AN ESTIMATE OF THE PROCESS DECONTAMINATION FACTORS REQUIRED TO MEET
FEDERAL EFFLUENT REGULATIONS FOR THE BURNING OF HTGR FUEL ELEMENTS*

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Abstract

Calculations are made of the various quantities of air required to dilute 139 isotopes, present at two reprocessing times, in HTGR fuel elements to meet existing federal effluent regulations. One isotope (Pu-238) represents 79% of the total, calculated isotopic potential hazard from the burning of HTGR fuel elements. The largest calculated decontamination factor required was 640,000 for Pu-238.

I. Introduction

The design philosophy of a plant for reprocessing the fueled graphite from a high-temperature gas-cooled reactor (HTGR) will be influenced by the existing regulations with regard to gaseous and liquid effluents. These regulations affect the inclusion or omission of certain process steps, gaseous and liquid waste handling procedures, structural integrities, equipment arrangements, etc. A useful way for the process designer to use the effluent regulations is to express them as overall process decontamination factors for the various amounts of isotopes actually present in the spent fuel elements at reprocessing time.

The proposed method for reprocessing HTGR fuel consists, in part, of burning the graphite fuel elements in air or oxygen and separating the fissile and fertile materials from the fission products by solvent extraction methods. The first step in this process is unprecedented in nuclear fuel reprocessing in that the fuel elements are prepared for dissolution by combustion. The large quantity of carbon present in the fuel elements is converted into carbon dioxide during this combustion step. This carbon dioxide, being formed in intimate contact with the spent fuel, will be contaminated with fission products.

At present it is not possible to predict the quantities of all of the isotopes or their chemical or physical forms in the carbon dioxide. However, some comparative means of estimating the decontamination factors actually required for the various amounts of the isotopes present would be useful in identifying the isotopes which will require the most attention during actual processing.

The isotopes that are of the most concern in HTGR reprocessing plant liquid effluents are those the reprocessing industry is presently aware of because of the similarity of these effluents to Light Water Reactor liquid wastes. This is not true for the gaseous effluents. The isotopes that will be present as contaminants in the carbon dioxide must first be identified and the appropriate off-gas decontamination processes developed. The identities of those that will

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be present as contaminants in the carbon dioxide must await hot-cell combustion studies using irradiated fuels. This paper presents an estimate of the overall gaseous process decontamination factors for 139 isotopes present in HTGR fuels at reprocessing times of 150 and 365 days after irradiation.

II. Estimation of the Significant Isotopes Present at Reprocessing Time

An estimate of the quantities of the various isotopes present in six-year-irradiated Fort St. Vrain Reactor fuel at reprocessing time was made using the ORIGEN isotope generation and decay code⁽¹⁾. The ORIGEN library contains nuclear transmutations by $n-\gamma$, $n-\alpha$, $n-p$, $n-2n$, $n-3n$, and n -fission products plus radioactive decay by β^- , β^+ , and alpha decay and isomeric transitions. The ORIGEN code computes the isotope inventories of more than 700 isotopes in the fuel as a function of the length of irradiation and postirradiation time. The elements whose isotopes are included in the ORIGEN library are shown in Figure 1.

The following conditions were assumed for calculational purposes:

1. The fuel elements are of the Fort St. Vrain⁽²⁾ HTGR type shown in Figure 2.
2. The fissile material is ^{235}U , and the fertile material is ^{232}Th homogeneously mixed with the carbon.
3. The carbon-to-heavy metal (U+Th) mole ratio is 150.
4. The fuel elements are irradiated for six years at an average flux of 6.63×10^{13} neutrons/sec-cm². The burnup is 100,000 MWd per metric ton of initial heavy metal.
5. The graphite block contains 1 ppm of lithium, 162 ppm of boron, 100 ppm of nitrogen, 17 ppm of silicon, and 50 ppm of iron as contaminants.

The results of the ORIGEN calculations are shown in Table 1 for 150- and 365-day-cooled fuel.

III. Existing Federal Effluent Regulations

Existing regulations for nuclear plant effluents are stated in Title 10, Chapter 1, Code of Federal Regulations, Part 20 (10 CFR, Part 20). The plant effluent concentrations at the plant boundary are specified for the various isotopes in Appendix B, Table II, Column 1, of 10 CFR, Part 20. This regulation limits the annual exposure from plant effluents to individuals living near the plant boundary to not more than 500 millirems per year. Since it is difficult or impossible to predict the exact chemical compounds that could be formed during the burning process, the permissible effluent concentrations used for calculational purposes is the lower of the "soluble" or "insoluble" values of Appendix B, Table II, Column 1 of 10 CFR, Part 20.

The concentration limits according to 10 CFR, Part 20 for 139 isotopes present in HTGR fuel from the Fort St. Vrain Reactor in significant amounts ($> 10^{-8}$ Ci/metric ton) are listed in Table 2. Certain values listed were obtained by using the decay mode and half-life (included in Table 2, for completeness) according to instructions given in 10 CFR, Part 20.

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GROUP
1A

H

Li

Na

K

Rb

Cs

Fr

Be

Mg

Ca

Sr

Ba

Ra

★

●

★★

7

LEGEND

LIGHT
ELEMENT

HEAVY
ELEMENT

FISSION
PRODUCT

INERT
GASES

He

Ne

F

Cl

Ar

Kr

Xe

Rn

O

S

Se

Br

I

Te

Po

N

P

As

Sb

Bi

C

Si

Ge

Sn

Pb

B

Al

Ga

In

Tl

III A

IV A

V A

VI A

VII A

Lu

Yb

Tm

No

FIGURE 2. SCHEMATIC OF THE FORT ST. VRAIN HTGR REACTOR FUEL ELEMENTS.

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Table 1. ORIGIN Calculation of the Radioactive Nuclide Concentrations Present at Reprocessing Time

Isotope	150 Day Cooled (Ci/metric ton) ^a	365 Day Cooled (Ci/metric ton) ^a
³ H	4.07×10^3	3.94×10^3
¹⁰ Be	1.49×10^{-2}	1.49×10^{-2}
¹⁴ C	5.91×10^1	5.91×10^1
³² P	1.09×10^{-4}	-
⁵¹ Cr	1.13×10^{-2}	5.31×10^{-5}
⁵⁴ Mn	9.18×10^0	5.61×10^0
⁵⁵ Fe	4.99×10^2	4.27×10^2
⁵⁹ Fe	2.15×10^0	7.88×10^{-2}
⁶⁰ Co	2.14×10^0	1.98×10^0
⁷⁹ Se	2.13×10^0	2.13×10^0
⁸⁵ Kr	6.56×10^4	6.32×10^4
⁸⁶ Rb	1.97×10^1	6.83×10^{-3}
⁸⁹ Sr	2.39×10^5	1.37×10^4
⁹⁰ Sr	3.06×10^5	3.02×10^5
⁹⁰ Y	3.06×10^5	3.02×10^5
⁹¹ Y	3.00×10^5	2.38×10^4
⁹³ Zr	7.20×10^0	7.20×10^0
⁹⁵ Zr	3.83×10^5	3.86×10^4
^{93m} Nb	1.34×10^0	1.52×10^0
⁹⁵ Nb	7.17×10^5	8.21×10^4
^{95m} Nb	8.11×10^3	8.20×10^3
⁹⁹ Mo	1.04×10^{10}	-
⁹⁹ Tc	3.38×10^1	3.38×10^1
^{99m} Tc	9.90×10^{-11}	-
¹⁰³ Ru	4.81×10^4	1.12×10^3
¹⁰⁶ Ru	8.25×10^4	5.50×10^4
^{103m} Rh	4.81×10^4	1.12×10^3
¹⁰⁶ Rh	8.25×10^4	5.50×10^4
¹⁰⁷ Pd	4.78×10^{-2}	4.78×10^{-2}
¹¹⁰ Ag	1.55×10^1	8.59×10^0
^{110m} Ag	1.19×10^2	6.61×10^1
¹¹¹ Ag	8.81×10^{-3}	2.07×10^{-11}
^{113m} Cd	1.93×10^{-1}	1.87×10^{-1}

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Table 1 (Contd.)

