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**OAK RIDGE
NATIONAL
LABORATORY**

MARTIN MARIETTA

**Risk Assessment for the Retrieval of
Transuranic Waste:**

**Pads 1,2, and 4
Technical Area-54, Area G
Los Alamos National Laboratory**

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**MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

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**Prepared by
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ACRONYMS

AEC	Atomic Energy Commission
ALARA	As Low As Reasonably Achievable
ATSDR	Agency for Toxic Substances and Disease Registry
CEDE	Committed Effective Dose Equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CMP	Corrugated Metal Pipe
CST	Chemical Science and Technology Division
D&D	Decontamination and Decommissioning
DOE	Department of Energy
DOT	Department of Transportation
EC	Electron Capture
EDE	Effective Dose Equivalent
EO	Equipment Operator
EPA	Environmental Protection Agency
FRP	Fiberglass-Reinforced Plywood
GENII	Generation II
HEPA	High-Efficiency Particulate Air
ICRP	International Commission on Radiological Protection
LLW	Low-Level Waste
LANL	Los Alamos National Laboratory
MEI	Maximally Exposed Individual
MFP	Mixed Fission Products
NAS	National Academy of Science
NIOSH	National Institute for Occupational Safety and Health
O&M	Operation and Maintenance
ORNL	Oak Ridge National Laboratory
PN	Property-Numbered
PNL	Pacific Northwest Laboratories
PPE	Personal Protective Equipment
PSAR	Preliminary Safety Analysis Report
RCRA	Resource Conservation and Recovery Act
TA	Technical Area
TD	Truck Driver
TRU	Transuranic
VOC	Volatile Organic Compound
WIPP	Waste Isolation Pilot Plant

EXECUTIVE SUMMARY

The Risk Assessment for the Retrieval of Transuranic Waste is a comparative risk assessment of the potential adverse human health effects resulting from exposure to contaminants during retrieval and post-retrieval aboveground storage operations of post-1970 earthen-covered transuranic waste. Two alternatives are compared: 1) Immediate Retrieval and 2) Delayed Retrieval. Under the Immediate Retrieval Alternative, retrieval of the waste is assumed to begin immediately. Under the Delayed Retrieval Alternative, retrieval is delayed 10 years. The current risk assessment is on Pads 1, 2, and 4, at Technical Area-54, Area-G, Los Alamos National Laboratory (LANL).

Risks are assessed independently for three scenarios: 1) incident-free retrieval operations, 2) incident-free storage operations, and 3) a drum failure analysis. Incident-free retrieval and storage operations are defined as operations that are performed under optimal conditions, assuming no accidents or abnormal events. The drum failure analysis evaluates container integrity under both alternatives and assesses the impacts of potential drum failures during retrieval operations.

The Risk Assessment for the Retrieval of Transuranic Waste indicates that risks to workers for incident-free retrieval and storage operations are similar for both the Immediate and Delayed Retrieval alternatives. While risks for the Immediate Retrieval Alternative are slightly higher than risks for Delayed Retrieval, risks predicted for incident-free operations are not different enough or significant enough to warrant a selection of either alternative.

Risks associated with a series of drum failures are potentially severe for workers, off-site receptors, and general on-site employees if retrieval is delayed 10 years and administrative and engineering controls remain constant. Under the Delayed Retrieval Alternative, an average of 300 drums out of 16,647 (or approximately 1 in 50) are estimated to fail during retrieval operations due to general corrosion, while minimal drums are predicted to fail under the Immediate Retrieval Alternative, assuming the corrosion processes are well described by a Poisson process. The dominating pathway in the drum failure analysis is the inhalation of alpha-emitting particulates released upon drum failure. The risks of concern are those for off-site and general on-site receptors, as use of worker personal protective equipment (e.g., respirators) is expected to mitigate the consequences of a drum failure for workers.

The results of the current study suggest that, based on risk, remediation of Pads 1, 2, and 4 at LANL should not be delayed. Although risks from incident-free operations in the Delayed Retrieval Alternative are low, risks due to corrosion and drum failures are potentially severe. Because increased administrative and engineering controls could substantially decrease the predicted risks, it is recommended that any decision-making regarding retrieval of earthen-covered transuranic waste be based on both risk and cost analyses. A cost analysis is not within the scope of the current risk assessment.

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1. INTRODUCTION

1.1 BACKGROUND

In November 1991, United States Department of Energy (DOE) headquarters established the Transuranic (TRU) Waste Projects Task Force to examine the scope, timing, and emphasis of site-specific TRU waste projects as they relate to the present Waste Isolation Pilot Plant (WIPP) disposal operations. Based on the findings of the Task Force, the Deputy Assistant Secretary for Environmental Restoration and Waste Management made recommendations to develop a more comprehensive systems approach to assure current site plans are consistent with WIPP strategy. One such recommendation was to undertake a comprehensive risk assessment of all TRU waste earthen-covered storage sites, comparing the risk of current retrieval, repackaging, and storage operations to the risk of doing this same work on a delayed schedule. The current risk assessment was initiated in response to that recommendation.

Between 1970 and the early 1990s, DOE sites stored containers of TRU waste under earthen cover. This interim storage practice occurred in anticipation that the waste would be retrieved within 20 years, certified, and shipped to the WIPP for permanent disposal. The projected 1988 opening of WIPP has been delayed and some containers have remained in the ground longer than their suggested 20-year lifetime limit (DOE 1988a), causing concern about degradation of containers. States are also mandating that sites bring container storage into compliance with new regulations. As a result, some sites may be ordered to retrieve the waste and activate above-ground on-site storage until WIPP is available.

1.2 SCOPE

The current study documents the risk assessment of retrieval and re-storage activities for TRU waste on Pads 1, 2, and 4 at Technical Area (TA)-54, Area G, Los Alamos National Laboratory (LANL). The scope of the risk assessment is to evaluate, compare, and document the potential risks to human health associated with predicted future exposures to TRU waste if retrieval of waste on Pads 1, 2, and 4 occurs (1) without delay or (2) with a 10-year delay. A 10-year delay beginning in 1993 was chosen to represent the potential delay in the opening of WIPP. Although the site evaluated in the current study has no option (immediate retrieval was mandated before completion of the current study), this comparative study is useful in that it provides relevant information that can be used to assist decision-making on a complex-wide scale. The objectives of this risk assessment are twofold:

- Provide risk information and recommendations to assist decision-making regarding retrieval and above-ground storage options for post-1970 earthen-covered TRU waste on Pads 1, 2, and 4 at LANL. The options evaluated in the risk assessment are Immediate Retrieval (remediation activities are assumed to begin immediately) and Delayed Retrieval (remediation activities are assumed postponed for 10 years). The analysis includes evaluation of incident-free retrieval and storage operations and a drum failure analysis. Incident-free operations are defined as routine operations performed under optimal conditions assuming no drum failures. The drum

failure analysis evaluates container integrity under both alternatives and assesses the impacts of potential drum failures during retrieval operations.

- Identify major areas of uncertainties and limitations in the current study, assess the potential impacts of the uncertainties, and provide recommendations where further analyses are deemed appropriate.

1.3 RISK ASSESSMENT APPROACH

TRU waste retrieval and re-storage activities are expected to generate some degree of long-term and short-term risks to the public and to workers. The magnitude of these risks and their target populations must be assessed to determine which retrieval alternative is least hazardous. The risk evaluation process provides a framework for evaluating and documenting health threats as well as a basis for comparing potential health impacts of each alternative. The approach of the current risk assessment is based on recognized risk assessment principles outlined by the National Academy of Science (NAS 1983) as described in the Environmental Protection Agency's Risk Assessment Guidance for Superfund (EPA 1989). The general tasks necessary for conducting the comparative risk assessment are as follows:

- Characterize the site. This task involves gathering and analyzing relevant site data, such as environmental setting information, waste storage configurations, and historical characteristics.
- Identify all contaminants of potential concern at the site. This stage involves identifying contaminants that are potentially hazardous to human health throughout the stages of retrieval and above-ground storage. Consideration is given to contaminant concentrations, environmental mobility, and potential human exposure.
- Conduct a toxicity assessment for site-related contaminants of potential concern.
- Conduct an exposure assessment for site-related contaminants of concern. This stage involves four steps: (1) analyzing any current or potential contaminant releases, (2) identifying the routes from the site capable of producing exposures, (3) identifying potentially exposed populations, and (4) estimating exposure point concentrations and quantifying exposure for exposure routes.
- Conduct the risk characterization to quantify contaminant- and pathway-specific risks to human health. This is the final step in the risk assessment and includes estimating the potential for occurrence of adverse health effects, evaluating uncertainty, and summarizing risk information.

1.4 ORGANIZATION OF THE RISK ASSESSMENT REPORT

This report is organized to follow the steps of the risk assessment process outlined in the Risk Assessment Guidance for Superfund (EPA 1989) and consists of eight sections.

Section 1. Introduction. Discusses the background, objectives, and organization of the risk assessment report. Provides a general background of LANL and Pads 1, 2, and 4, descriptions of local populations, and environmental setting information.

Section 2. Contaminants of Potential Concern. Identifies the contaminants of potential concern selected for this analysis. Discusses data collection and evaluation for this stage of the risk assessment. Discusses TRU waste forms on Pads 1, 2, and 4.

Section 3. Toxicity Assessment. Considers the types of adverse health effects associated with exposures to the radionuclides of potential concern.

Section 4. Incident-Free Retrieval Operations Analysis. Characterizes incident-free retrieval operations. Identifies potentially exposed populations and exposure routes for this scenario. Estimates the frequency, duration, and magnitude of potential human exposures for both Immediate and Delayed Retrieval Alternatives. Estimates potential carcinogenic risks and noncarcinogenic effects for potentially exposed populations and exposure routes. Discusses uncertainties associated with the exposure assessment and risk characterization and potential impacts of the uncertainties on the risk assessment.

Section 5. Incident-Free Storage Operations Analysis. Characterizes incident-free storage operations. Identifies potentially exposed populations and exposure routes for this scenario. Estimates the frequency, duration, and magnitude of potential human exposures for both Immediate and Delayed Retrieval Alternatives. Estimates potential carcinogenic risks and noncarcinogenic effects for potentially exposed populations and exposure routes. Discusses uncertainties associated with the exposure assessment and risk characterization and potential impacts of the uncertainties on the risk assessment.

Section 6. Accident Analysis. Characterizes the drum failure scenario. Evaluates the potential for corrosion of drums at LANL and estimates drum failures under each alternative. Identifies potentially exposed populations and exposure pathways. Estimates the magnitude of potential human exposures for the Delayed Retrieval Alternative. Estimates a range of potential carcinogenic risks and genetic effects for each potentially exposed population and exposure pathway. Discusses uncertainties associated with the estimation of corrosion rates, exposure assessment, and risk characterization and potential impacts of the uncertainties on the risk assessment.

Section 7. Summary and Conclusions. Provides a summary of each analysis in the risk assessment. Interprets results of the risk assessment and provides conclusions supported by the risk analysis. Qualitatively addresses additional concerns not quantified in the risk assessment.

Section 8. Recommendations for Further Study. Provides recommendations for an additional study to address major areas of uncertainties and limitations of the current study.

1.5 GENERAL SITE BACKGROUND

In January 1943 Project Y, the wartime Los Alamos National Laboratory, was established at the location of the Los Alamos Ranch School in north-central New Mexico as the nucleus of the War Department's scientific and technical effort to develop a fission bomb. The project culminated in the detonation of the first atomic bombs near Alamogordo, New Mexico, on July 5, 1945, and at the end of World War II. Since that time, the primary mission of LANL continues to be weapons research, including development of the first thermonuclear bomb. Expansion of laboratory effort has incorporated numerous programs to develop peaceful uses of nuclear energy in such areas as fission reactors, space technology, controlled thermonuclear reactions, and biomedical research.

1.5.1 Physical Setting

Los Alamos National Laboratory occupies a 111 km² (43 mi²) area in north central New Mexico, about 40 km (25 mi) northwest of Santa Fe, on the Pajarito Plateau between the Jemez Mountains and the Rio Grande Valley. The regional location of LANL is shown in Fig. 1.1. The topography consists of a series of finger-like mesas separated by deep east-to-west oriented canyons that are cut by streams with intermittent flow. Los Alamos National Laboratory is bordered on the south and west by the Bandelier National Monument, to the west and north by the Santa Fe National Forest, and on the north by private and county land. To the east, LANL is bordered by the San Ildefonso Pueblo and the communities of Pajarito Acres and White Rock. Land within the immediate vicinity of the facility is still largely undeveloped.

1.5.2 Local Populations

Los Alamos County has an estimated 1990 population of approximately 18,200 (based on the 1990 U.S. Census, adjusted to July 1, 1990). Two residential and related commercial areas exist in the county. The Los Alamos townsite (the original area of development, now including residential areas known as Eastern Area, Western Area, North Community, Barranca Mesa, and North Mesa) has an estimated population of 11,400. The White Rock, La Senda, and Pajarito Acres has about 6,800 residents. Population estimates for 1990 place about 213,000 persons within an 80 km (50 mi) radius of Los Alamos (Table 1.1).

Table 1.1. 1990 Population within 80 km of Los Alamos (Source: 1990 Census)

Direction	Distance from TA-53 (km)									Total
	1-2	2-4	4-8	8-15	15-20	20-30	30-40	40-60	60-80	
N	1	0	0	0	0	0	1,136	0	368	1,505
NNE	0	0	0	565	0	542	1,730	1,797	221	4,855
NE	1	0	0	0	317	15,352	1,009	1,135	3,846	21,660
ENE	0	0	0	1,940	1,563	2,716	2,729	1,187	2,214	12,349
E	0	0	83	25	556	1,145	696	0	1,402	3,907
ESE	0	0	0	0	0	293	23,151	1,067	1,476	25,987
SE	0	0	6,757	0	0	0	53,520	2,443	8	62,728
SSE	0	0	0	0	0	0	426	4,347	95	4,868
S	0	0	0	50	0	318	614	6,775	0	7,757
SSW	0	0	0	20	0	817	201	8,238	33,485	42,761
SW	0	0	0	0	0	0	315	4,157	0	4,472
WSW	0	0	0	0	0	315	313	2,545	207	3,380
W	0	0	0	0	0	0	0	164	132	296
WNW	0	1,435	6,535	0	0	0	0	0	3,081	11,051
NW	0	523	1,721	0	0	0	0	1,438	0	3,682
NNW	0	578	579	0	0	0	0	64	62	1,283
Total	2	2,536	15,675	2,600	2,436	21,498	85,840	35,357	46,597	212,541

1.5.3 Climatology and Meteorology

Los Alamos National Laboratory has a semiarid, temperate mountain climate. Average annual precipitation is nearly 47 cm (19"). About 36% of the annual precipitation occurs during July and August from thundershowers. Winter precipitation falls primarily as snow, with accumulations of about 150 cm (59") annually. Summers are generally sunny with moderate, warm days and cool nights. Maximum daily temperatures are usually below 32°C (90°F). Brief afternoon and evening thundershowers are common, especially in July and August. High altitude, light winds, clear skies, and dry atmosphere allow night temperatures to drop below 15°C (59°F). Winter temperatures typically range from about -9°C to -4°C (15°F to 25°F) during the night and from -1°C to 10°C (30°F to 50°F) during the day. Snow storms with accumulations exceeding 10 cm (4") are common in Los Alamos. Some storms can be associated with strong winds, frigid air, and dangerous wind chills (LANL 1992).

Source: LANL 1992.

Fig. 1.1. Regional Location of Los Alamos National Laboratory.

Because of complex terrain, surface winds in Los Alamos often vary greatly with time of day and location. With light, large-scale winds and clear skies, daytime winds are predominantly south to south-southwest as winds flow up the Rio Grand Valley. Thermally driven upslope winds from the southeast and east are also common toward the Jemez Mountains. Predominant winds are west to west-northwesterly at the west end of the Plateau to south southwesterly at the east end.

Historically, no tornadoes have been reported to have touched down in Los Alamos County. Strong dust devils can produce winds up to 34 m/s (75 mph) at isolated spots in the county, especially at lower elevations. Strong winds with gusts exceeding 27 m/s (60 mph) are common and widespread during the spring.

1.5.4 Geology

Most of the finger-like mesas in the LANL area are found in Bandelier Tuff. Ash fall, ash fall pumice, and rhyolite tuff form the surface of Pajarito Plateau. The tuff is over 300 m (1000 ft) thick in the western part of the plateau and thins to about 80 m (260 ft) eastward above the Rio Grande. It was deposited as a result of a major volcanic eruption in the Jemez Mountains about 1.1 to 1.4 million years ago.

The tuffs overlap onto the Tschicoma Formation that consists of older volcanics that form the Jemez Mountains. The tuff is underlain by the conglomerate of the Puye Formation in the central and eastern edge along the Rio Grande. Chino Mesa basalts interfinger with conglomerate along the river. These formations overlay the sediments of the Tesuque Formation, which extends across the Rio Grande Valley and is in excess of 1,000 m (3,300 ft) thick (LANL 1992).

1.5.5 Groundwater Hydrology

Groundwater occurs in three aquifers in the Los Alamos area: (1) water in shallow alluvium in canyons, (2) perched water (a groundwater body above an impermeable layer that separates it from the underlying main body of groundwater by an unsaturated zone), and (3) the main aquifer of the Los Alamos area.

Intermittent stream flows in canyons of the plateau have deposited alluvium that ranges from less than 1 m (3 ft) to as much as 30 m (100 ft) in thickness. The alluvium is permeable, in contrast to the underlying volcanic tuff and sediments. Intermittent runoff in canyons infiltrates the alluvium until its downward movement is impeded by the less permeable tuff and volcanic sediment. This results in a shallow alluvial groundwater aquifer that moves downgradient within the alluvium.

Perched water occurs in conglomerate and basalts beneath the alluvium in a limited area (about 37 m (120 ft)) deep in the midreach of Pueblo Canyon and in a second area about 45 to 60 m (150 to 200 ft) beneath the surface in lower Pueblo and Los Alamos canyons near their confluence. The second area is mainly in basalts and has one discharge point at Basalt Spring in Los Alamos Canyon.

The main aquifer of the Los Alamos area is the only aquifer in the area capable of serving as a municipal water supply. The surface of the aquifer rises westward from the Rio Grande

within the Tesuque Formation into the lower part of the Puye Formation beneath the central and western part of the plateau. Depth of the aquifer decreases from 360 m (1,200 ft) along the western margin of the plateau to about 180 m (600 ft) at the eastern margin. The main aquifer is isolated from alluvial and perched waters by about 110 to 190 m (350 to 620 ft) of dry tuff and volcanic sediments. Thus, there is little hydrologic connection or potential for recharge to the main aquifer from alluvial or perched water (LANL 1992).

1.5.6 Background of Pads 1, 2, and 4

Beginning in 1970 the Atomic Energy Commission (AEC), DOE's predecessor, directed its facilities, including LANL, to begin storing TRU waste in a manner that would allow for eventual retrieval and shipment to the WIPP. Before this, TRU waste at AEC facilities around the country, including LANL, was disposed of with low-level waste (LLW) in shallow landfills. As a consequence of the 1970 AEC directive, however, LANL began segregating TRU waste from LLW and, by the late 1970s, upgraded TRU waste storage facilities to provide a more retrievable configuration (LANL 1993). The result was the construction of three above-grade asphalt pads, called Pads 1, 2 and 4, on which TRU waste was placed in densely-packed arrays and covered with soil overburden. This configuration was intended to provide weather protection for the containers and was also consistent with the As-Low-As-Reasonably-Achievable (ALARA) principle, which states that worker exposure to radiation should be minimized whenever possible. Corrosion of containers on the pads was not anticipated because of the relatively dry climate of Los Alamos and the short expected life of the pad storage configuration.

