High-Level Waste Environmental
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TECHNICAL REPORT
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RADIATION EXPOSURES FROM SOLIDIFICATION PROCESSES FOR HIGH-LEVEL RADIOACTIVE LIQUID WASTES

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EPA REVIEW NOTICE

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PREFACE

The Office of Radiation Programs, U.S. Environmental Protection Agency, carries out a national program to evaluate individual and population exposure to ionizing and non-ionizing radiation and to promote development of controls for the protection of public health and the environment.

This report is technical support for EPA's high-level radioactive waste environmental standards; it estimates the potential environmental effect of solidification of high-level radioactive liquid wastes.

The Office of Radiation Programs invites readers to report omissions or errors, submit comments, or request further information.

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SUMMARY

The Office of Radiation Programs, U.S. Environmental Protection Agency (ORP/EPA), has prepared this analysis as technical support for EPA's proposed environmental radiation protection standards, 40 CFR 191, concerning the management and disposal of high-level radioactive wastes. For Subpart A of 40 CFR 191, waste management and storage operations, EPA proposes to extend the limitations of 40 CFR 190 to these operations.

EPA/ORP developed a generic high-level liquid waste solidification plant and assessed the potential environmental impact of atmospheric discharges during normal operations in four solidification processes: fluidized-bed calcination, spray calcination, and glassification by in-can melting and continuous melting. We used a newly developed computer code, AIRDOS-EPA, to perform the assessment.

Our assessment involves seven radionuclides that account for 88% of the doses due to the solidification process: H-3, I-129, Ru-106, Cs-134, Cs-137, Sr-90, and Pu-239. We estimated the decontamination factors for typical off-gas equipment components to remove these radionuclides and an overall off-gas cleanup system decontamination factor.

For purposes of comparison, we based our assessment on two hypothetical plant sites with widely different population size, food sources, and weather: an urban site, St. Louis, Missouri; and a rural site in the southeastern United States typified by the South Carolina sites of the Federal Government's Savannah River Plant and the commercial Barnwell Nuclear Fuel Plant.

We estimated off-gas releases during normal operations of the generic solidification plant and the resulting annual individual and population dose equivalents. We compared the doses to individuals and

the quantities of radioactive materials released with the limits in EPA's standards for the Uranium Fuel Cycle (UFC), 40 CFR 190.

Our assessment indicates that for fuel decayed for one year the maximum annual doses to an individual due to releases from a solidification facility at a rural site would be lower than the 40 CFR 190 standards; that maximum annual doses from a facility at an urban site would exceed the UFC standards. In the case of the radionuclide waste products that have decayed for five years or longer, the maximum annual dose to an individual at either site is lower than the 40 CFR 190 standards. Additional off-gas treatment for the solidification facility can also reduce the maximum annual doses.

GLOSSARY

ABBREVIATIONS

AEC - U.S. Atomic Energy Commission

40 CFR 190 - Title 40, Part 190, Code of Federal Regulations

Ci - Curie

DF - Decontamination Factor

DOE - U.S. Department of Energy

ERDA - U.S. Energy Research and Development Administration

EPA - U.S. Environmental Protection Agency

GWe - Gigawatts electrical; giga is a thousand million

HEPA - High-Efficiency Particulate Air Filter

HLLW - High-Level Liquid Wastes

INEL - Idaho National Engineering Laboratory

LLI - Lower Large Intestine

LWR - Light-Water Reactor

MWd - Megawatt days; mega is a million

MTHM - Metric tons of heavy metals (i.e. uranium and plutonium)

MTU - metric tons of uranium

NRC - U.S. Nuclear Regulatory Commission

ORNL - Oak Ridge National Laboratory

ORP - EPA's Office of Radiation Programs

PNL - Pacific Northwest Laboratories

UFC - Uranium Fuel Cycle

WCF - Waste Calcining Facility

TERMS

Actinides - The series of elements beginning with element No. 89, actinium and continuing through element No. 104.

Annual Dose - The dose received by an individual or a population from one year's release. It is the sum of the external dose received that year plus the 70-year dose commitment from internal radioactive material.

Burnup - A measure of reactor fuel consumption. It is usually expressed as either (a) the percentage of uranium atoms that have undergone fission or (b) as thermal energy produced per quantity of nuclear fuel (i.e. megawatt-days per metric ton).

Calcination - method of converting the solids in solution to a solid by atomizing and coating the liquid on small granules and heating to drive off the water.

Calcine - The resulting solid granule product from calcination.

Curie - The basic unit to describe the intensity of radioactivity in a material.

Decay (Radioactive) - The spontaneous transformation of one nuclide into a different nuclide or into a different energy state of the same nuclide usually resulting in the release of ionizing radiation. The process results in a decrease, with time, of the number of the original radioactive atoms in a sample.

Decontamination Factor - The ratio of the amount of a given type of radioactive material entering a process (or process step) to that which leaves the process (or process step).

Deposition Velocity - The ratio of the deposition rate to the ground-level concentrations.

Dose Commitment - Radionuclides which enter the body through ingestion or inhalation remain in the body as a continuing source of exposure for a length of time determined by biological and physical factors. The dose is cumulative and is evaluated in this report for 70 years and is included in the annual doses.

Dose Equivalent - A term used to express the amount of effective radiation when modifying factors have been considered such as quality and distribution factors.

E±00 Format - Throughout this report, numeric values are frequently expressed in a modified scientific format. For example, $0.00456 = 4.56 \times 10^{-3}$ may be expressed as 4.56 E-03 and $78900 = 7.89 \times 10^{4}$ as 7.89 E+04.

Fission Products - The radionuclides and their decay products formed by the fission of heavy elements.

Fuel Enrichment - Material such as uranium in which the percentage of a given isotope present has been artificially increased, so that it is higher than the percentage of that isotope naturally found in the material.

Fuel Reprocessing - The processing of spent reactor fuel to recover the unused fissionable uranium and plutonium.

Fluidized Bed - A cushion of air or hot gas blown through the porous bottom slab of a container which can be used to float a powdered material as a means of drying, heating or calcining the immersed object.

Generic - Characteristic of a whole class.

Glass Frit - The calcined or partly fused materials of which glass is made.

Glassification - Incorporation of wastes into a glass matrix.

High-Level Liquid Waste - The aqueous waste resulting from the operation of the chemical extraction systems in a facility for processing spent nuclear fuel.

High-Level Waste - High-level liquid waste, or the products from solidification of high-level liquid waste, or spent fuel elements, if discarded without processing.

Off-Gas - The normal gasborne discharge from any process vessel or other process equipment.

Scavenging Coefficient - The fraction of material reaching the ground per unit time due to the collection of particles and gases by cloud or precipitation droplets.

Spent Fuel - Any fuel removed from a nuclear reactor after it has been irradiated, usually to the extent that it can no longer effectively sustain a chain reaction.

1.0 INTRODUCTION

The Office of Radiation Programs (ORP), U.S. Environmental Protection Agency (EPA), is proposing generally applicable environmental radiation protection standards for management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes (1). These proposed standards would become Part 191 of the Code of Federal Regulations, Title 40 (40 CFR 191).

Subpart A of the proposed standards applies to normal waste management operations, which include preparation for storage or disposal (solidification of high-level liquid wastes, packaging of spent fuel), storage, and emplacement in a disposal repository.

Since the UFC standards exclude waste management operations, ORP/EPA prepared this radiation exposure analysis of airborne emissions as technical support for EPA's proposed 40 CFR 191 standards. For practical purposes the basic assumption for this analysis is that the only radioactive materials entering the general environment from a solidification facility are airborne discharges to the atmosphere; liquid releases or accidental releases were not considered. For Subpart A of the proposed standards, EPA proposes to extend the limitations of 40 CFR 190 to these operations.

2.0 SOLIDIFICATION OF RADIOACTIVE HIGH-LEVEL LIQUID WASTES

High-level liquid wastes (HLLW) are generated during the chemical reprocessing of spent nuclear fuel to recover uranium and plutonium. As of 1977, the inventory of high-level liquid wastes from Federal reprocessing of spent fuel amounted to about 0.3 million cubic meters, containing about 400 to 600 million curies. Most of these wastes have been reduced to solids or semi-liquids in the form of salt cake, crystals, sludges, and calcine. However, the government will probably continue to generate liquid wastes at a rate of a few thousand cubic meters per year. The Department of Energy (DOE) stores the wastes from Federal reprocessing plants at the Hanford Reservation in Washington, the Savannah River Plant in South Carolina, and the Idaho National Engineering Laboratory (INEL) in Idaho (2-6).

At Hanford, DOE is converting its own high-level liquid wastes to a salt cake, which is temporarily stored in underground tanks along with residual sludge and liquor; cesium-137 and strontium-90 are separated and stored in aboveground facilities. At the Savannah River Plant, DOE converts its HLLW to salt cake, without separating cesium and strontium. DOE's facility at INEL converts its HLLW to a granular calcine and stores it in specially designed underground vaults (2-6).

Federal policy at the present time is to defer commercial reprocessing of spent fuels from the nuclear power industry (7). Therefore, most spent fuel from commercially operated reactors is unprocessed and in temporary storage. As of 1976, commercial spent fuel in storage amounted to about 2343 metric tons of uranium (8). If the Federal Government permits reprocessing in the future, each metric ton processed will produce about five cubic meters of high-level liquid wastes (9).

A small amount of high-level liquid wastes from commercial reprocessing of spent fuel -- about 17 thousand cubic meters, containing approximately 40 million curies -- is stored at the Nuclear Fuel Services fuel reprocessing plant near West Valley, New York (10). Nuclear Regulatory Commission (NRC) regulations require that commercially produced high-level liquid wastes be converted to a stable solid form within five years after they are generated and then transferred to the Federal government for permanent disposal (11). Solidification immobilizes the wastes in order to isolate them from the environment. It also reduces the volume of wastes requiring storage by 80 to 90 percent.

Numerous solidification processes have been developed throughout the world; many have been demonstrated by pilot-plant or plant-scale operation (see Table B.4). Of the many technologies two seem to have emerged as the most prominent -- calcination and glassification.

As part of the Government's waste management program, DOE has developed solidification alternatives for commercial and Federal HLLW. Among the solidification processes DOE has proposed are calcination, which converts HLLW to a granular powder; and glassification, which incorporates the powder into a solid matrix that serves as an engineered barrier in preventing or delaying migration of the radionuclides to the environment (12-18).

During normal operations of a solidification plant, some of the radionuclides in the wastes are released to off-gas streams as volatile gases and particulates. Before release to the atmosphere these off-gases are routed to treatment systems to remove the radionuclides. The amount and concentration of radionuclides in the plant's exhaust stack discharge depends on the amount and concentration of radionuclides in the high-level liquid waste feed to the plant and on the

effectiveness of the treatment systems in removing the radionuclides from the off-gas streams before their release to the atmosphere.

Several major factors can affect the potential radiation dose to individuals and populations as a result of the discharge: proximity to the plant, the pathways by which the radionuclides can reach them, the length of time during which the radionuclides continue to pose a health hazard, decay time, meteorological factors, plant capacity, and off-gas treatment. The radioactive decay of the fission products and actinides in the fuel during storage before reprocessing and in the liquid waste before solidification causes a significant reduction in the amount of radioactive materials.

3.0 GENERIC SOLIDIFICATION PLANT

For the purposes of this analysis, the EPA developed a generic solidification plant for the calcination and glassification of high-level liquid wastes. Input data on actual solidification plant experience came from the Government's Waste Calcination Facility (WCF) in Idaho; input data on hypothetical HLLW were developed from proposed commercial spent fuel reprocessing plants. The analysis applies to both Government and commercial wastes. They contain the same major radionuclides. However, Government wastes are less radioactive and less thermally active because of different decay time for the fission products, different enrichments and burnup percentages, and different reactor operational characteristics (3, 13-15).

We chose the four most promising and advanced solidification processes: fluidized-bed and spray calcination; and glassification by in-can melting and continuous melting. (See Appendix A.)

From the hundreds of fission-product and actinide radionuclides, we selected seven for our analysis: tritum (H-3), iodine-129 (I-129), ruthenium-106 (Ru-106), cesium-134 (Cs-134), cesium-137 (Cs-137), strontium-90 (Sr-90) and plutonium-239 (Pu-239). We selected them because of their adverse health effects, high dose-equivalent conversion factors, half-lives, high release rates, and the fraction of the nuclide released to the environment. These seven radionuclides account for more than an estimated 88% of the maximum doses to the major organs of adults due to releases from the solidification of HLLW (19).

The feed rate to the generic solidification plant is the HLLW generated from the reprocessing of 1500 MTHM (metric tons of heavy metal) per year of spent fuel from light-water reactors.

The radionuclide inventory of this HLLW feed is determined by the radioactive inventory of the spent fuel, the length of time during which the spent fuel decayed before reprocessing, and the length of time the HLLW and fission products were in storage before solidification, and the radionuclide percentage carryover from spent fuel reprocessing.

