Effective DFs required to achieve 2.5-mrem/y whole body dose to MEI for 60-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	670	600	510	380	218	125	22.7	5.30	1.00	1.00
^{14}C	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
^{85}Kr	14.0	12.3	10.1	7.34	3.85	2.02	1.00	1.00	1.00	1.00
^{129}I	1893	1893	1893	1893	1893	1893	1893	1893	1893	1893

Table A.2-4. Dose contributions by radionuclide based on 60-GWd/tIHM PWR UOX fuel cooled up to 200 y using effective DFs from Table A.2-3

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	0.466	0.465	0.462	0.468	0.465	0.462	0.827	1.15	1.13	0.0041
^{14}C	0.599	0.599	0.598	0.598	0.597	0.597	0.595	0.594	0.592	0.584
^{85}Kr	0.807	0.807	0.807	0.807	0.807	0.807	0.446	0.123	0.076	2.74×10^{-5}
^{129}I	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.37	1.22

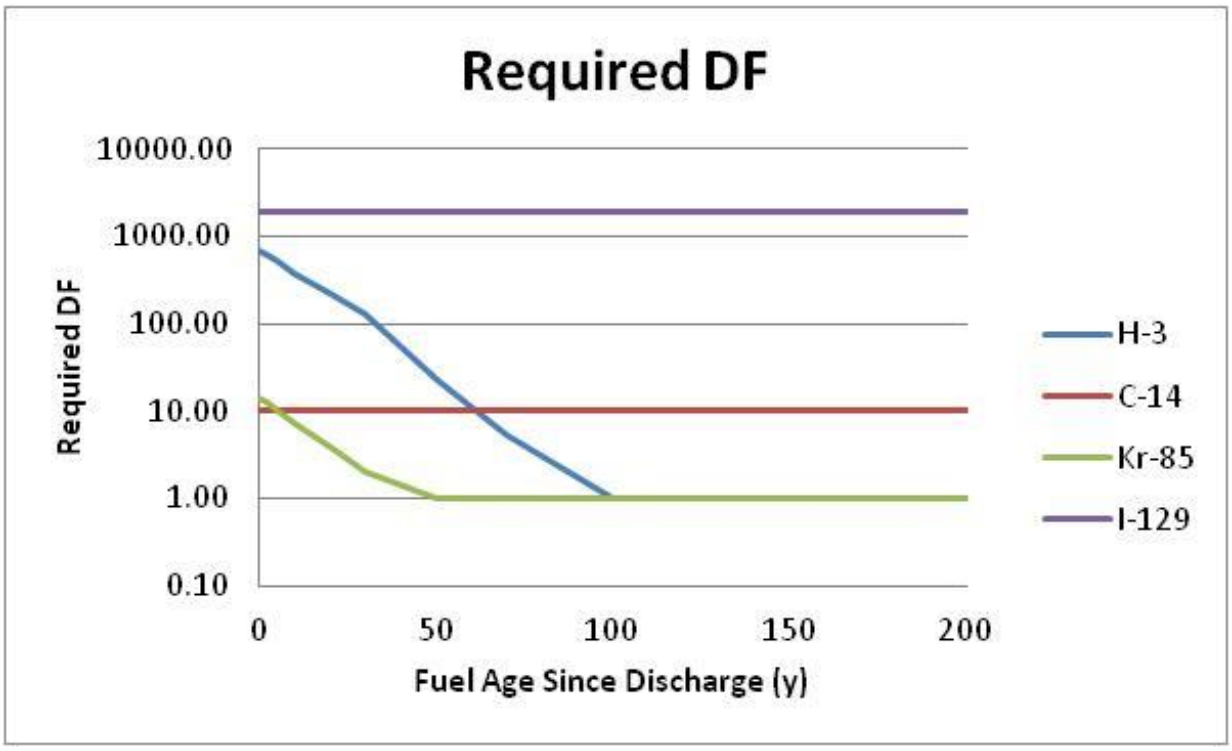


Figure A.2-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for iodine and krypton only results in a thyroid dose of 270 mrem/y for the processing of 2-y-cooled fuel decreasing to 132 mrem/y at 100-y cooled (Figure A.2-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

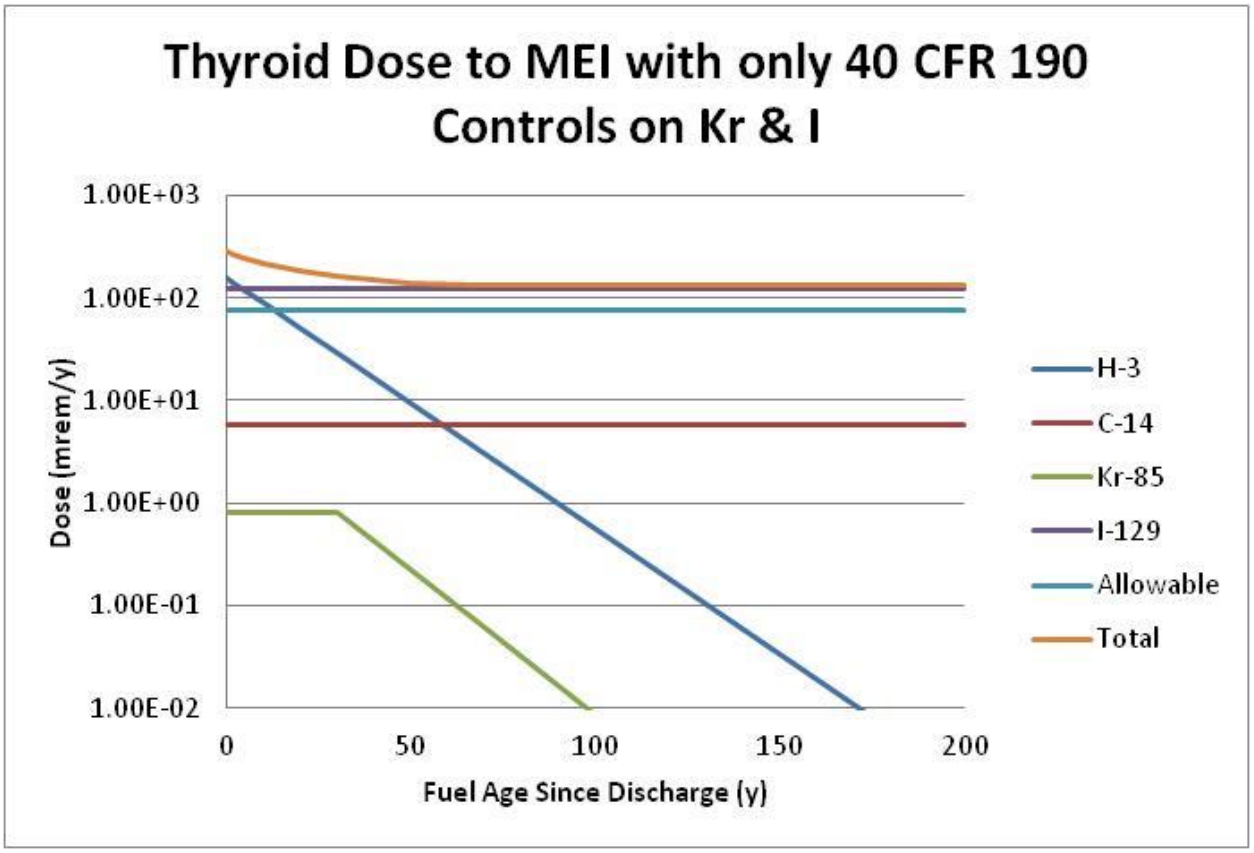


Figure A.2-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to ~138 mrem/y; thus, there is a clear requirement that some additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure A.2-8). Imposing an additional DF factor of 2 on ^{129}I reduces the thyroid dose to less than 75 mrem/y.

The total effective DF is shown in Table A.2-5, and the associated thyroid dose in Table A.2-6.

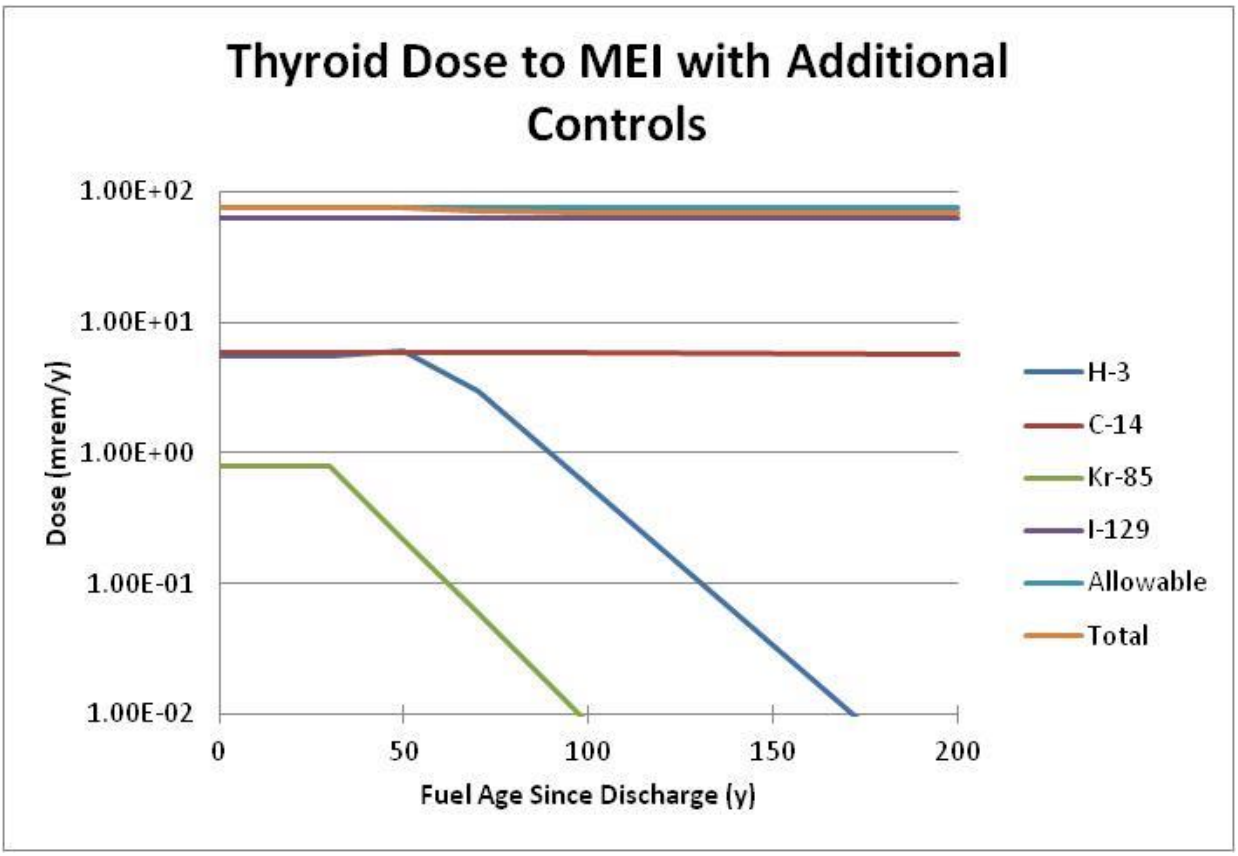


Figure A.2-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

Table A.2-5. Effective DFs required to achieve 75-mrem/y thyroid dose to MEI for 60-GWd/tIHM PWR UOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	28.0	25.0	21.2	16.0	9.10	5.18	1.52	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	7.01	6.16	5.07	3.67	1.92	1.01	1.00	1.00	1.00	1.00
^{129}I	378	378	378	378	378	378	378	378	378	378

Table A.2-6. Thyroid dose contributions by radionuclide based on 60-GWd/tIHM PWR UOX fuel cooled up to 200 y using effective DFs from Table A.2-5

Dose, mrem/y										
Isotope	Fuel cooling, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	5.50	5.51	5.49	5.49	5.50	5.51	6.10	3.01	5.58	0.0020
^{14}C	5.89	5.89	5.88	5.88	5.87	5.87	5.85	5.84	5.82	5.75
^{85}Kr	0.795	0.795	0.795	0.795	0.795	0.795	0.220	0.060	0.0087	1.35×10^{-5}
^{129}I	62.8	62.8	62.8	62.8	62.8	62.8	62.8	62.8	62.8	62.8
Allowable	75	75	75	75	75	75	75	75	75	75
Total	75	75	75	75	75	75	75	71.7	69.2	68.5

If the same apportionment of 10% is made for the volatile radionuclides as that for the whole body dose, and if the same additional controls are applied, the resulting thyroid dose is 13.8–13.1 mrem(Figure A.2-9). Iodine-129 accounts for approximately 91% of this dose. To reduce the thyroid dose to the 7.5-mrem/y level, an additional iodine DF of 2 is required, resulting in a total ^{129}I DF of ~3800.

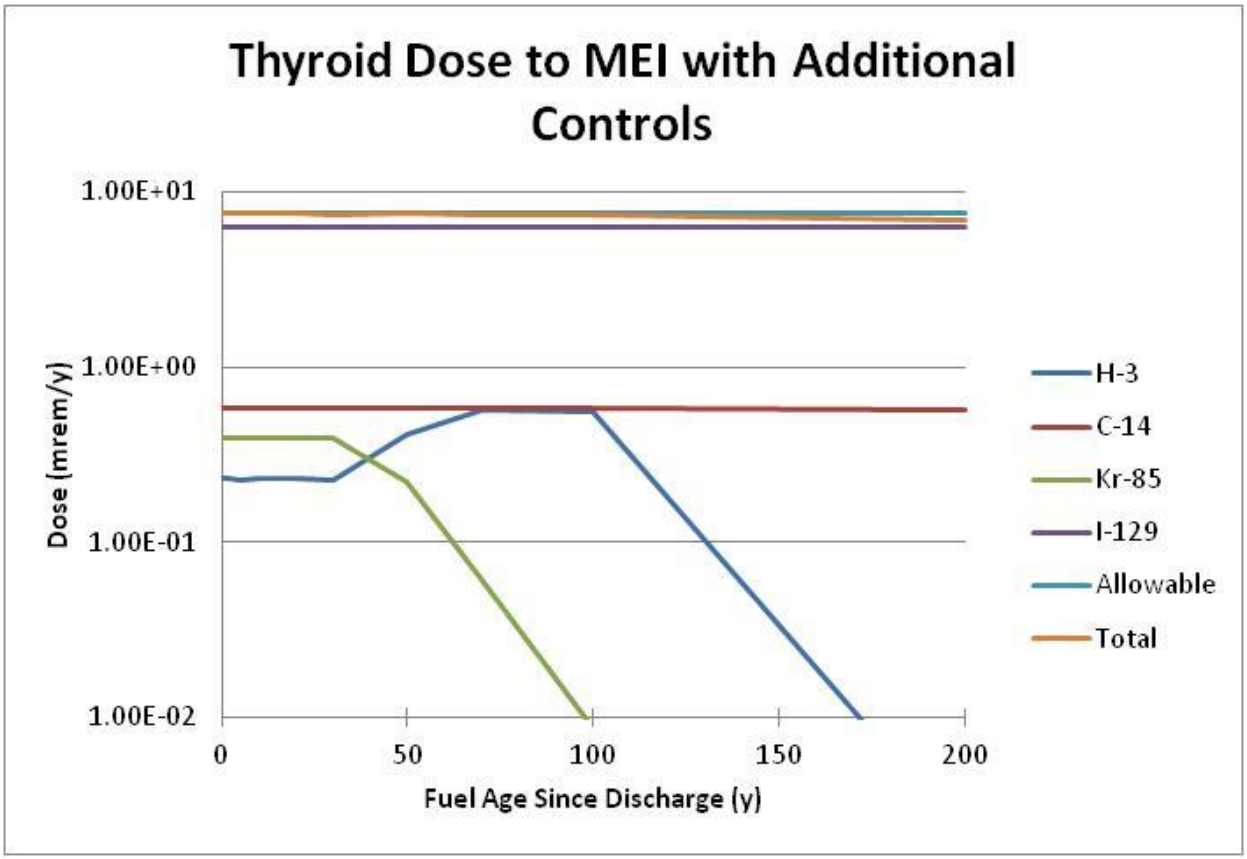


Figure A.2-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR UOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

APPENDIX B. MOX FUEL

B.1. PWR / MOX FUEL

The total dose to the MEI was determined from CAP-88 calculations for reference location with the same approach as used for PWR UOX fuel. This dose assumed no emission controls for the four radionuclides of interest. In the case of PWR MOX fuel, the maximum plant size for 30-GWd/tIHM fuel cooled 5 y is 25.3 t/y; if the fuel is cooled for 100 y, the plant size is increased slightly to 29.0 t/y (Figure B.1-1). At burnups of 60 GWd/tIHM, the maximum sizes are 13.3 t/y for 5-y-cooled fuel and 15.5 t/y for 100-y-cooled fuel. If the allowable contribution of the volatile components to the total dose is limited to 2.5 mrem/y (i.e., 10% of the total allowable dose), the plant sizes drop to 2.5 t/y and 2.9 t/y, respectively, for 30-GWd/tIHM fuel. For 5-y-cooled fuel, ^{129}I contributes 87.1% of the total dose and ^{3}H 12.4% of the total dose. At 100-y cooling, ^{129}I contributes 99.7% of the total dose.

The second phase of the evaluation examined the impact of time since discharge in three steps for each fuel type and fuel burnup.

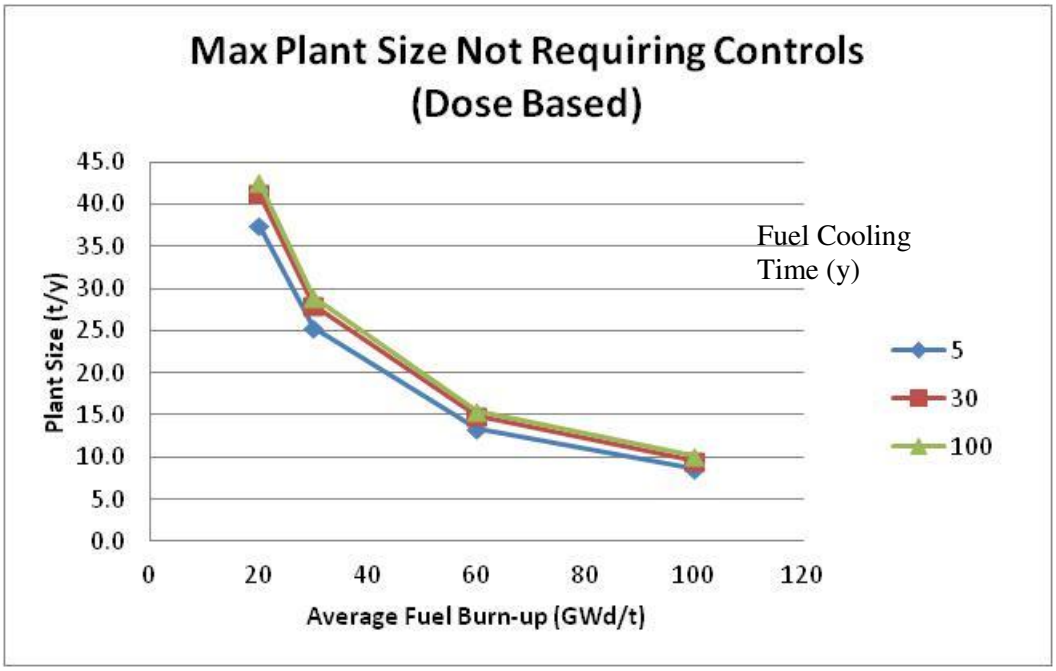


Figure B.1-1. Maximum plant size for processing PWR MOX fuel that would not require controls to limit exposure to the MEI to below 25 mrem/y/yr.

B.2. PWR / MOX – 20 GWD/TIHM

For the case of the 20 GWd/tIHM MOX fuel and a plant size of 1000 t/y, the total dose to the MEI ranges from 679 mrem/y at 2-y-cooled fuel to 587 mrem/y at 100-y cooled (Figure B.2-1). Iodine is the major contributor (586 mrem/y); at cooling times up to ~25 y cooling, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 1.18 mrem/y and ^{85}Kr could contribute up to 2.23 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table B.2-1.

If the ^{129}I and ^{85}Kr krypton release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 94.1 mrem/y at 2-y cooling and 3.64 mrem/y for 100-y-cooled fuel (Figure B.2-2). The ^{129}I contribution is reduced to 2.1 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 60 y. The ^{14}C again contributes 1.18 mrem/y, but ^{85}Kr contributions are reduced to less than ~0.54 mrem/y. It is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit and that from Figure B.2-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{129}I would also be required.

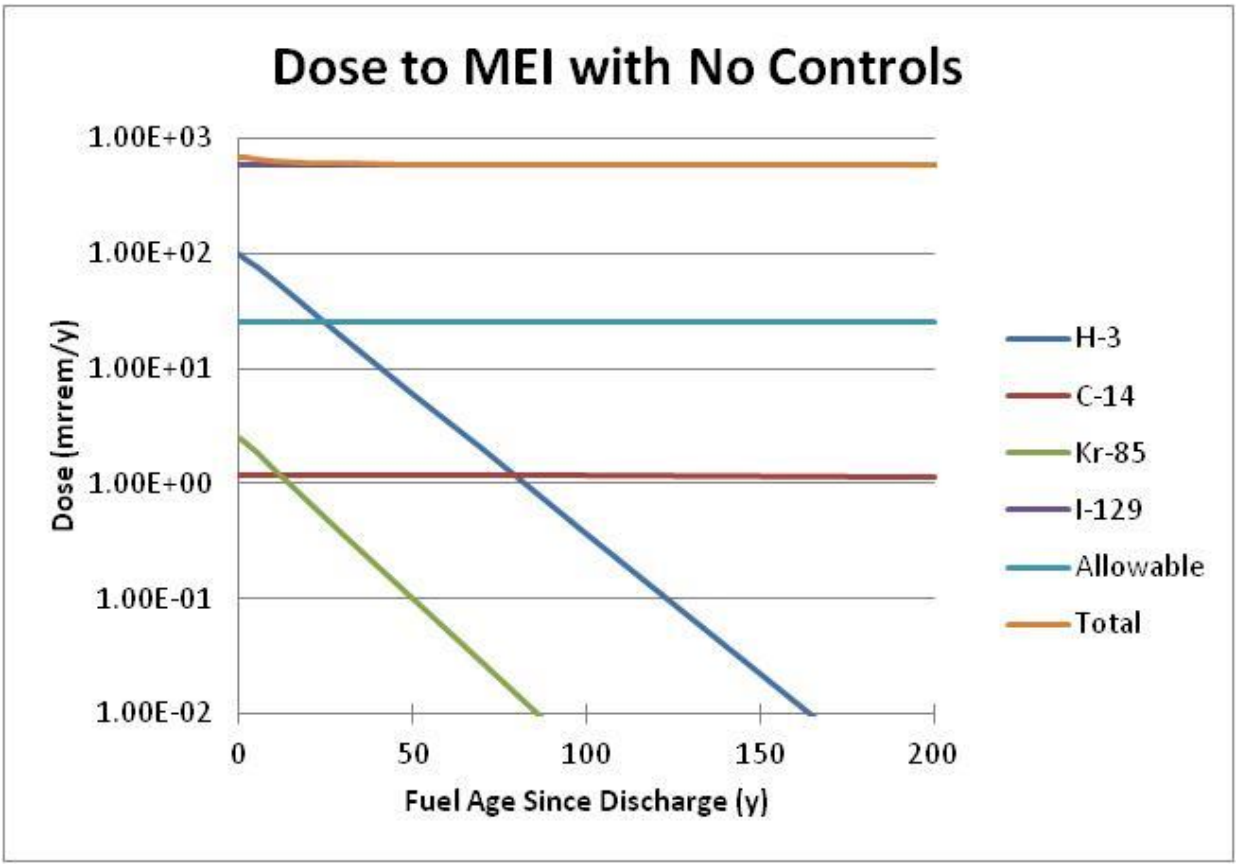


Figure B.2-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table B.2-1. Dose contributions by radionuclide based on 20-GWd/tIHM PWR MOX fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	101	90.2	76.2	57.6	32.8	18.7	6.08	1.97	0.366	0.0013
^{14}C	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.17	1.17	1.15
^{85}Kr	2.54	2.21	1.84	1.33	0.698	0.366	0.100	0.0275	0.0040	6.17×10^{-6}
^{129}I	586	586	586	586	586	586	586	586	586	586
Allowable	25	25	25	25	25	25	25	25	25	25
Total	690	679	665	646	620	606	593	589	587	587

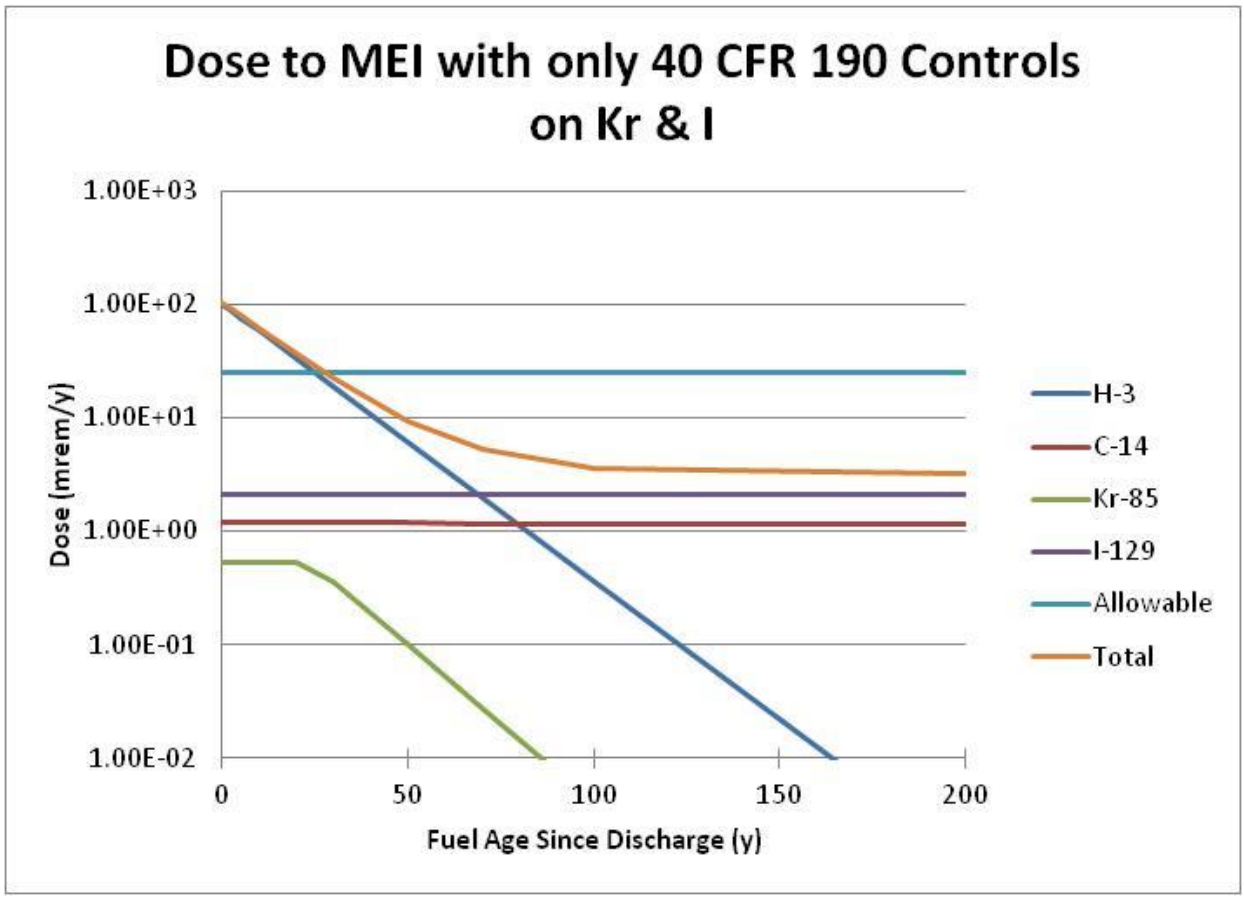


Figure B.2-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel with ^{129}I and ^{85}Kr controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

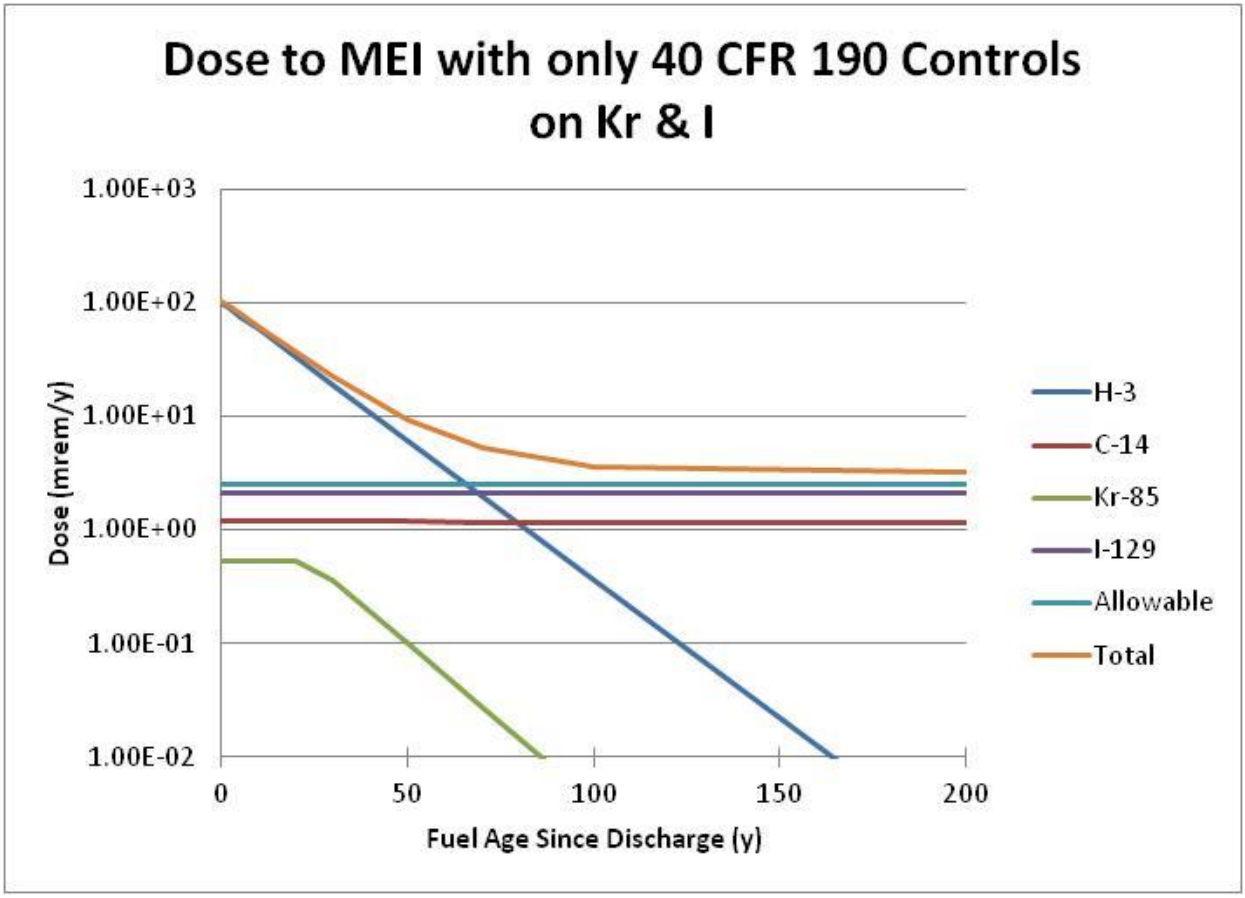


Figure B.2-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel with ^{129}I and ^{85}Kr controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 4.25 at 2-y cooling to 1.55 at 20-y cooling (Figure B.2-4 and Table B.2-2). Beyond 30-y fuel cooling, no additional ^{3}H capture is would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, as noted before, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed upon ^{129}I for all times, since these individually contribute nearly 2.1 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 20 y. An additional recovery factor of 10 was applied to ^{129}I at all times, raising the total DF to ~2800. Tritium DF values range from 158 for 2-y-cooled fuel to 1.81 at 70-y cooling. Figure B.2-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure B.2-6 depicts the DF requirements for each isotope as a function of cooling time. Table B.2-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table B.2-4 shows the resulting dose contributions.

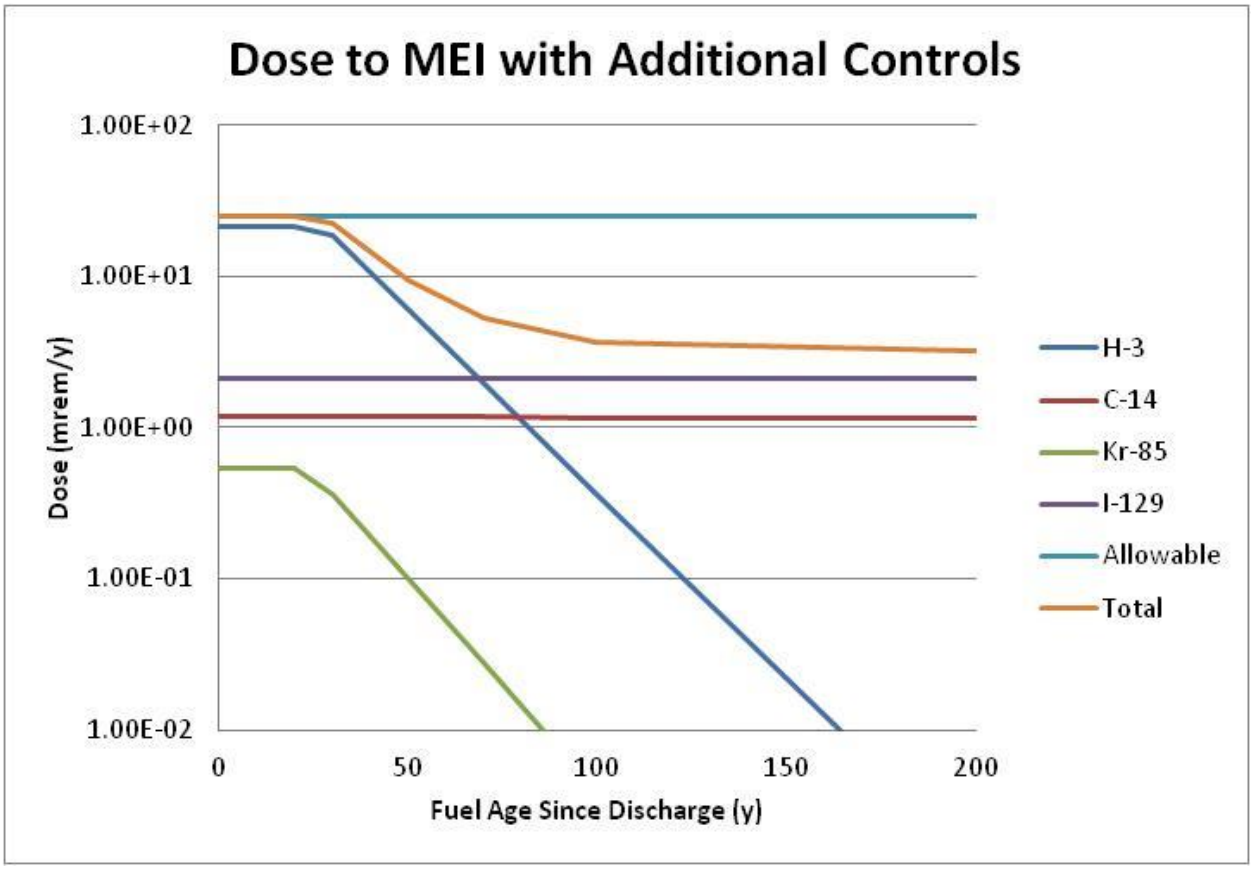


Figure B.2-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table B.2-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 20-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	4.76	4.25	3.60	2.72	1.55	1.00	1.00	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	4.73	4.15	3.42	2.48	1.30	1.00	1.00	1.00	1.00	1.00
^{129}I	279	279	279	279	279	279	279	279	279	279

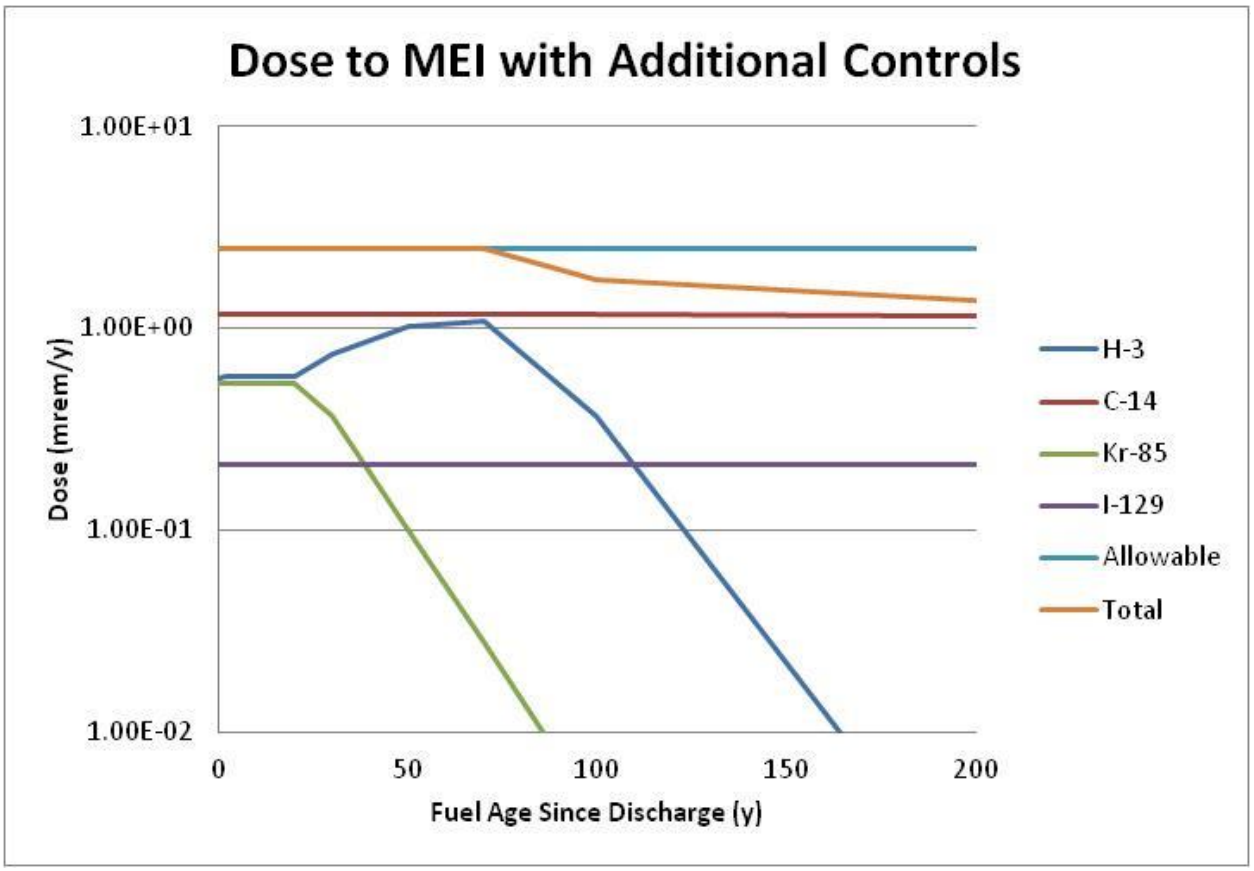


Figure B.2-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table B.2-3. Effective DFs required to achieve 2.5-mrem/y dose to MEI for 20-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	Fuel cooling, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	177	158	133	100	57.0	25.0	6.00	1.81	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	4.73	4.15	3.42	2.48	1.30	1.00	1.00	1.00	1.00	1.00
^{129}I	2791	2791	2791	2791	2791	2791	2791	2791	2791	2791

Table B.2-4. Dose contributions by radionuclide based on 30-GWd/tIHM PWR MOX fuel cooled up to 200 y using effective DF from Table B.2-3

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	0.570	0.571	0.573	0.576	0.576	0.748	1.01	1.09	0.366	0.0013
^{14}C	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.17	1.17	1.15
^{85}Kr	0.538	0.538	0.538	0.538	0.538	0.366	0.100	0.0275	0.0039	6.17×10^{-6}
^{129}I	0.210	0.210	0.210	0.210	0.210	0.210	0.210	0.210	0.210	0.210
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.75	1.37

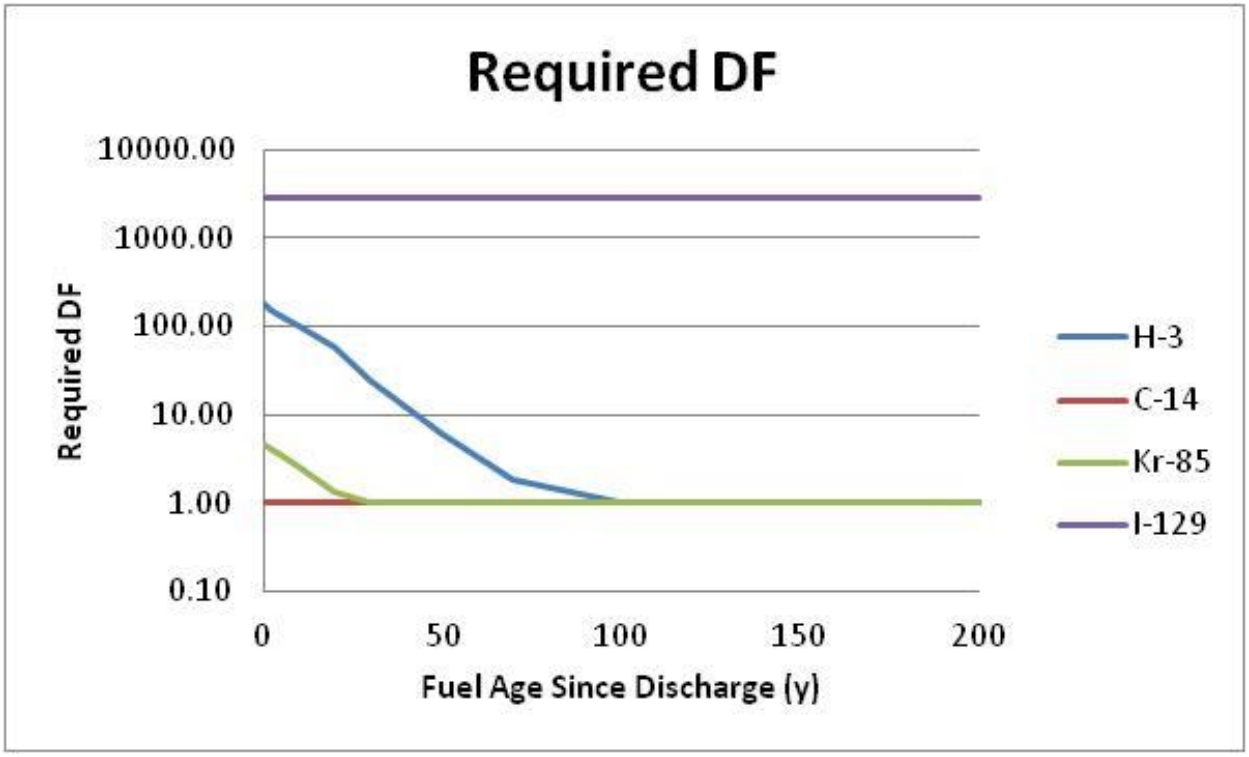


Figure B.2-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for ^{129}I and ^{85}Kr only results in a thyroid dose of 88 mrem/y for the processing of 2-y-cooled fuel decreasing to 43.2 mrem/y at 100-y cooled (Figure B.2-7). The two primary contributors to the dose are ^{129}I and ^{3}H tritium in the case of short cooling times.

