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Actinide Partitioning-Transmutation Program Final Report. VII. Long-Term Risk Analysis of the Geologic Repository

S. E. Logan
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OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A07 Microfiche A01

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ORNL/TM-6987
Dist. Category UC-70

NUCLEAR WASTE PROGRAMS

Waste Management Analysis for Nuclear Fuel Cycles
(Activity No. AP 05 25 10 0; 189 No. ONL-WH01)

ACTINIDE PARTITIONING-TRANSMUTATION PROGRAM FINAL REPORT. VII. LONG-TERM RISK ANALYSIS OF THE GEOLOGIC REPOSITORY

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Date Published: September 1980

Prepared by

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Los Alamos, New Mexico 87544

Under Purchase Order No. 85B31038X-08

for

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
NUCLEAR DIVISION
for the
DEPARTMENT OF ENERGY
Contract No. W-7405-eng-26

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EXECUTIVE SUMMARY

This report supports the overall assessment by Oak Ridge National Laboratory of actinide partitioning and transmutation by providing an analysis of the long-term risks associated with the terminal storage of wastes from a fuel cycle which incorporates partitioning and transmutation (P-T) and wastes from a cycle which does not. The system model and associated computer code, called AMRAW (Assessment Method for Radioactive Waste), are used for the analysis and are applied to the Los Medanos area in southeastern New Mexico.

A conservative approach has been used throughout: (1) where a parameter is uncertain or has a range of values, normally a value in the pessimistic region is used; (2) modeling is designed to permit release incidents and affected environment to continue their course unchanged by natural or man-made countermeasures; and (3) nuclides are retained in the analysis region for full accountability, even though much dilution would be expected from river flow, wind dispersion, etc. Therefore, calculated results are believed to be consistently higher than reasonable expectations from actual disruptive incidents at the site and are not directly suited for comparison with other analyses of the particular geologic location.

The assessment is made with (1) the probabilistic, or risk, mode that uses combinations of reasonably possible release incidents with their probability of occurrence distributed and applied throughout the assessment period, and (2) the consequence mode that forces discrete release events to occur at specific times. The time period studied is 1 million years from the time of repository closure in the year 2050 and is divided into 50 time increments. For each nuclide, releases are calculated to four environmental receptors--air, ground surface, surface water, and groundwater--through which its distribution to different geographical locations is effected. The model then follows the nuclide through the various regional environment-to-man pathways and calculates dose-rate commitment to the primary human organs, including the total body. A second code of AMRAW applies incidence rates of health effects and calculates overall health effects and associated economic costs.

For this application, the repository holds waste quantities corresponding to a 30-year accumulation from the moderately low-growth nuclear power case prepared in 1975 for ERDA use. The waste amounts to about 187,000 metric tons of spent fuel, or waste from nearly 17,000 GWyr(t) at 33,000 MWd/MTHM plus other materials acquiring activity during the power scenario. For convenience, the several waste forms are combined into two major categories: Type A, which includes high-level, concreted non-high-level, iodine, and carbon wastes, and Type B, which contains unconsolidated TRU waste and fuel-assembly structural material. Each category of waste independently provides a reference (no P-T) and a P-T source inventory to be studied which are then merged to provide results for the total (A + B) waste.

The model repository is sited at a depth of 800 m in the nearly horizontal lower Salado bedded-salt formation in a region that has been relatively stable for at least 570 million years. Groundwater movement from the repository is along an almost straight path southwest to the Pecos River at Malaga Bend, a distance of about 20 km. Useful groundwater discharge for man, animals, and plant life prior to this point is not considered because of the briny nature of the water and the arid, relatively unproductive character of the ground surface.

For assessment purposes, a region consisting of 13 New Mexico and Texas counties within a radius of 200 km of the repository is divided into 8 zones. Zone 8, which is an arable corridor along the Pecos River in Eddy County and includes the towns of Carlsbad and Artesia, is the most significant study zone because of its susceptibility to nuclide concentration through both expulsive and leaching releases. Also, the significant amount of farming in the zone supports the internal food and water pathways-to-man for calculation of health effects.