The initial radionuclide inventory of the spent fuel prior to reprocessing is based on an average burnup in a commercial pressurized light-water reactor of 33,000 megawatt days thermal per MTHM at a continuous power of 38.4 megawatts per MTHM. The original fuel enrichment averaged 3.3%. Table 3.1 gives the calculated inventory of the seven selected radionuclides, in the spent fuel after decaying for one, five, and ten years (3, 20).

The radionuclide carryover in the HLLW from spent fuel reprocessing is 5% of the tritium, 5% of the iodine, over 99% of the nonvolatile fission products, and 1% of the plutonium (21). Table 3.2 gives the calculated radionuclide inventory of the HLLW feed to the generic solidification plant.

TABLE 3.1

RADIONUCLIDE INVENTORY OF SPENT FUEL PRIOR TO REPROCESSING AND SOLIDIFICATION

RADIONUCLIDE	HALF-LIFE	DECAY PERIOD 1 YEAR	5 YEARS	10 YEARS
	(years)	(curies per MTHM)		
H-3	12.3	6.91 E+02	5.5 E+02	4.16 E+02
I-129	1.7 E+07	3.77 E-02	3.77 E-02	3.77 E-02
Ru-106	1.01	3.23 E+05	2.12 E+04	6.50 E+02
Cs-137	30.0	1.06 E+05	9.70 E+04	8.64 E+04
Cs-134	2.05	1.92 E+05	4.98 E+04	9.18 E+03
Sr-90	28.1	7.49 E+04	6.78 E+04	6.00 E+04
Pu-239	2.40 E+04	3.31 E+02	3.31 E+02	3.31 E+02

TABLE 3.2

RADIONUCLIDE INVENTORY OF THE HLLW FEED TO THE GENERIC SOLIDIFICATION PLANT

RADIONUCLIDE	DECAY PERIOD 1 YEAR	5 YEARS	10 YEARS
	(curies per year*)		
H-3	5.19 E+04	4.13 E+04	3.12 E+04
I-129	2.84 E+00	2.84 E+00	2.84 E+00
Ru-106	4.80 E+08	3.18 E+07	9.75 E+05
Cs-137	1.59 E+08	1.46 E+08	1.30 E+08
Cs-134	2.88 E+08	7.39 E+07	1.36 E+07
Sr-90	1.12 E+08	1.02 E+08	9.00 E+07
Pu-239	5.00 E+03	5.00 E+03	5.00 E+03

* Based on a reprocessing plant capacity of 1500 MTHM per year of spent fuel

4.0 OFF-GAS TREATMENT, DECONTAMINATION FACTORS AND DISCHARGE RATES AT THE GENERIC SOLIDIFICATION PLANT

The reduction of discharge rates from any solidification process occurs based on three factors: the off-gas treatment; the off-gas treatment system's decontamination factors; and the radionuclide decay time measured from the time the spent fuel was discharged from the reactor.

4.1 Off-Gas Treatment

Off-gas treatment reduces the discharge of airborne radioactive materials to the environment. The equipment and systems discussed in sections 4.1 and 4.2 present a brief review of the existing technologies. Additional and more detailed information on equipment is presented in references 9, 23, 53.

During calcination and glassification of HLLW, the tritium, iodine, and part of the ruthenium will volatilize; the cesium, strontium, plutonium, and a small fraction of the ruthenium will become entrained as particulates in the process' off-gas streams going to the plant's off-gas treatment system. Off-gas treatment technologies are readily available, and operational information is available on many components and systems.

Gaseous radionuclides are usually removed by chemical treatment systems, such as sorption techniques, catalyst reactions, or distillation. Particulates are usually removed by inertial separation (cyclone or gravity settling), filtration (fabric, glassfil, sandbeds, HEPA), precipitation (electric, thermal), sonic agglomeration, or liquid

scrubbing. Final filtration is either through deep beds of sand, fiberglass filters, or compact high-efficiency particulate air (HEPA) filters.

Off-gas treatment systems are used at reactors, spent fuel reprocessing facilities, fuel fabrication facilities, and the INEL's Waste Calcination Facility. The Waste Calcination Facility off-gas treatment system removes both particulates and gaseous products (except tritium) and includes scrubbing, filtering and absorption (9, 22-28).

4.2 Decontamination Factors

The effectiveness of an off-gas treatment component or system in removing a particular radionuclide from a plant's off-gas streams is measured by the decontamination factor (DF), which is the ratio of the concentration of a radionuclide before treatment to that after treatment. The estimated DF of a total treatment system includes the DFs of individual components or integrated systems.

The best available technology for off-gas treatment was chosen. The DFs are taken from the available literature. The overall DF for the EPA generic solidification plant assumes that the calcination and glassification are a combined process and that the off-gasses pass through several systems which selectively remove the various radionuclides. Existing technology permits radionuclide removal systems of almost any design. In some cases DF ranges are shown for the technologies because of differences in the data sources, varying operating conditions, and EPA conservatism.

A. Tritium Removal

The technical and economic feasibility of tritium control is still under investigation. Therefore we will assume that the DF for tritium in the calcination and glassification processes is one (9, 23, 29).

B. Iodine-129 Removal

Removal processes for radioactive iodine include aqueous scrubbing (reactive sprays, towers, wet filters) and adsorption (charcoal, activated charcoal, silver and other metallic zeolite adsorbents). Table 4.1 lists the known DFs for the various iodine-129 removal technologies (9, 23, 29-33). For iodine removal, the generic plant off-gas system consists of a mercuric nitrate-nitric acid scrubber and a silver-impregnated adsorber. The overall DF is estimated to be 1 E+03.

C. Ruthenium-106 Removal

In a high-temperature solidification process, ruthenium may be in the off-gas stream as both a gas and a particulate. Personnel at the Waste Calcining Facility at the Idaho Chemical Processing Plant estimated that DF for the total off-gas treatment system for volatilized ruthenium is about 1.0 E+07 (9, 22, 23, 25-32, 34-36). Table 4.2 lists the known DFs for the various ruthenium-106 removal technologies. for ruthenium removal, the generic plant off-gas system consists of the process cyclone, quench tank venturi scrubber, silica gel adsorber and HEPA filters. For particulate ruthenium the overall DF is estimated at 1 E+10.

TABLE 4.1
APPROXIMATE DECONTAMINATION FACTORS
FOR IODINE-129 REMOVAL TECHNOLOGIES

TECHNOLOGY	DECONTAMINATION FACTORS
Caustic Scrubbing	2 E+00 to 1 E+01
Silver-Impregnated Adsorbents	1 E+02 to 1 E+05
Metallic Zeolite Adsorbents (non-silver)	1 E+01
Mercuric Nitrate-Nitric Acid Scrubbing	1 E+01 to 1 E+02
Iodox Process	1 E+04 to 1 E+06
Charcoal Filters	1 E+01 to 1 E+02

TABLE 4.2
APPROXIMATE DECONTAMINATION FACTORS FOR
RUTHENIUM-106 REMOVAL TECHNOLOGIES

TECHNOLOGY AND COMPONENTS	DECONTAMINATION FACTORS	
	PARTICULATE RU	VOLATILIZED RU
Calciner and Cyclone	1 E+01 to 4 E+01	1 E+03 to 1 E+04
Scrubbing System	4 E+01 to 6 E+02	1 E+01 to 2 E+01
Silica Gel Adsorbers	3 E+00 to 8 E+00	8 E+02 to 1 E+03
HEPA Filters	1 E+03	1 E+00

D. Particulate Removal

The major radioactive particulates associated with the solidification processes are cesium-134, cesium-137, strontium-90, ruthenium-106 and actinides such as plutonium-239. Table 4.3 lists approximate DFs for several types of filtration components (9, 22-25, 27, 32, 34, 36-39). For particulate removal, the generic plant off-gas system uses the existing process cyclone, the wet scrubbing system and the adsorbers; for final filtration and particulate removal the off-gas system relies on HEPA filters and either a deep bed glass filter system or sintered metal filters. For particulate removal the overall DF is estimated at 1 E+10.

TABLE 4.3
APPROXIMATE DECONTAMINATION FACTORS
FOR PARTICULATE REMOVAL TECHNOLOGIES

COMPONENT	DECONTAMINATION FACTOR
Prefilters	6 E+00 to 1 E+01
Sand Bed Filters	1 E+01 to 1 E+02
Deep Bed Glass Filters	1 E+02 to 1 E+04
HEPA Filters	1 E+03
Sintered Metal Filters	1 E+03 to 1 E+05
Scrubbing Systems	1 E+01 to 1 E+02

4.3 Discharge Rates of Generic Solidification Plant

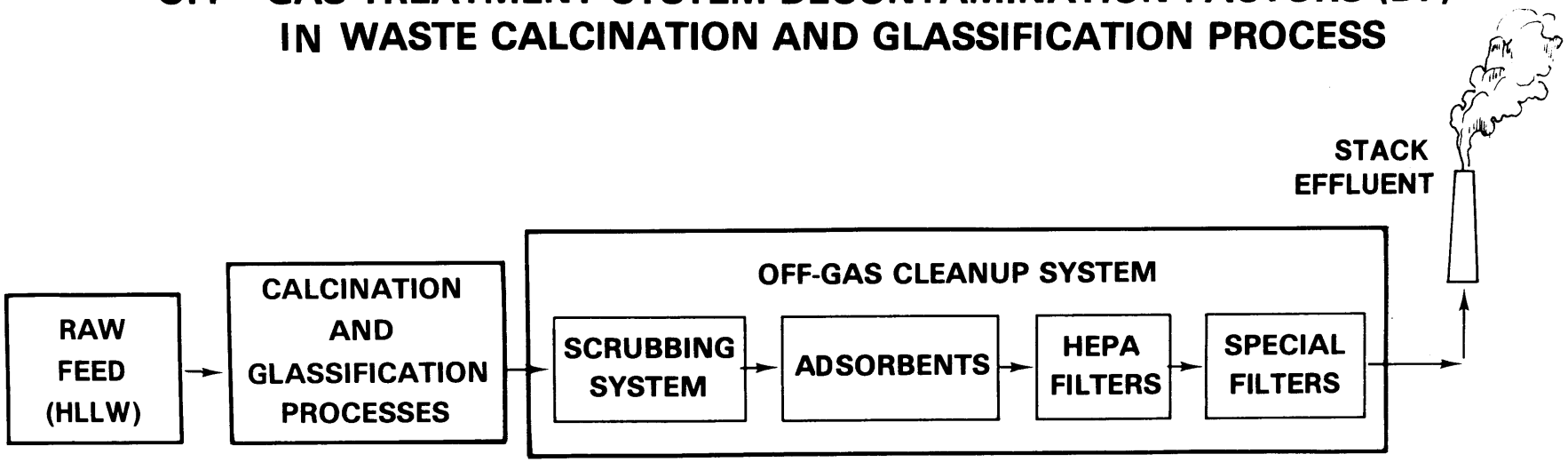
After determining the treatment system DFs for the seven major radionuclides we estimated the discharge rates to the atmosphere during normal operations of the generic solidification plant. Table 4.4 shows the DFs and the discharge rates based on decay periods of one, five and ten years. Figure 4.1 is a schematic of the off-gas treatment systems DFs for the HLLW calcination and glassification processes.

TABLE 4.4

DISCHARGE RATES AND DECONTAMINATION FACTORS
FOR THE GENERIC SOLIDIFICATION PLANT

RADIONUCLIDE	DF	DECAY PERIOD		
		1 YEAR	5 YEARS	10 YEARS
		(curies per year)		
H-3	1 E+00	5.19 E+04	4.13 E+04	3.12 E+04
I-129	1 E+03	2.84 E-03	2.84 E-03	2.84 E-03
Ru-106	1 E+07	4.80 E+01	3.19 E+00	9.75 E-02
Cs-137	1 E+10	1.59 E-02	1.46 E-02	1.30 E-02
Cs-134	1 E+10	2.88 E-02	7.39 E-03	1.36 E-03
Sr-90	1 E+10	1.12 E-02	1.02 E-02	9.00 E-03
Pu-239	1 E+10	5.00 E-07	5.00 E-07	5.00 E-07

OFF–GAS TREATMENT SYSTEM DECONTAMINATION FACTORS (DF) IN WASTE CALCINATION AND GLASSIFICATION PROCESS



SPECIES	COMPONENT DFs					TOTAL DF
TRITIUM	1	1	1	1	1	1
IODINE-129	1	10	10^2	1		10^3
RUTHENIUM-106	3.2×10^3	10	3.2×10^2	1	1	10^7
PARTICULATES: e.g. CS-134/137 Sr-90 Ru-106 Pu-239	10	10^2	10	10^3	10^3	10^{10}

Figure 4.1

5.0 ESTIMATES OF ANNUAL DOSE EQUIVALENTS

We estimated the annual dose equivalents (hereafter referred to simply as annual doses) to individuals and populations due to discharges from the generic solidification plant. For purposes of comparison, we based our assessments on two hypothetical sites with widely different demographic, meteorologic, and agricultural characteristics: an urban midwestern site at St. Louis, Missouri; and a rural site in the southeastern United States located adjacent to the commercial Barnwell Nuclear Fuel Plant and the Government's Savannah River Plant (5, 12, 40). We assumed the discharges listed in Table 4.4 and estimated annual doses to individuals and to the population within 80 kilometers of the plant at each site. The estimates include doses to the total body, thyroid, red bone marrow, lungs, endosteal cells, stomach wall, lower large intestine wall, liver, kidneys, testes, and ovaries. The computer program we used evaluates seven pathways: immersion in air containing radionuclides, exposure to contaminated land surfaces, immersion in contaminated water, inhalation of radionuclides in air, and ingestion of meat, milk, and leafy vegetables and fresh produce grown in the area (41).