In 1979, LANL began construction of the three pads in TA-54 Area G, Pads 1, 2, and 4. The pads, oriented roughly north-south, overlay and are perpendicular to three inactive LLW Pits 2, 4, and 5. Pad 1 operated from May 29, 1979 to December 29, 1981 and received 4,776 standard 55-gallon drums, ten 83-gallon drums, three 99-gallon drums, and 116 fiberglass-reinforced plywood (FRP) crates. Pad 2, located parallel to and east of Pad 1 operated from December 8, 1981 to August 20, 1985 and received 7,293 55-gallon drums, one 80-gallon drum, and 48 FRP crates. Pad 3, located between Pads 1 and 2, is used for above-ground dome-covered storage of post-1986 certifiable TRU waste and is fully inspectable in its current configuration; hence it is outside the scope of the risk assessment. Pad 4, the furthest east of the three pads, operated from March 18, 1985 to January 3, 1991 and received 4,554 55-gallon drums, seven 80-gallon drums, two 83-gallon drums, one 85-gallon drum, and 54 FRP crates. The total number of waste packages on Pads 1, 2, and 4 is 16,647 drums and 218 FRP crates. The locations of TA-54 and Pads 1, 2, and 4 in relation to other TRU storage areas including Trenches A, B, C, and D, Pit 9, Pit 29 and the corrugated metal pipe (CMP) storage area, are shown in Figs. 1.2 and 1.3, respectively.

Source: LANL 1992.

Fig. 1.2. Location of TA-54.

Source: O'Rear 1993.

Fig. 1.3. Map of TRU Waste Storage Areas at TA-54, Area G.

The carbon steel drums were stacked three to five high, depending on the pad, in dense arrays so that the packages are actually touching each other, with plywood between layers. Dimensions of the asphalt pads are approximately 10.2 cm (4") thick x 12.2 m (40 ft) wide x 79.2 m (260 ft) long. FRP crates line the pads and were often used to separate groups of drums into cells by placing them across the face of the stacks. Pad 4 has approximately two cells. Pads 1 and 2 have approximately three cells (Villareal 1993). A space of 0.6-0.9 m (2-3 ft) was left between each cell and a small amount of soil was backfilled into this space to act as a firewall. Each cell is enclosed with plywood and covered with overlapping plastic tarps for weather protection. The entire configuration is covered with at least 0.9 m (3 ft) of crushed tuff to reduce temperature cycling. A cutaway view of TRU pad storage is shown in Fig. 1.4.

1.5.7 Current Status of Pads 1, 2, and 4

On July 25, 1990, the state of New Mexico was delegated federal Resource Conservation and Recovery Act (RCRA) authority to regulate mixed wastes (LANL 1993). When Pads 1, 2, and 4 were included in a RCRA Part A Permit Application to New Mexico in 1991, they became subject to RCRA interim storage standards regulated by New Mexico. These standards specify that storage configurations support inspection and response to emergency conditions. The earthen-covered storage configuration of Pads 1, 2, and 4 is not in compliance with these regulations because the containers are under earthen cover.

In April 1992, 16 drums from Pad 2 were retrieved and examined. They exhibited varying stages of external corrosion. A pinhole perforation resulting from internal pitting corrosion was discovered in one drum, although no radiation leakage was detected. Soil sampling taken four months after the retrieval project confirmed that no contamination was present (LANL 1993). The New Mexico Environmental Department was informed of the degraded drum conditions in April 1992 and eight months later issued a compliance order to bring Pads 1, 2, and 4 into compliance with RCRA container storage requirements. The major implication of the order is that the waste must be retrieved and placed in an inspectable storage array. It is noted that before completion of the current study, the State of New Mexico mandated LANL to retrieve the waste without delay.

1-12

Source: LANL 1993

Fig. 1.4. Cutaway View of TRU Waste Storage Pad.

2. POTENTIAL CONTAMINANTS OF CONCERN

2.1 SELECTION OF CONSTITUENTS OF POTENTIAL CONCERN

Recent soil sampling (31 samples taken in August, 1992) confirmed that no release had occurred around Pads 1, 2, and 4 (LANL 1993). Moreover, no contamination of surrounding media has been detected from the inactive LLW Pits situated below the TRU waste pads. Due to these circumstances, no additional sampling was considered necessary for the purposes of this risk assessment. Contaminants of potential concern are derived from site reports and on-site databases, maintained in the Chemical Science and Technology Division (CST)-7 at LANL, that contain information pertaining to the contents of the containers.

The TRU waste on Pads 1, 2, and 4 contains both radionuclides and chemicals. The inventory of radionuclides obtained from the on-site database, their half-lives and decay modes are shown in Table 2.1. Because the number of radionuclides is low, screening was not necessary to reduce the list of contaminants of potential concern and all radionuclides are considered in the risk assessment, with the exception of cadmium-109, which has a half-life of only 464 days and one daughter with a half-life of 40 seconds.

Although the database contains approximate percentages of chemical constituents in the waste, it does not provide the concentrations of hazardous chemicals in the waste (Chen 1993, Stuhl 1994). Because the concentrations of chemicals in the waste stored on Pads 1, 2, and 4 are not available, a quantitative risk assessment addressing the hazardous chemicals in the pad waste is not possible. The risks associated with the remediation of Pads 1, 2, and 4 are quantified for radionuclides only.

2.2 DATA COLLECTION AND EVALUATION

During storage operations of Pads 1, 2, and 4 in the early 1970s, the CST-7 Division at LANL maintained records of (1) the activity of each radionuclide stored at the pads and (2) the total activity for certain material type codes that consisted of several radionuclides. These material type codes express radioactive constituents in curies of a specific radioactive material type, such as a heat-source waste stream. For this risk assessment, an estimate of the activity for each radionuclide in these type codes was obtained. A list of constituents in the material type and inventory (or percentage of constituent included in each material type) were obtained from the CST-7 Division for each material type code. The constituents of the waste codes were summed to obtain a total for each radionuclide. Where only a breakdown of the material type code was known [such as in the case of mixed fission products (MFPs)], a worst-case assumption was used. Each constituent classified by the code was assumed to constitute the entire inventory of that material type. This introduced some uncertainty into the inventory that may result in higher estimates for some radionuclides.

Table 2.1. Pads 1, 2, and 4 inventory

Isotope ^a	Half-Life ^b	Radiations Emitted ^b	Activity (Ci) ^c
²⁴¹ Am	4.32 x 10 ² yr	α , γ	7.70 x 10 ³
²⁴³ Am	7.38 x 10 ³ yr	α	5.70 x 10 ⁻¹
¹⁰⁹ Cd ^c	4.64 x 10 ² days	EC ^d	2.70 x 10 ³
²⁴³ Cm	2.85 x 10 yr	α	1.50
²⁴⁴ Cm	1.81 x 10 yr	α	2.20 x 10 ²
⁶⁰ Co	5.27 yr	β^- , γ	1.00 x 10 ³
²³⁷ Np	2.14 x 10 ⁶ yr	α , γ	4.20 x 10 ⁻⁴
²³¹ Pa	3.73 x 10 ⁴ yr	α , γ	1.10 x 10 ⁻³
²³⁶ Pu	2.85 yr	α , γ	6.33 x 10 ⁻³
²³⁸ Pu	8.78 x 10 yr	α , γ	2.00 x 10 ⁴
²³⁹ Pu	2.41 x 10 ⁴ yr	α , γ	3.34 x 10 ⁴
²⁴⁰ Pu	6.57 x 10 ³ yr	α	2.44 x 10 ³
²⁴¹ Pu	1.44 x 10 yr	α , β^-	2.14 x 10 ²
²⁴² Pu	3.76 x 10 ⁵ yr	α	2.61 x 10 ²
²⁴⁴ Pu	6.57 x 10 ³ yr	α	4.94 x 10 ⁻²
²²⁶ Ra	1.60 x 10 ³ yr	α , γ	9.00 x 10 ⁻¹
²³³ U	1.59 x 10 ⁵ yr	α , γ	2.6 x 10 ⁻¹
²³⁴ U	2.45 x 10 ⁵ yr	α , γ	4.84 x 10 ⁻⁵
²³⁵ U	7.04 x 10 ⁸ yr	α	6.02 x 10 ⁻³
²³⁶ U	2.34 x 10 ⁷ yr	α , γ	6.03 x 10 ⁻⁵
²³⁸ U	4.47 x 10 ⁹ yr	α , γ	4.79 x 10 ⁻¹

^a Chen 1993^b CRC 1985^c Dropped from the analysis due to its short half-life.^d Electron Capture

2.3 WASTE FORM CHARACTERISTICS

Generally, TRU waste forms at LANL include equipment such as decommissioned glove boxes, room and glove box trash (combustible and noncombustible), plutonium-processing line wastes (including precipitates, salts, and cakes), cemented sludges and liquids, high-efficiency particulate air (HEPA) filters, contaminated soils, building decommissioning debris, absorbed oils, graphite, and seven drums and one crate of unknown content (Warren and Dross 1986). While the waste is predominately solid waste, the potential exists for the presence of a small amount of liquid waste. The breakdown of waste forms on Pads 1, 2, and 4 is shown in Figs. 2.1 and 2.2.

Property Numbered (PN)-Equipment includes small equipment used in the lab, such as hand tools. Non-PN Equipment is large equipment from the lab, such as glove boxes or other large pieces of machinery. Filter media includes both HEPA filters and regular filters. Non-combustible building debris resulted from decontamination and decommissioning (D&D). The combustible/non-combustible trash category includes glass, plastics, towels, paper, and any personal protective equipment (PPE) the workers may have been wearing, such as gloves or overalls (Fig. 2.1). Combustible decon waste primarily consists of cheesecloth or chemwipes. Leached process residues are salt cake from the processing of plutonium salts that was cemented in gypsum cement. (Some drums excavated from Pad 2 in 1992 contained leached process residues that were dewatering.) The category "slag and porcelain" is classified and little information is available except that metals such as mercury and lead may be present (Corpian 1993) (Fig. 2.2).

Fig. 2.1. Waste Breakdown in Crates on Pads 1, 2, and 4.

Fig. 2.2. Waste Breakdown in Drums on Pads 1, 2, and 4.

3. TOXICITY ASSESSMENT

3.1 TOXICITY INFORMATION FOR RADIONUCLIDES

TRU waste is defined as waste that is contaminated with alpha-emitting transuranium radionuclides having atomic numbers greater than 92, half-lives greater than 20 years, and concentrations greater than 100 nCi/g at the time of assay (DOE 1988b). EPA classifies all radionuclides as Group A carcinogens based on their emissions of ionizing radiation and on the extensive evidence provided by epidemiological studies of high-dose-radiation-induced cancers in humans. Ionizing radiations have sufficient energy that their interactions with matter produce free radicals. Free radicals are highly reactive and may combine with other elements or compounds within a cell to produce toxins or otherwise disrupt the chemical balance. Ionizing radiation has been implicated in damage to the genetic material of cells that results in mutations or other damaging effects. Radionuclides are characterized by the type and energy level of the radiation emitted. Radiation emissions fall into two major categories: (1) particulate (electrons, alpha particles, beta particles, protons) and (2) electromagnetic radiation (gamma and X rays).

Alpha particles are emitted by certain radionuclides at a characteristic energy level specific to each radionuclide. The alpha particle, which consists of two protons and two neutrons, has a charge of +2 and a comparably large size. Alpha particles can react or ionize with other molecules; however, they have very little penetrating power and cannot pass through a piece of paper or human skin. If inhaled or ingested, however, alpha particles can be absorbed and emitted within soft tissues, such as in the lungs or liver, releasing large amounts of energy within a small volume of tissue.

Beta emissions generally refer to beta negative particle emissions. Radionuclides with an excess of neutrons achieve stability by beta decay. Beta-emitting radionuclides can cause injury to the skin and superficial body tissue but are most destructive when inhaled or ingested. Beta emitters are chemically similar to naturally occurring essential nutrients and therefore tend to accumulate in certain specific tissues. For example, ^{90}Sr is chemically similar to calcium and, as a result, accumulates in the bones where it causes continuous exposure. The health effects of beta particle emissions depend upon the target organ. Emissions seeking the bones cause prolonged exposure to the bone marrow and impact blood cell formation, possibly resulting in leukemia, other blood disorders, or bone cancers. Emissions seeking the liver result in liver diseases or cancers; those seeking the thyroid result in thyroid and metabolic disorders.

Gamma and X rays behave similarly but differ in their origin. Gamma emissions originate from the energy released from transformations of the atomic nucleus, while X rays result from changes in the orbiting electron structure. Gamma radiation penetrates the body from the outside and does not require ingestion or inhalation to damage body tissue. Gamma radiation is not directly ionizing; that is, it is not the direct cause of tissue damage in the body, as are alpha and beta radiation. Gamma emissions give up their energy in other reactions that yield another high energy particle, such as an electron. The electron then causes the tissue damage.

A multitude of extrinsic and intrinsic factors influence the effects of ionizing radiation on a living organism. Total dose, quality of the ionizing radiation, dose distribution over time and

body organs, and endogenous factors such as age, health, stress factors, and load of chemical carcinogens and promoters in the affected tissue before and after irradiation will determine the radiation risk. Both acute, nonstochastic effects showing a threshold level and stochastic effects for which a linear dose-effect relationship is assumed are found (Burkart 1988). The probability of stochastic effects is related to dose and no threshold is assumed (i.e., risk of development of cancer from radiation exposure). Nonstochastic effects only occur at high doses and the severity of the effect increases with increasing dose (i.e., acute radiation syndrome and cataract formation that occurs at high levels of exposures).

Radiation can damage cells in different ways. When reproductive cells are damaged by radiation, genetic damage can occur in the offspring of the person exposed. Radiation can cause damage to the strands of genetic material, DNA, in the cell, and the cell may not recover from this type of damage, or the cell may live on but function abnormally. If the abnormally functioning cell divides and reproduces, a tumor or mutation in the tissue may develop. The rapidly dividing cells that line the intestines and the stomach and cells that make blood cells in the bone marrow are sensitive to this damage. Organ damage results from damage caused to individual cells. This type of damage has been reported with doses of 10 to 500 rads. Acute radiation sickness is seen only after doses of greater than 50 rads. This dose usually only results from a nuclear accident.

In general, the behavior of radionuclides in the body will be indistinguishable from that of the corresponding stable element. Biological systems do not discriminate between different isotopes of an element. Even for tritium (^3H), which has three times the mass of ^1H , only small isotope effects in biological systems have been reported. For some of the unstable elements above lead, stable analogs may be helpful in predicting the fate of radionuclides taken up into the body (Burkart 1988). For this reason, effects of corresponding stable elements were outlined in some of the following profiles for the radionuclides of potential concern.

3.1.1 Americium

Americium was first discovered in 1944 at the Metallurgical Laboratory, the forerunner of Argonne National Laboratory. The isotope is named after America because europium, a similar rare-earth element, was named after the continent of its discovery. ^{241}Am is used in high-precision devices and smoke detectors. It decays via alpha-particle emission to ^{237}Np .

Few data exist on the distribution of americium in humans, although measurable amounts have been distributed world-wide as a result of nuclear weapons testing (ICRP 1987). The limited data gathered from experimental animals suggest that "americium behaves like plutonium with regard to initial partition between liver and skeleton" (ICRP 1987). For dosimetry purposes, all isotopes of americium are assumed "uniformly distributed over bone surface at all times following their deposition to the skeleton" (ICRP 1987).

3.1.2 Curium

Curium, element 96, was discovered in 1944 by Argonne National Laboratory shortly before the discovery of americium (element 95). Because it has properties similar to the rare-earth element gadolinium, named in honor of the rare-earth chemist Johan Gadolin, curium was named

in honor of Pierre and Marie Curie. No commercial applications for curium exist, although there is hope it can be used as a fuel in a lightweight thermoelectric power generator.

As for most transuranics, few toxicity studies of curium in humans have been conducted; thus, animal data are used to study the effects of curium in the body. Because the behavior of curium in animals has been observed to be similar to that of americium and because americium behaves like plutonium in terms of the initial partition between liver and bone, curium is also assumed to behave like plutonium (ICRP 1987).

3.1.3 Cobalt

^{60}Co is a synthetic isotope produced by irradiating naturally occurring ^{59}Co with neutrons. The isotope is widely used in industry, medicine, and medical research in place of X rays for detecting internal flaws in materials (Heiserman 1992). It also serves as a biological tracer in diagnosing defects of intestinal vitamin B_{12} absorption.

Important routes of human exposure to ^{60}Co are external exposure to gamma radiation, ingestion of contaminated foods or water, and inhalation of contaminated particulate matter. Radiological damage may occur to the gastrointestinal/respiratory tract during absorption of ^{60}Co , depending on the chemical form. Critical or target body organs include the whole body, lungs, gastrointestinal tract, and the lower large intestine.

3.1.4 Neptunium

Neptunium was artificially produced by Berkeley laboratories in 1940 before it was discovered in nature. The isotope is named after the planet Neptune because it falls on the periodic chart immediately after uranium, which is named after the next closest planet Uranus. Neptunium is produced as a by-product of breeder reactors from ^{235}U and ^{238}U .

The major health effects resulting from exposure to neptunium are expected to be similar to those resulting from exposure to plutonium, discussed in Sect. 3.1.6.

3.1.5 Protactinium

Protactinium is one of the rarest naturally occurring elements and is extremely radioactive. Protactinium was discovered in 1913 by Kasimir Fajans, who named it "brevium," or "brief," because of one of the isotope's brief appearance in the decay of ^{234}Th . The name was changed to protoactinium after a longer-lived isotope was discovered in 1917 and the name finally shortened in 1949. Protactinium occurs naturally in uranium ores in minute amounts (the atomic energy commission of Britain processed 60 tons of uranium ore to obtain 125 grams of protactinium metal) (Heiserman 1992).

Studies on rats indicate that protactinium entering the systemic circulation is mainly deposited in the skeleton with the liver and kidneys as secondary sites of deposition (ICRP 1987). Studies on a human accidentally contaminated with ^{231}Pa via a puncture wound in the hand indicate that after an early phase of excretion the remaining fraction of protactinium is retained in the body.

mainly in the skeleton, almost indefinitely (ICRP 1987, Newton et al. 1968, Newton and Brown 1974).

3.1.6 Plutonium

Plutonium, a predominantly synthetic radioactive metal, was discovered in 1941 by Glenn Seaborg, although the world did not learn of its existence until 1946. One kilogram of the isotope he found, ^{239}Pu , is capable of releasing the energy of 20,000 tons of dynamite and was used in the manufacture of the atom bomb. ^{238}Pu has been used as a nuclear power source for satellites and in thermoelectric generation systems in spacecraft, cardiac pacemakers, and other power sources, although it is mostly associated with nuclear weapons production and testing. ^{238}Pu and ^{239}Pu are the principal plutonium isotopes used in commerce and by the military because of the ease of production and long radioactive half-lives. Both ^{238}Pu and ^{239}Pu are anthropogenic alpha-emitting isotopes of plutonium.