The following table summarizes, for the scenarios indicated, the cumulative health effects calculated for both the reference and P-T cycle total (A + B) waste inventories. Also, the 1 million years health

Overall summary of 1 million years' health effects—
reference and P-T total (A + B) wastes

		Release Mode		
		Probabilistic	Consequence	
	Rank		Leaching at 1000 yr	Volcanism at 10^5 yr
Reference cycle	1	Tc-99 (91%)	Tc-99 (92%)	Ra-226 (77%)
	2	I-129 (8%)	I-129 (8%)	Pu-239 (12%)
	3	Ra-226 (1%)	Mo-93[a]	Th-229 (5%)
	4	Th-229[a]	C-14[a]	Np-237 (2%)
	5	Pu-239[a]	Np-237[a]	Pu-242 (1%)
Cumulative total health effects		3.63E + 04	2.70E + 06	1.40E + 07
P-T cycle	1	Tc-99 (92%)	Tc-99 (92%)	Ra-226 (83%)
	2	I-129 (8%)	I-129 (8%)	Sn-126 (5%)
	3	Ra-226[a]	Mo-93[a]	Pu-239 (5%)
	4	Th-229[a]	C-14[a]	Pu-242 (2%)
	5	Sn-126[a]	Np-237[a]	Th-229 (1%)
Cumulative total health effects		3.66E + 04	2.75E + 06	6.46E + 05
Ratio (%) (P-T)/(Ref)		100.8[c]	102.0[c]	4.6
Health effects to same population from natural background of ∼150 mrem/yr (2×10^{-4} HE/rem) - one million years[b]: 7.95E + 07 health effects				
Ratio Ref/Background effects		0.045%	3.4%	17.6%

[a] Less than 1% of last nonfootnoted nuclide.

[b] Population estimated at 2,650,000.

[c] Anomaly results from slightly higher burnup of P-T fuel giving slightly more fission products. This has no significance from standpoint of P-T benefits.

effects expected in the same population (~2,650,000 including those outside the study region ingesting contaminated food grown in the region) from natural background radiation is compared with these results and is noted to be much larger even for the improbable ($\sim10^{-12}$ events/year) scenario involving volcanic activity intersecting the repository and its direct distribution of radionuclides to the surface.

The principal results from the long-term risk assessment tasks are as follows:

1. In the probabilistic mode over the 1 million-year assessment period:

   a. ^{99}Tc and ^{129}I completely dominate cumulative effects based on their transport to man through leaching and movement with groundwater, causing about 33,000 health effects (deaths).

   b. P-T has no beneficial impact in the presence of ^{99}Tc and ^{129}I.

   c. In the absence of the above nuclides, P-T would decrease health effects from the very low non-P-T calculated value of 436 to about 20, over the period of 1 million years.

2. Consequence mode--leaching:

   a. ^{99}Tc and ^{129}I completely dominate effects.

   b. P-T has no beneficial impact, even in the absence of the above nuclides, for this particular situation.

3. Consequence mode--expulsive events:

   a. Nuclide significance is in relatively close accord with nuclide inventory activity rankings at the time of and subsequent to release.

   b. For an expulsive event occurring after decay of the shorter-lived fission products (e.g., ^{90}Sr and ^{137}Cs), P-T is effective in reducing cumulative effects to about 4.6% of the non P-T value.

Qualitative conclusions of this study are as follows:

1. P-T has only limited effectiveness in reducing long-term risk from a radionuclide waste repository under the conditions studied, and such effectiveness is essentially confined to the extremely unlikely (probability of occurrence $\sim 10^{-12}$/year) expulsive events.

2. Removal or immobilization of ^{99}Tc and ^{129}I might provide benefits that are sufficiently tangible (cumulative reduction of about 33,000 deaths--98.8% decrease) to warrant special consideration.

