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Y/OWI/TM-36/23

MASTER MASTER

TECHNICAL SUPPORT FOR GEIS: RADIOACTIVE WASTE ISOLATION IN GEOLOGIC FORMATIONS

Volume 23

Environmental Effluent Analyses

April 1978

Prepared By

Science Applications, Inc.
Post Office Box 843
800 Oak Ridge Turnpike
Oak Ridge, Tennessee 37830

UNION CARBIDE

OFFICE OF WASTE ISOLATION
OAK RIDGE, TENNESSEE

prepared for the U.S. DEPARTMENT OF ENERGY *under*
U.S. GOVERNMENT *Contract W-7405 eng 26*

This report was prepared by Science Applications, Inc. under Subcontract 62Y-45700 with Union Carbide Corporation, Nuclear Division. The subcontract was administered by the Office of Waste Isolation.

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TECHNICAL SUPPORT FOR GEIS:
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IN GEOLOGIC FORMATIONS

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TM-36/23	Environmental Effluent Analyses	SAI

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*These documents were prepared by Science Applications, Inc. (SAI), 800 Oak Ridge Turnpike, Oak Ridge, Tennessee 37830; Dames & Moore (D&M), 20 Haarlem Avenue, White Plains, New York 10603; and Parsons Brinckerhoff Quade & Douglas, Inc. (PBQD), 1 Penn Plaza, New York, New York 10001.

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ABSTRACT

This volume, Y/OWI/TM-36/23, "Environmental Effluent Analysis," is one of a 23-volume series, "Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations," Y/OWI/TM-36, which supplements the "Contribution to Draft Generic Environmental Impact Statement on Commercial Waste Management: Radioactive Waste Isolation in Geologic Formations," Y/OWI/TM-44. The series provides a more complete technical basis for the preconceptual designs, resource requirements, and environmental source terms associated with isolating commercial LWR wastes in underground repositories in salt, granite, shale and basalt. Wastes are considered from three fuel cycles: uranium and plutonium recycling, no recycling of spent fuel and uranium-only recycling.

This volume discusses the releases to the environment of radioactive and non-radioactive materials that arise during facility construction and waste handling operations, as well as releases that could occur in the event of an operational accident. The results of the analyses are presented along with a detailed description of the analytical methodologies employed.

PREFACE

Project Background

One of the major problems related to the production of electricity by light-water nuclear reactors is the management of radioactive wastes generated by the use of nuclear fuel. However, the subject is considered amenable to a rational solution, and the technology involved is considered to be well within the capabilities of our present-day technological base.

An important step toward the realization of an effective waste management program is the preparation of the generic environmental impact statement for commercial waste management. A pivotal issue in waste management is the means of providing long-term, permanent storage of these wastes in a manner that best assures their isolation from the biosphere. Analyses spanning two decades have generated the widely supported concept for providing final isolation of these nuclear wastes in deep geologic formations. Therefore, the Office of Waste Isolation* was assigned the responsibility for preparation of those sections of this generic statement dealing with deep geologic waste isolation.

The original concept for deep geologic disposal was first advanced in 1957 when a National Research Council Advisory Committee of the National Academy of Sciences suggested the burial of solid radioactive wastes in salt deposits. To date, the majority of the research, development, and demonstration (RD&D) activities have been in salt. The current United States Department of Energy (DOE) National Waste Terminal Storage (NWTS) program calls for the selection of two sites overlying suitable salt formations by 1979, followed by the construction and start-up in 1985 of one NRC-licensed repository designed for the permanent disposal/isolation of commercial nuclear wastes in a salt formation at one of these two sites. In addition to this activity in salt, vigorous RD&D programs have been initiated to determine the appropriateness of various hard rocks as host media for a repository.

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*Operated by Union Carbide Corporation-Nuclear Division for the Department of Energy.

The deep-geologic-isolation portion of the generic statement considers repositories located in salt, granite, shale, or basalt. The repositories are designed to handle wastes from the nuclear fuel cycle in which the spent fuel is considered a waste (no reprocessing), or from either of two fuel cycles that include reprocessing--the cycle with uranium and plutonium recycle and that with only uranium recycle. To prepare this contribution, the Office of Waste Isolation contracted with Dames & Moore, Parsons Brinckerhoff Quade & Douglas, Inc., and Science Applications, Inc. In order to prepare this description, generic sites were defined, preconceptual repository designs completed, and resource requirements and effluents from the repositories identified. The preconceptual repository designs for the salt host formation were based on more than two decades of analysis and in situ experimentation. The data base upon which the repository design for the non-salt host formations were based is more more sparse since repository-oriented analyses of these formations have been proceeding only for the last couple of years. For each of the host rocks additional analyses were performed during the conduct of these studies. Details of this additional technical work are described within the twenty-three volumes of this report.

For an overview of these preconceptual repository design studies, the study objectives and scope, and the major study assumptions, the reader is referred to Volume 1 of this series, the "Executive Summary" (Y/OWI/TM-36/1).

Volume Summary (Y/OWI/TM-36/23)

During construction and operational activities of a nuclear waste repository, effluents in the form of solids, liquids, and gases should be expected. The impact of these releases on the environment can only be determined by comparing their magnitude to existing state and federal regulations that specifically apply. For releases that are not governed by regulations, the convention of "as low as reasonably achievable (ALARA)," or its equivalent, is employed. The purpose of this document is to discuss and illustrate the sources as well as the magnitudes of these expected releases to the environment, so that environmental impact assessments can be performed.

Solid effluents arise mainly during construction of the underground facility in which large quantities of excavated rock will be brought to the surface. Roughly 50% of this rock would be stored on site, or nearby, for backfilling purposes; the remainder would require permanent disposal. Other sources of solid effluents would be surface excavation during construction, and refuse and sanitary wastes during operation. Refuse would include worn-out equipment, waste from maintenance activities, as well as paper and garbage from office and cafeteria facilities. All solids effluents are expected to be non-radioactive except the worn-out equipment and accessories from contaminated waste-handling areas. These effluents are discussed in sufficient detail in Sections 5.1 and 5.2 of the GEIS.

Liquid effluents would arise during construction from surface runoff and sewage wastes. These liquid effluents are not expected to be an environmental concern. During operation, however, decontamination procedures and, in the case of non-salt rocks, groundwater inflow could give rise to contaminated liquid effluents. The decontamination liquids and the groundwater, if contaminated, could require treatment to comply with EPA standards for potable water before being discharged. These effluents are discussed in detail in Sections 5.1 and 5.2 of the GEIS and Chapter 5 of Volume 22 of this series.

Airborne effluents result from mining activities, surface construction, and waste-handling operations. Airborne effluents are of greater concern in this report, since the release is less controllable than the other two forms; hence, a more detailed examination of their magnitudes are in order. All aspects of airborne releases are shown in detail in the following chapters of this report.

Construction-related airborne effluents would be vehicular exhausts, naturally-occurring gases from the mine, dust, and emissions from coal-fired steam generators. Except for the naturally occurring radon gases, these effluents are non-radioactive (Chapter 1).

Airborne radioactive effluents could result from normal waste handling and storage. Under normal conditions, small amounts of container surface contamination and internal activity could be released to the facility ventilation system. Even with conservative assumptions of these releases, once dispersed from the facility stack there will be no appreciable dose at the site fenceline (Chapter 2). Radiation-induced hydrogen production during normal storage was investigated as a potential fire hazard in a sealed storage room, and it was concluded that no potential for fires exists within the current repository design (Chapter 1).

Accidents to waste containers were considered and appropriate scenarios defined. The resulting airborne releases were assessed using conservative assumptions. The worst case involved concentrations at the site boundary of about 700 times the NRC limit for unrestricted areas considering OWI defined waste, and about 100 times the limit considering BPNL defined waste (Chapter 3).

Again, hydrogen generation was investigated as a possible fire hazard, but in this case, ILW fixed in bituminous material was considered as the source of hydrogen production. For purposes of this analysis, an alternative waste form (BPNL) specifying bitumen fixation of wet wastes was used. It was concluded, however, that the worst situation (or highest hydrogen generation rate in a sealed storage room) would result in concentrations of hydrogen in air of about 3 order of magnitude below the combustible limit (Chapter 4).

1.0 EFFLUENTS FROM CONSTRUCTION AND NORMAL OPERATIONS

Environmental effluents from the construction and normal operation of a waste repository have been discussed in Section 5.1 of the GEIS.[1] Calculations were necessary in the analyses of the emissions from coal-fired boilers, radon releases from the mine, vehicular exhaust emissions, and hydrogen gas production in storage rooms. The following sections give a detailed description of the calculations used for these analyses, along with the assumptions and design specifications employed. While other effluents are discussed in Section 5.1 of the GEIS, only these mentioned here require a more indepth analysis.

1.1 EMISSIONS FROM COAL-FIRED BOILERS

As outlined in Section 4.8.5 of the GEIS,[1] production of 200 psig steam for in-plant usage is assumed to be generated by four coal-burning boilers. The total steam capacity for all four boilers is designed to be 200,000 lb/hr. For saturated steam at 200 psig, the enthalpy is approximately 1200 Btu/lb. Using the design capacity of 200,000 lb/hr of steam, the total heat input required would approach 2.4×10^8Btu/hr. The heating value of bituminous coal can vary between 10,000 and 15,000 Btu/lb, depending upon mining location and other factors.[2] Using an average value of 13,000 Btu/lb. results in consumption of approximately 9 tons/hr of coal in the four boilers.

Average gaseous and particulate emission factors have been determined for coal combustion equipment.[3-5] Table 1-2 presents the average numbers given for power plants of the size under consideration. The release of oxides of sulfur (primarily SO_2) is highly dependent upon the sulfur content of the coal burned. From data on sulfur content of bituminous coal reserves in the U. S., the average content was found to be approximately 2 percent.[6]

Using the given emission factors, estimates of the total uncontrolled release rates for NO_x, particulates, and SO_2 were determined assuming 2 percent sulfur coal, with 10 percent ash, burned at a rate of 9 tons/hr. The resulting releases are as follows:

NO_x -	180 lb/hr
Particulates -	1350 lb/hr
SO_2 -	685 lb/hr

To ensure compliance with existing EPA regulations concerning emissions from coal-fired steam generators, furnace flue gases will be treated prior to discharge to the environment. Typical techniques available for particulate control are cyclones, spray towers and venturi scrubbers; throwaway and regenerative scrubbing processes for SO_2 treatment; and combustion control, absorption, and adsorption for control of NO_x (Table 1-3). Assuming use of a venturi scrubber for particulates, a limestone scrubber for SO_2 and flue gas recirculation (75%) for NO_x, the resulting stack releases would be

NO_x -	45 lb/hr	=	0.2 lb/10^6 Btu
Particulates -	6.8 lb/hr	=	0.03 lb/10^6 Btu
SO_2 -	140 lb/hr	=	0.6 lb/10^6 Btu

The regulations covering emissions from coal-fired plants are given in 40CFR60.[7] The limits given in this document are based on an emission level given as lb/10^6 Btu of energy output. For the assumed coal combustion process, about 2.4×10^8 Btu/hr is produced. The values given in Table 1-1 represent the previously determined controlled releases, in terms of lb/10^6Btu. All three releases are found to be under the federal regulations for such emissions.

1.2 RADON RELEASES FROM MINING OPERATIONS

During the mining and storage phase of repository operation, naturally occurring Rn-220 and Rn-222 will be released from the host rock. The magnitude of this release is dependent upon the radium and thorium content of the rock. For the media under consideration, the average concentrations of these trace elements are:[8,9]

	Thorium (Th-232)	Radium (Ra-226)
Salt	0.002 ppm	3×10^{-10} ppm
Shale	11.0 ppm	1.4×10^{-6} ppm
Granite	17.0 ppm	1.7×10^{-6} ppm
Basalt	2.2 ppm	2.1×10^{-7} ppm

Decay of these naturally occurring radioisotopes yields the gaseous radioactive daughters Rn-220, and Rn-222 (from Th-232 and Ra-226 respectively). During normal mining operations, blasting, crushing and transporting the crushed rock would release the entrapped gas, allowing it to migrate into the ventilation air. In addition, radon may emanate from already mined rooms, corridors, and other open surfaces, although at a much lower rate.

To estimate the magnitude of this release for the various rock types, an analysis was conducted based on the following conservative assumption. It was assumed that all radon contained in the mined rock was released during mining and rock handling. Although the actual release value is expected to be less than 50 percent, the added conservatism was included so that other sources (i.e. exposed surface emanation) could be ignored.[10]

Using specific activities of Th-232 and Ra-226 of 1.1×10^{-7}Ci/g and 0.99Ci/g respectively,[11] the average Curie content of each rock type due to these elements was determined. Assuming secular equilibrium, the activity of the radon daughters produced would be the same as their parents. To arrive at the total release, the maximum daily mining rates for each rock medium was coupled with the amount of Ra-226 and Th-232 contained in the rock. The activity of these mined isotopes would then equal the activity of radon released. As an example, consider the release from a granite repository at the peak mining period:

Rn-220

$$(17\text{ ppm Th})(16{,}000\text{ tons mined/day})\left(\frac{2000\text{ lb}}{1\text{ Ton}}\right)(454\text{g/lb})(1.09\times10^{-7}\text{Ci/g}) = 26.9\text{ mCi/day}$$

Rn-222

$$(1.7\text{x}10^{-6}\ \text{ppm Ra})\ (16{,}000\ \text{tons mined/day})(\frac{2000\ \text{lb}}{1\ \text{ton}})(454\text{g/lb})(.99\text{Ci/g}) = 24.5\ \text{mCi/day}$$

These calculations were repeated for each rock type at their peak mining rates. The results are presented in Table 1-4 along with the mining rates used. Rn-220 has a short half-life (56 sec) and therefore will not be present for very long in the mine ventilation system. Applying the estimated subterranean mining operation's ventilation rates ($1.25\text{x}10^6$ cfm for salt and shale, $1.75\text{x}10^6$ cfm for granite and basalt),[1] the estimated concentration values in µCi/ml were calculated.

All concentrations were found to be well below acceptable limits specified in 10CFR20 (Table 1-1).[12]

1.3 DIESEL EXHAUST EMISSIONS

The ventilation system designed for the mining areas will be adequate for sufficient dilution of the noxious gases (primarily CO, NO_x, aldehydes), particulates, and other by-products (H_2O, CO_2) arising from diesel combustion to safe levels. The following analysis was conducted to obtain estimates of the upper-limit concentrations expected in the mine air prior to discharge. For this study, an estimate of the maximum number of diesel-operated vehicles was obtained.[13] This maximum occurs for a granite mine utilizing blasting techniques, with the peak number, type, and horsepower of each unit being given as follows:

High-Level Zone	
5 transporters	318 hp
4 trucks	400 hp
1 loader	325 hp
1 dozer	140 hp
1 grater	140 hp
2 service vehicles	75 hp
2 personnel carriers	52 hp

ILW and Cladding Zone	
2 loaders	325 hp
6 trucks	400 hp
2 dozers	140 hp
1 grater	140 hp
3 service vehicles	75 hp
3 personnel carriers	52 hp
2 35-ton trucks	400 hp

Backfilling	
3 trucks	400 hp
2 dozers	140 hp

Sleeve Emplacement	
2 emplacers	130 hp

Miscellaneous	
3 service vehicles	75 hp
4 personnel carriers	52 hp
1 ready-mix truck	300 hp
1 construction vehicle	75 hp

The total brake horsepower (bhp) available in the mine, for this maximum case, is approximately 11,250 bhp arising from approximately 50 vehicles. Based on a study in which emission data from 10 diesel engines of various types and rated horsepowers was analyzed,[14] the following representative emission rates were determined.

CO	5.6 g/bhp-hr
NO_x	6.5 g/bhp-hr
HCHO(aldehydes)	0.25 g/bhp-hr
Particulates	0.2 g/bhp-hr

The actual emissions will depend upon the different types of diesels used, and the actual horsepower developed. In addition, to control these emissions within the confines of the mine, it is assumed that oxy-catalytic scrubbers would be required. These scrubbers are finding widespread usage in mine environments, and, according to manufacturers, can eliminate the following percentages of harmful exhaust gases:[15]

Oxides of nitrogen	10%
Carbon monoxide	90%
Formaldehyde(HCHO)	95%

The estimated diesel exhaust concentrations present in Table 1-1 were derived based on the assumption that the maximum bhp available in the mine (11,250 bhp) is operating at one time, emitting gaseous and particulate pollutants at the given rates, with control techniques operating according to specifications and a ventilation flow rate of 1.75×10^6 cfm.

For example, consider CO emissions

$$5.6 \text{ g/bhp-hr} \times 11250 \text{ bhp} \div 60 \text{ min./hr} = 1050 \text{ g/min}$$

$$1050 \text{ g/min} \div 1.75 \times 10^6 \text{ ft}^3\text{/min} = 6.0 \times 10^{-4} \text{ g CO/ft}^3\text{Air}$$

Converting grams of CO to ft^3 of gas:

$$6.0 \times 10^{-4} \text{ g/ft}^3 \div 28 \text{ g/g mole} = 2.14 \times 10^{-5} \text{ g mole/ft}^3$$

$$2.14 \times 10^{-5} \text{ g mole/ft}^3 \times 22.4 \text{ l/g mole} \times 0.035 \text{ ft}^3\text{/l} = 1.68 \times 10^{-5} \text{ ft}^3 \text{ CO/ft}^3\text{Air}$$

Assuming 90 percent is removed, then

$$1.68 \times 10^{-6} \frac{\text{ft}^3 \text{ CO}}{\text{ft}^3 \text{ Air}} \text{ remain}$$

or ∿2 ppm.

The resulting concentrations in all cases are below the recommended threshold limits for occupational exposure. Concentrations of CO_2 and H_2O will also result from diesel operation, however the ventilation requirements for the more noxious emissions will preclude any concern. In addition, under actual operating conditions, when less than 100 percent of the machinery will be operating, the concentrations of these emissions would be even lower.

1.4 HYDROGEN GAS PRODUCTION

The presence of water in the geologic media of a waste repository could lead to the formation of hydrogen gas. Radiolysis, corrosion, and hydrolysis would be the mechanisms of gas production. However, the generation rate will be dependent on the amount and composition of water that migrates into waste canister storage holes from the surrounding salt, shale, granite, or basalt. Each of these media possesses different characteristics which will influence both the radiolysis of water within the formation and the migration of water into the hole where it could react in hydrolysis and corrosion processes.

Jenks[16,17] has analyzed the problem of hydrogen generation in salt. His examination of PWR spent fuel and 2.1 kW/canister HLW cases resulted in the calculated brine inflow rates given in Figures 1-1 and 1-2. The amount of H_2 generated as a result of this brine inflow into the vicinity of high dose sources is not well known, nor is there any significant experimental data to substantiate it. However, as an upper bound to this value it is assumed that all the water entering the storage cavity reacts to form H_2. Since brine inflow is the only source of water in the repository, the value achieved here would be the maximum possible in a salt repository. The amount of H_2 produced would be on the order of 55 moles of H_2 per liter of brine inflow. As mentioned already, this is a very coarse and conservative estimate. Exact figures can be derived only through actual operating experience in a repository.

Using the above explanation and Figures 1-1 and 1-2, an estimation of the hydrogen concentration in ventilated and unventilated rooms can be prepared. From Figure 1-1, the total inflow over 25 years for a PWR-spent fuel cavity is around 850 ml. The average annual inflow is therefore 34 ml or 0.034 liters. A single canister would generate 0.034 liter/yrx55 moles H_2/liter or 1.87 moles H_2/yr. A maximum of 1150 PWR-canisters would be placed in a 18'x22'x3500' (volume = $1.386\text{x}10^6 \text{ft}^3$ or $3.925\text{x}10^4 \text{m}^3$) room. Therefore, approximately 2150 moles of H_2 would be released to the room per year. This quantity would occupy 48 m^3 or about 0.12 percent of the room volume. The volume percentage of H_2 in an unventilated room at 5 and 25 years is then calculated to be 0.6 and 3.1 percent respectively. The flammability limit of 4 percent H_2 in air[18] is greater than these conservative values. However, during waste emplacement operations the room would be ventilated at about 40,000 cfm and a room nearing completion of emplacement operations could attain H_2 concentrations of $\sim 10^{-6}$ percent, which is negligible.

Figure 1-1 gives the total inflow for a 2.1 kW HLW cavity over 5 years as about 3 liters. The average annual inflow is therefore 600 ml or 0.6 liters. A single canister would generate 0.6 liter/yr x 55 moles H_2/liter, or 33 moles H_2/yr. A maximum of 57 HLW canisters would be placed in an 18'x20'x560' (volume = $2.016 \times 10^5 \text{ft}^3$ or $5.71 \times 10^3 \text{m}^3$) room. Approximately 1880 moles of H_2 would be generated and released to the room per year. This quantity would occupy 42 m^3 or 0.7 percent of the room volume. Over 5 years the concentration in an unventilated room would reach 3.7 percent. A ventilated (40,000 cfm) room nearing completion of emplacement operations could attain a H_2 concentration of $\sim 10^{-6}$ percent.

Based on this analysis, hydrogen generation in a salt repository results in values close to the flammability limit of 4 percent (3.1 and 3.7 percent for SURF at 25 years and reprocessing at 5 years, respectively). Should concentrations on this order be encountered in repository operation, corrective action such as periodic ventilation would be required. However, it is unlikely that complete reaction of water would occur, especially since gaseous oxygen will be present around the sleeve.

Other geologic media could possibly have conditions suitable for greater hydrogen generation rates, although no data has been recorded in those areas. Mechanisms of water movement are different in salt than in the other media; therefore, the amount of water present in the storage cavity is unknown. It is possible, however, to monitor the hydrogen content in the air during retrievable storage and ventilate the room if the concentrations should approach combustible limits.

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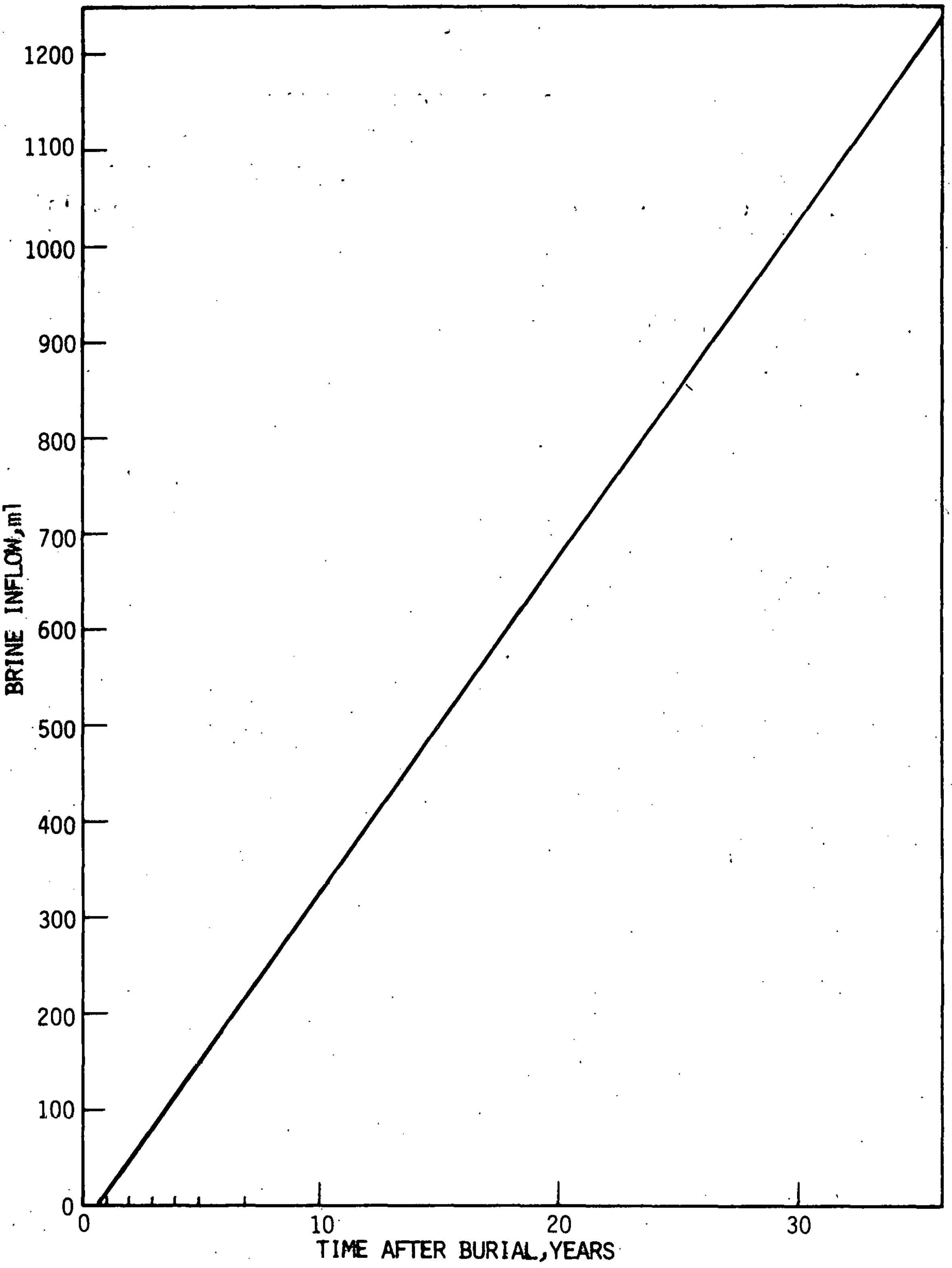
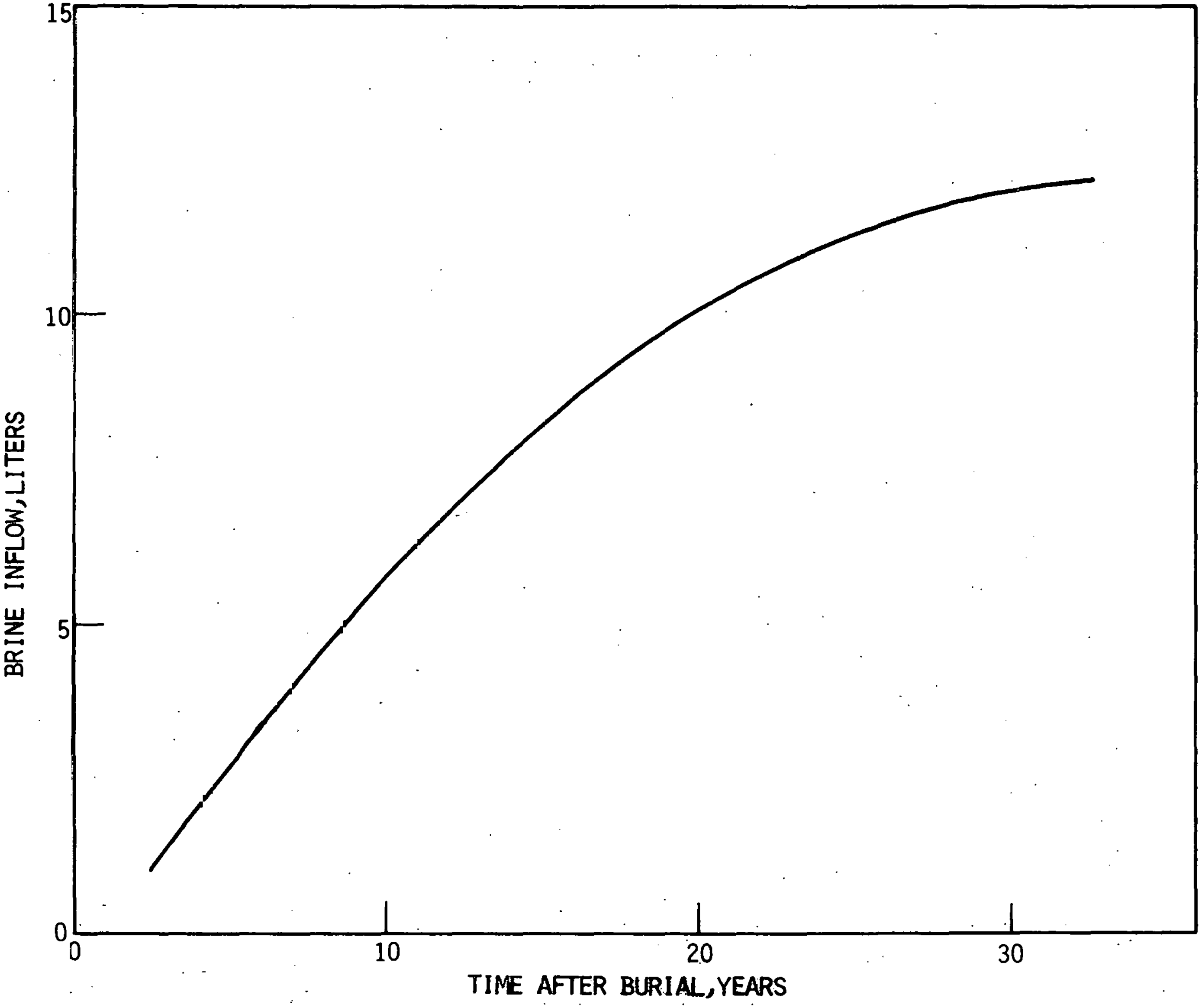
FIGURE 1-1. CUMULATIVE BRINE INFLOW VS. TIME AFTER BURIAL (GHL; SF; 60 KW/ACRE) MIDPLANE CONDITIONS, 1-FOOT-RADIUS HOLE IN SALT*