Atmospheric testing of nuclear weapons has been the predominant source of plutonium dispersed in the environment, where it can sorb to soil and sediment particles or bioaccumulate in terrestrial and aquatic food chains. Because of the low solubility of plutonium isotopes, inhalation of contaminated dust particles is considered to be the most harmful means of human exposure. Plutonium that has been inhaled may be absorbed through the lung and be deposited in other body tissues. Subsequent translocation of some of the plutonium from the lungs to tissues and organs distant from the site of entry results in radiation damage to these tissues as well as to the lung. Liver and bone are the primary sites of plutonium deposition. The assumed biological retention half-lives of plutonium isotopes accumulated in the liver and bone of the human body are 20 and 50 years, respectively. Therefore, after a single exposure, plutonium isotopes reside in the body for a long time, resulting in prolonged exposure of body organs to alpha radiation. The permissible levels for plutonium for health are the lowest of all the radioactive elements because plutonium concentrates directly on bone surfaces, rather than uniformly throughout the bone. This increases the possibility of damage from equivalent activities of plutonium and has led to adoption of extremely low permissible levels.

Inhaled ^{238}Pu is solubilized and is translocated from the lung to the bone and liver. Inhaled ^{239}Pu dioxide is insoluble and remains primarily in the lungs and associated lymph nodes. In plutonium laboratory tests with animals, the pattern of nonmalignant toxicity among the species tested was similar; however, species differences in the induction of cancer were apparent. With the exception of Syrian hamsters, cancer developed in animals in lower exposure groups or in animals that survived initial radiation damage to the lungs (ATSDR 1990).

3.1.7 Radium

Radium, discovered in 1898, glows in the dark and is highly radioactive. The handwritten notes of Pierre and Marie Curie, the discoverers of radium, are still too radioactive for handling. Radium is an alkaline/earth metal exhibiting metallic properties and a silvery grayish color. Radium is the only alkaline/earth metal that is radioactive. Until the seriousness of its accompanying health hazards were realized at the end of the 1950's, it was mixed with other phosphorescent materials and used to make luminous wristwatches, clocks, and instrument dials. (The "radium dial painters" are one of the most significant sources of data on radiation

carcinogenicity.) Radium is used in medicine (cancer treatment) and industry as a portable source of neutron radiation. ^{226}Ra has the longest half-life of all of the radium isotopes.

Because radium may bioaccumulate in plants and animals, exposure through the food chain is possible. Radon gas, a colorless, odorless, radioactive gas and primary daughter of radium, can infiltrate basements and water systems, causing exposure via inhalation pathways.

3.1.8 Uranium

Although uranium was first identified in 1789 by Martin Heinrich Klaproth, its radioactivity was not discovered until more than 100 years later by Henri Becquerel. The major uses of uranium are nuclear weapons and reactors, although small amounts are used in the production of ceramics, light bulbs, photographic chemicals, and household products (ATSDR 1990).

The study of uranium toxicity dates back to 1824 when C.G. Gmelin studied the toxic effects of uranium salts on dogs (Gmelin 1824). Toxicological effects from uranium result from the action of uranium as both a metal and as a radionuclide. The primary toxic chemical effect is in the kidney, although its radioisotope toxicity has been shown to cause lung cancer, apparently due to its decay into radon and its daughters.

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4. INCIDENT-FREE RETRIEVAL OPERATIONS ANALYSIS

4.1 CHARACTERIZATION OF INCIDENT-FREE RETRIEVAL OPERATIONS

Incident-free retrieval operations are defined as operations performed under optimal conditions, assuming no accidents or abnormal events. The objective of the incident-free retrieval operations analysis is to compare the risks of operations for both the Immediate and Delayed Retrieval Alternatives under routine, incident-free conditions. Although it is likely that the retrieval process will entail certain accidents or anomalous events, the likelihood of such occurrences is uncertain. An analysis of risks for incident-free operations is useful because it permits a comparison of risks independent of uncertain accidents or abnormal events. The major operations involved in the incident-free retrieval phase are summarized below. For more detailed information, the reader is referred to Benchmark (1993).

Retrieval of TRU waste from Pads 1, 2, and 4 entails the following major activities:

- Site preparation
- Construction of retrieval dome over the pads
- Excavation of soil
- Container removal
- Drum venting in a drum venting system and repackaging, as necessary
- Transport of containers to the storage domes

The current study focuses on those activities that may potentially pose increased risk in the event of a 10-year delay. Because construction of the retrieval domes entails no potential for increased risk in the event of a delay, this step is not considered in the analysis. Site preparation activities involve grading of the surrounding area, constructing access roads, preparing the site for emergency vehicles, contouring the site to meet storm water runoff control requirements, and removing most of the tuff overburden. After the retrieval dome is constructed, the majority of the remaining tuff over the working face of the stack is removed using a vacuum truck. The remaining thin layer of tuff is removed by laborers. Container removal involves the movement of containers from the stack using a custom-boom cage hoist. Drums may be vented or overpacked as required (Benchmark 1993). Drums will be vented in a drum venting system (specifications of a drum venting system were obtained from Wagner et. al. 1987 because specifications of the exact drum venting system to be used at LANL were not available at the time of the current study). Retrieved 55-gallon drums that are breached will be overpacked into 83-gallon drums within the retrieval area after they are removed from the stack [approximately 60% of 55-gallon drums from TRU pads will require overpacking into 83-gallon drums (LANL 1993)]. Damaged crates will be repaired as well by placing the damaged crate on a new plywood base and constructing a plywood crate around the damaged crate. Containers are assumed to be transported to the storage domes on a stakebed truck (Stuhl 1994). Drums will be palletized and banded before transport.

4.2 EXPOSURE ASSESSMENT

The steps of the exposure assessment include the following:

- Characterization of receptors
- Identification of sources and transport media
- Identification of exposure routes
- Quantification of exposure

Quantification of exposure includes estimation of source concentration and dose.

4.2.1 Characterization of Receptors

The exposure assessment for the incident-free retrieval operations is focused on exposure to the retrieval workers. Retrieval workers are defined as workers directly involved in retrieval activities. Public off-site and general on-site employee exposures from incident-free retrieval operations are not quantified (see Sect. 4.2.2). Characterization of the retrieval workers entails the following steps:

- Characterize retrieval operations involving potential exposures to workers
- Define worker types
- Determine number of workers involved in each activity
- Estimate shielding
- Estimate source-to-receptor distances
- Determine total hours required for each activity

Assessing risks to workers during retrieval requires evaluating the risks during each major phase involved in retrieval. The major phases of retrieval operations are (1) mobilization, (2) operation and maintenance (O&M), and (3) closure. The mobilization phase consists of site preparation activities such as materials gathering, site scoping, and initial steps of technology implementation. The O&M phase consists of technology implementation such as use of heavy equipment for excavation. The closure phase often contributes little risk or effort to the overall technology and includes activities such as monitoring and decontamination.

Within each phase of retrieval operations, the primary activity is divided into subactivities for which types and numbers of workers are identified for a specific remediation or waste handling task. Worker types are classified as laborers, equipment operators (EO), and truck drivers (TD). Laborers include health physicists, supervisors, and general laborers, or any worker not operating heavy equipment. Equipment operators are the workers who primarily operate heavy equipment. For each subactivity, crew sizes, shielding, source-to-receptor distances, and durations must be estimated. For the retrieval of TRU Pads 1, 2, and 4, the retrieval activities, worker types, and associated information are identified in Table 4.1.

Table 4.1. Characterization of retrieval operations and worker parameters

Activity	Phase	Subactivity	Worker Type	Crew Size ^a	Shielding	Source-Receptor Distance	Duration ^b (yr)	Total Person-Hours ^c (5 yrs)
EXCAVATION	Mobilization Phase	Site Preparation	Laborer	8	0.0014 m steel (drum thickness), 0.009 m wood (plywood), 1 m soil (overburden) ^d , 1 m (air) ^d	2.010 m	0.2500	3000
		Initial excavation of soil overburden using bulldozer or vacuum	Laborer	4	0.0014 m steel, 0.009 m wood, 0.610 m soil (unexcavated soil overburden) ^d , 1 m air ^d	1.620 m	0.4583	5500
			EO ^e	4	0.0014 m steel, 0.009 wood, 0.610 m soil ^d , 1 m air (ground to equipment), 0.01 steel m (equipment frame) ^f , 0.5 m air (equipment floor to worker)	2.130 m	0.4583	5500
	O&M ^d Phase	Vacuum remaining soil using vacuum truck or manually	Laborer	4	0.0014 m steel, 0.009 wood, 0.15 m soil, 1 m air ^d	1.160 m	0.5833	7000
			EO	4	0.0014 m steel, 0.009 wood, 0.15 m soil overburden, 1 m air ^d , 0.01 m steel (equipment frame) ^f , 0.5 m air (equipment floor to worker)	1.670 m	0.5833	7000
		Remove tarp and plywood	Laborer	4	0.0014 m steel (drum), 1 m air	1.001 m	0.0083	100
		Inspect and sample	Laborer	4	0.0014 m steel (drum), 1 m air	1.001 m	0.0167	200
CONTAINER REMOVAL	O&M Phase	Remove container using electric forklift with custom boom/hoist/cage	Laborer	4	0.0014 m steel (drum), 1 m air	1.001 m	0.8333	10000
			EO	4	0.0014 m steel, 0.0032 m steel (assumed thickness of safety cage) ^d , 3.0 m air (safety cage to forklift operator) ^f	3.005 m	0.8333	10000

Table 4.1. (continued)

Activity	Phase	Subactivity	Worker Type	Crew Size ^a	Shielding	Source-Receptor Distance	Duration ^b (yr)	Total Person-Hours ^b (5 yrs)
REPACKAGING	O&M Phase	Overpack containers not structurally sound	Laborer	4	0.0014 m steel (drum), 1 m air ^c	1.001 m	0.2500	3000
			EO	4	0.0014 m steel, 0.0032 m steel (assumed thickness of safety cage) ^d , 3.0 m air (safety cage to forklift operator) ^e	3.005 m	0.2500	3000
		Vent drums	Laborer	4	0.0014 m steel (drum) ^f , 15.24 m air (drum to worker distance) ^f	15.241 m	0.2500	3000
	Closure	D&D ^g equipment	Laborer	4	3 m air ^c	3.000 m	0.0292	350
			EO	4	0.01 m steel (frame) ^h , 0.5 m air (equipment floor to worker) ^h	0.510 m	0.0292	350
	O&M	Load, transport, and unload containers	TD ⁱ	8	0.0014 m steel, 0.0032 m steel (thickness of truck bed) ^j , 0.154 m air (gap between truck bed & cab) ^j , 0.0032 m aluminum (thickness of cab & frame) ^j	0.1618 m	0.1667	2000
Total							5.0	60,000.00

^a Best professional judgement

^b Based on one 12,000 hr work yr (one crew of eight working one 30 hr/wk shift, 50 wks/yr). The retrieval process is assumed to last five years (Baker 1993).

^c Equipment Operator

^d Operations and Maintenance

^e Decommissioning and Decontamination

^f Truck Driver

^g Based on specifications and drawings stated in Benchmark 1993.

^h Represents distance from the bottom of a worker's feet to the torso.

ⁱ Equipment shielding based on pamphlets obtained from JCB Excavators, LTD and Dresser Equipment and observation.

^j Wagner et. al. 1987.

^k EPA 1991.

^l Lambert 1993 and Mynatt 1993.

4.2.2 Sources and Transport Media

Because recent soil sampling (31 samples taken in August, 1992) has revealed no contamination of environmental media around Pads 1, 2, and 4, or the inactive LLW pits below, sources of potential exposures during incident-free retrieval operations for the Immediate and Delayed Retrieval Alternatives are the drums and crates and the waste they contain. Under both alternatives, the waste and waste containers pose a direct radiation hazard to retrieval workers during incident-free retrieval operations.

Air is a potential transport medium for radiological contamination due to non-fixed particulates on the surface of the containers (Benchmark 1993). Handling of the containers during incident-free retrieval operations may result in suspension of these particulates, exposing workers, general employees, and off-site receptors to airborne particulates. Exposure due to inhalation of airborne contamination is evaluated in Benchmark 1993. Because the Benchmark analysis is conducted assuming retrieval operations begin as soon as possible, this scenario is comparable to the Immediate Retrieval Alternative in the current study. Because the amount of surface contamination is unknown, the exterior of all waste containers is assumed contaminated with the maximum level permitted under the U.S. Department of Transportation (DOT) Regulations for alpha-emitting radionuclides, or 100 pCi/100 cm² (Benchmark 1993). Fifty percent of this non-fixed surface contamination is assumed to be released within the retrieval dome during incident-free waste handling operations. Benchmark's analysis found workers within the retrieval dome would be subject to an inhalation committed effective dose equivalent (CEDE) of less than 0.14 rem/yr due to airborne contamination. An off-site receptor in White Rock would be subject to an inhalation effective dose equivalent of 7.3×10^{-9} rem/yr (Benchmark 1993). On-site receptors in Area L would be subject to an effective dose equivalent (EDE) of 4.2×10^{-9} .

The potential exists for surface contamination to increase over the delayed retrieval period, thus increasing the dose to receptors. The first step in the quantitative analysis of the change in dose due to the delayed retrieval of the waste is to quantify the increase in surface contamination. While the DOT maximum allowable limit is a reasonable worst case assumption for the Immediate Retrieval Alternative, no equivalent assumption is applicable for a potential increase in surface contamination over the delayed retrieval period. An increase in surface contamination could be postulated, but lack of any supporting data renders this approach indefensible. The purpose of the study is to compare risks between two alternatives. Because it is not feasible to quantify increased exposure due to an increase in surface contamination in the Delayed Retrieval Alternative, it is not possible to identify a change in risk from surface contamination in the Immediate Retrieval Alternative, hence the risks from surface contamination are not quantified for either alternative. Because quantification of risks due to surface contamination for the Delayed Retrieval Alternative is not performed, a qualitative analysis is included in Sect. 4.5. The quantitative assessment of incident-free retrieval operations for both alternatives is focused on the associated radiological impacts from direct radiation.

4.2.3 Fate and Transport

The following sections discuss the general approach used to link sources with contaminated media and site-specific parameters used in fate and transport modeling.

For sources of external radiation during the retrieval phase, the MicroShield computer code, developed by Grove Engineering (1992), is used to estimate worker population EDE rates attributed to direct radiation. MicroShield uses the point kernel integration method (Gaussian numerical quadrature method) to estimate photon fluence rates and International Commission on Radiological Protection (ICRP) methods to estimate EDE rates. MicroShield deals primarily with gamma radiation and uses information such as source-to-receptor distances, number and type of shielding materials, and source geometry. MicroShield contains 10 different source-shield geometries and takes into account a variety of source configurations (e.g., cylinder, rectangular volume, and infinite plane). The geometry includes the distance, dimensions, locations, and orientations of intervening shields. MicroShield contains 14 source and shielding configurations and provides the flexibility to examine a variety of receptor locations relative to the source.

Microshield uses the shielding and material density information and input parameters such as buildup factors, energy levels, and fluence rates to estimate the dose received by a receptor at an exposure point. The EDE rate estimated by MicroShield is for rotational geometry. While geometry refers to the position of the receptor in relation to the source, rotational geometry represents a uniform dose to the worker's entire body. The rotational EDE is thus the dose that the receptor would receive if rotated 360° at a constant angular velocity at a fixed distance from a stationary source.

Most parameters required by MicroShield to model retrieval operations, such as source-to-receptors distances and shielding parameters, are found in Table 4.1. The working face of the array was modeled as a rectangular volume. The densities used in MicroShield to represent the waste forms on Pads 1, 2, and 4 (shown in Figs. 2.1 and 2.2) and are shown in Table 4.2.

Table 4.2. Waste density parameters used to model retrieval operations

General Waste Forms	Percent of Waste Volume ^a	Density g/cm ³
Miscellaneous Solids ^a	38	0.56 ^c
Metal	16	7.86 ^d
Cement	38	2.35 ^d
Soil	2	1.40 ^e
Glass	3	2.64 ^e
Slag/Porcelain	3	3.00 ^e

^a LANL 1993

^b Includes combustible and non-combustible trash, paper, plastic, rubber, cheese cloth, and chemwipes.

^c EG&G 1992

^d Grove Engineering 1992

^e Jansen 1993

4.2.4 Identification of Exposure Routes

Direct radiation is identified in Sect. 4.2.2 as the exposure route to be quantified for worker populations and activities during incident-free retrieval operations. Workers are susceptible to exposure from direct radiation emitting from the waste under both alternatives.

4.2.5 Quantification of Exposure

The next step in the exposure assessment process is to quantify the magnitude, frequency, and duration of exposure for the populations and exposure routes selected for quantitative evaluation. Quantification of exposure involves determining source concentrations and calculating the doses for the exposure route identified. To calculate the dose, the source concentration is evaluated in the context of the exposure scenario, exposure route, and exposure variables, such as duration of exposure.

4.2.5.1 Source concentration

Workers in the retrieval dome may be exposed to a maximum of 24 55-gallon drum equivalents at any given time during retrieval operations (Benchmark 1993). The contents of 24 containers are assumed to be homogenous and an average distribution of radionuclides is assumed. The contents of one 55-gallon drum equivalent are derived from Table 1.1. Given that all 16,647 drums on the pads are assumed to be full and contain 0.208 m³ of waste and all 218 FRP crates are assumed to contain an average of 3.17m³ (111.95 ft³) of waste [based on average dimensions of 1.22 m x 1.22 m x 2.13 m (4' x 4' x 7')], the total volume of waste is 4153.96 m³ (1.47 x 10⁵ ft³). The total activity of each isotope from Table 1.1 is divided by this total volume to obtain the waste concentration (Ci/m³) in one 55-gallon drum equivalent.

An example calculation for ²⁴¹Am is shown below:

$$\frac{7.70 \times 10^3 \text{ Ci}}{4153.96 \text{ m}^3} = 1.85 \frac{\text{Ci}}{\text{m}^3} (0.208 \text{ m}^3) = 3.86 \times 10^{-1} \text{ Ci.} \quad [4.1]$$

The average contents of one full 55-gallon drum equivalent are shown in Table 4.3.

Table 4.3. Average contents of one drum^a

Isotope	Total Activity (Ci)	Activity per Drum (Ci)	Isotope	Total Activity (Ci)	Activity per Drum (Ci)
²⁴¹ Am	7.70e+03	3.86e-01	²⁴⁰ Pu	2.44e+03	1.22e-01
²⁴³ Am	5.70e-01	2.85e-05	²⁴¹ Pu	2.14e+02	1.07e-02
²⁴³ Cm	1.50e+00	7.51e-05	²⁴² Pu	2.61e+02	1.31e-02
²⁴⁴ Cm	2.20e+02	1.10e-02	²⁴⁴ Pu	4.94e-02	2.47e-06
⁶⁰ Co	1.00e-03	5.01e-08	²²⁶ Ra	9.00e-01	4.51e-05
²³⁷ Np	4.24e-04	2.12e-08	²³⁵ U	2.60e-01	1.30e-05
²³¹ Pa	1.10e-03	5.51e-08	²³⁴ U	4.84e-05	2.42e-09
²³⁸ Pu	6.33e-03	3.17e-07	²³⁸ U	6.02e-03	3.01e-07
²³⁸ Pu	2.00e+04	1.00e+00	²³⁶ U	6.03e-05	3.02e-09
²³⁹ Pu	3.34e+04	1.67e+00	²³⁴ U	4.79e-01	2.40e-05

^a Derived from Table 1-1.