The use of the reference site, rural or urban, should not be construed as an endorsement of any particular region for siting of radioactive waste management facilities, but rather as a means of dealing with site-specific aspects for comparative radiation exposures.

5.1 Computer Code Input Parameters

A newly developed computer code called AIRDOS-EPA performed the calculations (41). Appendix C contains the AIRDOS-EPA computer code printouts relevant to the input data and the annual doses to individuals and the population.

Meteorological input data and other characteristics for the rural site came from the final environmental impact statements on the Barnwell Nuclear Fuel Plant and the Savannah River Plant (5, 42). The meteorological input data for the urban site came from the National Climatic Center in Asheville, North Carolina.

All of the releases from the generic solidification plant are through a 62-meter high stack. The gravitational fall velocity in all cases is zero; the deposition velocity, 0.01 meter per second (except zero for tritium); and the scavenging coefficient, 1.19 E-05 per second.

NRC developed the information used as agricultural input data (43). The characteristics of the generic urban site and the population data for both sites were taken from information developed for EPA (44). The individual and population doses calculated by the AIRDOS-EPA computer program include both an annual external dose and a 70-year internal dose commitment from one year's release. ORNL developed the dose conversion factors for the seven pathways as input data for each radionuclide and reference organ. These dose conversion factors were used by the computer code to calculate dose commitments from one year's release (41).

5.2 Results

Table 5.1 shows the annual individual dose to the most significant organ of interest and the radionuclides delivering the highest percentage of the dose. Table 5.2 shows the annual dose to the population within 80 kilometers of the generic plant at the rural and urban sites. The doses are due to exposure to the radionuclide waste products from spent fuel that have decayed one year, five years, and ten years before reprocessing and solidification.

Many factors affect the dose received by an individual: meteorological patterns, radionuclide activity at time of exposure, the significant pathways for exposure, and the proximity to the source of release. The maximum annual individual doses at the urban and rural sites occur at approximately 1000 and 3000 meters, respectively, from the release point. The main reason individuals receive higher doses at the urban site than at the rural site is because they are closer to the plant. Population doses are also higher at the urban site because there are more people closer to the plant.

Tables C.10 through C.21 in Appendix C show the annual individual dose and population dose for each of the eleven body organs and seven radionuclides. If the spent fuel decays for one or five years before reprocessing and solidification, most of the dose is due to exposure to Ru-106, with tritium the second largest contributor. The largest organ dose is to the lower large intestine (LLI) wall.

If the spent fuel decays for ten years before reprocessing and solidification, most of the dose is from tritium. The largest organ dose is to the thyroid because of exposure to tritium and I-129.

The pathways through which the highest percentages of dose are deposited follow the same general trends no matter whether the target is urban or rural, or an individual or a population. One year decayed fuel delivers its dose mainly through the surface and ingestion pathways. As the fuel is decayed longer the importance of the surface exposure decreases to a very small percentage (less than 10%) of the total dose while the ingestion pathway grows in importance (70 - 80% with ten year decayed fuel). Also with longer decayed fuel the inhalation pathway gains importance to a maximum of 15 - 25%.

TABLE 5.1

ANNUAL INDIVIDUAL DOSE DUE TO RELEASES
FROM GENERIC SOLIDIFICATION PLANT*

NUCLIDE	TOTAL BODY			LLI WALL			THYROID
	1 YR DECAY	5 YR DECAY	10 YR DECAY	1 YR DECAY	5 YR DECAY	10 YR DECAY	10 YR DECAY
	(millirem per year)			(millirem per year)			
			RURAL SITE				
H-3	0.5	0.4	0.3	0.5	0.4	0.3	0.3
Ru-106	1.5	0.1	0.0	23.1	1.5	0.05	--
I-129	--	--	--	--	--	--	0.2
All	2.1	0.6	0.3	23.7	1.9	0.4	0.5
			URBAN SITE				
H-3**	1.6	2.5	1.9	1.5	1.3	1.9	1.9
Ru-106	12.5	0.6	0.02	190	12.2	0.3	--
I-129	--	--	--	--	--	--	1.0
All	14.5	3.3	2.1	192	13.7	2.3	3

*Includes only the most significant organ doses from the radionuclides delivering the highest percentage of dose.

**The H-3 doses do not decrease as would be expected because of the method by which the AIRDOS-EPA computer program evaluates the summary results. The program selects the highest individual dose to the organ of interest and reports the dose contribution of each radionuclide to that individual. Therefore, the doses listed are not necessarily the maximum dose from that radionuclide to any individual in the population but rather are the dose contributions to the individual receiving the highest organ dose from all nuclides. In the case of H-3, a different individual was involved for each decay period.

-- Negligible

TABLE 5.2

ANNUAL POPULATION DOSE DUE TO RELEASES
FROM GENERIC SOLIDIFICATION PLANT*

NUCLIDE	TOTAL BODY			LLI WALL			THYROID
	1 YR DECAY	5 YR DECAY	10 YR DECAY	1 YR DECAY	5 YR DECAY	10 YR DECAY	10 YR DECAY
	(man-rem per year)			(man-rem per year)			
RURAL SITE							
H-3	8.6	6.8	5.1	8.6	6.9	5.2	5.2
Ru-106	19.6	1.2	0.04	135	8.7	0.3	--
I-129	--	--	--	--	--	--	1.5
All	28.9	8.6	5.6	144	16	5.8	7.0
URBAN SITE							
H-3	66.9	53.3	40.2	67.6	54	40.9	40
Ru-106	195	12.6	0.4	1072	69	2.2	--
I-129	--	--	--	--	--	--	10.5
All	269	71	44.8	1146	127	46	54

*Includes only the most significant organ doses from the radionuclides delivering the highest percentage of dose.

-- Negligible

6.0 DISCUSSION AND CONCLUSIONS

Under the EPA environmental standards for the uranium fuel cycle (UFC), 40 CFR 190, normal operations are to be conducted in such a manner as to provide reasonable assurance that: (a) 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 to the general environment from uranium fuel cycle operations and to radiation from these operations; (b) the total quantity of radioactive materials entering the general environment from the entire uranium fuel cycle, per gigawatt-year of electrical energy produced by the fuel cycle, contains less than 50,000 curies of krypton-85, 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 (45).

Since the UFC standards exclude waste management operations, ORP/EPA prepared this analysis as technical support for EPA's proposed environmental radiation protection standards, 40 CFR 191, concerning management and disposal of high-level radioactive wastes. For Subpart A of 40 CFR 191, waste management and storage operations, EPA proposes to extend the limitations of 40 CFR 190 to these operations.

We compared the estimated maximum annual doses to an individual at the two plant sites with the annual dose limits under the UFC standards. (See Table 6.1). We also compared estimated releases from the generic solidification plant with the release limits under the UFC standards. (See Table 6.2).

In the case of the radionuclide waste products that have decayed one year, our assessment indicates that maximum annual doses to an individual due to releases from a solidification facility at a rural site would be less than the 40 CFR 190 standards; that maximum annual doses from a facility at an urban site would exceed the UFC standards. However, in the case of the radionuclide waste products that have decayed for five years or longer, the maximum annual dose to an individual at either site would be less than 15 millirem.

Our assessment of the releases of the radionuclide waste products that have decayed for one year indicates that releases of krypton-85, iodine-129, and plutonium-239 are less than the allowable UFC release limits by at least a factor of 100.

The quantity of radionuclides in releases from a solidification plant is primarily determined by the DFs of the radionuclide removal systems. Additional off-gas components will change a plant's DF and reduce the quantity of radionuclides released to the environment. Plant siting is an important factor, as shown by the comparisons of doses due to releases from urban and rural plant sites. Urban characteristics (e.g. population, food crops produced or imported for local consumation, meat and diary animals) contribute to larger doses. The length of time the spent fuel's radionuclide waste products decay before reprocessing and solidification is also an important factor. Increasing the decay time from one to five years, for example, will reduce the dose to the lower large intestine wall by an order of magnitude. (Tables 5.1 and 6.1)

Since many solidification processes, as well as final waste forms (i.e. crystalline, cement, and metal matrices), are under development throughout the world, improvements are possible. All limitations have not necessarily been identified.

TABLE 6.1

COMPARISON OF THE ANNUAL DOSE EQUIVALENTS FROM THE GENERIC SOLIDIFICATION PLANT WITH THE ANNUAL DOSE EQUIVALENT LIMIT UNDER THE UFC STANDARDS

ORGAN	UFC DOSE LIMIT	ESTIMATED ANNUAL DOSES TO MAXIMALLY EXPOSED INDIVIDUAL (one-year-decayed fuel) RURAL SITE	URBAN SITE
	(millirem/yr)	(millirem/yr)	(millirem/yr)
Total body	25	2.1	14.5
Thyroid	75	2.2	15.7
Other organs			
lungs	25	3.5	21.3
liver	25	2.1	14.8
bone	25	2.4	17.3
endosteal cells	25	2.7	19.6
stomach wall	25	2.1	14.2
kidneys	25	2.1	14.9
lower large intestine wall	25	23.7	191.9
testes	25	2.3	16.3
ovaries	25	1.8	11.8

TABLE 6.2

COMPARISON OF RELEASES FROM THE GENERIC SOLIDIFICATION PLANT WITH RELEASE LIMITS UNDER THE UFC STANDARDS

RADIONUCLIDE	UFC STANDARDS RELEASE LIMIT	UFC STANDARDS RELEASE LIMIT EQUIVALENT(a)	ESTIMATED GENERIC SOLIDIFICATION PLANT RELEASE (One-Year decay)
	(Ci/GWe-yr)	(Ci/yr)	(Ci/yr)
Krypton-85	5 E+04	2.27 E+06	0
Iodine-129	5 E-03	2.27 E-01	2.94 E-03
Alpha (Pu-239)	5 E-04	2.27 E-02	5.02 E-07
H-3	(b)	---	5.21 E+04
Ru-106	(b)	---	4.80 E+01
Cs-137	(b)	---	1.59 E-02
Cs-134	(b)	---	2.88 E-02
Sr-90	(b)	---	1.12 E-02

(a) The conversion from Ci/GWe-yr to Ci/yr is based on an LWR operating at 33% thermal efficiency and producing approximately 33 MTHM of spent fuel at a burnup of 33,000 MWD/MTHM; all of the releases are assumed to be from a 1500 MTHM per year fuel reprocessing plant.

(b) Not included in UFC standard

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APPENDIX A

WASTE CALCINATION AND GLASSIFICATION PROCESSES

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WASTE CALCINATION AND GLASSIFICATION PROCESSES

A.1 CALCINATION

Calcination, the conversion of high-level liquid wastes to a calcine powder, is the most likely first step in the solidification process. This section covers the two most promising and advanced calcination processes (9, 22-24).

A.1.1 Fluidized-Bed Calcination

Fluidized-bed calcination was the first technique developed for the conversion of radioactive waste solutions to solids. The Atomic Energy Commission (AEC) sponsored its development in 1955 and built the Waste Calcining Facility (WCF) at the Idaho National Engineering Laboratory as part of the Federal Government's Idaho Chemical Processing Plant (4).

Fluidized-bed calcination solidifies radioactive high-level liquid wastes by pnuematically atomizing the waste solution into a bed of fluidized solid granules. In-bed combustion of kerosene with oxygen generates temperatures of 500 C. The waste solution is sprayed into the fluidized heated bed; water vapor and volatile gases flash from the spray droplets, depositing the oxides of metallic salts in the waste on bed particles. At equilibrium conditions, the effect of particle growth is balanced by the formation of new seed particles and by removal of the calcine product. The powdery solids and granules are continuously removed from the calciner and pneumatically transported to an integrated on-site storage facility. The off-gas from this process is composed primarily of the fluidizing air, the transport gas, and the gaseous

reaction products (9, 22-28). Figure A.1 shows the type of fluidized-bed calciner used at the Idaho National Engineering Laboratory.