*Source: Genks, G. H. "Reference Concept for Disposal Hole Retrievable Emplacement of Spent Fuel or HLW in Salt and Considerations of Buildup of Water Vapor and Other Gases and Solids," OWI Memo, to be published.

FIGURE 1-2. CUMULATIVE BRINE INFLOW VS. TIME AFTER BURIAL; (GHL; HLW; 150 KW/ACRE) MIDPLANE CONDITIONS*



*Source: Genks, G. H. "Reference Concept for Disposal Hole Retrievable Emplacement of Spent Fuel or HLW in Salt and Considerations of Buildup of Water Vapor and Other Gases and Solids," OWI Memo, to be published.

TABLE 1-1

ESTIMATED MAXIMUM AIRBORNE CONCENTRATIONS AND OTHER EMISSIONS FROM CONSTRUCTION AND OPERATION OF THE WASTE ISOLATION FACILITY

		Estimated Releases	Guide for Occupational Exposure	Fraction of Guideline
^{222}Rn (from Rock)	Salt	4×10^{-14} μCi/ml	3×10^{-8} μCi/ml[a]	$1. \times 10^{-6}$
	Shale	8×10^{-11} μCi/ml	3×10^{-8} μCi/ml[a]	0.003
	Granite	3×10^{-10} μCi/ml	3×10^{-8} μCi/ml[a]	0.01
	Basalt	5×10^{-11} μCi/ml	3×10^{-8} μCi/ml[a]	0.002
^{220}Rn (from Rock)	Salt	3×10^{-14} μCi/ml	3×10^{-7} μCi/ml[a]	1×10^{-7}
	Shale	7×10^{-11} μCi/ml	3×10^{-7} μCi/ml[a]	0.0002
	Granite	4×10^{-10} μCi/ml	3×10^{-7} μCi/ml[a]	0.001
	Basalt	4×10^{-11} μCi/ml	3×10^{-7} μCi/ml[a]	0.0001
H_2[d]		37,000 ppm	40,000 ppm[e]	0.9
Diesel Exhaust				
CO		2 ppm	50 ppm[b]	0.04
Nitrogen oxides (as NO)		17 ppm	25 ppm[b]	0.7
HCHO (aldehydes)		.04 ppm	2 ppm[b]	0.02
Particulates		.7 mg/m^3	5 mg/m^3[b]	0.14
Coal-Fired Boiler Emissions				
SO_2		0.6 lb/10^6 Btu	1.2 lb/10^{6}Btu[c]	0.5
NO_x		0.2 lb/10^6 Btu	0.7 lb/10^{6}Btu[c]	0.3
Particulates		0.03 lb/10^6 Btu	0.1 lb/10^{6}Btu[c]	0.3

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[a] Guidelines from 10CFR20, Appendix B.

[b] Guidelines from the American Conference of Industrial Hygienists, Threshold Limit Values for Chemical Substances and Physical Agents in the Workroom Environment, 1976.

[c] Guidelines from 40CFR60, "Standards for Performance of New Stationary Sources."

[d] Maximum occurs for the case of a salt repository.

[e] Lower Combustible limit from Handbook of Chemistry and Physics, 50th ed.

TABLE 1-2

EMISSION FACTORS FOR COAL COMBUSTION

Pollutant	Average Emission Factor
Oxides of Nitrogen	20 lb/ton of coal burned
Oxides of Sulfur	(38 times sulfur%) lb/ton of coal burned
Particulates	(15 times ash%) lb/ton of coal burned

TABLE 1-3

AVERAGE EFFICIENCIES OF FLUE GAS CONTROL EQUIPMENT

Emission	Control Technique	Efficiency(%)
Particulate[a]	Simple Cyclone	65.3
	Spray Tower	94.5
	Venturi Scrubber	99.5
SO_2[b]	Lime and Limestone Scrubbing	80-85 (plus 99% particulate removal)
	Magnesium Oxide Scrubbing	91 (plus 90% particulate removal)
	Alkali Scrubbing	90
NO_x[b,c]	Flue Gas Recirculation	60-90
	Absorption	30

[a] Source: NAPCA Compilation of Air Pollutant Emission Factors, AP-42. Washington, D.C. HEW, 1968.

[b] Source: Work, K. and Warner, C., Air Pollution - Its Origin and Control, Dun-Donnelley Publishers, 1976.

[c] Source: Bienstock, D., "Control of NOX Emissions in Coal Firing," 1972 Industrial Coal Conference, Purdue University, October, 1972.

TABLE 1-4

ESTIMATED RADON RELEASE RATES FROM MINING OPERATIONS

Medium	Peak Mining Rates (ton/day)*	Total Releases (mCi/day)	
		Rn-220	Rn-222
Salt	8000	1.6×10^{-3}	2.2×10^{-3}
Shale	3000	3.3	3.8
Granite	16000	27	24
Basalt	15000	3.3	2.8

*From Y/OWI/TM-36/8, -36/10, -36/12, -36/14 for salt, shale, granite, and basalt respectively.

2.0 RADIOACTIVE EFFLUENTS FROM NORMAL WASTE HANDLING

The purpose of this section is to present the assumptions and methodologies used in assessing the radioactive airborne effluents that could arise at a nuclear waste repository during normal routine operations. Both OWI and BPNL waste descriptions are considered here. Although analyses on both data sets are similar, differences in the assumptions used are pointed out in the following sections.

2.1 BACKGROUND

Releases are assumed to occur during two phases of routine operation. The first could be during the handling of waste containers, and the second may be while the container is securely stored in a particular location within the mine. Two mechanisms are considered to be responsible for radioactive releases during each of the above-mentioned phases of operation. One is the release of container surface contamination by resuspension and transfer of particulates to the ventilation system or to other surfaces in the area. The other is the release of internal activity through "pinhole" leaks in pressurized waste containers.

During handling, surface contamination on waste containers may become resuspended and be transferred to the surrounding air. The magnitude of this release would depend on the maximum allowed surface contamination for receipt at the repository and particular handling procedures. Pinhole leaks in waste canisters may result in release of internal radioactive particulates and gases to the working environment. The amount and composition of contaminants released will depend on the waste type, size of leak involved, and the container type.

During the storage phase of normal operations, transfer of surface contamination from canisters and drums would not occur. The only normal release considered during storage was leakage from "pinholes" in emplaced canisters before the rooms are backfilled. Radioactive releases of this type would be from pressurized canisters of HLW, spent fuel, ILW, and cladding waste. "Pinhole" leaks in the waste containers could arise from handling procedures, corrosion, and/or thermal effects. Seepage of these radioactive contaminants from the individual storage cavities would then result in release of contaminants to the mine ventilation air.

The radioactive releases under consideration are those arising from all possible waste forms: HLW (vitrified and calcined), spent fuel, ILW, cladding waste, and LLW. Except for the case of spent fuel, individual radionuclides were not considered. Rather, effluents were classified as particulates whose composition was reflected by the particular waste source terms. Breakdowns according to β-γ or α-activity were included where appropriate for use in comparison to regulated maximum permissible concentration values. In the case of spent fuel, three volatile radionuclides were of concern along with the particulates. These are: H-3, C-14, and Kr-85, which because of their half-lives (12.3 yr, 10.3 yr, and 5730 yr, respectively) are still significant at the age of receipt (10 yrs after discharge) whereas all other volatile radionuclides have decayed to negligible amounts.

It is assumed that all releases during handling and storage will be transported through the ventilation and exhaust system. As described in the GEIS,[1] ventilation air from the canistered waste surface facility will pass through two sets of HEPA filters having an assumed combined decontamination factor (DF) of 10^6 for particulates.[2,3] Subsurface ventilation air will be filtered through two sets of HEPA filters, having an assumed combined DF of 10^6 before release through the main stack. Ventilation air for the LLW facility also passes through two sets of HEPA filters prior to release through roof vents on the LLW building.

Estimates of radioactive releases from normal facility operations were developed for the generic salt repository design for both OWI and BPNL waste forms. It is not anticipated that the type of geologic formation would significantly affect the magnitude of these releases. Variations of no more than a few percent could occur due to differences in waste densities, and subsequently in canister and drum receipt rates for the different rock types. Variations also occur due to the differences between the OWI and BPNL waste forms, specifically the internal activity and receipt rates.

2.2 RELEASE MECHANISMS

2.2.1 Surface Activity

This release mechanism deals with the resuspension of transferrable surface contamination on waste containers. It is significant only during handling when the canister is likely to be jolted or jarred while being transferred by either bridge crane or forklift. While in storage, the container is stationary and out of direct ventilation flow (once the room is full); under these static conditions, surface contamination is not expected to be released.

During handling, it has been assumed that surface activity is released at a rate of 10 percent per hour. The amount available for release was assumed to be the maximum allowable transferrable surface contamination as specified by acceptance criteria. These criteria as described in the GEIS,[1] are:

- Beta - Gamma: 10,000 dis/min/100cm^2
- Alpha: 300 dis/min/100 cm^2

The release rate from an individual canister or drum is computed by the following relation

$$R = S_A \times A \times 10\% \times H$$

where R = release rate (Ci/can)
S_A = surface contamination (dis/min/cm^2)
A = surface area of canister (cm^2)
H = assumed time the canister is handled (1 hour)

The yearly total release of activity due to this mechanism is:

$$Y = R \times C$$

where Y = Yearly release (Ci/yr)
C = canister receipt rate (cans/yr)

2.2.1.1 Sample Calculations for Surface Release

Consider the case:

- OWI waste (Data in reference 4)
- ILW canisters from Total Recycle
- Dimensions - 1' diameter x 10' long ($3.1\text{x}10^4$ cm^2 area)
- Highest yearly receipt rate occurring in the year 2006 (20790 cans/yr)

For β-γ (S_A = 10,000 dis/min/100 cm^2)

$$R = 10{,}000\ \text{dis/min/100cm}^2(3.1\text{x}10^4\text{cm}^2\text{/can})(10\%\text{/hr})\text{x}$$
$$(4.5\text{x}10^{-13}\ \text{Ci/dis/min})(1\ \text{hr.})$$
$$R = 1.4\ \text{x}\ 10^{-7}\ \text{Ci/can}$$
$$Y = 1.4\ \text{x}\ 10^{-7}\ \text{Ci/can}\ (20787\ \text{cans/yr})$$
$$Y = 2.9\ \text{x}\ 10^{-3}\ \text{Ci/yr}$$

This effluent is filtered through two banks of HEPA filters with a DF = 10^6. The filtered yearly release (Y_F) is then:

$$Y_F = 2.9\ \text{x}\ 10^{-9}\ \text{Ci/yr}$$

This analysis performed on all the waste containers for each cycle for any one year will result in the total contribution of surface activity release to the yearly airborne releases from the entire repository.

2.2.2 Internal Leakage

Normal leakage of internal radioactivity is assumed to result from a small percentage of containers having minute holes, hairline fractures, seam weld leaks, etc. which develop during waste packaging procedures, transportation, handling at the repository, or storage conditions. HLW, spent fuel, ILW, and cladding waste canisters all contain a 5 psig helium backfill to provide a controlled atmosphere for the waste. This overpressure provides a motive force for possible radioactive release to the surroundings. The LLW drums being handled are not pressurized, and are of such low total activities that only major leaks (i.e., drum rupture) would release any significant amount of radioactive contaminants to the working environment. Hence, internal leakage from LLW is not considered in this chapter, but is covered under operational accidents (Section 5.3 of the GEIS[1] and Section 3.0 of this volume).

The repository has been designed to accept leaking waste containers. As described in Section 4.2.2 of the GEIS,[1] upon receipt at the repository canisters will be checked for possible leakage, and those that are found defective will be overpacked. While the exact instrumentation for detecting these leaks has not been specified, certainly one method that could be used is common helium leak detection. These detectors can be extremely sensitive to helium concentrations in air, and, because of the helium backfill within the canisters, they could provide a relatively easy method of detecting possible radioactive releases accompanying the escaping helium.

As described in the Preliminary Safety Analysis Report, Federal Repository, Kansas, the specification for acceptance of a waste canister for this repository design was that the container be in a "leakproof" condition.[5] A canister was considered in this condition when it exhibited a leak rate of $\leq 10^{-7}$ atm-cm^3/sec, as measured with a helium detector. This leak rate corresponds to the following volumetric flow rate through minute "pinholes" in the canister.

Pressure Differential = 5 psig (.34 atm)

$$\text{Leak Rate} = \frac{10^{-7}\ \text{atm cm}^3/\text{sec}}{.34\ \text{atm}} = 2.9\text{x}10^{-7}\ \text{cm}^3/\text{sec}$$

For a conservative scenario it was assumed that the leak rate be about 3000 times the detectable limit. The maximum expected equivalent "pinhole" dimensions to support a leak rate of this magnitude was then calculated using Poiseuilles equation.[6]

Poiseuille stated that:

$$\frac{DV}{dt} = \frac{\pi R^4}{16L\mu} \frac{(P_i^2-P_o^2)}{P_o}$$

where Dv/dt - leak rate (cm^3/sec)
R - pinhole radius (cm)
L - canister wall thickness (cm)
P_i - internal canister pressure ($dynes/cm^2$)
P_o - external pressure ($dynes/cm^2$)
μ - viscosity of helium ($dynes\text{-}sec/cm^2$)

For a leak rate of $2.9x10^{-7}x(3000) = 9x10^{-4}$ cm^3/sec, the hole size was calculated to be:

$DV/dt = 9x10^{-4}$ $cm^3/sec.$
$L = .95$ cm
$\mu = 1.94x10^{-4}$ $dynes\text{-}sec/cm^2$
$P_i = 1.4x10^6$ $dynes/cm^2$
$P_o = 1.0x10^6$ $dynes/cm^2$
$R \cong 10^{-3}$ cm

2.2.2.1 Sample Calculations for Leak Rate

The values on Table 2-1 were calculated using this method and adjusting properties to expected canister temperatures during handling.

HLW (175°C)
$P_i = 2.0x10^6$ $dynes/cm^2$
$\mu = 2.57x10^{-4}$ $dynes\text{-}sec/cm^2$
$DV/dt \cong 0.15$ cm^3/min

Spent Fuel (80°C)
$P_i = 1.6x10^6$ $dynes/cm^2$
$\mu = 2.20x10^{-4}$ $dynes\text{-}sec/cm^2$
$DV/dt \cong 0.085$ cm^3/min

Cladding, ILW (25°C)

P_i = 1.4×10^6 dynes/cm^2

μ = 1.94×10^{-4} dynes-sec/cm^2

DV/dt ≅ 0.05 cm^3/min

Values on Table 2-2 (BPNL waste) were calculated similarly; however, differences arise from varying container wall thicknesses.

2.2.2.2 Sample Calculations for Release of Internal Activity

Other factors which determine the magnitude of releases from canister leakage are the concentration of suspended radionuclides in the helium atmosphere (g/cm^3) and the specific activity of the waste (Ci/g). Since these factors are mainly waste dependent, the OWI and BPNL differences are noted (Sections 2.3 and 2.4).

Consider the case:

- Calcined HLW from Total Recycle (OWI)
- Assumed specific activity of 5 Ci/gram
- Assumed airborne particulates of 1 mg/cm^3

$$\text{Release Rate} = 1\ \text{mg/cm}^3(5\times10^{-3}\ \text{Ci/mg})(.15\ \text{cm}^3/\text{min}) = 7.5\times10^{-4}\ \text{Ci/min}$$

In terms of β-γ and α releases, ratios of α-actinides to all particulates were used from reference 4. For this example:

$$\beta\text{-}\gamma = 6.8\times10^{-4}\ \text{Ci/min}$$

$$\alpha = 7.0\times10^{-5}\ \text{Ci/min}$$

2.3 OWI WASTE

2.3.1 Assumed Waste Characteristics

2.3.1.1 HLW Glass

Due to the high stability of glass over the short period of repository operation,[7-10] it is assumed that there will be negligible airborne activity within the void volume of an HLW glass canister.

2.3.1.2 HLW Calcine

The possibility exists that small particles, or fines, could become dislodged from the calcine matrix and become suspended in the helium atmosphere of the canister. As a conservative estimate, it has been assumed that the concentration of these particles could approach 0.1 mg/cm^3 from jolting and vibration of the canister during handling operations. During storage a much lower concentration would be expected due to settling of larger particles, and a concentration of 1 μg/cm^3 was therefore assumed. The specific activity of calcined HLW, as determined from source term tables and assuming a density of 81 lb/ft^3 for calcined waste,[4] is approximately 5 Ci/g.

2.3.1.3 ILW

Specific source terms and waste composition for ILW were not available due to the variability of possible contents. As a conservative assumption, the same concentration of particles within the void volume of calcined HLW was assumed for ILW; 0.1 mg/cm^3 during handling procedures and 1 μg/cm^3 during storage. In addition, although the total activity of ILW is expected to be about 10^4 less than that of HLW, a conservative specific activity of 0.7 Ci/g was assumed for this analysis.

2.3.1.4 Cladding Waste

The majority of the activity within the cladding waste canister consists of Fe-55, Co-60, and Ni-63.[4] Most of this activity would be found within the structural matrix of the Zircaloy and be unavailable for direct release to the canister atmosphere. However, as a conservative estimate, it has been assumed that 0.01 percent of the total radioactivity of the cladding waste canister becomes airborne in the void volume as particulates and is available for release.

2.3.1.5 Spent Fuel

In the case of spent fuel canisters, the spent fuel is encased in Zircaloy cladding which is surrounded by a helium atmosphere. As a conservative estimate it is assumed that all the significant volatiles contained in the spent fuel at discharge from the reactor are present in the spent fuel upon receipt at the repository. Also, the spent fuel was assumed to be from a PWR since the source strengths of the nuclides are higher than in BWR's and represent the worst case (Part I, Tables A-1 and A-2 of reference 4). Assumed amounts in the void volume are 10 percent H-3, 50 percent C-14, 50 percent Kr-85, and 0.1 percent of the solids originally in the spent fuel (detailed in Section 3.1.1). For all spent fuel releases, 0.5 percent of the fuel rods are conservatively assumed to be leaking within the canister. This number was based on an NRCrecommended value of 0.25 percent for failures for Zircaloy-clad fuels and 0.1 percent failures for stainless-steel-clad fuels.[11]

2.3.1.6 LLW

Low-level waste drums are not pressurized with helium and thus would not experience any leakage of internal atmosphere. Even though suspended solids could be within the drum, no motive force is available for their release. Surface activity, on the other hand, is assumed to be present on drums at the maximum acceptable limit and is the only cause for contaminated airborne effluents from the low-level waste building.

2.3.2 Repository Operational Specifications

Handling procedures have an effect on the magnitude of normal releases in that the effluent is dependent on the number of exposed cans in an area at any one time, as well as on the ventilation specifications for that area. These factors can be cycle or media dependent and are reflected in the results.

2.3.2.1 Canistered Waste Building

The total radioactive release from the canistered waste building consists of both resuspension of surface activity and internal leakage of waste canisters. Surface activity releases are derived from the highest annual receipt rates until repository closing (anywhere from 2006-2008, depending upon the fuel cycle) for HLW, ILW, and cladding waste for Cycles I and III, and spent fuel canisters for Cycle II.[4] This annual rate is further delineated in terms of canisters per hour handled, based on a 250 day work year and a 3-shift-24 hour work day.

The repository design for overpack facilities was based on a one canister per day need. This corresponds to at least 1 percent of all canisters received that leaked above the detectable limit. Therefore, as a conservative estimate, it was assumed that 2 canisters per day were found to be leaking above the detectable limit. This leak was assumed to occur for a period of one hour prior to overpacking, and, as a conservative estimate, the canister that leaked was assumed to contain HLW (calcined) for Cycles I and III, and PWR spent fuel for Cycle II.

Releases from handling and leakage would be carried off by the ventilation air with passage through two sets of HEPA filters (10^6DF) prior to release to the atmosphere. The ventilation flow rate for all three cycles in the canistered waste building is approximately 91,000 cfm.[1]

2.3.2.2 Low-Level Waste Building

The major release pathway for the LLW building was considered to be that arising from resuspension of surface activity. Estimates for this release were based on the highest annual receipt rate for LLW drums during operation of the repository (reference 4). Releases are assumed to be carried off by the ventilation system, which has flow rates of approximately 12,000 cfm for Cycle I and approximately 8,000 cfm for Cycles II and III.[1] The ventilation air will pass through two sets of HEPA filters (10^6DF) prior to release to the atmosphere.

2.3.2.3 Mine

Releases from storage activities in the mine will consist of resuspension of surface activity during handling of waste containers (both canisters and drums) and leakage from canistered waste after emplacement in storage rooms. The surface activity was treated the same as before, with the release dependent upon the highest annual receipt rates.

Internal activity releases were assumed to occur through "pinhole" leaks in stored waste canisters. During retrievability (first five years of repository operation), it was conservatively assumed that 0.1 percent of all canisters stored up until that time are leaking at the maximum assumed rate, at any one time. In addition, no consideration was taken of decay of waste during that time; hence, all waste was assumed to remain at its receipt activity.

After leaking from the canister, particulates and gases could migrate around the storage plug, into the storage room, and then into ventilation air. It was assumed that, due to the complexity of the path required for escape to the room, only 10 percent of the particulates would be present in the mine ventilation. The ventilation flow rates for mine placement operations is assumed to be about 250,000 cfm.[4]

2.3.3 Repository Release Estimates

Table 2-3 presents the total estimated airborne radioactive releases from normal repository operation, computed according to the assumptions and methodology previously presented. From this table it is obvious that the magnitude of radioactive releases from such a generic repository are extremely small; the total particulate release for any cycle being no greater than 3 μCi/yr and the greatest gaseous release (Kr-85) from Cycle II being no greater than 7 Ci/yr.

The estimated airborne concentrations, after HEPA filtration, arising from each separate repository facility, are given in Table 2-4. The main stack release values are a combination of releases from the canistered waste building and mine activities.

2.4 BPNL WASTE

Differences in normal effluents arise between OWI and BPNL waste sets being assigned to the same repository design. The data are different with respect to receipt rates, source terms, and, to a lesser degree, container designs.