Isotope	150 Day Cooled (Ci/metric ton) ^a	365 Day Cooled (Ci/metric ton) ^a
^{115m} Cd	3.73×10^1	1.17×10^0
^{117m} Sn	1.57×10^{-4}	-
^{119m} Sn	9.24×10^0	5.09×10^0
^{123m} Sn	6.41×10^2	1.95×10^2
¹²⁵ Sn	2.39×10^{-1}	-
¹²⁶ Sn	1.22×10^0	1.22×10^0
¹²⁴ Sb	3.05×10^2	2.55×10^1
¹²⁵ Sb	1.92×10^4	1.65×10^4
¹²⁶ Sb	8.10×10^0	1.21×10^0
^{126m} Sb	1.22×10^0	1.22×10^0
¹²⁷ Sb	3.84×10^{-7}	-
^{123m} Te	3.00×10^0	8.39×10^{-1}
^{125m} Te	7.84×10^3	6.84×10^3
¹²⁷ Te	1.50×10^4	3.82×10^3
^{127m} Te	1.52×10^4	3.87×10^3
¹²⁹ Te	6.37×10^5	7.94×10^1
^{129m} Te	5.93×10^3	1.24×10^2
¹³² Te	1.70×10^{-8}	-
¹²⁹ I	1.34×10^{-1}	1.34×10^{-1}
¹³¹ I	2.27×10^0	2.07×10^{-8}
¹³² I	1.75×10^{-8}	-
^{129m} Xe	7.04×10^{-4}	-
^{131m} Xe	3.42×10^0	1.13×10^{-8}
¹³³ Xe	6.00×10^{-3}	-
¹³⁴ Cs	7.49×10^5	6.14×10^5
¹³⁵ Cs	9.29×10^{-1}	9.29×10^{-1}
¹³⁶ Cs	6.53×10^1	-
¹³⁷ Cs	3.25×10^5	3.20×10^5
^{137m} Ba	3.04×10^5	2.99×10^5
¹⁴⁰ Ba	4.99×10^2	4.39×10^{-3}
¹⁴⁰ La	5.74×10^2	5.05×10^{-3}
¹⁴¹ Ce	8.82×10^4	8.87×10^2
¹⁴⁴ Ce	1.04×10^6	6.14×10^5

DATA COLLECTED INDICATED IN TABLE 1 (AEC AIR CLEANING CONFERENCE, 1964)

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Table 1 (Contd.)

Isotope	150 Day Cooled (Ci/metric ton) ^a	365 Day Cooled (Ci/metric ton) ^a
¹⁴³ Pr	1.03 x 10 ³	1.95 x 10 ⁻²
¹⁴⁴ Pr	1.04 x 10 ³	6.14 x 10 ⁵
¹⁴⁷ Nd	6.89 x 10 ¹	1.02 x 10 ⁻⁴
¹⁴⁷ Pm	1.18 x 10 ⁵	1.01 x 10 ⁵
¹⁴⁸ Pm	4.62 x 10 ¹	1.33 x 10 ⁰
^{148m} Pm	5.75 x 10 ²	1.66 x 10 ¹
¹⁵¹ Sm	5.68 x 10 ²	5.66 x 10 ²
^{152m} Eu	3.57 x 10 ⁰	3.45 x 10 ⁰
¹⁵² Eu	3.57 x 10 ⁰	3.45 x 10 ⁰
¹⁵⁴ Eu	1.27 x 10 ⁴	1.24 x 10 ⁴
¹⁵⁵ Eu	1.07 x 10 ⁴	8.52 x 10 ³
¹⁵⁶ Eu	5.79 x 10 ²	2.80 x 10 ⁻²
¹⁶² Gd	1.65 x 10 ¹	1.10 x 10 ¹
¹⁶⁰ Tb	2.35 x 10 ²	2.97 x 10 ¹
¹⁶¹ Tb	1.39 x 10 ⁻⁵	-
^{162m} Tb	1.65 x 10 ¹	1.10 x 10 ¹
²⁰⁷ Tl	9.29 x 10 ⁻²	1.04 x 10 ⁻¹
²⁰⁸ Tl	4.78 x 10 ¹	5.44 x 10 ¹
²⁰⁹ Tl	1.62 x 10 ⁻³	1.80 x 10 ⁻³
²⁰⁹ Pb	9.13 x 10 ⁻²	1.01 x 10 ⁻¹
²¹¹ Pb	9.33 x 10 ⁻²	1.04 x 10 ⁻¹
²¹² Pb	1.33 x 10 ²	1.51 x 10 ²
²¹¹ Bi	9.33 x 10 ⁻²	1.04 x 10 ⁻¹
²¹² Bi	1.33 x 10 ²	1.51 x 10 ²
²¹³ Bi	9.13 x 10 ⁻²	1.01 x 10 ⁻¹
²¹² Po	8.50 x 10 ¹	9.66 x 10 ¹
²¹³ Po	8.93 x 10 ⁻²	9.93 x 10 ⁻²
²¹⁵ Po	9.33 x 10 ⁻²	1.04 x 10 ⁻¹
²¹⁶ Po	1.33 x 10 ²	1.51 x 10 ²
²¹⁷ At	9.13 x 10 ⁻²	1.01 x 10 ⁻¹
²¹⁹ Rn	9.33 x 10 ⁻²	1.04 x 10 ⁻¹
²²⁰ Rn	1.33 x 10 ²	1.51 x 10 ²
²²¹ Fr	9.13 x 10 ⁻²	1.01 x 10 ⁻¹
²²³ Fr	1.07 x 10 ⁻³	1.18 x 10 ⁻³

PLEASE OBSERVE INDICATED PAY RATE (\$.) PER HOUR () PER DAY () PER WEEK ()

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Table 1 (Contd.)

Isotope	150 Day Cooled (Ci/metric ton) ^a	365 Day Cooled (Ci/metric ton) ^a
²²³ Ra	9.33×10^{-2}	1.04×10^{-1}
²²⁴ Ra	1.33×10^2	1.51×10^2
²²⁶ Ra	9.19×10^{-2}	1.01×10^{-1}
²²⁸ Ra	5.52×10^{-2}	5.74×10^{-2}
²²⁶ Ac	9.13×10^{-2}	1.01×10^{-1}
²²⁷ Ac	9.52×10^{-2}	1.05×10^{-1}
²²⁸ Ac	5.52×10^{-2}	5.75×10^{-2}
²²⁷ Th	9.27×10^{-2}	1.02×10^{-1}
²²⁸ Th	1.33×10^2	1.50×10^2
²²⁹ Th	9.27×10^{-2}	1.01×10^{-1}
²³⁰ Th	9.00×10^{-3}	9.19×10^{-3}
²³¹ Th	4.16×10^{-3}	4.16×10^{-3}
²³² Th	9.40×10^{-2}	9.40×10^{-2}
²³⁴ Th	4.78×10^1	9.92×10^{-2}
²³¹ Pa	6.09×10^{-1}	6.09×10^{-1}
²³³ Pa	6.92×10^5	3.01×10^3
²³⁴ Pa	4.78×10^{-2}	9.93×10^{-5}
^{234m} Pa	4.78×10^1	9.93×10^{-2}
²³² U	2.23×10^2	2.21×10^2
²³³ U	1.54×10^2	1.55×10^2
²³⁴ U	3.59×10^1	3.60×10^1
²³⁵ U	4.16×10^{-3}	4.16×10^{-3}
²³⁶ U	3.38×10^{-1}	3.38×10^{-1}
²³⁷ U	2.28×10^{-1}	-
²³⁷ Np	6.61×10^{-1}	6.61×10^{-1}
²³⁹ Np	9.87×10^0	9.87×10^0
²³⁸ Pu	5.96×10^{-1}	5.17×10^{-1}
²³⁹ Pu	1.27×10^4	1.27×10^4
²³⁹ Pu	8.98×10^0	8.98×10^0
²⁴⁰ Pu	1.76×10^1	1.79×10^1
²⁴¹ Pu	7.15×10^3	6.95×10^3
²⁴² Pu	3.47×10^{-1}	3.47×10^{-1}
²⁴¹ Am	1.60×10^1	2.26×10^1

Table 1 (Contd.)