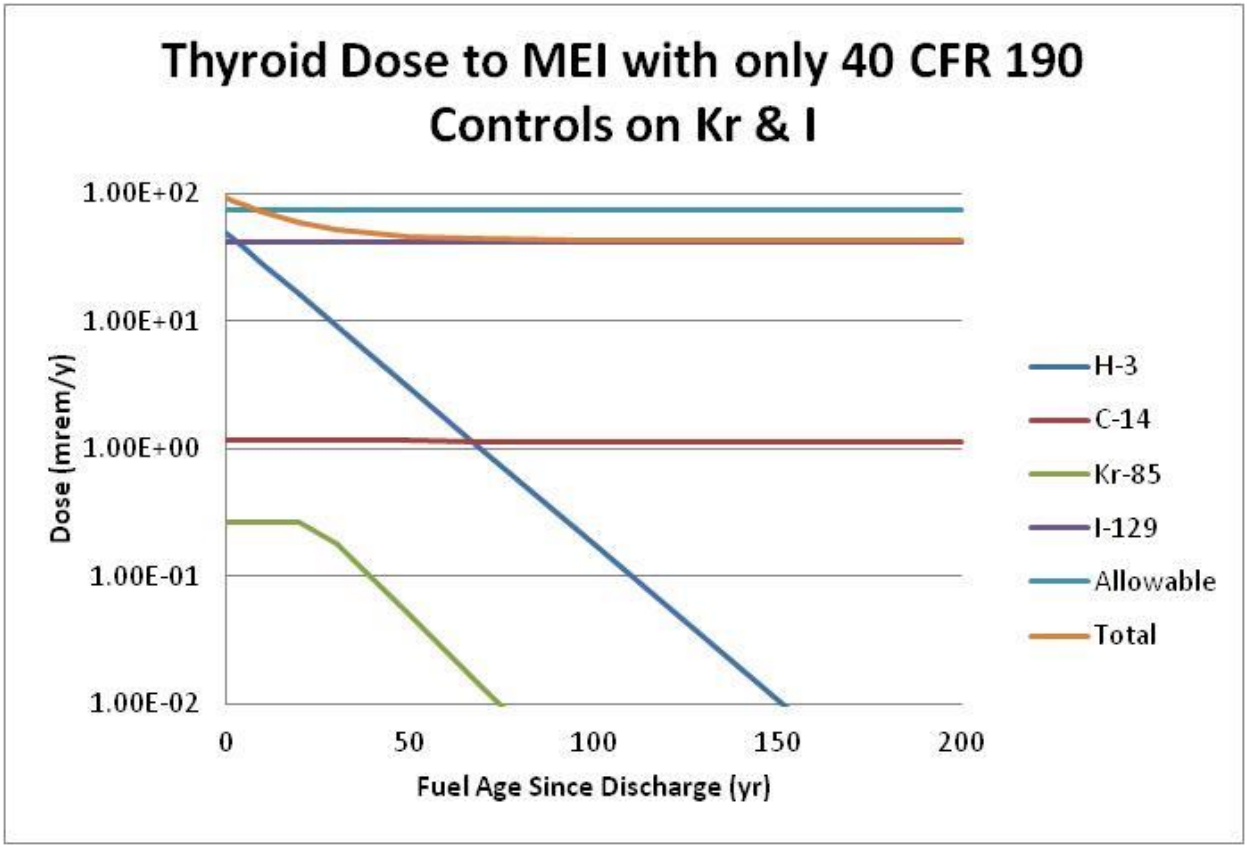


Figure B.2-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to <54 mrem; thus, no additional DF requirements would be needed beyond those to meet the 25-mrem whole body dose limit (Figure B.2-8).

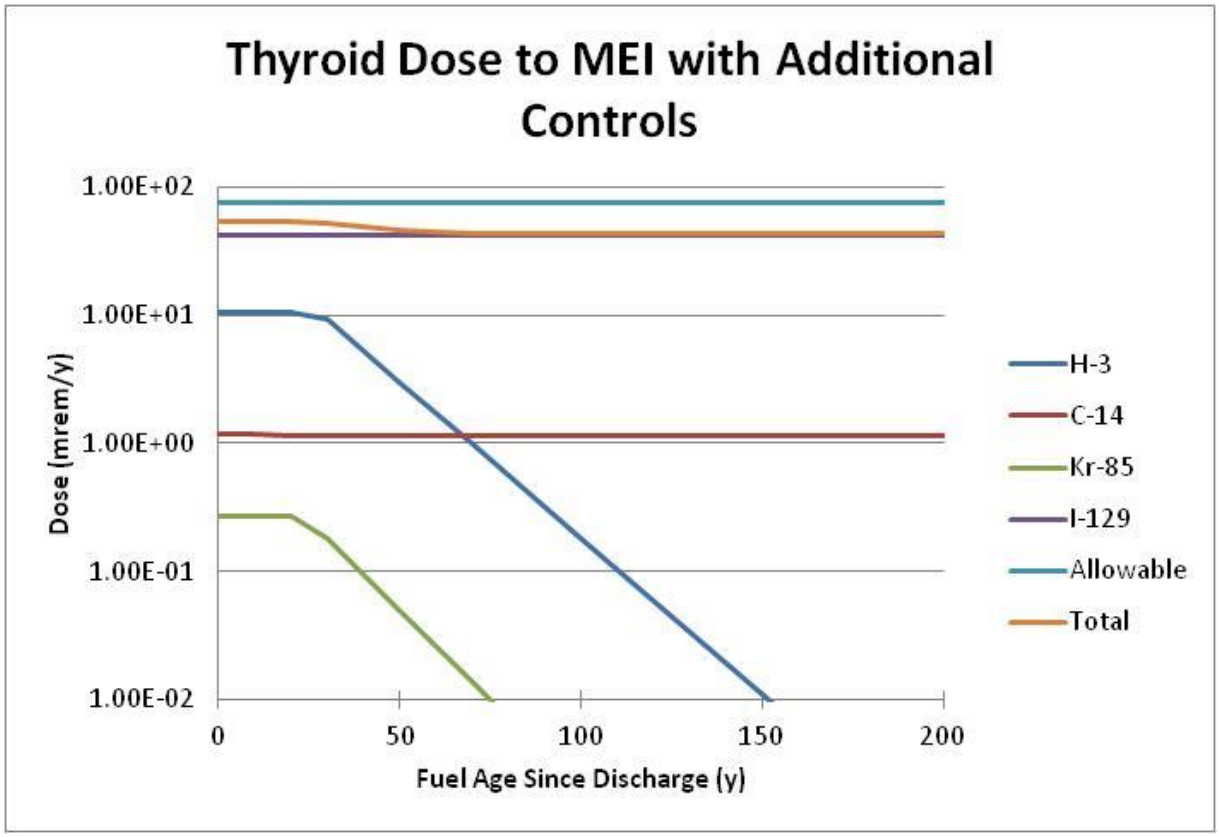


Figure B.2-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as that for the whole body dose, and if the same additional controls are applied, then the resulting thyroid dose is 5.9–5.5 mrem/y (Figure B.2-9). Iodine-129 accounts for approximately 70–75% of this dose, with ^{14}C the bulk of the remaining dose.

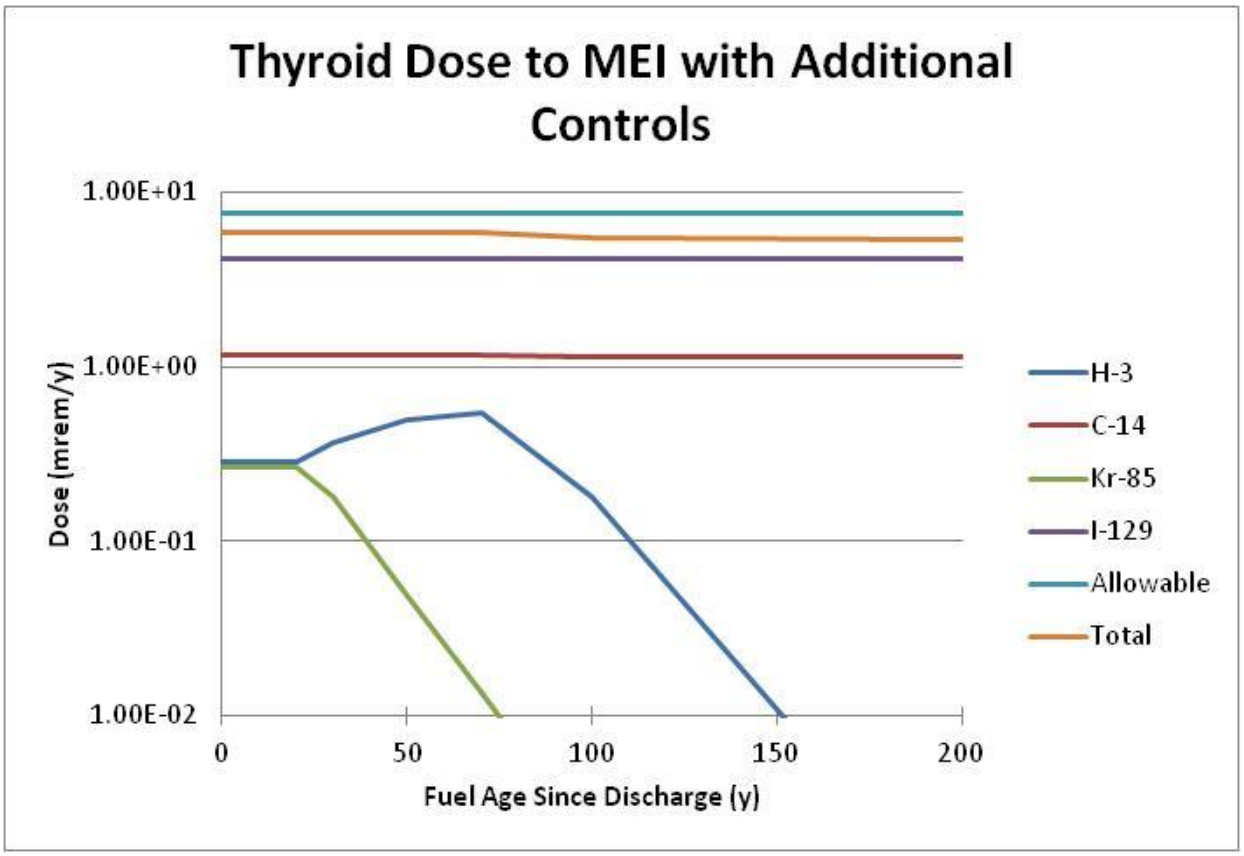


Figure B.2-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

B.3. PWR / MOX – 30 GWD/TIHM

The second phase of the evaluation examined the impact of time since discharge in three steps for each fuel type and fuel burnup. For the case of the 30-GWd/tIHM MOX fuel and a plant size of 1000 t/y, the total dose to the MEI ranges from 1010 mrem/y at 2-y-cooled fuel to 862 mrem/y at 100-y-cooled fuel (Figure B.3-1). Iodine-129 is the major contributor (859 mrem/y); at cooling times up to a little over 30 y, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 1.86 mrem/y and ^{85}Kr could contribute up to 3.7 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table B.3-1.

If the iodine and ^{85}Kr release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 151 mrem/y at 2-y cooling and 5.58 mrem/y for 100-y-cooled fuel (Figure B.3-2). The ^{129}I contribution is reduced to 3.15 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 70 y. The ^{14}C again contributes 1.87 mrem/y, but ^{85}Kr contributions are reduced to less than ~0.8 mrem/y. It is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25 mrem/y limit and that from Figure B.3-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{129}I would also be required.

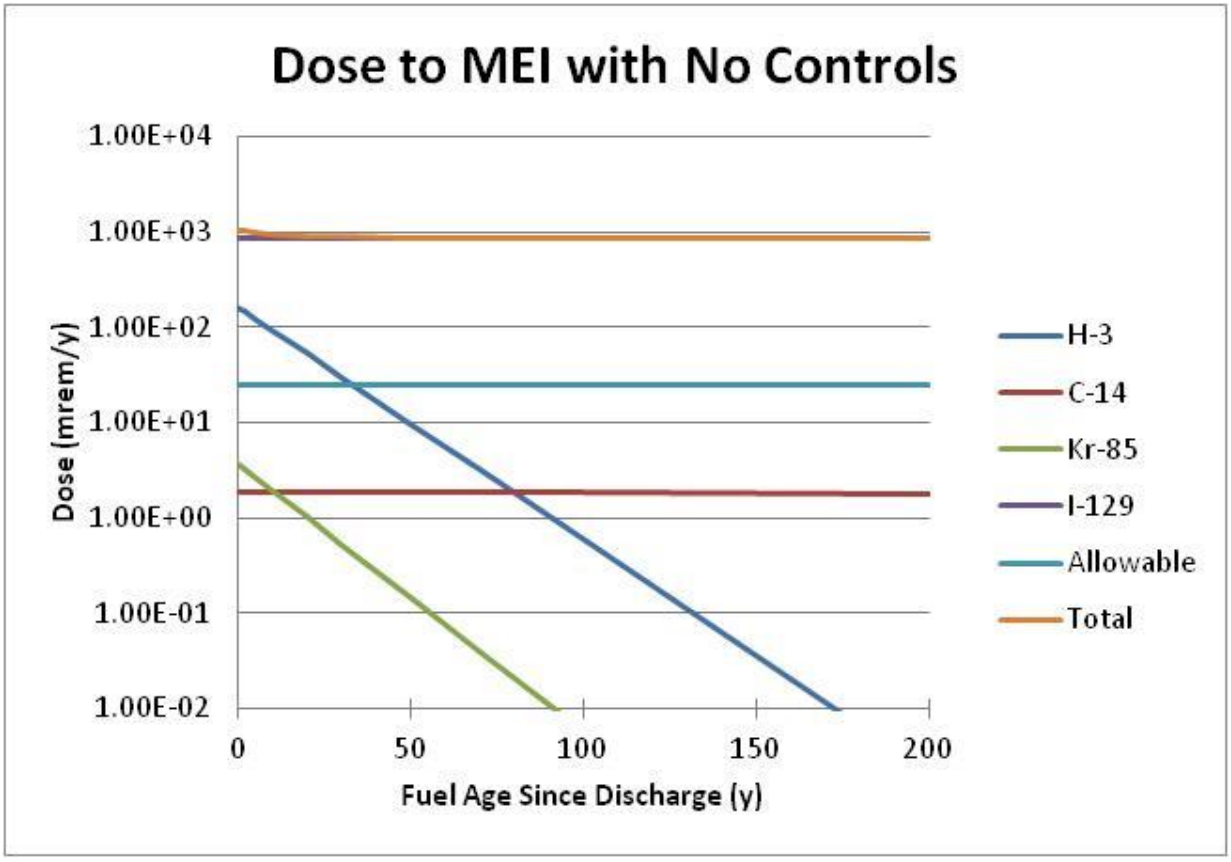


Figure B.3-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table B.3-1. Dose contributions by radionuclide based on 30-GWd/tIHM PWR MOX fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	162	145	1.23E+02	92.6	52.8	30.1	9.78	3.18	0.589	0.0021
^{14}C	1.86	1.86	1.86	1.86	1.86	1.86	1.85	1.85	1.84	1.82
^{85}Kr	3.69	3.24	2.67	1.93	1.01	0.530	0.145	0.0399	0.0057	8.94×10^{-6}
^{129}I	859	859	859	859	859	859	859	859	859	859
Allowable	25	25	25	25	25	25	25	25	25	25
Total	1030	1010	986	955	915	892	871	864	962	861

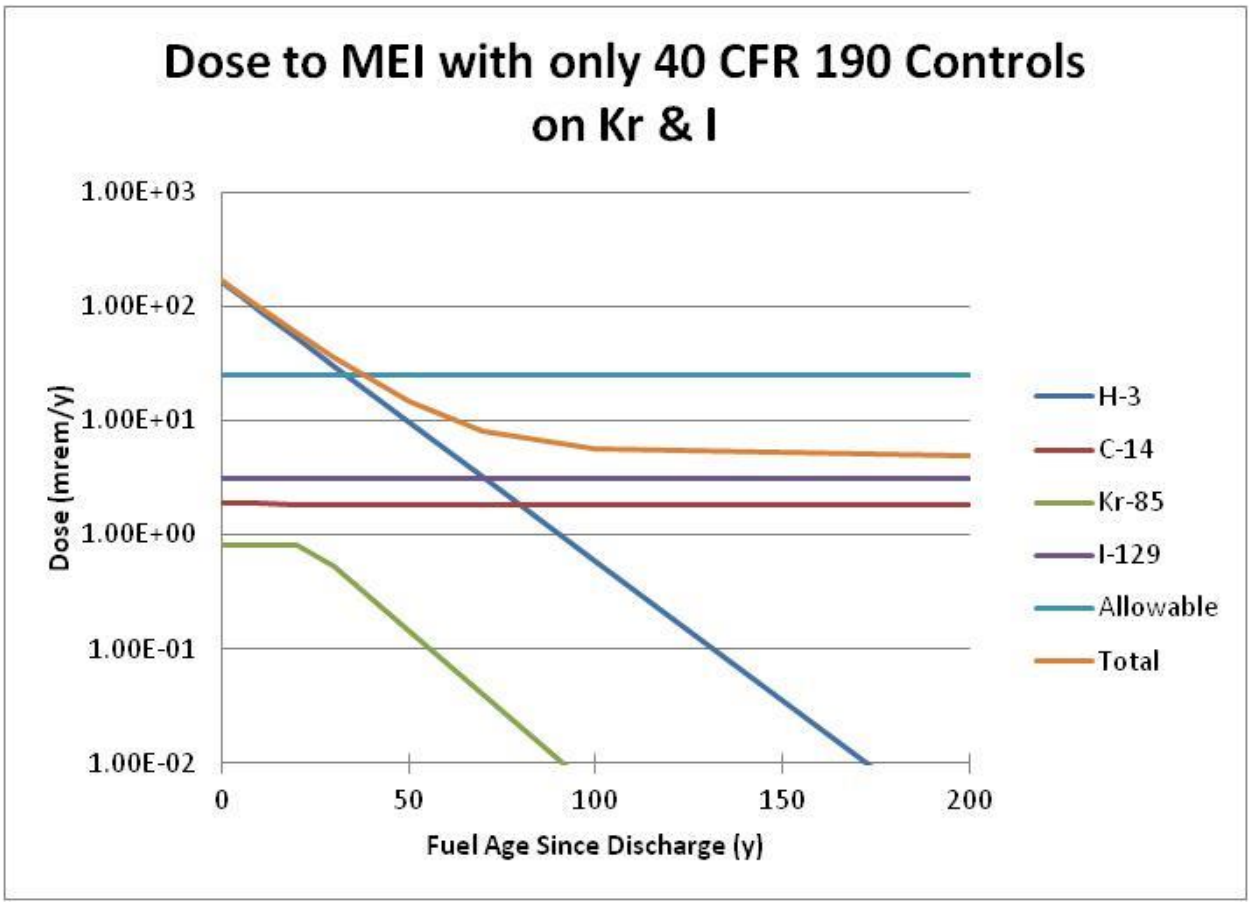


Figure B.3-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

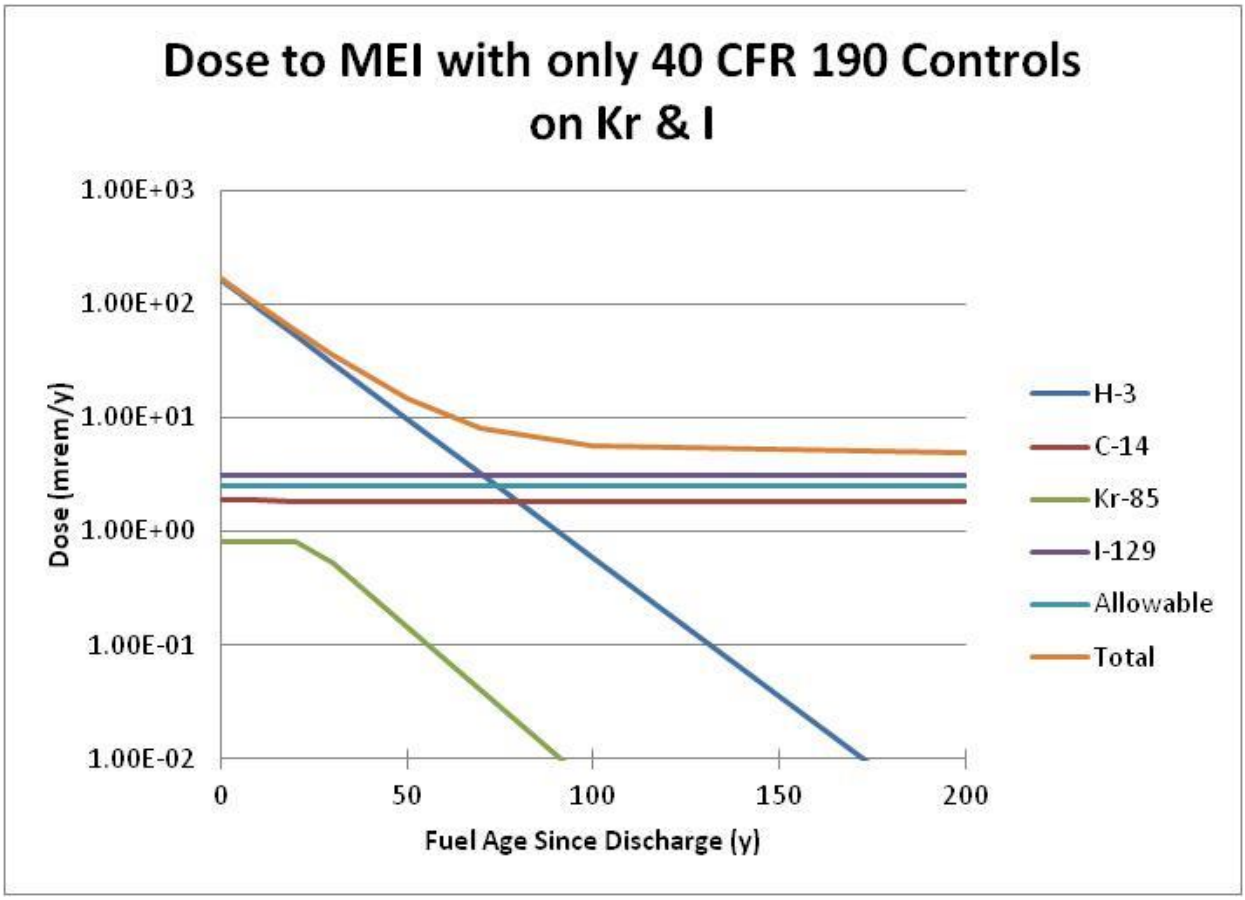


Figure B.3-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 7.6 at 2-y cooling to 1.55 at 30-y cooling (Figure B.3-4 and Table B.3-2). Beyond 30-y fuel cooling no additional ^{3}H capture would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, as noted before, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to ^{129}I at all times, raising the total DF to ~2700. A ^{14}C DF of 3 was also applied for all times to reduce its contribution to the total dose to ~0.6 mrem/y. Tritium DF values range from 193 for 2-y-cooled fuel to 2.08 at 70-y cooling. Figure B.3-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure B.3-6 depicts the DF requirements for each isotope as a function of cooling time. Table B.3-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table B.3-4 shows the resulting dose contributions.

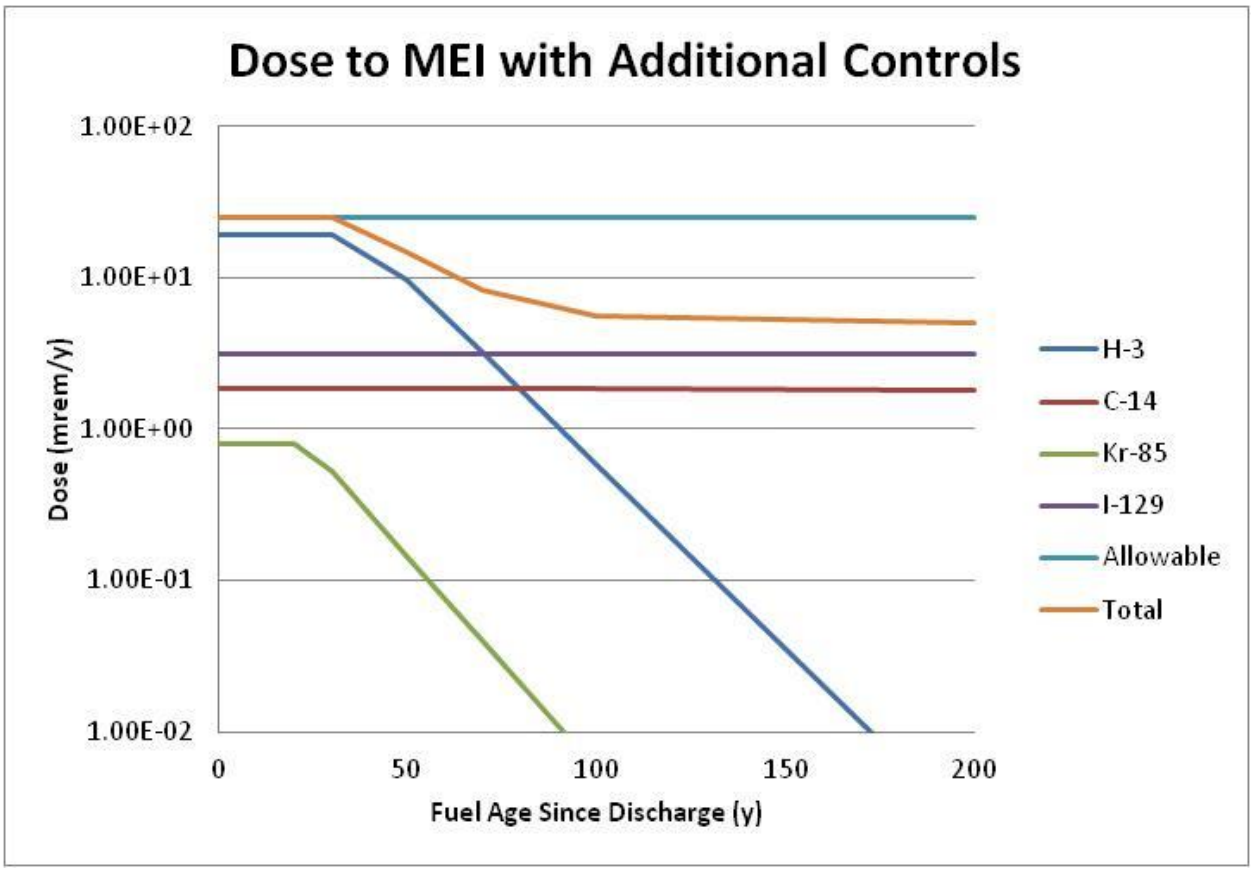


Figure B.3-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table B.3-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 30-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	8.45	7.55	6.40	4.83	2.75	1.55	1.00	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	4.57	4.01	3.31	2.39	1.25	1.00	1.00	1.00	1.00	1.00
^{129}I	273	273	273	273	273	273	273	273	273	273

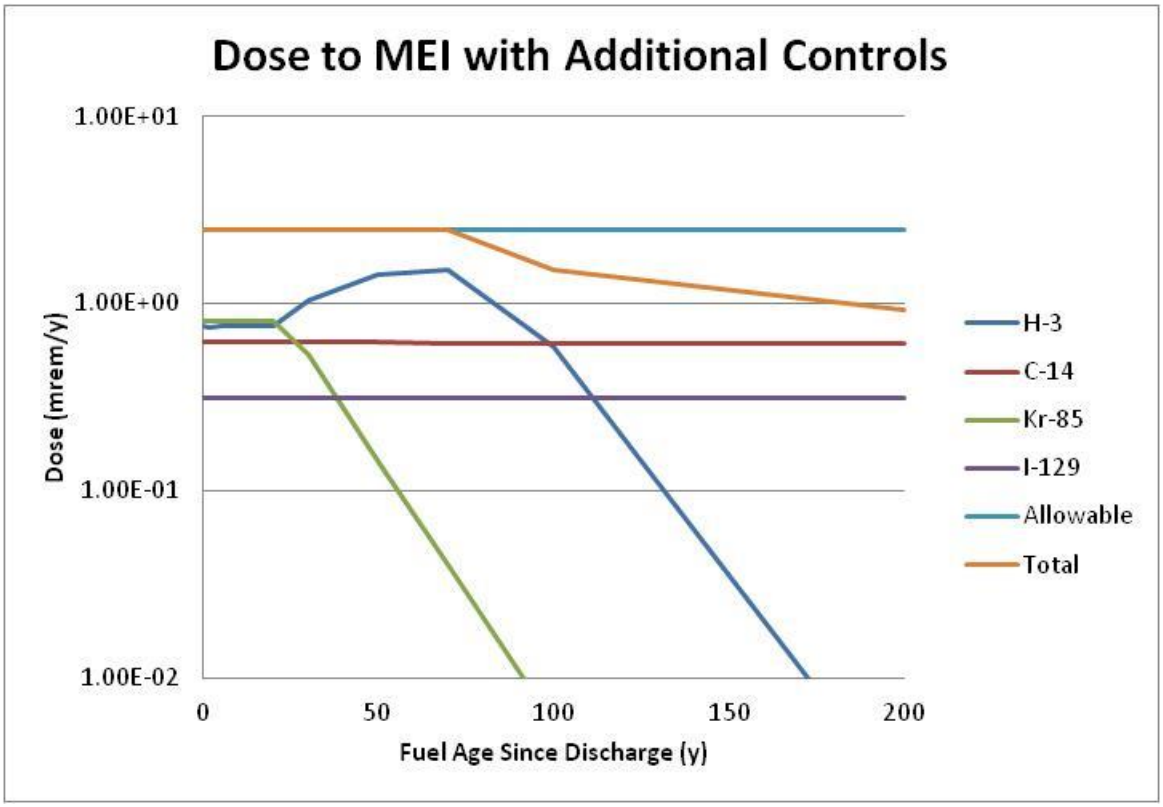


Figure B.3-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table B.3-3. Effective DFs required to achieve 2.5-mrem/y dose to MEI for 30-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	215	193	161	123	70.0	29.0	6.87	2.08	1.00	1.00
^{14}C	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
^{85}Kr	4.57	4.01	3.31	2.39	1.25	1.00	1.00	1.00	1.00	1.00
^{129}I	2730	2730	2730	2730	2730	2730	2730	2730	2730	2730

Table B.3-4. Dose contributions by radionuclide based on 30-GWd/tIHM PWR MOX fuel cooled up to 200 y using effective DF from Table B.3-3

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	0.756	0.752	0.762	0.753	0.754	1.04	1.42	1.53	0.589	0.0021
^{14}C	0.622	0.621	0.621	0.621	0.620	0.619	0.618	0.616	0.614	0.607
^{85}Kr	0.807	0.807	0.807	0.807	0.807	0.530	0.145	0.0399	0.0057	8.94×10^{-6}
^{129}I	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315	0.315
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.52	0.924

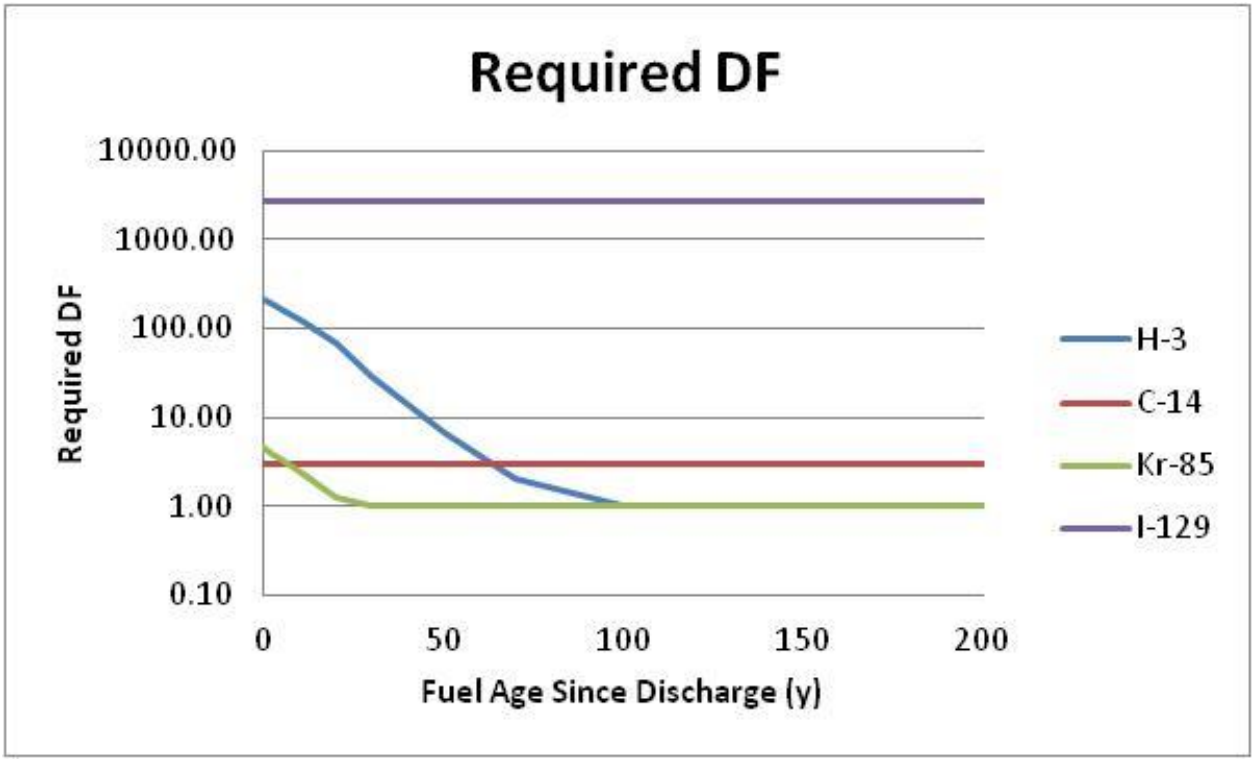


Figure B.3-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for iodine and krypton only results in a thyroid dose of 137 mrem/y for the processing of 2-y-cooled fuel, decreasing to 65 mrem/y at 100-y cooled (Figure B.3-7). The two primary contributors to the dose are ^{129}I and tritium in the case of short cooling times.