2.4.1 Assumed Waste Characteristics

2.4.1.1 HLW

All BPNL high-level waste is to be stored in the vitrified form. As with OWI vitrified HLW, no releases are expected to result from internal leakage of this waste.

2.4.1.2 Canistered ILW

Canisters of ILW will contain failed equipment from various steps in the supporting nuclear fuel cycle. This metallic waste was treated in the same manner as the Zircaloy cladding wastes described previously (Section 2.3.1.4). A conservative estimate that 0.01 percent of the total radioactivity would become airborne within the void volume was used in these calculations.

2.4.1.3 Cladding Waste

The same assumptions and modes of release used for OWI cladding waste (Section 2.3.1.4) were used for BPNL waste.

2.4.1.4 Spent Fuel

The same assumptions and modes of release used for OWI spent fuel canisters (Section 2.3.1.5) were used for the BPNL analysis.

2.4.1.5 ILW and LLW Drums and LLW Boxes

These waste containers have no helium backfill and therefore experience no leakage of internal activity. The surfaces are assumed to be contaminated to the maximum acceptable limits, and the mode of release was identical to that used for OWI waste.

2.4.2 Repository Operational Specifications

The same operational specifications described in Section 2.2.3.2 for OWI apply for the BPNL case. The only differences arise in the source of data (i.e. receipt rates) and ventilation flow rates. Ventilation for the BPNL waste repository is assumed to be broken down into the following:[1]

Canistered-Waste Building (Cycles I and III)	93,000 cfm
Canistered-Waste Building (Cycle II)	136,000 cfm
Low-Level-Waste Building	32,000 cfm
Mine (placement)	250,000 cfm

These flow rates are for controlled areas only and do not represent total building ventilation.

2.4.3 Repository Release Estimates

The total estimated airborne radioactive effluents from normal operation of a repository storing BPNL waste are presented in Tables 2-5 and 2-6. Table 2-5 lists the releases in terms of maximum yearly rates (Ci/yr) and Table 2-6 shows the estimated contaminant concentrations in ventilation streams after filtration. These resulting values compare generally with estimates for the OWI waste design, comparing the glass HLW and spent fuel options. The slight differences in total releases are the result of variations in source terms, receipt rates, and canister design considerations as previously described.

2.5 ATMOSPHERIC DISPERSION OF NORMAL RELEASES

Regulations have been established by the Nuclear Regulatory Commission concerning radioactive releases to unrestricted areas in the vicinity of nuclear facilities (10CFR20).[12] The estimated release rates presented in the preceding sections are for release from the 100-foot main ventilation exhaust stack for mine and canistered waste building effluents, and from a low-level waste building roof vent. To compare these effluents with the prescribed limits, atmospheric dispersion was applied to determine ground-level concentrations at the facility fenceline. The following sections discuss treatment of this dispersion in a generic manner.

2.5.1 Meteorology

The meteorological assumption used to calculate dilution and dispersion of radionuclides assumed to be released during routine operation of the generic waste repository were adapted from those deveoped by the Nuclear Regulatory Commission for Regulatory Guide 1.3.[13] The atmospheric diffusion model described in this document was developed for accidental releases from stacks at BWR-generating stations.

The basic equation for atmospheric diffusion of gases from an elevated release used in this report is:

$$\chi/Q = \frac{1}{\pi u \sigma_y \sigma_z} \exp\left(\frac{-h^2}{2\sigma_z^2}\right)$$

Where

χ = the short term average centerline value of the ground level concentration (Ci/m^3)

Q = amount of material released (Ci/sec)

u = average wind speed at effective stack height (m/sec)

σ_y = the horizontal standard deviation of the plume (m)

σ_z = the vertical standard deviation of the plume (m)

h = effective stack height (m)

This equation is based on the Gaussian plume model with dispersion patterns developed by Pasquill[14] and Gifford.[15] For time periods of release greater than 8 hours, the plume from an elevated release should be assumed to meander and spread uniformly over a 22.5° sector. The resultant equation is:

$$\chi/Q = \frac{2.032}{\sigma_z u x} \exp(-h^2/2\sigma_z^2)$$

where

x = distance from the release point (m). Other variables are as defined in the previous equation.

The magnitude of the diffusion factor, χ/Q, is highly dependent on atmospheric conditions prevalent for the period of time following release. Although there exists a wide range of possible atmospheric conditions, certain generalizations can be offered by using Pasquill stability class conditions. Under the Pasquill system, six classifications of atmospheric conditions are defined, ranging from Class A (unstable) to Class F (moderately stable). Table 2-7 contains a brief description of the wind and solar conditions which each of these different classes represent. The diffusion parameters, σ_y and σ_z, have been calculated as functions of these stability classes and downwind distances from the source. Graphs of these functions are shown in Figures 2-1 and 2-2.

The dispersion model described previously has been used to develop estimates of χ/Q for a variety of possible atmospheric conditions as a function of downwind distance and effective stack height. Estimated χ/Q values have been calculated for an 8 to 24-hour period following a release using an envelope of Pasquill stability categories (Figure 2-3). Windspeed was assumed to be 1 meter/sec, with variable direction within a 22.5° sector. The effective height of release was assumed to be 50 meters. This assumption reflects the 100-foot (30.5 meters) physical stack height and momentum effect from the discharged plume (up to 1,590,000 cfm). A maximum χ/Q value of approximately 1×10^{-4} sec/m^3 was obtained at a downwind distance of about 250 meters. According to the NRC, this type of atmospheric condition modeling is appropriate for use in estimating potential off-site exposures until adequate meteorological data can be obtained for the specific site. In some cases, available information such as topography and geographical location may dictate the use of a more restrictive model to ensure a conservative estimate.

To determine conservative or "worst case" dispersion conditions, the atmospheric condition known as fumigation was considered. Fumigation occurs when a layer of unstable air is trapped below an elevated inversion layer. Effluent releases from a stack just below this lid then become mixed in the shallow unstable layer next to the ground. This condition can give rise to the greatest ground-level concentrations observed in the neighborhood of a stack. Generally this condition will last for only 30 minutes or so, but it has been observed to persist for many hours and cover considerable distances from the source. Estimated χ/Q values have been determined for this worst-case condition and are presented as a function of effective stack height and distance from release point in Figure 2-4. Diffusion factors derived from Figures 2-3 and 2-4, for normal atmospheric conditions and fumigation conditions at two ground-level positions, are summarized in Table 2-8.

2.5.2 Ground-Level Concentrations of Radioactive Effluents Arising from Normal Facility Operations

Preliminary design considerations for the waste repository indicate that release of radioactive effluents will occur from the main ventilation stack and the LLW building vent. The main stack is assumed to have an effective height of 50 meters (physical height is 30 meters) and to be located 400 meters from the nearest exclusion fence. Maximum and fenceline ground-level concentrations of effluents arising from this stack were determined for the two meteorological conditions under consideration. This was accomplished by multiplying the appropriate diffusion factor (Table 2-8) by the stack release rates (Tables 2-3 and 2-5). Comparisons were then made with the maximum permissible concentration (MPC) limits set forth in 10CFR20[12] (Tables 2-9 and 2-10).

For either atmospheric condition, the maximum effluent concentrations occurred within the repository fenceline. The concentrations occurring at the exclusion fence are compared to Table II, Appendix B of 10CFR20 for the individual radionuclides under consideration. In the case of the generalized particulate waste form, where the identity and/or concentration of any radionuclide in the mixture is not known, the limiting value as given in footnote 2 of Table II was taken to be $2\text{x}10^{-14}$ μCi/ml for concentrations in air. In addition, no credit has been taken for particulate deposition from the effluent plume, although this could significantly reduce these off-site concentrations.

As can be seen in Tables 2-9 and 2-10, the estimated ground-level concentrations of radioactive effluents from normal facility operation at the fenceline of the OWI and BPNL repository designs fall well below the limits for release to an unrestricted area given in 10CFR20. Even the maximum concentrations (both found in restricted areas) were determined to be below these limits. Hence, it is assumed that no significant consequences would arise from these normal releases.

REFERENCES (Chapter 2)

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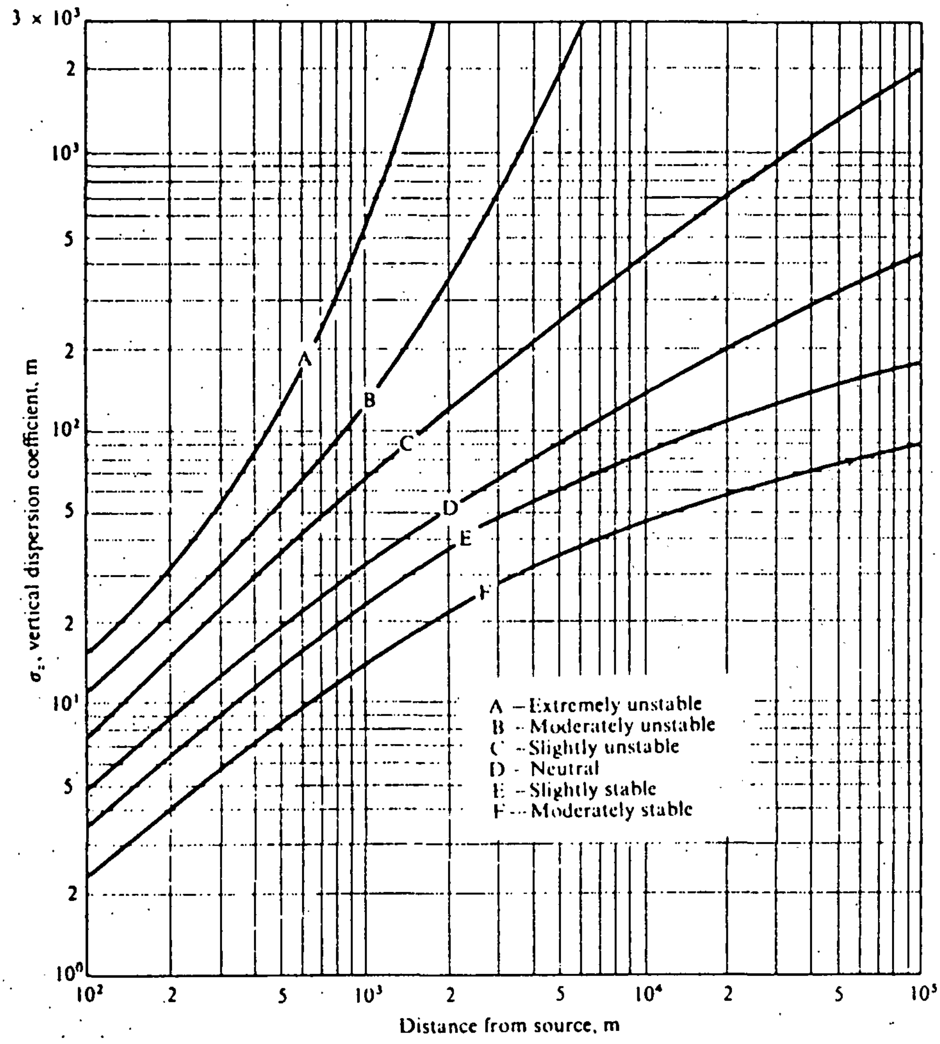


Figure 2-1 Vertical dispersion coefficient σ_Z as a function of distance from source for the various Pasquill conditions (from D.H. Slade, *op. cit.*, Reference 16).

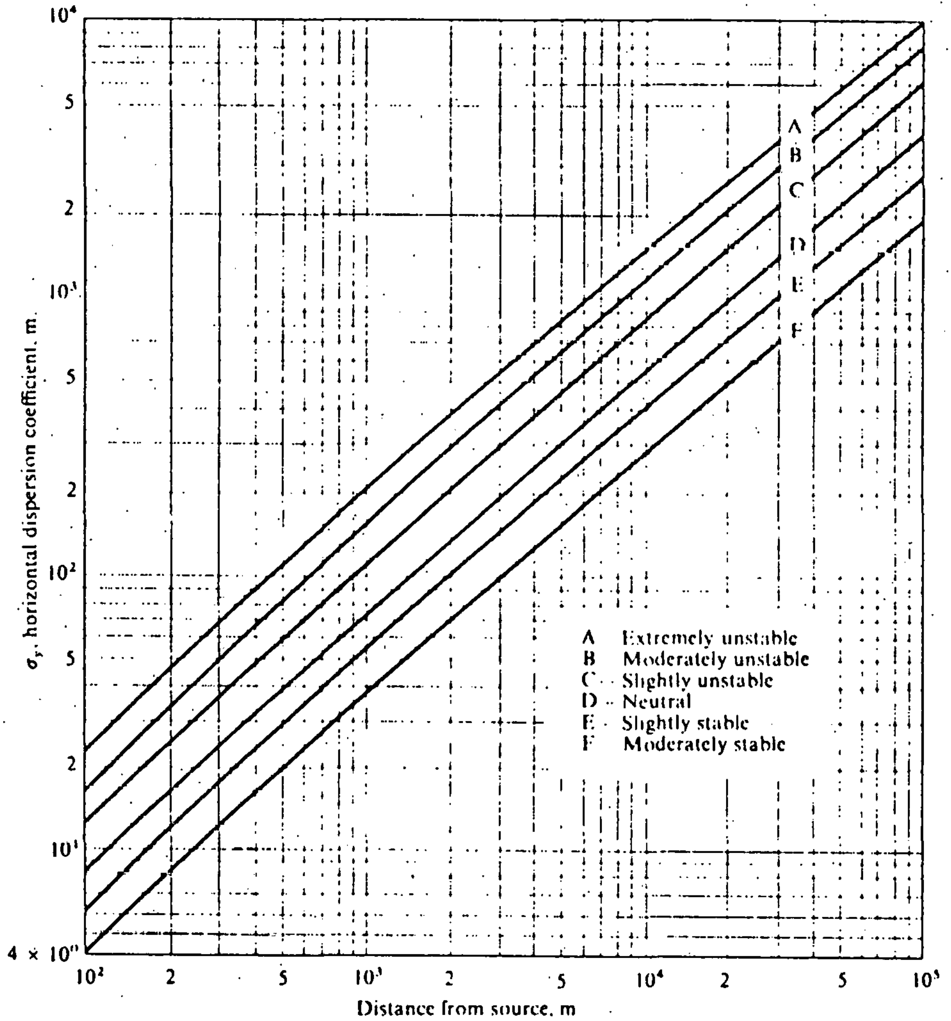
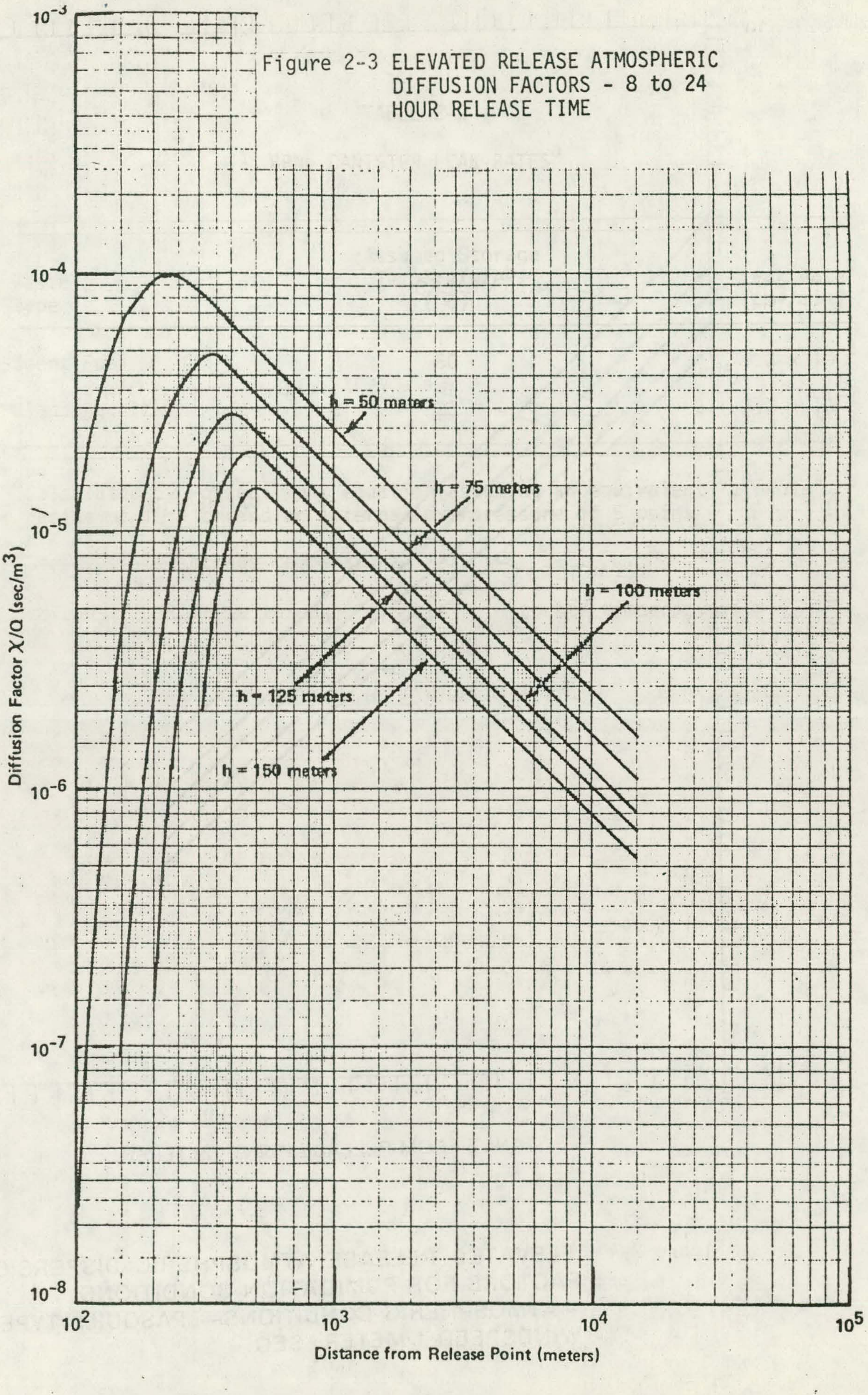


Figure 2-2 Horizontal dispersion coefficient σ_y as a function of distance from source for the various Pasquill conditions (from D.H. Slade, *op cit.*, Reference 16).

Figure 2-3 ELEVATED RELEASE ATMOSPHERIC DIFFUSION FACTORS - 8 to 24 HOUR RELEASE TIME



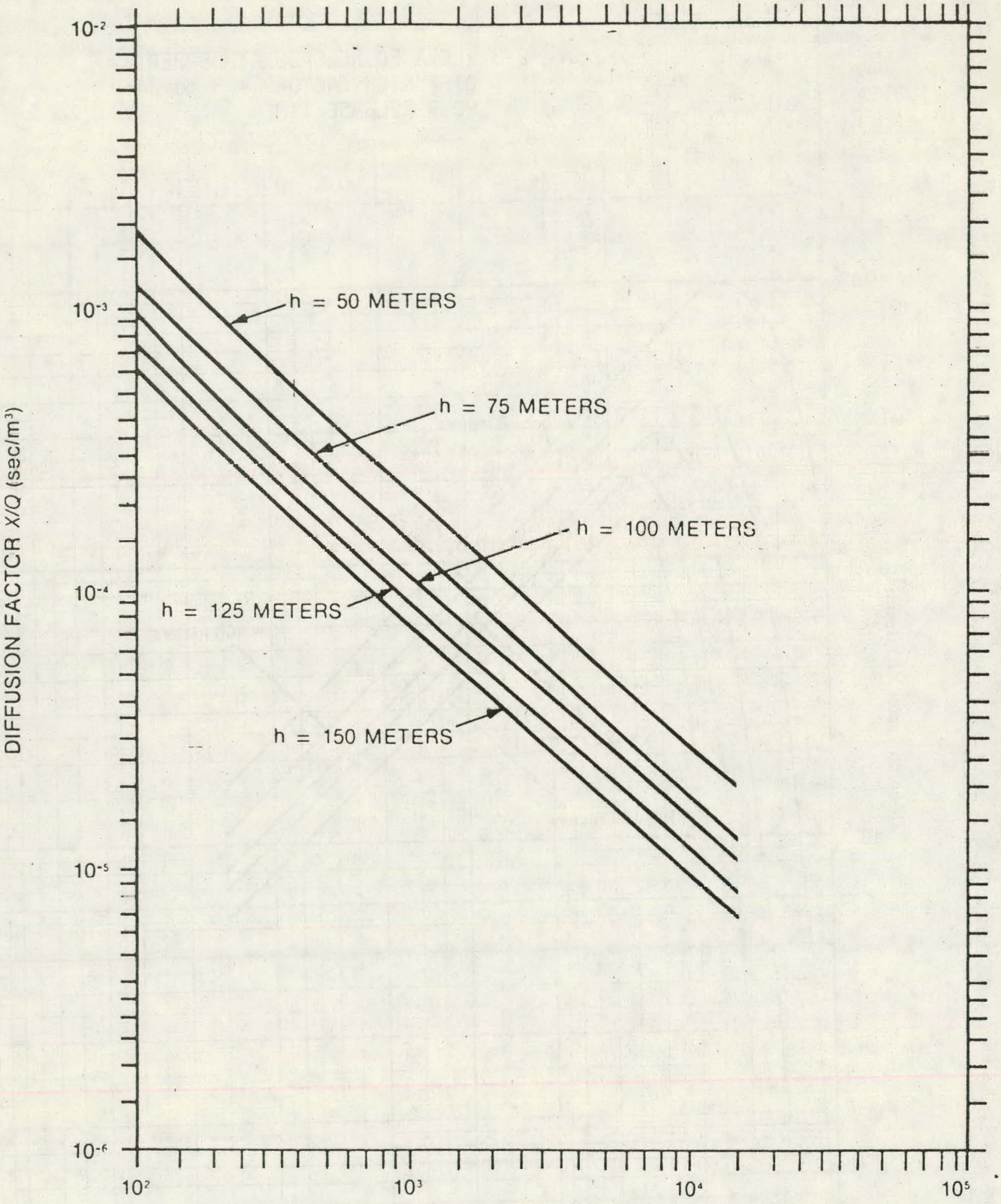


Figure 2-4 **ELEVATED RELEASE ATMOSPHERIC DISPERSION FACTORS FOR FUMIGATION CONDITIONS —ATMOSPHERIC CONDITIONS— PASQUILL TYPE F WINDSPEED 1 METER / SEC**

TABLE 2-1

OWI CANISTER LEAK RATES[a]

Waste Type	Assumed Storage Temperature[b] (°C)	Leak Rate[c] (cm^3/min)
HLW	175	1.5×10^{-1}
Spent Fuel	80	8.5×10^{-2}
Cladding, ILW	25	5.0×10^{-2}

[a] Calculated by Poiseuille's equation assuming an equivalent "pinhole" radius of 10^{-3} cm and an internal overpressure of 5 psig.

[b] Steady-state storage temperature

[c] Volumetric flowrate through "pinhole" at storage temperatures.

TABLE 2-2

BPNL CANISTER LEAK RATES[a]

Waste Type	Assumed Storage Temperature[b] (°C)	Leak Rate[c] (cm^3/min)
Spent Fuel	80	1.3×10^{-1}
Cladding, ILW	25	3.7×10^{-2}

[a] Calculated by Poiseuille's equation assuming an equivalent "pinhole" radius of 10^{-3} cm and an internal overpressure of 5 psig.

[b] Steady-state storage temperature.

[c] Volumetric flowrate through "pinhole" at storage temperatures.

TABLE 2-3

ESTIMATED TOTAL MAXIMUM AIRBORNE RELEASES OF RADIOACTIVE MATERIAL FROM NORMAL REPOSITORY OPERATION - OWI WASTE

Release Point	Total Release Rate (Ci/yr.)		
	Fuel Cycle		
	I	II	III
Main Stack Release			
Particulates[a] $(\beta-\gamma)$	3×10^{-6}		3×10^{-6}
(α)	2×10^{-7}		7×10^{-8}
Particulates[b] $(\beta-\gamma)$	3×10^{-7}		3×10^{-7}
(α)	3×10^{-9}		1×10^{-9}
Particulates[c] $(\beta-\gamma)$		2×10^{-7}	
(α)		6×10^{-9}	
H-3		1×10^{-1}	
C-14		1×10^{-4}	
Kr-85		7.0	
LLW Building Vent			
Particulates $(\beta-\gamma)$	7×10^{-9}	3×10^{-10}	7×10^{-10}
(α)	2×10^{-10}		2×10^{-11}

[a] Releases from calcined HLW, ILW, Cladding Waste, and LLW handling and storage.

[b] Releases from vitrified HLW, ILW, Cladding Waste, and LLW handling and storage.

[c] Releases from spent fuel and LLW handling and storage.

TABLE 2-4

ESTIMATED MAXIMUM AIRBORNE CONCENTRATIONS OF RADIOACTIVE MATERIALS FROM SURFACE FACILITIES AND MINE - OWI WASTE

Source of Release		Airborne Concentrations[d] (μCi/ml) Fuel Cycle I	Fuel Cycle II	Fuel Cycle III
Canistered Waste Building[e]				
Particulates[a]	(β-γ)	2×10^{-15}		2×10^{-15}
	(α)	2×10^{-16}		7×10^{-17}
Particulates[b]	(β-γ)	2×10^{-17}		2×10^{-17}
	(α)	3×10^{-20}		1×10^{-19}
Particulates[c]	(β-γ)		2×10^{-17}	
	(α)		3×10^{-19}	
H-3			6×10^{-13}	
C-14			1×10^{-15}	
Kr-85			3×10^{-11}	
Mine[f]				
Particulates	(β-γ)	1×10^{-16}		1×10^{-16}
	(α)	3×10^{-18}		1×10^{-18}
Particulates	(β-γ)	1×10^{-16}		1×10^{-16}
	(α)	3×10^{-18}		3×10^{-19}
Particulates	(β-γ)		3×10^{-17}	
	(α)		7×10^{-19}	
H-3			3×10^{-11}	
C-14			3×10^{-14}	
Kr-85			3×10^{-9}	
Main Stack Release[g]				
Particulates[a]	(β-γ)	7×10^{-16}		7×10^{-16}
	(α)	7×10^{-17}		2×10^{-17}
Particulates[b]	(β-γ)	7×10^{-17}		7×10^{-17}
	(α)	1×10^{-18}		3×10^{-19}
Particulates[c]	(β-γ)		4×10^{-17}	
	(α)		6×10^{-19}	
H-3			3×10^{-11}	
C-14			3×10^{-14}	
Kr-85			2×10^{-9}	
Low-Level Waste Building[h]				
Particulates	(β-γ)	7×10^{-17}	3×10^{-18}	7×10^{-18}
	(α)	2×10^{-18}		2×10^{-19}

Note: Footnotes listed on following page.