A.1.2 Spray Calcination

This process has been under development at DOE's Hanford Reservation for over 15 years. The Battelle Pacific Northwest Laboratories is now testing it with simulated wastes.

The liquid wastes are pneumatically atomized and sprayed into the top of a cylindrical calciner chamber, the walls of which have been heated to 700 C. The atomized liquid wastes are sequentially evaporated, dried, and calcined as they fall and are then discharged from the lower cone of the chamber (9, 22-24, 37, 46). Figure A.2 shows the type of spray calciner system used at Hanford.

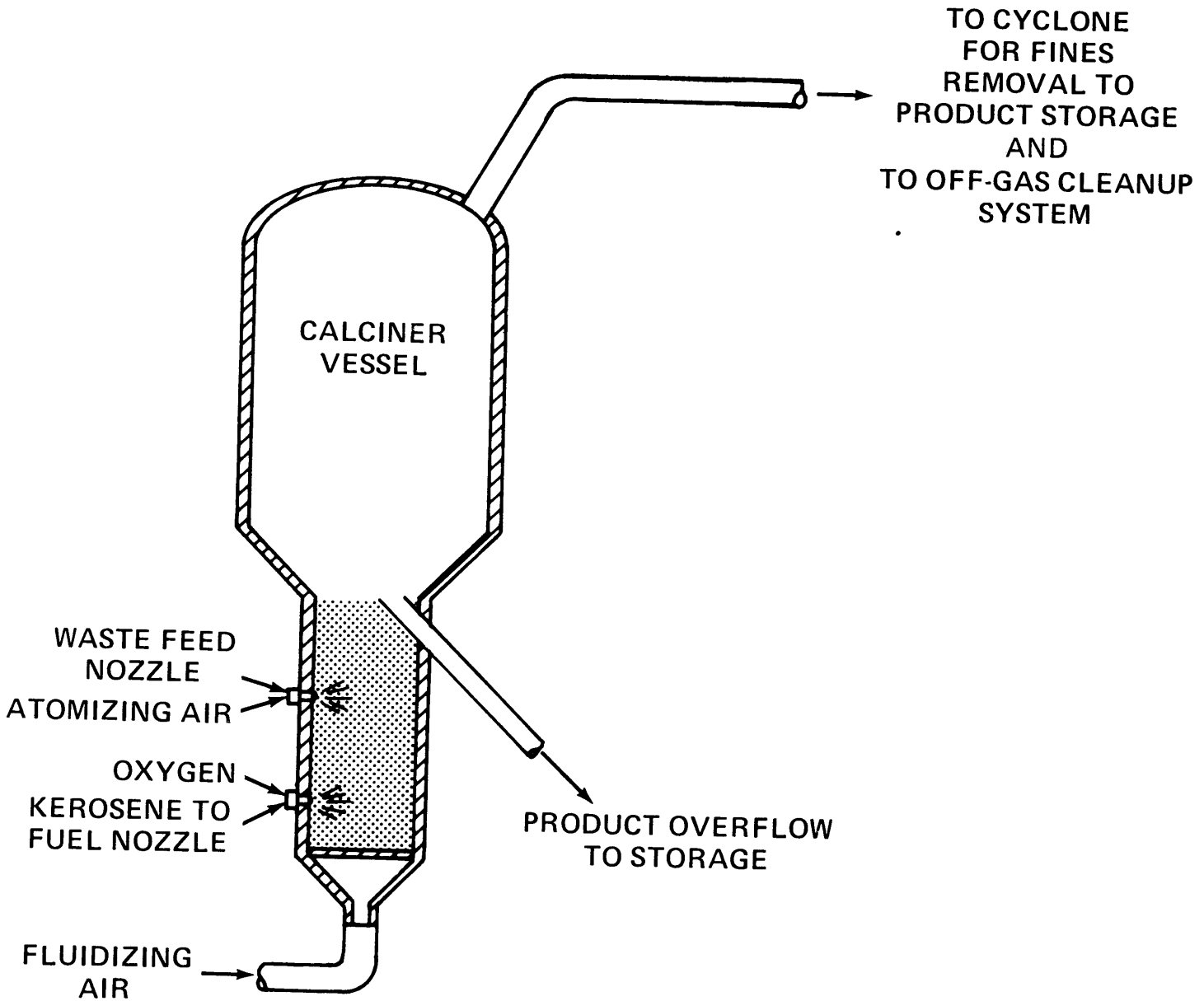

Figure A.1
FLUIDIZED-BED CALCINER

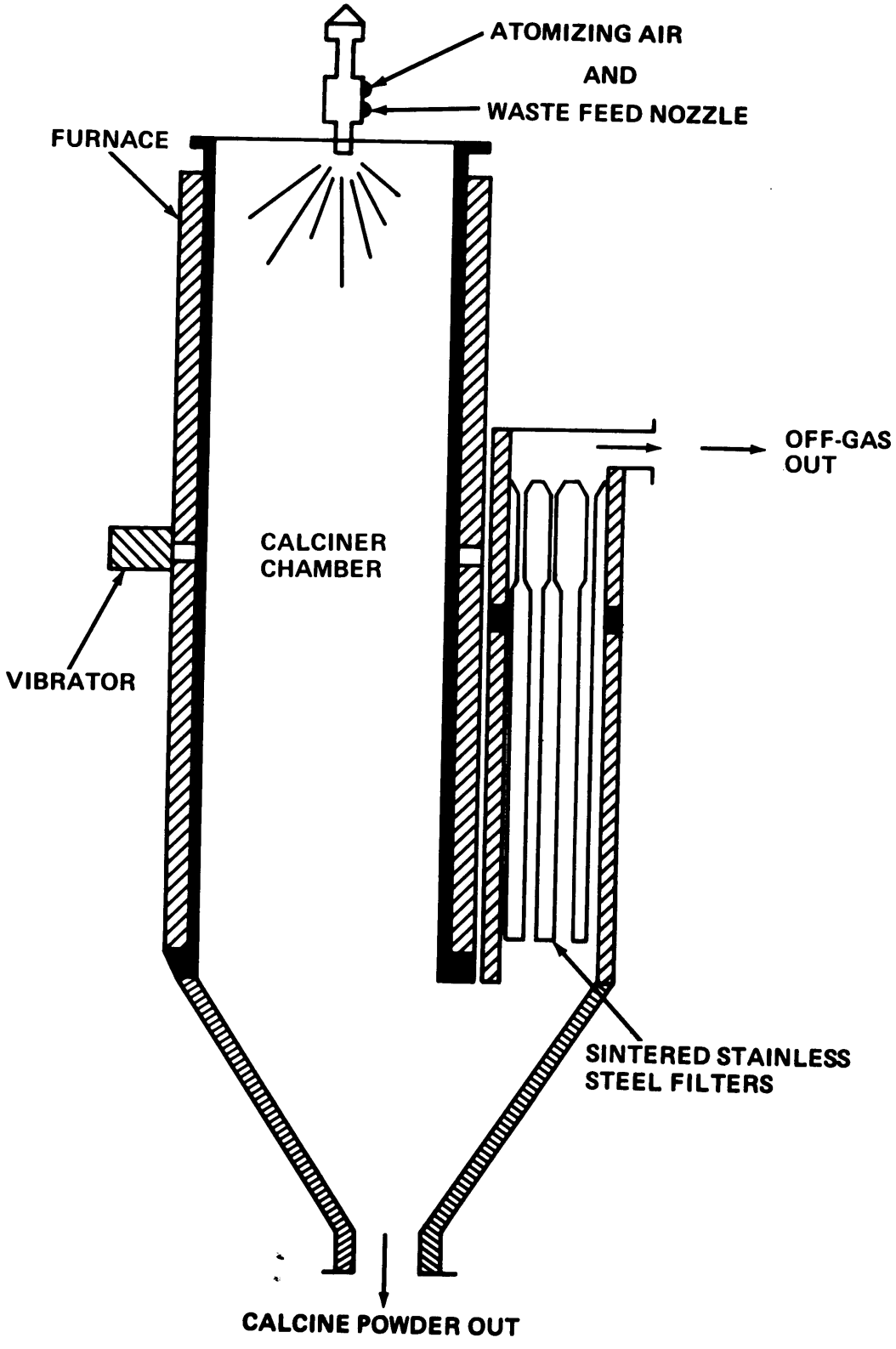

Figure A.2

SPRAY CALCINER

A.2 WASTE GLASSIFICATION

Glassification is a solidification process that incorporates high-level wastes in a solid matrix. The wastes and glass frit are combined, melted, and canned; the melt cools and solidifies. Over the past 20 years, many countries have developed various glassification processes. The two most promising candidates for commercial use in the United States are in-can melting and continuous melting (9, 22-24, 47-51).

The calcination and glassification processes can be coupled. Glassification is a batch process, and calcination is a continuous process; however, with diverter valve and multiple melting furnace canisters, the coupled systems become semicontinuous. The Battelle Pacific Northwest Laboratories is developing a tandem unit that combines spray calcination and in-can melting. France and West Germany have coupled the continuous melting system with the spray calciner and with another calcination process called rotary-kiln.

A.2.1 In-Can Melting

The Battelle Pacific Northwest Laboratories is developing the in-can melting batch process for the Department of Energy. In this process, the calcine powder and specially formulated glass frit fall directly into a close-coupled melter canister. The frit and the calcine are melted together in a metal canister in a multizone furnace at processing temperatures of 1000-1100 C. In-can melting offers several advantages: (a) simplicity in process steps and equipment; (b) non-transfer of melt; (c) complete fixation in glass of everything entering the melter except some volatile species; (d) disposability of the melter canister; and (e) sufficient flexibility to accommodate calcine products from a wide range of processes, such as spray or fluidized-bed calcination (9, 22-24, 48, 51). Figure A.3 illustrates the in-can melting process.

A.2.2 Continuous Melting

The Batelle Pacific Northwest Laboratories is also developing a continuous (or joule-heated) melter process that is similar to commercial electric-glass melter processes. It can be coupled with different kinds of waste calciners and can even receive liquid wastes directly (4, 9, 13). The process is carried out at temperatures ranging from 1000 to 1200 C in a refractory-lined melter with internal electrodes; the molten glass acts as its own electric-resistance heating element. Flexibility in glass composition and controlled draining of the glass-waste mixture from the melter permit changes in the final waste form package (9, 22, 24, 47, 48, 50). Figure A.4 shows the continuous melter.