For the Immediate Retrieval Alternative, the original inventory is decayed two years to represent the decay age of the youngest waste (Pad 4 closed in 1991). For the Delayed Retrieval Alternative the waste is decayed an additional 10 years, for a total of 12 years. All daughter products are accounted for. Although waste retrieval will be staggered over several years, initial dose assessment for storage workers for waste decayed at increments of two years up to 12 years showed little decrease in dose.

4.2.5.2 Estimation of dose

After representative individual EDE rates are estimated, the collective dose (population dose) and individual dose are estimated. Collective dose is estimated as follows:

$$\text{Collective Dose} = \text{EDE rate} * \text{ED}, \quad [4.2]$$

where:

EDE rate	=	Dose rate generated by MicroShield (rem/hr),
ED	=	Exposure duration (person-hr),

Exposure durations and the number of workers for each subactivity are found in Table 1.1. Individual EDEs are estimated for each subactivity for the fraction of time an individual worker spends doing that activity as follows:

$$\text{Individual Dose} = \frac{\text{EDE rate} * \text{ED}}{\text{NW}}, \quad [4.3]$$

where:

EDE rate	=	Dose rate generated by MicroShield (rem/hr),
ED	=	Exposure duration (person-hr),
NW	=	Number of workers exposed (unitless).

Individual and collective doses for the Immediate and Delayed Retrieval Alternatives are shown in Tables 4.4 and 4.5, respectively.

Table 4.4. Retrieval worker EDEs for incident-free Immediate Retrieval Alternative

Subactivity	Worker Type	Crew Size	Total Person-Hours	Calculated EDE rate (rem/hr)	Individual EDE (rem)	Collective EDE (person-rem)
Site Preparation	Laborer	8	3000	1.25e-08	4.70e-06	3.76e-05
Excavation	Laborer	4	5500	1.87e-07	2.57e-04	1.03e-03
Excavation	EO	4	5500	1.02e-07	1.40e-04	5.60e-04
Vacuum Soil	Laborer	4	7000	6.20e-06	1.08e-02	4.34e-02
Vacuum Soil	EO	4	7000	4.91e-09	8.59e-06	3.44e-05
Remove Tarp	Laborer	4	100	7.29e-05	1.82e-03	7.29e-03
Inspect/Sample	Laborer	4	200	7.29e-05	3.65e-03	1.46e-02
Remove Container	Laborer	4	10000	9.77e-06	2.44e-02	9.77e-02
Remove Container	EO	4	10000	4.95e-07	1.24e-03	4.95e-03
Overpack	Laborer	4	3000	9.77e-06	7.32e-03	2.93e-02
Overpack	EO	4	3000	4.95e-07	3.71e-04	1.49e-03
Vent Drums	Laborer	4	3000	6.01e-08	4.51e-05	1.80e-04
D&D Equipment	Laborer	4	350	1.54e-04	1.34e-02	5.38e-02
D&D Equipment	EO	4	350	7.70e-04	6.73e-02	2.69e-01
Transport	TD	8	2000	2.62e-05	6.55e-03	5.24e-02
Collective Dose	All Receptors	N/A	60000	N/A	N/A	5.76e-01

Table 4.5. Retrieval worker EDEs for incident-free Delayed Retrieval Alternative

Subactivity	Worker Type	Crew Size	Total Person-Hours	Calculated EDE rate (rem/hr)	Individual EDE (rem)	Collective EDE (person-rem)
Site Preparation	Laborer	8	3000	1.25e-08	4.68e-06	3.74e-05
Excavation	Laborer	4	5500	1.86e-07	2.57e-04	1.02e-03
Excavation	EO	4	5500	1.01e-07	1.39e-04	5.58e-04
Vacuum Soil	Laborer	4	7000	6.13e-06	1.07e-02	4.29e-02
Vacuum Soil	EO	4	7000	4.89e-09	8.55e-06	3.42e-05
Remove Tarp	Laborer	4	100	7.21e-05	1.80e-03	7.21e-03
Inspect/Sample	Laborer	4	200	7.21e-05	3.60e-03	1.44e-02
Remove Container	Laborer	4	10000	9.65e-06	2.41e-02	9.65e-02
Remove Container	EO	4	10000	4.95e-07	1.24e-03	4.95e-03
Overpack	Laborer	4	3000	9.65e-06	7.24e-03	2.90e-02
Overpack	EO	4	3000	4.95e-07	3.71e-04	1.49e-03
Vent Drums	Laborer	4	3000	5.95e-08	4.46e-05	1.78e-04
D&D Equipment	Laborer	4	350	1.52e-04	1.33e-02	5.32e-02
D&D Equipment	EO	4	350	7.60e-04	6.65e-02	2.66e-01
Transport	TD	8	2000	2.59e-05	6.48e-03	5.18e-02
Collective Dose	All Receptors	N/A	60000	N/A	N/A	5.69e-01

The reader should note that individual doses shown in Tables 4.4 and 4.5 are not annual individual doses; rather, they are the individual doses for a crew member for the fraction of time spent performing each subactivity throughout the entire retrieval operation. The individual EDEs are estimated for each subactivity (rather than for full time workers) because only the number of workers and person-hours required for each subactivity are known. Each worker will participate in various subactivities throughout the retrieval process. It is not known which series of subactivities a particular worker will be engaged in and, therefore, an actual average annual individual dose for retrieval workers is not available. However, we can calculate an average annual individual dose for a worker for any subactivity, assuming that worker performs one subactivity full time for one year. This assumption is unrealistic but can provide some perspective on the doses calculated by allowing us to compare the doses to regulatory limits. For example, the average annual individual dose for a worker working full time in the container removal stage, the most time-consuming stage of retrieval operations, is 0.01 rem/yr under both alternatives. The As Low As Reasonably Achievable concept employed at DOE facilities to limit exposures of workers to radionuclides states that exposures to radiological contaminants should be kept as low as achievable, or 20% of the DOE recommended limit. The DOE recommended dose limit for

workers specified in DOE Order 5480.11 is 5 rem/yr. Thus, 20% of the DOE recommended limit is 1 rem/yr.

This average annual individual dose of 0.01 rem/yr is the product of the dose rate for a worker in the container removal subactivity and the hours in one full working year. An example calculation is provided below. From Table 4.4, the EDE rate for removing the container is 9.77×10^{-6} rem/hr. Next, the annual individual dose is calculated, assuming a worker works full time in the container removal stage for one year and using Eq. 4.3:

$$\left(9.77 \times 10^{-6} \frac{\text{rem}}{\text{hr}} \right) \left(30 \frac{\text{hrs}}{\text{wk}} \right) \left(50 \frac{\text{wks}}{\text{yr}} \right) = 1.47 \times 10^{-2} \frac{\text{rem}}{\text{yr}} \quad [4.4]$$

The average annual individual dose for a worker working full time in the container removal stage is thus 0.01 rem/yr. A hypothetical annual individual dose can be derived for any subactivity in this manner, if one assumes that a worker works full time in one subactivity.

4.3 RISKS ASSOCIATED WITH INCIDENT-FREE RETRIEVAL OPERATIONS

The endpoints for risk evaluations of radionuclides are the following:

- Cancer fatality
- Cancer incidence
- Adverse genetic effects

Cancer fatality risk is the probability of an individual dying from cancer. The probability of an individual developing fatal and nonfatal cancers is cancer incidence. The probability of experiencing adverse genetic effects is the genetic effects risk value.

After the EDE is obtained, risks are estimated by multiplying the EDE by a risk factor. Cancer fatality or incidence risk factors are the values used to estimate cancer fatality, cancer incidence, and genetic effects risks from radionuclides. Risk factors and their respective endpoints are summarized in Table 4.6 for workers and the public (Although risks predicted in this section are worker risks only, public risk factors are also presented here for later reference).

Table 4.6. Summary of health effects endpoints

Types of Contaminant	Risk Factor (risk/rem)*		Endpoints
	Public	Workers	
Radionuclide	5.0e-4	4.0e-4	Cancer Fatality
Radionuclide	1.7e-3	1.4e-3	Cancer Incidence
Radionuclide	1.0e-4	6.0e-5	Genetic Effects

Source: ICRP 1991.

*The nominal probability coefficient for fatal cancers is used to derive the cancer incidence nominal probability coefficient. The probability of fatal cancer, F (which for workers is 80% of F, as described in ICRP 60) is divided by the cancer incidence nominal probability coefficient of 1.4×10^{-3} rem.

The following equation is used to estimate fatal cancer risk or cancer incidence for an individual:

$$Risk = RF * EDE, \quad [4.5]$$

where:

Risk	=	Probability of cancer fatality or incidence due to exposure to radiation from a radionuclide (dimensionless),
RF	=	Cancer fatality or incidence risk factor (risk/rem),
EDE	=	Effective dose equivalent (rem).

Individual and collective risks resulting from potential direct radiation exposure for the Immediate and Delayed Retrieval Alternatives are shown in Tables 4.7 and 4.8, respectively.

Table 4.7. Risks for incident-free retrieval: Immediate Retrieval Alternative

Subactivity	Worker Type	Individual Risks				Collective Risks			
		EDE (rem)	Cancer Fatalities	Cancer Incidence	Genetic Effects	EDE (rem)	Cancer Fatalities	Cancer Incidence	Genetic Effects
Site Preparation	Laborer	4.70e-06	1.88e-09	6.58e-09	2.82e-10	3.76e-05	1.50e-08	5.27e-08	2.26e-09
Excavation	Laborer	2.57e-04	1.03e-07	3.60e-07	1.54e-08	1.03e-03	4.11e-07	1.44e-06	6.17e-08
Excavation	EO	1.40e-04	5.60e-08	1.96e-07	8.41e-09	5.60e-04	2.24e-07	7.85e-07	3.36e-08
Vacuum Soil	Laborer	1.08e-02	4.34e-06	1.52e-05	6.51e-07	4.34e-02	1.74e-05	6.08e-05	2.60e-06
Vacuum Soil	EO	8.59e-06	3.44e-09	1.20e-08	5.16e-10	3.44e-05	1.37e-08	4.81e-08	2.06e-09
Remove Tarp	Laborer	1.82e-03	7.29e-07	2.55e-06	1.09e-07	7.29e-03	2.92e-06	1.02e-05	4.37e-07
Inspect/Sample	Laborer	3.65e-03	1.46e-06	5.10e-06	2.19e-07	1.46e-02	5.83e-06	2.04e-05	8.75e-07
Remove Container	Laborer	2.44e-02	9.77e-06	3.42e-05	1.46e-06	9.77e-02	3.91e-05	1.37e-04	5.86e-06
Remove Container	EO	1.24e-03	4.95e-07	1.73e-06	7.43e-08	4.95e-03	1.98e-06	6.93e-06	2.97e-07
Overpack	Laborer	7.32e-03	2.93e-06	1.03e-05	4.39e-07	2.93e-02	1.17e-05	4.10e-05	1.76e-06
Overpack	EO	3.71e-04	1.49e-07	5.20e-07	2.23e-08	1.49e-03	5.94e-07	2.08e-06	8.91e-08
Vent Drums	Laborer	4.51e-05	1.80e-08	6.31e-08	2.71e-09	1.80e-04	7.22e-08	2.53e-07	1.08e-08
D&D	Laborer	1.34e-02	5.38e-06	1.88e-05	8.06e-07	5.38e-02	2.15e-05	7.53e-05	3.23e-06
D&D	EO	6.73e-02	2.69e-05	9.43e-05	4.04e-06	2.69e-01	1.08e-04	3.77e-04	1.62e-05
Transport	TD	6.55e-03	2.62e-06	9.17e-06	3.93e-07	5.24e-02	2.10e-05	7.34e-05	3.14e-06
Collective Risk	All Receptors		N/A	N/A	N/A		2.30e-04	8.06e-04	3.46e-05

Table 4.8. Risks for incident-free retrieval: Delayed Retrieval Alternative

Subactivity	Worker Type	Individual Risks				Collective Risks			
		EDE (rem)	Cancer Fatalities	Cancer Incidence	Genetic Effects	EDE (rem)	Cancer Fatalities	Cancer Incidence	Genetic Effects
Site Preparation	Laborer	4.68e-06	1.87e-09	6.55e-09	2.81e-10	3.74e-05	1.50e-08	5.27e-08	2.26e-09
Excavation	Laborer	2.57e-04	1.03e-07	3.60e-07	1.54e-08	1.02e-03	4.09e-07	1.43e-06	6.13e-08
Excavation	EO	1.39e-04	5.58e-08	1.95e-07	8.37e-09	5.58e-04	2.23e-07	7.81e-07	3.35e-08
Vacuum Soil	Laborer	1.07e-02	4.29e-06	1.50e-05	6.44e-07	4.29e-02	1.72e-05	6.01e-05	2.58e-06
Vacuum Soil	EO	8.55e-06	3.42e-09	1.20e-08	5.13e-10	3.42e-05	1.37e-08	4.79e-08	2.05e-09
Remove Tarp	Laborer	1.80e-03	7.21e-07	2.52e-06	1.08e-07	7.21e-03	2.88e-06	1.01e-05	4.32e-07
Inspect/Sample	Laborer	3.60e-03	1.44e-06	5.04e-06	2.16e-07	1.44e-02	5.76e-06	2.02e-05	8.65e-07
Remove Container	Laborer	2.41e-02	9.65e-06	3.38e-05	1.45e-06	9.65e-02	3.86e-05	1.35e-04	5.79e-06
Remove Container	EO	1.24e-03	4.95e-07	1.73e-06	7.43e-08	4.95e-03	1.98e-06	6.93e-06	2.97e-07
Overpack	Laborer	7.24e-03	2.90e-06	1.01e-05	4.34e-07	2.90e-02	1.16e-05	4.05e-05	1.74e-06
Overpack	EO	3.71e-04	1.49e-07	5.20e-07	2.23e-08	1.49e-03	5.94e-07	2.08e-06	8.91e-08
Vent Drums	Laborer	4.46e-05	1.78e-08	6.24e-08	2.68e-09	1.78e-04	7.13e-08	2.50e-07	1.07e-08
D&D	Laborer	1.33e-02	5.32e-06	1.86e-05	7.97e-07	5.32e-02	2.13e-05	7.44e-05	3.19e-06
D&D	EO	6.65e-02	2.66e-05	9.31e-05	3.99e-06	2.66e-01	1.06e-04	3.72e-04	1.60e-05
Transport	TD	6.48e-03	2.59e-06	9.07e-06	3.89e-07	5.18e-02	2.07e-05	7.25e-05	3.11e-06
Collective Risk	All Receptors		N/A	N/A	N/A		2.28e-04	7.97e-04	3.42e-05

The reader should note that individual risks shown in Tables 4.7 and 4.8 are not annual individual risks, rather they are risks for a crew member for the fraction of time spent performing each subactivity throughout the entire retrieval operation. The individual risks are estimated for each subactivity (rather than for full time workers) because only the number of workers and person-hours required for each subactivity are known. Each worker will participate in various subactivities throughout the retrieval process. It is not known which series of subactivities a particular worker will be engaged in and, therefore, an actual annual individual risk for retrieval workers is not available. However, we can calculate an annual individual risk for a worker for any subactivity, assuming that worker does one subactivity full time for one whole year. This assumption is unrealistic, but can provide some perspective on the risks calculated by allowing us to compare the risks to risk goals. For example, the annual individual cancer fatality risk of a worker working full time for one year in the container removal phase, the most time-consuming phase in the retrieval operations, is 5.9×10^{-6} under both alternatives. The point of departure for individual risks is 10^{-4} - 10^{-6} for the Comprehensive Environmental and Response, Compensation, and Liability Act (CERCLA). Risks above this are considered significant or of regulatory concern.

This annual individual risk is the product of the dose for a worker, assuming full time in the container removal subactivity, the hours in one working year, and the appropriate risk factor.

An example calculation is provided below. In Eq. 4.4 we obtained a dose of 1.47×10^{-2} rems/yr. Thus, annual individual cancer fatality is calculated using Eq. 4.5, the risk factor for worker cancer fatalities (Table 4.6), and the dose from Eq. 4.4:

$$(1.47 \times 10^{-2}) (4.0 \times 10^{-4}) = 5.9 \times 10^{-6} \quad [4.7]$$

The annual individual cancer fatality risk of a worker working full time for one year in the container removal phase is 5.9×10^{-6} . A hypothetical annual individual risk can be derived for any subactivity in this manner, if one assumes the worker spends 100% of the time performing one subactivity and the appropriate risk factors are substituted.

4.4 UNCERTAINTIES IN THE INCIDENT-FREE RETRIEVAL OPERATIONS ANALYSIS

The results of any risk assessment are probabilistic estimates of risk. They are conditional estimates based on multiple assumptions. These assumptions introduce varying degrees of uncertainty into the results that may over- or under-estimate exposures and risks. The uncertainties inherent in every risk analysis must be evaluated to place risks in proper perspective. The goal of the present qualitative uncertainty analysis is to assess the general accuracy and acceptability of assumptions used in the risk assessment and to provide information concerning the quality of the assessment, including the effects assumptions have on the accuracy or reasonableness of the exposure and risk estimates developed.

Risk assessment is subject to uncertainty with regard to both the general aspects of risk assessment and the site-specific aspects of risk assessment. In general, the source of site-specific

uncertainties in this stage of the risk assessment is inadequate information concerning the experimental and operational data regarding specific retrieval parameters, including the following:

- Inventory
- Shielding
- Source-to-receptor distances
- Duration of exposure

Uncertainties with regard to site-specific retrieval aspects are shown in Table 4.9. The assumptions employed in these areas of uncertainty are based on information gathered from conversations with contacts at sites where similar activities are performed, conversations with engineers who are familiar with these activities, and best professional judgement. The table contains a summary of uncertain variables, the values and/or assumptions used, and the rationale for the value used. The final column of the table summarizes how this uncertainty is expected to affect the estimate of exposure.