TABLE 2-4 (Footnotes)

[a] Releases from calcined HLW, ILW, Cladding Waste, and LLW.

[b] Releases from glass HLW, ILW, Cladding Waste, and LLW.

[c] Releases from spent fuel and LLW.

[d] Concentrations occurring after HEPA filtration (DF = 10^6).

[e] Canistered Waste Building ventilation flowrate is approximately 90,000 cfm.

[f] Mine ventilation flowrate for placement operation is approximately 250,000 cfm.

[g] Main stack flow is a combination of Canistered Waste Building and Mine, with a rate of approximately 341,000 cfm.

[h] LLW Building ventilation flowrate is approximately 12,000 cfm for Cycle I and 8,000 cfm for Cycles II and III.

TABLE 2-5

ESTIMATED ANNUAL MAXIMUM AIRBORNE RELEASES OF RADIOACTIVE MATERIALS FROM NORMAL REPOSITORY OPERATION--BPNL WASTE

Release Point	Total Release Rates (Ci/yr.)		
	Fuel Cycle		
	I	II	III
Main Stack Release[a]			
Particulates (β-γ)	6×10^{-8}	6×10^{-7}	6×10^{-8}
(α)	1×10^{-9}	6×10^{-9}	7×10^{-11}
H-3		6×10^{-2}	
C-14		6×10^{-4}	
Kr-85		6.0	
LLW Building Vent[b]			
Particulates (β-γ)	4×10^{-9}	3×10^{-9}	4×10^{-9}
(α)	1×10^{-10}		7×10^{-12}

[a] For Cycles I and III, waste is vitrified HLW, ILW, and Cladding. For Cycle II, waste is PWR and BWR Spent Fuel.

[b] For Cycles I and III, waste is LLW-TRU. For Cycle II, waste is LLW.

TABLE 2-6

ESTIMATED MAXIMUM AIRBORNE CONCENTRATIONS OF RADIOACTIVE MATERIALS FROM SURFACE FACILITIES AND MINE - BPNL WASTE

Source of Release	Airborne Concentrations[e] (μCi/ml)		
	Fuel Cycle		
	I	II	III
Canistered Waste Building[a]			
Particulates (β-γ)	2×10^{-18}	2×10^{-17}	9×10^{-18}
(α)	2×10^{-19}	3×10^{-19}	2×10^{-20}
H-3		9×10^{-13}	
C-14		1×10^{-14}	
Kr-85		1×10^{-10}	
Mine[b]			
Particulates (β-γ)	1×10^{-17}	2×10^{-16}	1×10^{-17}
(α)	2×10^{-19}	2×10^{-18}	2×10^{-20}
H-3		2×10^{-11}	
C-14		2×10^{-13}	
Kr-85		2×10^{-9}	
Main Stack Release[c]			
Particulates (β-γ)	1×10^{-17}	2×10^{-17}	1×10^{-17}
(α)	2×10^{-19}	2×10^{-19}	2×10^{-20}
H-3		1×10^{-12}	
C-14		2×10^{-14}	
Kr-85		1×10^{-10}	
Low-Level Waste Building[d]			
Particulates (β-γ)	8×10^{-18}	7×10^{-18}	1×10^{-18}
(α)	2×10^{-19}		2×10^{-20}

[a] Canistered Waste Building ventilation flowrate is approximately 93,000 cfm for Cycles I and III, 136,000 for Cycle II.

[b] Mine ventilation flowrate for placement operations is approximately 250,000 cfm.

[c] Main stack flowrate is approximately 343,000 cfm for Cycles I and III, 386,000 cfm for Cycle II. (Combination of Mine and Canistered Waste Building.)

[d] LLW Building ventilation flowrate is approximately 32,000 cfm.

[e] After HEPA filtration (DF = 10^6).

TABLE 2-7

PASQUILL CLASSIFICATION OF ATMOSPHERIC CONDITIONS[a]

Surface Wind Speed at 10 m (m/sec)	Day			Night	
	Incoming Solar Radiation			Cloud Cover	
	Strong	Moderate	Slight	Mostly Overcast	Mostly Clear
	(1)[b]	(2)[b]	(3)[b]	(4)[b]	
<2	A[c]	A-B[c]	B	E[c]	F[c]
2-3	A-B	B	C[c]	E	F
3-5	B	B-C	C	D[c]	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

[a] U.S. Atomic Energy Commission, D. H. Slade, Editor, Meteorology and Atomic Energy, Washington, D.C., 1968.

[b] The following items refer to the classes numbered above:

(1) Clear skies, solar altitude greater than 60 degrees above the horizontal, typical of a sunny summer afternoon. Very convective atmosphere.

(2) Summer day with a few broken clouds.

(3) Typical of a sunny fall afternoon, summer day with broken low clouds, or summer day with clear skies and solar altitude from only 15 to 35 degrees above horizontal.

(4) Can also be used for a winter day.

[c] The neutral class, D, should be assumed for overcast conditions during day or night. Class A is the most unstable and Class F is the most stable, Class B moderately unstable, and Class E slightly stable.

TABLE 2-8

ATMOSPHERIC DISPERSION FACTORS[a]

Atmospheric Conditions	Dispersion Factors (sec/m^3) Maximum	Fenceline
Normal	1×10^{-4}[b]	6.5×10^{-5}
Fumigation	2×10^{-3}[c]	5.5×10^{-4}

[a] Assumptions:

(1) 50 m effective stack height
(2) 400 m to fence from stack
(3) 1 m/sec. windspeed
(4) Wind variable in one 22.5° sector

[b] Maximum concentration will occur at 250 m from stack.

[c] Maximum concentration will occur in the vicinity of the stack.

TABLE 2-9

ESTIMATED GROUND-LEVEL CONCENTRATIONS OF RADIOACTIVITY FROM NORMAL OPERATIONS--OWI WASTE

Cycle	Release From Facility Stack	Continuous Release Rate (Ci/sec)	Ground-Level Concentrations (μCi/ml)				Fraction of NRC Limits[b]
			Normal Atmospheric Conditions[a]		Fumigation Conditions[a]		
			Maximum	Fenceline	Maximum	Fenceline	
I	Particulates[c]						
	(β-γ)	1×10^{-13}	1×10^{-17}	7×10^{-18}	2×10^{-16}	6×10^{-17}	3×10^{-3}
	(α)	1×10^{-14}	1×10^{-18}	7×10^{-19}	2×10^{-17}	6×10^{-18}	3×10^{-4}
	Particulates[d]						
	(β-γ)	1×10^{-14}	1×10^{-18}	7×10^{-19}	2×10^{-17}	6×10^{-18}	3×10^{-4}
	(α)	2×10^{-16}	2×10^{-20}	1×10^{-20}	4×10^{-19}	1×10^{-19}	5×10^{-6}
II	Particulates						
	(β-γ)	7×10^{-15}	7×10^{-19}	5×10^{-19}	2×10^{-17}	4×10^{-18}	2×10^{-4}
	(α)	7×10^{-16}	7×10^{-20}	5×10^{-20}	2×10^{-18}	4×10^{-19}	2×10^{-5}
	H-3	5×10^{-9}	5×10^{-13}	3×10^{-13}	1×10^{-11}	3×10^{-12}	2×10^{-5}
	C-14	5×10^{-12}	5×10^{-16}	3×10^{-16}	1×10^{-14}	3×10^{-15}	3×10^{-8}
	Kr-85	3×10^{-7}	3×10^{-11}	2×10^{-11}	6×10^{-10}	2×10^{-10}	7×10^{-4}
III	Particulates[c]						
	(β-γ)	1×10^{-13}	1×10^{-17}	7×10^{-18}	2×10^{-16}	6×10^{-17}	3×10^{-3}
	(α)	3×10^{-15}	3×10^{-19}	2×10^{-19}	6×10^{-18}	2×10^{-18}	1×10^{-4}
	Particulates[d]						
	(β-γ)	1×10^{-14}	1×10^{-18}	7×10^{-19}	2×10^{-16}	6×10^{-18}	3×10^{-4}
	(α)	5×10^{-17}	5×10^{-21}	3×10^{-21}	1×10^{-19}	3×10^{-20}	2×10^{-6}

[a] From Table 2-8.

[b] Maximum permissible concentrations of radionuclides cited in 10CFR20, Appendix B, Table II, column 1; case with fumigation at fenceline used.

[c] Calcined HLW form.

[d] Glass HLW form.

TABLE 2-10

ESTIMATED GROUND-LEVEL CONCENTRATIONS OF RADIOACTIVITY FROM NORMAL OPERATIONS--BPNL WASTE

			Ground-Level Concentrations (μCi/ml)				
			Normal Atmospheric Conditions[a]		Fumigation Conditions[a]		
Cycle	Release From Facility Stack	Continuous Release Rate (Ci/sec)	Maximum	Fenceline	Maximum	Fenceline	Fraction of NRC Limits[b]
I	Particulates						
	(β-γ)	2×10^{-15}	2×10^{-19}	1×10^{-19}	4×10^{-18}	1×10^{-18}	5×10^{-5}
	(α)	3×10^{-17}	3×10^{-21}	2×10^{-21}	6×10^{-20}	2×10^{-20}	1×10^{-6}
II	Particulates						
	(β-γ)	2×10^{-14}	2×10^{-18}	1×10^{-18}	4×10^{-17}	1×10^{-17}	5×10^{-4}
	(α)	2×10^{-16}	2×10^{-20}	1×10^{-20}	4×10^{-18}	1×10^{-19}	5×10^{-6}
	H-3	2×10^{-9}	2×10^{-13}	1×10^{-13}	4×10^{-11}	1×10^{-12}	5×10^{-6}
	C-14	2×10^{-11}	2×10^{-15}	1×10^{-15}	4×10^{-13}	1×10^{-14}	1×10^{-7}
	Kr-85	2×10^{-7}	2×10^{-11}	1×10^{-11}	4×10^{-9}	1×10^{-10}	3×10^{-4}
III	Particulates						
	(β-γ)	2×10^{-15}	2×10^{-19}	1×10^{-19}	4×10^{-18}	1×10^{-18}	5×10^{-5}
	(α)	2×10^{-18}	2×10^{-22}	1×10^{-22}	4×10^{-21}	1×10^{-21}	5×10^{-8}

[a] From Table 2-8.

[b] Maximum permissible concentrations (MPC) of radionuclides cited in 10CFR20, Appendix B, Table II, column 1; case with fumigation at fenceline used.

3.0 RADIOACTIVE EFFLUENTS FROM ACCIDENTAL RELEASES DURING WASTE HANDLING

3.1 SOURCE TERM ASSUMPTIONS

The accident scenarios described in Section 5.3.1 of the GEIS[1] could can result in three types of effects on the waste containers: rupture, rupture in the presence of fire, and internal chemical explosion which ruptures the container. The last type of occurrence is postulated only for drums of low-level transuranic waste in which rags or other combustible materials may have been inadvertently placed. Although the probability of any of these occurrences is extremely low, releases of material could become airborne in each type of occurrence. The consequences of these remotely probable occurrences in terms of releases of radionuclides to the ventilation air are evaluated in later sections.

The radioactive materials considered in this analysis are the more volatile isotopes, including Kr-85, H-3, and C-14, along with particulates and aerosols. In addition to total particulate releases, that portion of the solids which consist of alpha-emitting transuranic isotopes with half-lives greater than 1 year (designated as α-TRU) are also considered. These are included because specific standards have been established by the EPA for releases of α-TRU particulates for other components of the nuclear fuel cycle.[2] These standards restrict the release of α-TRU particulates to 0.5 mCi per gigawatt year of electrical energy (GWe-Yr) generated from the entire uranium fuel cycle.

The types of waste which will be handled, depending on the fuel cycle, are canistered spent fuel, canistered high-level vitrified waste, canistered high-level calcined waste, canistered fuel cladding, canistered intermediate-level waste (ILW), and drummed low-level waste (LLW). Both OWI and BPNL waste data were analyzed. Differences in postulated accidental releases are observed which seem to arise from inconsistencies in waste activity between the two sets. A repository in salt was considered here because the HLW for salt has a higher activity than the HLW for other rock types, due to dilution.[1]

Two release scenarios have been evaluated in which airborne releases are estimated. These are: (1) a conservative case with maximum releases when the container is split open and its contents completely spilled. In the case of the SURF cycle it is also assumed that 100 percent of the fuel elements are ruptured; and note that considering that the maximum height to which a canister is lifted within the repository is a few feet, it is highly unlikely that, even if a canister is dropped, it will rupture,[3] and (2) a more probable release when the container is punctured and approximately 5 percent of the contents are spilled. The fractions of the activity within a container that become airborne during a case 1 occurrence are summarized in Table 3-1. A case 2 occurrence would release 5% of the fractions in Table 3-1. The assumptions used in estimating these fractions are presented below.

3.1.1 Canister of Spent Fuel

It is assumed that in the "worst case" a rupture of a spent fuel canister also ruptures 100 percent of the fuel element cladding. In the "more probable" case of 5 percent spillage, 5 percent of the claddings are considered to be broken. Particulate matter within the ruptured fuel assembly is assumed to become airborne to a total of 0.10 percent of all contained solids.

Gases in the spent fuel elements available for release are: 10 percent of H-3, 50 percent of C-14, and 50 percent of Kr-85. These estimates are based on the following considerations. Approximately 50 percent of tritium may escape from the fuel during irradiation, but it is mostly adsorbed in the Zircaloy cladding. This situation is similar to reprocessing operations, in which approximately 6 percent of the total tritium, in both gas and water vapor forms, is expected to be found in the offgas.[4-9] It is considered in WASH-1250[10] that 1 percent would be present in void spaces. Therefore, to be conservative, a maximum of 10 percent of that present in a fuel element will be assumed to be released as a gas from a ruptured fuel element. The form of carbon during spent-fuel dissolution is generally assumed to be CO_2 because of the oxidizing conditions.[4] While the form present within a clad spent-fuel element may be C or CO, that present in the gaps will be assumed to oxidize to the gaseous species CO and CO_2 when exposed to the atmosphere. The amount of carbon released from a ruptured fuel element has only been estimated, and a conservatively high value of 50 percent of the total is assumed. Estimates of the fraction of Kr-85 present in a fuel element that is available for release range from 30 percent (Table 4.25 of Reference 11) to 100 percent.[12,13] Other sources report only 1 to 5 percent is released from fuel during chopping operations.[14,15] A conservatively high value of 50 percent is used for purposes of the accident analyses in this report.

PWR spent fuel waste was assumed as the "worst case" since the nuclide source strengths are higher than in the BWR case.

3.1.2 Canister of Vitrified HLW (Glass)

In the very unlikely event that a canister is dropped and it ruptures, it would still be unlikely that any release of the vitrified HLW would occur because of the stable waste form itself. Studies on the long-term effect of αradiation on glass indicate that the glass will remain in a stable, vitrified form during the operational phase and therefore not be readily available for release after any rupture.[16-20] However, in this analysis it will be assumed that the rupture pulverizes 0.1 percent of the glass to a powder of which 10 percent becomes airborne. HLW from PWR's was assumed as a "worst case."

3.1.3 Canister of Calcined HLW

For these analyses, it is assumed that the calcined HLW consists of 1 percent fines material, which is loose and available for release. Further, it is assumed that a rupture accident pulverizes an additional 2 percent of the material. Finally, it is assumed that 10 percent of the fines and pulverized material is small enough to be airborne and transported. HLW from PWR's was assumed as a "worst case."

3.1.4 Canister of Cladding Waste

The treated cladding waste is not pyrophoric or combustible, but any fines produced (approximately 1 percent) during rupture could burn.[21] About 40 percent of the total fission product tritium is assumed to be adsorbed in the cladding. As cladding burns, it is assumed that all of the adsorbed tritium is released. Approximately 0.05 percent of contaminants on the surface of cladding wastes are assumed to be scraped off and released as airborne particulates if a canister is ruptured.

3.1.5 Container of Intermediate-Level Waste

The ILW container (drum or canister) may contain cemented wastes, contaminated metal components, and contaminated filter media. In the event that one of these containers is ruptured the following percentages are assumed: 0.05 percent of the contaminants from metal wastes are released; 0.10 percent of the cemented wastes are released; and, 0.10 percent of the filter media wastes are released. All these releases are expected to become airborne.

3.1.6 Container of Low-Level Waste

The LLW waste containers (drum or box) may contain such items as cemented incinerator ash and some contaminated metal. In the event that one of these containers is ruptured, 0.10 percent of the contaminants of cemented waste and 0.05 percent of metal wastes are assumed to become airborne as fine particulates. If the container is ruptured in the presence of a fire in the immediate vicinity, 20 percent of the contaminants are assumed to become airborne as fine particulates. In the unlikely event that a drum is ruptured by internal chemical explosion (due to inadvertently placed combustible material in the container), 50 percent of the contaminants are assumed to become airborne as fine particulates.

3.2 RELEASE CALCULATIONS

3.2.1 Sample Calculations for Source Terms

The following sections describe the methodology for arriving at the airborne releases (maximum and 5 percent) that are presented in Table 3-2 for OWI waste and Tables 3-3, 3-4, and 3-5 for BPNL waste. As an example consider the following case:

(1) Cycle I, vitrified HLW canister of PWR waste (OWI waste)

(2) Radioactive content of the canister from Part I, Table A-3 of Y/OWI/TM-36/2 is 6.63×10^5 Ci for particulates of which 2.4×10^4Ci are α-TRU.

(3) Release fraction from Table 3-1 is 0.0001 for maximum release.

Therefore, maximum particulate release is:

$(6.63\times10^5)(0.0001) = 66$ Ci

Five percent airborne release is simply:

$(66)(0.05\%) = 3.3$ Ci

Maximum α-TRU release is:

$(2.4\times10^4)(0.0001) = 2.4$ Ci

3.2.2 Effluent Transport Assumptions

The calculations of effluents at the stack resulting from airborne releases from the containers are based on the following additional assumptions and design data.

- In the unlikely event of a container rupture in the mine prior to discharge to the main stack, the mine exhaust air is processed by prefilters and two HEPA filter banks in series. Thus, the assumed decontamination factor (DF) for airborne particulates is 10^6 (Reference 22).

- Exhaust air from the high-level waste receiving building is prefiltered and then filtered by two HEPA filter banks in series. Again the assumed DF for airborne particulates is 10^6.

- Exhaust air from the low-level waste receiving building is prefiltered and then filtered by two HEPA filter banks in series prior to discharge to the atmosphere from roof vents on the building. The assumed DF for airborne particulates is 10^6.

- No removal of gaseous fission and activation products from the offgas is assumed.

- In surface facility areas, if a container would be ruptured, any material which becomes airborne fills the room atmosphere to a uniform concentration in a short time, compared with the ventilation air exchange rate for the area.

- In the mine storage areas, which are very large, if a container is ruptured, any material which becomes airborne is conservatively assumed to fill 1/4 of the room volume to a uniform concentration in a short time, compared with the ventilation air exchange rate for the area. Room air change rates are as follows:

High Level Waste Receiving Building	Room Air Changes/hr.*	
	OWI	BPNL
Transfer Cell (Hot)	2	6
Recan. Transfer Cell (Hot)	2	6
Transfer Cell (Cold)	2	6
Recan. Transfer Cell (Cold)	2	6
Canister Storage Feed Room	2	2
Low Level Waste Receiving Building		
Decon. and Overpack Room	10	10
Unload and Parking Room	10	10
Palletizing and Depalletizing Room	10	10
Drum Storage and Test	10	10
Mine		
Storage	2	2
LLW Transporter Loading	2	2
HLW Transporter Loading	2	2

The above room air changes were derived as follows:

$$\text{Room air changes/hr} = \frac{\text{Room air flow rate, ft}^3\text{/hr}}{\text{Room Volume, ft}^3}$$

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*Air changes derived from ventilation system design which varies for the two waste sets. These numbers are not medium dependent.

3.2.3 Sample Calculations for Stack Releases

The methodology described here was used to calculate the stack release rates for the airborne release from a ruptured container. This analysis pertains to the values displayed in Tables 3-6, 3-7, and 3-8 for OWI waste, and Tables 3-9, 3-10 and 3-11 for BPNL waste.

Using maximum airborne releases (Tables 3-2, 3-3, 3-4, and 3-5) and room air change data, stack releases were calculated using the following relation:

$$R = \frac{S \times C}{DF}$$

where

R = Release rate (Ci/sec)

S = Airborne release (Ci)

C = Room air change rate (changes/sec)

DF = Decontamination factor of filters (10^6)

For large rooms (i.e., storage rooms) in which the room is assumed to be only 1/4 filled with airborne material, the equation becomes:

$$R = \frac{S \times 4C}{DF}$$

The 24-hour average stack release rates were calculated by the following relation:

$$R_A = \frac{S}{T \times DF}$$

where R_A = Average release rate (Ci/sec)

S = Airborne release (Ci)

T = Time interval (sec)

DF = 10^6

For 24-hour average (T = 86,400)

$$R_A = \frac{S}{86{,}400 \times DF}$$

Note that the 24-hour average release rate is independent of location of spill; hence no room characteristics are found in the equation.

Consider the same case described in Section 3.2.1, and assume the release occurs in the canister storage feed room.

$S = 66$ Ci of particulates
$C = 2$ changes/hr
$DF = 10^6$

The stack release rate is then:

$$R = \frac{66 \times 2}{10^6 \times 3600 \text{ sec/hr}}$$

$$R = 3.7 \times 10^{-8} \text{ Ci/sec}$$

The 24-hour average release rate is:

$$R_A = 7.7 \times 10^{-10} \text{ Ci/sec}$$

Compare these results with values in Table 3-6 for this case.

3.3 ATMOSPHERIC DISPERSION OF ACCIDENTAL RELEASES

OWI's contribution to the commercial waste management GEIS contains only facility descriptions and release concentrations at the stack. BPNL is to supply the calculation of the impact on the environment. However, here in the technical support document, estimates of the releases to unrestricted areas have been derived using standard dispersion models.

3.3.1 Meteorology

The meteorological assumptions used to calculate dilution and dispersion of radionuclides assumed to be released during an accident are the same as those described for normal releases in Section 2.4.1. Again, the most conservative condition described in the NRC Regulatory Guide on which this analysis was based is fumigation. The range of Pasquill's classes provides a more realistic and probable set of conditions and is still conservative.

3.3.2 Estimated Ground Level Concentrations - OWI Waste

Applying the dispersion factors given in Table 2-8 to the 24-hour average release rates in Tables 3-6, 3-7, and 3-8 will result in ground-level concentrations at a maximum point and at the fenceline of the facility (assumed to be 400 m from stack). The 24-hour average values were used here because the criteria for NRC notification after an accident is based on the magnitude of the release averaged over a 24-hour period. Table 3-12 is a summary of the ground-level concentrations and the fraction of the NRC limits in 10CFR20.[23]

The worst accidental release, based on the scenarios defined in this document, would occur if a calcined HLW canister from U-only recycle were completely split open, and fumigation atmospheric conditions existed at the time. The fenceline concentration averaged over 24 hours would be approximately 700 times the NRC limits for unrestricted areas. For the same accident to a vitrified HLW canister, it has been predicted that the maximum fenceline concentrations would be about 25 times the NRC limit. The NRC allows these limits to be exceeded by 5000 times before immediate notification of the accident is required. The limits must be exceeded by 500 times before notification of the regional NRC office is required within 24 hours of the release.[24]

3.3.3 Estimated Ground Level Concentrations - BPNL Waste

The dispersion factors in Table 2-8 were applied to the 24-hour average release rates in Tables 3-9, 3-10 and 3-11. These have been compared to the limits set in 10CFR20 (Table 3-13).

The worst predicted release during accidental conditions would occur if a drum of LLW-filter media (Cycle I) from a MOX fuel fabrication plant (MOX-FFP) experiences an internal explosion. The resulting maximum fenceline concentration would be about 100 times the NRC limits for an unrestricted area. The NRC allows these limits to be exceeded by 500 times before 24-hour notice of an accident is required.[24]

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24. 10CFR20.403. "Notification of Incidents."

TABLE 3-1

MAXIMUM AIRBORNE RELEASE FRACTION FOR RUPTURED CONTAINERS

Waste[a]	Accident	Fractional Release[b]
Vitrified HLW	Rupture	0.0001
Calcined HLW	Rupture	0.003
Cladding	Rupture	0.0005
	Rupture + Fire	0.0005 + 0.004 H-3
ILW (Metals)	Rupture	0.0005
ILW (Cement)	Rupture	0.001
ILW (Filter Media)	Rupture	0.001
LLW (Metals)	Rupture	0.0005
	Rupture + Fire	0.20
	Internal Explosion	0.50
LLW (Cement)	Rupture	0.001
	Rupture + Fire	0.20
	Internal Explosion	0.50
LLW (Filter Media)	Rupture	0.001
	Rupture + Fire	0.20
	Internal Explosion	0.50
Spent Fuel (H-3)	Rupture	0.10
Spent Fuel (C-14)	Rupture	0.50
Spent Fuel (Kr-85)	Rupture	0.50
Spent Fuel (Particulates)	Rupture	0.001

[a] Accident pertains to all container types (i.e., drum, canister, etc.)