ACTINIDE PARTITIONING—TRANSMUTATION PROGRAM FINAL REPORT
VII. LONG-TERM RISK ANALYSIS OF THE GEOLOGIC REPOSITORY

S. L. Logan, R. L. Conarty, H. S. Ng, L. J. Rahal, and C. G. Shirley

ABSTRACT

This report supports the overall assessment by Oak Ridge National Laboratory of actinide partitioning and transmutation by providing an analysis of the long-term risks associated with the terminal storage of wastes from a fuel cycle which incorporates partitioning and transmutation (P-T) and wastes from a cycle which does not. The system model and associated computer code, called AMRAW (Assessment Method for Radioactive Waste), are used for the analysis and are applied to the Los Medanos area in southeastern New Mexico.

Because a conservative approach is used throughout, calculated results are believed to be consistently higher than reasonable expectations from actual disruptive incidents at the site and therefore are not directly suited for comparison with other analyses of the particular geologic location.

The assessment is made with (1) the probabilistic, or risk, mode that uses combinations of reasonably possible release incidents with their probability of occurrence distributed and applied throughout the assessment period, and (2) the consequence mode that forces discrete release events to occur at specific times. An assessment period of 1 million years is used. The principal results are summarized as follows:

1. In all but the expulsive modes, ^{99}Tc and ^{129}I completely dominate cumulative effects based on their transport to man through leaching and movement with groundwater, effecting

about 33,000 health effects (deaths) over the 1 million years.

2. P-T has only limited effectiveness in reducing long-term risk from a radionuclide waste repository under the conditions studied, and such effectiveness is essentially confined to the extremely unlikely (probability of occurrence $\sim 10^{-12}$/year) expulsive events.

3. Removal or immobilization of ^{99}Tc and ^{129}I might provide benefits sufficiently tangible (cumulative reduction of about 33,000 deaths—98.8% decrease) to warrant special consideration.

1. INTRODUCTION

1.1 Summary of Actinide Partitioning and Transmutation Program

The Actinide Partitioning and Transmutation (P-T) Program is a multisite effort that is being coordinated at the Oak Ridge National Laboratory (ORNL). The overall program objective is to evaluate the feasibility and incentives for partitioning (separating) the long-lived biologically significant isotopes from fuel cycle wastes and transmuting (burning) them to shorter-lived or stable isotopes in power reactors. In FY 1979, the major effort was directed toward a detailed assessment of the costs, risks, and benefits associated with this concept. The program has produced: (1) realistic waste treatment partitioning flowsheets which have been at least partly verified by experimental work, (2) a realistic transmutation scheme based on sophisticated reactor physics calculations, (3) an evaluation of partitioning and transmutation impacts on all phases of the nuclear fuel cycle, (4) a meaningful risk-cost-benefit analysis, and (5) a program plan for future development and demonstration requirements for eventual implementation in commercial operations. This analysis constitutes a reasonably firm technical basis for determining whether P-T represents a viable waste management alternative for handling long-lived waste nuclides that are generated by a nuclear power economy.

1.2 Waste Repository Risk Task

This report presents results of the repository long-term risk analysis performed in support of the P-T Program. Wastes from two fuel cycles are considered: (1) reference cycle with reprocessing but without partitioning of actinides, and (2) P-T cycle with actinide P-T in power reactors. A model repository in bedded salt is assumed for disposal, and the long-term effects from potential release scenarios are evaluated to obtain comparisons between the two fuel cycles.

1.3 Review of AMRAW Methodology

The analysis was made with the use of AMRAW (Assessment Method for Radioactive Waste). This model and its associated computer code were developed with U. S. Environmental Protection Agency (EPA) support [EPA 78]. AMRAW is a generic model that calculates and follows released material. It includes (1) the transport to and accumulation of radionuclides in various receptors in the biosphere, (2) pathways from those environmental concentrations, (3) radiation dose to man, and (4) an economic evaluation of health effects. AMRAW is an executive code that brings together input parameters established by other existing specialized codes. It incorporates features to handle such concerns as time-dependent leaching, air resuspension, transfers between environmental receptors, and environmental decay. In addition, the code accounts for radiation dose from agricultural products exported from a study region, calculates health effects, and performs an economic analysis. When operated with a probabilistic treatment of release scenarios, the results provide a risk analysis; when disruptive events initiated at discrete times are considered, the results comprise a consequence analysis. Details are presented in later sections of this report.