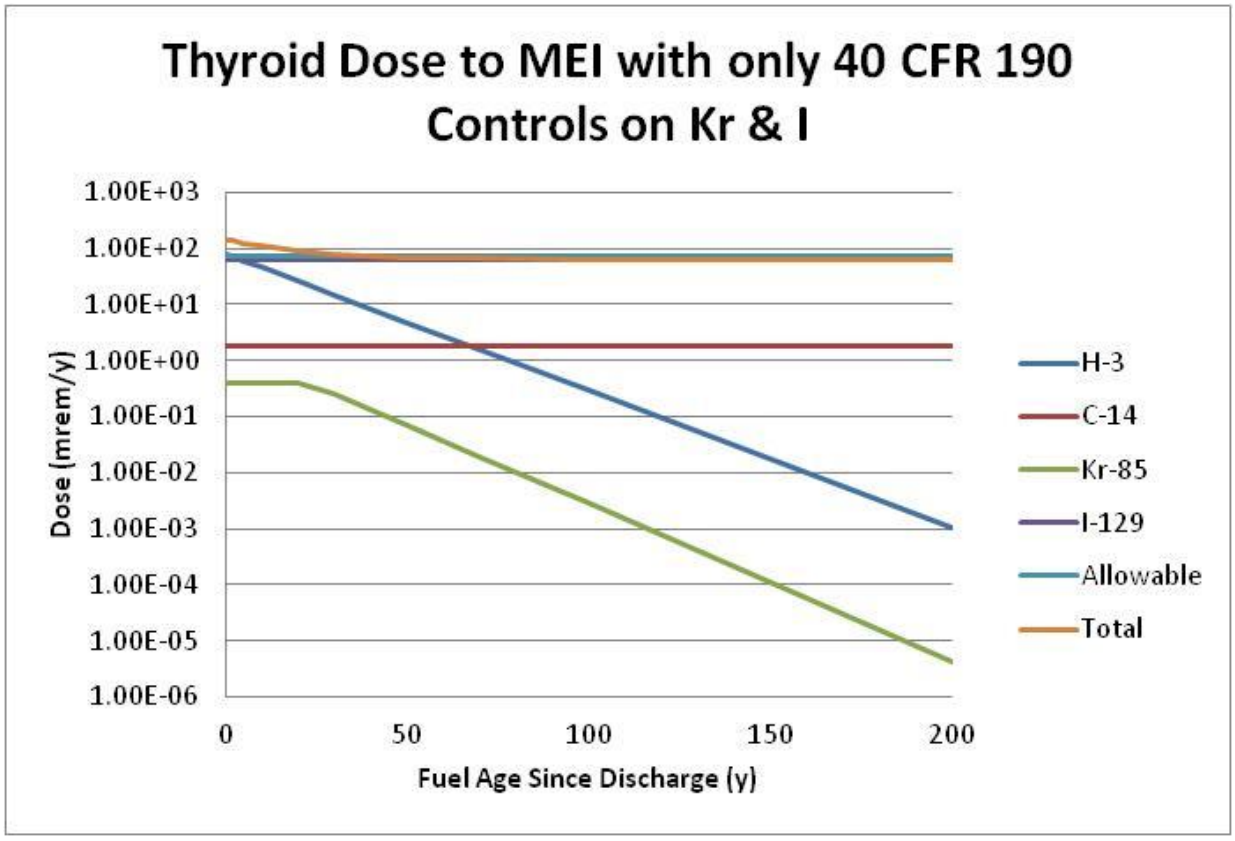


Figure B.3-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to 65 - 74.5 mrem/y thus no additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure B.3-8).

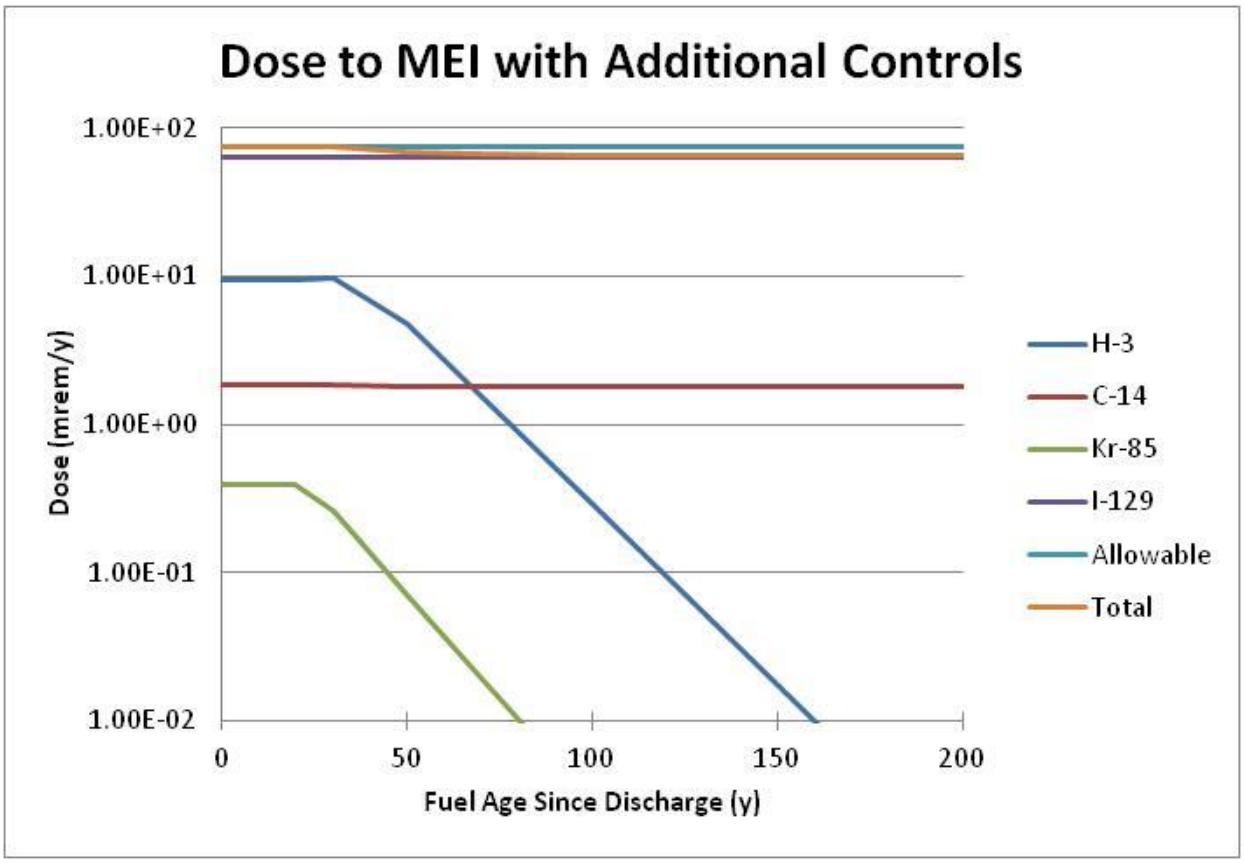


Figure B.3-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied as for the whole body dose, the resulting thyroid dose is 7.66–7.18 mrem/y (Figure B.3-9). Iodine-129 accounts for over 80% of this dose, with ^{14}C the bulk of the remaining dose. A slight increase in the iodine DF from ~ 2730 to 2800 would be required to limit the thyroid dose to 7.5 mrem/y.

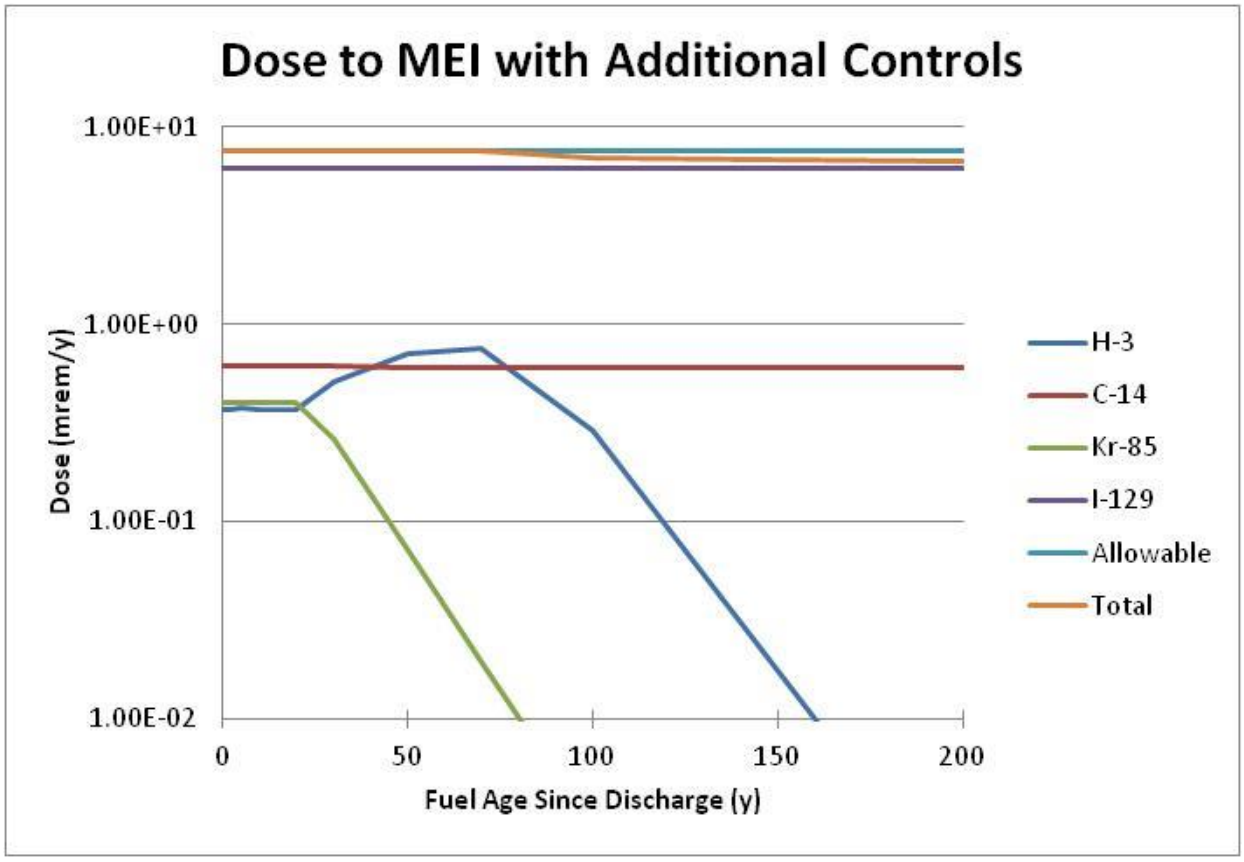


Figure B.3-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

B.4. PWR / MOX - 60 GWD/TIHM

For the same MOX fuel/reactor but at a burnup of 60 GWd/tIHM, the second phase analysis results are as follows: For a plant size of 1000 t/y, the total dose to the MEI ranges from 1930 mrem/y at 2-y-cooled fuel to 1610 mrem/y at 100-y cooled (Figure B.4-1). Iodine is the major contributor (1600 mrem/y); at cooling times up to ~40 y, tritium dose contributions exceed 25 mrem/y; ^{14}C contributes 4.32 mrem/y and ^{85}Kr could contribute up to ~7 mrem/y at short cooling times (Table B.4-1).

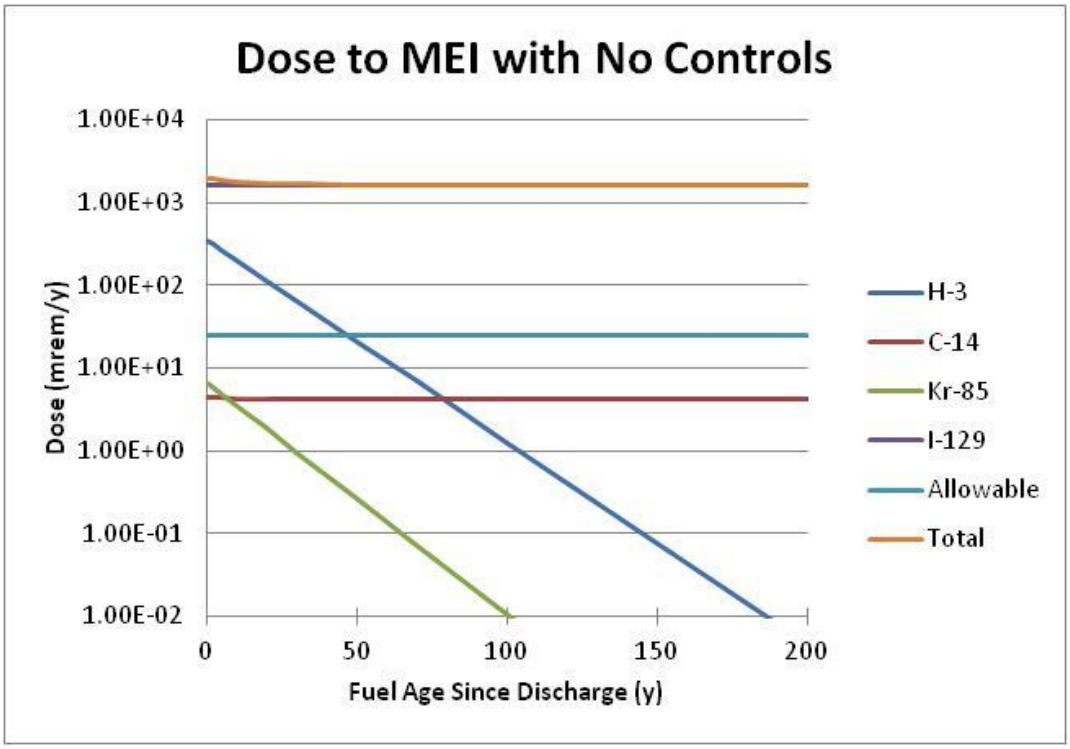


Figure B.4-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table B.4-1. Dose contributions by radionuclide based on 60-GWd/tIHM, PWR MOX fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	3482	311	263	198	113	64.5	21.0	6.81	1.26	0.0046
^{14}C	4.32	4.32	4.32	4.32	4.31	4.31	4.30	4.29	4.27	4.22
^{85}Kr	6.65	5.84	4.81	3.48	1.83	0.956	0.262	0.0720	0.0104	1.61×10^{-5}
^{129}I	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600
Allowable	25	25	25	25	25	25	25	25	25	25
Total	1960	1930	1880	1810	1720	1670	1630	1620	1610	1610

If the iodine and krypton release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 323 mrem/y at 2-y cooling and 11.8 mrem/y for 100-y-cooled fuel (Figure B.4-2). The iodine contribution is reduced to 6.29 mrem/y, and tritium becomes the major contributor at cooling times less than 70 y. The ^{14}C again contributes 4.32 mrem/y, but ^{85}Kr contributions are reduced to less than 1.61 mrem/y. Again, it is clear from this figure that additional controls at least on tritium would be required to meet a 25-mrem/y limit and that from Figure B.4-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for iodine and ^{14}C would also be required. Additional ^{85}Kr DF may also be required as krypton contributed ~67% of the allocated dose contribution.

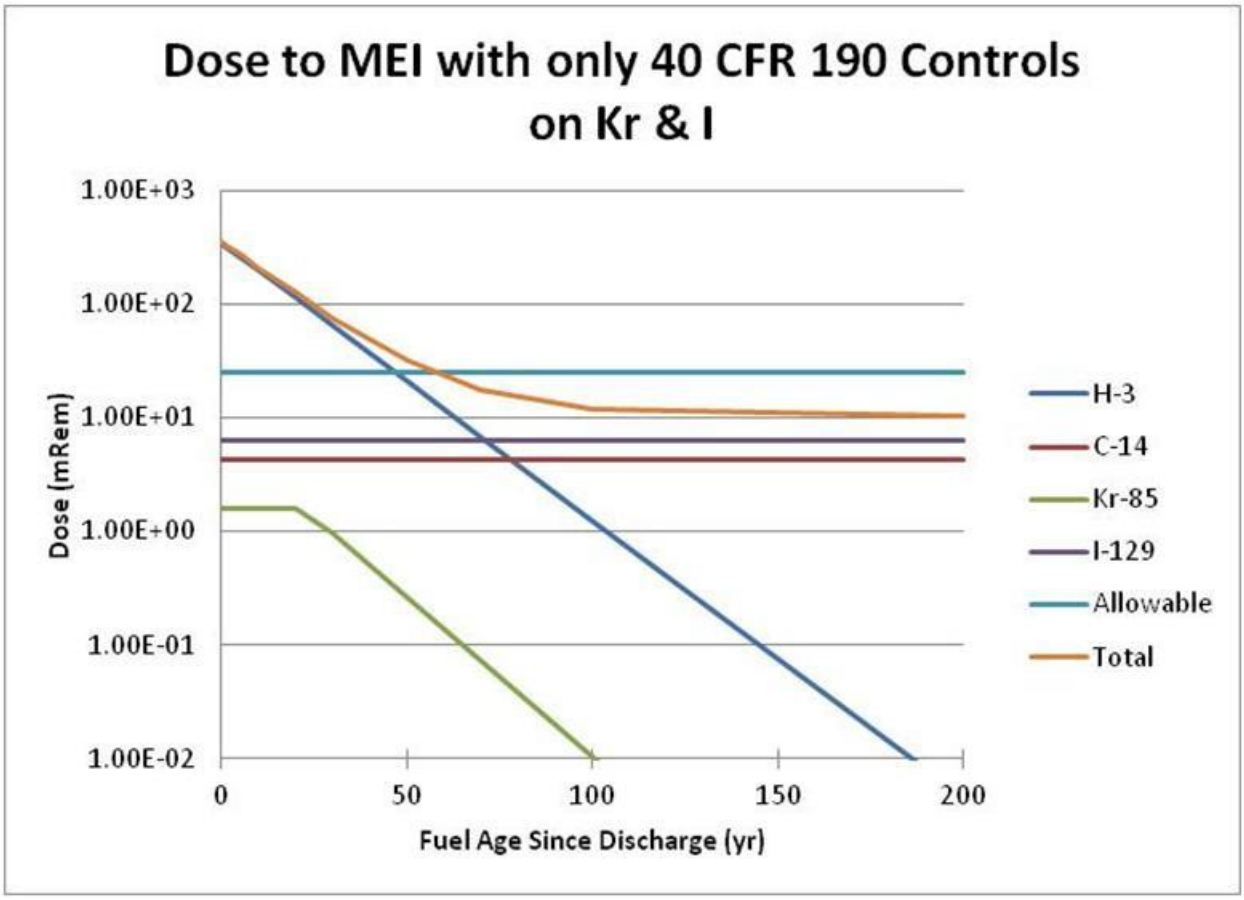


Figure B.4-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

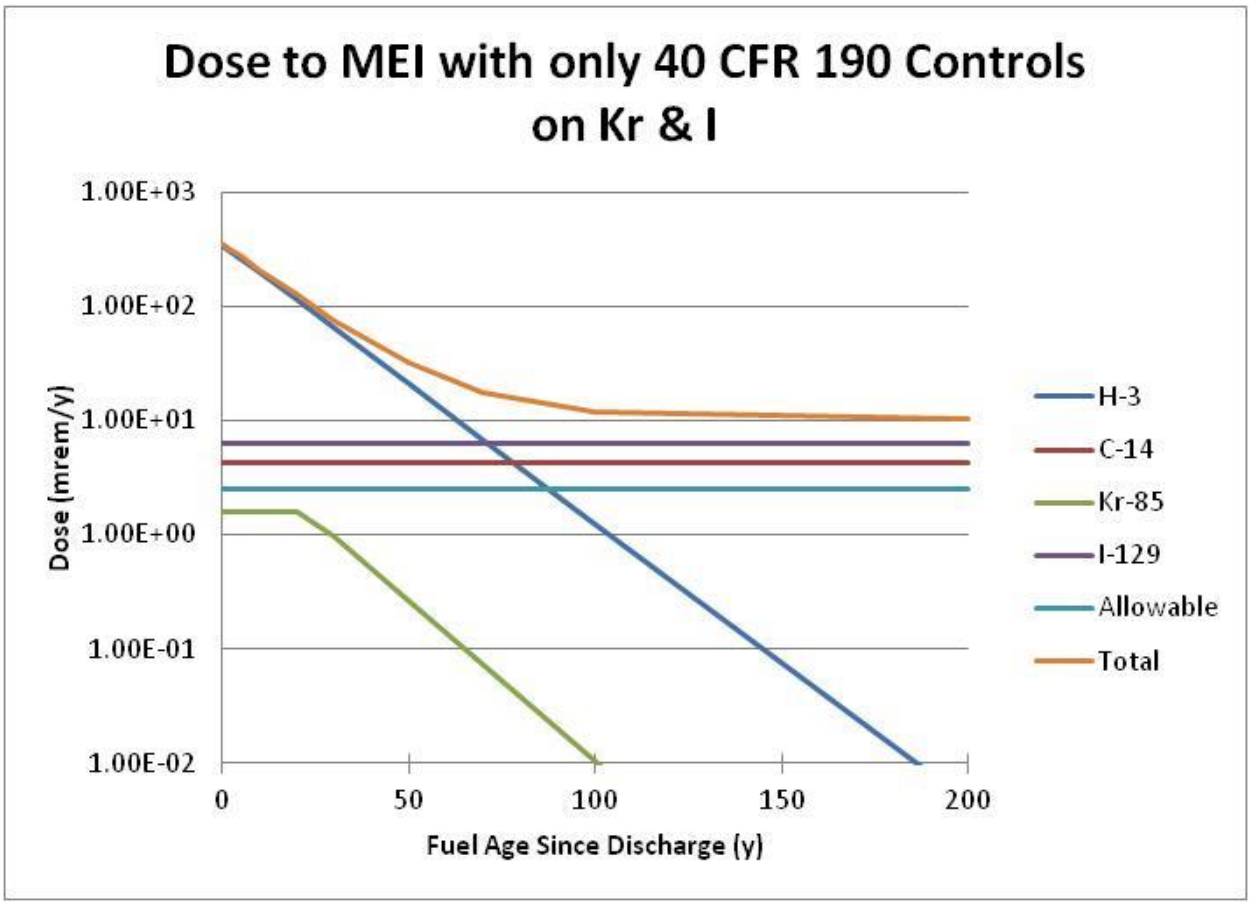


Figure B.4-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for tritium. Tritium DF requirements ranged from 24.3 at 2-y cooling to 1.48 at 50-y cooling (Figure B.4-4 and Table B.4-2). Beyond ~60 y fuel cooling, no additional tritium capture would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and tritium contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to iodine at all times, raising the total DF to ~2600. A ^{14}C DF of 10 for times up to 200 y was applied to reduce its contribution to the total dose to ~0.4 mrem/y. Additional ^{85}Kr DF requirements were also imposed for the same time frames as required by the 40 CFR 190 discharge release limit for krypton (up to 30-y cooling) due to the relatively large contribution of ^{85}Kr (1.6 mrem/y out of 2.5 mrem/y). Tritium DFs range from 490 for 2-y-cooled fuel to ~5 at 70-y-cooled fuel. Beyond 100 y no tritium recover would be required. At 30-y cooling, the increase in krypton contribution to the total dose is the result of the elimination of a krypton recovery requirement (DF = 1). This then required a corresponding decrease in the tritium contribution. Figure B.4-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure B.4-6 depicts the DF requirements for each isotope as a function of cooling time. Table B.4-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table B.4-4 shows the resulting dose contributions.

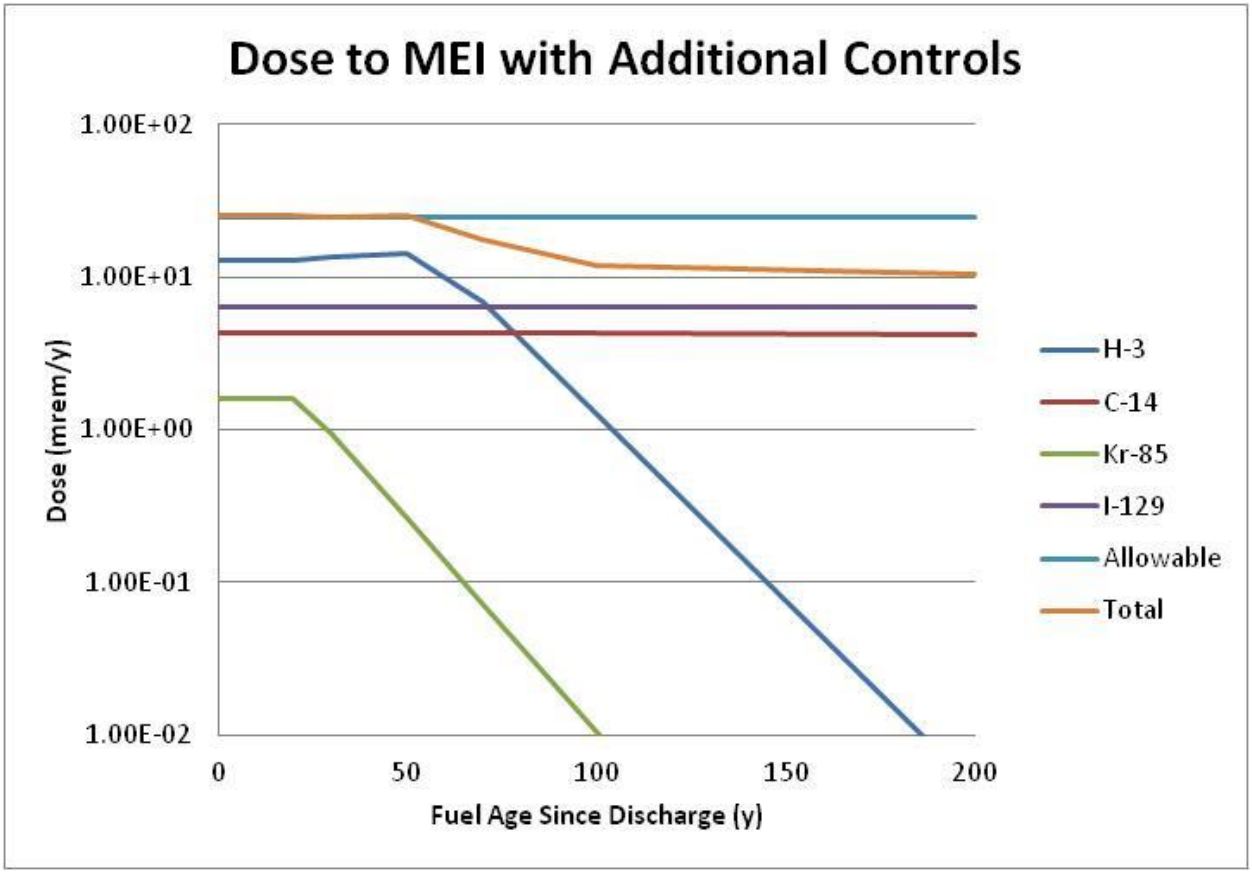


Figure B.4-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table B.4-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 60-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	27.2	24.3	20.5	15.5	8.85	4.80	1.48	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	4.12	3.62	2.98	2.16	1.13	1.00	1.00	1.00	1.00	1.00
^{129}I	255	255	255	255	255	255	255	255	255	255

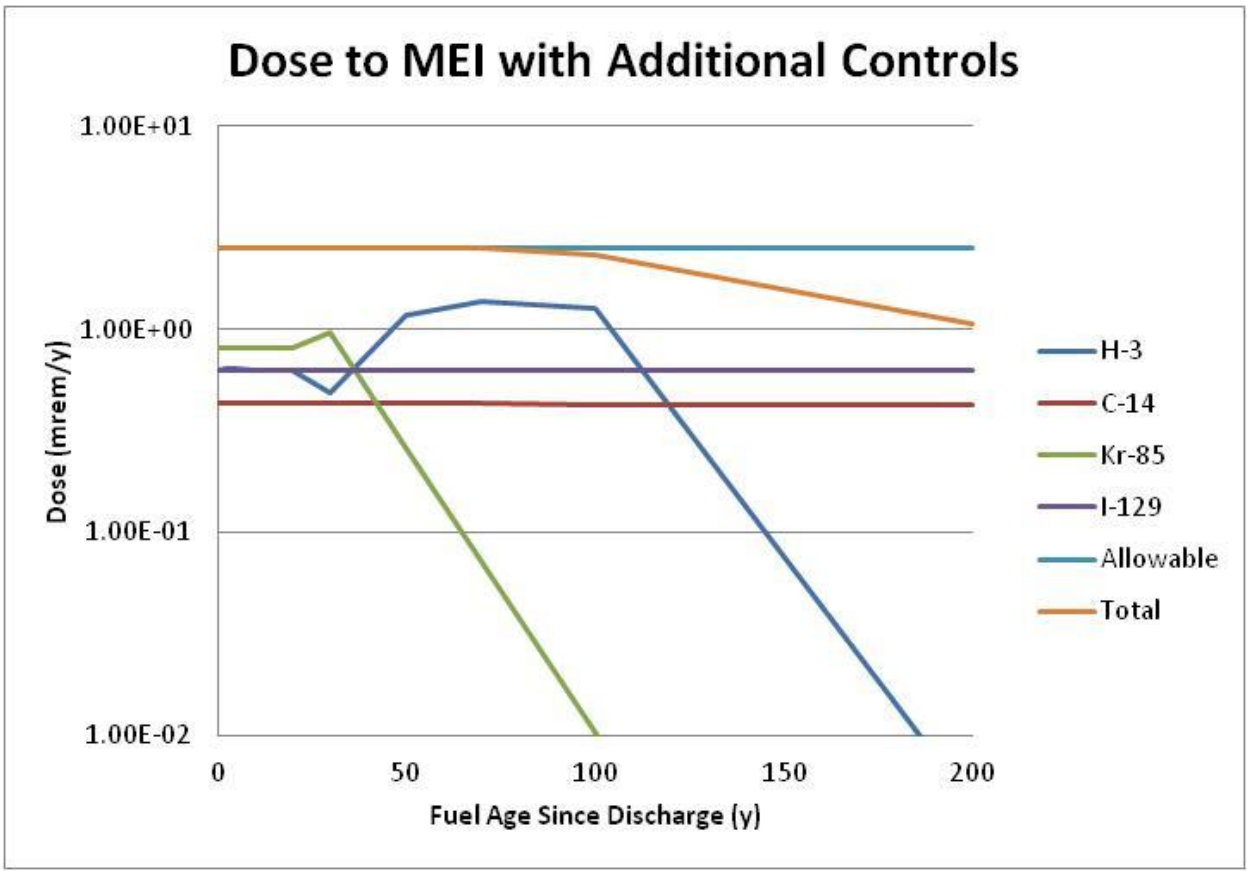


Figure B.4-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table B.4-3. Effective DFs required to achieve 2.5-mrem/y whole body dose to MEI for 60-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	550	490	415	315	180	133	17.8	4.96	1.00	1.00
^{14}C	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
^{85}Kr	8.24	7.24	5.97	4.32	2.26	1.00	1.00	1.00	1.00	1.00
^{129}I	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550

Table B.4-4. Dose contributions by radionuclide based on 60-GWd/tIHM PWR MOX fuel cooled up to 200 y using effective DFs from Table B.4-3

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	0.633	0.635	0.633	0.630	0.629	0.485	1.18	1.37	1.26	0.0046
^{14}C	0.432	0.432	0.432	0.432	0.431	0.431	0.430	0.429	0.427	0.422
^{85}Kr	0.807	0.807	0.807	0.807	0.807	0.956	0.262	0.0720	0.0104	1.61×10^{-5}
^{129}I	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629	0.629
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.3	1.1

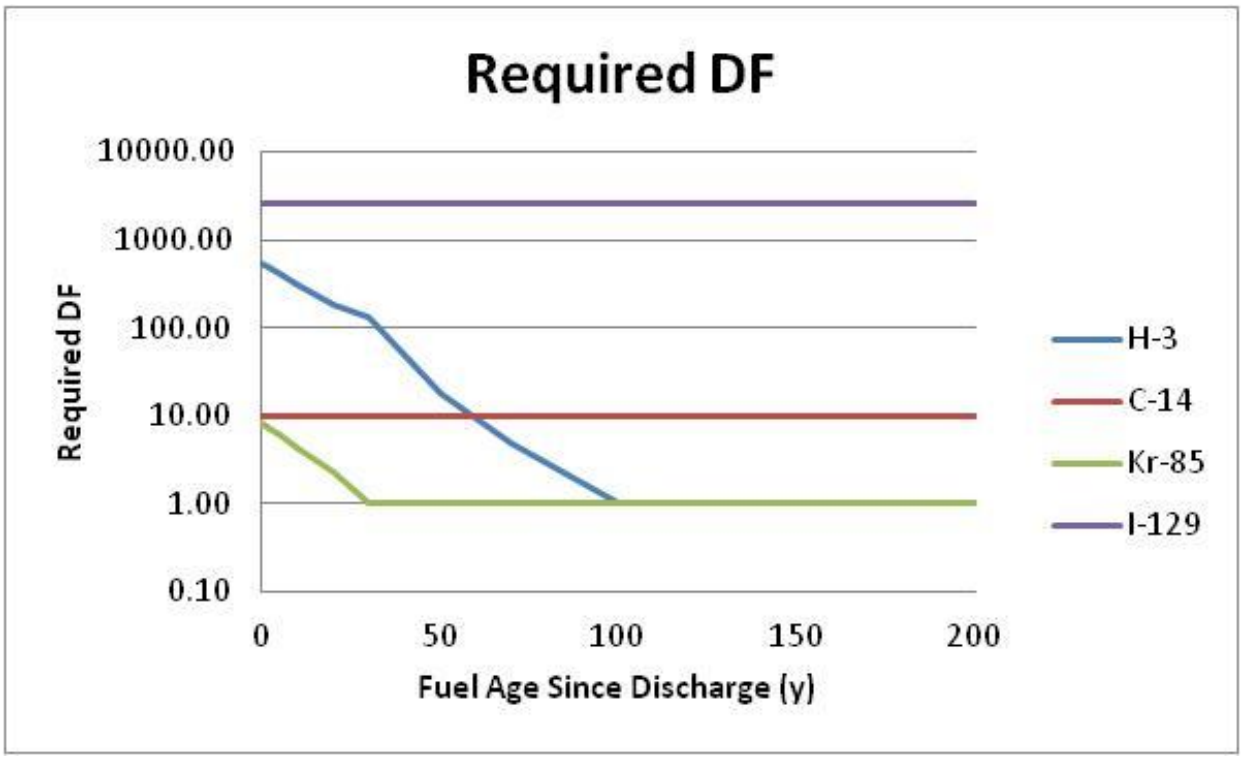


Figure B.4-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for iodine and krypton only results in a thyroid dose of 284 mrem/y for the processing of 2-y-cooled fuel decreasing to 130 mrem/y at 100-y cooled (Figure B.4-7). The two primary contributors to the dose are ^{129}I and tritium in the case of short cooling times.

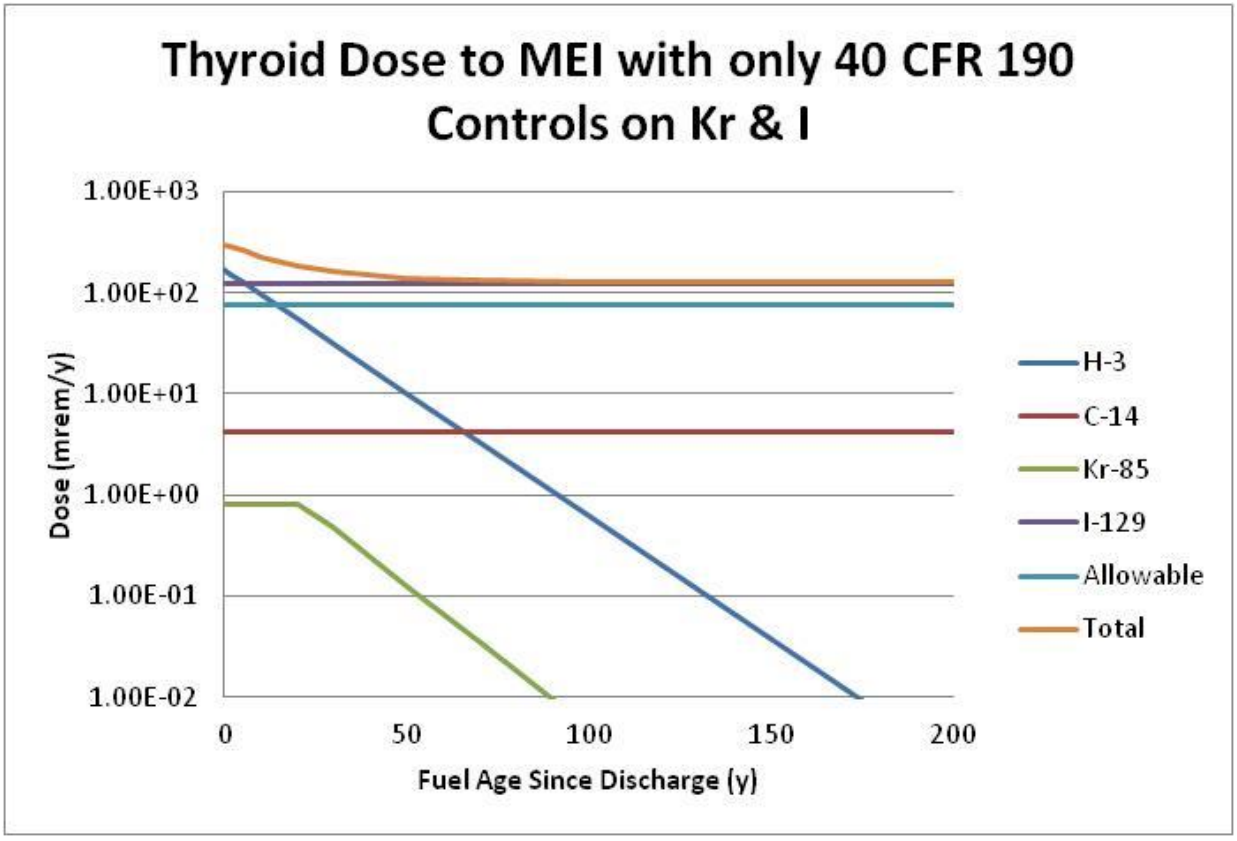


Figure B.4-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to 137 to 130 mrem/y; thus, additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure B.4-8). An additional iodine DF of ~2 for a total iodine DF of ~510 would be required to reduce the total dose to <75 mrem/y.