Table 4.9. Uncertainty in the incident-free retrieval operations analysis

Variables	Value/Assumption	Justification or Source	Effect of Uncertainty
Contents of drums	Homogenous distribution of radionuclides	Best professional judgement	May over- or under-estimate dose
Exposure Duration	Table 4.1	Baker 1993 Best professional judgement	May over- or under-estimate dose
Air Gaps in Shielding	Worker remains at a fixed distance from the drums	Conservative estimate	May over-estimate dose. It is probable that air gaps are on average larger than those assumed for modeling purposes.
Shielding used for EO during excavation, container removal, and overpacking	Table 4.1	Benchmark 1993 JCB Excavators, LTD Dressor Equipment Best professional judgement	May over-estimate dose
Shielding used for drum venting activities	Typical drum venting system that is remotely operated	EPA 1991 Best professional judgement	May over-estimate dose
Source-to-receptor distances	Table 4.1	Best professional judgement	May over- or under-estimate dose

4.5 SUMMARY OF INCIDENT-FREE RETRIEVAL OPERATIONS ANALYSIS

The calculated individual worker risks for both alternatives for all activities were in the range of 2.8×10^{-10} to 9.4×10^{-5} . The calculated collective risks were in the range of 3.4×10^{-5} to 8.1×10^{-4} . The driver of worker risks for both alternatives in this analysis is direct radiation exposure. Quantification of internal exposure due to inhalation of contaminants from potential surface

contamination for incident-free retrieval operations is not possible because of the impracticality of making an assumption about surface contamination in 10 years. Therefore, the only difference between the two alternatives is the decay of the waste. However, if Level of Protection B is assumed for the workers (includes a respirator), worker inhalation risks would be decreased by a factor of 1000, according to the assigned protection factors for respiratory equipment (NIOSH 1990). Risks to off-site receptors were not quantified. Any potential release of radionuclide particulates from the retrieval dome during incident-free retrieval operations would be reduced by a factor of 1000 due to the HEPA filters in the retrieval dome (Benchmark 1993).

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5. INCIDENT-FREE STORAGE OPERATIONS ANALYSIS

5.1 CHARACTERIZATION OF INCIDENT-FREE STORAGE OPERATIONS

Incident-free storage operations are defined as operations performed under optimal conditions, assuming no accidents or abnormal events. The objective of the analysis of incident-free storage operations is to compare the risks of operations for both alternatives under routine, incident-free conditions. Although it is likely the storage process will entail certain accidents or anomalous events, the likelihood of such occurrences is uncertain. An analysis of risks for incident-free storage operations is useful because it permits a comparison of risks independent of uncertain accidents or abnormal events. The waste that is retrieved from Pads 1, 2, and 4 will be stored in six aboveground domes. The storage activities are assumed to be the same for all six domes and are based on the storage scenario in Pad 3, the aboveground storage dome at TA-54. The activities involved in storage of Pad 1, 2, and 4 waste are described below (for more detailed information, the reader is referred to Benchmark 1993):

- Construct storage domes
- Receive, clean, and swipe containers, ultrasonically check containers for structural integrity
- Label container
- Transport containers from the receiving area in the storage dome to the container storage area by forklift
- Monitor/inspect containers

The current study focuses on those activities that may potentially pose increased risk in the event of a 10-year delay. Because construction of the storage domes entails no potential for increased risk in the event of a delay, this step was not considered in the analysis.

5.2 EXPOSURE ASSESSMENT

The steps of the exposure assessment include the following:

- Characterization of receptors
- Identification of sources and transport media
- Identification of exposure routes
- Quantification of exposure

Quantification of exposure includes estimation of source concentration and dose.

5.2.1 Characterization of Receptors

The exposure assessment for the incident-free storage operations is focused on exposure of the storage workers. Public off-site and general on-site employee exposure due to incident-free storage operations are not considered. The distance of off-site and general on-site employees from the storage domes is assumed to reduce risk of exposures in this phase of operations to insignificant levels.

Storage workers are defined as those workers directly involved in storage activities. Characterization of the storage workers entails the following steps:

- Characterize storage operations involving potential exposures to workers
- Define worker types
- Determine number of workers involved in each activity
- Estimate shielding
- Estimate source-to-receptor distances
- Determine total hours required for each activity

Storage worker types are classified as (1) radiation control technicians, (2) RCRA inspectors, and (3) technicians. Storage workers are characterized for the Immediate and Delayed Retrieval Alternatives in Tables 5.1 and 5.2, respectively.

Table 5.1. Characterization of storage operations: Immediate Retrieval Alternative

Worker Type	Activities	Hrs/Month ^a (Ea. Dome)	Hrs/Yrs (2 Domes ^b)	Total Hrs 15-Yr Storage (6 Domes)
Radiation Control Technician	Records general background fields for radiation. Takes radiation smears, checks postings and labelings for controlled areas. Replaces CAM filters.	1.5	2 Domes (15 yrs) - 540 2 Domes (13 yrs) - 468 2 Domes (11 yrs) - 396	1404
RCRA Inspector	Checks labels. Checks for leaks, loss of contaminant.	6	2 Domes (15 yrs) - 2160 2 Domes (13 yrs) - 1872 2 Domes (11 yrs) - 1584	5616
Technician	Receives containers. Moves containers. Drives forklift. Checks domes. Checks for leaks.	160 [‡]	2 Domes (15 yrs) - 12800 2 Domes (13 yrs) - 8960 2 Domes (11 yrs) - 7040	28800
Total Person Hours	All activities.	167.5	2 Domes (15 yrs) - 15500 2 Domes (13 yrs) - 11300 2 Domes (11 yrs) - 9020	35820

^a Based on Pad 3 storage scenario (Christensen 1993).

^b Because the retrieval process will take place over a five-year period, storage of all waste from Pads 1, 2, and 4 will not begin simultaneously, but will be staggered. Storage durations for the Immediate Retrieval Alternative are assumed to be 15 years (2 domes), 13 years (2 domes), and 11 years (2 domes), for Pads 1, 4, and 2 waste, respectively.

[‡] An estimate of 1-40 hrs/week was given, depending upon the work required. As a worst case scenario, the highest number of hours potentially spent inside the dome is used.

Table 5.2. Characterization of storage operations: Delayed Retrieval Alternative

Worker Type	Activities	Hrs/Month* (Ea. Dome)	Hrs/Yrs (2 Domes*)	Total Hrs 5-Yr Storage (6 Domes)
Radiation Control Technician	Records general background fields for radiation. Takes radiation smears, checks postings and labelings for controlled areas. Replaces CAM filters.	1.5	2 Domes (5 yrs) - 180 2 Domes (3 yrs) - 108 2 Domes (1 yrs) - 36	324
RCRA Inspector	Checks labels. Checks for leaks, loss of contaminant.	6	2 Domes (5 yrs) - 720 2 Domes (3 yrs) - 432 2 Domes (1 yrs) - 144	1296
Technician	Receives containers. Moves containers. Drives forklift. Checks domes. Checks for leaks.	160‡	2 Domes (5 yrs) - 6400 2 Domes (3 yrs) - 2560 2 Domes (1 yrs) - 640	9600
Total Person Hours	All activities.	167.5	2 Domes (5 yrs) - 7300 2 Domes (3 yrs) - 3100 2 Domes (1 yrs) - 820	11220

* Based on Pad 3 storage scenario (Christensen 1993).

† Because the retrieval process will take place over a five-year period, storage of all waste from Pads 1, 2, and 4 will not begin simultaneously, but will be staggered. Storage durations for the Delayed Retrieval Alternative are assumed to be five years (2 domes), 3 years (2 domes), and 1 year (2 domes), for Pads 1, 4, and 2 waste, respectively.

‡ An estimate of 1-40 hrs/week was given, depending upon the work required. As a worst case scenario, the highest number of hours potentially spent inside the dome is used.

The workers are assumed to be standing in the middle of an aisle in the storage dome surrounded by two rows of waste. Shielding offered by the drum wall and various waste densities is considered. Shielding provided by internal packaging is not considered because some of the containers do not contain any internal packaging.

5.2.2 Sources and Transport Media

Incident-free operations for the storage of waste from Pads 1, 2, and 4 involve receiving, moving, and inspecting waste containers in the storage domes (Tables 5.1 and 5.2). The waste stored in the containers poses a direct radiation hazard to workers during incident-free storage operations in both alternatives. Because the containers will either be overpacked or cleaned by the time they arrive at the storage domes, exposure due to surface contamination is not a concern.

A potential exists for storage workers to be exposed to volatile organic compounds (VOCs) during the storage phase. After the drums are retrieved, they will be vented with HEPA filters. As the temperature fluctuates, the drum respires. As the air cools and the drums contract, gases could be released into the air. A qualitative analysis eliminated this source from further quantitative analysis: because the construction of the domes entails that they be open on one side, circulation is sufficient to dissipate and move VOCs out of the dome quickly. The current storage configuration on Pad 3 supports this conclusion as the presence of VOCs has not been detected (Christensen 1993).

The quantitative assessment of incident-free storage operations for both the Delayed and Immediate Retrieval alternatives is focused on the associated radiological impacts from direct radiation.

5.2.3 Fate and Transport

The following sections discuss the general approach used to link sources with contaminated media and site-specific parameters used in fate and transport modeling.

For sources of external radiation during the storage phase, MicroShield computer program (Grove Engineering 1992) is used to assess the impacts of worker exposure. Information about MicroShield is provided in Sect. 4.2.3. Waste density assumptions are found in Table 2.2. Additional parameters required by MicroShield to model worker exposures throughout the storage phase, such as aisle space between storage arrays and container storage configuration, are found in Table 5.5.

Table 5.3. Additional parameters used to model storage operations

Variable	Value
Location of worker in dome	Between rows
Number of rows in dome	49 (derived from Benchmark 1993 and Christensen 1993)
Length of row	10 m (33'4") (Baker 1993)
Aisle space between rows	71 cm (28") (derived from Benchmark 1993 and Christensen 1993)
Assumed container type	All containers 55-gallon drum-equivalents
Storage array of containers	Containers are stored in an inspectable array having a base of 4 55-gallon drum-equivalents on pallets stacked 3 high
Number of containers in dome	2700 55-gallon drum equivalents (derived from Benchmark 1993 and Christensen 1993)

5.2.4 Identification of Exposure Routes

Direct radiation is the exposure route to be quantified for worker populations and activities during incident-free storage operations. Workers are at risk of exposure due to direct radiation from the waste for both alternatives.

5.2.5 Quantification of Exposure

The next step in the exposure assessment process is to quantify the magnitude, frequency, and duration of exposure for the populations and exposure routes selected for quantitative evaluation. Quantification of exposure involves determining source concentrations and calculating the doses for the exposure route identified. To calculate the dose, the source concentration is evaluated in the context of the exposure scenario, exposure route, and exposure variables, such as duration of exposure.

5.2.5.1 Source concentration

The Radiation Control Technician and RCRA Inspector are exposed to a maximum of 48 55-gallon drum equivalents at any given time during the incident-free storage scenario given the conservative assumption that the workers in the storage dome are located in the middle of the aisle

between two rows of 55-gallon drum equivalents. The technician, for risk assessment purposes, is assumed conservatively to be on a forklift carrying four drums. The contents of the containers are assumed to be homogeneous. The inventory is decayed two years for the Immediate Retrieval Alternative and an additional 10 years for the Delayed Retrieval Alternative. Although waste retrieval and storage will be staggered over several years, initial dose assessment for storage workers for waste decayed at increments of two years up to 12 years showed insignificant increase in dose.

5.2.5.2 Estimation of dose

After representative EDE rates are estimated the collective and individual doses are estimated using Eqs. 4.2 and 4.3. Exposure durations and the number of workers for each subactivity are found in Tables 5.1 and 5.2. Individual and collective doses for the Immediate and Delayed Retrieval Alternatives are shown in Table 5.4.

Table 5.4. Worker EDEs for incident-free storage operations

Worker Type	Individual EDE ^a (rem)	
	Immediate Retrieval	Delayed Retrieval
Radiation Control Technician	2.7×10^{-1}	6.1×10^{-2}
RCRA Inspector	1.1	2.4×10^{-1}
Technician	2.0×10^{-1}	6.6×10^{-2}
Total Dose	1.5	3.7×10^{-1}

^a Collective cumulative dose and individual cumulative dose are the same for the storage workers because only one worker is involved in each activity.

The individual doses shown in Table 5.4 reflect doses for the fraction of time spent in the storage dome over the entire storage period, not average annual individual doses. Except for the technician, assumed conservatively to work full time in the storage dome, the time period is less than the full storage period because the Radiation Control Technician and the RCRA Inspector spend only a fraction of the year in the storage dome. The average annual individual dose for the Radiation Control Technician and the RCRA Inspector can be calculated using the same methodology in Eqs. 4.4 and 4.5. The average annual individual dose for the technician, the worker potentially spending the most time in the storage dome, is 0.01 rem/yr under both alternatives. The As Low As Reasonably Achievable concept employed at DOE facilities to limit exposures of workers to radionuclides states that exposures to radiological contaminants should be kept as low as reasonably achievable, or 20% of the DOE recommended limit. The DOE recommended dose limit for workers specified in DOE Order 5480.11 is 5 rem/yr. Thus, 20% of the DOE recommended limit is 1 rem/yr.

Because the technician is assumed to work full time in the storage dome, the average annual individual dose is obtained by dividing the doses in Table 5.4 by the number of hours for the respective alternative (from Tables 5.1 and 5.2) and multiply by one full working year (2000 hrs for the storage workers based on 40 hrs/wk). For example, the average annual individual dose for the technician for the Immediate Retrieval Alternative is calculated as follows:

$$\left(\frac{2.0 \times 10^{-1} \text{ rem}}{28800 \text{ hrs}} \right) 2000 \text{ hrs} = 1.34 \times 10^{-2} \text{ rem.} \quad [5.1]$$

The average annual individual dose for the technician is 0.01 rem/yr, well below the DOE recommended dose limit of 1 rem/yr.

5.3 RISKS ASSOCIATED WITH INCIDENT-FREE STORAGE OPERATIONS

Risks are calculated using the methodology outlined in Sect. 4.3 and Eq. 4.5. Risks for the Incident-Free Storage Operations analysis for the Immediate and Delayed Retrieval Alternatives are shown in Tables 5.5 and 5.6, respectively.

Table 5.5. Risks for incident-free storage: Immediate Retrieval Alternative

Receptor	Cancer Fatalities	Cancer Incidence	Genetic Effects
Radiation Control Technician	1.1×10^{-4}	3.7×10^{-4}	1.6×10^{-5}
RCRA Inspector	4.3×10^{-4}	1.5×10^{-3}	6.4×10^{-5}
Technician	8.1×10^{-5}	2.8×10^{-4}	1.2×10^{-5}
Cumulative Risk	6.1×10^{-4}	2.2×10^{-3}	9.2×10^{-5}

Table 5.6. Risks for incident-free storage: Delayed Retrieval Alternative

Receptor	Cancer Fatalities	Cancer Incidence	Genetic Effects
Radiation Control Technician	2.4×10^{-5}	8.5×10^{-5}	3.7×10^{-6}
RCRA Inspector	9.8×10^{-5}	3.4×10^{-4}	1.5×10^{-5}
Technician	2.7×10^{-5}	9.3×10^{-5}	4.0×10^{-6}
Cumulative Risk	1.5×10^{-4}	5.2×10^{-4}	2.2×10^{-5}

The individual risks shown in Tables 5.5 and 5.6 reflect risks for the fraction of time spent in the storage dome over the entire storage period, not annual individual risks. Except for the technician, assumed conservatively to work full time in the storage dome, the time period is less than the full storage period because the Radiation Control Technician and the RCRA Inspector spend only a fraction of the year in the storage dome. The annual individual risk for the Radiation Control Technician and the RCRA Inspector can be calculated using Eq. 4.5. The individual annual cancer fatality risk for the technician, the worker potentially spending the most time in the storage dome, is 5.6×10^{-6} under both alternatives. The point of departure for individual risks is 10^{-4} - 10^{-6} for CERCLA. Risks above this are considered significant or of regulatory concern. Because the technician is assumed to work full time in the storage dome, the annual individual risk is obtained by dividing the risks in Tables 5.5 and 5.6 by the number of hours for the respective alternative (from Tables 5.1 and 5.2) and multiplying by one full working year (2000 hrs for the

storage workers based on 40 hrs/wk). For example, the individual cancer fatality risk for the technician under the Immediate Retrieval Alternative is calculated as follows:

$$\left(\frac{8.1 \times 10^{-5}}{28800 \text{ hrs}} \right) 2000 \text{ hrs} = 5.6 \times 10^{-6}. \quad [5.2]$$

Annual cancer incidence and genetic effects for the technician can be calculated in the same manner by substituting the appropriate risk factor.

5.4 UNCERTAINTIES IN THE INCIDENT-FREE STORAGE OPERATIONS ANALYSIS

Less uncertainty exists in site-specific parameters for the storage scenario than the retrieval scenario. Operations are assumed to be identical to current above-ground Pad 3 storage operations and, hence, specific data were readily available. In general, the basis of site-specific uncertainties in this stage of the risk assessment is inadequate information concerning the inventory and source-to-receptor distances. The assumptions employed in these areas of uncertainty are based on information gathered from conversations with contacts at LANL and best professional judgement. Uncertainties affecting the incident-free storage operations analysis are shown in Table 5.7. The table contains a summary of uncertain variables, the values and/or assumptions used, as well as the rationale for the values used. The final column of the table summarizes how this uncertainty is expected to affect the estimate of exposure.

Table 5.7. Uncertainties in incident-free storage operations analysis

Variable	Value or Assumption	Justification or Source	Effect of Uncertainty
Contents of 55-gallon drum equivalents	Drums are full (0.208 m ³) Average distribution of radionuclides in homogenous waste	Best professional judgement	May over- or under-estimate dose
Location of Radiation Control Technician and RCRA Inspector	Center of aisle Aisle is 71 cm (28") wide	Best professional judgement Aisle width from Benchmark 1993	May over-estimate dose
Location of technician	Assumed sitting on forklift exposed to a pallet of 4 drums	Best professional judgement	May over-estimate dose

5.5 SUMMARY OF INCIDENT-FREE STORAGE OPERATIONS ANALYSIS

The calculated individual worker risks associated with storage operations ranged from 3.8×10^{-6} to 1.5×10^{-3} , with the higher risks predicted for the RCRA inspector for both alternatives. Risks for the Immediate Retrieval Alternative are slightly higher, with the driver of worker risks for both alternatives being direct radiation exposure. The only difference between the two alternatives is decay. Inhalation of VOCs was not quantified for either alternative because a preliminary screening analysis indicated significant exposure to potential VOCs is not a concern. Risks to off-site receptors were not quantified because the distance of off-site receptors and on-site general employees from the storage domes is assumed to reduce exposure to much lower levels.

6. ACCIDENT ANALYSIS

6.1 CHARACTERIZATION OF THE ACCIDENT ANALYSIS

Benchmark Environmental Corporation (1993) conducted a qualitative accident analysis of all hazards unique to the retrieval process of Pads 1, 2, and 4 in order to identify specific accidents that could impact on-site personnel, off-site receptors, or the environment. Benchmark's approach systematically identified, evaluated, and screened all potential hazards associated with all phases of the retrieval operation (Benchmark 1993). Hazards identified to be of a standard industrial nature, such as electrical hazards and hazards typical to manual operations such as noise, heat stress, and temperature extremes, were eliminated from further consideration. A qualitative assessment was conducted of the likelihood and severity of hazards unique to the retrieval process.

This risk assessment focused on the accidents identified in Benchmark's preliminary safety analysis report (PSAR) (Benchmark 1993) as anticipated, or having the highest nominal frequency (10^{-2} to 1) of occurring. Anticipated events in the PSAR are defined as "events anticipated to occur at least once within the life of the facility" (Benchmark 1993). Accidents having the highest probability of occurring are shown in Table 6.1.