^a Curies per metric ton of uranium plus thorium present at the start of irradiation.

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Table 2. Concentration Limits in Air Above Background
for Unrestricted Areas as Specified by Appendix B,
Table II, Column 1, of 10 CFR Part 20

Isotope	Half-Life ^a	Decay Mode	Chemical ^b Form	Concentration Limit (μCi/ml)
³ H	1.2 x 10 ¹ y	β	S,I	2 x 10 ⁻⁷
¹⁰ Be	2.5 x 10 ⁶ y	β	c	1 x 10 ⁻¹⁰
¹⁴ C	5.6 x 10 ³ y	β	Sub ^{d,e}	1 x 10 ⁻⁶
³² P	1.4 x 10 ¹ d	β	S	2 x 10 ⁻⁹
⁶¹ Cr	2.8 x 10 ¹ d	γ	S	4 x 10 ⁻⁷
⁶⁴ Mn	3.0 x 10 ² d	γ	S,I	1 x 10 ⁻⁹
⁶⁵ Fe	2.9 x 10 ⁰ y	EC	S,I	3 x 10 ⁻⁸
⁶⁹ Fe	4.5 x 10 ¹ d	γ	I	2 x 10 ⁻⁹
⁶⁰ Co	5.3 x 10 ⁰ y	γ	I	3 x 10 ⁻¹⁰
⁷⁹ Se	6.5 x 10 ⁴ y	β	c	1 x 10 ⁻¹⁰
⁸⁶ Kr	1.1 x 10 ¹ y	β	Sub ^d	3 x 10 ⁻⁷
⁸⁶ Rb	1.9 x 10 ¹ d	β	I	2 x 10 ⁻⁹
⁸⁹ Sr	5.2 x 10 ¹ d	β	S	3 x 10 ⁻¹⁰
⁹⁰ Sr	2.8 x 10 ¹ y	β	S	3 x 10 ⁻¹¹
⁹⁰ Y	6.4 x 10 ¹ h	β	I	3 x 10 ⁻⁹
⁹¹ Y	5.9 x 10 ¹ d	β	S,I	1 x 10 ⁻⁹
⁹³ Zr	1.5 x 10 ⁶ y	β	S	4 x 10 ⁻⁹
⁹⁵ Zr	6.5 x 10 ¹ d	β	I	1 x 10 ⁻⁹
^{95m} Nb	1.4 x 10 ¹ y	γ	S	4 x 10 ⁻⁹
⁹⁵ Nb	3.5 x 10 ¹ d	β	I	3 x 10 ⁻⁹
^{95m} Nb	9.0 x 10 ¹ h	γ	c	1 x 10 ⁻¹⁰
⁹⁹ Mo	6.7 x 10 ¹ h	β	I	7 x 10 ⁻⁹
⁹⁹ Tc	2.2 x 10 ⁶ y	β	I	2 x 10 ⁻⁹
^{99m} Tc	6.0 x 10 ⁰ h	γ	I	5 x 10 ⁻⁷
¹⁰³ Ru	4.0 x 10 ¹ d	β	I	3 x 10 ⁻⁹
¹⁰⁶ Ru	3.7 x 10 ² d	β	I	2 x 10 ⁻¹⁰
^{103m} Ru	5.7 x 10 ¹ m	γ	I	2 x 10 ⁻⁶
¹⁰⁶ Rh	3.0 x 10 ¹ s	β	Sub ^d	3 x 10 ⁻⁸
¹⁰⁷ Pd	7.5 x 10 ⁶ y	β	c	1 x 10 ⁻¹⁰
¹¹⁰ Ag	2.4 x 10 ¹ s	β	Sub ^d	3 x 10 ⁻⁸
^{110m} Ag	2.5 x 10 ² d	γ	I	3 x 10 ⁻¹⁰
¹¹¹ Ag	7.5 x 10 ⁰ d	β	I	8 x 10 ⁻⁹

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Table 2 (Contd.)

Isotope	Half-Life ^a	Decay Mode	Chemical ^b Form	Concentration Limit ($\mu\text{Ci/ml}$)
^{113m} Cd	1.4×10^1 y	β	c	1×10^{-10}
^{116m} Cd	4.3×10^1 d	β	S, I	1×10^{-9}
^{117m} Sn	1.4×10^1 d	γ	c	1×10^{-10}
^{119m} Sn	2.5×10^2 d	γ	c	1×10^{-10}
^{123m} Sn	1.3×10^2 d	β	c	1×10^{-10}
¹²⁵ Sn	9.4×10^0 d	β	I	3×10^{-9}
¹²⁶ Sn	1.0×10^5 y	β	c	1×10^{-10}
¹²⁴ Sb	6.0×10^1 d	β	I	7×10^{-10}
¹²⁵ Sb	2.7×10^0 y	β	I	9×10^{-10}
¹²⁶ Sb	1.3×10^1 d	β	c	1×10^{-10}
^{128m} Sb	1.9×10^1 m	β	Sub ^d	3×10^{-8}
¹²⁷ Sb	9.3×10^1 h	β	c	1×10^{-10}
^{123m} Te	1.2×10^2 d	γ	c	1×10^{-10}
^{126m} Te	5.8×10^1 d	γ	I	4×10^{-9}
¹²⁷ Te	9.4×10^0 h	β	I	3×10^{-8}
^{127m} Te	1.1×10^2 d	γ	I	1×10^{-9}
¹²⁹ Te	6.9×10^1 m	β	I	1×10^{-7}
^{129m} Te	3.4×10^1 d	β	I	1×10^{-9}
¹³² Te	7.8×10^1 h	β	I	4×10^{-8}
¹²⁹ I	1.7×10^7 y	β	S	2×10^{-11}
¹³¹ I	8.1×10^0 d	β	S	1×10^{-10}
¹³² I	2.3×10^0 h	β	S	3×10^{-8}
^{129m} Xe	8.0×10^0 d	γ	c	1×10^{-10}
^{131m} Xe	1.2×10^1 d	γ	Sub ^d	4×10^{-7}
¹³³ Xe	5.3×10^0 d	β	Sub ^d	3×10^{-7}
¹³⁴ Cs	2.1×10^0 y	β	I	4×10^{-10}
¹³⁵ Cs	3.0×10^6 y	β	I	3×10^{-9}
¹³⁶ Cs	1.3×10^1 d	β	I	6×10^{-9}
¹³⁷ Cs	3.0×10^1 y	β	I	5×10^{-10}
^{137m} Ba	2.6×10^0 m	γ	Sub ^d	3×10^{-8}
¹⁴⁰ Ba	1.3×10^1 d	β	I	1×10^{-9}
¹⁴⁰ La	4.0×10^1 h	β	I	4×10^{-9}
¹⁴¹ Ce	3.3×10^1 d	β	I	5×10^{-9}
¹⁴⁴ Ce	2.8×10^2 d	β	I	2×10^{-10}

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Table 2 (Contd.)