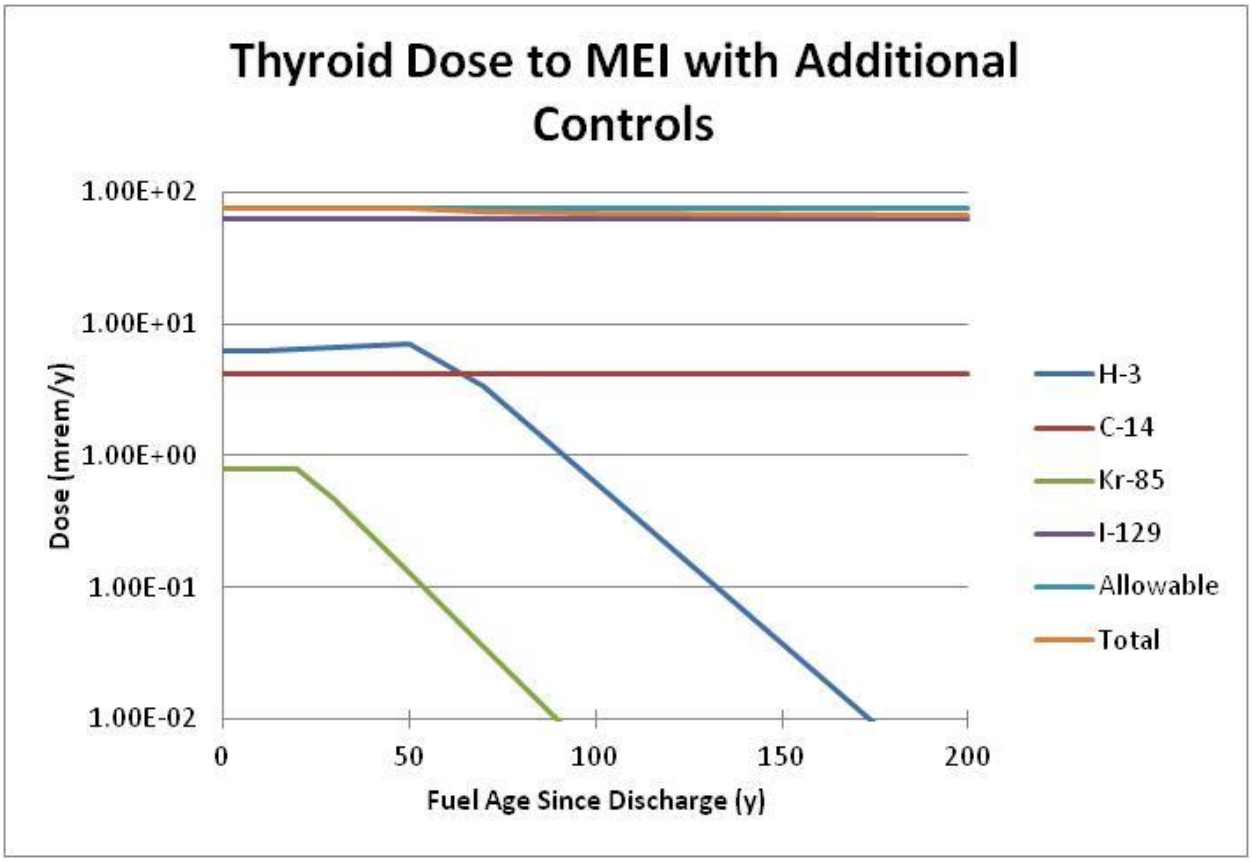


Figure B.4-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is ~13.7 mrem/y (Figure B.4-9). Iodine-129 accounts for approximately 90+% of this dose with ^{14}C the bulk of the remaining dose, especially at longer cooling times. An additional iodine DF of ~2 for a total iodine DF of ~5100 would be required to reduce the total dose to <7.5 mrem/y.

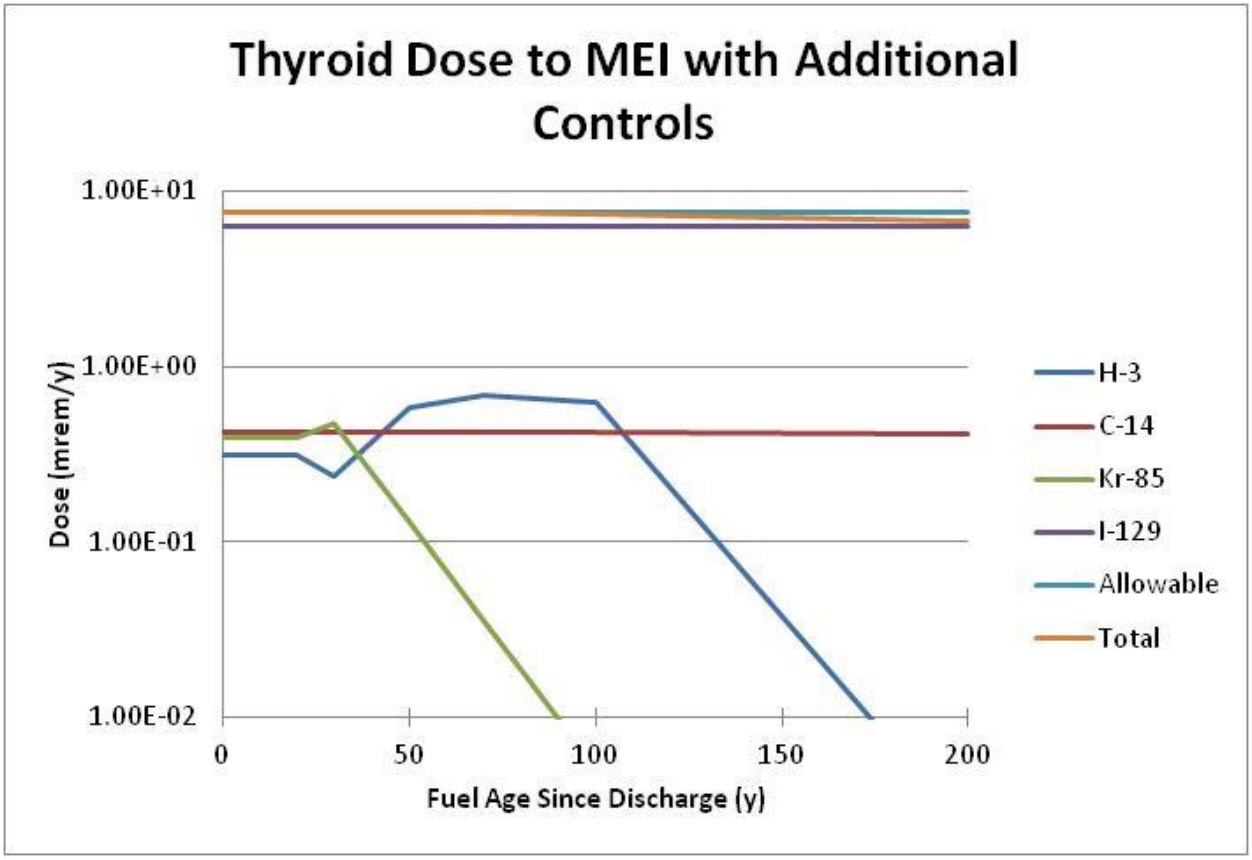


Figure B.4-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

B.5. PWR / MOX - 100 GWD/TIHM

For the same MOX fuel/reactor but with a further burnup of 100 GWd/tIHM, the second phase analysis results are provided below.

For a plant size of 1000 t/y, the total dose to the MEI ranges from ~3000 mrem/y at 2-y-cooled fuel to 2480 mrem/y at 100-y cooled (Figure B.5-1). Iodine-129 is the major contributor (2470 mrem/y); at cooling times up to ~60 y, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 8.53 mrem/y and ^{85}Kr could contribute up to ~8.63 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table B.5-1.

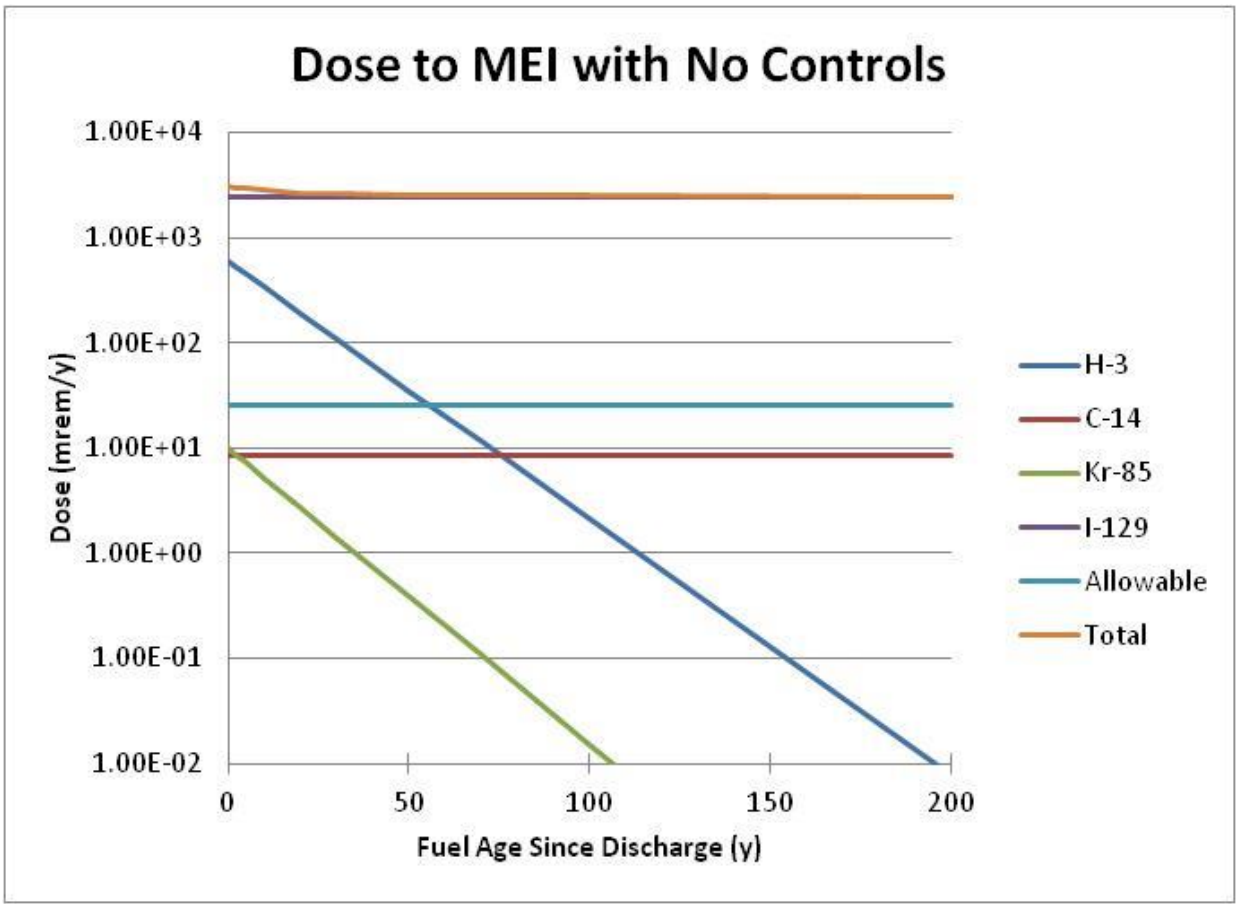


Figure B.5-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

If the ^{129}I and ^{85}Kr release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 549 mrem/y at 2-y cooling and 21.1 mrem/y for 100-y -cooled fuel (Figure B.5-2). The ^{129}I contribution is reduced to 10.5 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 70 y. Carbon-14 again contributes 8.53 mrem/y, but ^{85}Kr contributions are reduced to less than 2.7 mrem/y. Again, it is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit and that from Figure B.5-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{129}I, ^{14}C and ^{85}Kr would also be required.

Table B.5-1. Dose contributions by radionuclide based on 100-GWd/tIHM PWR MOX fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	5.90E+02	5.27E+02	4.45E+02	3.36E+02	1.92E+02	1.09E+02	3.55E+01	1.15E+01	2.14E+00	7.74E-03
^{14}C	8.53E+00	8.53E+00	8.53E+00	8.52E+00	8.51E+00	8.50E+00	8.48E+00	8.46E+00	8.43E+00	8.33E+00
^{85}Kr	9.82E+00	8.63E+00	7.11E+00	5.14E+00	2.70E+00	1.41E+00	3.88E-01	1.06E-01	1.53E-02	2.38E-05
^{129}I	2.47E+03	2.47E+03	2.47E+03	2.47E+03	2.47E+03	2.47E+03	2.47E+03	2.47E+03	2.47E+03	2.47E+03
Allowable	25	25	25	25	25	25	25	25	25	25
Total	3.08E+03	3.01E+03	2.93E+03	2.82E+03	2.67E+03	2.59E+03	2.51E+03	2.49E+03	2.48E+03	2.48E+03

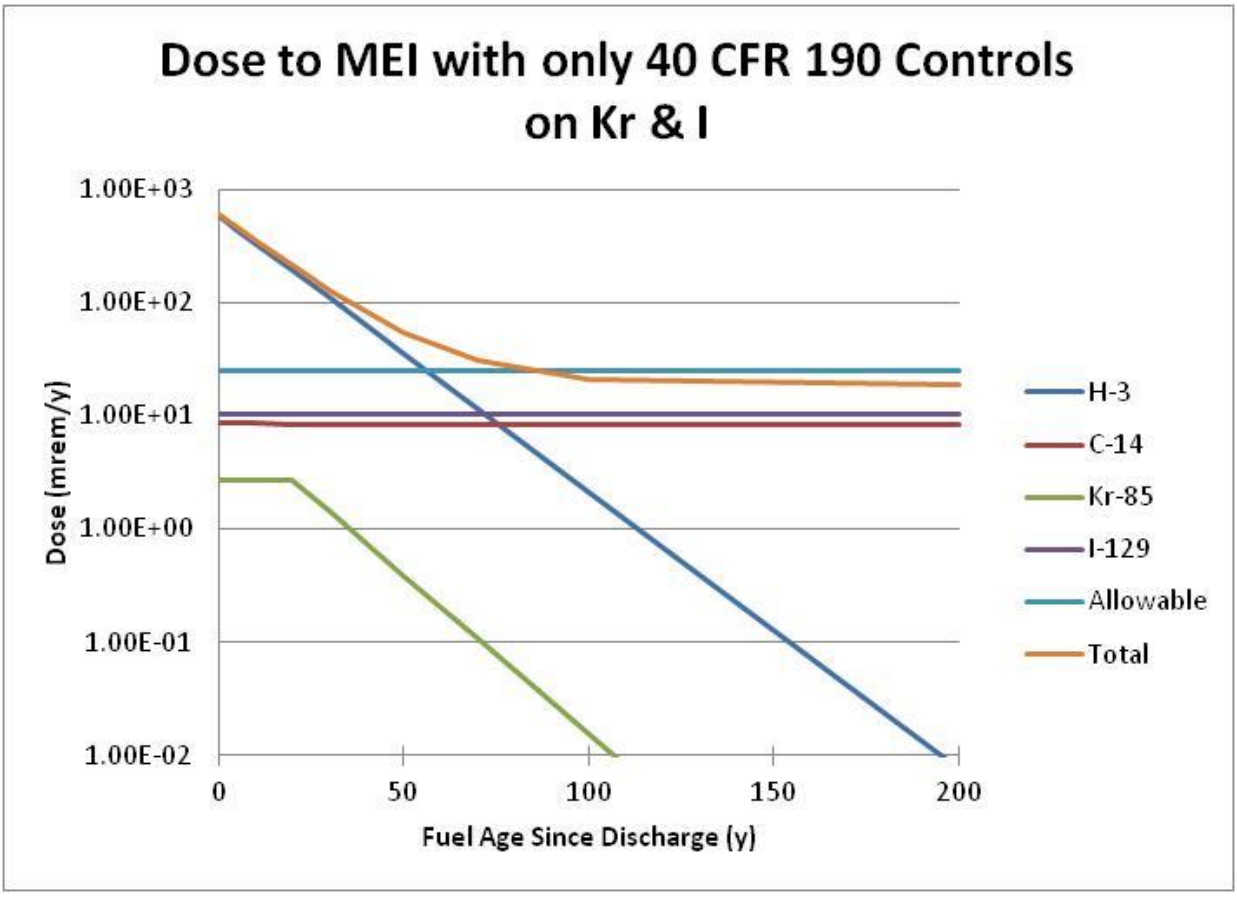


Figure B.5-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

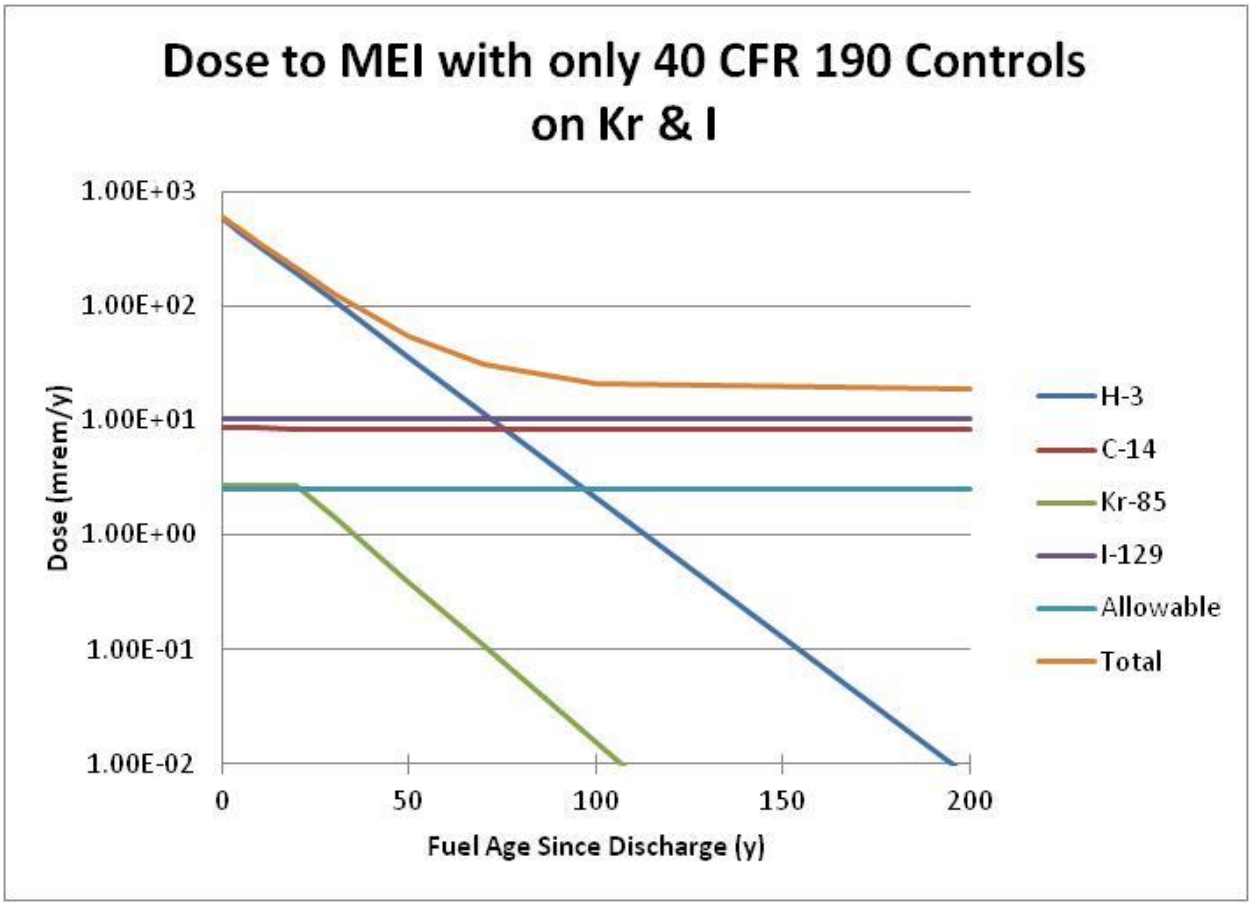


Figure B.5-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for tritium. Tritium DF requirements ranged from 160 at 2-y cooling to ~2 at 70-y cooling (Figure B.5-4 and Table B.5-2). Beyond ~80-y fuel cooling, no additional ^{3}H capture would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. Krypton-85 also contributes more than 2.5 mrem/y until the fuel is aged more than ~25 y. An additional recovery factor of 20 was applied to iodine at all times, raising the total DF to ~4700. A ^{14}C DF of 15 was applied to reduce its contribution to the total dose to ~0.85 mrem/y. Additional ^{85}Kr DF requirements were also imposed up to 30-y cooling due to the relatively large contribution of ^{85}Kr, bringing the total ^{85}Kr DF to a range of 2 to 13 for cooling times up to 30 y. Tritium DFs range from 720 for 2-y-cooled fuel to ~2 at 100-y-cooled fuel. Beyond 110-y cooling, no ^{3}H recover would be required. Figure B.5-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure B.5-6 depicts the DF requirements for each isotope as a function of cooling time. Table B.5-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table B.5-4 shows the resulting dose contributions.

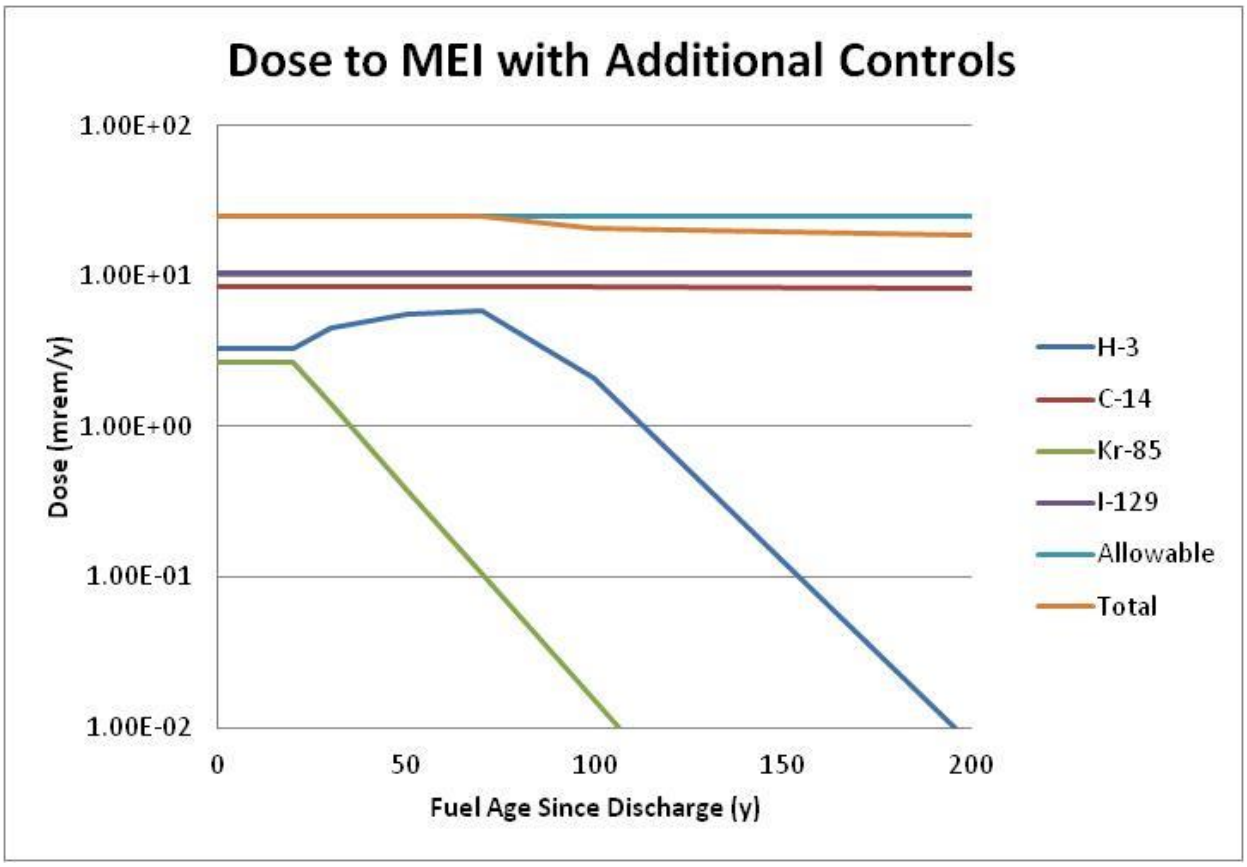


Figure B.5-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table B.5-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 100-GWd/tIHM PWR MOX fuel processed in 1000-t/y facility

Effective DF										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	180.00	160.00	135.00	102.00	58.00	24.00	6.30	1.95	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	3.65	3.21	2.64	1.91	1.00	1.00	1.00	1.00	1.00	1.00
^{129}I	235.32	235.32	235.32	235.32	235.32	235.32	235.32	235.32	235.32	235.32

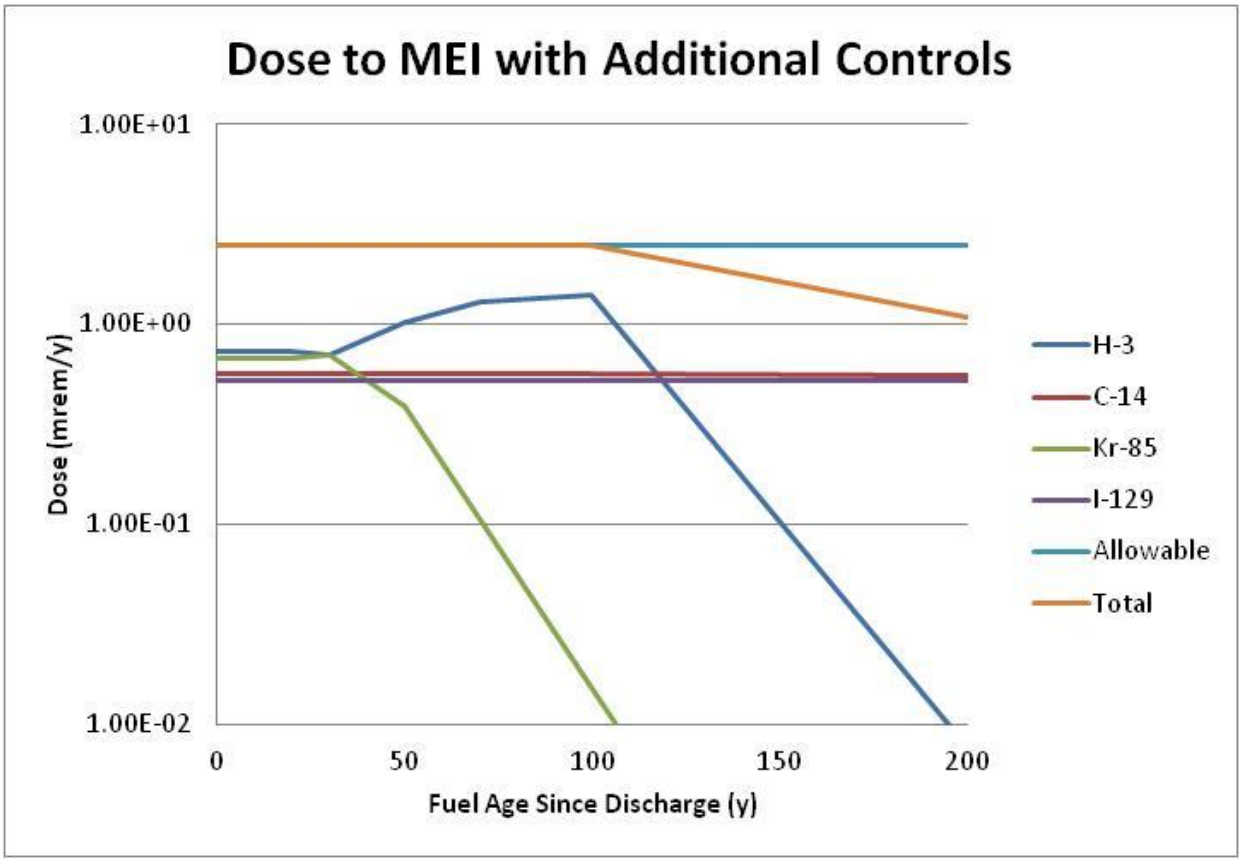


Figure B.5-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table B.5-3. Effective DFs required to achieve 2.5 mrem/y whole body dose to MEI for 100 GWd/tIHM PWR MOX fuel processed in 1000 t/y facility

Effective DF										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	800.00	720.00	610.00	460.00	260.00	155.00	34.70	8.85	1.53	1.00
^{14}C	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
^{85}Kr	14.60	12.83	10.57	7.65	4.01	2.00	1.00	1.00	1.00	1.00
^{129}I	4706.36	4706.36	4706.36	4706.36	4706.36	4706.36	4706.36	4706.36	4706.36	4706.36

Table B.5-4. Dose contributions by radionuclide based on 100-GWd/tIHM PWR MOX fuel cooled up to 200 y using effective DFs from Table B.5-3

Dose, mrem/y										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	7.38E-01	7.32E-01	7.30E-01	7.31E-01	7.37E-01	7.05E-01	1.02E+00	1.30E+00	1.40E+00	7.74E-03
^{14}C	5.69E-01	5.69E-01	5.69E-01	5.68E-01	5.68E-01	5.67E-01	5.65E-01	5.64E-01	5.62E-01	5.55E-01
^{85}Kr	6.72E-01	6.72E-01	6.72E-01	6.72E-01	6.72E-01	7.06E-01	3.88E-01	1.06E-01	1.53E-02	2.38E-05
^{129}I	5.24E-01	5.24E-01	5.24E-01	5.24E-01	5.24E-01	5.24E-01	5.24E-01	5.24E-01	5.24E-01	5.24E-01
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.1

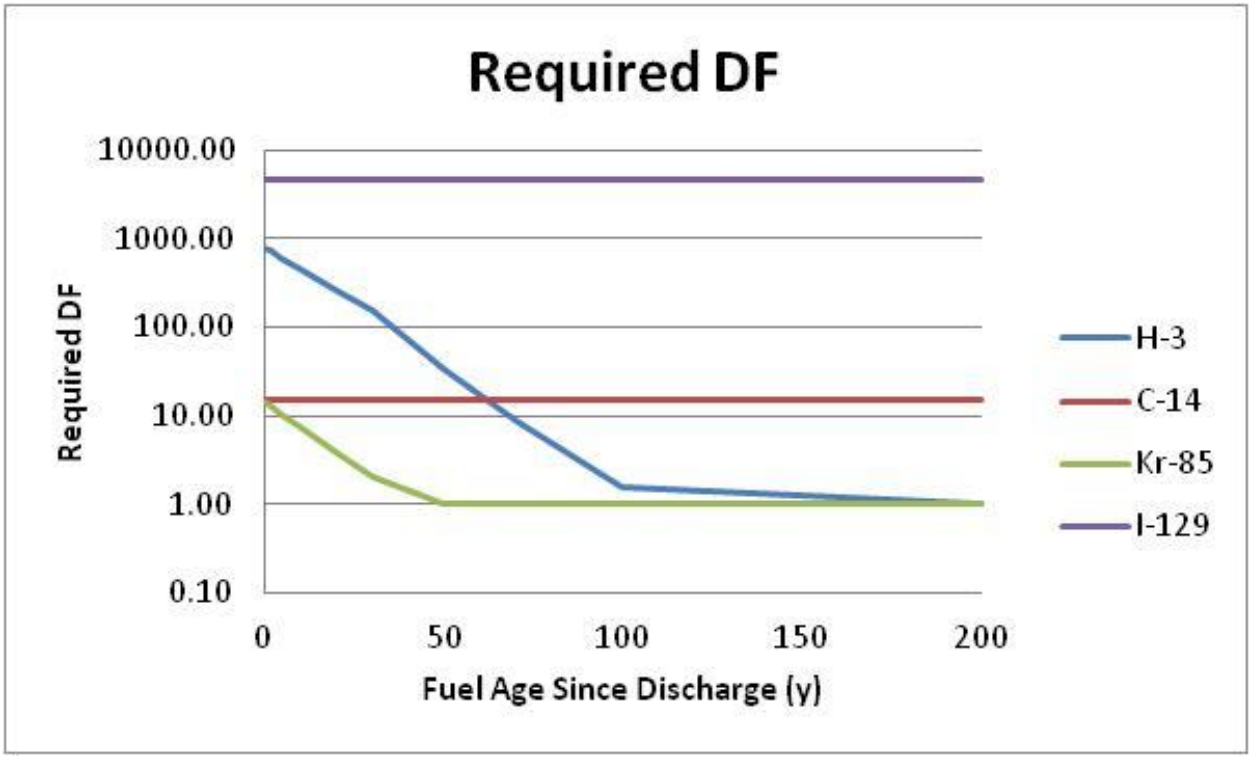


Figure B.5-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for ^{129}I and ^{85}Kr only results in a thyroid dose of 479 mrem/y for the processing of 2-y-cooled fuel decreasing to 219 mrem/y at 100-y cooled (Figure B.5-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

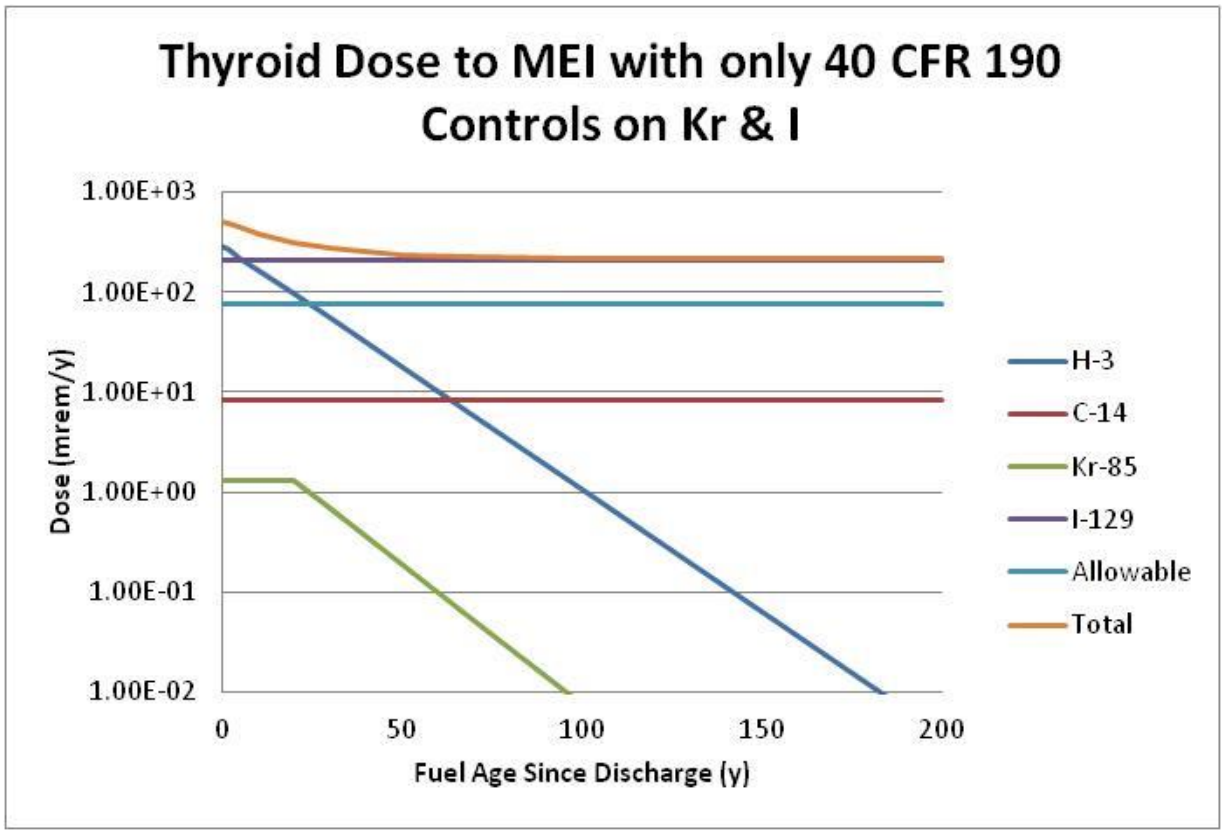


Figure B.5-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that the dose to the thyroid is reduced to 221 mrem/y. Thus, additional DF requirements would be needed beyond those to meet the 25 mrem/y whole body dose limit (Figure B.5-8). Since the primary contributor to the dose is ^{129}I, an additional DF of 3.3 is applied, making the required iodine DF ~770.