Table 6.1. Anticipated accidents

Hazard	Postulated Accident	Potential Consequence
Heavy Equipment	1. A forklift punctures a waste container during retrieval. Less than 1 percent of container contents spill.	Release of radioactive material to environment. Exposure to worker.
Degraded Waste Container	1. Exterior corrosion weakens drum. Failure of integrity during lifting. 50% of drum contents spilled. 2. Interior corrosion creates pinhole (s). Drum leaks contaminated liquid during lifting. 3. Moisture infiltration weakens box. Failure during lifting.	Release of radioactive material to environment. Exposure to worker. Release of radioactive material to environment. Exposure to worker. Release of radioactive material to environment. Exposure to worker.

Source: Benchmark 1993.

Because all the accidents identified as "anticipated" in Benchmark's analysis involve a spill or leak of waste from the container during retrieval operations, a similar accident was chosen for quantitative risk analysis in the current study. The specific accident scenario chosen for this study is the failure of drum integrity during lifting as a result of container degradation. While crates may also fail due to a loss of integrity, no methods or data exist to support a quantitative analysis of the rate of crate failure. Crate failure is considered qualitatively in Sect. 7.2.

Degraded drum failure poses a direct radiation hazard to retrieval workers and the potential for release of airborne contamination that may expose workers, off-site receptors, and on-site general employees.

The drum failure analysis entails the following steps:

- Prediction of drum failures for each alternative
- Estimate dose consequences of one drum failure
- Estimate risks for one drum failure
- For each alternative, multiply risks by number of drum failures

6.2 PREDICTION OF DRUM FAILURES

Prediction of drum failures entails the following steps:

- Characterize the types and causes of corrosion at LANL
- Establish distributions for corrosion rates and drum wall thickness
- Define drum failure
- Generate probability distribution of drum failures as a function of time
- Quantify drum failures at LANL for each alternative

6.2.1 Types and Causes of Corrosion at LANL

Two types of corrosion were seen in drums excavated from Pad 2 in 1992, general and pitting corrosion. General corrosion is defined as corrosion that results in a gradual decrease in drum wall thickness over an extended surface area. Pitting corrosion is defined as corrosion that results in a localized perforation of the drum wall. Both pitting and general corrosion may be the result of either exterior or interior corrosion, or both. Exterior corrosion is generally caused by external catalysts, such as the surrounding environmental medium. A drum under earthen cover may corrode as a function of the soil aeration and moisture content, for example. Interior corrosion may be caused by a deleterious reaction of the inner wall of the container with the contents. A drum containing waste in direct contact with the drum wall at LANL contained one pinhole as a result of internal pitting corrosion. The current study focuses on prediction of failures due to exterior corrosion. Quantification of failures due to interior corrosion is extremely difficult as insufficient data exist to support such an analysis. A qualitative analysis of the causes and possible impacts of interior corrosion is included in Sect. 6.2.1.1.

6.2.1.1 Interior corrosion

Interior corrosion may occur at LANL during the earthen-covered storage phase due to the following phenomena:

- Corrosive agents in direct contact with the drum wall
- Water condensation on the interior surface of the containers due to the humid environment and desorbing waste forms

In 1992 drums from TA-50 (a LANL generator) on Pad 3 (TRU above-ground storage dome) were found to be corroding internally. That same year, 16 drums were excavated from Pad 2. Out of the 16 drums, two drums were also from TA-50. The TA-50 drums were examined after they were retrieved to see if any internal corrosion was also occurring underground. The TA-50 drums contained cemented sludge in direct contact with the drum wall. Due to lack of restriction on waste packaging at the time, the drums from TA-50 were not lined with plastic bags. One of the TA-50 drums was found to have pinhole corrosion as a result of this corrosive agent in contact with the drum wall. No other drums were found to have pinhole corrosion. The other 14 drums were from TA-55 (another generator). These drums contained cementation of a residue and some were found to be dewatering. These drums are lined with a plastic bag. The bag prohibited contact of water with the drum wall.

The potential for waste to leach out of the containers while they are still underground and contaminate the surrounding environmental media was considered. Results of this analysis are documented in Appendix A. The analysis indicated that water flow is slow and minimum transport is expected. Hence, flow of potentially leached waste away from the stack into surrounding media is unlikely. Although exposure from corroded containers before retrieval is not a concern, exposure due to failure of containers during retrieval is a concern and is the focus of the drum failure analysis.

Interior corrosion may also be caused by diurnal variations in the temperature in the post-retrieval aboveground storage phase. When the drums are retrieved, they will be fitted with HEPA filters. As temperatures fluctuate, the drum respires. The drum may "inhale" carbon dioxide when it contracts at night. The carbon dioxide may interact with the chemicals and promote interior corrosion. While this may contribute to internal corrosion during the storage phase, the impacts would be minimal. Because regular inspections occur, a penetration of the drum wall as a result of internal corrosion would be detected early and corrective measures implemented before serious exposures could occur.

6.2.1.2 Exterior corrosion

Exterior corrosion of TRU waste containers may potentially occur at LANL during the earthen-covered storage phase due to the following phenomena:

- The humid environment inside the cells promoting water condensation on the exterior surface of the containers
- By-products of degraded plywood in contact with drums
- Structural weaknesses of the drum
- Soil potentially in contact with drums outside the protective tarp

The drums on Pads 1, 2, and 4 are placed within cells surrounded by crates, plywood, and a protective plastic tarp. The tarp over the cells creates a humid environment inside the cells with relatively little temperature variation. The humid environment promotes water condensation on the exterior surface of the containers. Another factor potentially contributing to exterior corrosion is degrading plywood. In 1992, plywood surrounding the cells was found to be degrading. The potential exists for by-products of the corroded plywood to interact with the drum wall and accelerate the corrosion of the drums (Kosiewicz 1992; Morton 1982). The fire-retardant material put in the plywood may further accelerate the corrosion process. The drums are not assumed to

be in contact with soil for this analysis because the plywood and the plastic tarp overlay the drums and prohibit direct contact with soil. It is noted that 6 out of 16 drums were found to be in contact with soil when they were excavated in 1992 because they were placed outside of the protective plastic tarp during storage.

6.2.2 Estimation of Corrosion Rate

Over the years, slow progress has been made in the science of predicting general and pitting corrosion. The frustrations of corrosion engineers over the decades are demonstrated in the following quotations:

- 1957 "underground corrosion that has occurred can be explained, but..theory does not permit accurate prediction of the extent of corrosion to be expected to occur." (Romanoff 1957)
- 1978 "It has been stated that metallic corrosion is an art rather than a science and that, at present, insufficient knowledge is available to predict with any certainty how a particular metal or alloy will behave in a specific environment...the decision to use a particular metal or alloy in preference to others in a given environment...is based usually on previous experience and empirical testing rather than on the application of scientific knowledge." (Shreir 1978)
- 1986 "Obviously, more research is needed before practical and scientific questions can be answered successfully and the results applied to the problems in the field." (Szklańska-Smiałowski 1986)
- 1991 "No model at present can quantitatively predict the formation and incubation time of pits." (Farmer 1991)

Many aspects of the corrosion process are better understood today than they were 36 years ago, but a method to confidently predict corrosion rates is still unavailable. Typically, when a process is too complicated to simulate mechanistically, empirical or phenomenological methods are used based on available data. The current analysis included the following steps to predict general and pitting corrosion rates on Pads 1, 2, and 4:

- Review previous studies on corrosion of TRU waste drums
- Establish distribution of general corrosion rates and drum wall thickness
- Generate probability distribution for number of drum failures

Various studies of corrosion in which soil and atmospheric corrosion exist were reviewed (Romanoff 1957, Bhattacharjee et al. 1993, Feliu et al. 1993, Kriikku 1991, Duncan et al. 1992, Morton 1982). The studies done at Savannah River Site (Kriikku 1991) and Hanford Site (Duncan et al. 1992 and Morton 1982) were on corrosion of TRU waste containers. These studies were used as a guide in estimating the potential for general and pitting corrosion of drums on Pads 1, 2, and 4.

6.2.2.1 General corrosion

Morton (1982) found that drums at Hanford in a similar environment as drums on Pads 1, 2, and 4 at LANL that were in contact with the tarp corroded at a maximum rate of 1 mil/yr (1 mil is equal to 10^{-3} in or 2.54×10^{-3} cm). At INEL, a general corrosion rate of 2 mil/yr was assumed, based on drums that had been under earthen cover 18-21 years (Morton 1982). Duncan (1992) assumed a general corrosion rate of 1 mil/yr for painted 17-H drums under a tarp.

Due to the uncertainty in these corrosion rates and the variation in observed rates at different sites, this study incorporated uncertainty in the prediction of corrosion rates. To account for the uncertainty, corrosion rates are calculated using a range of likely values, rather than a single value. Based on the available data, a most likely rate of general corrosion is about 1 mil/yr, with an upper bound of 2-3 mils/yr. Duncan et al. (1992) assumed that for galvanized drums in a similar environment, the corrosion rate was approximately 0.5 mil/yr. This served as a lower bound. A triangular distribution is used over the range [0.5,2] mils/yr with a most likely value of 1 mil/yr. A triangular distribution is chosen when a both a finite range of possible values and a most likely value is known with reasonable confidence and additional details about the uncertainty are not yet known. A triangular distribution may be symmetric or, as in this case, positively skewed. In this positively skewed triangular distribution the mean is greater than the mode (peak).

6.2.2.2 Pitting corrosion

Pitting corrosion occurs significantly more rapidly than general corrosion. In soil, pitting rates can be as high as 10 to 20 mils/yr or higher, depending on the environment and container contents. Duncan (1992) assumed that pitting/crevice corrosion is essentially twice as fast as general corrosion. An average pitting rate of 2 mils/yr is assumed for painted 17-H drums stacked under a tarp. For the current study, the distribution used for the pitting corrosion rates is obtained by essentially doubling the general corrosion rate distributions. A triangular distribution is used over the range [1,4] mils/yr with a most likely value of 2 mils/yr.

6.2.2.3 Drum wall thickness

The average thickness of a painted 55 gallon drum is about 55 mils, although it can range from 50 to 60 mils. A uniform distribution was used over the range [50,60] mils.

6.2.3 Definition of Drum Failure

A definition of failure is required before calculating the number of drums to fail under both the Immediate and Delayed Retrieval Alternatives. The current study defines drum failure as the loss of structural integrity such that the drum is likely to break apart during the retrieval process. For general corrosion, Duncan (1992) assumed structural integrity is lost when the drum thickness is equal to or less than 10 mils. This wall thickness was not chosen on the basis of stress analyses. For pitting corrosion, drum failure is defined as the penetration of a single pinhole through the drum wall.

A range of drum failures due to pitting corrosion is obtained, although risks due to pitting failures are not quantified in the accident analysis because it is assumed that a pit would not cause a drum to break apart during retrieval. The loss of overall structural integrity is required for a

drum to collapse, and this is postulated in the current study to occur from general corrosion. It is accepted that many pits may also cause a drum to lose overall structural integrity. However, in the current definition, a drum failure due to pitting corrosion is defined as the occurrence of one pit. Inadequate scientific methods or data exist to analyze the rate of pits forming on the drums and the number of pits required for loss of overall structural integrity. Only drum failures due to general corrosion are used to quantify risks in the current analysis. A qualitative analysis of increased exposure due to pitting is included in Sect. 6.6.

6.2.4 Probability Distribution of Drum Failures

Both general and pitting corrosion are estimated using a Poisson process. A Poisson process is typically used to estimate how many occurrences one can expect within a given period of time, given an average occurrence rate. In the context of corrosion, an occurrence is defined as the loss of a specified amount of drum wall thickness, either at a certain location (for pitting corrosion) or across the entire drum surface (for general corrosion) over a specified period of time. For example, the probability of a certain depth of corrosion (mils) over the surface of the drum (for general corrosion) can be calculated for a specified period of time using the following equation:

$$p(L,T) = 1 - \frac{e^{-RT}(RT)^L}{L!} \quad [6.1]$$

where:

$p(L,T)$	=	Probability of exactly L mils of general corrosion over exactly T years (unitless)
R	=	Average corrosion rate (mils/yr)
T	=	Time (years)
L	=	Corrosion over the surface of the drum (mils)

Using this equation, we can calculate, for example, the probability of exactly 5 mils of general corrosion over the surface of the drum given an average corrosion rate of 1 mil/yr and a period of 8 years:

$$p(5,8) = 1 - \frac{(e^{-(1\text{ mil/yr} \cdot 8\text{ yrs})} (1\text{ mil/yr} \cdot 8\text{ yrs})^5}{5!} = .092 \quad [6.2]$$

The probability of general corrosion at a depth of 5 mils occurring over the surface of a drum in 8 years given an average corrosion rate of 1 mil/yr is 9.2%.

For the current study, the probability of drum failure is calculated. Thus, Eq. 6.1 is modified to calculate the probability of exactly L mils *or more* of corrosion for a given time period; L is the amount of corrosion that results in a drum thickness of 10 mils (which corresponds to drum failure for general corrosion, according to the definition from Sect. 6.2.3):

$$P(L,T) = 1 - \sum_{l=0}^{L-1} \frac{e^{-RT}(RT)^l}{l!}, \quad [6.3]$$

where:

P(L,T)	=	Probability of exactly L mils <i>or more</i> of general corrosion over exactly T years (unitless)
T	=	Time (years)
L	=	Corrosion over the surface of the drum (mils) which will result in failure
l	=	Maximum number of corrosion occurrences that does not result in failure (unitless)
R	=	Average Corrosion Rate (mils/yr)

Equation 6.3 is then repeated for all years of interest. The Poisson process leads to a statistical realization that drums begin to fail at significant rates after some critical length of time. For general corrosion, this critical time is found to be about 20 years, while for pitting corrosion this time occurs at about 13 years. The 20-year critical point is significant for LANL because that is the approximate age of the drums on Pads 1 and 2 in the Delayed Retrieval Alternative.

A range of drum failures due to general and pitting corrosion was calculated by conducting 1000 iterations of Latin hypercube sampling using the distributions on drum wall thickness and corrosion rates as specified in Sects. 6.2.2.1 and 6.2.2.2. The numerical results of the analysis are shown in Table 6.2. Presented in the table are the percentage of drums to fail as a function of time due to the Poisson distribution that is a) averaged over all average corrosion rates and wall thickness (mean); b) taken for the 5th percentile average corrosion rate (slow) and wall thickness; c) taken for the median average corrosion rate and wall thickness; and d) taken for the 95th percentile average corrosion rate (fast) and wall thickness.

Table 6.2. Numerical results of Latin Hypercube simulations

Age of Drum Since Placement in Ground (yrs)	Percent of Drums to Fail Due to General Corrosion				Percent of Drums to Fail Due to Pitting Corrosion			
	Mean	5%	Median	95%	Mean	5%	Median	95%
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0.01
10	0	0	0	0	0.03	0	0	0.11
11	0	0	0	0	0.14	0	0	0.71
12	0	0	0	0	0.48	0	0	2.95
13	0	0	0	0	1.31	0	0	8.81

Age of Drum Since Placement in Ground (yrs)	Percent of Drums to Fail Due to General Corrosion				Percent of Drums to Fail Due to Pitting Corrosion			
	Mean	5%	Median	95%	Mean	5%	Median	95%
14	0.01	0	0	0.01	2.84	0	0.01	20.16
15	0.02	0	0	0.05	5.24	0	0.04	36.27
16	0.05	0	0	0.18	8.51	0	0.17	54.34
17	0.13	0	0	0.51	12.55	0	0.58	71.48
18	0.28	0	0	1.28	17.18	0	1.60	84.10
19	0.54	0	0	2.80	22.23	0	3.73	92.12
20	0.96	0	0	5.46	27.52	0	7.61	96.53
21	1.60	0	0.01	9.64	32.91	0	13.68	98.63
22	2.50	0	0.02	15.57	38.29	0	22.23	99.51
23	3.70	0	0.04	23.23	43.60	0.01	32.94	99.85
24	5.21	0	0.09	32.34	48.76	0.02	44.97	99.95
25	7.05	0	0.20	42.36	53.73	0.05	56.92	99.99
26	9.18	0	0.40	52.63	58.46	0.11	67.98	100
27	11.58	0	0.74	62.47	62.92	0.25	77.72	100
28	14.21	0	1.35	71.35	67.07	0.51	85.35	100
29	17.02	0	2.26	78.92	70.78	0.99	90.88	100
30	19.97	0	3.63	85.05	74.38	1.78	94.62	100

6.2.5 Drum Failures Due to General Corrosion at LANL

The next step in predicting drum failures on Pads 1, 2, and 4 under both alternatives is to calculate the distribution of drum failures on each pad using the following equation:

$$DF = PF * ND, \quad [6.4]$$

where:

- DF = Drum Failures (unitless)
- PF = Probability of failure (unitless)
- ND = Number of drums on pad (unitless).

The age of the drums on each pad was determined by computing the age of the drums (starting with the close of the pad) at the time of retrieval for each alternative. For example, Pad 1 closed in 1981. The Immediate Retrieval Alternative calls for drums to be retrieved immediately (beginning in 1993), hence the drums are 12 years old at the time of retrieval. Pad 4 will be

remediated two years after Pad 1, and Pad 2 will be remediated four years after Pad 1 (LANL 1993). Thus, drums on Pad 4 will be 4 years old and drums on Pad 2 will be 12 years old at the initiation of remediation. For the Delayed Retrieval Scenario, 10 years were added to the age of the drums from the Immediate Retrieval Alternative. The age of the drums at the initiation of remediation operations under each alternative are shown in Table 6.3.

Table 6.3. Age of drums at initiation of remediation

Pad	Year Pad Closed	Immediate Retrieval Alternative		Delayed Retrieval Alternative	
		Initial Year of Remediation	Age of Drum at Remediation (yrs)	Initial Year of Remediation	Age of Drum at Remediation (yrs)
Pad 1	1981	1993	12	2003	22
Pad 2	1985	1997	12	2007	22
Pad 4	1991	1995	4	2005	14

Using Eq. 6.4, the age of the drum in Table 6.3, the number of drums on the pad, and the probability of a drum failing at that age, the probability of a drum failure under each alternative is calculated. For example, the mean number of drums to fail on Pad 1 under the Immediate Retrieval Alternative is calculated as follows:

$$(3.29 \times 10^{-6}) (4789) = 0.02$$

[6.5]

The mean number of drums to fail on Pad 1 under the Immediate Retrieval Alternative is 0.02. (Note: we use 3.29×10^{-6} as the probability of a 12-year old drum failing although zero appears in Table 6.2 due to formatting to the second significant digit.) The total drum failures predicted for each alternative are shown in Table 6.4.

Table 6.4. Drums failures due to general corrosion on Pads 1, 2, and 4

Pad	Years in Operation	Drums per pad	Number of Drums to Fail					
			Immediate Retrieval Alternative			Delayed Retrieval Alternative		
			Mean	5th	95th	Mean	5th	95th
Pad 1	1979-1981	4789	0.02	0	0.02	119.73	0	747.08
Pad 2	1981-1985	7294	0.02	0	0.03	182.35	0	1137.86
Pad 4	1985-1991	4564	0	0	0	0.28	0	0.62
Total	--	16647	0.04	0	0.05	302.36	0	1885.57

The results suggest that zero drums may fail under the Immediate Retrieval Alternative while up to 1886 drums may fail under the Delayed Retrieval Alternative, with a mean of 302.