Isotope	Half-Life ^a	Decay Mode	Chemical ^b Form	Concentration Limit ($\mu\text{Ci/ml}$)
¹⁴³ Pr	1.4×10^1 d	β	I	6×10^{-9}
¹⁴⁴ Pr	1.7×10^1 m	β	Sub ^d	3×10^{-8}
¹⁴⁷ Nd	1.1×10^1 d	β	I	8×10^{-9}
¹⁴⁷ Pm	2.6×10^0 y	β	S	2×10^{-9}
¹⁴⁸ Pm	5.4×10^0 d	β	c	1×10^{-10}
^{148m} Pm	4.2×10^1 d	β	c	1×10^{-10}
¹⁵¹ Sm	8.7×10^1 y	β	S	2×10^{-9}
^{152m} Eu	9.3×10^0 h	β, EC	S, I	1×10^{-8}
¹⁵² Eu	1.2×10^1 y	β, EC	S	4×10^{-10}
¹⁵⁴ Eu	1.6×10^1 y	β	S	1×10^{-10}
¹⁵⁵ Eu	1.8×10^0 y	β	S, I	3×10^{-9}
¹⁵⁶ Eu	1.5×10^1 d	β	c	1×10^{-10}
¹⁶² Gd	1.0×10^0 y	β	c	1×10^{-10}
¹⁶⁰ Tb	7.2×10^1 d	β	I	1×10^{-9}
¹⁶¹ Tb	6.9×10^0 d	β	c	1×10^{-10}
^{162m} Tb	2.2×10^0 h	β	c	1×10^{-10}
²⁰⁷ Tb	4.8×10^0 m	β	c	3×10^{-8}
²⁰⁸ Tl	3.1×10^0 m	β	Sub ^d	3×10^{-8}
²⁰⁹ Tl	2.2×10^0 m	β	c	3×10^{-8}
²⁰⁹ Pb	3.3×10^0 h	β	c	1×10^{-10}
²¹¹ Pb	3.6×10^1 m	β	c	3×10^{-8}
²¹² Pb	1.1×10^1 h	β	S	6×10^{-10}
²¹¹ Bi	2.2×10^0 m	α	c	2×10^{-14}
²¹² Bi	6.1×10^1 m	α, β	S	3×10^{-9}
²¹³ Bi	4.7×10^1 s	α	c	2×10^{-14}
²¹² Po	3.0×10^{-7} s	α	c	2×10^{-14}
²¹³ Po	4.2×10^{-6} s	α	c	2×10^{-14}
²¹⁵ Po	1.8×10^{-3} s	α	c	2×10^{-14}
²¹⁶ Po	1.5×10^{-1} s	α	c	2×10^{-14}
²¹⁷ At	1.8×10^{-2} s	α	c	2×10^{-14}
²¹⁹ Rn	3.9×10^0 s	α	c	2×10^{-14}
²²⁰ Rn	5.5×10^1 s	α	S	1×10^{-8}
²²¹ Fr	4.8×10^0 m	α	c	2×10^{-14}
²²³ Fr	2.1×10^1 m	β	c	3×10^{-8}

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Table 2. (Contd.)

Isotope	Half-Life ^a	Decay Mode	Chemical ^b Form	Concentration Limit ($\mu\text{Ci/ml}$)
²²³ Ra	1.2×10^1 d	α	I	8×10^{-12}
²²⁴ Ra	3.6×10^0 d	α	I	2×10^{-11}
²²⁵ Ra	1.5×10^1 d	β	c	3×10^{-9}
²²⁶ Ra	6.7×10^0 y	β	I	1×10^{-12}
²²⁶ Ac	1.0×10^1 d	α	c	2×10^{-14}
²²⁷ Ac	2.2×10^1 y	β	S	8×10^{-14}
²²⁸ Ac	6.1×10^0 d	β	I	6×10^{-10}
²²⁷ Th	1.8×10^1 d	α	c	2×10^{-14}
²²⁸ Th	1.9×10^0 y	α	I	2×10^{-13}
²²⁹ Th	7.3×10^3 y	α	c	2×10^{-14}
²³⁰ Th	8.0×10^4 y	α	S	8×10^{-14}
²³¹ Th	2.6×10^1 h	β	c	1×10^{-10}
²³² Th	1.4×10^{10} y	α	S, I	1×10^{-12}
²³⁴ Th	2.1×10^1 d	β	I	1×10^{-9}
²³¹ Pa	3.3×10^4 y	α	S	4×10^{-14}
²³³ Pa	2.7×10^1 d	β	I	6×10^{-9}
²³⁴ Pa	6.7×10^0 h	β	c	1×10^{-10}
^{234m} Pa	1.2×10^1 y	β	c	3×10^{-8}
²³² U	7.2×10^1 y	α	I	9×10^{-13}
²³³ U	1.6×10^5 y	α	I	4×10^{-12}
²³⁴ U	2.5×10^5 y	α	I	4×10^{-12}
²³⁵ U	7.1×10^8 y	α	I	4×10^{-12}
²³⁶ U	2.4×10^7 y	α	I	4×10^{-12}
²³⁷ U	6.8×10^0 d	β	c	1×10^{-10}
²³⁷ Np	2.1×10^6 y	α	S	1×10^{-13}
²³⁹ Np	2.4×10^0 d	β	I	2×10^{-8}
²³⁸ Pu	2.9×10^0 y	α	c	2×10^{-14}
²³⁸ Pu	8.6×10^1 y	α	S	7×10^{-14}
²³⁹ Pu	2.4×10^4 y	α	S	6×10^{-14}
²⁴⁰ Pu	6.6×10^3 y	α	S	6×10^{-14}
²⁴¹ Pu	1.3×10^1 y	β	S	3×10^{-12}
²⁴² Pu	3.8×10^5 y	α	S	6×10^{-14}
²⁴¹ Am	4.6×10^2 y	α	S	2×10^{-13}
²⁴² Am	1.6×10^1 h	β, EC	S	1×10^{-9}

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Table 2 (Contd.)

Isotope	Half-Life ^a	Decay Mode	Chemical ^b Form	Concentration Limit (μCi/ml)
^{242m} Am	1.5×10^2 y	γ	S	2×10^{-13}
²⁴³ Am	8.0×10^3 y	α	S	2×10^{-13}
²⁴² Gm	1.6×10^2 d	α	S	4×10^{-12}
²⁴³ Gm	3.2×10^1 y	α	S	2×10^{-13}
²⁴⁴ Gm	1.8×10^1 y	α	S	3×10^{-13}

^a s ≡ second, m ≡ minute, h ≡ hour, d ≡ day, y ≡ year.

^b The chemical forms indicated are those with the lowest permissible concentration limit listed in Appendix B, Table II, Column 1, of 10 CFR Part 20. S ≡ soluble, I ≡ insoluble.

^c Concentration limits for this nuclide are not given in Appendix B, Table II, Column 1, of 10 CFR Part 20. Concentration limits used are based on half-life, decay mode, and chemical form according to Appendix B, Table II, Column 1, of 10 CFR Part 20.

^d "Sub" means that the values given are for submersion in a semispherical infinite cloud of airborne material.

^e Concentration limit is for CO₂.