[b] Fraction of total internal activity that becomes airborne.

TABLE 3-2 - ESTIMATED AIRBORNE RELEASES FROM INDIVIDUAL CONTAINER DURING ACCIDENTS - OWI WASTE DATA

FUEL: CYCLES[a]	CONTAINER	CONTENTS	ACCIDENTAL OCCURENCE	TYPE OF RELEASE	NATURE OF AIRBORNE MATERIAL	QUANTITY OF AIRBORNE MATERIAL PER CONTAINER	
						MAXIMUM WITH COMPLETE SPILLAGE OF CONTENTS	PROBABLE WITH 5 PERCENT SPILLAGE OF CONTENTS
II	Canister of spent fuel	Spent fuel element assembly	Rupture[c]	Fission product gases, small amount fuel solids.	Fission product gases in chemical forms: HTO (small amount HT), CO and CO$_2$, Kr., Particulate spent fuel.	PWR 14 Ci H-3, 4.2×10^{-2} Ci C-14, 1.1×10^{3} Ci Kr-85, 190 Ci Particulates, 2.8 Ci α-*TRU*	PWR 0.70 Ci H-3, 2.3×10^{-3} Ci C-14, 55 Ci Kr-85, 9.5 Ci Particulates, 0.14 Ci α-*TRU*
						BWR 4.7 Ci H-3, 1.2×10^{-6} Ci C-14, 3.6×10^{2} Ci Kr-85, 62 Ci Particulates, 0.97 Ci α-*TRU*	BWR 0.24 Ci H-3, 6.0×10^{-8} Ci C-14, 18 Ci Kr-85, 3.1 Ci Particulates, 0.049 Ci α-*TRU*
I	Canister of glass	Vitrified HLLW	Rupture[c]	Fractured glass, small amount pulverized	Pulverized glass	PWR 66 Ci Particulates, 2.4 Ci α-*TRU*	PWR 3.3 Ci Particulates; 0.12 Ci α-*TRU*
						BWR 54 Ci Particulates, 6.4 Ci α-*TRU*	BWR 2.7 Ci Particulates; 0.32 Ci α-*TRU*
I	Canister of calcine	Calcined HLLW	Rupture[c]	Dispersal of calcine, some fines airborne	Calcine fines	PWR 2.0×10^{3} Ci Particulates; 72 Ci α-*TRU*	PWR 100 Ci Particulates; 3.6 Ci α-*TRU*
						BWR 1.6×10^{3} Ci Particulates; 1.9×10^{2} Ci α-*TRU*	BWR 31 Ci Particulates; 9.6 Ci α-*TRU*
III	Canister of glass	Vitrified HLLW containing Pu	Rupture[c]	Fractured glass, small amount pulverized	Pulverized glass	PWR 84 Ci Particulates; 1.7 Ci α-*TRU*	PWR 4.2 Ci Particulates; 9.0×10^{-2} Ci α-*TRU*
						BWR 70 Ci Particulates; 1.7 Ci α-*TRU*	BWR 3.5 Ci Particulates; 9.0×10^{-2} Ci α-*TRU*
III	Canister of Calcine	Calcined HLLW containing Pu	Rupture[c]	Dispersal of calcine, some fines airborne	Calcine fines	PWR 2.2×10^{3} Ci Particulates; 47 Ci α-*TRU*	PWR 1.1×10^{2} Ci Particulates; 2.4 Ci α-*TRU*
						BWR 1.9×10^{3} Ci Particulates; 44 Ci α-*TRU*	BWR 95 Ci Particulates; 2.3 Ci α-*TRU*
I	Canister of ILW	ILW	Rupture[c]	Dispersal of contents; small amount surface containments scraped off & airborne	Surface containments as particulates	PWR 44 Ci Particulates; 41 Ci α-*TRU*	PWR 2.2 Ci Particulates; 2.1 Ci α-*TRU*
						BWR 33 Ci Particulates; 23 Ci α-*TRU*	BWR 2.0 Ci Particulates, 1.4 Ci α-*TRU*
III	Canister of ILW	ILW	Rupture[c]	Dispersal of contents; small amount surface contaminants scraped off & airborne	Surface contaminants as particulates	PWR 85 Ci Particulates; 8.3 Ci α-*TRU*	PWR 4.3 Ci Particulates, 0.42 Ci α-*TRU*
						BWR 75 Ci Particulates; 3.0 Ci α-*TRU*	BWR 3.8 Ci Particulates, 0.40 Ci α-*TRU*
I, III	Canister of cladding	Fuel hulls	Rupture[c]	Dispersal of contents in area	Particulate spent fuel	PWR 4.0 Ci Particulates 3.6×10^{-3} Ci α-*TRU*	PWR 0.20 Ci Particulates, 1.8×10^{-4} Ci α-*TRU*
						BWR 7.2 Ci Particulates, 3.1×10^{-3} α-*TRU*	BWR 0.36 Ci Particulates, 1.6×10^{-4} Ci α-*TRU*
			Rupture[c] plus fire	Dispersal of contents & burning of F.P. gases	Same as above plus H-3, from burned cladding fines	PWR 4.0 Ci Part., 0.004 Ci α-*TRU*, 4.0 Ci H-3	PWR 0.20 Ci Part., 1.8×10^{-4} Ci α-*TRU*, 0.2 Ci H-3
						BWR 7.2 Ci Part., 0.003 Ci α-*TRU*, 5.1 Ci H-3	BWR 0.36 Ci Part., 1.6×10^{-4} Ci α-*TRU*, 0.25 Ci H-3
I. II, III	55 Gal. drum LLW-*TRU*	Non combustible waste & inadvertently placed combustible material	Rupture	Dispersal of contents	Surface contaminants as particulates; *TRU* elements, nitrates, oxides	0.37 Ci Particulates, (predominantly α-*TRU* except for cycle II)	1.9×10^{-2} Ci Particulates, (predominantly α-*TRU* except for cycle II)
			Rupture plus fire	Dispersal & burning of contents;	Same as above plus Airborne Oxides of surface contaminants nitrates, oxides.	0.74 Ci Particulates, (predominantly α-*TRU* except for cycle II)	3.7×10^{-2} Ci Particulates, (predominantly α-*TRU* except for cycle II)
			Internal chemical explosion	Same as above	Same as above	1.9 Ci Particulates, (predominantly α-*TRU* except for cycle II)	9.3×10^{-2} Ci Particulates, (predominantly α-*TRU* except for cycle II)

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[a] Fuel Cycles: I. Total Recycle; II. SURF, III. U Recycle Only, Pu in HLW;

[b] α-TRU - α-emitting transuranic radionuclides with half-lives greater than 1 year

[c] Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-3- ESTIMATED AIRBORNE RELEASES FROM INDIVIDUAL CONTAINERS DURING ACCIDENTS- TOTAL RECYCLE, BPNL WASTE DATA

CONTAINER	CONTENTS	SURFACE DOSE (R/HR)	ACCIDENTAL OCCURANCE	TYPE OF RELEASE	NATURE OF AIRBORNE MATERIAL	QUANTITY OF AIRBORNE MATERIAL PER CONTAINER	
						MAXIMUM WITH COMPLETE SPILLAGE OF CONTENTS	PROBABLE WITH 5 PERCENT SPILLAGE OF CONTENTS
12"x10' canister of HLW	Vitrified HLLW	>10	Rupture	Fractured glass, small amount pulverized	Pulverized glass	134 Ci Particulates, 2.05 Ci α-*TRU*	6.7 Ci Particulates, 0.10 Ci α-*TRU*.
30"x10' canister of cladding	Cladding hulls	>10	Rupture	Dispersal of contents	Particulate spent fuel	9.0 Ci Particulates, 7.5×10^{-2} Ci α-*TRU*	0.45 Ci Particulates 3.75×10^{-3} Ci α-*TRU*
			Rupture plus fire	Dispersal of contents and burning of fines produced from rupture.	Particulate spent fuel and H-3 from burned cladding fines.	9.0 Ci Particulates 7.5×10^{-2} Ci α-*TRU* 5.62 Ci H-3	0.45 Ci Particulates 3.75×10^{-3} Ci α-*TRU* 0.28 Ci H-3
55 gal. drum of ILW: 30" x 10' canister of ILW	Noncombustible trash; failed equipment; cemented ash; cemented LILW; HEPA filter media.	0.2-1.0 1.0-10 >10	Rupture	Dispersal of contents, small amount of surface contaminants scraped from metal wastes.	Surface contaminants as particulates, cement fines, pulverized glass.	Maximum ILW release during rupture is from drums of filter media: 1.38 Ci Particulates, 1.2 Ci α-*TRU*. Other waste forms experience negligible airborne releases after rupture.	From filter media: 0.07 Ci Particulates, 0.06 Ci α-*TRU*
55 gal. drum of LLW, 4'x6'x6' box of LLW	Noncombustible trash; failed equipment; cemented ash; cemented LLLW; filter media.	<0.2	Rupture	Dispersal of contents.	Surface contaminants as particulate; *TRU* elements, Nitrates, Oxides.	Maximum LLW release during rupture is from drums of filter media: 0.678 Ci Particulates, 0.60 Ci α-*TRU*. Other waste forms experience negligible releases.	From filter media: 3.4×10^{-2} Ci Particulates, 3.0×10^{-2} Ci α-*TRU*
55 gal. drum of LLW	Noncombustible trash from PuO_2 facility and inadvertently placed combustible material.	<0.2	Rupture plus fire	Dispersal and burning of contents	Same as above, plus airborne oxides of surface contaminants, nitrates, oxide.	63.4 Ci Particulates 56 Ci α-*TRU*	3.17 Ci Particulates 2.8 Ci α-*TRU*
4'x6'x6' Box of LLW	Failed equipment -PuO_2 conversion and inadvertently placed combustible material	<0.2	Rupture plus fire	Same as above	Same as above	27.2 Ci Particulates 24 Ci α-*TRU*	1.36 Ci Particulates 1.2 Ci α-*TRU*
55 gal drum of LLW	Noncombustible trash - MOX-FFP and inadvertently placed combustible material.	<0.2	Rupture plus fire	Same as above	Same as above	9.96 Ci Particulates 8.8 Ci α-*TRU*	0.50 Ci Particulates 0.44 Ci α-*TRU*

TABLE 3-3 (Cont'd)

CONTAINER	CONTENTS	SURFACE DOSE (R/HR)	ACCIDENTAL OCCURANCE	TYPE OF RELEASE	NATURE OF AIRBORNE MATERIAL	QUANTITY OF AIRBORNE MATERIAL PER CONTAINER	
						MAXIMUM WITH COMPLETE SPILLAGE OF CONTENTS	PROBABLE WITH 5 PERCENT SPILLAGE OF CONTENTS
55 gal. drum of LLW	Filter media; MOX-FFP and inadvertently placed combustible material	<0.2	Rupture plus fire	Same as above	Particulates and pulverized fiberglass	135.6 Ci Particulates 120 Ci α-TRU	6.78 Ci Particulates 6.0 Ci α-TRU
55 gal. of LLW	Cemented ash; MOX-FFP and inadvertently placed combustible material	<0.2	Rupture plus fire	Same as above	Particulates, nitrates, oxides	114 Ci Particulates 10 Ci α-TRU	0.57 Ci Particulates 0.5 Ci α-TRU
4'x6'x6' Box of LLW	Failed equipment; MOX-FFP and inadvertently placed combustible material	<0.2	Rupture plus fire	Same as above	Surface contaminants as particulates, airborne oxides of surface contaminants, nitrates, oxides	2.8 Ci Particulates 2.4 Ci α-TRU	0.14 Ci Particulates 0.12 Ci α-TRU
55 gal. drum of LLW	Noncombustible trash from PuO_2 conversion and inadvertently placed explosive material	<0.2	Internal explosion	Dispersal of contents	Airborne particulates, surface contaminants as particulates	158.5 Ci Particulates 140 Ci α-TRU	7.93 Ci Particulates 7.0 Ci α-TRU
4'x6'x6' box of LLW	Failed equipment; PuO_2 conversion and inadvertently placed explosive material	<0.2	Internal explosion	Same as above	Same as above	68.0 Ci Particulates 60.0 Ci α-TRU	3.4 Ci Particulates 3.0 Ci α-TRU
55 gal. drum of LLW	Noncombustible trash; MOX-FFP and inadvertently placed explosive material	<0.2	Internal explosion	Same as above	Same as above	2.49 Ci Particulates 22.0 Ci α-TRU	1.25 Ci Particulates 1.1 Ci α-TRU
55 gal. drum of LLW	Cemented wet wastes; MOX-FFP and inadvertently placed explosive material	<0.2	Internal explosion	Same as above	Particulates and cement fines	5.6 Ci Particulates 4.9 Ci α-TRU	0.34 Ci Particulates 0.3 Ci α-TRU

TABLE 3-3 (Cont'd)

CONTAINER	CONTENTS	SURFACE DOSE (R/HR)	ACCIDENTAL OCCURANCE	TYPE OF RELEASE	NATURE OF AIRBORNE MATERIAL	QUANTITY OF AIRBORNE MATERIAL PER CONTAINER	
						MAXIMUM WITH COMPLETE SPILLAGE OF CONTENTS	PROBABLE WITH 5 PERCENT SPILLAGE OF CONTENTS
55 gal drum of LLW	Filter media; MOX-FFP and inadvertently placed explosive material.	<0.2	Internal explosion	Same as above	Particulates and pulverized fiberglass	339 Ci Particulates 300 Ci α-*TRU*	16.95 Ci Particulates 15 Ci α-*TRU*
55 gal drum of LLW	Cemented Ash-MOX-FFP and inadvertently placed explosive material	<0.2	Internal explosion	Same as above	Particulates and cement fines	28.5 Ci Particulates 2.5 Ci α-*TRU*	1.45 Particulates 1.25 Ci α-*TRU*
4'x6'x6' box of LLW	Failed equipment; MOX-FFP and inadvertently placed explosive material.	<0.2	Internal explosion	Same as above	Airborne particulates, surface contaminants as particulates	7.0 Ci Particulates 6.0 Ci α-*TRU*	0.35 Ci Particulates 0.3 Ci α-*TRU*

TABLE 3-4- ESTIMATED AIRBORNE RELEASES FROM INDIVIDUAL CONTAINERS DURING ACCIDENTS- SURF CYCLE, BPNL WASTE DATA

						QUANTITY OF AIRBORNE MATERIAL PER CONTAINER	
CONTAINER	CONTENTS	SURFACE DOSE (R/HR)	ACCIDENTAL OCCURANCE	TYPE OF RELEASE	NATURE OF AIRBORNE MATERIAL	MAXIMUM WITH COMPLETE SPILLAGE OF CONTENTS	PROBABLE WITH 5 PERCENT SPILLAGE OF CONTENTS
Canister of spent fuel	Spent Fuel assembly	>10	Rupture	Fission product gases, small amount solid fuel.	Fission product gases in chemical forms: HTO (small amount HT), CO, and CO_2, Kr, Particulate spent fuel.	PWR 16.8 Ci H-3, 0.19 Ci C-14, 1.75 x 10^3 Ci Kr-85, 244 Ci Particulates, 2.58 Ci α-*TRU*	PWR 0.84 Ci H-3, 9.5 x 10^{-3} Ci C-14, 87.5 Ci Kr-85, 12.2 Ci Particulates, 0.13 Ci α-*TRU*
						BWR 5.16 Ci H-3, 5.6 x 10^{-2} C-14. 535 Ci Kr-85; 73.2 Ci Particulates, 0.7 Ci α-*TRU*	BWR 0.26 Ci H-3, 2.8 x 10^{-3} Ci C-14, 26.8 Ci Kr-85, 3.66 Ci Particulates, 3.5 x 10^{-2} Ci α-*TRU*
55 gal drum and 4'x6'x6' box of LLW	Noncombustible trash, cemented ash, failed equipment.	<0.2	Rupture	Dispersal contents	Surface contaminants as particulates: oxides, nitrates.	Negligible releases from LLW containers during these occurances.	
			Rupture plus fire	Same as above and burning of contents	Same as above plus airborne oxides, nitrates.		
			Internal explosion	Same as above	Same as above		

TABLE 3-5 - ESTIMATED AIRBORNE RELEASES FROM INDIVIDUAL CONTAINERS DURING ACCIDENTS- U-ONLY RECYCLE, BPNL WASTE DATA

CONTAINER	CONTENTS	SURFACE DOSE (R/HR)	ACCIDENTAL OCCURANCE	TYPE OF RELEASE	NATURE OF AIRBORNE MATERIAL	QUANTITY OF AIRBORNE MATERIAL PER CONTAINER	
						MAXIMUM WITH COMPLETE SPILLAGE OF CONTENTS	PROBABLE WITH 5 PERCENT SPILLAGE OF CONTENTS
12"x10' canister of glass HLW	Vitrified HLLW	>10	Rupture	Fractured glass, small amount pulverized	Pulverized glass	130 Ci Particulates 1.8 Ci α-*TRU*	5.52 Ci Particulates 9.0×10^{-2} Ci α-*TRU*
30"x10' canister of cladding	Cladding hulls	>10	Rupture	Dispersal of contents	Particulate spent fuel	9.0 Ci Particulates 1.2×10^{-3} Ci α-*TRU*	0.45 Ci Particulates 5×10^{-5} Ci α-*TRU*
			Rupture plus fire	Same as above with burning of fines produced by the rupture	Same as above with H-3 from burned cladding fires	9.0 Ci Particulates, 1.2×10^{-3} Ci α-*TRU* 5,62 Ci H-3	0.45 Ci Particulates 5×10^{-5} Ci α-*TRU* 0.28 Ci H-3
55 gal drum of ILW 30" x 10" canister of ILW	Noncombustible trash, failed equipment, cemented ash, cemented LILW and HEPA filter media.	0.2-1.0 1.0-10 >10	Rupture	Dispersal of contents, small amounts of surface contaminants scraped from metal wastes	Surface contaminants as particulates, cement fines, pulverized glass.	Maximum ILW release during rupture is from drums of cemented wet wastes: 0.92 Ci Particulates, 0.80 Ci α-*TRU*. Other waste forms experience negligible releases.	Cemented wet waste; 4.6×10^{-2} Ci Particulates, 4.0×10^{-2} Ci α-*TRU*
55 gal of LLW, 4'x6'x6' box of	Noncombustible trash, cemented ash, failed equipment	<0.2	Rupture	Dispersal of contents	Surface contaminants as particulates: *TRU* elements, nitrates, oxides.	Negligible releases from LLW containers during any of the accidental occurances.	
			Rupture plus fire	Same as above with burning of contents	Same as above plus airborne oxides of surface contaminants, nitrates, oxides.		
			Internal explosion	Dispersal of contents	Same as above		

TABLE 3-6 - ESTIMATED AIRBORNE RELEASE RATES TO STACK OF RADIONUCLIDES RESULTING FROM AN ACCIDENT TO A SINGLE CONTAINER - TOTAL RECYCLE, OWI WASTE DATA

				AIRBORNE RELEASE RATES, Ci/sec.					
				INITIAL RELEASE RATE AT STACK[a]			24-HR. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	H-3	PARTICULATES	α-TRU[b]	H-3	PARTICULATES	α-TRU[b]
Canistered Waste Receiving Building	Transfer Cell (hot), Recan Transfer Cell (hot), Transfer Gallery (cold), Recan Transfer Gallery (cold), Canister Storage Feed Room	Canister of glass	Rupture[c]	2.2×10^{-3}	3.7×10^{-8}	1.3×10^{-9}	4.7×10^{-5}	7.7×10^{-10}	2.8×10^{-11}
		Canister of calcine	Rupture[c]		1.1×10^{-6}	4.0×10^{-8}		2.3×10^{-8}	8.3×10^{-10}
		Canister of cladding	Rupture		2.2×10^{-9}	2.0×10^{-12}		4.7×10^{-11}	4.2×10^{-14}
			Rupture + Fire		2.2×10^{-9}	2.0×10^{-12}		4.7×10^{-11}	4.2×10^{-14}
		Canister of ILW	Rupture[c]		2.5×10^{-8}	2.3×10^{-8}		5.1×10^{-10}	4.8×10^{-10}
Low-Level Waste Receiving Building	Unloading & Parking Room, Decon & Overpack Room, Palletizing and Depalletizing Room	55-gal. drum LLW-TRU	Rupture		1.0×10^{-9}	1×10^{-9}		4.3×10^{-12}	4×10^{-12}
			Rupture + Fire		2.1×10^{-9}	2×10^{-9}		8.6×10^{-12}	8×10^{-12}
			Int. Chemical Explosion		5.3×10^{-9}	5×10^{-9}		2.2×10^{-11}	2×10^{-11}
Mine	Canister Storage Room	Canister of glass	Rupture[c]	8.9×10^{-3}	1.5×10^{-7}	5.3×10^{-9}	4.7×10^{-5}	7.6×10^{-10}	2.9×10^{-11}
		Canister of calcine	Rupture[c]		4.4×10^{-6}	1.6×10^{-7}		2.3×10^{-8}	8.3×10^{-10}
		Canister of cladding	Rupture		8.9×10^{-9}	8.0×10^{-12}		4.6×10^{-11}	4.2×10^{-14}
			Rupture + Fire		8.9×10^{-9}	8.0×10^{-12}		4.6×10^{-11}	4.2×10^{-14}
		Canister of ILW	Rupture[c]		9.8×10^{-8}	9.1×10^{-8}		5.1×10^{-10}	4.7×10^{-10}
	LLW Storage Room	55-gal. drum LLW-TRU	Rupture		8.2×10^{-10}	8.0×10^{-10}		4.3×10^{-12}	4×10^{-12}
			Rupture + Fire		1.6×10^{-9}	1.4×10^{-9}		8.6×10^{-12}	8×10^{-12}
			Int. Chemical Explosion		4.2×10^{-9}	4.0×10^{-9}		2.2×10^{-11}	2×10^{-11}

a. For high-level waste receiving building and for mine, "stack" is main stack. For low-level waste receiving building, "stack" is building exhaust.

b. α-TRU = α-emitting transuranic radionuclides with half-lives greater than 1-year.

c. Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-7 - ESTIMATED AIRBORNE RELEASE RATES TO STACK OF RADIONUCLIDES RESULTING FROM AN ACCIDENT TO A SINGLE CONTAINER - SURF CYCLE, OWI WASTE DATA

				AIRBORNE RELEASE RATES, Ci/Sec					
				INITIAL RELEASE RATE AT STACK[a]			24-Hr. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	Kr-85	PARTICULATES	α-TRU[b]	Kr-85	PARTICULATES	α-TRU[b]
Canistered Waste Receiving Building	Transfer cell (hot), Recan Transfer cell (hot), Transfer Gallery (cold), Recan Transfer Gallery (cold), Canister Storage & Feed Room	Canister of Spent Fuel	Rupture[c]	0.62	1.1×10^{-7}	1.6×10^{-9}	1.3×10^{-2}	2.2×10^{-9}	3.3×10^{-11}
Low-level Waste Receiving Building	Unloading & Parking Room, Decon & Overpack Room, Palletizing and Depalletizing Room	55-gal. drum LLW	Rupture		1.0×10^{-9}			4.3×10^{-12}	
			Rupture + Fire		2.1×10^{-9}			8.6×10^{-12}	
			Int. Chemical Explosion		5.3×10^{-9}			2.2×10^{-11}	
Mine	HLW Storage Room	Canister of Spent Fuel	Rupture[c]	2.4	4.2×10^{-7}	6.2×10^{-9}	1.3×10^{-2}	2.2×10^{-9}	3.3×10^{-11}
	LLW Storage Room	55-gal. drum of LLW	Rupture		8.2×10^{-10}			4.3×10^{-12}	
			Rupture + Fire		1.6×10^{-9}			8.6×10^{-12}	
			Int. Chemical Explosion		4.2×10^{-9}			2.2×10^{-11}	

a. For high-level waste receiving building and for mine, "stack" is main stack. For low-level waste receiving building, "stack" is building exhaust.

b. α-TRU = α-emitting transuranic radionuclides with half-lives greater than one year.

c. Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-8 - ESTIMATED AIRBORNE RELEASE RATES TO STACK OF RADIONUCLIDES RESULTING FROM AN ACCIDENT TO A SINGLE CONTAINER - U-ONLY RECYCLE, OWI WASTE DATA