6.3 EXPOSURE ASSESSMENT

The steps of the exposure assessment include the following:

- Characterization of receptors
- Identification of sources and transport media
- Identification of exposure routes
- Quantification of exposure

Quantification of exposure includes estimation of source concentration and dose.

6.3.1 Characterization of Receptors

Receptors of potential exposures resulting from the drum failure scenario are the off-site population, general on-site employees, and workers inside the retrieval dome at the time of a drum collapse. Characterization of each receptor population for this scenario entails the following steps:

- Identify number of receptors in each receptor group potentially exposed
- Identify location and distance relative to the release point
- Identify relevant activity patterns

6.3.1.1 Off-site population

The off-site residential population includes residents within a 80 km (50 mi) radius of the release point. The off-site population is identified in Sect. 1.5.2. Analysis of sensitive subpopulations such as pregnant women, children, and the elderly are outside of the scope of the off-site public assessment. A hypothetical maximally exposed individual (MEI) is also evaluated for the accident scenario. The off-site MEI is assumed to be standing 5.6 km (3.5 mi) southeast of the release point, which corresponds to the sector having the greatest air concentration at the LANL boundary. The potentially exposed off-site population is assumed to eat only food that is grown within a 80 km (50 mi) radius of the release point. All food grown in that area is assumed to be eaten by the population in that area; there is no export of potentially contaminated products.

6.3.1.2 General on-site employees

The on-site population, 11,549, includes all full-time employees, contractors, and subcontractors. Although the number of on-site employees is known, the direction and distance of these employees from the release site is not available. Exposure of on-site employees is evaluated only for the air pathway because they are assumed to have no contact with surface water or agricultural food products and their drinking water is assumed to be filtered and treated or supplied as bottled water.

The on-site MEI is assumed to be standing 800 m (0.5 mi) due east from the release point. A distance of 800 m (0.5 mi) is the shortest distance the computer code used to model this scenario will calculate from the release point (see Sect. 6.3.3 for description of the computer code). Due east of the release point at 800 m (0.5 m) corresponds to the area within the laboratory boundary having the greatest air concentration.

6.3.1.3 Characterization of retrieval workers

The container removal phase of the retrieval process involves four laborers and four equipment operators, assumed to be present when the drum fails. Source-to-receptor distances for this stage are shown in Fig. 6.1.

Fig. 6.1. Source to Receptor Distances for Drum Failure Analysis

6.3.2 Sources and Transport Media

The source of exposure in the drum failure analysis is the waste that is spilled out of a drum after the fall. The modified forklift with boom, cage, and hoist is designed to preclude the possibility of a container falling more than a few inches after loss of structural integrity. A spill, however, is not precluded by a short fall. A potential transport mechanism is direct radiation. A potential transport medium is air.

6.3.3 Fate and Transport

The following sections discuss the general approach used to link sources with contaminated media and site-specific parameters used in fate and transport modeling.

MicroShield is used to quantify direct radiation impacts from exposure to external penetrating radiation to the workers inside the retrieval dome. Information about MicroShield is provided in Sect. 4.2.3.

Generation II (GENII) computer code is used to quantify impacts from direct radiation, inhalation, and ingestion pathways for off-site and on-site general employee receptors. GENII is an EPA evaluated fate and transport computer code that utilizes a selection of straight-line Gaussian-plume models to estimate atmospheric concentrations (Ci/m^3) on a grid comprising 16 directions and 10 radial distances out to 80 km (50 mi) from the point of release. The atmospheric concentrations are then multiplied by the population in each sector to obtain population weighted concentrations. GENII uses the population weighted atmospheric concentrations to predict the exposure and dose to potential receptors. GENII can be used to model chronic releases, acute releases (as in this case), or both. Internal radiation dose calculations are performed using the methods recommended by the ICRP as described in ICRP 26 and 20 (ICRP 1977; ICRP 1979-1982).

GENII is used in concert with a unit risk approach to calculate public and on-site general employee health risks for the drum failure scenario. The unit risk approach operates under the assumption that unit risks (risk/Ci for each radionuclide) can be established for the site and then multiplied by a specific source term to estimate public health risks associated with various release scenarios. Unit doses and risks have been generated using GENII and LANL-specific information for wind distribution, agricultural yields, and receptor locations and have been stored in a database. To create unit doses (rem/Ci) GENII is run using an emission rate of 1 Ci/yr for each radionuclide in the inventory in Table 1.1. The unit doses are manipulated according to scenario-specific variations in release parameters, such as effective stack height, flow rate, and release period, to estimate risks for the drum failure scenario.

The effective stack height is the height reached by the plume after it exits the stack before it moves horizontally. This height is a function of the stack parameters associated with the release (i.e. stack height, stack diameter, exit flow rate, and exit temperature) as well as the speed, direction, and stability of prevailing winds. The unit doses in the database correspond to an effective stack height of 50 m (164 ft). To make the database applicable to any release scenario, the database adjusts the unit doses to correspond with the effective stack height specified.

6.3.4 Identification of Exposure Routes

Workers may be exposed to direct radiation and inhalation of particulates suspended after the fall of a drum. Potential exposure routes for general on-site employees are inhalation and direct radiation. Potential exposure routes for public receptors are inhalation, ingestion of contaminated agricultural products and soil, and direct radiation from plume immersion and exposure to contaminated soil.

6.3.5 Quantification of Exposure

The next step in the exposure assessment process is to quantify the magnitude, frequency, and duration of exposure for the populations and exposure routes selected for quantitative evaluation. Quantification of exposure involves determining source concentrations and calculating the doses for the exposure route identified. To calculate the dose, the source concentration is evaluated in the context of the exposure scenario, exposure route, and exposure variables, such as duration of exposure.

6.3.5.1 Source concentration

Source concentrations for workers and on-site personnel are determined for the direct radiation and inhalation pathways. Source concentrations for off-site receptors are determined for the inhalation, ingestion, and direct radiation pathways.

6.3.5.1.1 Source concentration for worker exposure

Air concentration for the workers in the drum failure scenario is calculated using the following formula:

$$AC = \frac{SF * AF * RF}{V}, \quad [6.6]$$

where:

AC	=	Air concentration (pCi/m ³)
SF	=	Spill Fraction pCi (unitless)
AF * RF	=	Airborne fraction * Respirable Fraction (unitless)
V	=	Volume of room in which waste disperses in 1 minute (m ³)

After a drum collapse, 50% of the contents are assumed to be spilled onto the asphalt pad. All drums that collapse are assumed to be full (0.208 m³) and to contain an average distribution of nuclides in homogeneous waste (Table 1.1). The workers are assumed conservatively to be exposed to 100% of the spilled contents. Internal packaging is not considered in this analysis. Internal packaging may reduce a release after a spill. However, because some drums are known to have no internal packaging, the exclusion of this potential factor from this analysis is a reasonable conservative assumption. Inhalation concentrations are calculated assuming the workers are not wearing respirators, which would reduce the amount inhaled through normal breathing.

The laborers are assumed to be exposed to the initial air concentration longer than the equipment operators because they are standing closer to the spill as it occurs and more time is required for laborers to move away from the spill. To account for this higher exposure at closer proximity to the spill, two zones of air concentration are calculated. All the laborers and equipment operators are initially assumed to be standing in a 1000 m³ (10m x 10m x 10m) (3.53 x 10⁴ ft³) volume of air space. The spill is assumed to occur in the center of the work space. As the workers exit the zone of higher concentration, they enter a larger area of work space, assumed to be a 4962 m³ (1.75 x 10⁵ ft³) box of air space [assumed size of retrieval area (Benchmark 1993)] and a zone of lower concentration. Parameters used to calculate source concentrations for the workers are shown in Table 6.5.

Table 6.5. Parameters used to calculate source concentrations for workers

Variable	Value
Spill fraction	50% of inventory in Table 4.3
Product of airborne fraction and respirable fraction of the waste spill	0.001 (Benchmark 1993)
Dispersion time	1 minute
Volume of room in which waste disperses	Initial area of higher concentration: 1000 m ³ Area of lower concentration: 4962 m ³ (Benchmark 1993)
Ventilation rate	Not considered because of short dispersion time
Personal Protective Equipment	Respirators not assumed

Using Eq. 6.6 and the parameters in Table 6.5, the air concentration in the zone of higher concentration is 1.60 x 10⁻⁶ Ci/m³. The air concentration in the zone of lower concentration is 3.22 x 10⁻⁷ Ci/m³.

6.3.5.1.2 Source concentration for off-site and general employee exposure

Before source concentrations for the off-site and general employee exposure assessment can be calculated, the release from the retrieval dome is calculated. The volumetric flow rate is calculated using the following formula:

$$FL = \pi r^2 * EV, \quad [6.7]$$

where:

- FL = Volumetric flow rate (m³/sec)
- r = Stack radius (m)
- EV = Effluent velocity (m/sec)

The parameters used to calculate volumetric flow rate from the retrieval dome are shown in Table 6.6. Credit was given to on-line filters to reduce release by a factor of 1000.

Table 6.6. Parameters used to calculate source concentrations off-site and general employee exposure

Variable	Value
Stack height	2.69 m (8.8 ft) (Benchmark 1993)
Stack radius	0.355 m (1.16 ft) (Benchmark 1993)
Effluent velocity	14.37 m/s (47.15 ft/sec) (Benchmark 1993)
Annual ambient temperature	8.8°C (47.8°F) (Benchmark 1993)
Adjustment for HEPA filters	Reduce atmospheric releases by a factor of 1000 (Benchmark 1993)

Using Eq. 6.7 and the parameters in Table 6.6, the release rate from the retrieval dome is calculated as 5.69 m³/sec (201 ft³/sec). Due to the use of the unit risk approach output of doses and risks only, concentrations at exposure points are not available.

6.3.5.2 Estimation of dose

The following sections describe the methodologies used to calculate doses to workers, the public, and on-site general employee population and provides the doses calculated.

6.3.5.2.1 Estimation of worker dose

External doses for workers are calculated using the methodology discussed in Sect. 4. Internal doses for the workers are calculated using the following equation:

$$I = IR * AC * ED, \quad [6.8]$$

where:

- I = Contaminant-specific individual intake (pCi)
- IR = Inhalation rate (m³/min)
- AC = Air concentration (pCi/m³)
- ED = Exposure duration (minutes)

The inhalation rate is 0.02 m³/min (20 L/min). The two zones of air concentration are calculated in Sect. 6.3.5.1.1. Exposure duration is calculated assuming all workers are located in the area of the initial high concentration when they begin walking away. Workers are assumed to immediately begin walking away from the spill after it occurs at a speed of 1 m/sec (3.28 ft/sec) (MMES 1992). The formula used to calculate exposure duration in the area of higher concentration within the work space as workers walk away is:

$$t_m = \frac{(r - r_0)}{S - t_H}, \quad [6.10]$$

where:

t_m = time exposed (sec)
 r = distance from center of area to edge (m)
 r_0 = initial distance to release of closest person (m)
 S = escape speed (m/sec)
 t_H = time that individual holds breath (0 sec. assumed)

While the equipment operators are able to exit the high concentration area in 2 seconds, 4.7 seconds are required for the laborers to exit that area. An additional 5.6 seconds are required for the workers to exit the lower concentration area and the entire contaminated work space.

After the worker intake is calculated, the intake is converted to an EDE using the following equation:

$$EDE = I * DCF_i * 3.7, \quad [6.11]$$

where:

EDE = Effective dose equivalent (rem),
 DCF_i = Inhalation dose conversion factor (Sv/Bq),
 3.7 = Conversion factor (rem-Bq/Sv-pCi).

EPA (1988) dose conversion factors are used. For some daughter products, dose conversion factors are not available (^{217}At , ^{211}Bi , ^{221}Fr , $^{240\text{m}}\text{Np}$, $^{234\text{m}}\text{Pa}$, ^{211}Po , ^{212}Po , ^{213}Po , ^{214}Po , ^{215}Po , ^{216}Po , ^{218}Po , ^{219}Rn , ^{220}Rn , ^{222}Rn , ^{207}Tl , ^{208}Tl , ^{209}Tl). All daughter products were accounted for, except those without dose conversion factors. Internal and external doses for workers are shown in Table 6.7.

Table 6.7. Worker doses for the drum failure analysis

Receptors	Individual Dose ^a		Collective Dose ^a	
	External (rem)	Internal (rem)	External (person-rem)	Internal (person-rem)
Laborers	2.0×10^{-7}	9.9×10^{-1}	7.9×10^{-7}	3.9
Equipment Operators	1.3×10^{-8}	5.3×10^{-1}	5.1×10^{-8}	2.1
Total Dose	N/A	N/A	8.4×10^{-7}	6.0

^a External dose in terms of EDE. Internal dose in terms of CEDE.

6.3.5.2.2 Estimation of public and general employee dose

Equation 6.8 can be used as the basic equation used to estimate inhalation and ingestion intake. Direct radiation exposure is modeled using GENII. After the volumetric flow rate is calculated, GENII disperses the released particulates using joint frequency distribution data for the Los Alamos area. The joint frequency distribution data used for the current study were obtained at the LANL meteorological tower on 12/1/92 (PNL 1993). Joint frequency distribution data provide wind speed and direction for sixteen 22.5-degree sectors, five wind-speed groups, and six Pasquill stability classes. Stability classes are indications of atmospheric stability and are used to determine vertical motion and vertical expansion of plumes.

Other parameters required by GENII to model the off-site source concentrations relate to terrestrial food ingestion and animal production consumption within of 80 km (50 mi) radius of the release point. The assumptions used to model off-site exposure scenario are shown in Tables 6.8 and 6.9.

Table 6.8. Terrestrial food ingestion^a

Food Type	Human Consumption Rate (kg/yr)	Holdup ^b (days)	Grow Time (days)	Yield (kg/m ²)
Leafy Vegetables	28.1	14.0	90.0	2.56
Root Vegetables	28.1	14.0	90.0	1.26
Fruit	49.1	14.0	90.0	0.67
Grain	72.0	180.0	90.0	0.18

^a Shor et.al. 1982

^b Assumed time between harvest and consumption.

Table 6.9. Animal production consumption^a

Food Type	Human Consumption ^b Rate kg/yr	Holdup (days) ^c	Diet Fraction		Grow Time (days)		Yield (kg/m ²)		Storage (days)	
			Stored Feed ^d	Fresh Forage ^e	Stored Feed	Fresh Forage	Stored Feed	Fresh Forage	Stored Feed	Fresh Forage
Beef	35.1	34.0	0.73	0.27	90.0	45.0	0.53	0.02	180.0	100.0
Poultry	8.5	34.0	1.0	—	90.0	—	0.22	—	180.0	—
Milk	105.0	4.0	0.73	0.27	45.0	30.0	0.53	0.02	100.0	0.0
Eggs	29.4	18.0	1.0	—	90.0	—	0.22	—	180.0	—

^a Shor et.al. 1982, except where indicated

^b Napier et. al. 1988

^c Holdup time between harvest and consumption

^d Fraction of animal diet consisting of contaminated grain

^e Fraction of animal diet consisting of contaminated hay

General exposure parameters used in the current study are shown in Table 6.10.

Table 6.10. Exposure parameters

Variable	Value
Exposure duration ^a	50 yrs (Napier et. al. 1988)
Exposure frequency ^a	350 d/yr (EPA 1989)
Inhalation rate ^a	20 m ³ /d
Public exposure frequency to soil contamination	122 d/yr (Napier et. al. 1988).
Ingestion rate of soil	Adult: 100 mg/d Child: 200 mg/d

^a Applicable to both off-site public and on-site general employee receptors. Although on-site employees have an on-site exposure duration of 8 hr/d and an off-site exposure duration of 16 hr/d, they are included in the off-site population exposure assessment that assumes 24 hr/d exposure, assuming they live within 80 km (50 mi) of the site. This additional 8-hr exposure period causes the off-site population exposure to be overestimated for those residents that are also on-site employees.

Doses for the off-site public and on-site personnel are shown in Table 6.11.

Table 6.11. Public and general employee doses for the drum failure analysis

Receptors	MEI Dose ^a		Collective Dose ^a	
	External (rem)	Internal (rem)	External (person-rem)	Internal (person-rem)
General On-Site Population	1.2×10^{-11}	1.9×10^{-4}	1.3×10^{-9}	2.1×10^{-2}
Off-Site Population	2.1×10^{-12}	3.4×10^{-5}	4.8×10^{-9}	7.7×10^{-2}

^a External dose in terms of EDE. Internal dose in terms of CEDE.

6.4 RISKS ASSOCIATED WITH THE DRUM FAILURE ANALYSIS

Risks for the retrieval workers and on-site and off-site receptors are calculated for one drum failure. These risks are multiplied by the range of drums calculated to fail in both alternatives. Risks for workers are shown in Table 6.12 for one drum failure. Risks for off-site receptors and on-site general employee personnel for one drum failure are shown in Table 6.13. Total risks for the Delayed Retrieval Alternative are shown in Table 6.14. Because less than one drum is predicted to fail in the Immediate Retrieval Alternative, no risks are predicted.

Table 6.12. Worker risks for one drum failure

Receptor	Pathway	Individual Risks			Collective Risks		
		Cancer Fatalities	Cancer Incidence	Genetic Effects	Cancer Fatalities	Cancer Incidence	Genetic Effects
Laborers	Direct Radiation	7.9×10^{-11}	2.8×10^{-10}	1.2×10^{-11}	3.2×10^{-10}	1.1×10^{-9}	4.7×10^{-11}
	Inhalation	3.9×10^{-4}	1.4×10^{-3}	5.9×10^{-5}	1.6×10^{-3}	5.5×10^{-3}	2.4×10^{-4}
Equipment Operators	Direct Radiation	5.1×10^{-12}	1.8×10^{-11}	7.6×10^{-13}	2.0×10^{-11}	7.1×10^{-11}	3.0×10^{-12}
	Inhalation	2.1×10^{-4}	7.4×10^{-4}	3.2×10^{-5}	8.5×10^{-4}	3.0×10^{-3}	1.3×10^{-4}
All Receptors	All Pathways	N/A	N/A	N/A	2.4×10^{-3}	8.5×10^{-3}	3.6×10^{-4}

Table 6.13. On-Site and off-site receptor risks for one drum failure

Receptor		Cancer Fatalities	Cancer Incidence	Genetic Effects
On-Site General Employee Population	MEI	9.5×10^{-4}	3.2×10^{-3}	1.9×10^{-4}
	Population	1.1×10^{-3}	3.6×10^{-3}	2.1×10^{-4}
Off-Site Population	MEI	1.8×10^{-4}	5.8×10^{-4}	3.4×10^{-5}
	Population	3.9×10^{-5}	1.3×10^{-4}	7.7×10^{-6}

Table 6.14. Risks Associated with total drum failures predicted for the Delayed Retrieval Alternative

Receptor	Cancer Fatalities			Cancer Incidence			Genetic Effects		
	Mean	Lower 95th	Upper 95th	Mean	Lower 95th	Upper 95th	Mean	Lower 95th	Upper 95th
Retrieval Workers	7.4×10^{-1}	0	4.6	2.6	0	1.6×10^1	1.1×10^{-1}	0	6.8×10^{-1}
MEI On-Site	2.9×10^{-5}	0	1.8×10^{-4}	9.7×10^{-5}	0	6.0×10^{-4}	5.7×10^{-6}	0	3.6×10^{-5}
On-Site Population	3.3×10^{-3}	0	2.1×10^{-2}	1.1×10^{-2}	0	6.8×10^{-2}	6.3×10^{-4}	0	4.0×10^{-3}
MEI Off-Site	5.4×10^{-6}	0	3.4×10^{-5}	1.8×10^{-5}	0	1.1×10^{-4}	1.0×10^{-6}	0	6.4×10^{-6}
Off-Site Population	1.2×10^{-2}	0	7.4×10^{-2}	3.9×10^{-2}	0	2.5×10^{-1}	2.3×10^{-3}	0	1.5×10^{-2}

6.5 UNCERTAINTIES IN THE DRUM FAILURE ANALYSIS

Many uncertainties exist in site-specific parameters for the drum failure analysis. Areas of major uncertainty concern the corrosion estimation and off-site exposure estimation. The assumptions employed in these areas are based on information gathered from conversations with contacts at LANL, engineers familiar with these processes, and best professional judgement. Uncertainties affecting the drum failure analysis are shown in Table 6.15. The table contains a summary of uncertain variables, the values and/or assumptions used, as well as the rationale for the value used. The final column of the table summarizes how this uncertainty is expected to affect the estimate of exposure.