IV. Process Decontamination Factors

A measure of the hazard of an isotope is the quantity of air required to dilute the isotope to the concentration limit shown in Table 2. Use of this dilution as a basis for calculating overall gaseous process decontamination factors has simplicity and relates to the maximum value of the hazard, since no consideration is given to the paths of travel to human beings. The dilution values calculated for 150- and 365-day-cooled fuels are shown in Tables 3 and 4 respectively.

Normalization of the gas dilution required* yields a number that is a measure of the calculated relative gaseous potential hazard (RGPH) of the various isotopes. One isotope (Pu-238) represents 79% of the total calculated isotopic potential hazard (for 150-day-cooled fuel) from the combustion of HTGR fuel elements. Other isotopes that are of major potential hazards are: Cm-244 (6%), Sn-90 (4%), Po-216 (3%), Ce-144 (2%), Po-212 (2%), Pu-241 (1%), and Cs-134 (1%). By contrast, the more volatile isotopes have the following relative gaseous potential hazards: Kr-85 ($9 \times 10^{-5}\%$), I-131 ($1 \times 10^{-5}\%$), H-3 ($9 \times 10^{-6}\%$), I-129 ($3 \times 10^{-6}\%$), C-14 ($3 \times 10^{-6}\%$). It must be remarked that this comparison says nothing about actual amounts contained in the burner off-gas; it compares the isotopes to each other on the basis of the amounts in the fuel elements and permissible discharge limits.

Stoichiometric combustion of the graphite associated with 1 metric ton of heavy metal produces a minimum volume (STP) of about 5.2×10^5 ft³ of carbon dioxide. Reprocessing plant stacks can be designed to give a stack dilution of 5.2×10^{-8} . A 1-metric ton/day HTGR reprocessing plant with such a stack would have a dilution of about 10^{-13} metric ton/ft³. Multiplication of the values given in Tables 3 and 4 by 10^{-13} metric ton/ft³ gives the overall gaseous process decontamination factors that must be obtained during the combustion process, i.e., before release from the stack. The overall gaseous process decontamination factors thus calculated are shown in Figures 3-7. Elements with overall gaseous process decontamination factors greater than unity require decontamination prior to release to the stack. It should be noted that, if both the overall gaseous process decontamination factors and the calculated relative gaseous potential hazards of the various isotopes are arranged in descending sequences, a 1:1 correspondence exists as to the location of a given isotope in both sequences.

V. Conclusions

The simple procedure of comparing the various isotopes present in HTGR fuel elements at reprocessing time on the basis of the amount of air required to dilute each isotope to meet existing gaseous effluent regulations provides a helpful way of understanding which isotopes are likely to become major problems during the actual burning of spent fuel elements. Isotopes with the larger calculated dilution volumes will require larger overall process decontamination factors in order to meet the existing gaseous effluent regulations.

*The normalization is carried out as follows:

$$RGPH_i = \frac{X_i}{\sum_{i=1}^n X_i}, \text{ where } X_i = \text{gas dilution required (ft}^3/\text{metric ton) for isotope } i.$$

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Table 3. Dilution Required per Metric Ton of Heavy Metal
for Six-Year-Irradiated FSVR Fuel Calculated According
to Appendix B, Table II, Column 1, of 10 CFR Part 20

Gas Dilution Required for 150-day-cooled Fuel

Isotope	ft ³ /metric ton	Isotope	ft ³ /metric ton
1. ²³⁸ Pu	6.4 x 10 ¹⁸	33. ¹⁰³ Ru	5.7 x 10 ¹⁴
2. ²⁴⁴ Cm	4.7 x 10 ¹⁷	34. ²³¹ Pa	5.4 x 10 ¹⁴
3. ⁹⁰ Sr	3.6 x 10 ¹⁷	35. ^{127m} Te	5.4 x 10 ¹⁴
4. ²¹⁶ Po	2.3 x 10 ¹⁷	36. ^{137m} Ba	3.6 x 10 ¹⁴
5. ¹⁴⁴ Ce	1.8 x 10 ¹⁷	37. ^{129m} Te	3.5 x 10 ¹⁴
6. ²¹² Po	1.5 x 10 ¹⁷	38. ²³⁴ U	3.2 x 10 ¹⁴
7. ²⁴¹ Pu	8.4 x 10 ¹⁶	39. ²²⁴ Ra	2.3 x 10 ¹⁴
8. ¹³⁴ Cs	6.6 x 10 ¹⁶	40. ²³⁷ Np	2.3 x 10 ¹⁴
9. ⁸⁹ Sr	2.8 x 10 ¹⁶	41. ^{123m} Sn	2.3 x 10 ¹⁴
10. ²²⁸ Th	2.3 x 10 ¹⁶	42. ²⁴² Pu	2.0 x 10 ¹⁴
11. ¹³⁷ Cs	2.3 x 10 ¹⁶	43. ¹⁵⁶ Eu	2.0 x 10 ¹⁴
12. ²⁴² Cm	2.0 x 10 ¹⁶	44. ^{148m} Pm	2.0 x 10 ¹⁴
13. ¹⁰⁶ Ru	1.5 x 10 ¹⁶	45. ²¹¹ Bi	1.6 x 10 ¹⁴
14. ⁹⁶ Zr	1.4 x 10 ¹⁶	46. ²¹⁶ Po	1.6 x 10 ¹⁴
15. ⁹¹ Y	1.1 x 10 ¹⁶	47. ²¹⁸ Rn	1.6 x 10 ¹⁴
16. ²⁴⁰ Pu	1.0 x 10 ¹⁶	48. ²²⁹ Th	1.6 x 10 ¹⁴
17. ²³² U	8.7 x 10 ¹⁵	49. ²²⁷ Th	1.6 x 10 ¹⁴
18. ⁸⁶ Nb	8.4 x 10 ¹⁵	50. ²¹⁷ At	1.6 x 10 ¹⁴
19. ²³⁹ Pu	5.3 x 10 ¹⁵	51. ²²⁶ Ac	1.6 x 10 ¹⁴
20. ¹⁵⁴ Eu	4.5 x 10 ¹⁵	52. ²¹³ Bi	1.6 x 10 ¹⁴
21. ²⁴³ Am	4.2 x 10 ¹⁵	53. ²²¹ Fr	1.6 x 10 ¹⁴
22. ²³³ Pa	4.1 x 10 ¹⁵	54. ²¹³ Po	1.6 x 10 ¹⁴
23. ⁹⁰ Y	3.6 x 10 ¹⁵	55. ¹⁵⁶ Eu	1.3 x 10 ¹⁴
24. ^{86m} Nb	2.9 x 10 ¹⁵	56. ¹⁰⁶ Rh	9.7 x 10 ¹³
25. ²⁴¹ Am	2.8 x 10 ¹⁵	57. ^{242m} Am	7.0 x 10 ¹³
26. ¹⁴⁷ Pm	2.1 x 10 ¹⁵	58. ^{126m} Te	6.9 x 10 ¹³
27. ²⁴³ Cm	1.5 x 10 ¹⁵	59. ²²⁷ Ac	4.2 x 10 ¹³
28. ²³³ U	1.4 x 10 ¹⁵	60. ¹⁴⁰ Ba	1.8 x 10 ¹³
29. ¹⁴⁴ Pr	1.2 x 10 ¹⁵	61. ¹²⁷ Te	1.8 x 10 ¹³
30. ²³⁶ Pu	1.1 x 10 ¹⁵	62. ¹⁴⁸ Pm	1.6 x 10 ¹³
31. ¹²⁶ Sb	7.5 x 10 ¹⁴	63. ¹²⁴ Sb	1.5 x 10 ¹³
32. ¹⁴¹ Ce	6.2 x 10 ¹⁴	64. ^{110m} Ag	1.4 x 10 ¹³

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Table 3 (Contd.)