				AIRBORNE RELEASE RATES, Ci/sec.					
				INITIAL RELEASE RATE AT STACK[a]			24-HR. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	H-3	PARTICULATES	α-TRU[b]	H-3	PARTICULES	α-TRU[b]
Canistered Waste Receiving Building	Transfer Cell (hot), Recan Transfer Cell (hot), Transfer Gallery (cold), Recan Transfer Gallery (cold), Canister Storage Feed Room	Canister of glass	Rupture[c]	2.2×10^{-3}	4.7×10^{-8}	9.4×10^{-10}	4.7×10^{-5}	9.7×10^{-10}	2.0×10^{-11}
		Canister of calcine	Rupture[c]		1.2×10^{-6}	2.6×10^{-8}		2.6×10^{-8}	5.5×10^{-10}
		Canister of cladding	Rupture		2.2×10^{-9}	2.0×10^{-12}		4.7×10^{-11}	4.2×10^{-14}
			Rupture + Fire		2.2×10^{-9}	2.0×10^{-12}		4.7×10^{-11}	4.2×10^{-14}
		Canister of ILW	Rupture[c]		4.4×10^{-8}	4.6×10^{-9}		9.8×10^{-10}	9.6×10^{-11}
Low-level Waste Receiving Building	Unloading & Parking Room, Decon & Overpack Room, Palletizing and Depalletizing Room	55-gal. drum LLW-TRU	Rupture		1.0×10^{-9}	1.0×10^{-9}		3.9×10^{-12}	3.8×10^{-12}
			Rupture + Fire		2.1×10^{-9}	2.0×10^{-9}		8.6×10^{-12}	8.5×10^{-12}
			Int. Chem. Expl.		5.3×10^{-9}	5.1×10^{-9}		2.2×10^{-11}	2.1×10^{-11}
Mine	HLW Storage Room	Canister of glass	Rupture[c]		1.9×10^{-7}	9.1×10^{-8}		9.7×10^{-10}	2.0×10^{-11}
		Canister of calcine	Rupture[c]		4.9×10^{-6}	1.0×10^{-7}		2.5×10^{-8}	5.4×10^{-10}
	ILW & CW Storage Room	Canister of cladding	Rupture	8.9×10^{-3}	8.9×10^{-9}	8.0×10^{-12}	4.7×10^{-5}	4.6×10^{-11}	4.2×10^{-14}
			Rupture + Fire		8.9×10^{-9}	8.0×10^{-12}		4.6×10^{-11}	4.2×10^{-14}
		Canister of ILW	Rupture[c]		1.9×10^{-7}	1.8×10^{-8}		9.8×10^{-10}	9.6×10^{-11}
	LLW Storage Room	55-gal. drum LLW-TRU	Rupture		8.2×10^{-10}	8.1×10^{-10}		4.3×10^{-12}	4×10^{-12}
			Rupture + Fire		1.6×10^{-9}	1.4×10^{-9}		8.6×10^{-12}	8×10^{-12}
			Int. Chemical Explosion		4.2×10^{-9}	4.0×10^{-9}		2.2×10^{-11}	2×10^{-11}

a. For high-level waste receiving building and for mine, "stack" is main stack. For low-level waste receiving building, "stack" is building exhaust.

b. α-TRU = α-emitting transuranic radionuclides with half-lives greater than 1 year.

c. Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-9 - ESTIMATED AIRBORNE RELEASE RATES TO STACK OF RADIONUCLIDES FROM AN ACCIDENT TO A SINGLE CONTAINER - TOTAL RECYCLE, BPNL WASTE DATA

				AIRBORNE RELEASE RATES, Ci/sec.					
				INITIAL RELEASE RATE AT STACK[a]			24-HR. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	H-3	PARTICULATES	α-TRU[b]	H-3	PARTICULATES	α-TRU[b]
Canistered Waste Receiving Building	Transfer Gallery (cold). Transfer Cell, Transfer Gallery (hot), Decon Wells, Shaft Transfer Cell	Canister of HLW	Rupture[c]		2.2×10^{-7}	3.4×10^{-9}		1.6×10^{-9}	2.4×10^{-11}
		Canister of Cladding	Rupture Rupture + Fire	9.4×10^{-3}	1.5×10^{-8} 1.5×10^{-8}	1.3×10^{-10} 1.3×10^{-10}	6.5×10^{-5}	1.0×10^{-10} 1.0×10^{-10}	8.7×10^{-13} 8.7×10^{-13}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		2.3×10^{-9}	2.0×10^{-9}		1.6×10^{-11}	1.4×10^{-11}
	Waste Container Feed Room	Canister of HLW	Rupture[c]		7.4×10^{-8}	1.1×10^{-9}		1.6×10^{-9}	2.4×10^{-11}
		Canister of Cladding	Rupture Rupture + Fire	3.1×10^{-3}	5.0×10^{-9} 5.0×10^{-9}	4.2×10^{-11} 4.2×10^{-11}	6.5×10^{-5}	1.0×10^{-10} 1.0×10^{-10}	8.7×10^{-13} 8.7×10^{-13}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		7.7×10^{-10}	6.7×10^{-10}		1.6×10^{-11}	1.4×10^{-11}
Underground Canistered Waste Receiving Station	Transfer Gallery, Transfer Cell, Transporter Loading Room	Canister of HLW	Rupture[c]		7.4×10^{-8}	1.1×10^{-9}		1.6×10^{-9}	2.4×10^{-11}
		Canister of Cladding	Rupture Rupture + Fire	3.1×10^{-3}	5.0×10^{-9} 5.0×10^{-9}	4.2×10^{-11} 4.2×10^{-11}	6.5×10^{-5}	1.0×10^{-10} 1.0×10^{-10}	8.7×10^{-13} 8.7×10^{-13}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		7.7×10^{-10}	6.7×10^{-10}		1.6×10^{-11}	1.4×10^{-11}
Low-Level Waste Receiving Building and Underground LLW Receiving Station	Drum Unloading Bay, Decon and Overpack cell, Drum Storage and Test Cells, Transporter Loading Room	Drum of LLW	Rupture		1.9×10^{-9}	1.7×10^{-9}		7.8×10^{-12}	6.9×10^{-12}
		Box of LLW	Rupture	Negligible Releases					
		Drum of LLW, non-combustible trash from PuO_2 facility	Rupture + Fire Internal Explosion		1.8×10^{-7} 4.4×10^{-7}	1.6×10^{-7} 3.9×10^{-7}		7.3×10^{-10} 1.8×10^{-9}	6.5×10^{-10} 1.6×10^{-9}
		Box of LLW, failed equipment from PuO_2 conversion	Rupture + Fire Internal Explosion		7.6×10^{-8} 1.9×10^{-7}	6.7×10^{-8} 1.7×10^{-7}		3.2×10^{-10} 7.8×10^{-10}	2.8×10^{-10} 6.9×10^{-10}
		Drum of LLW, non-combustible trash from MOX-FFP	Rupture + Fire Internal Explosion		2.8×10^{-8} 6.9×10^{-8}	2.4×10^{-8} 6.1×10^{-8}		1.2×10^{-10} 2.9×10^{-10}	1.0×10^{-10} 2.5×10^{-10}
		Drum of LLW-Filter Media from MOX-FFP	Rupture + Fire Internal Explosion		3.8×10^{-7} 9.4×10^{-7}	3.3×10^{-7} 8.3×10^{-7}		1.6×10^{-9} 3.9×10^{-9}	1.4×10^{-9} 3.5×10^{-9}
		Drum of LLW-Cemented ash from MOX-FFP	Rupture + Fire Internal Explosion		3.2×10^{-8} 7.9×10^{-8}	2.8×10^{-8} 6.9×10^{-8}		1.3×10^{-10} 3.3×10^{-10}	1.2×10^{-10} 2.9×10^{-10}
		Box of LLW-failed equipment from MOX-FFP	Rupture + Fire Internal Explosion		7.8×10^{-9} 1.9×10^{-8}	6.7×10^{-9} 1.7×10^{-8}		3.2×10^{-11} 8.1×10^{-11}	2.8×10^{-11} 6.9×10^{-11}
Mine	HLW Storage	Canister of HLW	Rupture[c]		3.0×10^{-7}	4.6×10^{-9}		1.6×10^{-9}	2.4×10^{-11}

TABLE 3-9 (Cont'd)

				AIRBORNE RELEASE RATES, Ci/sec					
				INITIAL RELEASE RATE AT STACK[a]			24-Hr. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	H-3	PARTICULATES	α-TRU[b]	H-3	PARTICULATES	α-TRU[b]
Mine	ILW Storage	Canister of Cladding	Rupture Rupture + Fire	1.2×10^{-2}	2.0×10^{-8} 2.0×10^{-8}	1.7×10^{-10} 1.7×10^{-10}	6.5×10^{-5}	1.0×10^{-10} 1.0×10^{-10}	8.7×10^{-13} 8.7×10^{-13}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		3.1×10^{-9}	2.7×10^{-9}		1.6×10^{-11}	1.4×10^{-11}
	LLW Storage	Drum of LLW	Rupture		1.5×10^{-9}	1.3×10^{-9}		7.8×10^{-12}	6.9×10^{-12}
		Box of LLW	Rupture	Negligible Releases					
		Drum of LLW, non-combustible trash from PuO_2 facility	Rupture + Fire Internal Explosion		1.4×10^{-7} 3.5×10^{-7}	1.2×10^{-7} 3.1×10^{-7}		7.3×10^{-10} 1.8×10^{-9}	6.5×10^{-10} 1.6×10^{-9}
		Box of LLW, failed equipment from PuO_2 conversion	Rupture + Fire Internal Explosion		6.0×10^{-8} 1.5×10^{-7}	5.3×10^{-8} 1.3×10^{-7}		3.2×10^{-10} 7.8×10^{-10}	2.8×10^{-10} 6.9×10^{-10}
		Drum of LLW, non-combustible trash from MOX-FFP	Rupture + Fire Internal Explosion		2.2×10^{-8} 5.5×10^{-8}	2.0×10^{-8} 4.9×10^{-8}		1.2×10^{-10} 2.9×10^{-10}	1.0×10^{-10} 2.5×10^{-10}
		Drum of LLW-filter media from MOX-FFP	Rupture + Fire Internal Explosion		3.0×10^{-7} 7.5×10^{-7}	2.7×10^{-7} 6.7×10^{-7}		1.6×10^{-9} 3.9×10^{-9}	1.4×10^{-9} 3.5×10^{-9}
		Drum of LLW-Cemented Ash from MOX-FFP	Rupture + Fire Internal Explosion		2.5×10^{-8} 6.3×10^{-8}	2.2×10^{-8} 5.6×10^{-8}		1.3×10^{-10} 3.3×10^{-10}	1.2×10^{-10} 2.9×10^{-10}
		Box of LLW-failed equipment from MOX-FFP	Rupture + Fire Internal Explosion		6.2×10^{-9} 1.6×10^{-8}	5.3×10^{-9} 1.3×10^{-8}		3.2×10^{-11} 8.1×10^{-11}	2.8×10^{-11} 6.9×10^{-11}

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[a] For high-level waste receiving building and for mine, Stack" is main stack. For low-level waste receiving building, "stack" is building exhaust.

[b] α-TRU - α-emitting transuranic radionuclides with half-lives greater than one year.

[c] Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-10 - ESTIMATED AIRBORNE RELEASE RATES TO STACK OF RADIONUCLIDES RESULTING FROM AN ACCIDENT TO A SINGLE CONTAINER - SURF CYCLE, BPNL WASTE DATA

				AIRBORNE RELEASE RATES, Ci/sec					
				INITIAL RELEASE RATE AT STACK[a]			24-HR. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	Kr-85	PARTICULATES	α-TRU[b]	Kr-85	PARTICULATES	α-TRU[b]
Canistered Waste Receiving Building	Transfer Gallery (cold), Transfer Cell, Transfer Gallery (hot), Decon Well, Shaft Transfer Cell	Canister of PWR Spent Fuel	Rupture[c]	2.9 $+2.8 \times 10^{-2}$ H-3	4.1×10^{-7}	4.3×10^{-9}	2.0×10^{-2} $+1.9 \times 10^{-4}$ H-3	2.8×10^{-9}	3.0×10^{-11}
		Canister of BWR Spent Fuel	Rupture[c]	0.9 $+8.6 \times 10^{-3}$ H-3	1.2×10^{-7}	1.2×10^{-9}	6.2×10^{-3} $+6.0 \times 10^{-5}$ H-3	8.5×10^{-10}	8.1×10^{-12}
	Waste Canister Feed Room	Canister of PWR Spent Fuel	Rupture[c]	1.0 $+9.3 \times 10^{-2}$ H-3	1.4×10^{-7}	1.4×10^{-9}	2.0×10^{-2} $+1.9 \times 10^{-4}$ H-3	2.8×10^{-9}	3.0×10^{-11}
		Canister of BWR Spent Fuel	Rupture[c]	3.0×10^{-2} $+2.9 \times 10^{-2}$ H-3	4.1×10^{-8}	3.9×10^{-10}	6.2×10^{-3} $+6.0 \times 10^{-5}$ H-3	8.5×10^{-10}	8.1×10^{-12}
Underground Canistered Waste Receiving Station	Transfer Gallery, Transfer Cell, Transporter Loading Room	Canister of PWR Spent Fuel	Rupture[c]	1.0 $+9.3 \times 10^{-2}$ H-3	1.4×10^{-7}	1.4×10^{-9}	2.0×10^{-2} $+1.9 \times 10^{-4}$ H-3	2.8×10^{-9}	3.0×10^{-11}
		Canister of BWR Spent Fuel	Rupture[c]	3.0×10^{-2} $+2.9 \times 10^{-2}$ H-3	4.1×10^{-8}	3.9×10^{-10}	6.2×10^{-3} $+6.0 \times 10^{-5}$ H-3	8.5×10^{-10}	8.1×10^{-12}
Low-level Waste Receiving Building and Underground LLW Receiving Station	All areas	Drum of LLW Box of LLW	Rupture Rupture + Fire Internal Explosion	Negligible Releases Negligible Releases Negligible Releases					
Mine	Spent Fuel Storage	Canister of PWR Spent Fuel	Rupture[c]	3.9 $+3.7 \times 10^{-2}$ H-3	5.4×10^{-7}	5.7×10^{-9}	2.0×10^{-2} $+1.9 \times 10^{-4}$ H-3	2.8×10^{-9}	3.0×10^{-11}
		Canister of BWR Spent Fuel	Rupture[c]	1.2 $+1.1 \times 10^{-2}$ H-3	1.6×10^{-7}	1.6×10^{-9}	6.2×10^{-3} $+6.0 \times 10^{-5}$ H-3	8.5×10^{-10}	8.1×10^{-12}
	LLW Storage	Drum of LLW Box of LLW	Rupture Rupture + Fire Internal Explosion	Negligible Releases Negligible Releases Negligible Releases					

[a] For high-level waste receiving building and for mine, "stack" is main stack. For low-level waste receiving building, "stack" is building.

[b] α-TRU - α-emitting transuranic radionuclides with half-lives greater than 1 year.

[c] Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-11 - ESTIMATED AIRBORNE RELEASE RATES TO STACK OF RADIONUCLIDES RESULTING FROM AN ACCIDENT TO A SINGLE CONTAINER - U-ONLY RECYCLE, BPNL WASTE DATA

				AIRBORNE RELEASE RATES, Ci/sec.					
				INITIAL RELEASE RATE AT STACK[a]			24-HR. AVG. RELEASE RATE AT STACK[a]		
FACILITY	AREA	WASTE TYPE	ACCIDENT	H-3	PARTICULATES	α-TRU[b]	H-3	PARTICULATES	α-TRU[b]
Canistered Waste Receiving Building	Transfer Gallery (cold), Transfer Cell, Transfer Gallery (hot), Decon Well, Shaft Transfer Cell	Canister of HLW	Rupture[c]		2.2×10^{-7}	3.0×10^{-9}		1.5×10^{-9}	2.1×10^{-11}
		Canister of cladding	Rupture Rupture + Fire	9.4×10^{-3}	1.5×10^{-8} 1.5×10^{-8}	2.0×10^{-12} 2.0×10^{-12}	6.5×10^{-5}	1.0×10^{-10} 1.0×10^{-10}	1.4×10^{-14} 1.4×10^{-14}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		1.5×10^{-9}	1.3×10^{-9}		1.1×10^{-11}	9.3×10^{-12}
	Waste Container Feed Room	Canister of HLW	Rupture[c]		7.2×10^{-8}	1.0×10^{-9}		1.5×10^{-9}	2.1×10^{-11}
		Canister of cladding	Rupture Rupture + Fire	3.1×10^{-3}	5.0×10^{-9} 5.0×10^{-9}	6.7×10^{-13} 6.7×10^{-13}	$6.5\ 10^{-5}$	1.0×10^{-10} 1.0×10^{-10}	1.4×10^{-14} 1.4×10^{-14}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		5.1×10^{-10}	4.4×10^{-10}		1.1×10^{-11}	9.3×10^{-12}
Low-Level Waste Receiving Building and Underground LLW Receiving Station	All Areas	Drum of LLW Box of LLW	Rupture Rupture + Fire Internal Explosion	Negligible Releases Negligible Releases Negligible Releases					
Mine	HLW Storage	Canister of HLW	Rupture[c]		2.9×10^{-7}	4.0×10^{-9}		1.5×10^{-9}	2.1×10^{-11}
	ILW Storage	Canister of cladding	Rupture Rupture + Fire	1.2×10^{-2}	2.0×10^{-8} 2.0×10^{-8}	2.7×10^{-12} 2.7×10^{-12}	6.5×10^{-5}	1×10^{-10} 1×10^{-10}	1.4×10^{-14} 1.4×10^{-14}
		Canister of ILW	Rupture[c]	Negligible Releases					
		Drum of ILW	Rupture[c]		2.0×10^{-9}	1.8×10^{-9}		1.1×10^{-11}	9.3×10^{-12}
	LLW Storage	Drum of LLW Box of LLW	Rupture Rupture + Fire Internal Explosion	Negligible Releases Negligible Releases Negligible Releases					

[a] For high-level waste receiving building and for mine, "stack" is main stack. For low-level waste receiving building, "stack" is building exhaust.

[b] α-TRU - α-emitting transuranic radionuclides with half-lives greater than 1-year.

[c] Rupture in presence of fire would have negligible effect on the quantities of released radionuclides.

TABLE 3-12

ESTIMATED GROUND LEVEL CONCENTRATIONS OF RADIOACTIVITY FROM ACCIDENTAL RELEASES - OWI WASTE DATA

Cycle	Release	24-Hour Average Release Rate (Ci/sec)	Normal Atmospheric Conditions[a]		Fumigation Conditions[a]		Releases Relative of 10CFR20 Limits[b]
			Maximum (μCi/ml)	Fenceline (μCi/ml)	Maximum (μCi/ml)	Fenceline (μCi/ml)	
	Particulates[d]						
	Vitrified HLW						
I Total Recycle	(β-γ)	7.4×10^{-10}	7.4×10^{-14}	4.8×10^{-14}	1.5×10^{-12}	4.1×10^{-13}	20
	(α)	2.8×10^{-11}	2.8×10^{-15}	1.8×10^{-15}	5.6×10^{-14}	1.5×10^{-14}	0.77
	Calcined HLW						
	(β-γ)	2.3×10^{-8}	2.3×10^{-12}	1.5×10^{-12}	4.6×10^{-11}	1.3×10^{-11}	650
	(α)	8.3×10^{-10}	8.3×10^{-14}	5.4×10^{-14}	1.7×10^{-12}	4.6×10^{-13}	23
	H-3	2.0×10^{-4}	2.0×10^{-8}	1.3×10^{-8}	4.0×10^{-7}	1.1×10^{-7}	0.55
	C-14	5.0×10^{-7}	5.0×10^{-11}	3.3×10^{-11}	1.0×10^{-9}	2.8×10^{-10}	0.0003
II SURF	Kr-85	1.3×10^{-2}	1.3×10^{-6}	8.5×10^{-7}	2.6×10^{-5}	7.2×10^{-6}	24.00
	Particulates[c]						
	(β-γ)	2.2×10^{-9}	2.2×10^{-13}	1.4×10^{-13}	4.4×10^{-12}	1.2×10^{-12}	60.50
	(α)	3.3×10^{-11}	3.3×10^{-15}	2.2×10^{-15}	6.6×10^{-14}	1.8×10^{-14}	1.00
	Particulates[d]						
	Vitrified HLW						
III U-Only Recycle	(β-γ)	9.5×10^{-10}	9.5×10^{-14}	6.2×10^{-14}	1.9×10^{-12}	5.2×10^{-13}	26
	(α)	2.0×10^{-11}	2.0×10^{-15}	1.3×10^{-15}	4.0×10^{-14}	1.1×10^{-14}	0.55
	Calcined HLW						
	(β-γ)	2.6×10^{-8}	2.6×10^{-12}	1.7×10^{-12}	5.2×10^{-11}	1.4×10^{-11}	700
	(α)	5.5×10^{-10}	5.5×10^{-14}	3.6×10^{-14}	1.1×10^{-2}	3.0×10^{-13}	15

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[a] Table 2-8.

[b] MPC limits from Appendix B, Table II, Column 1. Ratio computed using fenceline with fumigation conditions.

[c] PWR rst Case).

[d] Worst Case.

TABLE 3-13

ESTIMATED GROUND LEVEL CONCENTRATIONS OF RADIOACTIVITY FROM ACCIDENTAL RELEASES - BPNL WASTE SET

Cycle	Release	24-Hour Average Release Rate (Ci/sec)	Atmospheric Conditions[a]		Fumigation Conditions[a]		Releases Relative to 10CFR20 Limits
			Maximum (Ci/ml)	Fenceline (Ci/ml)	Maximum (Ci/ml)	Fenceline (Ci/ml)	
I Total Recycle	Particulates[d]						
	(β-γ)	4.0×10^{-10}	4.0×10^{-14}	2.6×10^{-14}	8.0×10^{-13}	2.2×10^{-13}	11
	(α)	3.5×10^{-9}	3.5×10^{-13}	2.3×10^{-13}	7.0×10^{-12}	1.9×10^{-12}	96
II SURF	H-3	2.0×10^{-4}	2.0×10^{-8}	1.3×10^{-8}	4.0×10^{-7}	1.1×10^{-7}	0.55
	C-14	2.2×10^{-6}	2.2×10^{-10}	1.4×10^{-10}	4.4×10^{-9}	1.2×10^{-9}	0.012
	Kr-85	2.0×10^{-2}	2.0×10^{-6}	1.3×10^{-6}	4.0×10^{-5}	1.1×10^{-5}	37
	Particulates[c]						
	(β-γ)	2.8×10^{-9}	2.8×10^{-13}	1.8×10^{-13}	5.6×10^{-12}	1.5×10^{-12}	75
	(α)	3.0×10^{-11}	3.0×10^{-15}	2.0×10^{-15}	6.0×10^{-14}	1.7×10^{-14}	0.83
III U-Only Recycle	Particulates[e]						
	(β-γ)	1.5×10^{-9}	1.5×10^{-13}	9.8×10^{-14}	3.0×10^{-12}	8.3×10^{-13}	41
	(α)	2.1×10^{-11}	2.1×10^{-15}	1.4×10^{-15}	4.2×10^{-14}	1.2×10^{-14}	0.58

[a] Table 2-8.
[b] MPC limits from Appendix B, Table II, Column 1. Ratio computed using fenceline with fumigation conditions.
[c] Rupture of PWR container (Worse Case).
[d] Explosion in LLW-Filter Media container (Worst Case).
[e] Rupture of Vitrified HLW canister (Worst Case).

4.0 MINE FIRE ANALYSIS

4.1 POSSIBLE FIRE HAZARDS FROM THE EVOLUTION OF RADIOLYTIC HYDROGEN

Bitumen fixation of wet wastes has been considered by BPNL as a possible alternative waste form. Ionizing radiation in the waste will liberate hydrogen from the molecular structure of the bitumen at a rate dependent on the energy deposited within the material. The possibility that the hydrogen generated in the waste and released to the room could result in a fire hazard is investigated herein. A hydrogen-in-air mixture becomes combustible when the hydrogen concentration falls between 4% and 74% by volume.

4.1.1 Generation of Hydrogen - Background

Alpha, beta, and gamma-emitting wastes could conceivably be included in a matrix of bitumen for storage. This waste would be in the form of fine particles dispersed evenly through the matrix. Short-range alpha and beta radiation would be stopped in the bitumen in the immediate vicinity of their sources. Small amounts of the gamma radiation would also be absorbed by the bitumen in the container while most of this higher energy radiation escapes. The radiation absorption excites the bitumen molecules sufficiently to make some of these molecules undergo free radical formation and chemical reaction. Through these chemical reactions saturated bitumen compounds will be converted to unsaturated compounds and molecular hydrogen. Carbon dioxide and light hydrocarbons may also be produced in minor amounts. The amount of hydrogen generated by such reactions would be dependent on the properties of the bitumen and the energy absorbed. The amount of energy absorbed by the bitumen is indicated by the waste heat generation properties. Unsaturated and aromatic hydrocarbons are less susceptible to hydrogen formation, since these substances are better at dissipating energy without chemical reaction. The bitumen used in waste fixation may be considered to be unsaturated and aromatic in nature, both by choice of material and by the generation of unsaturated bonds during irradiation.

Research conducted by Watson and Parkinson[1] with natural and artificial membrane materials shows that approximately 0.34 molecules of H_2 is produced for every 100 eV of ionizing energy absorbed, compared to 4 molecules per 100 eV for saturated hydrocarbons. The generated H_2 will form voids in the material and causes the bitumen to swell. Swelling occurs rapidly, which increases the volume approximately 25 percent for an irradiation of 10^7 rads. An expansion of this magnitude would adversely affect the container. As the absorbed dose increases above 10^7 rads, evolution of the gas becomes important. At high doses (>10^8 rads) the evolution rate approaches 0.8 cc (at STP) per gram per 10^8 rads.[1]

For this analysis, it is assumed that the gas escapes the asphalt at the same rate it is generated and that no swelling occurs because of low viscosity (bubbles migrate to surface), or because of very high viscosity (material cracks, allowing gas to escape). Also, aromatic and olefinic asphalts are assumed to give a gas production rate of 0.8 cc (at STP) per gram per 10^8 rads. An aliphatic asphalt could conceivably generate 10 times as much gas; however, since most of the energy will be deposited by short range alpha radiation, the small volumes surrounding the radioactive particles would soon be converted to unsaturated compounds which yield the lower gas generation rates.

4.1.2 Calculations

The BPNL combustible waste data set (Table 4-1) was used here because it specifies three types of waste drums containing bitumen: one in the low-level regime and the other two in the intermediate-level regime. Since container swelling should be avoided, the use of materials that do not swell is assumed. This zero-expansion case yields the hydrogen generation rate that is used in mine fire hazard determination.

Since thermal data are only defined for the ILW (>10R/hr) cemented case,[2] doses will be calculated from these data and then ratioed for the other two cases by using the ratios of actinide activities from (Appendix E, Tables E-2 and E-15 of Reference 2).