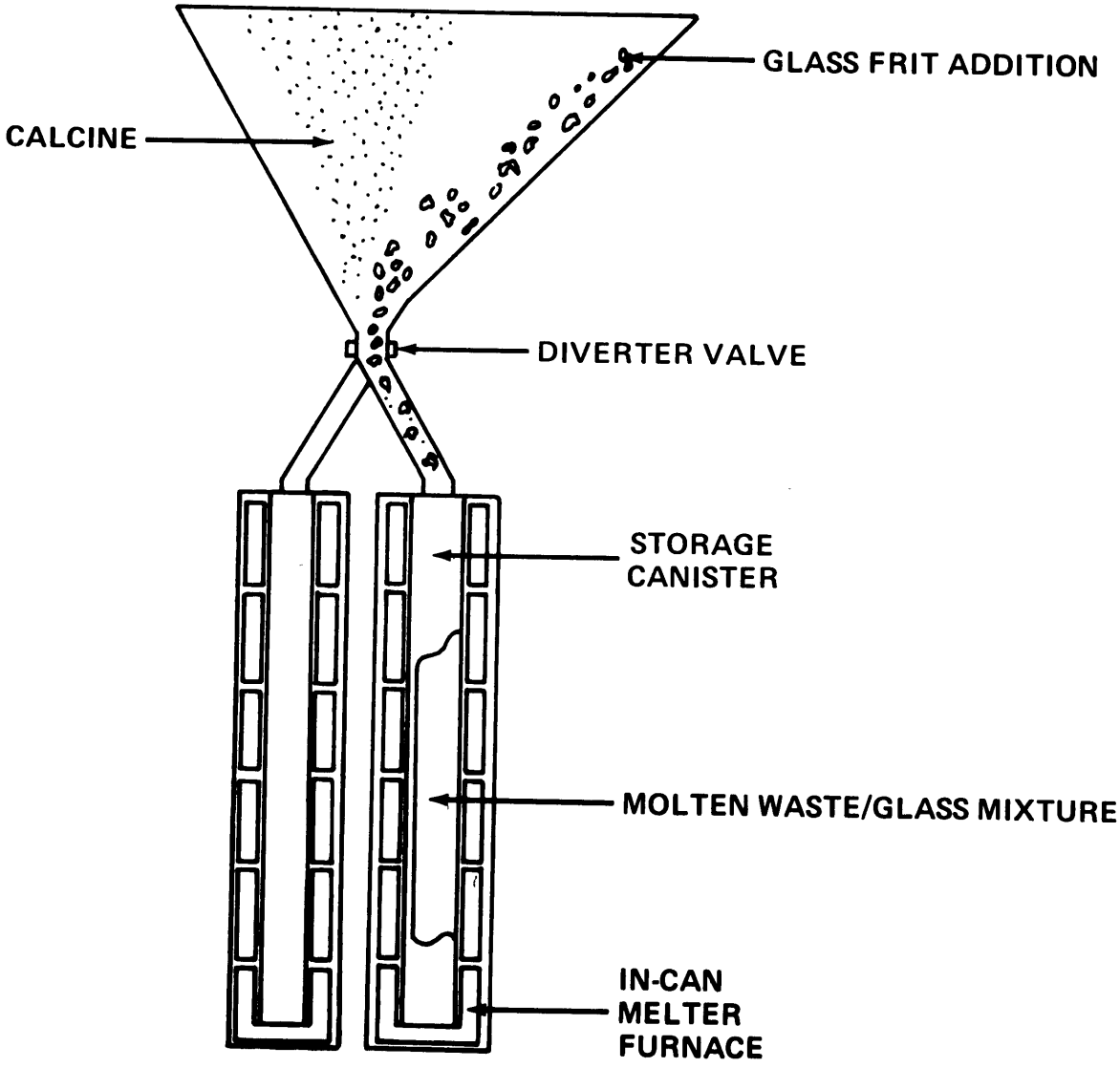

Figure A.3

IN-CAN MELTER

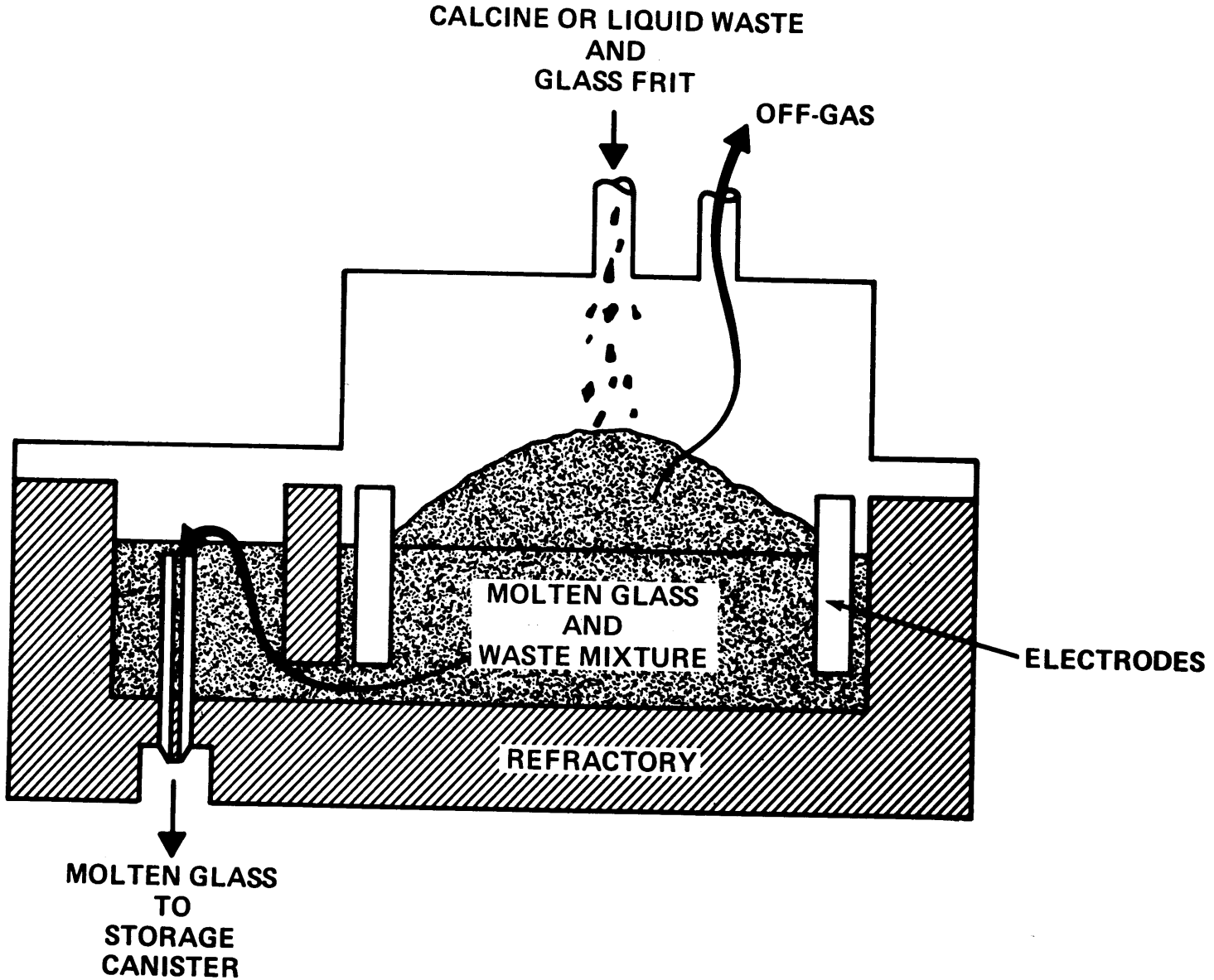

Figure A.4
CONTINUOUS MELTER

APPENDIX B

DOE AND NRC GENERIC SOLIDIFICATION

PLANT STUDIES

APPENDIX B

DOE AND NRC GENERIC SOLIDIFICATION PLANT STUDIES

Both the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE) have contracted studies involving the gaseous discharge from high-level waste solidification processes (19, 21, 23, 52, 53, 54).

B.1 NRC Contract Studies

Oak Ridge National Laboratory (ORNL) personnel conducted studies for NRC. They evaluated the gaseous effluents released from a generic high-level waste solidification facility similar to the New Waste Calcining Facility at the Idaho National Engineering Laboratory; this generic facility also glassified the calcine. Estimated decontamination factors are one for tritium, 100 for iodine, and 5 E+08 for ruthenium. The DFs for other radionuclides range from 5 E+09 to 1 E+10.

Table B.1 shows the ORNL list of likely radionuclide source terms and expected decontamination factors during the calcination and glassification processes. The generic facility is based on HLLW from a 5 MTU/day spent fuel reprocessing plant that processes 213- day-decayed material irradiated to 29,000 MWD/MTU.

TABLE B.1

DECONTAMINATION FACTORS EXPECTED DURING THE CALCINATION AND GLASSIFICATION OF HLLW (19)

	Decontamination Factor		
Radionuclides	Calcination	Glassification	Overall(a)
Tritium	1.0 E+00	(b)	1.0 E+00
Iodine	1.0 E+02	(b)	1.0 E+02
Particulates	1.0 E+10	1.0 E+12	9.9 E+09
Ruthenium	5.0 E+08	3.8 E+11	5.0 E+08
Cesium	1.0 E+10	7.7 E+09	4.4 E+09

(a) The overall process consists of calcining liquid waste at about 500°C, mixing the calcined solids with a glass frit, and glassifying the mixture by heating to about 1000°C.

(b) All tritium and iodine are volatized in the calcination step.

TABLE B.2

MAXIMUM ANNUAL DOSE EQUIVALENTS (a) TO AN INDIVIDUAL (b) DUE TO GASEOUS RELEASES FROM A GENERIC HLLW SOLIDIFICATION FACILITY (c) (19)

		Major Nuclides Causing Dose (% of Total Dose)				
Adult Organ	Dose (millirem)	H-3	Sr-90	Ru-106	I-129	Cs-134 & -137
Total Body	3.9 E-01	58				30
G.I. Tract	1.3 E+00	18		75		
Bone	5.0 E-01	45	10			28
Thyroid	8.0 E-01	29			52	
Lungs	3.8 E-01	60		10		27
Liver	3.8 E-01	60				30
Kidney	3.9 E-01	58		13		26
Testes	4.0 E-01	56				32
Ovaries	3.0 E-01	75				18

(a) Fifty-year dose commitment for 1-year exposure.
(b) Individual dose is at site boundary (2319 m from the release) and downwind.
(c) Ingestion is the principal exposure pathway.

TABLE B.3

MAXIMUM ANNUAL DOSE EQUIVALENTS TO AN INDIVIDUAL AT THE SITE BOUNDARY DUE TO GASEOUS RELEASES FROM HLLW SOLIDIFICATION PLANT (52)

Adult Organ	Dose (millirem)
G.I. Tract	1.7
Bone	0.7
Thyroid	1.1
Lung	0.5
Total Body	0.52

After evaluating the source terms and the control technology available and necessary for dose reduction, ORNL personnel prepared a table of the maximum annual total-body dose and organ doses to an individual due to gaseous effluent releases from their generic facility (see Table B.2).

Battelle Pacific Northwest Laboratories personnel prepared Table B.3 for the NRC in a review of environmental impacts from the release of radionuclides during the operation of a generic HLLW solidification plant; the plant processes high-level liquid waste from a 2000 MT/year spent fuel reprocessing plant that processes 160-day-decayed material irradiated to 33,000 MWd/MT (52).

B.2 DOE Contract Studies

The DOE contract studies were based primarily on the assessment of control technology for treating airborne effluents from the solidification processes. The assessment included processes developed throughout the world. (See Table B.4) Additional assessments included decontamination factors for off-gas cleanup and some estimated annual doses from gaseous effluents. Table B.5 shows the dose assessment.

TABLE B.4

SUMMARY OF ESTIMATED DECONTAMINATION FACTORS FOR SOLIDIFICATION PROCESSES (53)

Process	Feed-to-Atmospheric Release DF	
	Particulates	Volatilized Ru
USA ICPP Fluid-Bed[a]	2 E+10	2 E+11
USA PNL Fluid-Bed[b]	1 E+10	1 E+06
Eurochemic LOTES	6 E+08	1 E+07
USA PNL Spray	1 E+12	1 E+10[c]
German VERA	1 E+12[d]	1 E+13
PNL Pot	1 E+12	1 E+10
British FINGAL	1 E+15	1 E+13
British HARVEST	1 E+13	1 E+08 to E+09
French PIVER[e]	1 E+13 to E+14	1 E+10 to E+11
Italian Pot Phosphate Glass[e]	1 E+14 to E+15	1 E+10
Borosilicate	1 E+14 to E+15	1 E+09
USA PNL Phosphate Glass	1 E+12	1 E+10
French Rotary Kiln[e]	1 E+10 to E+11	1 E+06 to E+07
German FIPS[e]	1 E+11 to E+12	1 E+05
German PAMELA[e]	1 E+13 to E+14	1 E+09
USA PNL Proposed System[e,f]	1 E+12 to E+14	1 E+10

(a) With a second HEPA filter.
(b) Including final HEPA filter.
(c) Data are for total Ru, but since total Ru DF is 0.01 times total Cerium DF, one may assume the majority of released Ru is in volatized form.
(d) If final HEPA filter is included in ventilation system, particulate DF will be increase by a factor of approximately E+02.
(e) Waste evaporator (concentrator) included in integrated system.
(f) USA PNL spray calciner with in-pot melter assumed. DF for iodine equals 1 E+03.

TABLE B.5

MAXIMUM ANNUAL DOSE EQUIVALENTS TO AN INDIVIDUAL DUE TO GASEOUS RELEASES FROM CALCINATION AND GLASSIFICATION FACILITIES (a)(23, 54, 55)

Adult Organ	DOSE (millirem)	
	Calcinaton	Glassification
Total Body	2.8 E-01	2.4 E-01
Thyroid	2.4 E-01	2.5 E-01
Lung	2.4 E-01	2.4 E-01
Bone	8.7 E-06	1.4 E-05

(a) The doses are based on a uranium-plutonium recycle scenario which used the additive pathways of air submersion, inhalation, and ingestion.

APPENDIX C

SELECTED TABLES
FROM AIRDOS-EPA
COMPUTER PROGRAM

APPENDIX C

SELECTED TABLES FROM AIRDOS-EPA COMPUTER PROGRAM

The following tables contain selected data developed in the AIRDOS-EPA computer calculations of annual dose equivalents to individuals and populations (41, 44).

Tables C.1 and C.2 presents the input data for the rural and urban sites. Tables C.3 through C.10 lists the input data for each radionuclide studied.

Tables C.11 through C.22 list the total dose equivalents to individuals and populations near rural and urban sites for one year, five years, and ten years. The tables also list the radionuclide contributions to the organ doses by percentage.