Isotope	ft ³ /metric ton	Isotope	ft ³ /metric ton
65. ¹⁵¹ Sm	1.0 x 10 ¹³	99. ¹²⁹ I	2.4 x 10 ¹¹
66. ¹⁶⁰ Tb	8.3 x 10 ¹²	100. ²³¹ Th	1.5 x 10 ¹¹
67. ²¹² Pb	7.8 x 10 ¹²	101. ²³⁷ U	8.0 x 10 ¹⁰
68. ⁸⁵ Kr	7.7 x 10 ¹²	102. ^{113m} Cd	6.8 x 10 ¹⁰
69. ¹⁴³ Pr	6.1 x 10 ¹²	103. ⁹³ Zr	6.4 x 10 ¹⁰
70. ^{162m} Tb	5.8 x 10 ¹²	104. ^{234m} Pa	5.6 x 10 ¹⁰
71. ¹⁶² Gd	5.8 x 10 ¹²	105. ²⁰⁸ Tl	5.6 x 10 ¹⁰
72. ¹⁴⁰ La	5.1 x 10 ¹²	106. ⁵⁹ Fe	3.8 x 10 ¹⁰
73. ²³⁰ Th	4.0 x 10 ¹²	107. ²³⁵ U	3.7 x 10 ¹⁰
74. ²³² Th	3.3 x 10 ¹²	108. ²⁰⁹ Pb	3.2 x 10 ¹⁰
75. ^{119m} Sn	3.3 x 10 ¹²	109. ¹¹⁰ Ag	1.8 x 10 ¹⁰
76. ²³⁸ U	3.0 x 10 ¹²	110. ²³⁹ Np	1.7 x 10 ¹⁰
77. ¹²⁶ Sb	2.9 x 10 ¹²	111. ²³⁴ Pa	1.7 x 10 ¹⁰
78. ¹²⁹ Te	2.2 x 10 ¹²	112. ¹⁰⁷ Pd	1.7 x 10 ¹⁰
79. ²²⁸ Ra	1.9 x 10 ¹²	113. ²⁴² Am	1.4 x 10 ¹⁰
80. ²³⁴ Th	1.7 x 10 ¹²	114. ^{162m} Eu	1.3 x 10 ¹⁰
81. ²¹² Bi	1.6 x 10 ¹²	115. ^{93m} Nb	1.2 x 10 ¹⁰
82. ^{115m} Cd	1.3 x 10 ¹²	116. ¹³⁵ Cs	1.1 x 10 ¹⁰
83. ^{123m} Te	1.1 x 10 ¹²	117. ¹⁰ Be	5.3 x 10 ⁹
84. ¹⁰³ Rh	8.5 x 10 ¹¹	118. ²²⁸ Ac	3.2 x 10 ⁹
85. ¹³¹ I	8.0 x 10 ¹¹	119. ¹²⁵ Sn	2.8 x 10 ⁹
86. ⁷⁹ Se	7.5 x 10 ¹¹	120. ¹⁴ C	2.1 x 10 ⁹
87. ³ H	7.2 x 10 ¹¹	121. ^{126m} Sb	1.4 x 10 ⁹
88. ⁹⁹ Tc	6.0 x 10 ¹¹	122. ^{131m} Xe	3.0 x 10 ⁸
89. ⁵⁵ Fe	5.9 x 10 ¹¹	123. ^{129m} Xe	2.5 x 10 ⁸
90. ²²⁰ Rn	4.7 x 10 ¹¹	124. ²¹¹ Pb	1.1 x 10 ⁸
91. ¹²⁶ Sn	4.3 x 10 ¹¹	125. ²⁰⁷ Tl	1.1 x 10 ⁸
92. ²²³ Ra	4.1 x 10 ¹¹	126. ²²⁵ Ra	1.1 x 10 ⁸
93. ¹³⁶ Cs	3.8 x 10 ¹¹	127. ^{117m} Sn	5.5 x 10 ⁷
94. ⁸⁶ Rb	3.5 x 10 ¹¹	128. ¹¹¹ Ag	3.9 x 10 ⁷
95. ⁵⁴ Mn	3.2 x 10 ¹¹	129. ¹⁶¹ Tb	4.9 x 10 ⁸
96. ¹⁵² Eu	3.2 x 10 ¹¹	130. ³² P	1.9 x 10 ⁸
97. ¹⁴⁷ Nd	3.0 x 10 ¹¹	131. ²⁰⁹ Tl	1.9 x 10 ⁸
98. ⁶⁰ Co	2.5 x 10 ¹¹	132. ⁵¹ Cr	1.0 x 10 ⁸

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Table 3 (Contd.)

Isotope		ft ³ /metric ton	Isotope		ft ³ /metric ton
133.	¹³³ Xe	7.1×10^6	136.	¹³² Te	1.5×10^2
134.	¹²⁷ Sb	1.4×10^6	137.	⁹⁹ Mo	5.2×10^{-1}
135.	¹³² I	2.1×10^2	138.	^{99m} Tc	7.0×10^{-3}

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Table 4. Dilution Required per Metric Ton of Heavy Metal
for Six-Year-Irradiated FSVR Fuel Calculated According
to Appendix B, Table II, Column 1, of 10 CFR Part 20

Gas Dilution Required for 365-day-cooled Fuel

Isotope	ft ³ /metric ton	Isotope	ft ³ /metric ton
1. ²³⁸ Pu	6.4 x 10 ¹⁸	32. ²³⁴ U	3.2 x 10 ¹⁴
2. ²⁴⁴ Cm	4.6 x 10 ¹⁷	33. ^{95m} Nb	2.9 x 10 ¹⁴
3. ⁹⁰ Sr	3.6 x 10 ¹⁷	34. ²²⁴ Ra	2.7 x 10 ¹⁴
4. ²¹⁸ Po	2.7 x 10 ¹⁷	35. ²³⁷ Np	2.3 x 10 ¹⁴
5. ²¹² Po	1.7 x 10 ¹⁷	36. ²⁴² Pu	2.0 x 10 ¹⁴
6. ¹⁴⁴ Ce	1.1 x 10 ¹⁷	37. ²¹¹ Bi	1.8 x 10 ¹⁴
7. ²⁴¹ Pu	8.2 x 10 ¹⁶	38. ²¹⁶ Po	1.8 x 10 ¹⁴
8. ¹³⁴ Cs	5.4 x 10 ¹⁶	39. ²¹⁹ Rn	1.8 x 10 ¹⁴
9. ²²⁸ Th	2.7 x 10 ¹⁶	40. ²²⁷ Th	1.8 x 10 ¹⁴
10. ¹³⁷ Cs	2.3 x 10 ¹⁶	41. ²¹⁷ At	1.8 x 10 ¹⁴
11. ²⁴⁰ Pu	1.1 x 10 ¹⁶	42. ²²⁶ Ac	1.8 x 10 ¹⁴
12. ¹⁰⁶ Ru	9.7 x 10 ¹⁵	43. ²¹³ Bi	1.8 x 10 ¹⁴
13. ²³² U	8.7 x 10 ¹⁵	44. ²²¹ Fr	1.8 x 10 ¹⁴
14. ²⁴² Cm	7.8 x 10 ¹⁵	45. ²²⁸ Th	1.8 x 10 ¹⁴
15. ²³⁹ Pu	5.3 x 10 ¹⁵	46. ²¹³ Po	1.8 x 10 ¹⁴
16. ¹⁵⁴ Eu	4.4 x 10 ¹⁵	47. ^{127m} Te	1.4 x 10 ¹⁴
17. ²⁴¹ Am	4.0 x 10 ¹⁵	48. ¹⁵⁵ Eu	1.0 x 10 ¹⁴
18. ⁹⁰ Y	3.6 x 10 ¹⁵	49. ^{242m} Am	6.9 x 10 ¹³
19. ²⁴³ Am	2.7 x 10 ¹⁵	50. ^{123m} Sn	6.9 x 10 ¹³
20. ¹⁴⁷ Pm	1.8 x 10 ¹⁵	51. ¹⁰⁶ Rh	6.5 x 10 ¹³
21. ⁸⁹ Sr	1.6 x 10 ¹⁵	52. ^{125m} Te	6.0 x 10 ¹³
22. ²⁴³ Cm	1.5 x 10 ¹⁵	53. ²²⁷ Ac	4.6 x 10 ¹³
23. ²³³ U	1.4 x 10 ¹⁵	54. ²³³ Pa	1.8 x 10 ¹³
24. ⁹⁶ Zr	1.4 x 10 ¹⁵	55. ¹⁰³ Ru	1.3 x 10 ¹³
25. ⁹⁵ Nb	9.7 x 10 ¹⁴	56. ¹⁵¹ Sm	1.0 x 10 ¹³
26. ²³⁸ Pu	9.1 x 10 ¹⁴	57. ²¹² Pb	8.9 x 10 ¹²
27. ⁹¹ Y	8.4 x 10 ¹⁴	58. ^{110m} Ag	7.8 x 10 ¹²
28. ¹⁴⁴ Pr	7.2 x 10 ¹⁴	59. ⁸⁶ Kr	7.4 x 10 ¹²
29. ¹²⁵ Sb	6.5 x 10 ¹⁴	60. ¹⁴¹ Ce	6.3 x 10 ¹²
30. ²³¹ Pa	5.4 x 10 ¹⁴	61. ^{148m} Pm	5.8 x 10 ¹²
31. ^{137m} Ba	3.5 x 10 ¹⁴	62. ¹²⁷ Te	4.5 x 10 ¹²