Table E-15 lists the thermal power of cemented ILW (>10R/hr) as 0.25 watts per drum and 0.17 watts per drum at time zero and ten years, respectively. Over this interval the decrease in thermal power may be approximated as an exponential decay:

$$P_T = P_o e^{-\lambda}$$

Where P_T = power at time T (watts)
P_o = power at time 0 (watts)
T = time (years)

Setting $P_o = 0.25$ watt/drum, $P_{10} = 0.17$ watt/drum, and T = 10 years yields $\lambda = 0.0386\ \text{yr}^{-1}$. This simple model should not be extrapolated beyond T = 10 years.

The cumulative energy deposition in the cemented ILW is obtained by integrating the thermal power over time:

$$\text{cumulative energy deposition} = \int_0^T P_o e^{-\lambda t} dt = \int_0^T 0.25 e^{-0.0386t} dt$$

$$= 6.477 e^{-0.0386t} \Big[_0^T$$

$$= 6.477(1-e^{-0.0386T}) \text{ [watt-year/drum]}$$

Using the above relation, the energy deposited in ILW as a function of time is given in Table 4-2.

The energy deposition function for cemented ILW derived above may be applied to bituminized ILW through the use of an appropriate scale factor, since thermal data were only available for the cemented ILW case (Reference 2). This assumption is valid because cementation and bituminization are alternate methods of treating the same wastes. Therefore, the isotopic distribution, total activity, and total thermal power would be the same for either waste type. The main difference between the two forms would be the concentration of the wastes. As defined by BPNL (Table 4-1), 2526 drums of cemented wet wastes (ILW>10R/hr), or 685 drums of bituminized wet wastes (ILW>10R/hr), would be produced from the reprocessing of 2000 MTHM. The ratio of waste concentrations is then

$$\frac{\text{2526 drums cemented waste}}{\text{685 drums bitumized waste}} = 3.69$$

This factor is used to relate cemented waste properties to bitumized waste properties such as total activity, thermal power, and energy deposition.

As stated before, 2 ILW cases and 1 LLW case were investigated. For identification, ILW, with a dose rate of >10 R/hr, is referred to as ILW Case 1 and the ILW with a dose range of 0.2-1 R/hr is referred to as ILW Case 2.

Intermediate-Level Waste Case 1. (>10R/hr)

The hydrogen production for ILW Case 1 (bituminized wet wastes, >10R/hr) may be obtained by using the previously derived relationships in the following expression:

$$V = 3.69\, C\, E_c$$

where

V = volume of hydrogen gas produced (cm^3)

C = proportionality constant, which yields volume of hydrogen produced per unit of energy deposited in waste

$$= 0.8\ \frac{cm^3(STP)}{10^8\ Rad\ g} \times \frac{1\ Rad}{100\ erg/g} = 8x10^{-11}\ \frac{cm^3(STP)}{erg}$$

E_c = energy absorbed in cemented waste drum (erg/drum)

3.69 = scale factor for converting the cemented waste absorbed energy to bituminized waste absorbed energy.

Substituting the value for C into the equation yields (at STP)

$$V = 2.95x10^{-10} E_c\ \left(\frac{cm^3 H_2}{drum}\right)$$

$$= 1.04x10^{-14} E_c\ \left(\frac{ft^3 H_2}{drum}\right)$$

Based on the energy deposition (Table 4-2), the hydrogen generation from an ILW drum containing bitumen were calculated and are presented as a function of time during the retrievability phase in Table 4-3. From Table 4-3, the total hydrogen generated in the 5-year retrievable period (Years 5-10) is:

$$6.79 - 3.72 = 3.1\ \text{ft}^3\text{H}_2/\text{drum} \quad \text{(Table 4-4)}$$

Yearly generation rates are presented in Table 4-4.

Intermediate-Level Waste Case 2 (.2-1.0 R/hr)

Assuming that the nuclide distribution of Case 2 waste is the same as Case 1 waste, the same power decay rate may be applied to Case 2. The hydrogen production for Case 2 may then be scaled from Case 1. An appropriate scale factor is assumed to be the ratio of the actinide activities (Table 4-1) for the two waste forms:

$$\text{Scale factor} = \frac{\text{Case 2 actinides}}{\text{Case 1 actinides}} = \frac{0.66\ \text{Ci}}{550\ \text{Ci}} = 1.2\text{x}10^{-3}$$

Applying this factor to the hydrogen volume calculated for Case 1 gives the volume generated for the 5-year retrievable period as

$$1.2\text{x}10^{-3}(3.1\ \text{ft}^3\text{H}_2/\text{drum}) = 3.72\text{x}10^{-3}\ \text{ft}^3\text{H}_2/\text{drum}.$$

Over the retrievability period, the average production would be

$$7.44\text{x}10^{-3}\ \text{ft}^3/\text{year} \text{ (Table 4-4)}.$$

Low-Level Waste (<0.2 R/hr)

Worst case (i.e. MOX fabrication waste from a fuel reprocessing plant - FRP) hydrogen production is calculated in the same manner used in ILW Case 2 above.

The actinide ratio of LLW and ILW Case 1 (Table 4-1) is found using the following scale factor.

$$\text{Scale factor} = \frac{35\ \text{Ci}}{550\ \text{Ci}} = 0.064$$

Applying this factor to the hydrogen volume calculated for Case 1 yields the volume generated for the 5-year retrievable period as

$$0.064(3.1\ \text{ft}^3\text{H}_2/\text{drum}) = 0.2\ \text{ft}^3\text{H}_2/\text{drum}$$

Over the retrievability period, the average production would be $3.97\text{x}10^{-2}$ ft^3/year (Table 4-4).

4.1.3 Concentrations in the Mine

The hydrogen concentration in the room air is calculated by using the hydrogen generation results, the number of drums per room and the size of the rooms. All the hydrogen generated during 5 years is assumed to remain in the room air.

4.1.3.1 Intermediate-Level Rooms

In salt, ILW drum storage rooms have the following specifications:

20' high x 36' wide x 1645' long
20' high x 36' wide x 3295' long
20' high x 36' wide x 1990' long

At 2580 drums in the 1645' long room, the loading density is 1.5 drums/linear foot (same for all room lengths).

The percentage of drums that contain bitumen, from Table 4-1 (based on 2000 MTHM)

$$\frac{685\ \text{Case 1 drums}}{12261\ \text{Total ILW drums}} = 0.06\ \text{or}\ 6\%$$

$$\frac{659\ \text{Case 2 drums}}{12261\ \text{Total ILW drums}} = 0.06\ \text{or}\ 6\%$$

Case 1 and 2 make up 6% each

$$1.5(6\%) = 0.09\ \text{drums/linear foot}$$

H_2 concentration per linear foot is: (Using Table 4-4)

$$0.09(3.1\ ft^3/drum) + 0.09(3.72 \times 10^{-3}\ ft^3/drum) = 0.28\ ft^3/linear\ foot$$

$$\text{Concentration} = \frac{0.28\ ft^3}{20 \times 36 \times 1\ ft^3} = 4.0 \times 10^{-4}$$

or 400 ppm in room

As a worst case, assume all the drums in the room contain bitumen as in ILW Case 1. The concentration would now be:

$$400\ ppm\ \frac{100}{6} = 6700\ ppm$$

The lower flammability limit for hydrogen-air mixtures is 40,000 ppm H_2.

4.1.3.2 Low-Level Rooms

Storage room specifications in salt for LLW drums are:
20' high x 36' wide x 640' long
20' high x 36' wide x 1600' long

At a maximum of 37,440 drums in a 1600' long room, the loading density is 23.5 drums/linear foot.

Since the drums are stored on the floor, the void air space per linear foot is equal to (20 x 36 x 1) - 23.5 (7.35 ft^3/drum) = 550 ft^3.

The percentage of drums that contain bitumen, from Table 4-1 (based on 2000 MTHM).

$$\frac{2342\ drums}{22{,}745\ total\ LLW\ drums} = 0.10\ or\ 10\%$$

10%(23.5) = 2.35 drums/linear foot

H_2 concentration is (using Table 4-4):

$$2.35(0.2\ ft^3/drum) = 0.47\ ft^3/linear\ foot$$

$$\frac{0.47\ ft^3}{550\ ft^3\ void} = 8.55 \times 10^{-5} = 85\ ppm$$

As a worst case, assume all LLW drums contain bitumen, then:

$$85(\frac{100}{10}) = 850 \text{ ppm}$$

4.2 COMBUSTIBLE WASTE STORAGE

4.2.1 Probabilities of Fires in the Nuclear Waste Repository

Several fires have occurred in containers of low-level wastes at commercial and government-operated waste burial grounds. Most of these fires have been caused by spontaneous combustion of loosely packed pyrophoric materials consisting of mixtures of rags, paper, cardboard, wood, plastics, and rubber. In some instances, the waste may be partially wetted with solvents or reactive chemicals that serve as self-ignition sources. Fires have also occurred as a result of handling accidents in which containers have been ruptured. Documentation of three major government waste burial grounds are found in References 3, 4, and 5

A low-level waste burial ground has been operated on an extensive scale at the Savannah River Plant (SRP) since 1953.[3] The miscellaneous low-level wastes processed at the SRP are similar to those that might be processed at the deep geologic repository if combustible waste forms were allowed. Therefore, the occurrence of fires at the SRP can be used as a basis for estimating the frequency of fires that could occur at the repository.

During the 23-year period from 1953 through 1975, 252,000 m^3 of miscellaneous solid wastes were buried at the SRP. Until 1973, the combustible wastes were not packaged in separate containers from the noncombustible wastes; consequently, fires could conceivably have occurred in nearly all of the waste materials handled. During this period, less than a dozen small fires occurred at the SRP burial grounds, with a resulting frequency of one fire for approximately 21,000 m^3 of wastes handled.

In the case of the generic waste repository, the average annual rate of heavy metal reprocessing is estimated to be 6000 MTHM. This recycle activity will produce an average of 15,000 m^3 of combustible low-level and intermediate-level wastes per year, that had not been immobilized in cement or bitumen, to be processed at the repository. Based on the actual experience at SRP for processing similar wastes, one combustible waste fire would be predicted to occur during handling and storage at the underground repository every 1.4 years on the average. Immobilization of low-level liquid wastes in a bituminous binder has come into fairly general practice, particularly in Europe, during the past years. There is as yet no long-term experience for handling bitumen-stabilized wastes comparable to the actual SRP experience with handling large volumes of unstabilized wastes.

Present experience indicates that most fires involving miscellaneous low-level wastes have occurred because of exothermic reactions causing spontaneous combustion of mixtures of partially compacted waste materials. Investigations at the Royal Military School (RMS) in Brussels, Belgium were performed on bitumen containing salts of $NaNO_3$ and $NaNO_2$ together with insoluble solids.[6] Through the use of differential thermograms, it was concluded that no exothermic reaction occurs below 295°C (563°F). On this basis, fires involving wastes in a bituminous binder would be limited to those caused by handling accidents, and fires caused by a spontaneous combustion would be virtually eliminated. Conservatively assuming that 10 percent of the fires in waste handling operations have been the result of handling accidents, a fire would then be expected to occur after approximately 210,000 m^3 of bitumen stabilized wastes are handled. Using the data from the sample case (Table 4-1), about 2300 m^3 of bituminized wastes would be processed annually with a predicted occurrence of a fire only once in 90 years of operation.

4.2.2 Waste Compositions

For this analysis, the case of packaged intermediate and low-level wastes in combustible forms defined by BPNL was used (Table 4-1). In terms of potentially combustible materials, the LLW and ILW combustible trash are representative and are considered here for estimations of heat release rates and ash and smoke generation. These wastes are applicable to both recycle cases. However, the material was provided from BPNL for the Total Recycle case only.

To calculate maximum heat generation rates, a detailed chemical composition of the waste is required. The breakdown shown in Table 4-5 for low-level TRU waste is based on a standardized waste composition used in the development of an acid digestion process for the low-level TRU wastes at the Hanford Engineering Development Laboratory.

4.2.3 Accident Scenarios

Possible accidental occurrences have been detailed in Table 4-6. For purposes of this analysis, the accident scenarios are considered to result in one of two incidents involving untreated combustible wastes: (1) the container is completely opened and the ignited contents are exposed to the air and burn freely, or (2) two approximately six-inch diameter holes are punctured into the drum in relative locations such that a draft can go through the drum and result in slow burning of the ignited contents. In the second case, the burn rate will be determined by the rate of transport of oxygen into the drum which, for this study, has been equated to the ventilation flow rate in the area of the accident.

4.2.4 Burning Rates

The intensity of fires occurring in combustible waste containers depends on a large number of variables that are not well defined. They include the compacted density of the solid wastes, the combustible character of the packaged wastes, (i.e., the proportions of rags, paper, wood, and plastics in a particular container), the integrity of the container lids and seals restricting air ingress during a fire, the concentration of reactive chemicals that could initiate spontaneous combustion, and the ability of the container to withstand high temperatures. Most of the fires are predicted to be caused by spontaneous combustion within a waste container with an ill-fitting cover. Under these conditions, the fire is typified by the evolution of dense smoke; however, the heat generation rate remains low and the fire is generally confined to a single container. On infrequent occasions, a waste container may be ruptured by a handling accident and the exposed waste materials may then be ignited by any of several causes. If this situation occurs, the supply of oxygen to the fire may not be limiting, and burning may proceed rapidly with a high heat generation rate.

Experience with burning of combustible low-level waste trash in an incinerator under favorable combustion conditions indicates that a maximum of approximately 250-to-300 lbs/hr of waste can be burned.[7] Since conditions of air circulation into and through the burning mass are likely to be less than optimum in an accident situation, it is estimated that a maximum burning rate of approximately 150 lbs/hr will result when a drum of untreated combustible trash is completely opened.

When a drum is punctured, the rate of burning of the contents will be controlled by the rate at which air can be drawn into the drum while the combustion products escape. For a laminar flow of air, the rate of air ingress into the drum with two equal-sized holes can be approximated by the equation $Q=A \times V$, where Q = rate of ingress of air, A = area of hole, and V = velocity of ventilation air through the rooms. For the punctured drum accident, 6-inch diameter holes (0.20 ft^2 area) are assumed. The velocity of ventilation air through the room is different for the different areas. The velocities for the various areas and the resultant rates of ingress of air into a drum are listed in Table 4-7 for complete recycle of U and Pu. The intermediate-level waste will be received in the high-level waste receiving building.

The following combustion equations are used in calculating the burning rates in Table 4-7:

Latex, vulcanized:

$$\frac{1}{n}(C_5H_8)_n + 7\,O_2 \rightarrow 5CO_2 + 4H_2O\ (g) \qquad (1)$$

Cellulose:

$$\frac{1}{n}(C_{11}H_{18}O_8)_n + \frac{23}{2}O_2 \rightarrow 11\,CO_2 + 9H_2O\ (g) \qquad (2)$$

Neoprene, vulcanized:

$$\text{half } \frac{1}{n}\,(C_4H_5Cl)_n + \frac{21}{4}\,O_2 \rightarrow 4CO_2 + \frac{5}{2}\,H_2O(g) + \frac{1}{2}\,Cl_2\ (g) \qquad (3)$$

$$\text{half } \frac{1}{n}\,(C_4H_5Cl)_n + 5O_2 \rightarrow 4CO_2 + 2H_2O(g) + HCl(g) \qquad (4)$$

Polyvinyl chloride:

$$\text{half } \frac{1}{n}\,(C_2H_3Cl)_n + \frac{11}{4}\,O_2 \rightarrow 2CO_2 + \frac{3}{2}\,H_2O(g) + \frac{1}{2}\,Cl_2\ (g) \qquad (5)$$

$$\text{half } \frac{1}{n}\,(C_2H_3Cl)_n + \frac{5}{2}\,O_2 \rightarrow 2CO_2 + H_2O(g) + HCl(g) \qquad (6)$$

Using the approximate waste composition given in Table 4-5, one calculates that the complete combustion of 1 lb of waste consumes 1.69 lbs of O_2 or 103 scf of air.

For an open container, burning of the contents at the maximum rate of 150 lbs/hr will consume oxygen from 258 scfm of air. This corresponds to the following percentages of air flowing through the different handling and storage areas:

LLW Receiving Building:

Decon & overpack room	60.0%
Palletizing & depalletizing room	10.0%
Unloading & parking room	6.5%

HLW Receiving Building:

Cask unloading & decon room (smallest)	1.0%
Transfer cell (hot)	40.0%
Recan transfer cell (hot)	29.0%
Transfer cell (cold)	26.0%
Recan tranfer cell (cold)	8.2%
Canister storage feed room	1.0%

Mine:

LLW storage area	0.53%
ILW storage area:	
Type 1 (majority of rooms)	0.33%
Type 2	0.53%

For the opened container, the maximum oxygen consumption rate is small compared with the total room air flow rate, except for the decontamination and overpack room in the LLW receiving building and the hot transfer cell in the HLW receiving building. Thus, in those areas, after an initial fast burn rate of near 150 lbs/hr, the average burn rate would decrease.

4.2.5 Heat Release Rates

In order to estimate the heat release rates during combustion of untreated trash, standard enthalpies of formation (ΔH_f^o) for all the reactants and combustion products are needed. The necessary data obtained from the literature are tabulated in Table 4-8. In calculating the combustion heats, it is assumed that the vulcanized forms of latex and neoprene are in the waste. It was necessary to estimate the standard enthalpy of formation for neoprene; details are given in Appendix A.

The standard enthalpy change for a chemical reaction is calculated from the equation

$$\Delta H^o_{\text{reaction}} = \Sigma\Delta H^o_{f,\text{products}} - \Sigma\Delta H^o_{f,\text{ reactants}}$$

where the individual ΔH_f^o's are for the stoichiometric quantities in the balanced reaction equation. In the case of combustion reactions, $\Delta H^o_{\text{reaction}} = \Delta H^o_{\text{combustion}}$.

The data in Table 4-8 were used to calculate the combustion heats for each of reactions (1) through (6). The combustion heats were converted to a weight basis for each waste constituent, and, using the waste composition of Table 4-5, the heat of combustion per unit weight of waste mixture was calculated to be -5.88 kcal/g or -10,600 Btu/lb. Since a drum of combustible trash contains 55 lbs of trash (Table 4-1), the maximum heat available for release from the burning of the contents of one drum is 580,000 Btu.

The rates of heat release for the different accident cases are listed in Table 4-9. The burn rates from Section 4.2.4 were used (150 lbs/hr for opened container, and as listed in Table 4-7 for punctured containers), along with the heat release of 10,600 Btu/lb in arriving at the figures.

4.2.6 Flame Temperatures

The estimated heat of combustion (-5880 cal/g waste mixture) is used to calculate the temperature of combustion products in the flame. As a first approximation, the combustion process is assumed to be adiabatic. After calculating the maximum flame temperature using this assumption, corrections are made for practical deviations from the idealized maximum calculated temperature.

For an adiabatic process, the heat released from the combustion is absorbed by the combustion products, and the following relationship holds[8]:

$$-\Delta H^{\circ}_{combustion} = \int_{298}^{T_f} \Sigma(nC_p)_{products} dT$$

The heat generated is $-\Delta H^{\circ}_{combustion}$ and C_p is heat capacity. The final flame temperature is T_f. The combustion heat is calculated at 298°K.

Heat capacity equations tabulated by Kelley[9] were used for the combustion products CO_2, $H_2O(g)$, N_2, HCl(g), and Cl_2 (g) and for TiO_2, along with the stoichiometric equations (1) through (6) and the waste composition given in Table 4-5 to derive a total heat capacity for the products of

$$C_p = 2.18 + 3.64\text{x}10^{-4}\ T - \frac{1.20\text{x}10^{4}}{T^2} \text{ cal (deg C)}^{-1} \text{ (g waste)}^{-1}$$

The major non-conbustible material in the waste is considered to be TiO_2, which is a component of latex.

An idealized maximum flame temperature is calculated to be 2190°C. The actual temperature of a flame is a few hundred degrees lower because some heat is lost to the surrounding air containing inert nitrogen which must be heated. Excess air is required for complete combustion. Some dissociation of H_2O and CO_2 may occur, and other possible products than CO_2 and H_2O may form.[8]

Perry and Chilton list adiabatic flame temperatures and actual maximum flame temperatures for a number of hydrocarbons.[10] The difference averages approximately 300°C and the average actual flame temperature is approximately 1900°C. Therefore, it is assumed that the actual flame temperature of the burning waste mixture will be approximately 1890°C (3430°F), 300°C lower than the idealized adiabatic temperature.

Estimating the flame temperature is important from the standpoint of effects on waste drums or equipment that might be in direct contact with the flame. If the object is not directly in the flame, then any adverse effects would be caused by heat released by the burning waste (Section 4.2.5). The temperatures resulting from indirect heating would be much lower than the actual flame temperature.

4.2.7 Airborne Releases of Smoke and Radioactive Materials

Some insight into the quantities of radioactivity that may become airborne as a consequence of a fire in a low-level waste container can be deduced from experiments at Harwell, England,[6], in incinerating low-level solid wastes. Measurements of the amounts of the ash product showed that 95 percent of the radioactivity was retained in the ash in the incinerator, while the remaining 5 percent was carried into the incinerator offgas system as smoke and fly ash. Further, the entrained particulates and aerosols consist of particles between 0.01 and 200 μm with 20 percent (or 1 percent of the combustible waste) consisting of particles less than 8 μm. If products of similar characteristics is assumed to be formed when the contents of a container are burned accidentally, then 5 percent of the radioactivity within the container would be released to operating or storage areas. Further dispersal then occurs by means of the facility ventilation system.

There are several areas within the repository facility in which low- and intermediate-level containers are handled or processed. In these operation areas, the ventilation system will provide for air interchange at the rate of 2 to 10 times in an hour. The maximum ventilation air velocity is expected to occur in the LLW cargo carrier unloading area and is calculated to be 0.2 ft per second. Using the formula from page 5-45 of reference 10, the maximum size of a particle that would be swept into the facility ventilation system in this area can be calculated:

$$V_{c,h} = 270 \left(\frac{\rho s}{\rho_s + 62.3} \right) D_s^{0.40}$$

$V_{c,h}$ = carrying velocity of the air stream, ft per sec.

ρ_s = density of the solids particle, lb per ft^3.
= 125 lb per ft^3 for carbon; density = 2 grams/cm^3

D_s = diameter of largest particle conveyed, ft

$$0.2 = \frac{125}{125 + 62.3} D_s^{0.40}$$

D_s = 0.012 μm, (this is also the smallest assumed particle size)

In summary, a fire limited to the contents of a single container of unstabilized wastes would probably release less than 5 percent of the radioactivity in the wastes to the operating space surrounding the container. Because the air velocity maintained within the operating spaces is on the order of 0.2 feet per second, all but the very small particles (less than 0.012 μm) would remain in the area. Since about 1 percent of the waste consists of particles less than 8 μm in size, it has been assumed that 0.1 percent of the waste consists of particles less than 0.012 μm.

Estimated airborne quantities of radioactive contaminants are expressed in terms of percentage of the total assumed activity present in a given container (Table 4-1). Five percent of the burning waste is released, and 0.1 percent of that burned is swept into the ventilation system.

Applying the above percentages to the burn rates (Section 4.2.4), the release rates of particulates (smoke and ash) and of radionuclides are calculated. These results are displayed in Table 4-10 and are representative of the areas that have the highest burn rate.

4.2.8 Consequences of a Waste Fire

In the event of a fire confined to the contents of a single ILW drum, the filters of the ventilation system would be expected to be exposed to a particulate loading of 5.5×10^{-2} pounds of particulates containing approximately 6×10^{-4} Ci of radioactive products as shown in Table 4-10 for the ILW container with the maximum radioactivity content. The facility ventilation system with two sets of HEPA filters is expected to have an efficiency in excess of 99.7 percent per set for particles less than 0.3 µm, DF of 10^6; therefore, the total radioactivity released to the facility stack would be expected to be approximately 6×10^{-10} Ci.

Since the release occurs in a period of 22 minutes (highest burn rate), the average release rate from the stack during this time would be about 2.73×10^{-11} Ci/min. Applying an atmospheric dispersion factor of 5.5×10^{-4} sec/m^3 (worst case for fenceline from Table 2-8), the ground-level concentration would be about 2.5×10^{-16} µCi/ml. This value is about 80 times below the NRC guidelines for concentrations of radionuclides in an unrestricted area.

The area in which the fire occurred would be contaminated by the radioactivity that would be released from the drum, but this radioactivity would consist of particles too large to be swept into the ventilation system. If the fire were to involve a single ILW drum containing the maximum radioactivity, then approximately 3×10^{-2} Ci of activity contained in approximately 3 pounds of particulates would be dispersed within the room in which the fire occurred. The impact of the fire would be essentially limited to the decontamination efforts necessary to restore the area to normal radiation levels.

4.2.9 Spread of Fire to Adjacent Drums

When the combustible contents of a drum are exposed and ignited, a concern may exist about whether nearby drums of combustible material may also be ignited by exposure to the heat from the fire, and thus initiate a chain reaction. Experience with accidental fires to combustible LLW at the Savannah River Plant indicates that the likelihood of multiple drum fires is very small. Of the few (less than a dozen) occurrences of fire to waste drums, none has resulted in ignition of additional drummed combustible waste.[2]

The wastes will be received at the repository in containers that meet or exceed the requirements for transport of radioactive materials issued by the Department of Transportation.[11] Under these regulations, any shipping package containing an aggregate in excess of 20 Ci of transuranic isotopes (Pu, Am, Np, Cf) and some of the isotopes of thorium and uranium, must be transported in a container capable of withstanding exposure to a fire at 1475°F with an emissivity of 0.9 for 30 minutes without release of radioactivity, with the exception of radioactivity in gases or the transport package coolant. Based on these regulations, until the shipping units are unloaded, a fire in the repository receiving area could not spread to the contents of the shipping units.