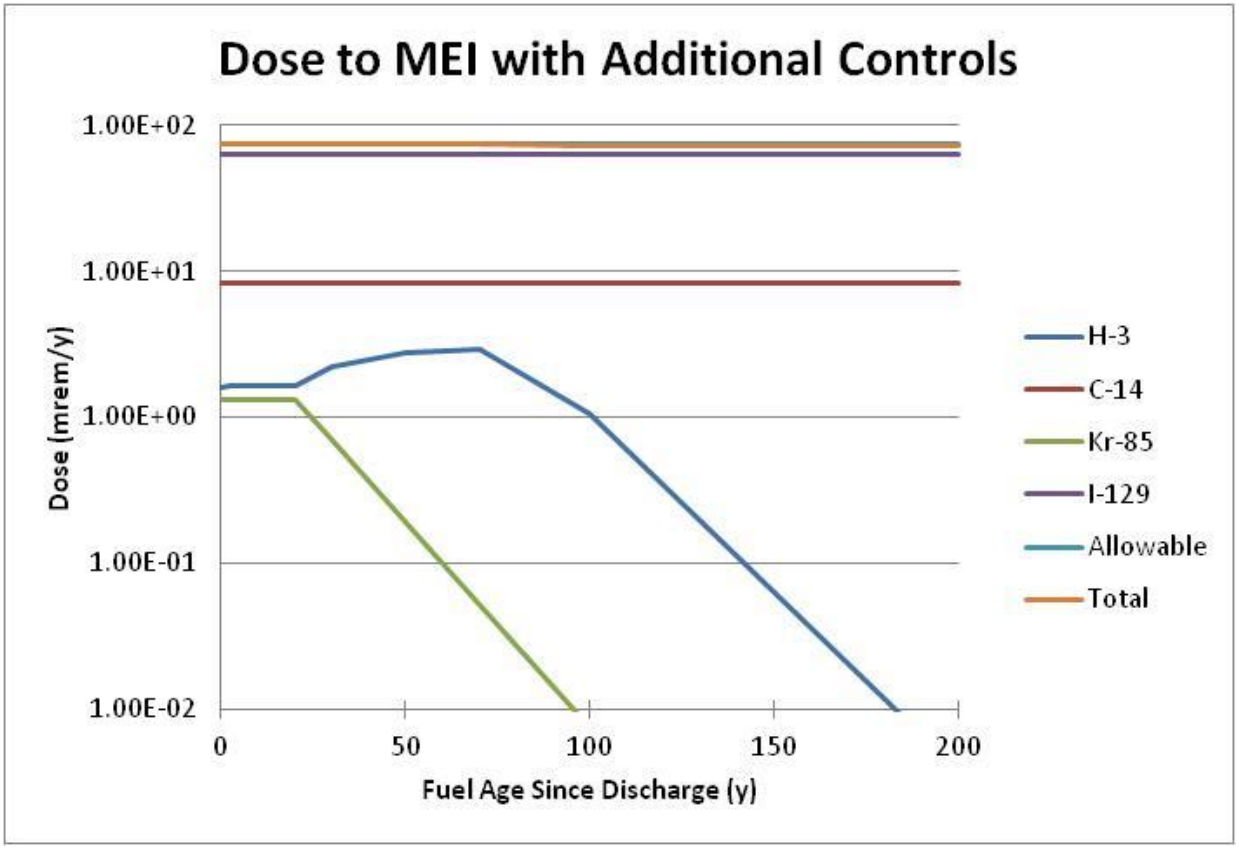


Figure B.5-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is 6.1–5.8 mrem/y (Figure B.5-9). Iodine-129 accounts for approximately 90% of this dose. Since the primary contributor to the dose is ^{129}I, an additional DF of 1.6 is applied, making the required ^{129}I DF ~8000.

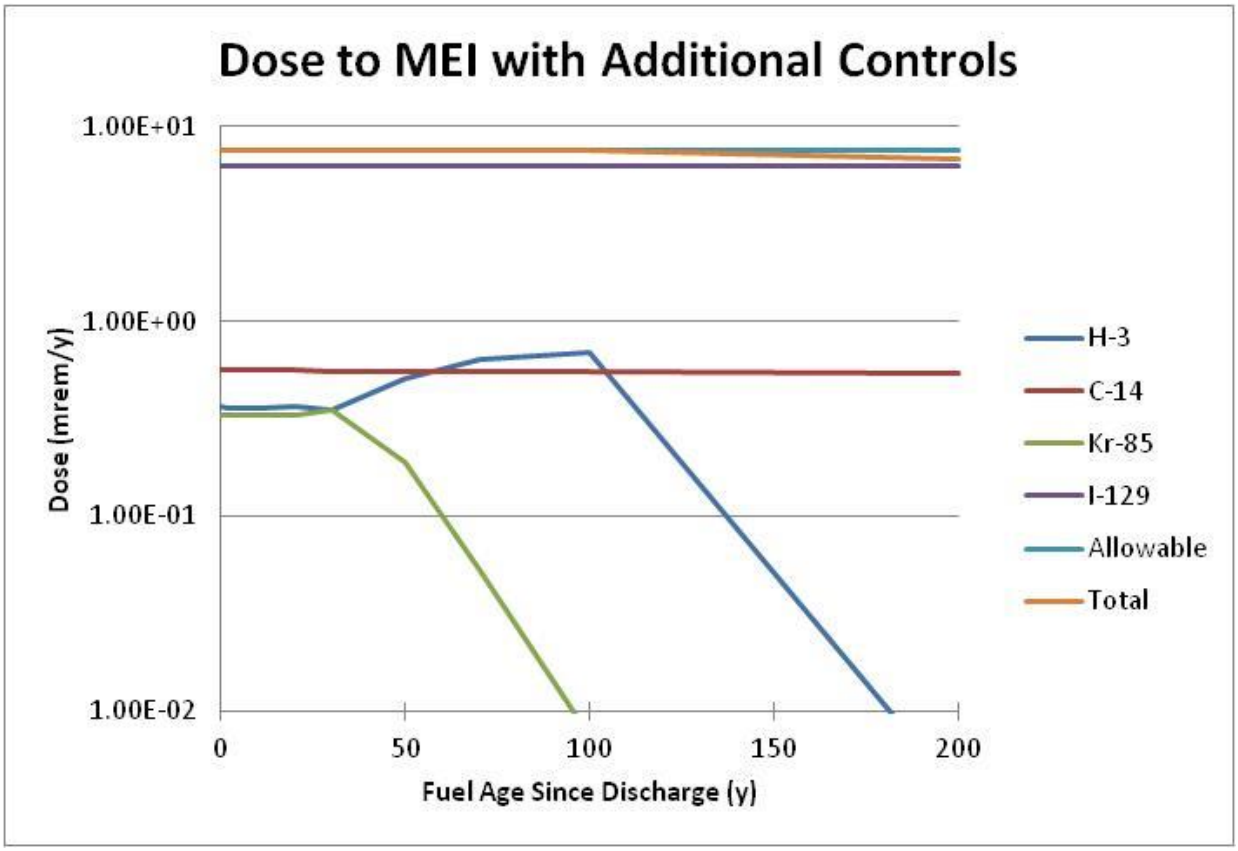


Figure B.5-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM PWR MOX fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

APPENDIX C

ADVANCED HIGH-TEMPERATURE GAS-COOLED REACTOR (AHTGR)

AHTGR FUEL

The total dose to MEI was determined from CAP-88 calculations for the reference location in the same approach as used for PWR UOX fuel. This dose assumed no emission controls for the four radionuclides of interest. In the case of AHTGR fuel, the maximum plant size for 30-GWd/tIHM fuel cooled 5 y is 36.4 t/y; if the fuel is cooled 100 y, the plant size is increased slightly to 47.1 t/y (Figure C-1). At burnups of 60 GWd/tIHM, the maximum sizes are 17.4 t/y for 5-y-cooled fuel and 21.6 t/y for 100-y-cooled fuel. If the allowable contribution of the volatile components to the total dose is limited to 2.5 mrem/y (i.e., 10% of the total dose), the plant sizes drop to 3.6 t/y and 4.7 t/y at 5-y and 100-y cooling times, respectively, for 30-GWd/tIHM fuel. At 5-y cooling, ^{129}I contributes 76.2% of the total dose and ^{3}H contributes 22.0% of the total dose. At 100-y cooling, ^{129}I contributes 98.6% of the total dose.

The second phase of the evaluation examined the impact of time since discharge in three steps for each fuel type and fuel burnup.

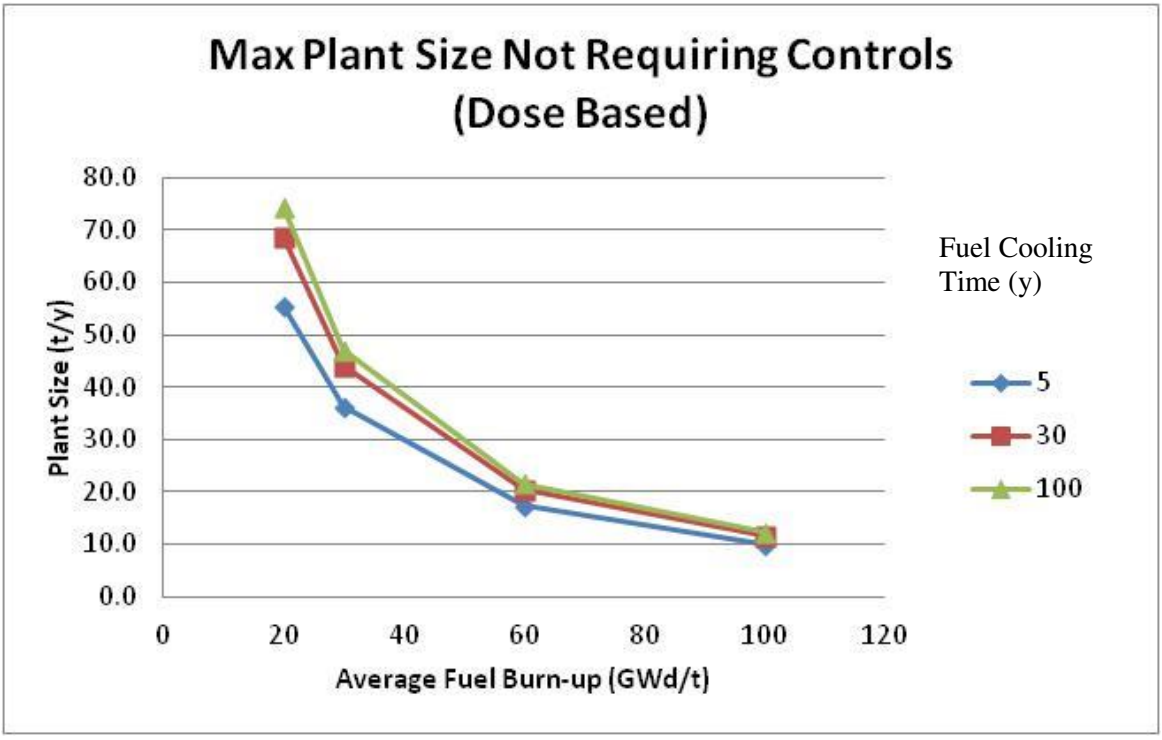


Figure C-1. Maximum plant size for processing AHTGR fuel that would not require controls to limit exposure to the MEI to below 25 mrem/y.

C.1. AHTGR / 20 GWD/T FUEL

For the case of the 20-GWd/tIHM AHTGR fuel and a plant size of 1000 t/y, the total dose to the MEI ranges from 471 mrem/y at 2-y-cooled fuel to 336 mrem/y at 100-y cooled (Figure C.1-1). Iodine-129 is the major contributor (331 mrem/y); at cooling times up to ~32 y cooling, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 4.42 mrem/y and ^{85}Kr could contribute up to 4.91 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table C.1-1.

If the ^{129}I and ^{85}Kr release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 138 mrem/y at 2-y cooling and 7.00 mrem/y for 100-y-cooled fuel (Figure C.1-2). The ^{129}I contribution is reduced to 2.10 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 60 y. Carbon-14 again contributes 4.42 mrem/y, but ^{85}Kr contributions are reduced to less than ~0.54 mrem/y. It is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit and that from Figure C.1-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{14}C and most likely ^{129}I would also be required.

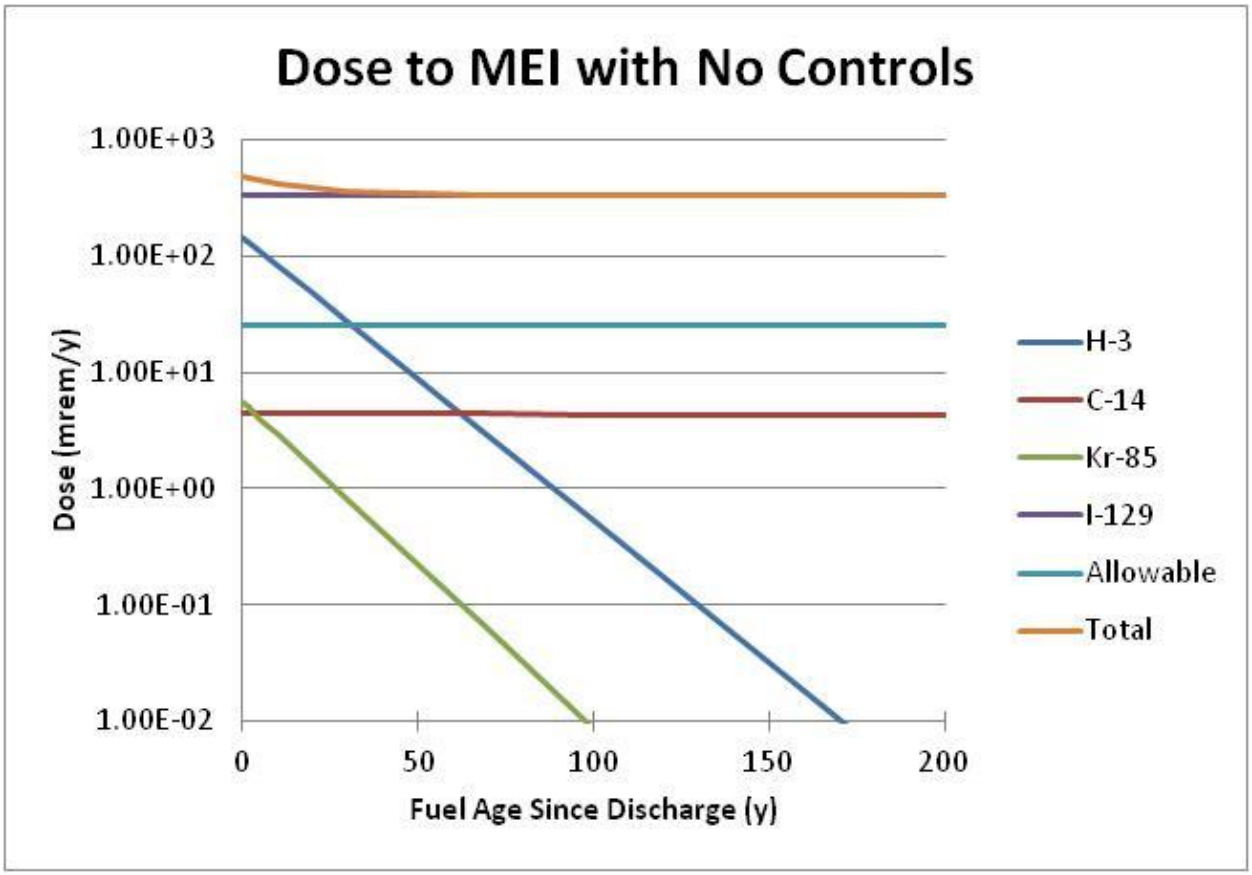


Figure C.1-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table C.1-1. Dose contributions by radionuclide based on 20-GWd/tIHM, AHTGR fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	147	131	111	83.7	47.7	27.2	8.83	2.87	0.532	0.0019
^{14}C	4.42	4.42	4.41	4.41	4.41	4.40	4.39	4.38	4.36	4.31
^{85}Kr	5.59	4.91	4.04	2.93	1.53	0.804	0.221	0.00605	0.0087	1.36×10^{-5}
^{129}I	331	331	331	331	331	331	331	331	331	331
Allowable	25	25	25	25	25	25	25	25	25	25
Total	488	471	450	422	384	363	344	338	336	335

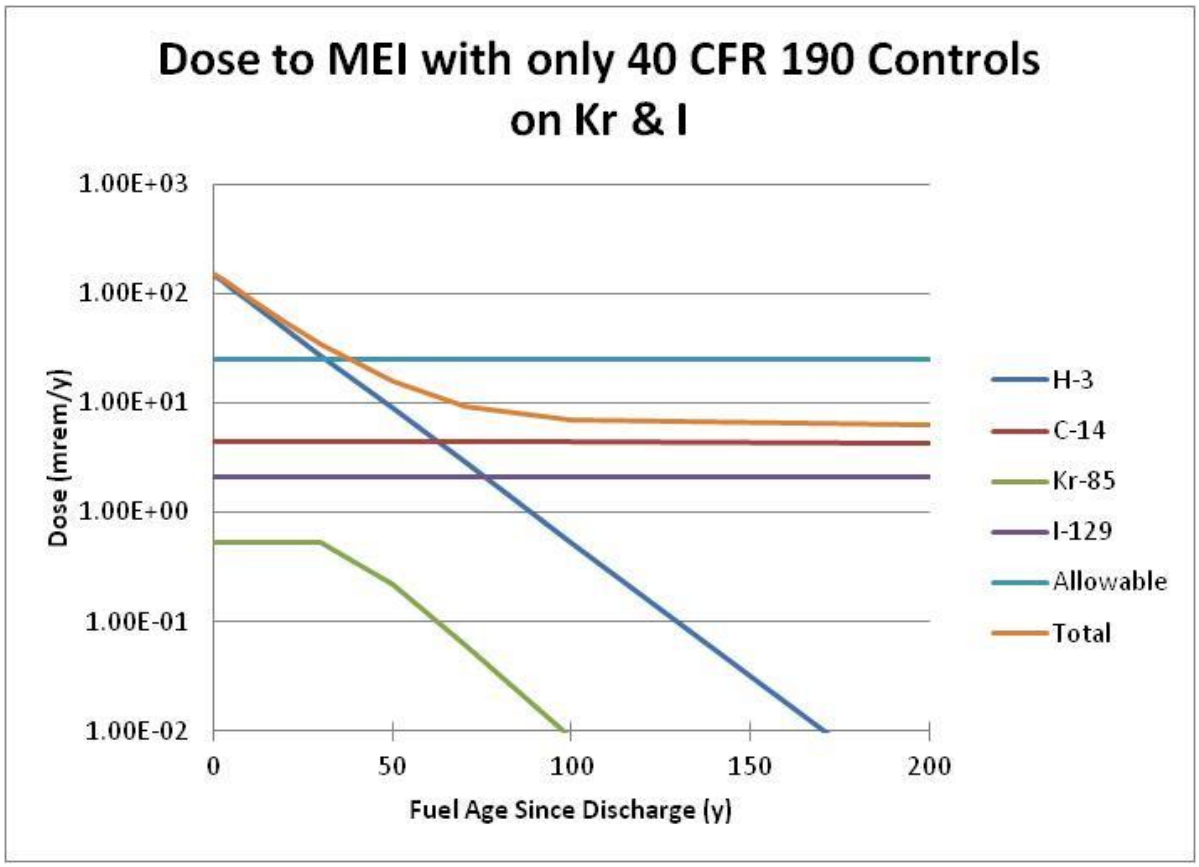


Figure C.1-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

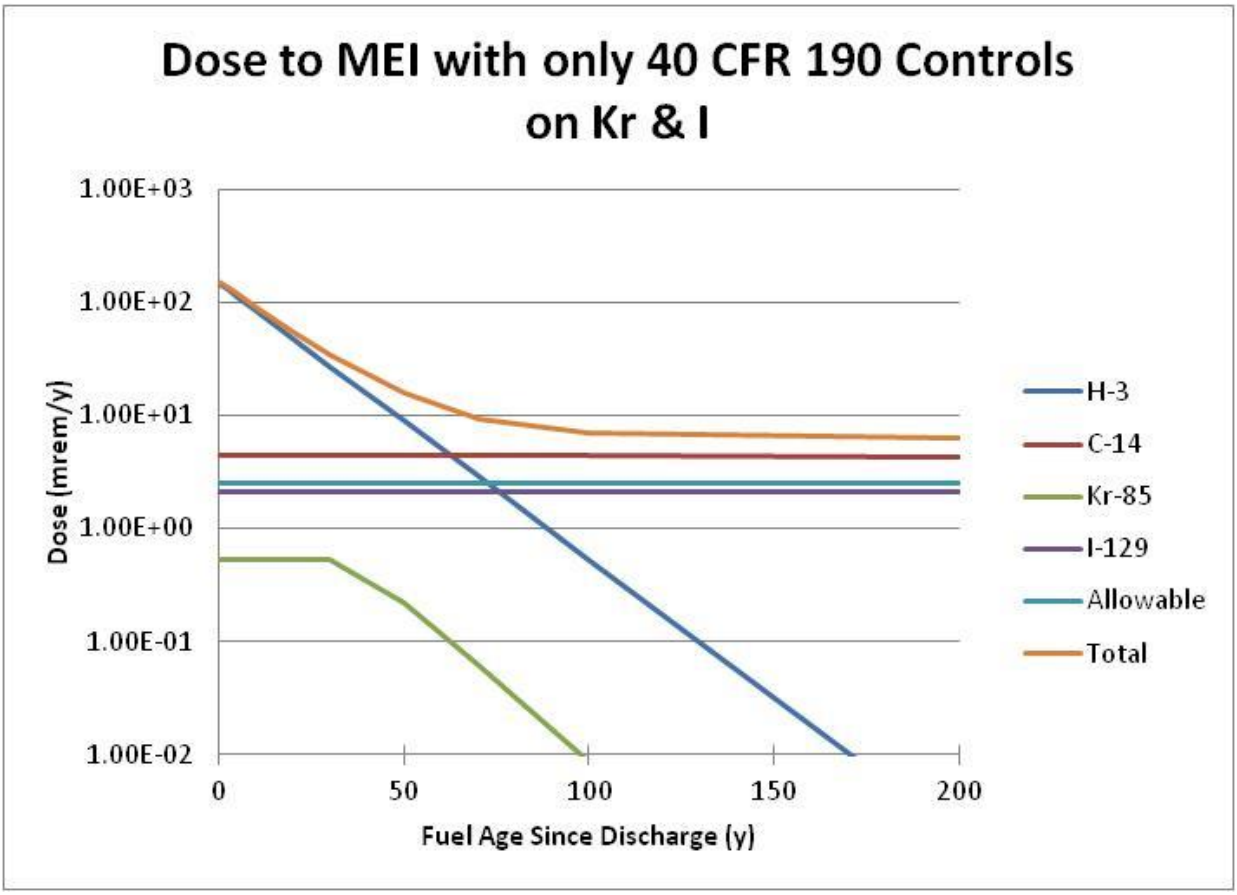


Figure C.1-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 7.3 at 2-y cooling to 1.51 at 30-y cooling (Figure C.1-4 and Table C.1-2). Beyond 40-y fuel cooling, no additional ^{3}H capture would be required if the total dose to the MEI only from the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I was taken into account. However, as noted before, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed upon ^{129}I for all times, since these individually contribute nearly 2.1 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 20 y. An additional recovery factor of 10 was applied to ^{129}I at all times, raising the total DF to ~1600. Since ^{14}C is also over the 2.5-mrem/y limit, a DF of 5 is applied to reduce its contribution to <0.9 mrem/y. Tritium DF values range from 151 for 2-y-cooled fuel to 2.12 at 70-y cooling. Figure C.1-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure C.1-6 depicts the DF requirements for each isotope as a function of cooling time. Table C.1-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table C.1-4 shows the resulting dose contributions.

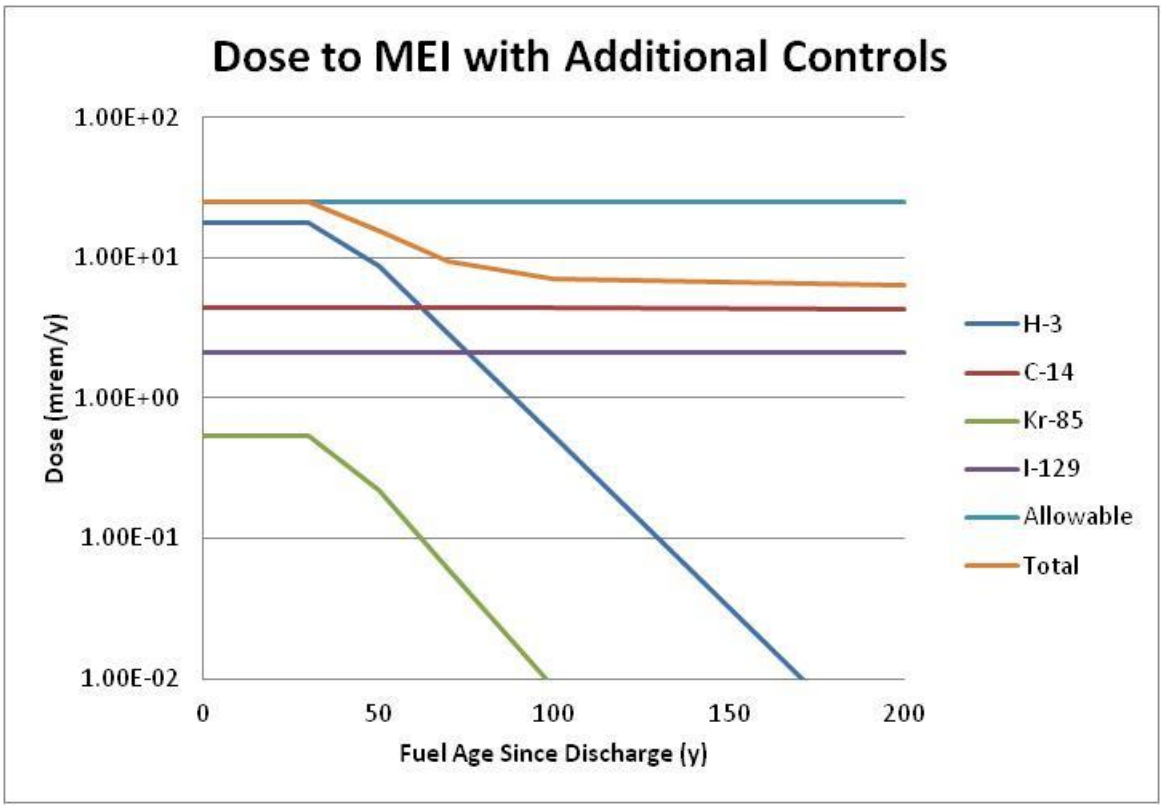


Figure C.1-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table C.1-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 30-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	8.17	7.30	6.18	4.65	2.65	1.51	1.00	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	10.39	9.13	7.52	5.44	2.85	1.49	1.00	1.00	1.00	1.00
^{129}I	157	157	157	157	157	157	157	157	157	157

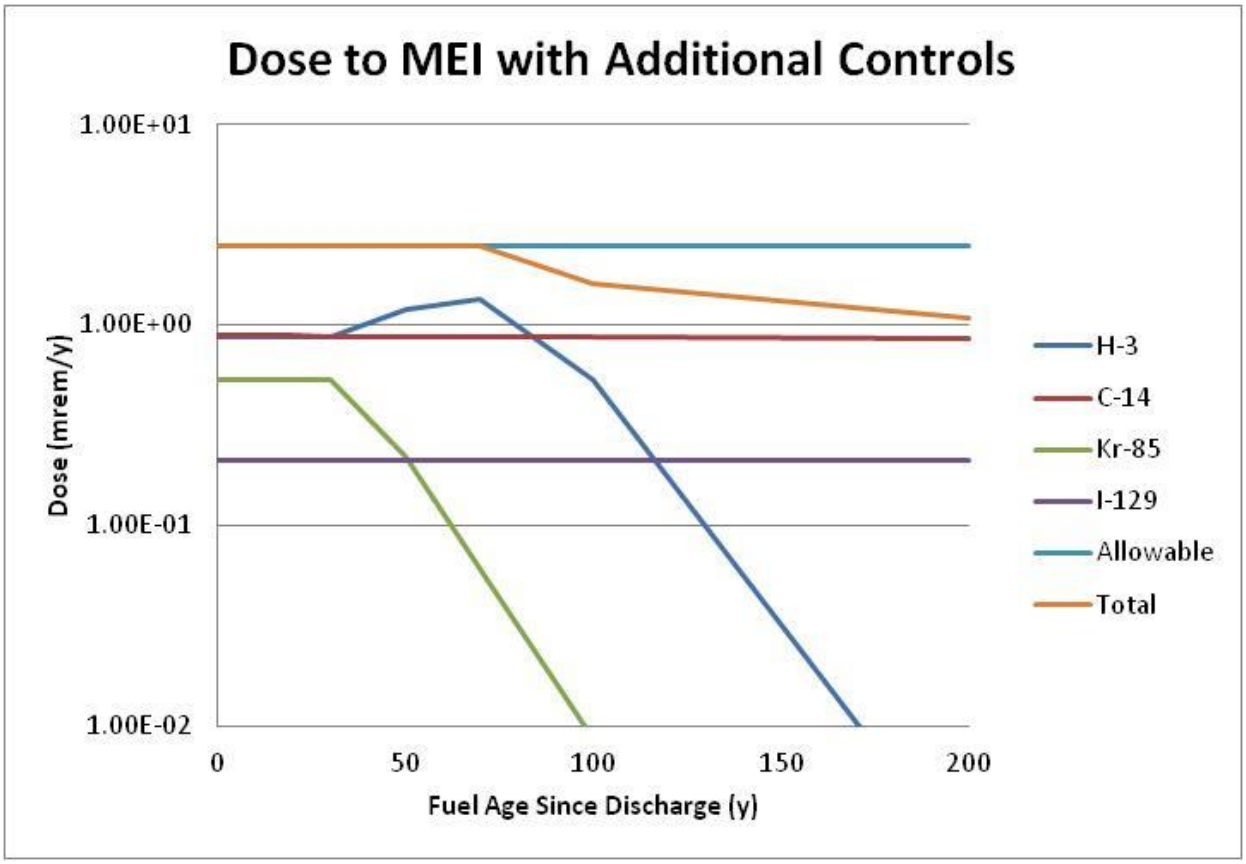


Figure C.1-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table C.1-3. Effective DFs required to achieve 2.5-mrem/y dose to MEI for 20-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	169	151	128	96.0	55.0	31.0	7.40	2.12	1.00	1.00
^{14}C	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
^{85}Kr	10.4	9.13	7.52	5.44	2.85	1.49	1.00	1.00	1.00	1.00
^{129}I	1577	1577	1577	1577	1577	1577	1577	1577	1577	1577

Table C.1-4. Dose contributions by radionuclide based on 30-GWd/tIHM AHTGR fuel cooled up to 200 y using effective DF from Table C.1-3

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	0.868	0.869	0.866	0.871	0.867	0.877	1.19	1.35	0.532	0.0019
^{14}C	0.883	0.883	0.883	0.882	0.881	0.880	0.878	0.876	0.873	0.862
^{85}Kr	0.538	0.538	0.538	0.538	0.538	0.538	0.221	0.0605	0.0087	1.36×10^{-5}
^{129}I	0.210	0.210	0.210	0.210	0.210	0.210	0.210	0.210	0.210	0.210
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.62	1.07

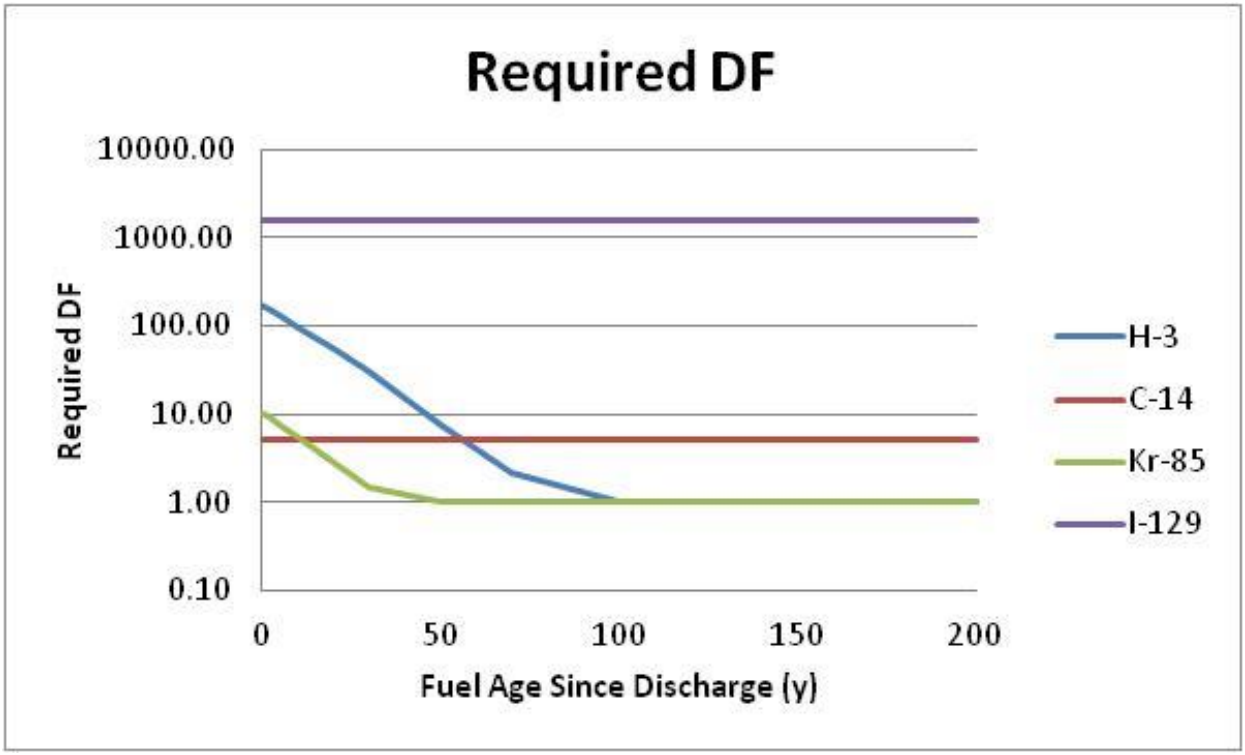


Figure C.1-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for ^{129}I and ^{85}Kr only results in a thyroid dose of 111 mrem/y for the processing of 2-y-cooled fuel, decreasing to 46.4 mrem/y at 100-y cooled (Figure C.1-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

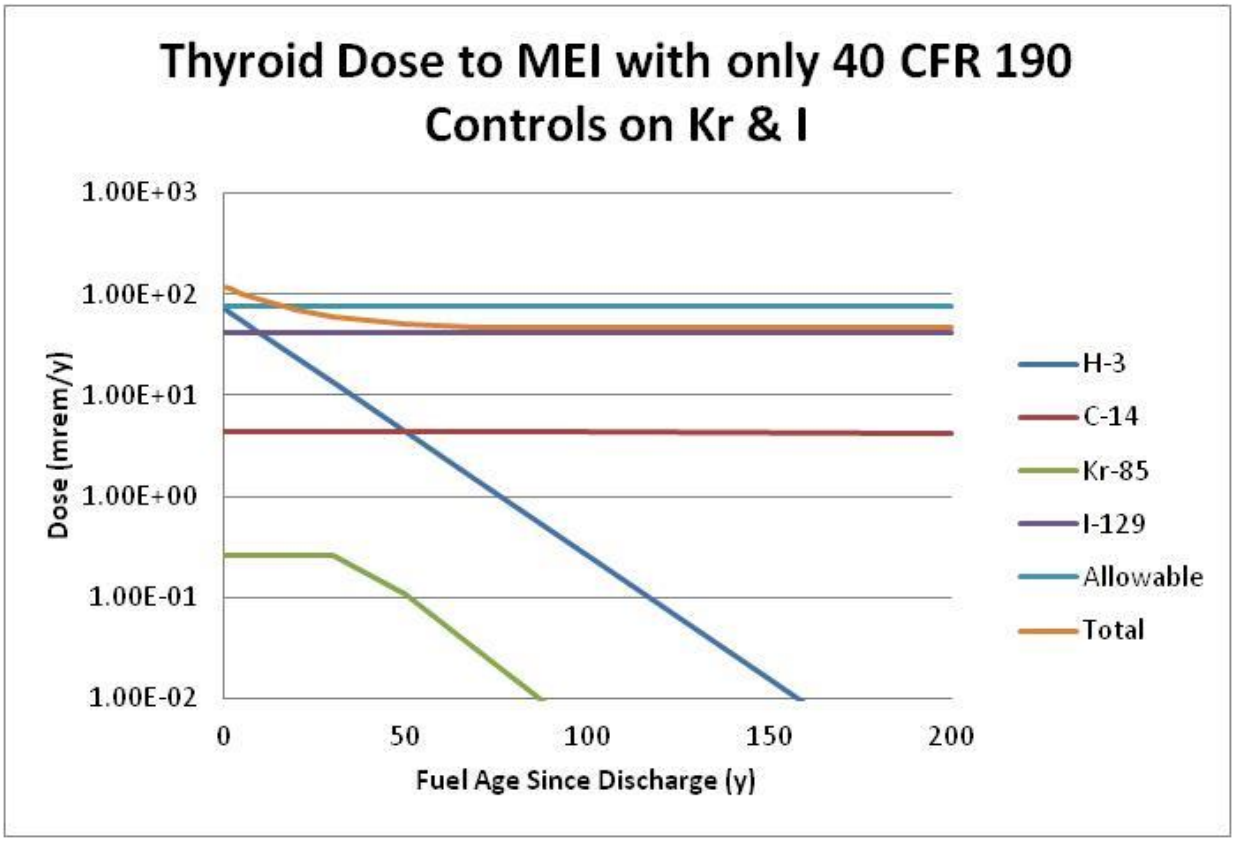


Figure C.1-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to <56 mrem/y; thus, no additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure C.1-8).