Table C.1

LIST OF INPUT VALUES FOR RADIONUCLIDE-INDEPENDENT VARIABLES

NUMBER OF NUCLIDES CONSIDERED	7
TIME DELAY--INGESTION OF PASTURE GRASS BY ANIMALS (HR)	0.0
TIME DELAY--INGESTION OF STORED FEED BY ANIMALS (HR)	0.2160E+04
TIME DELAY--INGESTION OF LEAFY VEGETABLES BY MAN (HR)	0.3360E+03
TIME DELAY--INGESTION OF PRODUCE BY MAN (HR)	0.3360E+03
REMOVAL RATE CONSTANT FOR PHYSICAL LOSS BY WEATHERING (PER HOUR)	0.2100E-02
PERIOD OF EXPOSURE DURING GROWING SEASON--PASTURE GRASS (HR)	0.7200E+03
PERIOD OF EXPOSURE DURING GROWING SEASON--CROPS OR LEAFY VEGETABLES (HR)	0.1440E+04
AGRICULTURAL PRODUCTIVITY BY UNIT AREA (GRASS-COW-MILK-MAN PATHWAY (KG/SQ. METER))	0.2800E+00
AGRICULTURAL PRODUCTIVITY BY UNIT AREA (PRODUCE OR LEAFY VEG INGESTED BY MAN (KG/SQ. METER))	0.7160E+00
FRACTION OF YEAR ANIMALS GRAZE ON PASTURE	0.4000E+00
FRACTION OF DAILY FEED THAT IS PASTURE GRASS WHEN ANIMAL GRAZES ON PASTURE	0.4300E+00
CONSUMPTION RATE OF CONTAMINATED FEED OR FORAGE BY AN ANIMAL IN KG/DAY (WET WEIGHT)	0.1560E+02
TRANSPORT TIME FROM ANIMAL FEED-MILK-MAN (DAY)	0.4000E+01
RATE OF INGESTION OF PRODUCE BY MAN (KG/YR)	0.1760E+03
RATE OF INGESTION OF MILK BY MAN (LITERS/YR)	0.1120E+03
RATE OF INGESTION OF MEAT BY MAN (KG/YR)	0.9400E+02
RATE OF INGESTION OF LEAFY VEGETABLES BY MAN (KG/YR)	0.1800E+02
AVERAGE TIME FROM SLAUGHTER OF MEAT ANIMAL TO CONSUMPTION (DAY)	0.2000E+02
FRACTION OF PRODUCE INGESTED GROWN IN GARDEN OF INTEREST	0.1000E+01
FRACTION OF LEAFY VEGETABLES GROWN IN GARDEN OF INTEREST	0.1000E+01
PERIOD OF LONG-TERM BUILDUP FOR ACTIVITY IN SOIL (YEARS)	0.1000E+03
EFFECTIVE SURFACE DENSITY OF SOIL (KG/SQ. M, DRY WEIGHT) (ASSUMES 15 CM PLOW LAYER)	0.2150E+03
VEGETABLE INGESTION RATIO-IMMEDIATE SURROUNDING AREA/TOTAL WITHIN AREA	0.1000E+01 0.5000E+00 *
MEAT INGESTION RATIO-IMMEDIATE SURROUNDING AREA/TOTAL WITHIN AREA	0.1000E+01 0.5000E+00
MILK INGESTION RATIO-IMMEDIATE SURROUNDING AREA/TOTAL WITHIN AREA	0.1000E+01 0.5000E+00

MINIMUM FRACTIONS OF FOOD TYPES FROM OUTSIDE AREA LISTED BELOW ARE ACTUAL FIXED VALUES

MINIMUM FRACTION VEGETABLES INGESTED FROM OUTSIDE AREA	0.0 0.2000E+00
MINIMUM FRACTION MEAT INGESTED FROM OUTSIDE AREA	0.0 0.2000E+00

Table C.1 continued

MINIMUM FRACTION MILK INGESTED FROM OUTSIDE AREA	0.0
INHALATION RATE OF MAN (CUBIC CENTIMETERS/HR)	0.2000E+00
BUILDUP TIME FOR RADIONUCLIDES DEPOSITED ON GROUND AND WATER (DAYS)	0.9167E+06
DILUTION FACTOR FOR WATER FOR SWIMMING (CM)	0.3650E+05
FRACTION OF TIME SPENT SWIMMING	0.1524E+03
MUSCLE MASS OF ANIMAL AT SLAUGHTER (KG)	0.1000E-01
FRACTION OF ANIMAL HERD SLAUGHTERED PER DAY	0.2000E+03
MILK PRODUCTION OF COW (LITERS/DAY)	0.3810E-02
FALLOUT INTERCEPTION FRACTION-VEGETABLES	0.1100E+02
FALLOUT INTERCEPTION FRACTION-PASTURE	0.2000E+00
FRACTION OF RADIOACTIVITY RETAINED ON LEAFY VEGETABLES AND PRODUCE AFTER WASHING	0.5700E+00
	0.1000E+01

*Indented values were used for the population dose assessment; all other values were used for both individual and population assessments.

Table C.2

COMPUTED VALUES FOR THE AREA (Rural)

TOTAL POPULATION	477127.0
TOTAL NUMBER OF MEAT ANIMALS	202801
TOTAL NUMBER OF MILK CATTLE	14404
TOTAL AREA OF VEGETABLE FOOD CROPS (SQUARE METERS)	0.3740E+08
TOTAL MEAT CONSUMPTION (KG PER YEAR)	0.4485E+08
TOTAL MEAT PRODUCTION (KG PER YEAR)	0.5641E+08
TOTAL MILK CONSUMPTION (LITERS/YEAR)	0.5344E+08
TOTAL MILK PRODUCTION (LITERS/YEAR)	0.5783E+08
TOTAL VEGETABLE FOOD CONSUMPTION (KG PER YEAR)	0.9256E+08
TOTAL VEGETABLE FOOD PRODUCED (KG PER YEAR)	0.2678E+08

COMPUTED VALUES FOR THE AREA (Urban)

TOTAL POPULATION	2486049.0
TOTAL NUMBER OF MEAT ANIMALS	689632
TOTAL NUMBER OF MILK CATTLE	38000
TOTAL AREA OF VEGETABLE FOOD CROPS (SQUARE METERS)	0.1638E+09
TOTAL MEAT CONSUMPTION (KG PER YEAR)	0.2337E+09
TOTAL MEAT PRODUCTION (KG PER YEAR)	0.1918E+09
TOTAL MILK CONSUMPTION (LITERS/YEAR)	0.2784E+09
TOTAL MILK PRODUCTION (LITERS/YEAR)	0.1526E+09
TOTAL VEGETABLE FOOD CONSUMPTION (KG PER YEAR)	0.4823E+09
TOTAL VEGETABLE FOOD PRODUCED (KG PER YEAR)	0.1173E+09

Table C.3

LIST OF INPUT DATA FOR NUCLIDE H-3

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.1540E-03
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
DOSE CONVERSION FACTOR FOR FOOD INGESTION (REM-CC/PCI-YEAR)	0.6180E+01
DOSE CONVERSION FACTOR FOR WATER INGESTION (REM-CC/PCI-YEAR)	0.5700E-01

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATE (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.125E-03	0.830E-04	0.0	0.0	0.0
S WALL	0.125E-03	0.108E-03	0.0	0.0	0.0
LLI WALL	0.133E-03	0.143E-03	0.0	0.0	0.0
LUNGS	0.125E-03	0.836E-04	0.0	0.0	0.0
KIDNEYS	0.129E-03	0.856E-04	0.0	0.0	0.0
LIVER	0.124E-03	0.828E-04	0.0	0.0	0.0
OVARIES	0.124E-03	0.829E-04	0.0	0.0	0.0
R MAR	0.124E-03	0.826E-04	0.0	0.0	0.0
ENDOST	0.985E-04	0.656E-04	0.0	0.0	0.0
TESTES	0.125E-03	0.830E-04	0.0	0.0	0.0
THYROID	0.124E-03	0.828E-04	0.0	0.0	0.0

Table C.4

LIST OF INPUT DATA FOR NUCLIDE SR-90

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.6540E-04
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
AVERAGE FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH L OF MILK (DAYS/L)	0.2400E-02
FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH KG OF FLESH (DAYS/KG)	0.3000E-03
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL FOR PASTURE AND FORAGE (IN PCI/KG DRY WEIGHT PER PCI/KG DRY SOIL)	0.1200E+01
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL BY EDIBLE PARTS OF CROPS (IN PCI/KG WET WEIGHT PER PCI/KG DRY SOIL)	0.2900E+00
GI UPTAKE FRACTION (INHALATION)	0.2000E+00
GI UPTAKE FRACTION (INGESTION)	0.2000E+00
PARTICLE SIZE (MICRONS)	0.1000E+01
SOLUBILITY CLASS	D

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATER (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.241E+00	0.945E-01	0.0	0.0	0.0
S WALL	0.197E-03	0.876E-03	0.0	0.0	0.0
LLI WALL	0.141E-01	0.778E-01	0.0	0.0	0.0
LUNGS	0.989E-02	0.594E-08	0.0	0.0	0.0
KIDNEYS	0.146E-01	0.599E-02	0.0	0.0	0.0
LIVER	0.146E-01	0.571E-02	0.0	0.0	0.0
OVARIES	0.146E-01	0.599E-02	0.0	0.0	0.0
R MAR	0.110E+01	0.430E+00	0.0	0.0	0.0
ENDOST	0.220E+01	0.859E+00	0.0	0.0	0.0
TESTES	0.146E-01	0.599E-02	0.0	0.0	0.0
THYROID	0.146E-01	0.599E-02	0.0	0.0	0.0

Table C.5
LIST OF INPUT DATA FOR NUCLIDE RU-106

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.1882E-02
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
AVERAGE FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH L OF MILK (DAYS/L)	0.6100E-06
FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH KG OF FLESH (DAYS/KG)	0.1800E-02
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL FOR PASTURE AND FORAGE (IN PCI/KG DRY WEIGHT PER PCI/KG DRY SOIL)	0.1700E+00
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL BY EDIBLE PARTS OF CROPS (IN PCI/KG WET WEIGHT PER PCI/KG DRY SOIL)	0.1600E-01
GI UPTAKE FRACTION (INHALATION)	0.4000E-01
GI UPTAKE FRACTION (INGESTION)	0.4000E-01
PARTICLE SIZE (MICRONS)	0.1000E+01
SOLUBILITY CLASS	Y

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATER (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.618E-01	0.594E-02	0.129E+03	0.258E-01	0.276E+00
S WALL	0.696E-02	0.641E-02	0.123E+03	0.246E-01	0.264E+00
LLI WALL	0.137E+00	0.260E+00	0.921E+02	0.184E-01	0.197E+00
LUNGS	0.385E+01	0.217E-03	0.121E+03	0.242E-01	0.259E+00
KIDNEYS	0.895E-02	0.825E-02	0.113E+03	0.225E-01	0.241E+00
LIVER	0.115E-01	0.827E-02	0.110E+03	0.221E-01	0.236E+00
OVARIES	0.767E-02	0.896E-02	0.571E+02	0.114E-01	0.122E+00
R MAR	0.937E-02	0.831E-02	0.144E+03	0.288E-01	0.308E+00
ENDOST	0.100E-01	0.957E-02	0.160E+03	0.319E-01	0.341E+00
TESTES	0.697E-02	0.814E-02	0.136E+03	0.272E-01	0.291E+00
THYROID	0.919E-02	0.806E-02	0.105E+03	0.210E-01	0.224E+00

Table C.6

LIST OF INPUT DATA FOR NUCLIDE I-129

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.1209E-09
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
AVERAGE FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH L OF MILK (DAYS/L)	0.9900E-02
FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH KG OF FLESH (DAYS/KG)	0.7000E-02
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL FOR PASTURE AND FORAGE (IN PCI/KG DRY WEIGHT PER PCI/KG DRY SOIL)	0.2000E+00
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL BY EDIBLE PARTS OF CROPS (IN PCI/KG WET WEIGHT PER PCI/KG DRY SOIL)	0.5500E-01
GI UPTAKE FRACTION (INHALATION)	0.9500E+00
GI UPTAKE FRACTION (INGESTION)	0.9500E+00
PARTICLE SIZE (MICRONS)	0.1000E+01
SOLUBILITY CLASS	D

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATER (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.205E-02	0.318E-02	0.554E+01	0.301E-02	0.133E-01
S WALL	0.461E-04	0.784E-04	0.234E+01	0.127E-02	0.554E-02
LLI WALL	0.428E-04	0.670E-04	0.827E+00	0.449E-03	0.196E-02
LUNGS	0.788E-03	0.179E-03	0.288E+01	0.156E-02	0.682E-02
KIDNEYS	0.449E-03	0.702E-03	0.315E+01	0.171E-02	0.747E-02
LIVER	0.466E-03	0.724E-03	0.229E+01	0.124E-02	0.543E-02
OVARIES	0.378E-03	0.592E-03	0.217E+01	0.118E-02	0.514E-02
R MAR	0.605E-03	0.942E-03	0.788E+01	0.428E-02	0.187E-01
ENDOST	0.564E-03	0.879E-03	0.109E+02	0.590E-02	0.258E-01
TESTES	0.357E-03	0.558E-03	0.724E+01	0.393E-02	0.172E-01
THYROID	0.497E+01	0.778E+01	0.574E+01	0.312E-02	0.136E-01