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Table 4 (Contd.)

Isotope	ft ³ /metric ton	Isotope	ft ³ /metric ton
63. ^{129m} Te	4.4 x 10 ¹²	95. ¹²⁹ Te	2.8 x 10 ¹⁰
64. ²³⁰ Th	4.1 x 10 ¹²	96. ^{103m} Rh	2.0 x 10 ¹⁰
65. ¹⁶² Gd	3.9 x 10 ¹²	97. ²³⁹ Np	1.7 x 10 ¹⁰
66. ^{162m} Tb	3.9 x 10 ¹²	98. ¹⁰⁷ Pd	1.7 x 10 ¹⁰
67. ²³² Th	3.3 x 10 ¹²	99. ²⁴² Am	1.4 x 10 ¹⁰
68. ²³⁶ U	3.0 x 10 ¹²	100. ^{93m} Nb	1.3 x 10 ¹⁰
69. ²²⁸ Ra	2.0 x 10 ¹²	101. ^{152m} Eu	1.2 x 10 ¹⁰
70. ^{119m} Sn	1.8 x 10 ¹²	102. ¹³⁶ Cs	1.1 x 10 ¹⁰
71. ²¹² Bi	1.8 x 10 ¹²	103. ¹¹⁰ Ag	1.0 x 10 ¹⁰
72. ¹²⁴ Sb	1.3 x 10 ¹²	104. ¹⁵⁶ Eu	9.9 x 10 ⁹
73. ¹⁸⁰ Tb	1.0 x 10 ¹²	105. ¹⁰ Be	5.3 x 10 ⁹
74. ⁷⁹ Se	7.5 x 10 ¹¹	106. ²³⁴ Th	3.5 x 10 ⁹
75. ³ H	7.0 x 10 ¹¹	107. ²²⁸ Ac	3.4 x 10 ⁹
76. ⁹⁹ Tc	6.0 x 10 ¹¹	108. ¹⁴ C	2.1 x 10 ⁹
77. ²²⁰ Rn	5.4 x 10 ¹¹	109. ^{126m} Sb	1.4 x 10 ⁹
78. ⁶⁶ Fe	5.0 x 10 ¹¹	110. ⁶⁹ Fe	1.4 x 10 ⁹
79. ¹⁴⁸ Pm	4.7 x 10 ¹¹	111. ¹⁴⁰ Ba	1.5 x 10 ⁸
80. ²²³ Ra	4.6 x 10 ¹¹	112. ²¹¹ Pb	1.2 x 10 ⁸
81. ¹²⁶ Sn	4.3 x 10 ¹¹	113. ²⁰⁷ Tl	1.2 x 10 ⁸
82. ¹²⁶ Sb	4.3 x 10 ¹¹	114. ⁸⁶ Rb	1.2 x 10 ⁸
83. ¹⁶² Eu	3.0 x 10 ¹¹	115. ²²⁵ Ra	1.2 x 10 ⁸
84. ^{123m} Te	3.0 x 10 ¹¹	116. ^{234m} Pa	1.2 x 10 ⁸
85. ¹²⁸ I	2.4 x 10 ¹¹	117. ¹⁴³ Pr	1.1 x 10 ⁸
86. ⁶⁰ Co	2.3 x 10 ¹¹	118. ¹⁴⁰ La	4.5 x 10 ⁷
87. ⁵⁴ Mn	2.0 x 10 ¹¹	119. ²³⁴ Pa	3.5 x 10 ⁷
88. ²³¹ Th	1.5 x 10 ¹¹	120. ²⁰⁹ Tl	2.1 x 10 ⁶
89. ^{113m} Cd	6.6 x 10 ¹⁰	121. ¹⁴⁷ Nd	4.5 x 10 ⁶
90. ²⁰⁸ Tl	6.4 x 10 ¹⁰	122. ¹³¹ I	7.3 x 10 ³
91. ⁹³ Zr	6.4 x 10 ¹⁰	123. ⁵¹ Cr	4.7 x 10 ³
92. ^{116m} Cd	4.1 x 10 ¹⁰	124. ^{131m} Xe	1.0 x 10 ³
93. ²³⁵ U	3.7 x 10 ¹⁰	125. ¹¹¹ Ag	9.1 x 10 ⁻²
94. ²⁰⁹ Pb	3.6 x 10 ¹⁰		

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<u>HYDROGEN</u> 3 7.2×10^{-2}					
<u>LITHIUM</u>	<u>BERYLLIUM</u> 10 5.3×10^{-4}				
<u>SODIUM</u>	<u>MAGNESIUM</u>				
<u>POTASSIUM</u>	<u>CALCIUM</u>	<u>SCANDIUM</u>	<u>TITANIUM</u>	<u>VANADIUM</u>	<u>CHROMIUM</u>
<u>RUBIDIUM</u> 86 3.5×10^{-2}	<u>STRONTIUM</u> 90 3.6×10^{-4} 89 2.8×10^{-3}	<u>YTTORIUM</u> 91 1.1×10^{-3} 90 3.6×10^{-2}	<u>ZIRCONIUM</u> 95 1.4×10^{-3} 93 6.4×10^{-3}	<u>NIOBIUM</u> 95 8.4×10^{-2} 95M 2.9×10^{-2} 93M 1.2×10^{-2}	<u>MOLYBDENUM</u>
<u>CESIUM</u> 134 6.6×10^{-3} 137 2.3×10^{-3} 136 3.8×10^{-2}	<u>BARIUM</u> 137M 3.6×10^{-1} 140 1.8	<u>LANTHANUM</u> 140 $\times 10^{-1}$	<u>HAFNIUM</u>	<u>TANTALUM</u>	<u>TUNGSTEN</u>
<u>FRANCIUM</u> 221 1.6×10^{-1}	<u>RADIUM</u> 224 2.3×10^{-1} 228 1.9×10^{-1} 223 4.1×10^{-2} 225 1.1×10^{-3}	<u>ACTINIUM</u> 224 1.6×10^{-1} 227 4.2 228 3.2×10^{-4}			

FIGURE 3. GROUPS 1A THROUGH 6B ISOTOPIC GAS-PHASE DECONTAMINATION FACTORS FOR 6-YEAR-IRRADIATED FSVR FUEL ACCORDING TO 10 CFR, PART 20.