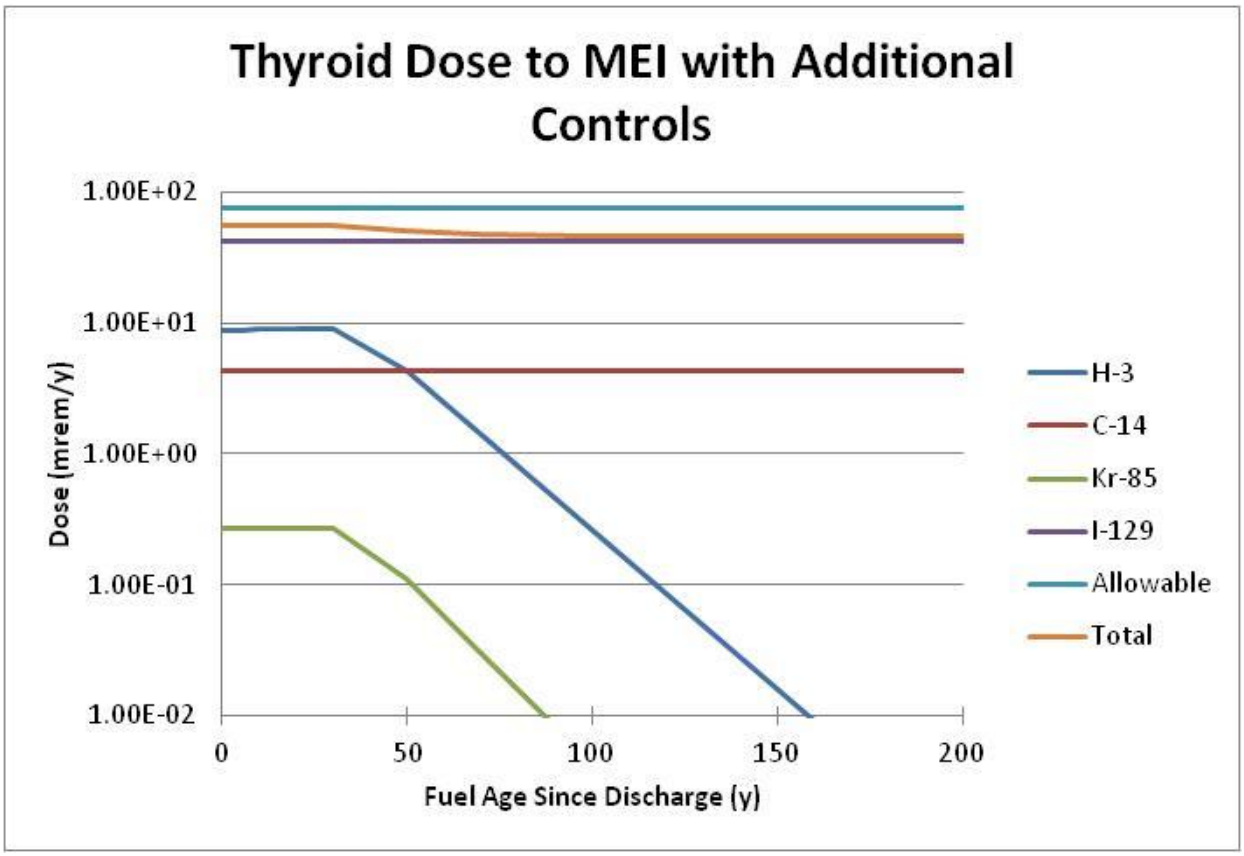


Figure C.1-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is 5.8–5.3 mrem/y (Figure C.1-9). Iodine-129 accounts for approximately 70–75% of this dose, with ^{14}C the bulk of the remaining dose.

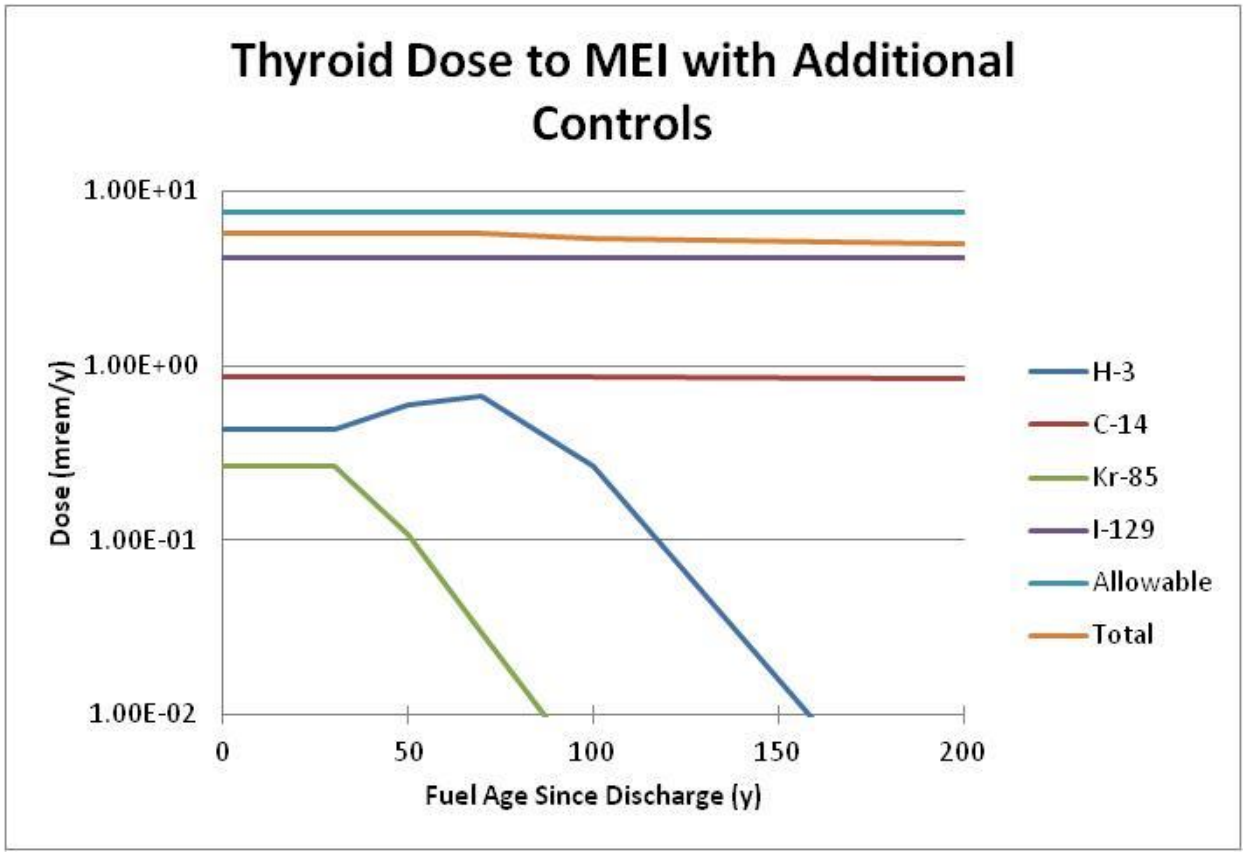


Figure C.1-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 20-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

C.2. AHTGR / 30 GWD/T FUEL

The second phase of the evaluation examined the impact of time since discharge in three steps for each fuel type and fuel burnup. For the case of the 30-GWd/tIHM AHTGR (PBR) fuel and a plant size of 1000 t/y, the total dose to the MEI ranges from 716 mrem/y at 2-y-cooled fuel to 531 mrem/y at 100-y cooled (Figure C.2-1). Iodine-129 is the major contributor (523 mrem/y); at cooling times up to ~40 y cooling, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 6.63 mrem/y and ^{85}Kr could contribute up to 6.93 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table C.2-1.

If the iodine and krypton release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 190 mrem/y at 2-y cooling and 10.4 mrem/y for 100-y-cooled fuel (Figure C.2-2). The ^{129}I contribution is reduced to 3.15 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 50 y. Carbon-14 again contributes 6.57 mrem/y and is the dominant contributor to the dose at longer cooling times. The ^{85}Kr contributions are reduced to less than ~0.8 mrem/y. It is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit and that from Figure C.2-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{129}I and ^{14}C would be required.

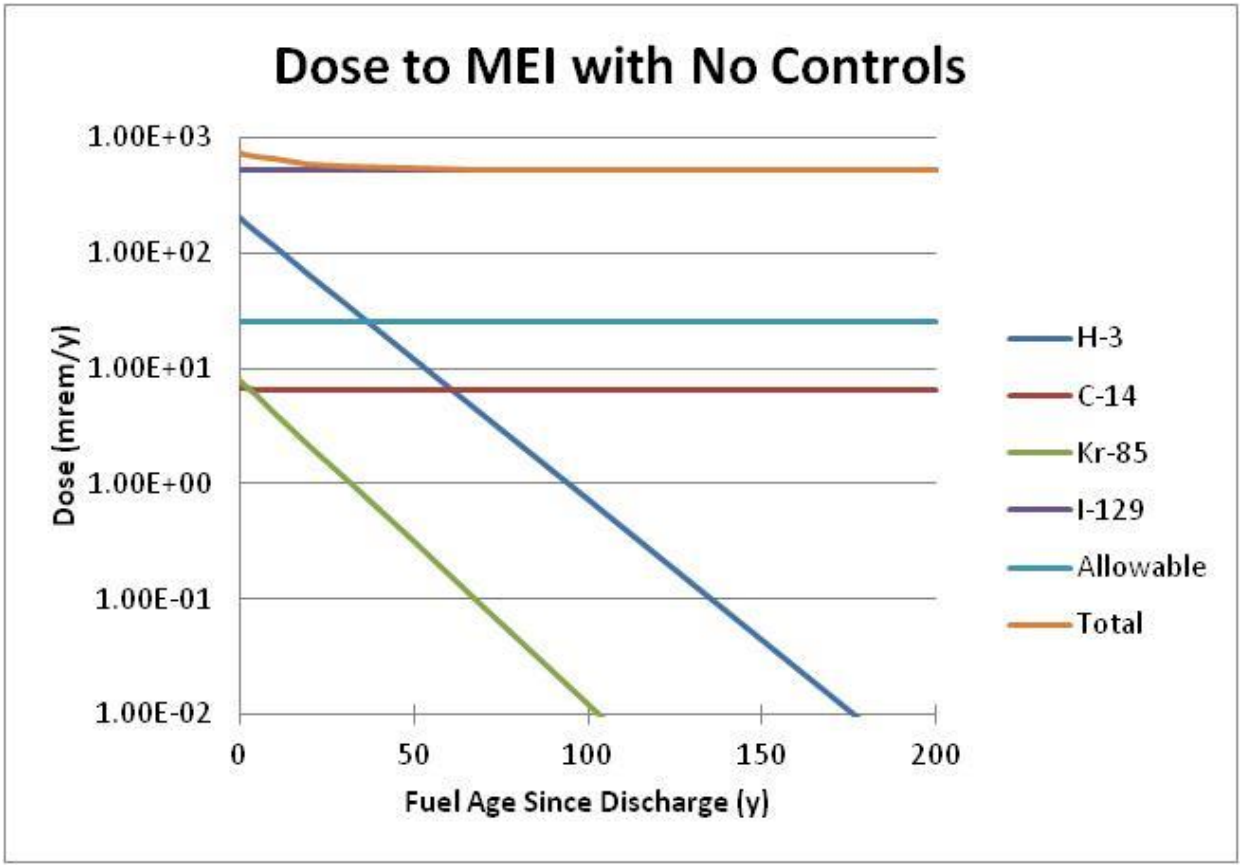


Figure C.2-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table C.2-1. Dose contributions by radionuclide based on 30 GWd/tIHM, AHTGR fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	2.00E+02	1.79E+02	1.51E+02	1.14E+02	6.51E+01	3.71E+01	1.21E+01	3.92E+00	7.26E-01	2.63E-03
^{14}C	6.63E+00	6.62E+00	6.62E+00	6.62E+00	6.61E+00	6.60E+00	6.59E+00	6.57E+00	6.55E+00	6.47E+00
^{85}Kr	7.89E+00	6.93E+00	5.71E+00	4.13E+00	2.16E+00	1.13E+00	3.11E-01	8.54E-02	1.23E-02	1.91E-05
^{129}I	5.23E+02	5.23E+02	5.23E+02	5.23E+02	5.23E+02	5.23E+02	5.23E+02	5.23E+02	5.23E+02	5.23E+02
Allowable	25	25	25	25	25	25	25	25	25	25
Total	7.38E+02	7.16E+02	6.87E+02	6.48E+02	5.97E+02	5.68E+02	5.42E+02	5.34E+02	5.31E+02	5.30E+02

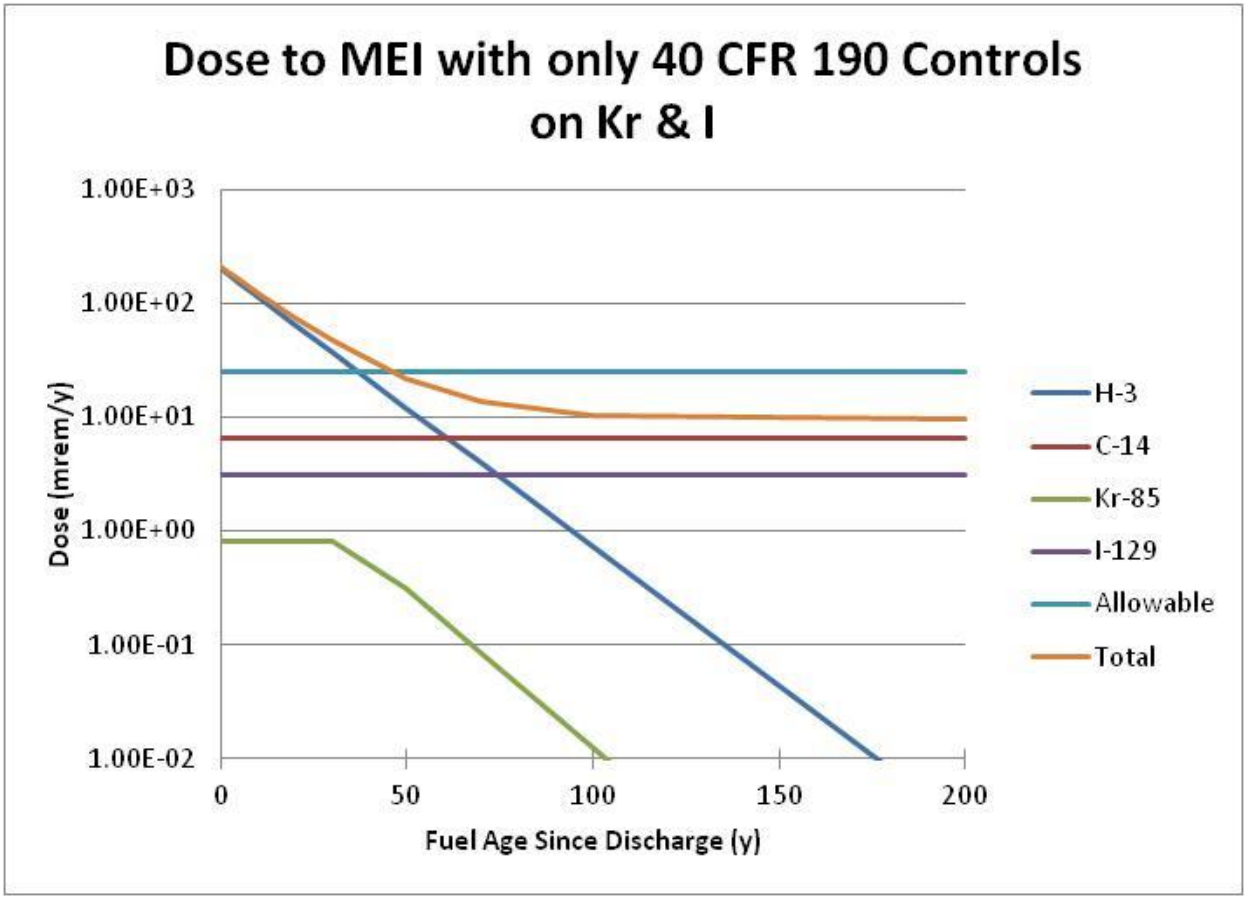


Figure C.2-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

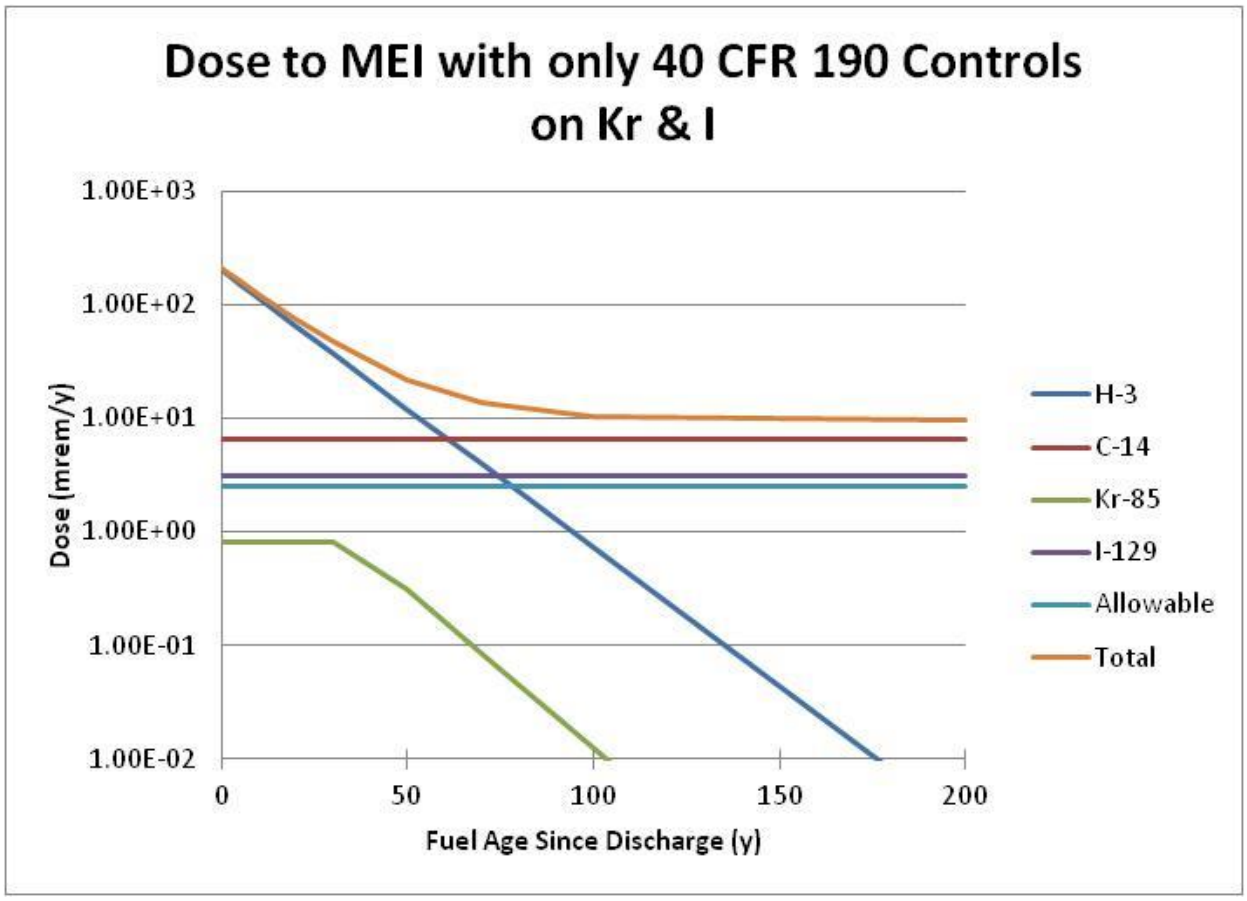
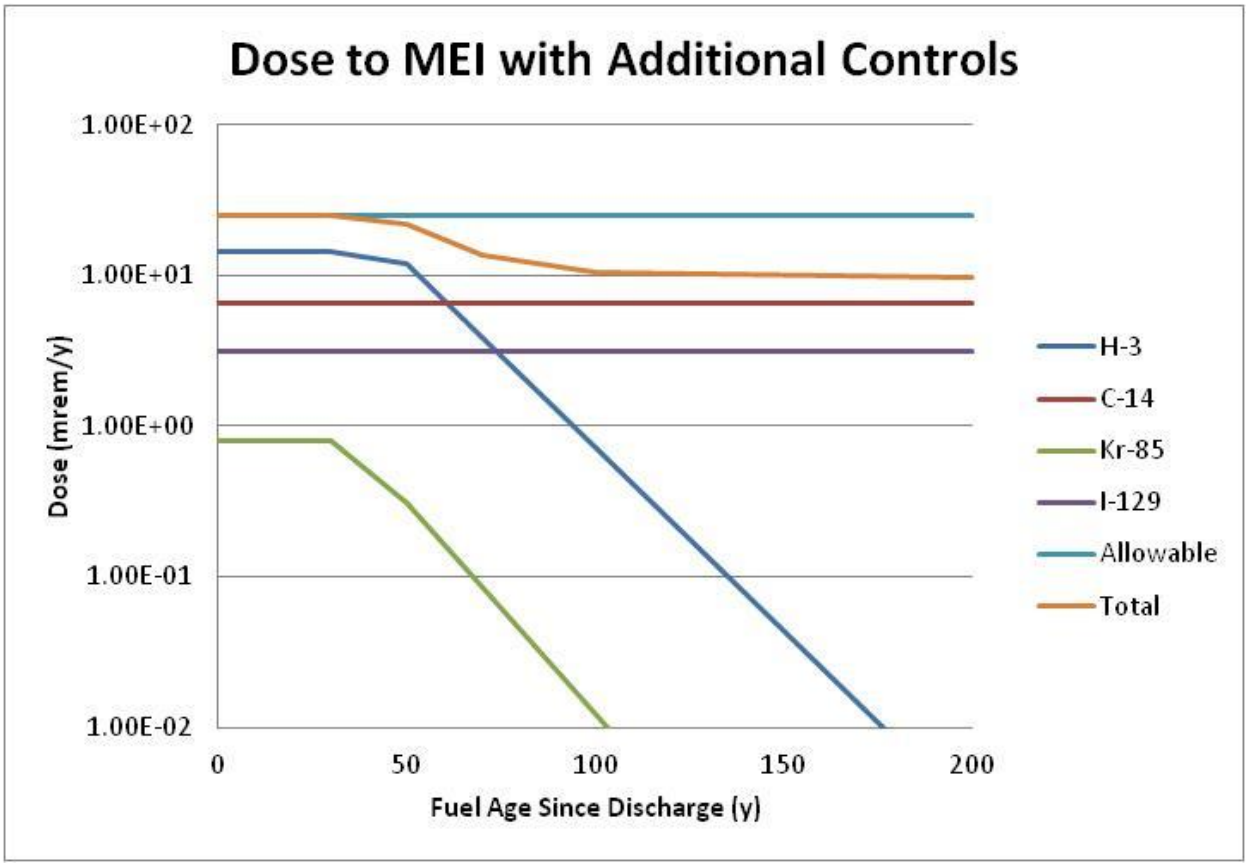


Figure C.2-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 12.4 at 2-y cooling to 2.57 at 30-y cooling (Figure C.2-4 and Table C.2-2). Beyond ~45-y fuel cooling, no additional ^{3}H capture would be required if the total dose to the MEI was taken into account only with the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, as noted before, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to ^{129}I at all times, raising the total DF to ~1700. A ^{14}C DF of 10 was also applied for all times to reduce its contribution to the total dose to ~0.7 mrem/y. Tritium DFs range from 251 for 2-y-cooled fuel to 2.71 at 70-y cooling. Figure C.2-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure C.2-6 depicts the DF requirements for each isotope as a function of cooling time. Table C.2-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table C.2-4 shows the resulting dose contributions.



FigureC.2-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table C.2-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 30-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

Effective DF										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	13.90	12.40	10.50	7.90	4.50	2.57	1.00	1.00	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	9.77	8.59	7.07	5.12	2.68	1.41	1.00	1.00	1.00	1.00
^{129}I	166.33	166.33	166.33	166.33	166.33	166.33	166.33	166.33	166.33	166.33

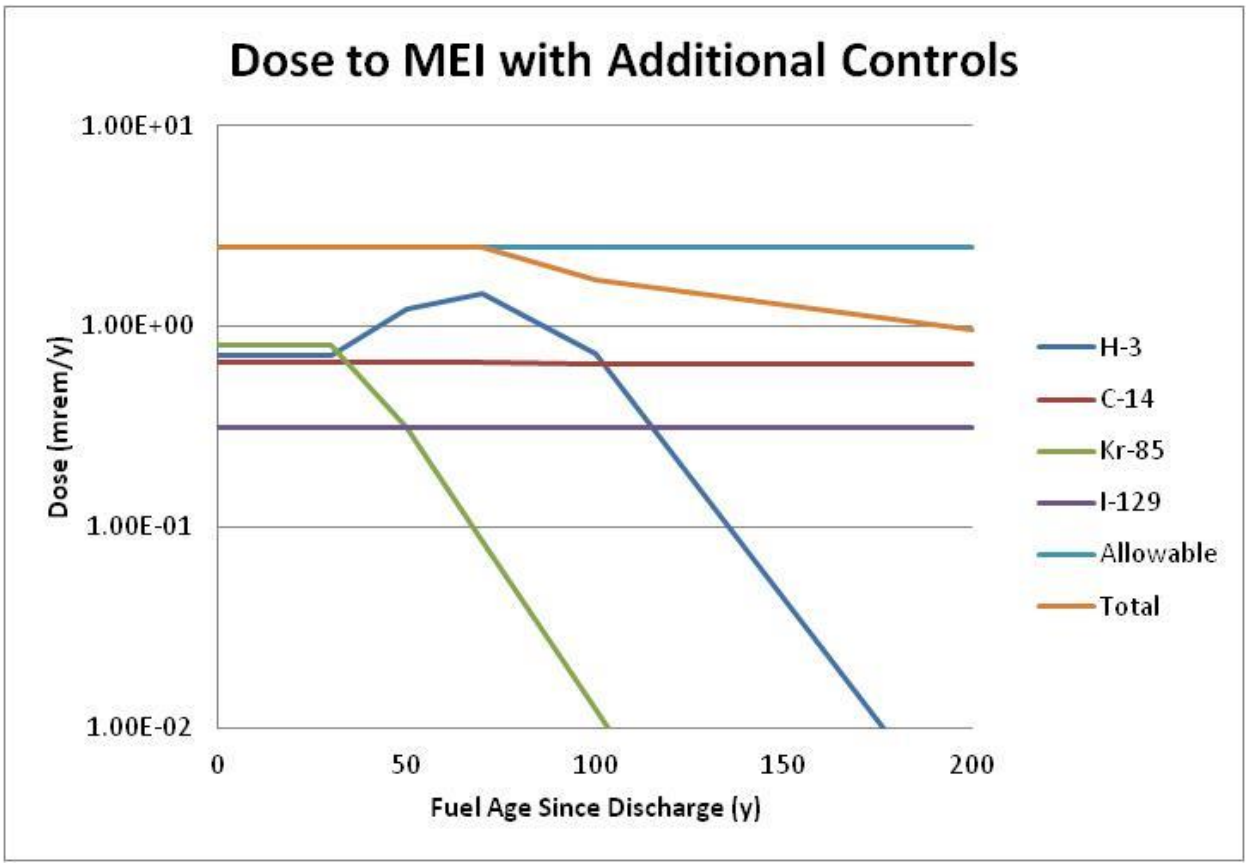


Figure C.2-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table C.2-3. Effective DFs required to achieve 2.5-mrem/y dose to MEI for 30-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

Effective DF										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	280.00	251.00	210.00	160.00	91.00	52.00	9.90	2.71	1.00	1.00
^{14}C	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
^{85}Kr	9.77	8.59	7.07	5.12	2.68	1.41	1.00	1.00	1.00	1.00
^{129}I	1663.27	1663.27	1663.27	1663.27	1663.27	1663.27	1663.27	1663.27	1663.27	1663.27

Table C.2-4. Dose contributions by radionuclide based on 30-GWd/tIHM AHTGR Fuel cooled up to 200 y using Effective DF from Table C.2-3.

Dose, mrem/y										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	7.16E-01	7.14E-01	7.21E-01	7.14E-01	7.16E-01	7.14E-01	1.22E+00	1.45E+00	7.26E-01	2.63E-03
^{14}C	6.63E-01	6.62E-01	6.62E-01	6.62E-01	6.61E-01	6.60E-01	6.59E-01	6.57E-01	6.55E-01	6.47E-01
^{85}Kr	8.07E-01	8.07E-01	8.07E-01	8.07E-01	8.07E-01	8.07E-01	3.11E-01	8.54E-02	1.23E-02	1.91E-05
^{129}I	3.15E-01	3.15E-01	3.15E-01	3.15E-01	3.15E-01	3.15E-01	3.15E-01	3.15E-01	3.15E-01	3.15E-01
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	1.71E+00	9.64E-01

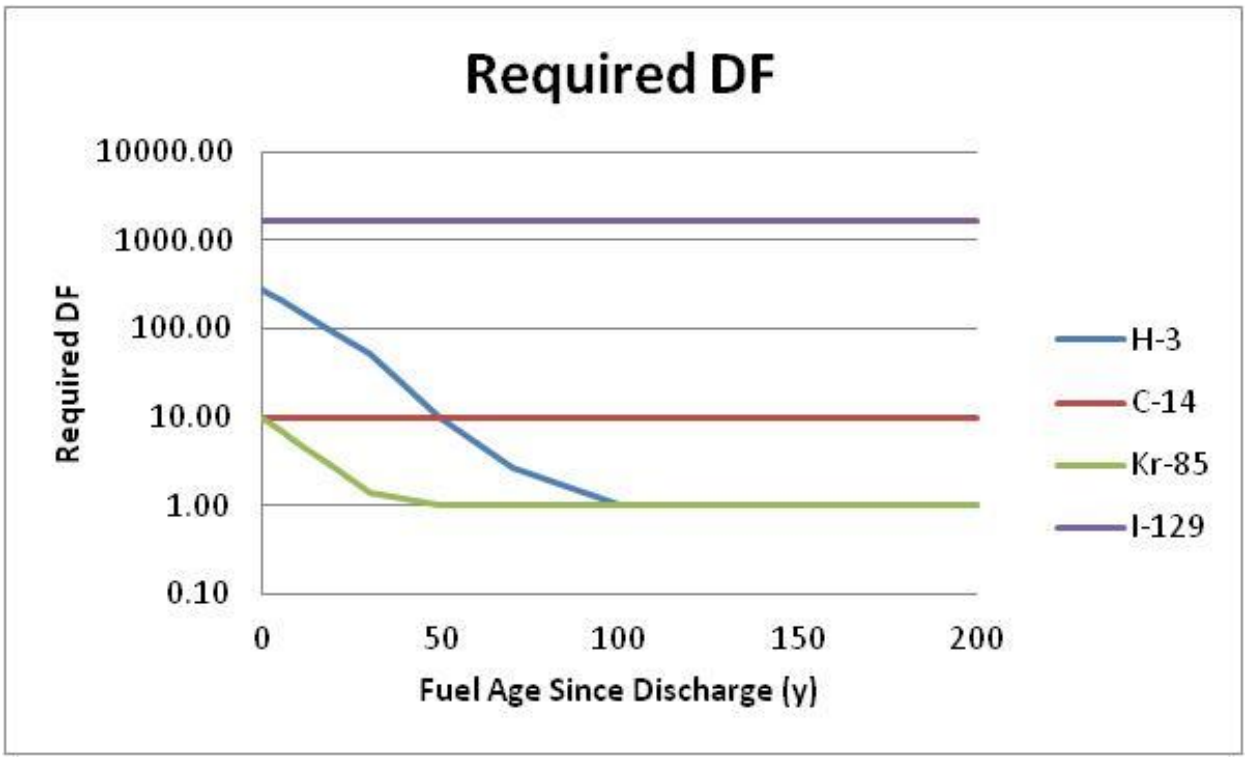


Figure C.2-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for ^{129}I and ^{85}Kr only results in a thyroid dose of 158 mrem/y for the processing of 2-y-cooled fuel decreasing to 70 mrem/y at 100-y cooled (Figure C.2-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

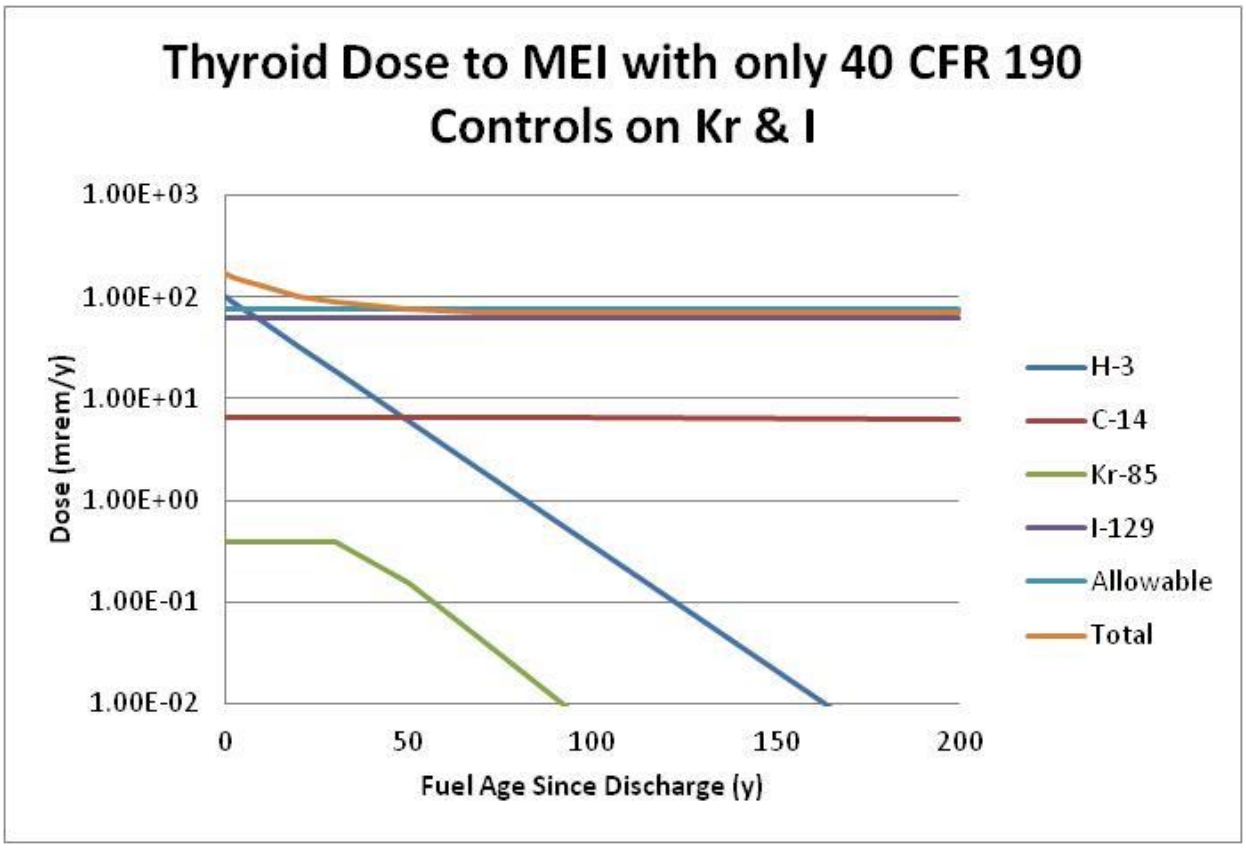


Figure C.2-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to 82.5 at 2-y cooling time and to 69.6 mrem/y at 100-y cooling; thus, some small additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure C.2-8). Iodine-129 contributes ~75% of the total dose to the thyroid, and an increase in the ^{129}I DF from 166.3 to ~172 will reduce the thyroid dose to75 mrem/y.

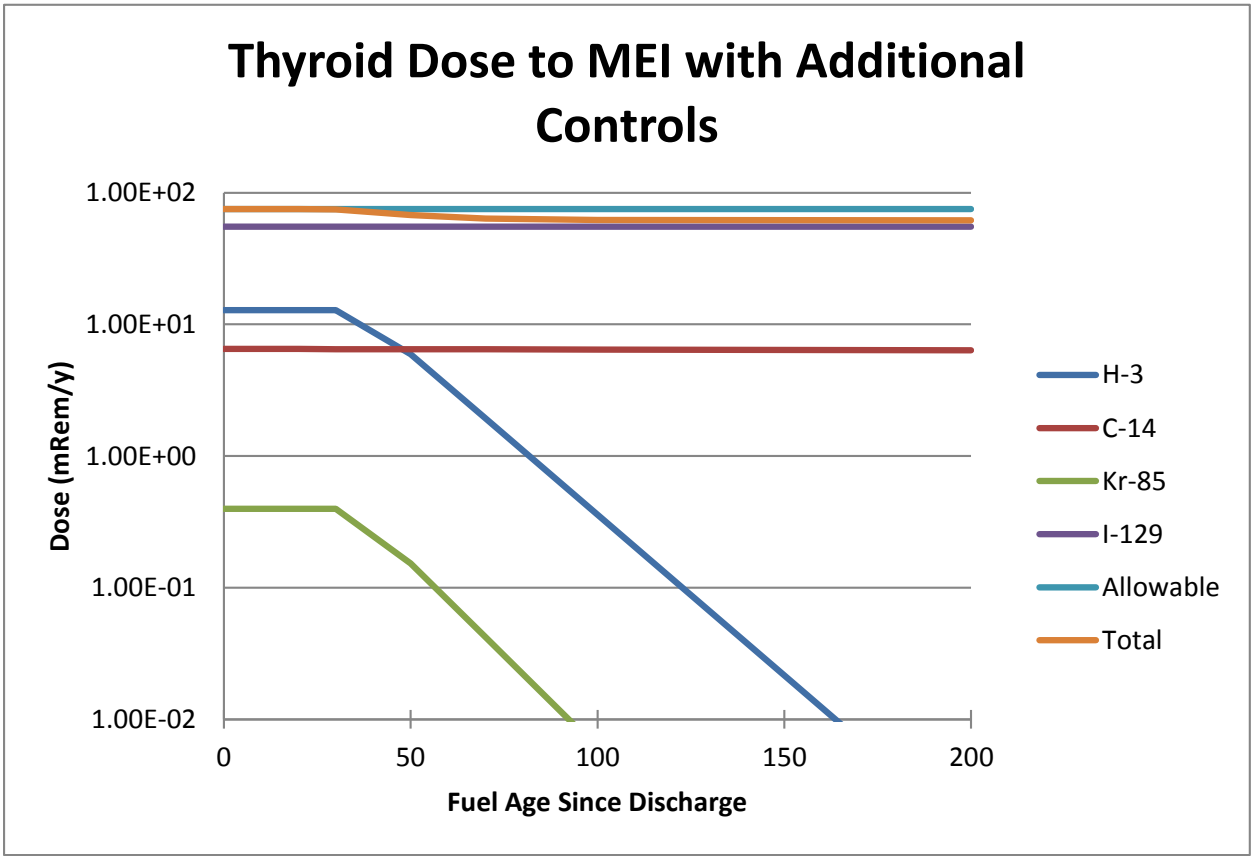


Figure C.2-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied as for the whole body dose, the resulting thyroid dose is 7.66–7.18 mrem/y (Figure C.2-9). Iodine-129 accounts for over 80% of this dose, with ^{14}C and ^{3}H making up the bulk of the remaining dose. Again a slight increase in the ^{129}I DF from ~ 1660 to ~1713 would be required to limit the thyroid dose to 7.5 mrem/y.