2. TASK OBJECTIVES

Objectives of the repository long-term risk analysis are to obtain comparisons between the reference and P-T fuel cycles as follows:

1. Obtain time-dependent dose rates and accumulated total dose for each group of consolidated waste types. The term "dose," whenever used in this report, refers to "dose commitment."

2. Obtain results separately for major release categories (i.e., expulsive and leaching with groundwater migration) to compare relative contributions.

3. Obtain results for both a risk analysis, which uses probabilistic release events, and a consequence analysis, which consider discrete events initiated at specific times. Subsequently, conduct a sensitivity analysis which exposes the effects of variations in leach rates and other parameters.

4. Obtain time-dependent health effect incidence rates and total accumulated health effects corresponding to the calculated dose rates and accumulated dose.

5. Obtain the time-dependent and total dollar costs corresponding to the calculated health effects using 0% and 7% discount rates.

6. Identify the major radionuclides contributing to the various combinations of the above conditions.

The AMRAW methodology used is described in Sect. 3.1. A time horizon of 1 million years is considered. The repository site in bedded salt chosen for the study is described in Sect. 3.2. The waste types, the two consolidated waste type groups, and initial radionuclide inventories in the model repository are described in Sect. 3.3. The contents of the repository when it is sealed are assumed to be from the accumulated emplacement of 10-year-old wastes. Sealing of the repository is assumed to take place in the year 2050. The several series of computer runs are identified and defined in Sect. 3.4.

3. METHODOLOGY USED IN RISK TASK

3.1. Computer Codes Used

The Radioactive Waste Management Systems Model (Fig. 3.1) has several parallel paths, each representing a phase in the waste management sequence: residuals treatment, waste transport, repository operations, and terminal storage. The terminal storage phase applies to the Waste Repository Risk Task. Implementation of the model is by the AMRAW computer code (Assessment Method for Radioactive Waste Management), which is divided into two parts, each run separately: (1) AMRAW-A, consisting of the Source Term, Release Model, and Environmental Model, and (2) AMRAW-B, which translates the output of AMRAW-A into health effect and economic terms. The flow of calculations is amplified in Fig. 3.2, which illustrates a typical branch of the systems model.

In addition, other specialized codes are used to develop certain input data, to format output data files for linkage between codes, and to perform and output certain interpretive operations with AMRAW results.

3.1.1 AMRAW-A

The total period of time studied in this application, 1 million years, is divided into 50 time increments, each identified by the time at the end of the increment. Various time-dependent parameters are averaged in each time increment as the calculations proceed. The increments are small (5 years) at the beginning and increase to 100,000-year increments after 100,000 years. The code runs one nuclide at a time through each increment for calculation of releases, migration during subsequent increments, and concentration in environmental receptors and geographical locations at all increments.