					<u>HELIUM</u>
<u>BORON</u>	<u>CARBON</u> 14 2.1×10^{-4}	<u>NITROGEN</u>	<u>OXYGEN</u>	<u>FLUORINE</u>	<u>NEON</u>
<u>ALUMINUM</u>	<u>SILICON</u>	<u>PHOSPHORUS</u>	<u>SULFUR</u>	<u>CHLORINE</u>	<u>ARGON</u>
<u>GALLIUM</u>	<u>GERMANIUM</u>	<u>ARSENIC</u>	<u>SELENIUM</u> 79 7.5×10^{-2}	<u>BROMINE</u>	<u>KRYPTON</u> 85 7.7×10^{-1}
<u>INDIUM</u>	<u>TIN</u> 123M 2.3×10^{-1} 119M 3.3×10^{-1} 126 4.3×10^{-2} 125 2.8×10^{-4}	<u>ANTIMONY</u> 125 7.6×10^{-1} 124 1.5 126 2.9×10^{-1} 126M 1.4×10^{-4}	<u>TELLURIUM</u> 127M 5.4×10^{-1} 129M 3.5×10^{-1} 125M 6.9 127 1.8 129 2.2×10^{-1} 123M 1.1×10^{-1}	<u>IODINE</u> 131 8.0×10^{-2} 129 2.4×10^{-2}	<u>XENON</u> 131M 3.0×10^{-5} 129M 2.5×10^{-5}
<u>THALLIUM</u> 208 5.6×10^{-3} 207 10^{-5}	<u>LEAD</u> 212 7.8×10^{-1} 209 10^{-3} 211 3.2×10^{-5}	<u>BISMUTH</u> 211 1.6×10^{-1} 213 1.6×10^{-1} 212 1.6×10^{-1}	<u>POLONIUM</u> 216 2.3×10^{-4} 212 1.5×10^{-4} 215 1.6×10^{-1} 213 1.6×10^{-1}	<u>ASTATINE</u> 217 1.6×10^{-1}	<u>RADON</u> 219 1.6×10^{-2} 220 4.7×10^{-2}

FIGURE 4. GROUPS 3A THROUGH 1G ISOTOPIC GAS-PHASE DECONTAMINATION FACTORS FOR 6-YEAR-IRRADIATED FSFR FUEL ACCORDING TO 10 CFR, PART 20.

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<u>MANGANESE</u> 54 3.2×10^{-2}	<u>IRON</u> 55 5.9×10^{-2} 59 3.8×10^{-3}	<u>COBALT</u> 60 2.5×10^{-2}	<u>NICKEL</u>	<u>COPPER</u>	<u>ZINC</u>
<u>TECHNETIUM</u> 99 6.0×10^{-2}	<u>RUTHENIUM</u> 106 1.5×10^{-3} 103 5.7×10^{-3}	<u>RHODIUM</u> 106 9.7 103M 8.5×10^{-2}	<u>PALLADIUM</u> 107 1.7×10^{-3}	<u>SILVER</u> 110M 1.4 110 1.8×10^{-3}	<u>CADMIUM</u> 115M 1.3×10^{-1} 113M 6.8×10^{-3}
<u>RHENIUM</u>	<u>OSMIUM</u>	<u>IRIDIUM</u>	<u>PLATINUM</u>	<u>GOLD</u>	<u>MERCURY</u>

FIGURE 5. GROUPS 7B THROUGH 2B ISOTOPIC GAS-PHASE DECONTAMINATION FACTORS FOR 6-YEAR-IRRADIATED FSVR FUEL ACCORDING TO 10 CFR, PART 20.

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<u>CERIUM</u> 144 1.8×10^4 141 6.2×10	<u>PRASEODYMIUM</u> 144 1.2×10^2 143 6.1×10^{-1}	<u>NEODYMIUM</u> 147 3.0×10^{-2}	<u>PROMETHIUM</u> 147 2.1×10^2 148M 2.0×10 148 1.6	<u>SAMARIUM</u> 151 1.0	<u>EUROPIUM</u> 154 4.5×10^2 156 2.0×10 155 1.3×10 152Y 3.2×10^{-2} 152H 1.5×10^{-3}	<u>GADOLINIUM</u> 162 5.8×10^{-1}
<u>TERBIUM</u> 160 6.3×10^{-1} 162M 5.8×10^{-1}	<u>DYSPROSIUM</u>	<u>HOLMIUM</u>	<u>ERBIUM</u>	<u>THULIUM</u>	<u>YTTERBIUM</u>	<u>LUTETIUM</u>

FIGURE 6. LANTHANIDE ISOTOPIC GAS-PHASE DECONTAMINATION FACTORS FOR 6-YEAR-IRRADIATED FSVR FUEL ACCORDING TO 10 CFR, PART 20.

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<u>THORIUM</u>	<u>PROTACTINIUM</u>	<u>URANIUM</u>	<u>NEPTUNIUM</u>	<u>PLUTONIUM</u>	<u>AMERICIUM</u>	<u>CURIUM</u>
228 2.3×10^3	235 4.1×10^2	232 8.7×10^2	237 2.3×10	238 6.4×10^3	243 4.2×10^2	244 4.7×10^4
229 1.6×10	231 5.4×10	233 1.4×10^2	239 1.7×10^{-3}	241 8.4×10^3	241 2.8×10^2	242 2.0×10^3
227 1.6×10	234M 5.6×10^{-3}	234 3.2×10		240 1.0×10^3	242M 7.0	243 1.5×10^2
230 4.0×10^{-1}	234 1.7×10^{-3}	236 2.0×10^{-1}		239 5.3×10^2	242 1.4×10^{-3}	
231 3.3×10^{-1}		237 8.0×10^{-3}		236 1.1×10^2		
232 1.7×10^{-1}		235 3.7×10^{-3}		242 2.0×10		
231 1.3×10^2						
<u>BERKELIUM</u>	<u>CALIFORNIUM</u>	<u>EINSTEINIUM</u>	<u>FERMIUM</u>	<u>MENDELEVIUM</u>	<u>NOBELIUM</u>	

FIGURE 7. ACTINIDE ISOTOPE GAS-PHASE DECONTAMINATION FACTORS FOR 6-YEAR-IRRADIATED FSVR FUEL ACCORDING TO 10 CFR, PART 20.

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The amount of air required to dilute the Pu-238 contained in a metric ton (preirradiation) of spent HTGR fuel is approximately twenty times that required for diluting Sr-90. By way of comparison, the amount of water required to dilute the Pu-238 is 0.25% of that required to dilute the Sr-90⁽³⁾. Thus, consideration of only the isotopes that are known to be of major importance in liquid effluents plus those that are highly volatile is insufficient for identifying potential problems to be encountered in decontaminating the burner off-gas.

If a researcher multiplies the calculated dilution volumes by the relative volatilities (assume rare gases = 1), then he can arrange the isotopes in a sequence that will be representative of the actual relative hazards of the isotopes contaminating the carbon dioxide. Such a sequence would be of invaluable aid in trying to develop a burner off-gas decontamination process.

VI. References

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3. J. W. Snider, unpublished calculations, Oak Ridge National Laboratory.