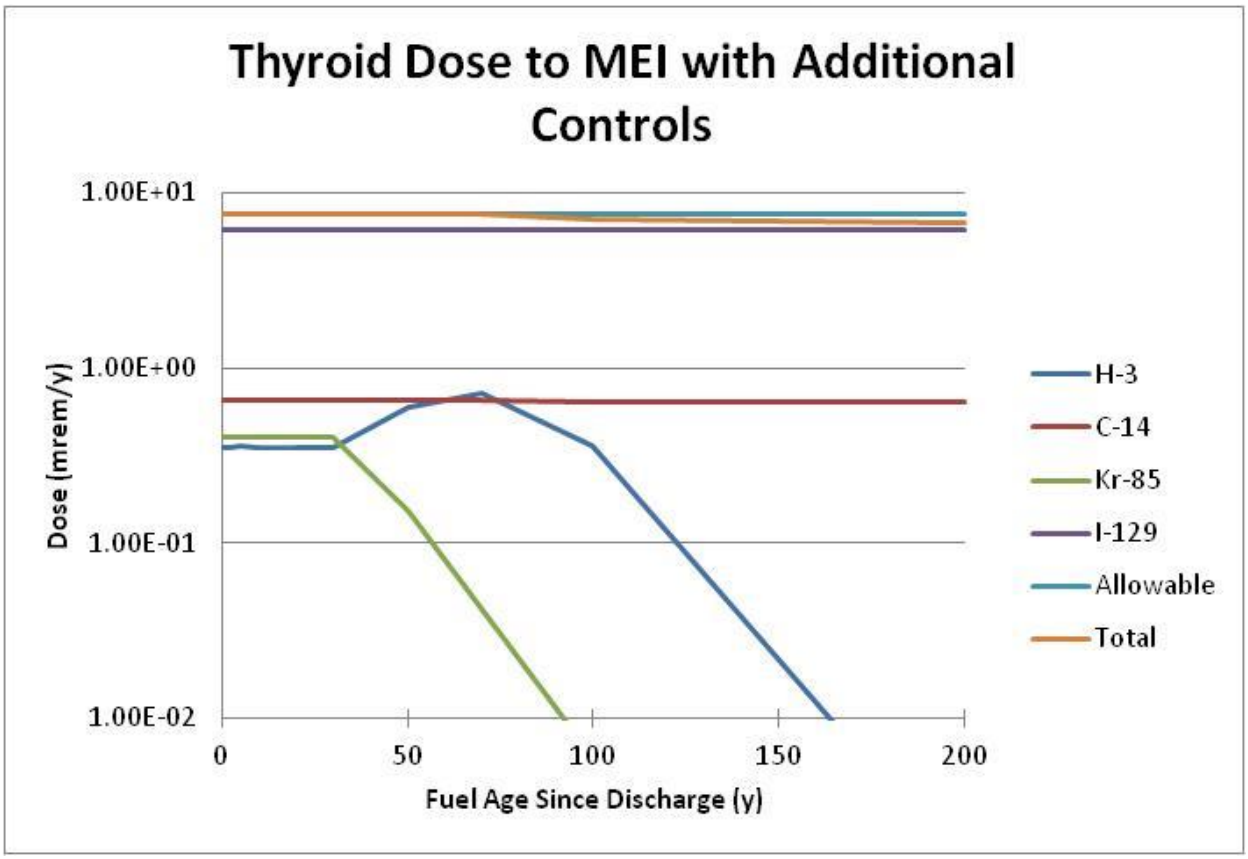


Figure C.2-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 30-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

C.3. AHTGR / 60 GWD/T FUEL

For the same AHTGR PBR fuel/reactor but at a burnup of 60 GWd/tIHM, the second-phase analysis results are as follows: For a plant size of 1000 t/y, the total dose to the MEI ranges from 1490 mrem/y at 2-y-cooled fuel to 1160 mrem/y at 100-y cooled (Figure C.3-1). Iodine-129 is the major contributor (1140 mrem/y); at cooling times up to ~45 y, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 13.6 mrem/y and ^{85}Kr could contribute up to ~12 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table C.3-1.

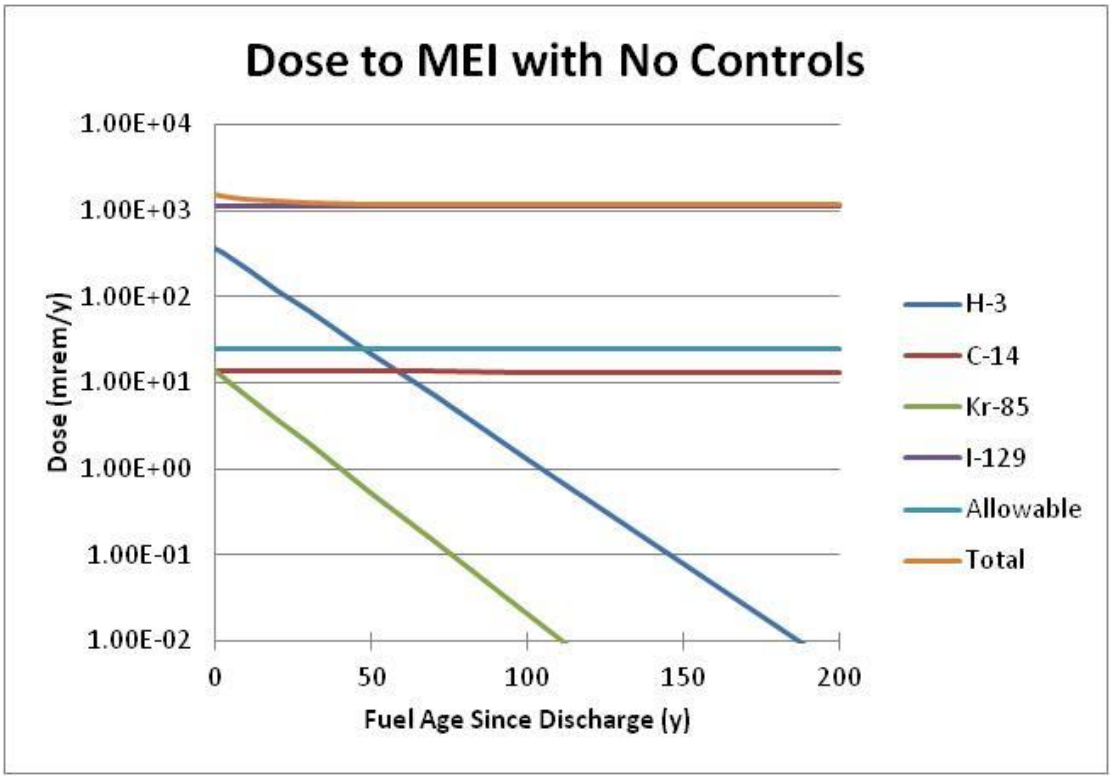


Figure C.3-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

Table C.3-1. Dose contributions by radionuclide based on 60-GWd/tIHM, AHTGR fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

	Dose, mrem/y									
	Fuel cooling, y									
	0	2	5	10	20	30	50	70	100	200
^{3}H	3.64E+02	3.26E+02	2.75E+02	2.08E+02	1.18E+02	6.75E+01	2.19E+01	7.13E+00	1.32E+00	4.78E-03
^{14}C	1.36E+01	1.36E+01	1.36E+01	1.36E+01	1.35E+01	1.35E+01	1.35E+01	1.35E+01	1.34E+01	1.32E+01
^{85}Kr	1.35E+01	1.18E+01	9.74E+00	7.05E+00	3.69E+00	1.94E+00	5.31E-01	1.46E-01	2.10E-02	3.27E-05
^{129}I	1.14E+03	1.14E+03	1.14E+03	1.14E+03	1.14E+03	1.14E+03	1.14E+03	1.14E+03	1.14E+03	1.14E+03
Allowable	25	25	25	25	25	25	25	25	25	25
Total	1.53E+03	1.49E+03	1.44E+03	1.37E+03	1.28E+03	1.23E+03	1.18E+03	1.16E+03	1.16E+03	1.16E+03

If the ^{129}I and ^{85}Kr release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 347 mrem/y at 2-y cooling and 21.0 mrem/y for 100-y-cooled fuel (Figure C.3-2). The ^{129}I contribution is reduced to 6.29 mrem/y, and ^{3}H becomes the major contributor at cooling times less than ~60 y. Carbon-14 again contributes 13.6 mrem/y, but ^{85}Kr contributions are reduced to less than 1.61 mrem/y. Again, it is clear from this figure that additional controls at least on ^{3}H would be required to meet a 25-mrem/y limit and that from Figure C.3-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{129}I and ^{14}C would also be required. Additional ^{85}Kr DF may also be required as ^{85}Kr contributed ~64% of the allocated dose contribution at short cooling times.

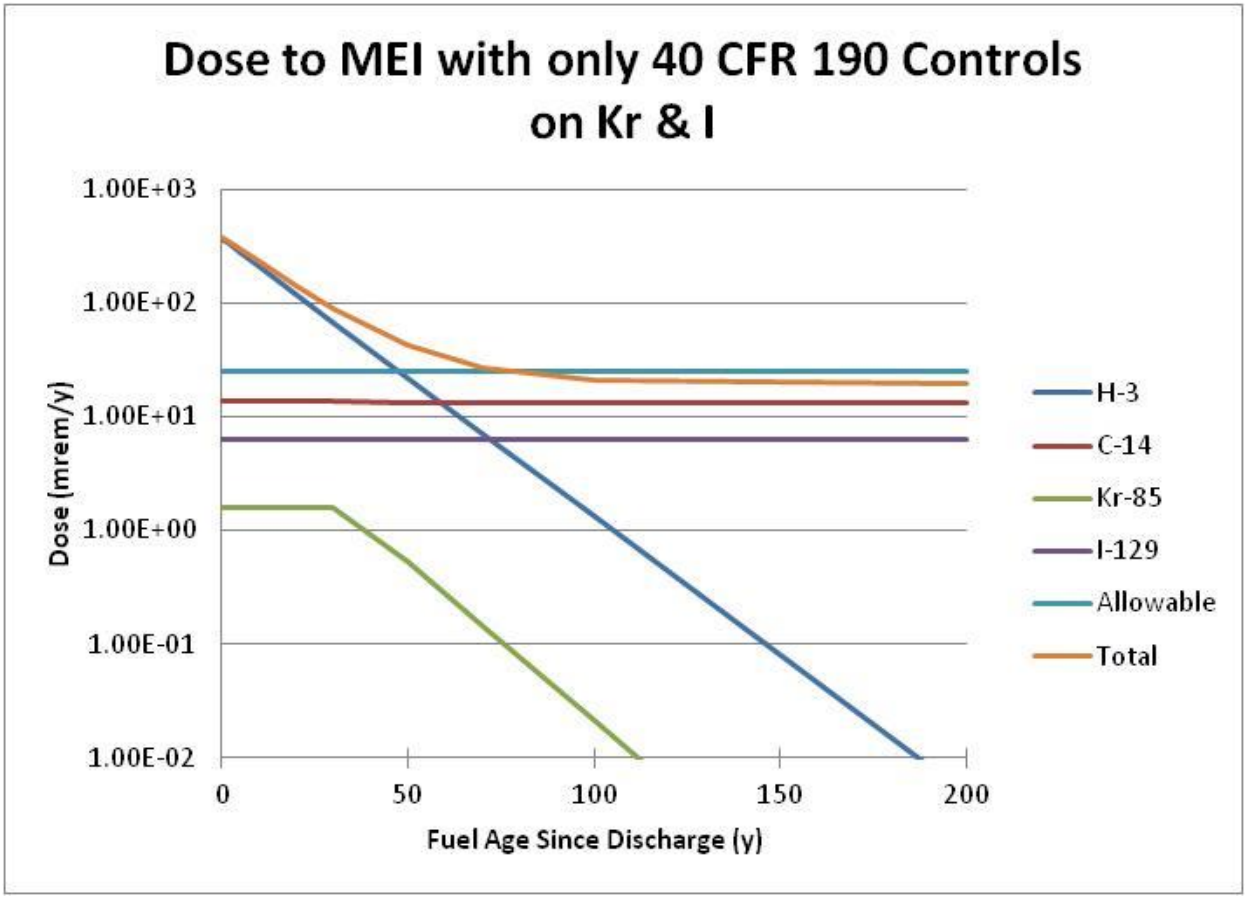


Figure C.3-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

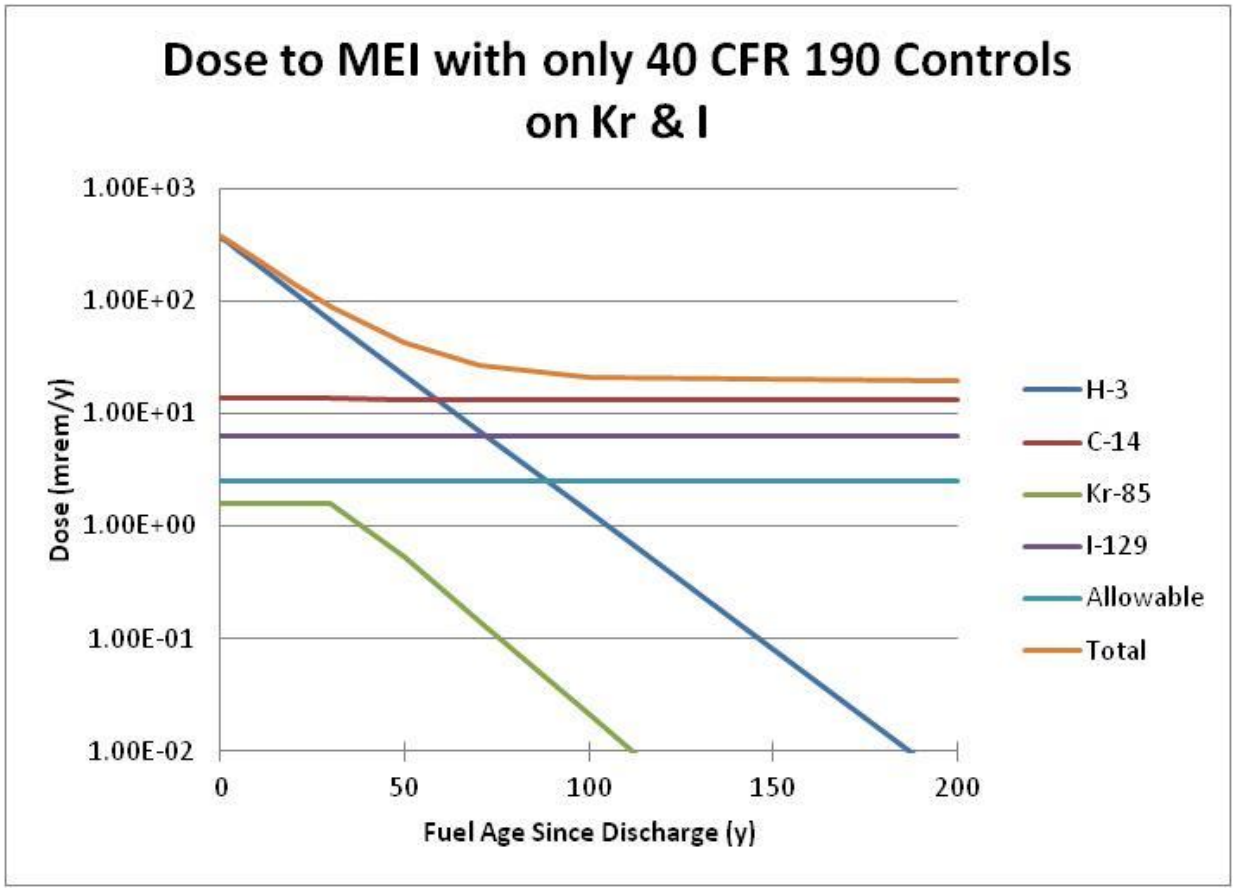


Figure C.3-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H. Tritium DF requirements ranged from 91 at 2-y cooling to 1.4 at 70-y cooling (Figure C.3-4 and Table C.3-2). Beyond ~80-y fuel cooling, no additional ^{3}H capture would be required if the total dose to the MEI were accounted for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. An additional recovery factor of 10 was applied to ^{129}I at all times, raising the total DF to ~1800. A ^{14}C DF of 20 for times up to 200 y was applied to reduce its contribution to the total dose to ~0.7 mrem/y. Additional ^{85}Kr DF requirements were also imposed for the same time frames as required by the 40 CFR 190 release limit for ^{85}Kr (up to 30-y cooling) due to the relatively large contribution of ^{85}Kr (1.6 mrem/y out of 2.5 mrem/y). Tritium DFs range from 500 for 2-y-cooled fuel to ~1.12 at 100-y-cooled fuel. Beyond ~105 y no ^{3}H recover would be required. Figure C.3-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure C.3-6 depicts the DF requirements for each isotope as a function of cooling time. Table C.3-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table C.3-4 shows the resulting dose contributions.

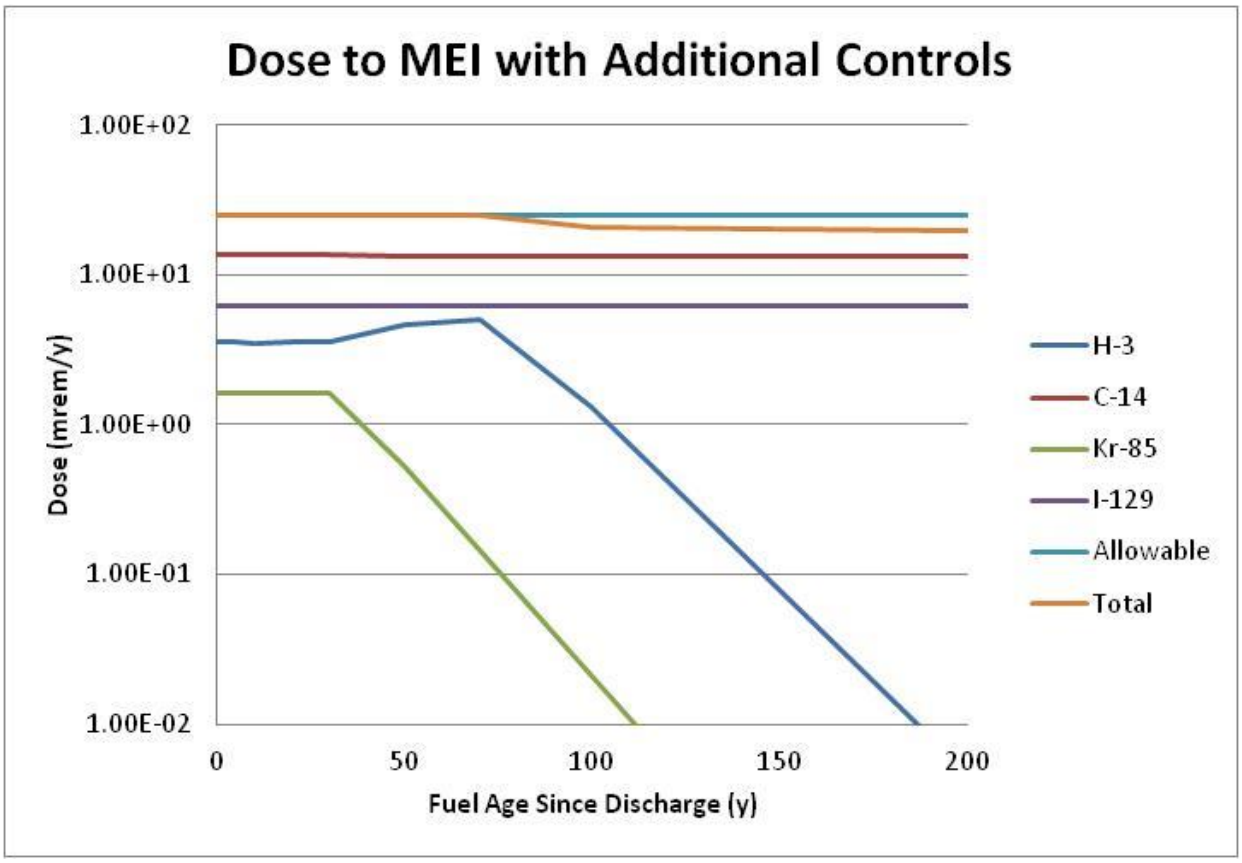


Figure C.3-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table C.3-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 60-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

	Effective DF									
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	103.00	91.00	77.00	59.00	33.00	19.00	4.70	1.40	1.00	1.00
^{14}C	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
^{85}Kr	8.34	7.33	6.04	4.37	2.29	1.20	1.00	1.00	1.00	1.00
^{129}I	181.55	181.55	181.55	181.55	181.55	181.55	181.55	181.55	181.55	181.55

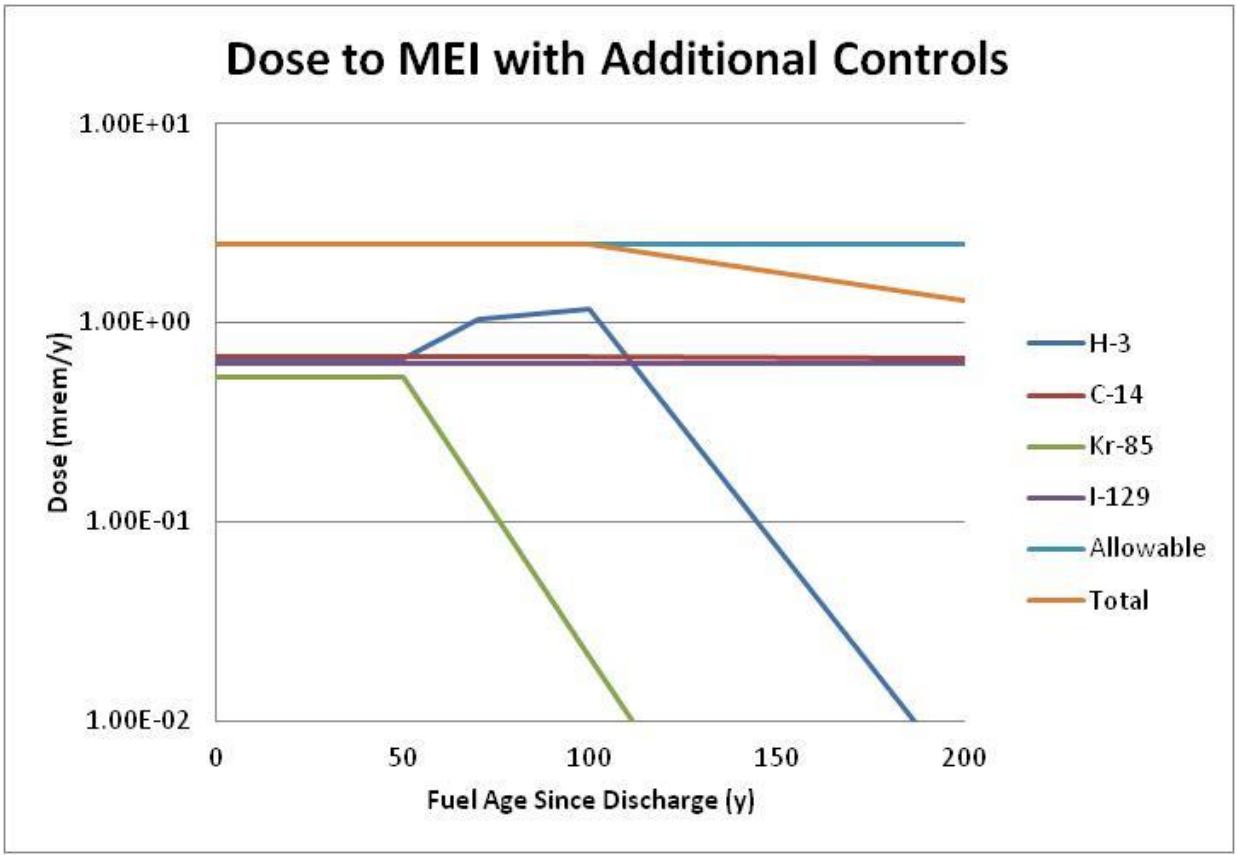


Figure C.3-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table C.3-3. Effective DFs required to achieve 2.5-mrem/y whole body dose to MEI for 60-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

	Effective DF									
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	560.00	500.00	420.00	315.00	180.00	103.00	33.00	6.80	1.12	1.00
^{14}C	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
^{85}Kr	25.02	21.99	18.11	13.11	6.87	3.60	1.00	1.00	1.00	1.00
^{129}I	1815.54	1815.54	1815.54	1815.54	1815.54	1815.54	1815.54	1815.54	1815.54	1815.54

Table C.3-4. Dose contributions by radionuclide based on 60-GWd/tIHM, AHTGR fuel cooled up to 200 y using effective DFs from Table C.3-3

Dose, mrem/y										
	Fuel cooling, y									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	6.51E-01	6.51E-01	6.55E-01	6.59E-01	6.58E-01	6.55E-01	6.64E-01	1.05E+00	1.18E+00	4.78E-03
^{14}C	6.78E-01	6.78E-01	6.78E-01	6.78E-01	6.77E-01	6.76E-01	6.74E-01	6.73E-01	6.70E-01	6.62E-01
^{85}Kr	5.38E-01	5.38E-01	5.38E-01	5.38E-01	5.38E-01	5.38E-01	5.31E-01	1.46E-01	2.10E-02	3.27E-05
^{129}I	6.29E-01	6.29E-01	6.29E-01	6.29E-01	6.29E-01	6.29E-01	6.29E-01	6.29E-01	6.29E-01	6.29E-01
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	2.50E+00	1.30E+00

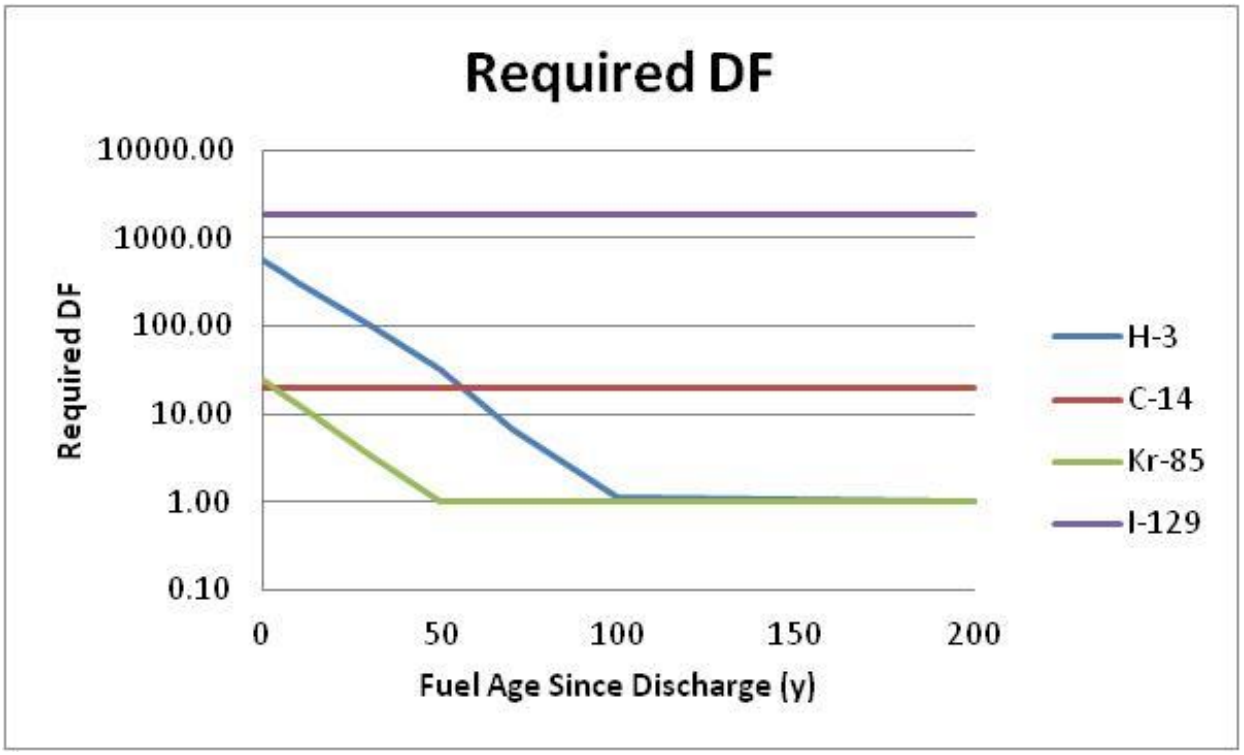


Figure C3-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75-mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for ^{129}I and ^{85}Kr only results in a thyroid dose of 300 mrem/y for the processing of 2-y-cooled fuel decreasing to 139 mrem/y at 100-y cooled (Figure C.3-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

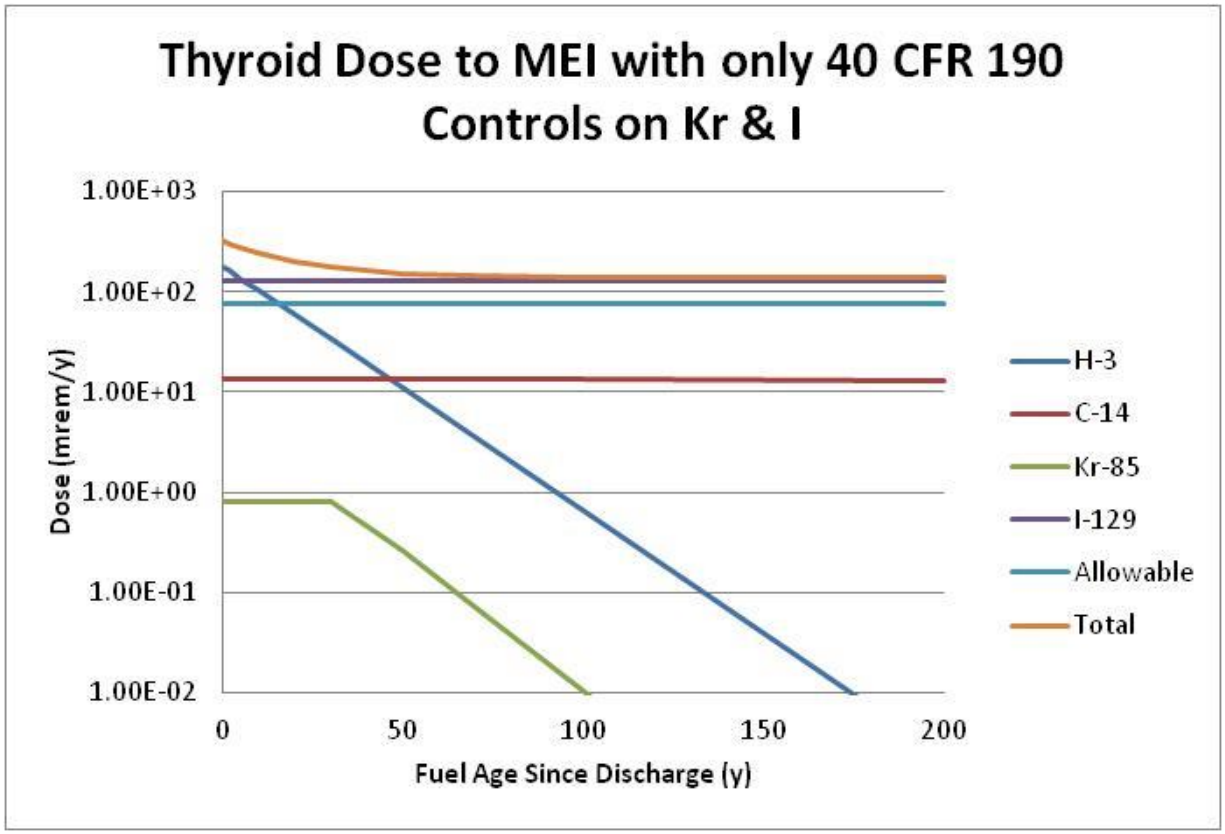


Figure C.3-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that dose to the thyroid is reduced to 141 to 139 mrem/y; thus, additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure C.3-8). An additional DF of ~2.13 on ^{129}I for a total ^{129}I DF of ~390 would be required to reduce the total dose to <75 mrem/y.

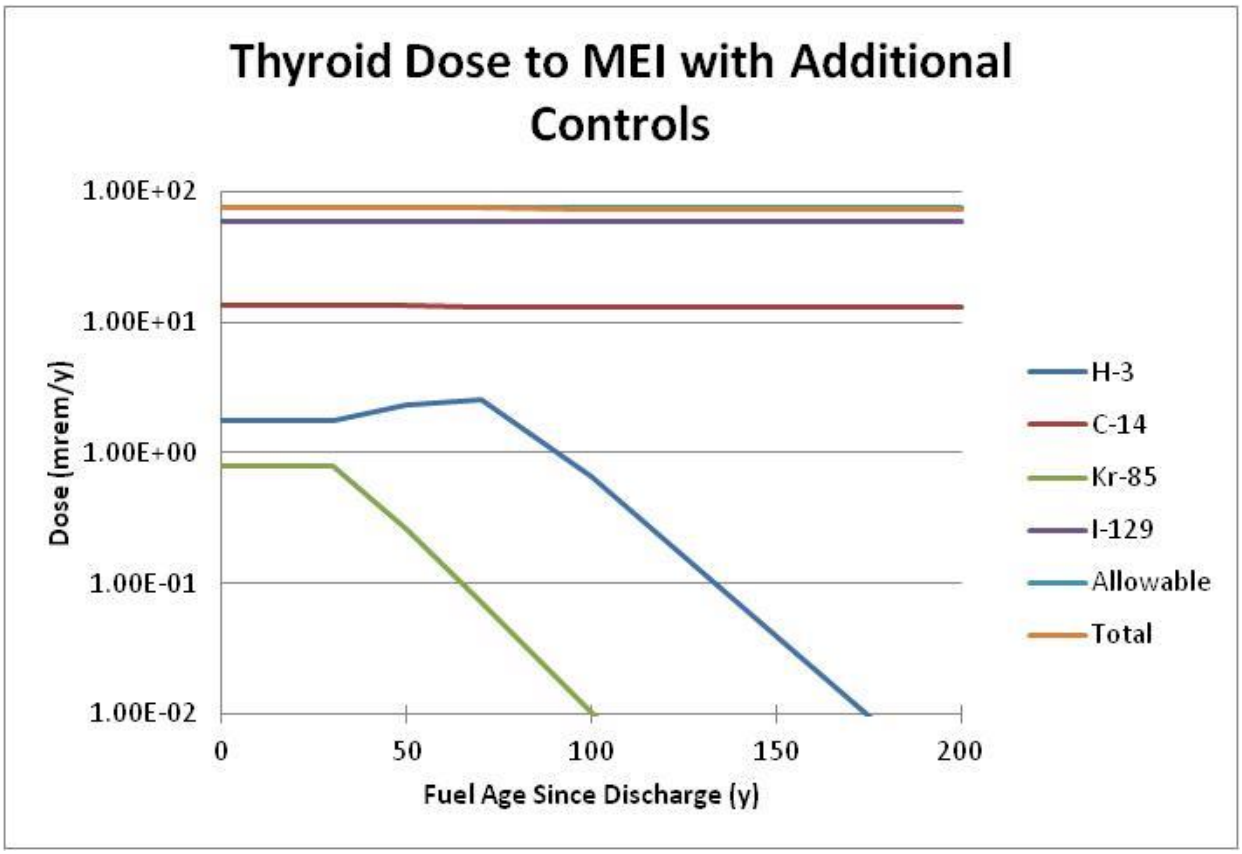


Figure C.3-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25 mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y.

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is 13.8 mrem/y (Figure C.3-9). Iodine-129 accounts for approximately 90+% of this dose with ^{14}C the bulk of the remaining dose, especially at longer cooling times. An additional DF of ~2 on ^{129}I for a total ^{129}I DF of ~3650 would be required to reduce the total dose to <7.5 mrem/y.

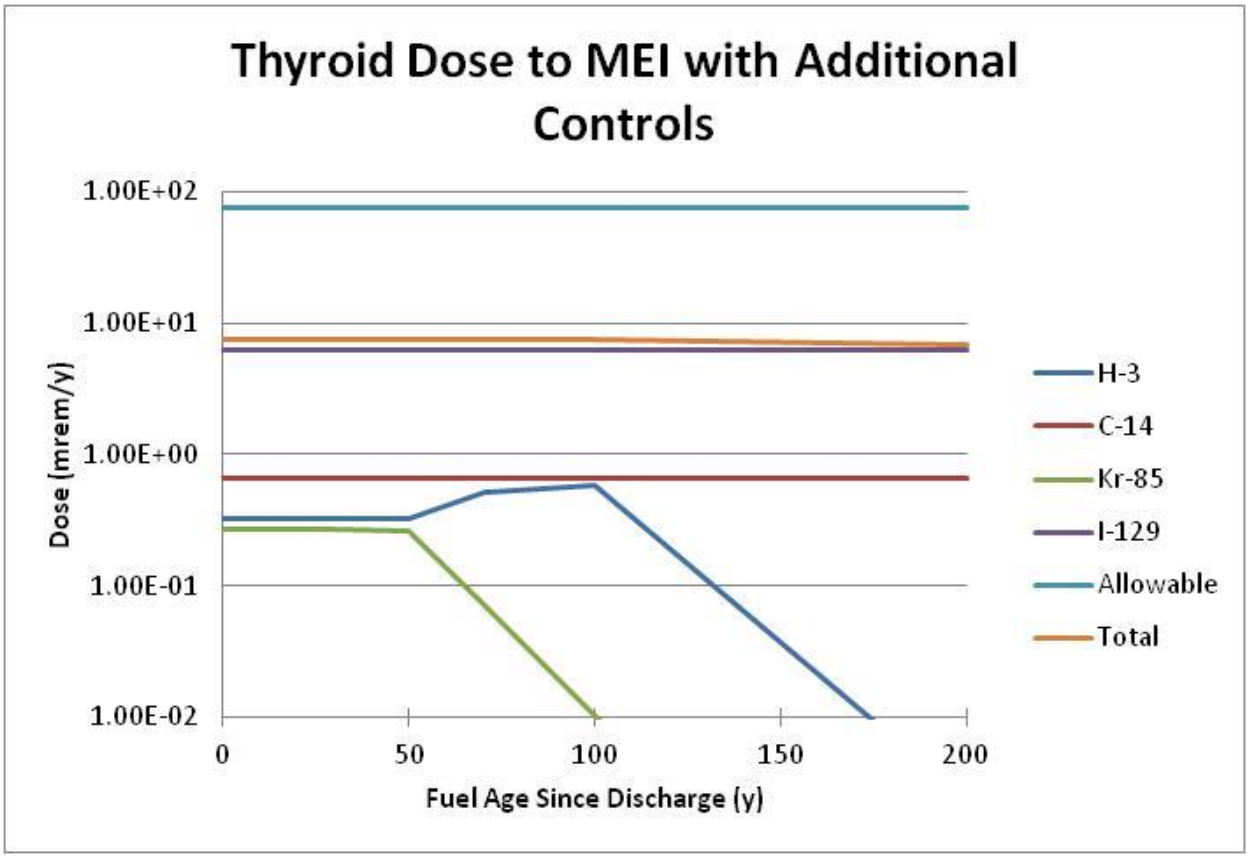


Figure C.3-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 60-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5 mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.