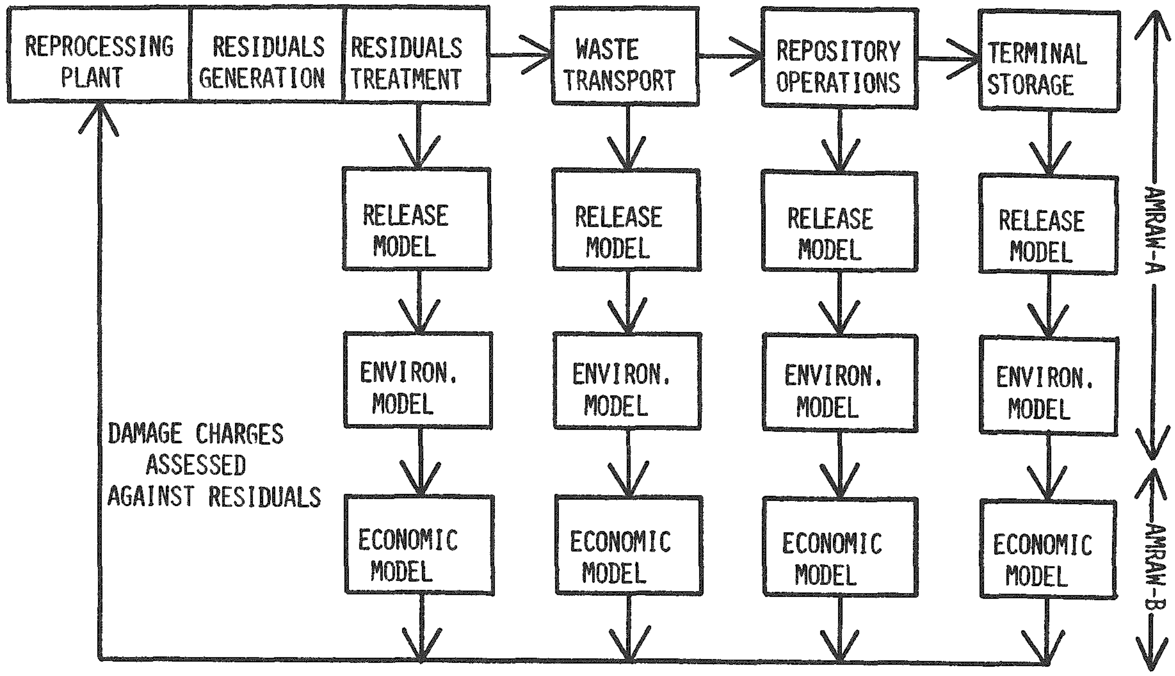


Fig. 3.1. Radioactive waste management systems model.

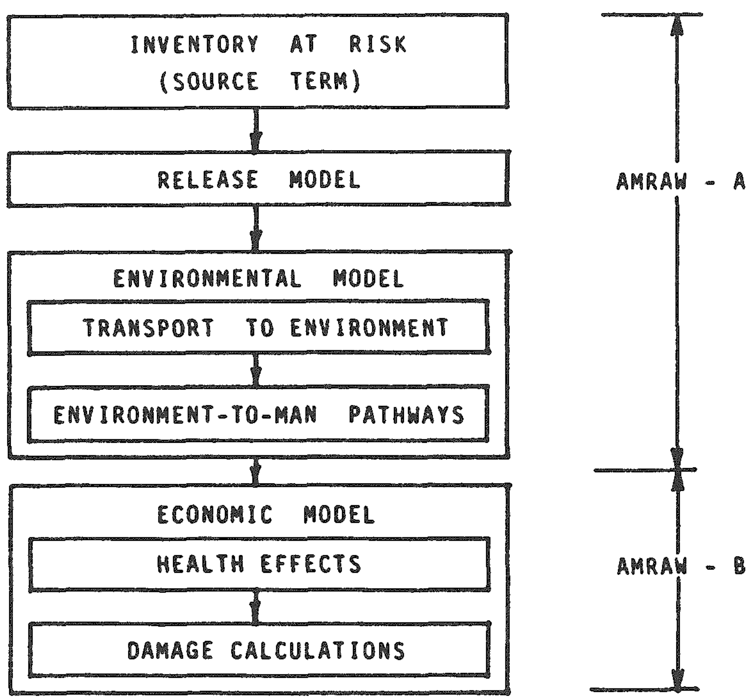


Fig. 3.2. One branch of systems model.