Table C.7

LIST OF INPUT DATA FOR NUCLIDE CS-134

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.9208E-03
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
AVERAGE FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH L OF MILK (DAYS/L)	0.5600E-02
FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH KG OF FLESH (DAYS/KG)	0.1400E-01
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL FOR PASTURE AND FORAGE (IN PCI/KG DRY WEIGHT PER PCI/KG DRY SOIL)	0.1400E+00
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL BY EDIBLE PARTS OF CROPS (IN PCI/KG WET WEIGHT PER PCI/KG DRY SOIL)	0.9100E-02
GI UPTAKE FRACTION (INHALATION)	0.9500E+00
GI UPTAKE FRACTION (INGESTION)	0.9500E+00
PARTICLE SIZE (MICRONS)	0.1000E+01
SOLUBILITY CLASS	D

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATER (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.455E-01	0.684E-01	0.968E+03	0.192E+00	0.208E+01
S WALL	0.326E-01	0.499E-01	0.893E+03	0.177E+00	0.192E+01
LLI WALL	0.371E-01	0.575E-01	0.670E+03	0.133E+00	0.144E+01
LUNGS	0.338E-01	0.468E-01	0.909E+03	0.180E+00	0.196E+01
KIDNEYS	0.677E-01	0.102E+00	0.870E+03	0.172E+00	0.187E+01
LIVER	0.699E-01	0.105E+00	0.827E+03	0.164E+00	0.178E+01
OVARIES	0.645E-01	0.974E-01	0.466E+03	0.923E-01	0.100E+01
R MAR	0.616E-01	0.926E-01	0.105E+04	0.208E+00	0.227E+01
ENDOST	0.589E-01	0.886E-01	0.119E+04	0.235E+00	0.255E+01
TESTES	0.513E-01	0.773E-01	0.980E+03	0.194E+00	0.211E+01
THYROID	0.519E-01	0.781E-01	0.765E+03	0.151E+00	0.165E+01

Table C.8

LIST OF INPUT DATA FOR NUCLIDE CS-137

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.6293E-04
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
AVERAGE FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH L OF MILK (DAYS/L)	0.5600E-02
FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH KG OF FLESH (DAYS/KG)	0.1400E-01
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL FOR PASTURE AND FORAGE (IN PCI/KG DRY WEIGHT PER PCI/KG DRY SOIL)	0.1400E+00
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL BY EDIBLE PARTS OF CROPS (IN PCI/KG WET WEIGHT PER PCI/KG DRY SOIL)	0.9100E-02
GI UPTAKE FRACTION (INHALATION)	0.9500E+00
GI UPTAKE FRACTION (INGESTION)	0.9500E+00
PARTICLE SIZE (MICRONS)	0.1000E+01
SOLUBILITY CLASS	D

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATER (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.326E-01	0.491E-01	0.370E+03	0.740E-01	0.790E+00
S WALL	0.139E-01	0.218E-01	0.345E+03	0.689E-01	0.736E+00
LLI WALL	0.160E-01	0.259E-01	0.257E+03	0.514E-01	0.549E+00
LUNGS	0.162E-01	0.199E-01	0.347E+03	0.694E-01	0.741E+00
KIDNEYS	0.513E-01	0.773E-01	0.332E+03	0.664E-01	0.710E+00
LIVER	0.523E-01	0.787E-01	0.316E+03	0.632E-01	0.676E+00
OVARIES	0.500E-01	0.754E-01	0.166E+03	0.331E-01	0.354E+00
R MAR	0.491E-01	0.738E-01	0.408E+03	0.815E-01	0.871E+00
ENDOST	0.531E-01	0.799E-01	0.457E+03	0.913E-01	0.976E+00
TESTES	0.444E-01	0.668E-01	0.382E+03	0.765E-01	0.817E+00
THYROID	0.447E-01	0.672E-01	0.292E+03	0.585E-01	0.625E+00

Table C.9

LIST OF INPUT DATA FOR NUCLIDE PU-239

RADIOACTIVE DECAY CONSTANT (PER DAY)	0.7750E-07
ENVIRONMENTAL DECAY CONSTANT--SURFACE (PER DAY)	0.0
ENVIRONMENTAL DECAY CONSTANT--WATER (PER DAY)	0.0
AVERAGE FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH L OF MILK (DAYS/L)	0.4500E-07
FRACTION OF ANIMAL'S DAILY INTAKE OF NUCLIDE WHICH APPEARS IN EACH KG OF FLESH (DAYS/KG)	0.4100E-06
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL FOR PASTURE AND FORAGE (IN PCI/KG DRY WEIGHT PER PCI/KG DRY SOIL)	0.2200E-02
CONCENTRATION FACTOR FOR UPTAKE OF NUCLIDE FROM SOIL BY EDIBLE PARTS OF CROPS (IN PCI/KG WET WEIGHT PER PCI/KG DRY SOIL)	0.2000E-03
GI UPTAKE FRACTION (INHALATION)	0.3000E-04
GI UPTAKE FRACTION (INGESTION)	0.3000E-04
PARTICLE SIZE (MICRONS)	0.1000E+01
SOLUBILITY CLASS	Y

DOSE CONVERSION FACTORS

ORGAN	INHALATION (REMS/MICROCURIE)	INGESTION (REMS/MICROCURIE)	SUBMERSION IN AIR (REMS-CUBIC CM/ MICROCURIE-HR)	SURFACE EXPOSURE (REMS-SQUARE CM/ MICROCURIE-HR)	SUBMERSION IN WATER (REMS-CUBIC CM/ MICROCURIE-HR)
TOT.BODY	0.169E+03	0.951E-01	0.486E-01	0.959E-04	0.112E-03
S WALL	0.272E-02	0.442E-02	0.238E-01	0.470E-04	0.548E-04
LLI WALL	0.115E+00	0.196E+00	0.209E-01	0.413E-04	0.482E-04
LUNGS	0.580E+03	0.935E-07	0.317E-01	0.625E-04	0.729E-04
KIDNEYS	0.103E+03	0.633E-01	0.255E-01	0.504E-04	0.588E-04
LIVER	0.797E+03	0.491E+00	0.267E-01	0.527E-04	0.614E-04
OVARIES	0.363E+01	0.225E-02	0.161E-01	0.318E-04	0.371E-04
R MAR	0.599E+03	0.372E+00	0.611E-01	0.121E-03	0.141E-03
ENDOST	0.416E+04	0.258E+01	0.730E-01	0.144E-03	0.168E-03
TESTES	0.114E+02	0.707E-02	0.442E-01	0.872E-04	0.102E-03
THYROID	0.585E+01	0.363E-02	0.422E-01	0.834E-04	0.972E-04

Table C.10 Maximum Individual Dose to a Rural Individual from One-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE(REMS)
TOT.BODY	0.2106E-02
R MAR	0.2436E-02
LUNGS	0.3511E-02
ENDOST	0.2698E-02
S WALL	0.2057E-02
LLI WALL	0.2368E-01
THYROID	0.2237E-02
LIVER	0.2127E-02
KIDNEYS	0.2145E-02
TESTES	0.2313E-02
OVARIES	0.1760E-02

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	24.6135	21.2492	14.7620	18.6414	25.1907	2.2083	23.1389	24.3355	24.2676	22.4056	29.4069
PU-239	0.0000	0.0001	0.0001	0.0009	0.0000	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000
I-129	0.0257	0.0283	0.0071	0.0349	0.0097	0.0003	7.9104	0.0099	0.0132	0.0271	0.0112
RU-106	72.8232	74.8595	84.1493	76.0782	72.9445	97.6280	67.1858	73.5411	73.5695	75.5113	68.8571
CS-137	1.3556	1.3433	0.7143	1.3525	1.2172	0.0815	1.0906	1.2590	1.2956	1.3204	0.9231
CS-134	0.7348	0.7611	0.3672	0.7199	0.6337	0.0493	0.6477	0.8275	0.8262	0.7099	0.7678
SR-90	0.4471	1.7584	0.0000	3.1722	0.0042	0.0326	0.0267	0.0267	0.0278	0.0258	0.0339

Table C.11 Annual Dose to the Rural Population
from One-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (MAN-REMS)
TOT.BODY	0.2887E+02
R MAR	0.3164E+02
LUNGS	0.5940E+02
ENDOST	0.3413E+02
S WALL	0.2774E+02
LLI WALL	0.1442E+03
THYROID	0.2765E+02
LIVER	0.2707E+02
KIDNEYS	0.2741E+02
TESTES	0.3025E+02
OVARIES	0.2043E+02

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	29.8487	27.1834	14.5081	24.0343	31.0680	6.0630	31.1068	31.7777	31.6650	28.4828	42.0957
PU-239	0.0001	0.0002	0.0001	0.0012	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000
I-129	0.0286	0.0351	0.0068	0.0446	0.0117	0.0008	5.2765	0.0122	0.0164	0.0335	0.0153
RU-106	67.6867	69.6624	84.5110	72.0816	66.8374	93.5906	61.6153	65.9234	65.9826	69.2162	55.9950
CS-137	1.5377	1.5832	0.6745	1.6397	1.4393	0.2105	1.3307	1.4838	1.5278	1.5485	1.1306
CS-134	0.7095	0.7522	0.2994	0.7476	0.6418	0.1043	0.6582	0.7905	0.7955	0.7076	0.7465
SR-90	0.1887	0.7835	0.0000	1.4511	0.0018	0.0308	0.0125	0.0122	0.0126	0.0114	0.0169

Table C.12. Maximum Annual Dose to an Urban Individual from One-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE(REMS)
TOT.BODY	0.1447E-01
R MAR	0.1734E-01
LUNGS	0.2134E-01
ENDOST	0.1956E-01
S WALL	0.1422E-01
LLI WALL	0.1919E+00
THYROID	0.1570E-01
LIVER	0.1479E-01
KIDNEYS	0.1492E-01
TESTES	0.1633E-01
OVARIES	0.1177E-01

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	10.8021	9.0060	14.8768	7.7523	10.9919	0.8217	9.9458	10.5589	10.5190	9.5739	13.2588
PU-239	0.0000	0.0001	0.0001	0.0005	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
I-129	0.0308	0.0328	0.0067	0.0397	0.0116	0.0003	9.2601	0.0117	0.0156	0.0316	0.0138
RU-106	86.1276	86.4952	84.0918	86.2594	86.7865	99.0120	78.7033	86.9265	86.9219	87.9962	84.6052
CS-137	1.6245	1.5545	0.6766	1.5358	1.4503	0.0828	1.2799	1.4915	1.5333	1.5405	1.1361
CS-134	0.8801	0.8803	0.3479	0.8170	0.7547	0.0500	0.7597	0.9797	0.9773	0.8278	0.9445
SR-90	0.5348	2.0312	0.0000	3.5954	0.0050	0.0332	0.0312	0.0316	0.0329	0.0300	0.0417

Table C.13. Annual Dose to the Urban Population from One-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (MAN-REMS)
TOT.BODY	0.2693E+03
R MAR	0.2944E+03
LUNGS	0.5933E+03
ENDOST	0.3182E+03
S WALL	0.2572E+03
LLI WALL	0.1146E+04
THYROID	0.2496E+03
LIVER	0.2477E+03
KIDNEYS	0.2513E+03
TESTES	0.2810E+03
OVARIES	0.1780E+03

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	24.8642	22.6922	11.2872	19.7993	26.0336	5.9486	26.7657	26.9699	26.8883	23.8272	37.5340
PU-239	0.0001	0.0002	0.0001	0.0013	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000
I-129	0.0312	0.0389	0.0070	0.0495	0.0131	0.0010	4.2620	0.0137	0.0184	0.0373	0.0180
RU-106	72.5373	74.1578	87.7147	76.4639	71.6748	93.6251	66.7795	70.5613	70.5815	73.6972	60.3727
CS-137	1.6844	1.7294	0.6961	1.7887	1.5987	0.2716	1.4906	1.6362	1.6849	1.6955	1.2848
CS-134	0.7370	0.7742	0.2949	0.7749	0.6784	0.1258	0.6922	0.8091	0.8170	0.7340	0.7765
SR-90	0.1459	0.6072	0.0000	1.1224	0.0014	0.0279	0.0100	0.0096	0.0099	0.0089	0.0140

Table C.14. Maximum Annual Dose to a Rural Individual from Five-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (REMS)
TOT.BODY	0.5513E-03
R MAR	0.6044E-03
LUNGS	0.6300E-03
ENDOST	0.6498E-03
S WALL	0.5366E-03
LLI WALL	0.1931E-02
THYROID	0.7133E-03
LIVER	0.5434E-03
KIDNEYS	0.5477E-03
TESTES	0.5592E-03
OVARIES	0.5101E-03