C.4. AHTGR / 100 GWD/T FUEL

For the same AHTGR (PBR) fuel/reactor but with a further burnup of 100 GWd/t, the second-phase analysis results are provided below.

For a plant size of 1000 t/y, the total dose to the MEI ranges from ~2580 mrem/y at 2-y-cooled fuel to 2040 mrem/y at 100-y cooled (Figure C.4-1). Iodine-129 is the major contributor (2010 mrem/y); at cooling times up to ~60 y, ^{3}H dose contributions exceed 25 mrem/y; ^{14}C contributes 23.9 mrem/y and ^{85}Kr could contribute up to ~16.5 mrem/y at short cooling times. Uncontrolled dose contributions by isotope are presented in Table C.4-1.

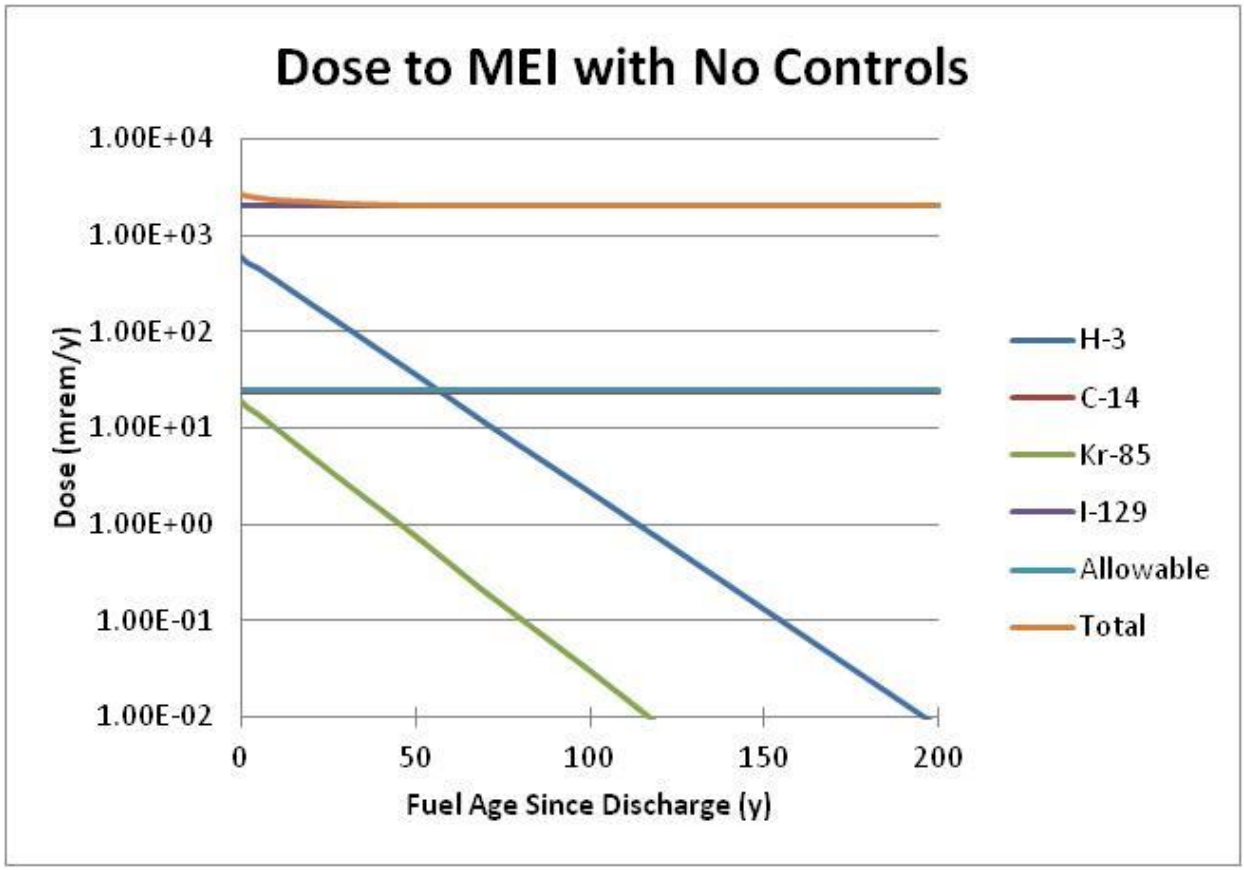


Figure C.4-1. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

If the ^{129}I and ^{85}Kr release limits imposed by 40 CFR 190 are then applied to these values, the whole body dose to the MEI is reduced to 568 mrem/y at 2-y cooling and 36.3 mrem/y for 100-y-cooled fuel (Figure C.4-2). The ^{129}I contribution is reduced to 10.5 mrem/y, and ^{3}H becomes the major contributor at cooling times less than 70 y. The ^{14}C again contributes 23.9 mrem/y, but ^{85}Kr contributions are reduced to less than 2.7 mrem/y. Again, it is clear from this figure that additional controls at least on ^{3}H and ^{14}C would be required to meet a 25-mrem/y limit and that from Figure C.4-3 for a 2.5-mrem/y apportioned limit, additional controls (DF) for ^{129}I and ^{85}Kr would also be required.

Table C.4-1. Dose contributions by radionuclide based on 100-GWd/tIHM, AHTGR fuel cooled up to 200 y processed in 1000-t/y recycle plant without effluent controls

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	595	531	449	339	193	110	35.8	11.6	2.15	0.0078
^{14}C	23.9	23.9	23.9	23.9	23.8	23.8	23.8	23.7	23.6	23.3
^{85}Kr	18.7	16.5	13.6	9.82	5.51	2.70	0.740	0.203	0.0292	4.55×10^{-5}
^{129}I	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010
Allowable	25	25	25	25	25	25	25	25	25	25
Total	2650	2580	2500	2380	2230	2150	2070	2050	2040	2030

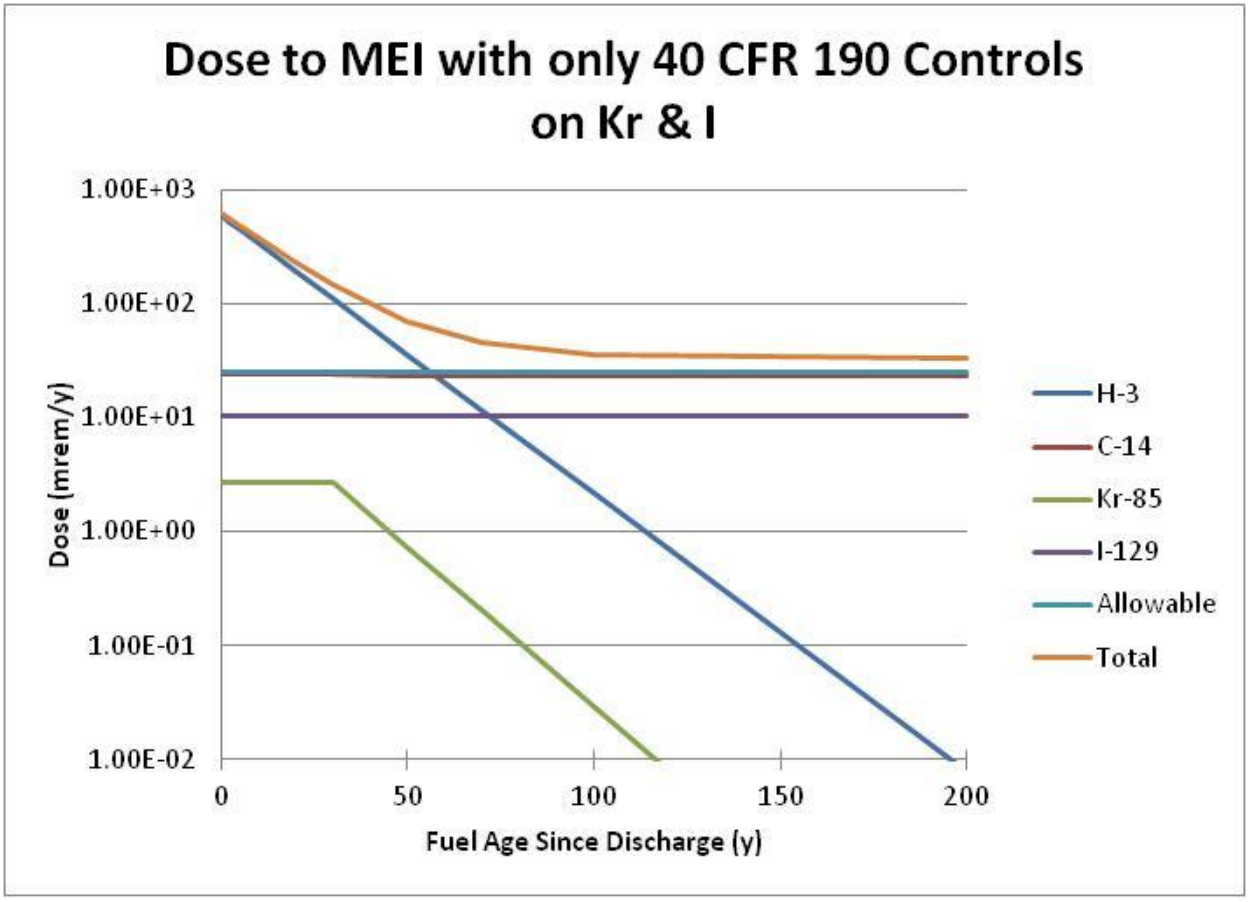


Figure C.4-2. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 25-mrem/y whole body dose level.

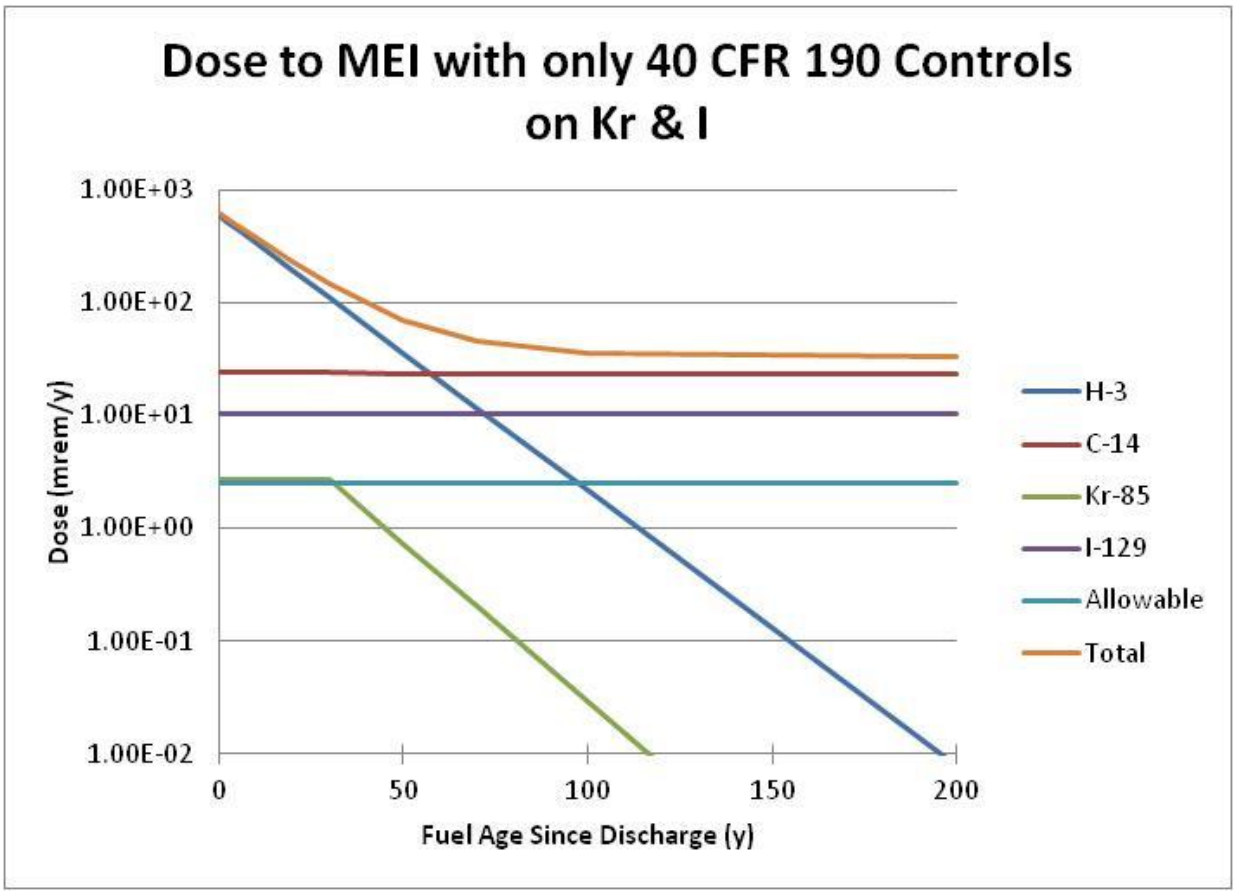


Figure C.4-3. Total whole body dose and dose contributions arising from the volatile radionuclides to the MEI from 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel with iodine and krypton controls per 40 CFR 190. Allowable dose limit is shown at the 2.5-mrem/y whole body dose level.

The next step was then to impose additional controls on individual isotopes in order to reduce the calculated emissions to the extent required to reduce the dose to the MEI to regulatory limit or to a portion of the regulatory limit. For the 25-mrem/y limit case, additional controls were imposed for ^{3}H, ^{14}C, and ^{129}I. Tritium DF requirements ranged from 41.4 at 2-y cooling to ~2.4 at 50-y cooling. An additional ^{129}I DF of 3 was included, raising the overall ^{129}I DF to ~575. A DF on ^{14}C of 4 was imposed to reduce its contribution to ~6 mrem/y (Figure C.4-4 and Table C.4-2). Beyond ~70-y fuel cooling, no additional ^{3}H capture would be required if the total dose to the MEI were account for by only the ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I. However, this is most likely not the case, and if these four radionuclides are apportioned 2.5 mrem/y or 10% of the dose, then additional controls must be placed on ^{129}I and ^{14}C for all times, since these individually contribute more than 2.5 mrem/y and ^{3}H contributes more than 2.5 mrem/y until the fuel is aged over 70 y. Krypton-85 also contributes >2.5 mrem/y until the fuel is aged more than ~30 y. An additional recovery factor of 20 was applied to ^{129}I at all times, raising the total DF to ~3850. A ^{14}C DF of 30 for times up to 200 y was applied to reduce its contribution to the total dose to ~0.8 mrem/y. Additional ^{85}Kr DF requirements were also imposed up to 30-y cooling due to the relatively large contribution of ^{85}Kr, bringing the total ^{85}Kr DF to a range of 10 to ~61 for cooling times up to 30 y. Tritium DFs range from 585 for 2-y-cooled fuel to ~2 at 100-y-cooled fuel. Beyond 110-y cooling, no ^{3}H recover would be required. Figure C.4-5 shows the resulting total dose to the MEI and the individual dose contributions as a function of cooling time. Figure C.4-6 depicts the DF requirements for each

isotope as a function of cooling time. Table C.4-3 shows the overall DFs required to limit the dose to the MEI to 2.5 mrem/y, and Table C.4-4 shows the resulting dose contributions.

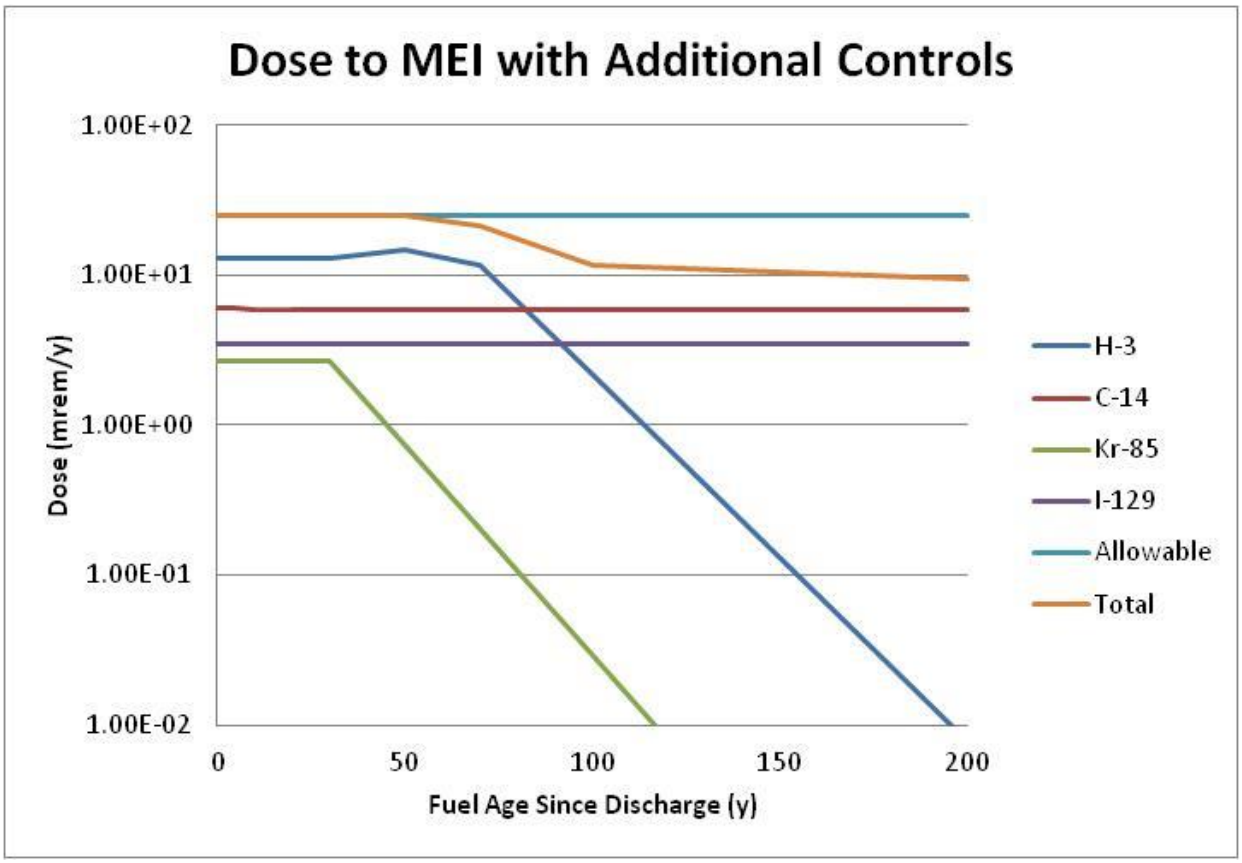


Figure C.4-4. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 25 mrem/y.

Table C.4-2. Effective DFs required to achieve 25-mrem/y whole body dose to MEI for 100-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	46.3	41.4	35.0	26.4	15.0	8.55	2.42	1.00	1.00	1.00
^{14}C	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
^{85}Kr	6.97	6.12	5.05	3.65	1.91	1.00	1.00	1.00	1.00	1.00
^{129}I	575	575	575	575	575	575	575	575	575	575

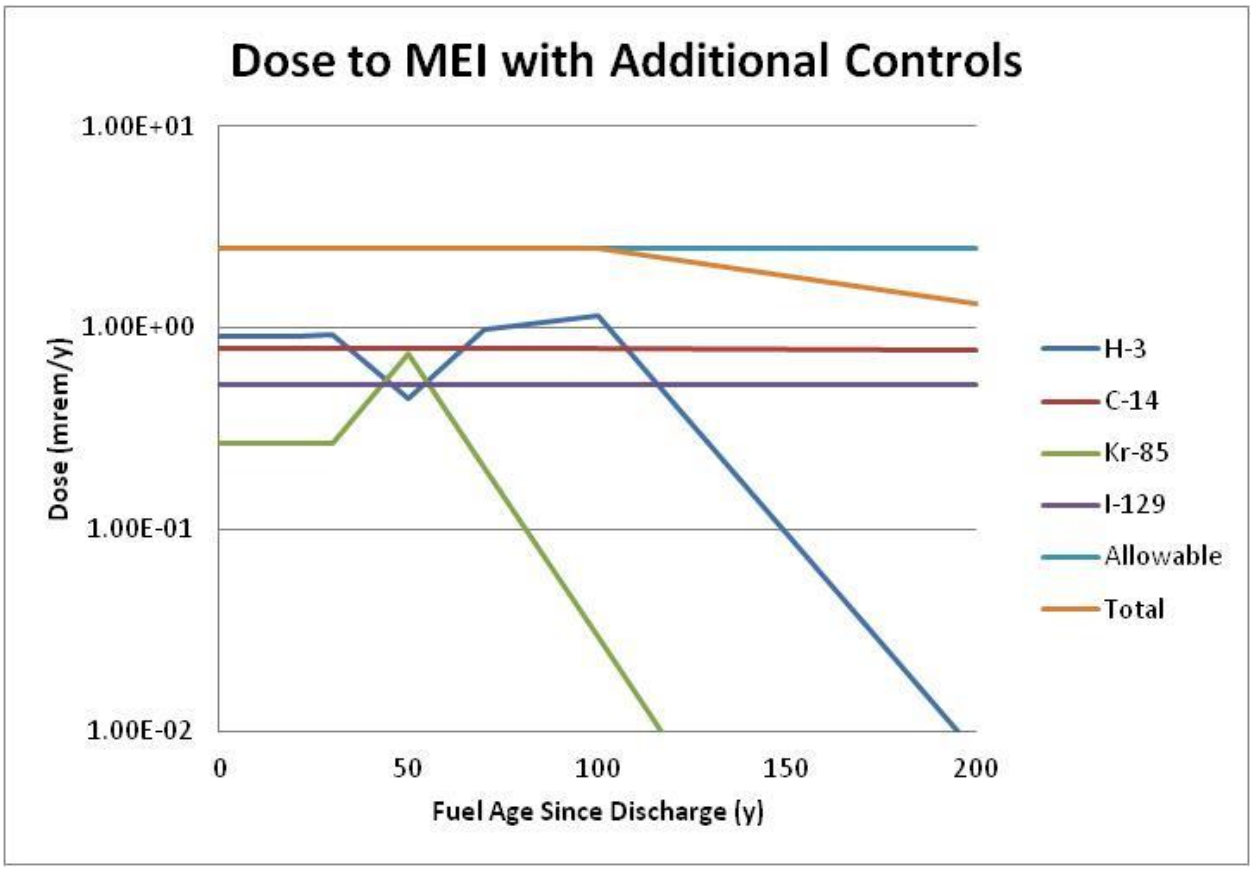


Figure C.4-5. Dose to MEI total and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

Table C.4-3. Effective DFs required to achieve 2.5-mrem/y whole body dose to MEI for 100-GWd/tIHM AHTGR fuel processed in 1000-t/y facility

Effective DF										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	650	585	495	373	212	120	80.0	11.8	1.86	1.00
^{14}C	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
^{85}Kr	69.7	61.2	50.4	36.5	19.1	10.0	1.00	1.00	1.00	1.00
^{129}I	3830	3830	3830	3830	3830	3830	3830	3830	3830	3830

Table C.4-4. Dose contributions by radionuclide based on 100-GWd/tIHM AHTGR fuel cooled up to 200 y using effective DFs from Table C.4-3

Dose, mrem/y										
Isotope	**Fuel cooling, y**									
	0	**2**	**5**	**10**	**20**	**30**	**50**	**70**	**100**	**200**
^{3}H	0.915	0.908	0.907	0.909	0.911	0.918	0.447	0.986	1.16	0.0078
^{14}C	0.797	0.796	0.796	0.796	0.795	0.794	0.792	0.790	0.787	0.778
^{85}Kr	0.269	0.269	0.269	0.269	0.269	0.269	0.740	0.203	0.0292	4.55×10^{-5}
^{129}I	0.524	0.524	0.524	0.524	0.524	0.524	0.524	0.524	0.524	0.524
Allowable	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Total	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.3

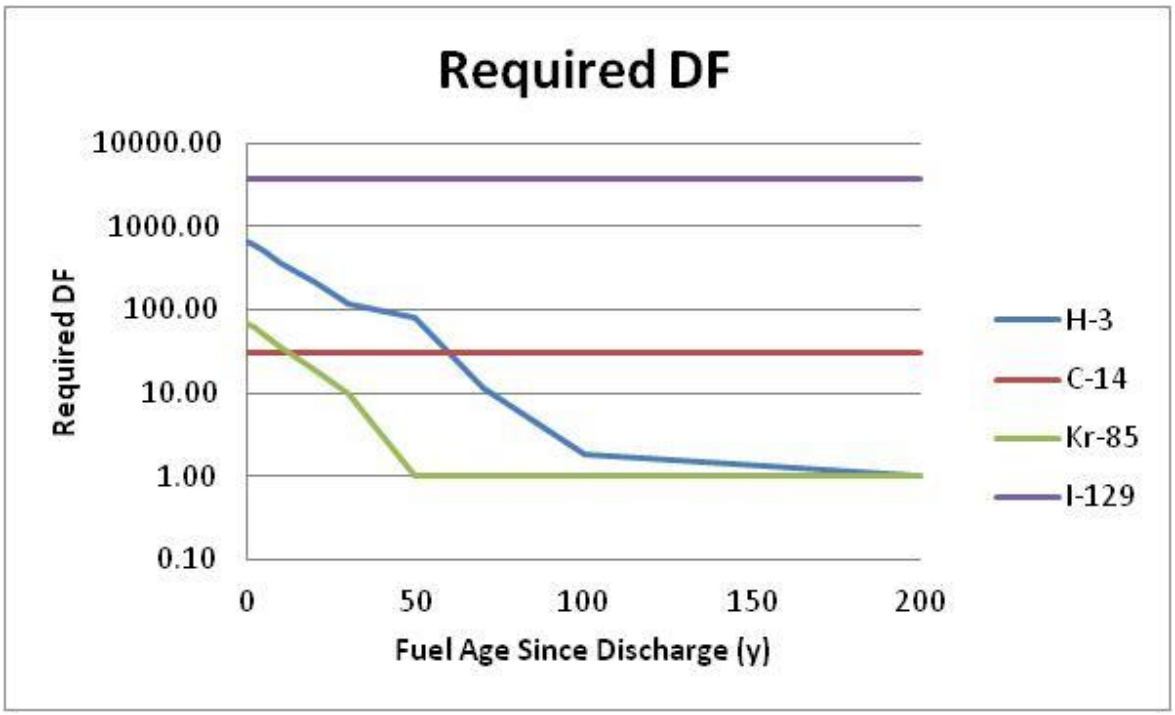


Figure C.4-6. Required DFs for each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 and additional controls needed to meet an allowable dose limit at 2.5 mrem/y.

In addition to meeting the whole body dose, there are limits to specific organs. The dose limit to the thyroid is specified as 75 mrem/y. Appling the same DFs previously to meet the 40 CFR 190 discharge limits for ^{129}I and ^{85}Kr only results in a thyroid dose of 496 mrem/y for the processing of 2-y-cooled fuel decreasing to 234 mrem/y at 100-y cooled (Figure C.4-7). The two primary contributors to the dose are ^{129}I and ^{3}H in the case of short cooling times.

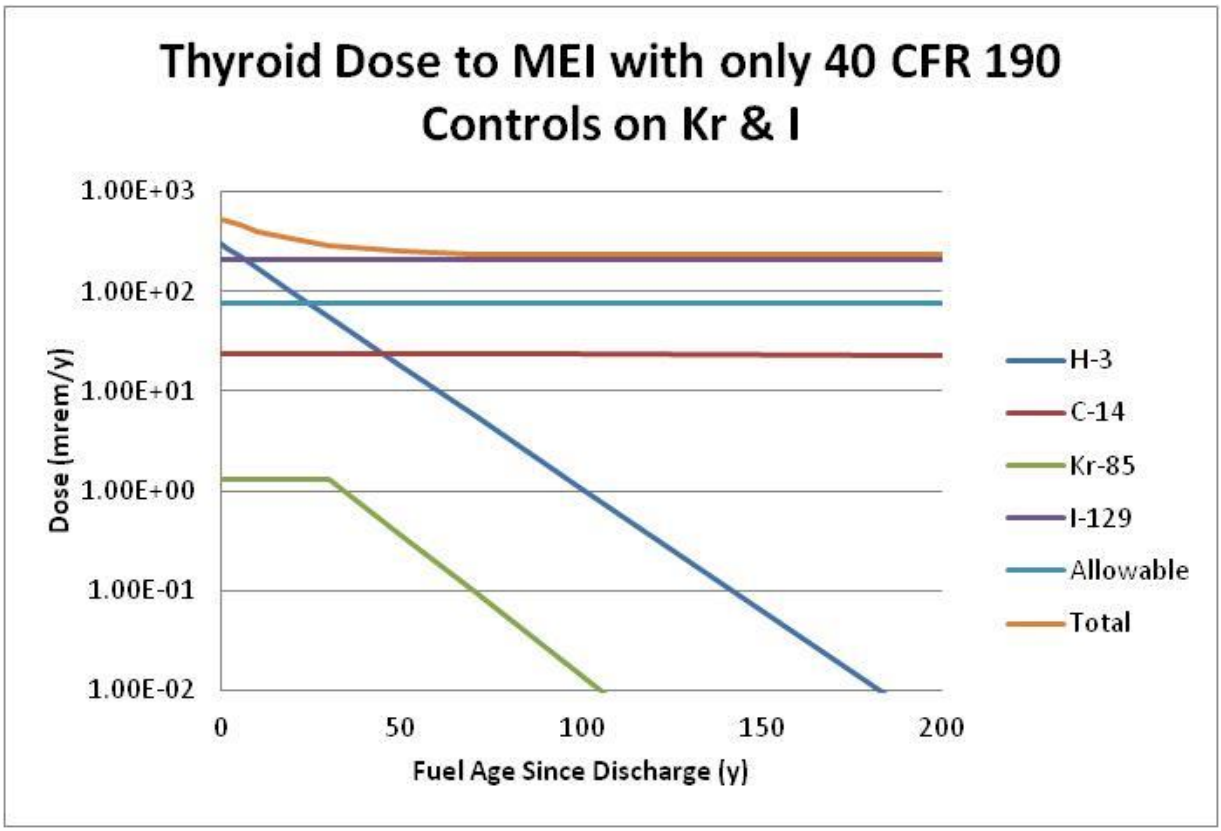


Figure C.4-7. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit. Allowable thyroid dose shown is 75 mrem/y.

Now applying the same additional DF requirements as imposed to meet the whole body dose limit of 25 to the thyroid dose calculations shows that the dose to the thyroid is reduced to 83.3 mrem/y; thus, additional DF requirements would be needed beyond those to meet the 25-mrem/y whole body dose limit (Figure C.4-8). Since the primary contributor to the dose is ^{129}I, an additional DF is applied, raising the ^{129}I DF from 575 to ~650.

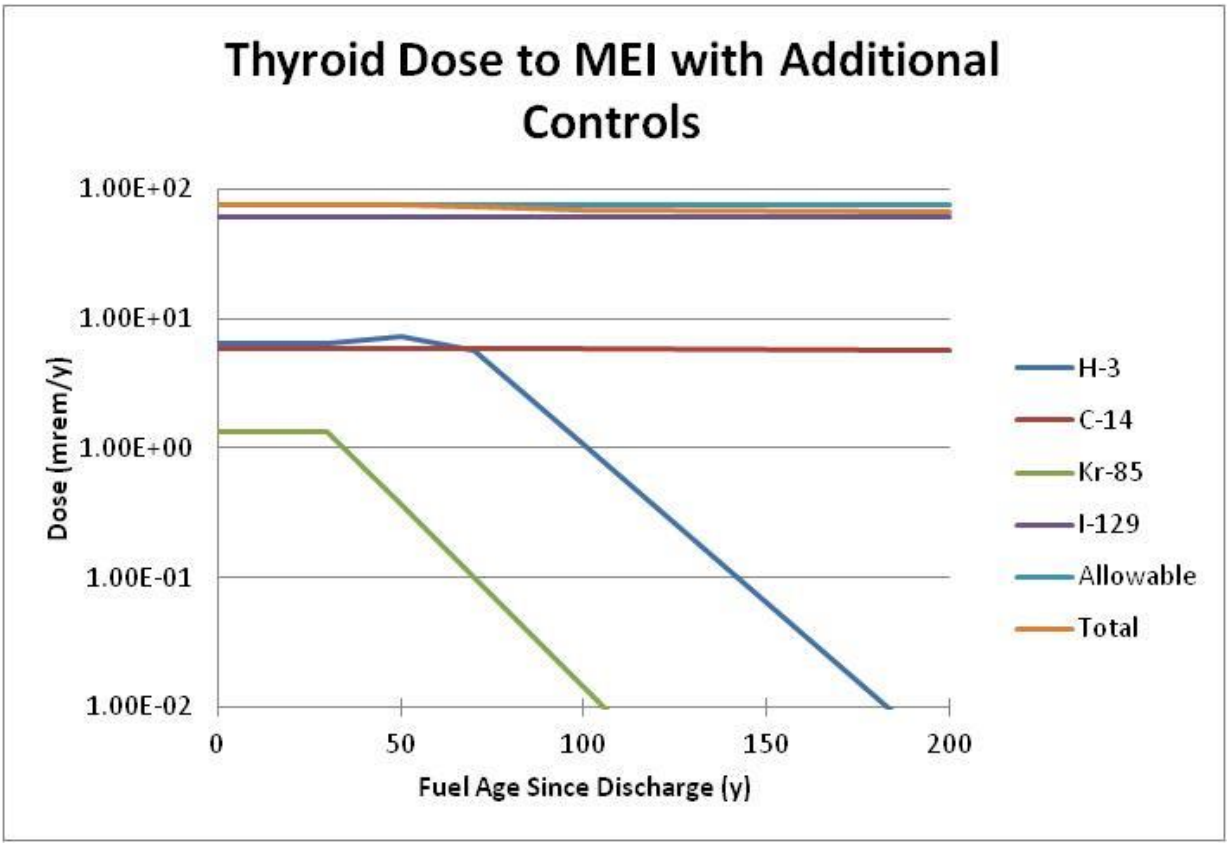


Figure C.4-8. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet the 25-mrem/y whole body dose limit. Allowable thyroid dose shown is 75 mrem/y**.**

If the same apportionment of 10% is made for the volatile radionuclides as for the whole body dose and if the same additional controls are applied, the resulting thyroid dose is 11.8 mrem/y (Figure C.4-9). Iodine-129 accounts for approximately 90% of this dose. Since the primary contributor to the dose is ^{129}I, an additional DF is applied, raising the total DF from ~3850 to ~6550.

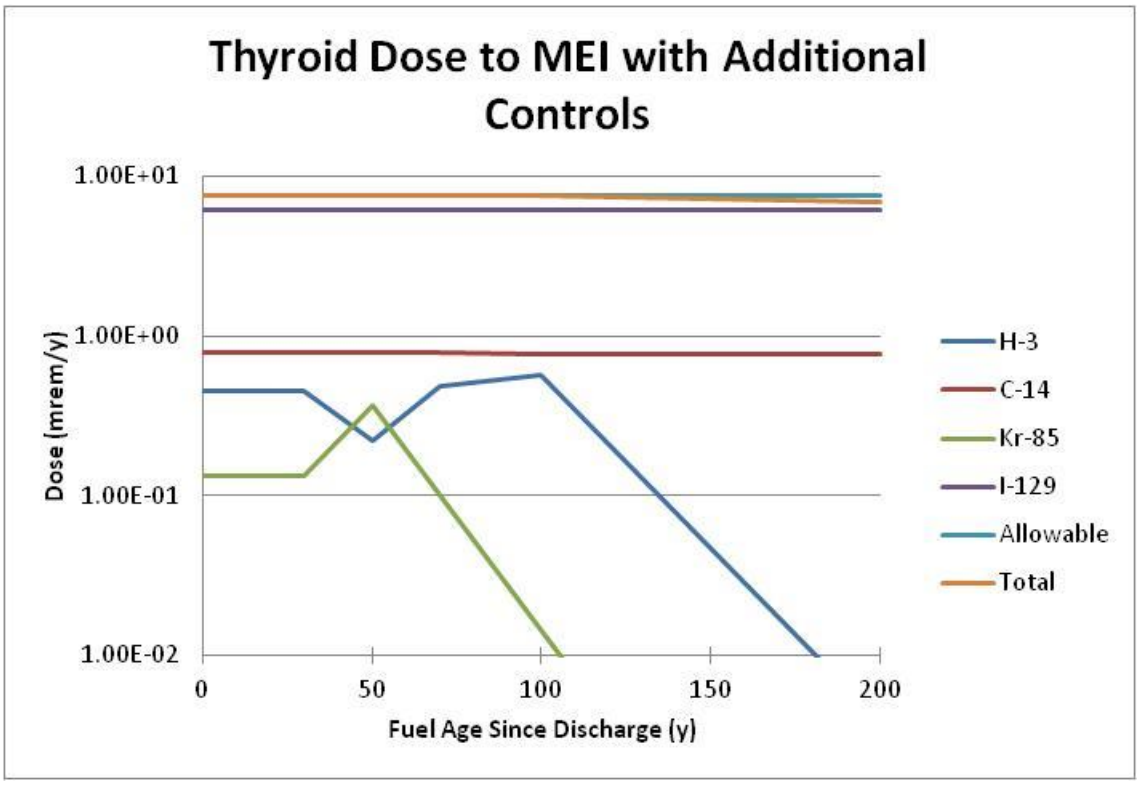


Figure C.4-9. Dose to the thyroid and dose contribution from each of the volatile radionuclides, as a function of fuel age for a 1000-t/y recycle plant processing 100-GWd/tIHM AHTGR fuel. Implementing controls required by 40 CFR 190 release limit and additional controls required to meet an allocated 2.5-mrem/y whole body dose limit. Allowable thyroid dose shown is 7.5 mrem/y.