It is conceivable that a single handling accident at the repository might result in the destruction of the three inner containers of intermediate-level waste packaged in a storage basket. (Design indicates 3 drums per basket.) If the entire contents of the three containers were to be ignited, then a fire could result with a heat generation rate of approximately 80,000 Btu/minute with flame temperatures of 1900°C (Table 4-9). A primary fire of this magnitude could serve as an ignition source for secondary fires within waste containers immediately adjacent to the primary fire. These secondary fires would be limited in severity by the integrity of the intact waste containers. If these containers were in turn partially breached by the combined actions of the primary and secondary fires, the heat generation rates of the secondary fires would be expected to approximate the cases for punctured drums listed in Table 4-9. These heat generation rates (a maximum of about 2100 Btu/minute) are not sufficient to permit the further spread of a fire to intact waste containers adjacent to the secondary fires.

If the fire were considered to have spread from the primary source of three containers to include six more containers of intermediate-level wastes in the immediate vicinity as secondary fires, then a total of nine containers could conceivably be involved in the fire. Under these conditions, the total radioactivity released to the facility stack could be expected to be approximately a factor of 10 more than the release from a single container, or about 6×10^{-9} Ci. The fenceline concentration resulting from this release would also be about 10 times higher than the single can fire, or less than 2.5×10^{-15} μCi/ml. This concentration is approximately one order of magnitude less than NRC limits for unrestricted areas.

This rationale would also apply to low-level waste drums on pallets. However, it is most likely that combustible and non-combustible waste drums will be intermixed on the exposed pallets. If a fire were to spread, a very conservative estimate of the stack releases would be 20 times the release from a single container or 7.3×10^{-10} Ci. With a burn rate of 7.8 lb/hr (Table 4-7) the fire would last approximately 7 hours (if uncontrolled). The average release from the stack during this time would be about 1.73×10^{-12} Ci/min. Applying a conservative dispersion model to this release, as in Section 4.2.8, (dispersion factor of 5.5×10^{-4} sec/m^3), the ground-level concentrations at the fence would be about 1.6×10^{-17} μCi/ml. This concentration is about 3 orders of magnitude less than the NRC limits for unrestricted areas.

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Table 4-1* PACKAGED INTERMEDIATE AND LOW-LEVEL TRU WASTES FROM FRP

Plutonium and Uranium Recycle

Waste Treatment: Minimum Treatment, Bitumen Fixation, Packaging

Packaged Waste Description	Container	Containers/ 2000 MTHM	Packaged Density g/cc	Radioactivity, Ci/Container			Surface Dose (1) R/hr	Treated Waste Composition
				FPs	Actinides	Activation		
LLW Combustible Trash	55 gal drums	12,000	0.12	2.3×10^{-4}	3.4×10^{-5}		< 0.2 (0.003)	Paper rags. PVC neoprene, latex, wood
LLW Combustible Trash	55 gal drums	700	0.12	1.0×10^{-2}	2.6×10^{-2}	3.5×10^{-4}	< 0.2 (0.12)	Paper, rags, PVC neoprene, latex, wood
Noncombustible Trash - General	55 gal drums	431	0.25	1.6×10^{-2}	2.3×10^{-3}		< 0.2 (0.1)	90% Ferrous Metals 10% Glass
Noncombustible Trash, PuO_2 Conversion	55 gal drums	52	0.25		4.4×10^{2}		< 0.2 (0.01 - .015)	90% Ferrous Metals 10% Glass
Failed Equipment General	4'x6'x6' boxes	50	0.5	7.5×10^{-2}	1.1×10^{-2}		< 0.2 (0.1)	100% Metal
Failed Equipment PuO_2 Conversion	4'x6'x6' boxes	10	0.5		2.0×10^{2}		< 0.2 (6×10^{-4})	100% Metal
Bitumenized Wet Wastes	55 gal drums	42	0.8	5.2×10^{-2}	8.9×10^{-1}		< 0.2 (0.13)	Bitumen, Silica Gel
Noncombustible General Trash	55 gal drums	1500	0.25	8.9×10^{-2}	1.3×10^{-3}		< 0.2 - 1.0 (0.5)	90% Ferrous Metals 10% Glass
Noncombustible Trash, PuO_2 Conversion	55 gal drums	6	0.25		2.7×10^{3}		< 0.2 - 1.0 (0.6)	90% Ferrous Metals 10% Glass

*From BPNL, dated November 11, 1977.

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Table 4-1 (Continued) PACKAGED INTERMEDIATE AND LOW-LEVEL TRU WASTES FROM FRP

Plutonium and Uranium Recycle

Waste Treatment: Minimum Treatment, Bitumen Fixation, Packaging

Packaged Waste Description	Container	Containers/ 2000 MTHM	Packaged Density g/cc	Radioactivity, Ci/Container			Surface Dose (1) R/hr	Treated Waste Composition
				FPs	Actinides	Activation		
Failed Equipment	55 gal drums	445	0.4	1.0×10^{-1}	1.5×10^{-2}		0.2 - 1.0 (0.7)	100% Ferrous Alloys
Failed Equipment	30" x 10' canisters	67	0.4	6.9×10^{-1}	9.7×10^{-2}		0.2 - 10 (0.7)	100% Ferrous Alloys
Bitumenized Wet Wastes	55 gal drums	659	1.3	1.3	6.6×10^{-1}		0.2 - 1.0 (0.35)	Bitumen, Fluorinator Fines, (Al_2O_3, CaF_2)
Noncombustible Trash	55 gal drums	1940	0.25	1.3	1.9×10^{-2}		1 - 10 (7.3)	90% Metal 10% Glass
Failed Equipment	55 gal drums	26	0.5	9.1×10^{-1}	1.3×10^{-1}		1 - 10 (2.4)	100% Ferrous Alloys
Failed Equipment	4'x6'x6' boxes	4	0.5	5.5	7.9×10^{-1}		1 - 10 (7.1)	100% Ferrous Alloys
ILW Combustible Trash	55 gal drums	6500	0.12	5.2×10^{-1}	7.3×10^{-2}	2.9×10^{-3}	1.0 - 10 (6.0)	Paper, rags, PVC neoprene, latex, wood
Filters	80 gal drums	2900	0.16	17	2.5×10^{2}		< 10 (142)	60% Metal 40% Glass Fiber
Noncombustible Trash	55 gal drums	500	0.25	56	8.2	3.8	10 <(310)	90% Metal 10% Glass
Bitumenized Wet Wastes	55 gal drums	685	1.1	1.1×10^{3}	5.5×10^{2}	2.8	10 <(1370)	Bitumen, Misc. salts resins, filter sludge

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Table 4-1 (Continued) PACKAGED INTERMEDIATE AND LOW-LEVEL TRU WASTES FROM FRP

Plutonium and Uranium Recycle

Waste Treatment: Minimum Treatment, Bitumen Fixation, Packaging

Packaged Waste Description	Container	Containers/ 2000 MTHM	Packaged Density g/cc	Radioactivity, Ci/Container			Surface Dose (1) R/hr	Treated Waste Composition
				FPs	Actinides	Activation		
Combustible Trash	55 gal drum	1050	0.12		68		< 0.2 (0.001)	Cellulosics, PVC Polyethylene, Latex Neoprene, Polystyrene
Noncombustible Trash	55 gal drums	394	0.25		62		< 0.2 (0.001)	90% Metal 10% Glass
Failed Equipment	4'x6'x6' boxes	20	1.0		18		< 0.2 (5×10^{-5})	80% Metal 20% Insulating Brick
Filters	80 gals drums	350	0.16		4.8×10^2		< 0.2	60% Metal 40% Glass Fiber
Bitumenized Wet Wastes	55 gal drums	460	1.0		35		< 0.2 (2×10^{-4})	Bitumen, Inorganic Salts

(1) The surface dose rate is divided into four classes, < 0.2, 0.2 - 1.0, 1 - 10, and > 10 R/hr. The numbers in parenthesis are the calculated average dose rates. A distribution of dose rates about the average is to be expected.

TABLE 4-2

ENERGY DEPOSITION IN ONE DRUM OF ILW CEMENTED WASTE

	Cumulative Energy	
T (years)	Watt-Years	Ergs[a]
1	0.245	7.72×10^{13}
4	0.927	2.92×10^{14}
5[b]	1.137	3.58×10^{14}
6	1.339	4.22×10^{14}
7	1.534	4.83×10^{14}
8	1.721	5.42×10^{14}
9	1.901	5.99×10^{14}
10[c]	2.074	6.53×10^{14}

[a] 1 watt-year = 3.15×10^{14} ergs.

[b] Assumed arrival at repository (end of year).

[c] Assumed end of 5-year retrievability phase (end of year).

TABLE 4-3

CUMULATIVE HYDROGEN GENERATION PER ILW DRUM (>10 R/HR)
(Bitumen Fixation)

T (years)	Ergs	H_2 (ft^3)
1	7.72×10^{13}	0.8
4	2.92×10^{14}	3.0
5	3.58×10^{14}	3.7
6	4.22×10^{14}	4.4
7	4.83×10^{14}	5.0
8	5.42×10^{14}	5.6
9	5.99×10^{14}	6.2
10	6.53×10^{14}	6.8

TABLE 4-4

RADIOLYTIC HYDROGEN GENERATION FROM BITUMENIZED WASTE

	Low Level	Intermediate Level	
Years in Storage	Annual ft^3/drum	Annual ft^3/drum[a]	
		Case 1[b]	Case 2[c]
1	3.97×10^{-2}	0.68	7.44×10^{-4}
2	3.97×10^{-2}	0.62	7.44×10^{-4}
3	3.97×10^{-2}	0.62	7.44×10^{-4}
4	3.97×10^{-2}	0.59	7.44×10^{-4}
5	3.97×10^{-2}	0.56	7.44×10^{-4}
Total Accumulated/drum	0.2 ft^3	3.1 ft^3	3.72×10^{-3} ft^3

[a] These values for total H_2 generated per drum for one year.

[b] >10 R/hr.

[c] 0.2 - 1.0 R/hr.

TABLE 4-5

APPROXIMATE CHEMICAL COMPOSITION OF LOW-LEVEL TRU WASTE

Substance	Scientific Name	Chemical Formula	Weight Percent
Paper	Cellulose	$(C_{11}H_{18}O_8)_n$	10
Rags	Cellulose	$(C_{11}H_{18}O_8)_n$	10
Wood	Cellulose	$(C_{11}H_{18}O_8)_n$	8
PVC	Polyvinyl Chloride	$(C_2H_3Cl)_n$	30
Neoprene	Polychloroprene	$(C_4H_5Cl)_n$	20
Latex	Polyisoprene	$(C_5H_8)_n$	16.5
Non-Combustibles	Inorganic Oxides	-----	5.5

TABLE 4-6

ACCIDENT SCENARIOS WHICH MAY RESULT IN FIRE

Accident Scenario	Possible Occurrence or Consequence
	Probable Events
1. Loose lid on drum in storage.	Spontaneous combustion starts with smoldering in drum containing untreated combustible material.
2. Head-on collision of transport vehicle with other equipment or structure or other incident causing drum crushing or rupture (puncture) during transfer in presence of external fire.	Drum rupture small-to-moderate, with moderate loss of contents. Ignition of untreated combustible contents with slow-to-moderate burn rate.
3. Explosion, such as fuel tank ignition, etc.	Rupture in drum with ignition and burning of untreated combustible contents.
4. Drum dropped on electrical wires.	If drop is less than 10 feet, no rupture; drums designed to withstand 10-foot drop. Electrical wires shorted through drum may melt an area and cause ignition of untreated combustible contents. Only smoldering expected if only one hole is formed in drum.
5. Drum failure resulting from excessive internal pressure due to external fire probably in conjunction with one or more other events.	Small rupture in drum with ignition and slow burning of untreated combustible contents.

TABLE 4-6 (Cont'd)

Accident Scenario	Possible Occurrence or Consequence
	Maximum Credible Events
1. Direct hit by meteorite on drums.	Major rupture and scattering of contents. Ignition and rapid burning of combustible material. Several drums affected. Probability of occurrence approximately 5 x 10^{-11}/plant year.[a]
2. Aircraft crashes into surface facility causing major damage to drums.	Major rupture of drum. Ignition and rapid burning of contents due to combustion of airplane fuel. A few drums affected. Probability of occurrence <1 x 10^{-9}/year.[b]
3. Sabotage related explosion causing major damage to drums.	Major rupture of drum with ignition and rapid burning of untreated combustible contents. A few drums affected. Insufficient data available to establish statistically significant probability of occurrence.[c]

[a] Based on the data presented in Claiborne, H.C. and Gera, F., Potential Containment - Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico, ORNL-TM-4639, October, 1974, the probability of a meteorite of about 10 inches in diameter striking a 200-ft x 200-ft vulnerable surface area causing severe damage is estimated to be:

$$P = \left(\frac{5 \times 10^{-8} \text{ events}}{\text{mi}^2 - \text{yr}}\right)(10^{-3} \text{ mi}^2) = 5 \times 10^{-11} \text{ events/yr}$$

TABLE 4-6 (Cont'd)

[b] In U.S. Nuclear Regulatory Commission, Reactor Safety Study, Failure Data, WASH 1400, Appendix III, October, 1975, it was estimated that the probability of a fatal aircraft crash per mi^2 per aircraft movement at 10 miles from end of airport runway is about 1×10^{-9}. This number decreases with increasing distance from the airport. The movement of aircraft over the selected burial site can only be roughly estimated at this point and is assumed to be one of the site selection factors. A value of 1000 aircraft movements/year is estimated for a remote location. Another assumption is made that only one-half the aircraft are large enough to cause significant damage. Therefore, the probability that an aircraft would crash into the surface facility with 200 ft x 200 ft vulnerable surface area causing severe damage is estimated to be:

$$P = \left(<1 \times 10^{-9} \frac{\text{crash}}{\text{mi}^2 - \text{movement} - \text{yr}}\right)(10^3 \text{ movements})(10^{-3} \text{ mi}^2) = \leq 1 \times 10^{-9} \frac{\text{crash}}{\text{yr}}$$

[c] See discussion in U.S. Nuclear Regulatory Commission, Reactor Safety Study, Response to Comments on WASH 1400 Draft, WASH-1400, (NUREG 75/014), Appendix XI, October, 1975.

TABLE 4-7

APPROXIMATE RATES OF AIR INGRESS INTO A PUNCTURED DRUM AND BURN RATES OF COMBUSTIBLE CONTENTS*

Area	Linear Air Velocity ft/min	Air Ingress to Drum SCFM	Burn Rate lbs/hr
LLW Receiving Building	12	2.4	1.5
HLW Receiving Building:			
Cask unloading & decon room	3.9	0.78	0.42
All other handling areas	2.4	0.48	0.26
Mine:			
LLW Storage area	67	13	7.8
ILW Storage areas:			
Type 1 (majority of rooms)	105	21	12
Type 2	67	13	7.8

*Two 6-inch diameter holes assumed.

TABLE 4-8

THERMOCHEMICAL DATA USED IN CALCULATING COMBUSTION RATES

Substance	$\Delta H^{o}f$, kcal mole^{-1} 298K	Reference
$CO_2(g)$	-94.051	12, 13
$H_2O(g)$	-57.796	12, 13
$HCl(g)$	-22.063	12, 13
$Cl(g)$	0	----
$(C_5H_8)_n$, polyisoprene (latex):		
Unvulcanized	-7.82	14, 15, 16, 17
Vulcanized	-21.42	----
$(C_{11}H_{18}O_8)_n$, cellulose	-489.3	14, 18
$(C_4H_5Cl)_n$, neoprene:		
Unvulcanized	-7.0 ± 5	Estimated (See Appendix A.)
Vulcanized	-20.6 ± 6	Estimated (See Appendix A.)
$(C_2H_3Cl)_n$, polyvinyl chloride	-27.7 ± 0.	14, 19, 20, 21, 22

TABLE 4-9

APPROXIMATE HEAT RELEASE RATES DURING BURNING OF UNTREATED COMBUSTIBLE TRASH

Type of Accident	Area	Type of Trash	Heat Release Rate BTU/min
Completely Opened Drum	Any	LLW or ILW	27,000
Punctured Drum:	LLW Receiving Building:	LLW	265
	HLW Receiving Building:		
	Cask unloading & decon room	ILW	74
	All other handling areas	ILW	46
	Mine:		
	LLW Storage area	ILW	1,400
	ILW Storage areas:		
	Type 1 (majority of rooms)	ILW	2,100
	Type 2	ILW	1,400

TABLE 4-10

ESTIMATED RELEASES OF AIRBORNE MATERIALS FROM BURNING OF ONE DRUM OF WASTE

		Releases To Room				Releases To Ventilation System			
Type of Waste (Burn Time)	Area[a]	Ash lbs	Fission Products Ci	Actinides Ci	Activation Products Ci	Ash lbs	Fission Products Ci	Actinides Ci	Activation Products Ci
				Release Rates/hr					
Open Drum of Combustible LLW (22 min.)	Any	7.5	1.4×10^{-3}	3.6×10^{-3}	4.8×10^{-5}	0.15	2.7×10^{-5}	7.1×10^{-5}	9.6×10^{-7}
Punctured Drum of Combustible LLW	1	7.3×10^{-2}	1.4×10^{-5}	3.5×10^{-5}	4.7×10^{-7}	1.5×10^{-3}	2.7×10^{-7}	6.9×10^{-7}	9.3×10^{-9}
	2	3.9×10^{-1}	7.1×10^{-5}	1.9×10^{-4}	2.5×10^{-6}	7.9×10^{-3}	1.4×10^{-6}	3.7×10^{-6}	5.0×10^{-8}
Open Drum of Combustible ILW (22 min.)	Any	7.5	7.0×10^{-2}	1.0×10^{-2}	4.0×10^{-4}	0.15	1.4×10^{-3}	2.0×10^{-4}	7.9×10^{-6}
Punctured Drum of Combustible ILW	3	2.1×10^{-2}	2.0×10^{-4}	2.8×10^{-5}	1.1×10^{-6}	4.2×10^{-4}	4.0×10^{-6}	5.7×10^{-7}	2.2×10^{-8}
	4	6.1×10^{-1}	5.8×10^{-3}	8.1×10^{-4}	3.2×10^{-5}	1.2×10^{-2}	1.2×10^{-4}	1.6×10^{-5}	6.3×10^{-7}
				Total Releases - End of Fire					
Drum of Combustible LLW		2.8	5.0×10^{-4}	1.0×10^{-3}	1.8×10^{-5}	5.5×10^{-2}	1.0×10^{-5}	2.6×10^{-5}	3.5×10^{-7}
Drum of Combustible ILW		2.8	2.6×10^{-2}	3.7×10^{-3}	1.5×10^{-4}	5.5×10^{-2}	5.2×10^{-4}	7.3×10^{-5}	2.9×10^{-6}

[a] 1 = LLW Receiving Building (burn time = 38 hours).
2 = Mine Storage room for LLW (burn time = 7 hours).
3 = HLW Receiving Building, worst case area (burn time = 133 hours).
4 = Mine Storage room for ILW, worst case area (burn time = 5 hours).

[b] Burn time is the length of time to consume all combustible waste in the container if unattended by fire fighting equipment.

[c] Independent of Area and type of accident (i.e., open drum or punctured drum).

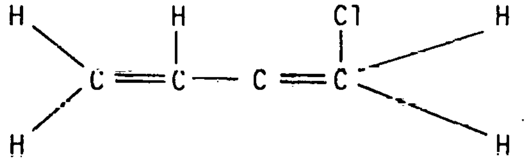
APPENDIX A

ESTIMATION OF ΔH_f^o OF NEOPRENE

The heat of polymerization of chloroprene (liq.) to form neoprene is known. Apparently, the standard enthalpy of formation of neither chloroprene nor neoprene has been measured. Chloroprene is very unstable, which probably accounts for the fact that it has not yet been studied. In the manufacture of neoprene, chloroprene is formed just prior to polymerization.

The standard enthalpy of formation (ΔH_f^o) may be estimated from two methods.

<u>Method 1</u>. Group contributions [K. K. Verma and L. K. Doraiswamy, Inc. Eng. Chem. Funds, <u>4</u>, 389 (1965); R. C. Reid and T. K. Sherwood, <u>The Properties of Gases and Liquids</u>, 2nd Edition, McGraw-Hill, 1965, Ch. 5]. The method approximates that groups contribute to the overall enthalpy of formation of the molecule in a fixed manner and that each group has characteristic constants in an equation of the form $\Delta H_f^o = A+BT$. Chloroprene has the structure



The individual group constants are as follows.

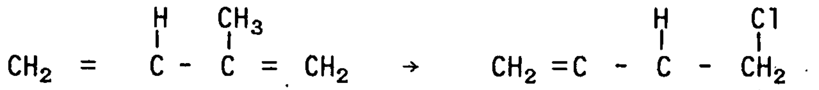
Group	A	Bx10²	Comments
-Cl	-7.965	+0.050	B is estimated from other -Cl attached groups. Uncertainty is calculated ΔH: ±0.2 kcal/mole
$>C=CH^2$	16.725	-0.150	
$^{H}>C=CH^2$	16.323	-0.437	
Σ	25.083	-0.537	

The calculated ΔH_f° for chloroprene at 298K is 23.48±0.5 kcal mole^{-1}.

A similar calculation for ΔH_f° (isoprene) yields ΔH_f° (isoprene, g) = 21.05 kcal mole^{-1}. The actual (measured) value for isoprene is 18.10±0.24 kcal mole^{-1}. Chloroprene differs in structure from isoprene only in that a methyl group is replaced by the Cl. Thus, the group contribution estimate may be too high by approximately 21.05-18.10=2.95 kcal mole^{-1}.

Method 2. Reid and Sherwood (ibid), state that substitution of a CH_3 group by a Cl has no effect on ΔH_f° for the first Cl on a C. Each additional Cl adds 4.5 kcal mole^{-1} to ΔH_f°. A tabulation of $R\text{-}CH_3 \rightarrow R\text{-}Cl$ reaction heats for aliphatic compounds by D. R. Stull, E. F. Westrum, Jr., and G. C. Sinke, The Chemical Thermodynamics of Organic Compounds, J. Wiley, 1969, p. 490, has an average value of -1.67 kcal mole^{-1}. For the unsaturated compound, the value of -1.7±1.0 kcal mole^{-1} is used here.

Thus, for



$$CH_2 = \overset{H}{\overset{|}{C}} - \overset{CH_3}{\overset{|}{C}} = CH_2 \rightarrow CH_2 = C - \overset{H}{\overset{|}{C}} - \overset{Cl}{\overset{|}{CH_2}}$$

Isoprene Chloroprene

ΔH° reaction = 1.7±1.0 kcal mole^{-1}. The ΔH_f° for isoprene (gas) is 18.1 kcal mole^{-1}. Therefore, ΔH_f° (chloroprene, gas) = 16.4±1 kcal mole^{-1}.

The average value for ΔH_f° (chloroprene, gas) from the two methods of estimation is 18.5±3 kcal mole^{-1} at 298K.

To calculate ΔH_f° (chloroprene, liq.) the value of ΔH_{vap}° for chloroprene is needed. From the vapor pressure equation, $\log_{10} p_{Torr} = \frac{1545.3}{T} + 7.537$ [W. H. Carothers, et al., J. Amer. Chem. Soc., 53, 4203 (1931)] a value of ΔH_{vap}° = 7.07 kcal mole-1 is calculated. Kirk-Othmer Encyclopedia of Chemical Technology, 2nd Edition, v. 5. (1964) lists values for ΔH_{vap}° of 79.5 kcal mole-1 at 0°C and 72.3 kcal mole-1 at 60°C, but these are obviously in error by a factor of ten. The value for isoprene is 6.40 kcal mole-1, indicating that the smaller value for chloroprene is correct.

Using the value of 7.1 kcal mole-1 for ΔH_{vap}°, one calculates ΔH_f° (chloroprene, liq.) = ΔH_f° (chloroprene, gas) - ΔH_{vap}° (chloroprene) = (18.5±3 kcal) mole^{-1}.

Finally, $\Delta H_{polymerization}$ for the liquid is listed in Volume 5 of the Kirk-Othmer Encyclopedia of Technology, 2nd Edition, 1964, as 16.2±0.3 kcal mole^{-1} [S. Ekegran et al, Acta Chem. Scand., 4, 126-139 (1950); Chem. Abstr., 44, 8758 (1950)] and 15.1 kcal mole^{-1} (duPont unpublished data). The $\Delta H_{polymerization}$ has an unexplained dependence on the amount of initiator. In Volume 7 of the Kirk-Othmer ECT, an unreferenced value for $\Delta H_{polymerization}$ of 21.1±1.6 kcal mole^{-1} is reported by C. A. Hargreaves II and D. C. Thompson of duPont. This value may be the most reliable. Averaging the three values and weighting the last by a factor of two yields a value of 18.4±2.7 kcal mole^{-1} for $\Delta H_{polymerization}$.

Thus, ΔH_f^o (neoprene, unvulcanized) = (11.4±3) - (18.4±2.7) = -7.0±5 kcal mole^{-1}. This figure is for the unvulcanized form of neoprene and compares well with the measured value of -7.8 kcal mole^{-1} for polyisoprene (latex). The ΔH_f^o of the vulcanized form of polyisoprene is -21.4 kcal mole^{-1}. Thus, the vulcanized form of neoprene has an approximate value of ΔH_f^o = -20.6±6 kcal mole^{-1}.

Note that the difference between the vulcanized and unvulcanized values has only a small effect on the calculated heats of combustion. For example, in the combustion of latex, the $\Delta H_{combustion}$ values are -10.8 (unvulcanized) and -10.6 (vulcanized) kcal g^{-1}. By the same token, the uncertainties in the estimates for neoprene will not have a significant effect.

In view of the close agreement with the ΔH_f^o for polyisoprene, the uncertainties for neoprene may be less than estimated.