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE N	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	75.0285	68.3589	65.6495	61.7693	77.0806	21.6065	57.9194	76.0237	75.8568	73.9667	80.9870
PU-239	0.0002	0.0006	0.0005	0.0038	0.0000	0.0000	0.0000	0.0009	0.0001	0.0000	0.0000
I-129	0.0983	0.1141	0.0394	0.1450	0.0373	0.0037	24.8104	0.0388	0.0517	0.1121	0.0387
RU-106	17.8851	19.4030	30.1514	20.3106	17.9832	76.9615	13.5497	18.5101	18.5283	20.0845	15.2787
CS-137	4.7219	4.[illegible]80	3.6298	5.1211	4.2559	0.9112	3.1196	4.4944	4.6278	4.9808	2.9048
CS-134	0.7260	0.7936	0.5293	0.7732	0.6285	0.1563	0.5255	0.8379	0.8371	0.7596	0.6854
SR-90	1.5401	6.3919	0.0002	11.8770	0.0146	0.3608	0.0754	0.0944	0.0982	0.0962	0.1055

Table C.15. Annual Dose to the Rural Population from Five-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (MAN-REMS)
TOT.BODY	0.8649E+01
R MAR	0.9035E+01
LUNGS	0.1052E+02
ENDOST	0.9168E+01
S WALL	0.8483E+01
LLI WALL	0.1601E+02
THYROID	0.9805E+01
LIVER	0.8440E+01
KIDNEYS	0.8536E+01
TESTES	0.8720E+01
OVARIES	0.7857E+01

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	79.5149	75.9769	65.3708	71.4140	81.0699	43.5757	70.0122	81.3348	81.1515	78.8709	87.3731
PU-239	0.0002	0.0006	0.0005	0.0044	0.0000	0.0000	0.0000	0.0009	0.0001	0.0000	0.0000
I-129	0.0956	0.1228	0.0382	0.1662	0.0384	0.0072	14.8805	0.0392	0.0527	0.1163	0.0397
RU-106	14.5277	15.6872	30.6800	17.2563	14.0519	54.1952	11.1732	13.5945	13.6244	15.4423	9.3639
CS-137	4.6809	5.0565	3.4730	5.5672	4.2916	1.7286	3.4224	4.3396	4.4740	4.8997	2.6814
CS-134	0.6126	0.6815	0.4373	0.7201	0.5429	0.2429	0.4801	0.6558	0.6608	0.6351	0.5022
SR-90	0.5681	2.4745	0.0002	4.8719	0.0053	0.2504	0.0318	0.0352	0.0365	0.0357	0.0396

Table C.16. Maximum Annual Dose to an Urban Individual from Five-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE(REMS)
TOT.BODY	0.3327E-02
R MAR	0.3631E-02
LUNGS	0.3839E-02
ENDOST	0.3889E-02
S WALL	0.3241E-02
LLI WALL	0.1370E-01
THYROID	0.4259E-02
LIVER	0.3281E-02
KIDNEYS	0.3306E-02
TESTES	0.3371E-02
OVARIES	0.3089E-02

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	76.1476	69.6780	65.9827	63.2152	78.1529	9.1833	59.4170	77.1291	76.9686	75.1381	81.9184
PU-239	0.0002	0.0006	0.0005	0.0040	0.0000	0.0000	0.0000	0.0009	0.0001	0.0000	0.0000
I-129	0.0938	0.1093	0.0372	0.1395	0.0355	0.0043	23.9261	0.0370	0.0494	0.1071	0.0368
RU-106	17.0915	18.5945	30.0500	19.5426	17.1425	89.1549	13.0692	17.6577	17.6758	19.1814	14.5308
CS-137	4.5048	4.7313	3.4293	4.9265	4.0561	1.0575	3.0082	4.2862	4.4139	4.7562	2.7620
CS-134	0.6926	0.7605	0.5001	0.7438	0.5990	0.1813	0.5068	0.7991	0.7985	0.7254	0.6517
SR-90	1.4696	6.1258	0.0002	11.4284	0.0139	0.4188	0.0728	0.0900	0.0937	0.0919	0.1003

Table C.17. Annual Dose to the Urban Population from Five-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (MAN-REMS)
TOT.BODY	0.7109E+02
R MAR	0.7433E+02
LUNGS	0.9117E+02
ENDOST	0.7515E+02
S WALL	0.6954E+02
LLI WALL	0.1269E+03
THYROID	0.7855E+02
LIVER	0.6884E+02
KIDNEYS	0.6979E+02
TESTES	0.7177E+02
OVARIES	0.6273E+02

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	75.1727	71.7442	58.6218	66.9189	76.8563	42.8699	67.8895	77.4658	77.2664	74.4668	85.0025
PU-239	0.0002	0.0008	0.0006	0.0056	0.0000	0.0000	0.0000	0.0012	0.0001	0.0000	0.0000
I-129	0.1182	0.1542	0.0457	0.2098	0.0485	0.0095	13.5456	0.0493	0.0664	0.1463	0.0511
RU-106	17.6692	18.8902	36.7039	20.8222	17.0483	54.3627	13.6470	16.3293	16.3414	18.5571	11.0158
CS-137	5.8190	6.2479	4.1313	6.9082	5.3931	2.2370	4.3203	5.3702	5.5325	6.0550	3.3249
CS-134	0.7223	0.7934	0.4964	0.8489	0.6492	0.2939	0.5691	0.7532	0.7610	0.7435	0.5700
SR-90	0.4984	2.1694	0.0002	4.2865	0.0047	0.2270	0.0286	0.0311	0.0322	0.0313	0.0358

Table C.18. Maximum Annual Dose to a Rural Individual from Ten-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (REMS)
TOT.BODY	0.3463E-03
R MAR	0.3771E-03
LUNGS	0.3384E-03
ENDOST	0.4064E-03
S WALL	0.3354E-03
LLI WALL	0.3835E-03
THYROID	0.5118E-03
LIVER	0.3372E-03
KIDNEYS	0.3399E-03
TESTES	0.3414E-03
OVARIES	0.3277E-03

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	89.8030	82.3773	91.9009	74.2560	92.7152	81.7985	60.6920	92.1098	91.8925	91.0865	94.7865
PU-239	0.0003	0.0010	0.0009	0.0061	0.0000	0.0000	0.0000	0.0014	0.0002	0.0000	0.0000
I-129	0.1565	0.1829	0.0733	0.2319	0.0597	0.0187	34.5808	0.0625	0.0334	0.1836	0.0603
RU-106	0.9041	0.9876	1.7827	1.0313	0.9136	12.3060	0.5997	0.9472	0.9460	1.0446	0.7553
CS-137	6.7398	7.0963	6.0595	7.3416	6.1047	4.1139	3.8983	6.4938	6.6854	7.3146	4.0543
CS-134	0.2141	0.2356	0.1826	0.2290	0.1863	0.1458	0.1357	0.2501	0.2499	0.2305	0.1976
SR-90	2.1824	9.1196	0.0003	16.9043	0.0208	1.6174	0.0936	0.1354	0.1409	0.1403	0.1462

Table C.19. Annual Dose to the Rural Population from Ten-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (MAN-REMS)
TOT.BODY	0.5635E+01
R MAR	0.5837E+01
LUNGS	0.5613E+01
ENDOST	0.5855E+01
S WALL	0.5547E+01
LLI WALL	0.5813E+01
THYROID	0.6967E+01
LIVER	0.5542E+01
KIDNEYS	0.5605E+01
TESTES	0.5619E+01
OVARIES	0.5386E+01

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	91.7534	88.4160	92.1134	84.0616	93.2134	90.2337	74.0758	93.1237	92.9159	92.0103	95.8147
PU-239	0.0003	0.0010	0.0010	0.0069	0.0000	0.0000	0.0000	0.0014	0.0002	0.0000	0.0000
I-129	0.1468	0.1901	0.0717	0.2602	0.0587	0.0199	20.9418	0.0597	0.0803	0.1805	0.0579
RU-106	0.7080	0.7710	1.8259	0.8579	0.6824	4.7399	0.4993	0.6574	0.6589	0.7609	0.4337
CS-137	6.4413	7.0172	5.8360	7.8148	5.8845	4.2687	4.3182	5.9251	6.1089	6.8165	3.5066
CS-134	0.1742	0.1954	0.1518	0.2088	0.1538	0.1239	0.1252	0.1850	0.1864	0.1826	0.1357
SR-90	0.7761	3.4093	0.0003	6.7897	0.0072	0.6140	0.0398	0.0477	0.0494	0.0493	0.0514

Table C.20. Maximum Annual Dose to an Urban Individual from Ten-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE(REMS)
TOT.BODY	0.2108E-02
R MAR	0.2285E-02
LUNGS	0.2064E-02
ENDOST	0.2450E-02
S WALL	0.2045E-02
LLI WALL	0.2323E-02
THYROID	0.3061E-02
LIVER	0.2056E-02
KIDNEYS	0.2072E-02
TESTES	0.2080E-02
OVARIES	0.2001E-02

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE N	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	90.3539	83.2555	92.2642	75.4174	93.1220	82.6993	62.1568	92.5474	92.3412	91.5760	95.0835
PU-239	0.0003	0.0010	0.0010	0.0063	0.0000	0.0000	0.0000	C.C014	0.0002	0.0000	0.0000
I-129	0.1480	0.1737	0.0692	0.2214	0.0563	0.0178	33.2922	C.0590	0.0788	0.1736	0.0568
RU-106	0.8566	0.9384	1.7747	0.9847	0.8627	11.6977	0.5774	C.8549	0.8957	0.9874	0.7124
CS-137	6.3743	6.7417	5.7184	7.0090	5.7635	3.9096	3.7528	6.1332	6.3151	6.9127	3.8231
CS-134	0.2025	0.2239	0.1723	0.2186	0.1759	0.1385	0.1306	C.2363	0.2360	0.2178	0.1864
SR-90	2.0645	8.6659	0.0003	16.1424	0.0197	1.5371	0.09C1	0.1279	0.1331	0.1326	0.1378

Table C.21. Annual Dose to the Urban Population from Ten-Year-Decayed Spent Fuel

TOTAL DOSE TO EACH ORGAN THROUGH ALL PATHWAYS

ORGAN	DOSE (MAN-REMS)
TOT.BODY	0.4478E+02
R MAR	0.4636E+02
LUNGS	0.4474E+02
ENDOST	0.4610E+02
S WALL	0.4404E+02
LLI WALL	0.4597E+02
THYROID	0.5421E+02
LIVER	0.4391E+02
KIDNEYS	0.4453E+02
TESTES	0.4472E+02
OVARIES	0.4230E+02

CONTRIBUTORS TO ORGAN DOSES

PERCENT

NUCLIDE N	TOT.BODY	R MAR	LUNGS	ENDOST	S WALL	LLI WALL	THYROID	LIVER	KIDNEYS	TESTES	OVARIES
H-3	89.7222	86.4774	89.7966	82.0013	91.2373	88.9650	73.9462	91.2983	91.0427	89.8423	94.7805
PU-239	0.0004	0.0013	0.0013	0.0091	0.0000	0.0000	0.0000	0.0018	0.0002	0.0000	0.0000
I-129	0.1876	0.2473	0.0931	0.3420	0.0766	0.0261	19.6248	0.0773	0.1040	0.2347	0.0757
RU-106	0.8907	0.9617	2.3747	1.0777	0.8548	4.7648	0.6278	0.8128	0.8133	0.9456	0.5188
CS-137	8.2825	8.9810	7.5467	10.0950	7.6349	5.5361	5.6117	7.5477	7.7741	8.7117	4.4212
CS-134	0.2124	0.2356	0.1873	0.2563	0.1899	0.1503	0.1527	0.2187	0.2209	0.2210	0.1566
SR-90	0.7043	3.0958	0.0004	6.2188	0.0066	0.5578	0.0369	0.0434	0.0449	0.0447	0.0472

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RADIATION EXPOSURES FROM SOLIDIFICATION PROCESSES FOR HIGH-LEVEL RADIOACTIVE LIQUID WASTES

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9. Performing Organization Name and Address
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14.

15. Supplementary Notes

16. Abstracts The Office of Radiation Programs, U.S. Environmental Protection Agency (ORP/EPA) has prepared this analysis as technical support for EPA's proposed environmental radiation protection standards, 40 CFR 191, concerning the management and disposal of high-level radioactive wastes. For Subpart A of 40 CFR 191, waste management and storage operations, EPA proposes to extend the limitations of 40 CFR 190 to these operations.

EPA/ORP developed a generic high-level liquid waste solidification plant and assessed the potential environmental impact of atmospheric discharges during normal operations in four solidification processes: fluidized-bed calcination, spray calcination and glassification by in-can melting and continuous melting. We used a newly developed computer code, AIRDOS-EPA, to perform the assessment.

17. Key Words and Document Analysis. 17a. Descriptors

17b. Identifiers/Open-Ended Terms

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