Table 6.15. Uncertainty in drum failure analysis

Variable	Value or Assumption	Justification or Source	Effect of Uncertainty
Model/Approach used to describe corrosion process	Poisson process	Duncan 1992	May over- or under-estimate corrosion rate depending upon conditions on the pad
General corrosion rate	0.5-2 mils/yr	Duncan 1992	May over- or under-estimate general corrosion rate
Definition of failure due to general corrosion	Drum thickness less than or equal to 10 mils	Duncan 1992	May over- or under-estimate number of drums to fail
Drum contents	Drums are full (0.208 m ³) Average distribution of radionuclides in homogenous waste	Best professional judgement	May over- or under-estimate dose to workers
Area of waste spill	Fig. 6.1	Best professional judgement	May over- or under-estimate dose to all receptors
Worker dose point	Fig. 6.1	Based on height of 6 ft	May over-estimate dose to workers
Dispersion rate of particulates inside the dome	Instantaneous dispersion	Most conservative for short time-span	May over-estimate dose to workers
Retrieval dome ventilation rate	Ventilation rate not considered	Most conservative for short-time span	May over-estimate dose to workers
Settling of particulates inside the dome	Settling not considered	Most conservative for short-time span	May over-estimate dose to workers
Release rate from the retrieval dome	5.69 m ³ /s	Benchmark 1993	May over-estimate risks to receptors
Distribution of agricultural products in 50-mi radius	Agricultural food products are not imported or exported in 50-mi radius	Most conservative assumption	May over-estimate risks to off-site receptors
Change in population over 50-yr time span	Population size and distribution are assumed to remain constant	Best professional judgement	May over- or under-estimate risks
Distribution of population	Population rings originate from the center of the installation rather than from the point of release	Best available data	May over- or under-estimate risks

6.6 SUMMARY OF THE DRUM FAILURE ANALYSIS

The results of the drum failure analysis indicate that risks from Immediate Retrieval are minimal, while risks from Delayed Retrieval are potentially high due to a possibly large number

of degraded drum failures (1886 out of 16,647) during retrieval operations, if administrative and engineering controls remain constant. Significant carcinogenic effects are possible if the drums are left under earthen cover an additional 10 years as continued container degradation is imminent. Because worker risks could be reduced by approximately a factor of 1000 if Level B protection is assumed (includes respirators) (NIOSH 1990), public and on-site general employee risks are the deciding factor. The driver of risks for all receptors is the inhalation pathway.

Several phenomena were not quantitatively analyzed that may potentially contribute to an increase in risks. Crate failure is not analyzed because no scientific methods or data are available to confidently predict corrosion rate of crates. Significant crate corrosion may occur if retrieval is delayed 10 years, potentially increasing risks.

A quantitative analysis of the effects of pitting corrosion was not conducted because a method of predicting growth rate of pits and number of pits required for loss of overall structural integrity is not available. Significant pitting may increase exposures of direct radiation and delay the retrieval process because overpacking would be required.

7. SUMMARY AND CONCLUSIONS

7.1 SUMMARY OF THE RISK ASSESSMENT

The results of the Risk Assessment for the Retrieval of Transuranic Waste are summarized with the following points:

- Worker risks for incident-free retrieval and storage operations are slightly higher for the Immediate Retrieval Alternative. The only variable between the two alternatives is the decay of the waste an additional 10 years, and worker risks are quantified for the direct radiation exposure route only.
- The calculated individual worker risks of cancer fatalities, cancer incidence or genetic effects ranged from 2.8×10^{-10} to 9.4×10^{-5} for incident-free immediate retrieval operations under the Immediate Retrieval Alternative, and from 2.8×10^{-10} to 9.3×10^{-5} under the Delayed Retrieval Alternative.
- The calculated individual worker risks of cancer fatalities, cancer incidence or genetic effects ranged from 1.2×10^{-5} to 1.5×10^{-3} for incident-free storage operations under the Immediate Retrieval Alternative, and from 3.7×10^{-6} to 3.4×10^{-4} under the Delayed Retrieval Alternative.
- Drums on Pads 1, 2, and 4 will reach their critical lifetime limit of 20 years if they are left under earthen cover an additional 10 years.
- The drum failure analysis is the determining risk-based factor in choosing an alternative. Worker, off-site, and on-site general employee population risks for the drum failure analysis are potentially severe if retrieval of the waste is delayed and administrative and engineering controls remain constant. The driver of risks in the drum failure analysis is the inhalation pathway. While worker risks may be reduced by a factor of 1000 with the use of respirators (assuming Level B of protection) (NIOSH 1990), public and on-site general employee risks would be more difficult to reduce. Risks due to drum failures are not predicted under the Immediate Retrieval Alternative because less than one drum is predicted to fail under that alternative.
- Risks based on the mean number of drums predicted to fail in the drum failure analysis for the Delayed Retrieval scenario are shown in Table 7.1.

Table 7.1. Risks Associated with the drum failure analysis: Delayed Retrieval^a

Receptor	Cancer Fatalities	Cancer Incidence	Genetic Effects
Retrieval Workers ^{b,c}	7.4×10^{-1}	2.6	1.1×10^{-1}
MEI On-Site	2.9×10^{-5}	9.7×10^{-5}	5.7×10^{-6}
On-Site Population ^{b,d}	3.3×10^{-3}	1.1×10^{-2}	6.3×10^{-4}
MEI Off-Site	5.4×10^{-6}	1.8×10^{-5}	1.0×10^{-6}
Off-Site Population ^{b,e}	1.2×10^{-2}	3.9×10^{-2}	2.3×10^{-3}

^a Based on mean number of drum failures

^b Cumulative collective risks

^c Worker population is 8

^d On-site population is 11,549

^e Off-site population is 212,541

7.2 ADDITIONAL CONCERNS

Several issues were not quantitatively addressed in the risk assessment, but may impact risks. These issues are addressed below with a discussion of the potential impacts on the retrieval operations.

- The current study of the risks of retrieval operations is limited to radionuclides. Chemicals are present on the pads; concentrations of the chemicals in the containers, however, are unknown. Risk due to chemical exposures may or may not be a concern during operations.
- No accurate scientific methods or data exist to confidently predict corrosion as a function of the unique conditions at LANL. While the current study is based on the best available data, many uncertainties remain. The assumptions are believed to be conservative, however the potential exists for predicted corrosion rates to be higher or lower. For example, drums on the outside of the stack may corrode faster due to contact with the tarp than drums on the inside of the stack. Although this may increase the number of drum failures predicted, no quantitative method exists to account for this potential. A decision whether to choose the Immediate or Delayed Retrieval Alternative is most appropriately based on the drum failure analysis. Hence, the drum failure analysis is the most critical analysis; it is also the section with the greatest amount of uncertainty.
- Because no surface contamination has been measured or detected on the drums, the current study of incident-free operations does not include potential risks associated with surface contamination. The potential exists for the surface of the drums to be contaminated. Because the greatest risk posed by exposure to transuranics is via inhalation, risks could potentially increase as a result of surface contamination.
- Degradation of crates is not quantified because quantitative information on crate failure is unavailable. However, the possibility exists that crates may fail faster than drums. The crates

mostly contain large pieces of machinery, however, and risks due to inhalation could be minimal.

- In 1992, an excavation of 16 drums from Pad 2 revealed six drums outside of the protective tarp. The drums exhibited significant general corrosion. The general corrosion rates in the current study are based on the assumptions that all drums are under the protective plastic tarp. If other drums are currently outside of the protective plastic tarp, the number of drum failures would increase because corrosion rates are much faster for drums in contact with soil.
- While failure rate due to pitting is predicted, risks due to pitting corrosion are not quantified. Because only the potential exists for liquids to be present in the drums, significant contamination escaping through pinholes is unlikely. However, drums that develop pinholes will require special attention and overpacking and will be an additional source of external radiation exposure. Because of this special attention, the retrieval process may be prolonged, subjecting workers to additional exposure.
- Analysis of sensitive subpopulations, such as pregnant women and the elderly is outside the scope of the off-site public assessment and risks to these populations may be higher than those presented in the current report.

7.3 CONCLUSIONS

Based on these findings, it is recommended that remediation of Pads 1, 2, and 4 not be delayed. While risks due to incident-free operations are low, risks from drum failures are potentially severe if retrieval is delayed and administrative and engineering controls remain constant. The Delayed Retrieval Alternative entails many drums reaching the critical 20-yr lifetime storage under earthen cover. A potentially significant number of drums may fail during retrieval as a result. The Immediate Retrieval Alternative, however, entails minimal drum failures.

A similar conclusion was reached at Savannah River (Kriikku 1991), where studies of galvanized carbon steel drums showed that significant pitting corrosion had begun by 14 years. Due to the uncertainties in the speed of the corrosion processes, they also concluded that storage of the drums under earthen cover should not continue for more than 20 years. Because the drums at LANL are painted, not galvanized, faster corrosion rates at LANL can be expected.

We stress that our recommendations are based on risk only and that risk should not be the only factor to consider in decision-making. Cost is also a crucial factor. The risks calculated in this study for total drum failures are only predictions and are to be considered unrealistic. If, after retrieval operations are initiated, the drums are found to have deteriorated such that many drums would fail during retrieval operations, DOE would initiate greater engineering and administrative controls to protect workers and the public from the predicted risks. These risks were calculated so that the potential for risks to occur above the acceptable limit could be identified and additional costs due to potentially necessary increased controls could be anticipated. Because greater controls could substantially decrease risk, the question of one alternative or another should be considered in terms of risk *and* cost.

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8. RECOMMENDATIONS FOR FURTHER STUDY

The description of the general corrosion process and the subsequent prediction of drum failures is a major area of uncertainty in this risk assessment. The current methods available for predicting drum corrosion are not sufficiently developed to make confident statements about the future. Corrosion prediction remains, as one corrosion engineer noted, a "black art."

Despite the limitations in predicting corrosion, DOE must make decisions regarding the retrieval of TRU waste that ultimately hinge on the results of predictive efforts. Because these decisions are critical to the national TRU waste system, we believe it vital that uncertainties and limitations in the corrosion estimation process be addressed and every effort made to reduce them.

DOE has a rare opportunity to make a potentially significant contribution to the body of knowledge regarding the corrosion process as it occurs within the environments and storage configurations present across the DOE complex. Numerous promising models are available that, if refined with suitable data, may provide invaluable tools for evaluating corrosion potential at other sites. Regardless of when Pads 1, 2, and 4 will be remediated, it is certain the waste will be retrieved eventually. It is absolutely vital that the retrieval operations entail the gathering of as much data as can be obtained. These data have the potential for providing insight into the science of corrosion and the decisions that are based thereon.

DOE should develop and implement a strategy to gather these data at the remediation sites. It is recommended that this strategy be a collaborative inter-laboratory effort. The data collection process should include the following:

- Corrosion impacts as a function of drum position in the stack, environment around the drum, and drum contents, including inventory, waste form, and internal packaging;
- Condition of any protective features, such as plastic tarp or plywood;
- Detailed measurements of general and pitting corrosion on each container, including surface area, pit depths, and container wall thickness;
- General container characterization such as specifications for material and coating
- Comprehensive photographic records of conditions and retrieval operations.

Prediction of the corrosion process is an essential consideration in the decision to retrieve earthen-covered TRU waste. The computational models currently available are not sufficiently developed to predict the impacts of corrosion on TRU containers with complete accuracy. With the addition of the data strategically garnered as part of the retrieval effort at LANL, many uncertainties in estimating corrosion at other sites may be reduced, thereby making the decisions based on future predictions more sound.

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APPENDIX A

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APPENDIX A

Analysis of Potential for Chronic Release from Degraded Drums

A range in the number of drums predicted to fail in the event retrieval is delayed was obtained. The possibility that contaminants could be released from a corroded drum before retrieval is examined in this appendix. A release could contaminate the surrounding soil and eventually reach the aquifer. Movement of a hypothetical chronic release away from corroded containers, through the facility, vadose zone, and finally to the aquifer requires that certain conditions be satisfied. The most important conditions are those that allow sufficient flow of water through the tarp, plywood, containers in the stack, and vadose zone. A number of circumstances make this scenario very unlikely, including the following:

- The plastic tarp over the top of the containers prevents water from flowing into the stack. The tarp over one of the pads was found to be intact in 1992 and no indication exists that suggests it may be damaged elsewhere. (In 1992, 6 out of 16 drums excavated were found to be stored outside of the tarp and in contact with soil. This is considered an anomaly and no other occurrences of containers outside the tarp are expected.)
- If water did manage to get into the facility, possibly through overlapping pieces of tarp, the water would have to flow into corroded containers and back out again, becoming contaminated in the process. Because very little water is potentially present at any given time inside the stack array, flow of water in and out of a corroded drum is unlikely. Moreover, most of the waste in the drums is packed inside additional packaging, such as plastic bags and paint cans, inside of the drum. Both the wall of the drum and the internal packaging would have to fail over the next 10 years for a release to occur, which is unlikely.

Despite these mitigating circumstances, the potential for contaminated water to exit the waste stack is considered. The crates on the pads potentially contain small amounts of liquid, facilitating a potential release. Also, the cemented waste inside the drums was found to be dewatering during the excavation in 1992. Dewatering sludge could escape from internal packaging, contribute to internal corrosion, and facilitate a potential release. Because there is uncertainty in estimating a release, a screening analysis was conducted to assess the likelihood of contaminated water moving from the facility, through the vadose zone, and eventually reaching the aquifer in the event of a hypothetical release. FEMWATER (Yeh 1981) was used to calculate the following:

- The likelihood of hypothetically leached waste propagating to the aquifer given that it had already passed through the waste stack and into the vadose zone
- The likelihood of transport of hypothetically leached waste from the waste stack, away from the pads, and into the vadose zone

This screening analysis included the assumption that waste had already leached from corroded containers. A detailed discussion of the likelihood and severity of loss of container integrity due to corrosion appears in Sect. 6.2.

A lower bound of the time required for hypothetically leached TRU waste to reach the aquifer is obtained by determining the time required for water to pass from the surface of the waste stack

to the aquifer. The rate of transport of the leached waste is limited by the rate of transport of the infiltrating water and chemical interaction between the contaminant and soil. To model the movement of water through the waste stack a number of conservative values and assumptions (best possible conditions) are generated to determine the most conservative (fastest) rate of water flow. These values and assumptions, justification or source, and the possible effect on the flow rate are shown in Table A.1.

Table A.1. FEMWATER values and assumptions

Variables and Modeling Assumptions	Value	Justification or Source	Effect of Uncertain Values
Thickness of Vadose Zone (ft)	450	Gallaher 1993, LANL 1987	Measured value.
Soil Moisture Content	0.02-0.4	Gallaher 1993, LANL 1987, Yeh 1981	Measured values.
Darcy Velocity/Recharge Flux (cm/sec)	1.5×10^{-4}	Gallaher 1993, LANL 1987. Equal to 1% of rainfall in the Los Alamos area.	May over-estimate flow rate.
Assumed Bandalier Tuff parameters: K_{sat} (cm/sec) Porosity _{sat} Moisture _{sat} Van Genuchten Van Genuchten alpha	10^{-4} - 10^{-3} 0.33-0.4 0.02 $n=1.5$ 0.0144	Gallaher 1993 Sullivan and Suen 1989	Little anticipated effect on flow rate.
Assumed Asphalt Parameters: K_{sat} (cm/sec) Porosity _{sat} Moisture _{sat} Van Genuchten Van Genuchten alpha	10^{-12} 0.1 0.01 $n=10$ 0.01	Values were selected to divert water around the asphalt pad.	Little anticipated effect on flow rate.
Assumed properties of plastic tarp: Thickness of tarp K_{sat} (cm/sec) Tarp Intact Tarp Integrity Compromised Porosity _{sat} Moisture _{sat} Van Genuchten Van Genuchten alpha	0.5 mm 1.5×10^{-9} 1.0×10^{-12} 0.1 0.01 $n=1.2$ 0.01	Limitation of code requires that tarp be a porous medium. Values were selected to render the tarp as impervious to water flow as possible given this limitation.	May over-estimate flow through tarp.
Vadose zone modeled as a porous medium. Fracture flow and spatial heterogeneity are neglected.	N/A	Fracture flow is a limitation of FEMWATER.	Neglects fractures.
Assume pads are flat, not mounded.	N/A	Numerical convergence problem created in FEMWATER when mound was used.	May slightly over-estimate waste flow through the facility.
Assume inside of stack is soil, not drums. Soil is assumed to be Bandalier Tuff.	N/A	FEMWATER requires a porous medium inside the facility.	Limits analysis to exterior of facility.
Steady-State Flow Rate (Not time-dependent)	N/A	Average flow rate over wet and dry periods. Most suitable for screening-level calculations.	Creates most uncertainty in flow rate in top 20 feet. Effects probably insignificant below top 20 feet because flow rate is minute.

Results of the screening analysis showed that travel time of water from the surface of the pad to the aquifer is 2900 years. This result is supported by a more detailed experimental analysis discussed in LANL 1987. Using core samples from the TRU waste storage area, only the top 20 feet of the vadose zone were found to be affected by surface moisture infiltration. Below the surface the soil is very dry and water transport is expected to be by a vapor, rather than a capillary mechanism (LANL 1987). This field assessment and the results of the current screening analysis both indicate that hydrologic transport of contaminants through the vadose zone and to the aquifer is not a concern.

Although the likelihood that TRU waste leachate can propagate to the aquifer is low, the potential exists for transport of leachate into the surrounding soil in the immediate vicinity of the pads. FEMWATER was used to estimate the soil-moisture content and Darcy velocity through the waste stack and surrounding soil. Transport velocities for water in the vicinity of the waste containers were found to be approximately 1.5×10^{-7} cm/sec or about 5 cm/yr. Should waste move out of the containers, transport through the surrounding soil could be at most a meter or two over the next 10 years. Because any contaminated soil would be excavated during retrieval, contamination of ground water is not a concern. Because many of the assumptions and values used to assess the likelihood of leachate moving away from the containers and into the surrounding soil were worst case, and only minuscule movement was found, contamination of surrounding soil is deemed unlikely and unworthy of further quantitative or qualitative analysis.

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