The AMRAW code is structured with compartments sequentially linked by transfer coefficients. The receptors represent the progress of releases, environmental concentrations, concentrations in food and drink, radiation doses, health effects, and associated economic damages. The transfer coefficients are evaluated in subroutines using externally determined input data. Factors for dispersion, biological accumulation, dose, etc., used in the transfer coefficients are evaluated externally by various existing transport and dose codes. Calculation of leach rates and coefficients expressing groundwater transport are both performed analytically in subprograms in AMRAW. Each of these can be replaced by alternate subprograms if the need develops.

Calculations commence with the mass of each significant nuclide in the "Inventory at Risk." In this task, there are six separate inventories (discussed in Sect. 3.3) provided by the Oak Ridge National Laboratory for evaluation and comparison. These inventories of 29 nuclides each are converted to curies by the activity transfer coefficient (specific activity), and all subsequent calculations are made in the latter unit. The handling of nuclide inventory by AMRAW assumes that the total inventory as a function of time is not affected by movement of portions of the inventory. Although this is a valid assumption for the inventory as a whole, it can lead to errors in some instances when using the simplified groundwater transport model alternative for precursor and daughter nuclides that do not migrate together.

The next stage in AMRAW-A is the application of potential release mechanisms to the inventory at risk based on the specific analysis to be performed. The primary hosts to which the radionuclides can be released are called the preliminary environmental input receptors—air, ground surface, surface water, and groundwater. These receptors are of fundamental importance throughout the computation process because of their peculiar characteristics, which are applicable to nuclide interreceptor and geographical migration and biological uptake.

In this application the critical release-causing events can be categorized as follows:

1. Rapid processes—meteorite impact, volcanism, etc., and
2. Slow processes—faulting, followed by leaching, erosion, glaciation.

Although the expulsive-type occurrences could be expected to produce the most serious short-term exposure and distribution of radionuclides, the probabilities for such events in the area selected for the waste-repository risk task are so low ($\cong 2 \times 10^{-12}$/year) that there is little likelihood of an occurrence except over the most extended time period. On the other hand, earthquake and faulting probabilities are more meaningful in the time frame of 1 million years; however, their effects must assume possible interconnection of aquifers through the repository and then await the time-dependent mechanics of leaching and movement in the aquifer to ultimate exposure or extraction.

AMRAW was modified for the task to better simulate the response following initiation of a leaching incident. As discussed further in Sect. 3.3.2.2, a provision was added that accounts for progressive exposure of additional waste canisters due to salt dissolution.

The release to the four preliminary environmental input receptors is calculated for each nuclide and for each release mechanism in turn through use of a transfer coefficient which, when multiplied by the release time increment of interest, gives the fraction of the radionuclide inventory transferred during that increment. The transfer coefficient is the product of the annual probability of release through a particular mechanism and the fraction of the inventory released to a particular receptor if the event occurs. Calculations are performed for release events and time functions of the release probability suited for the chosen scenario.

The basic scenario used for this task is one in which all potential release events occur, with annual occurrence probabilities obtained from the applicable probability density function distributed over the 1 million years of interest. This is called the "probabilistic distribution" or "risk" mode, and although it does not give real short-term or incremental results because of the unique release modes, it does provide a good measure of risk or mathematical expectation of effects over the long term. More important, because it uses a standard, comprehensive scenario, it can be useful in making comparisons among alternative options. In addition, by confining calculations to a single or selected combination of release events, comparative analysis can be made of the different factors contributing to risk. For the probabilistic applications, risk is defined as the product of the probability of occurrence of an event and the consequences of the occurrence. Consequences can be any selected effect of interest such as dose rate, health effects, or economic costs.

The other major release mode used for the risk task involves discrete events forced to occur at specific times. This corresponds to the so-called "what if" question and provides for analysis of event consequences and thus is termed the "consequence analysis" mode.

The next calculational stage is transport of released nuclides to and calculation of concentrations by environmental receptors at specifically defined geographical zones surrounding the repository. The steps taken by the model at this stage are:

1. calculate dispersion to the geographic zones,
2. adjust for transfers between receptors,
3. calculate residual activity during each time increment following release, and
4. accumulate concentrations from all current and previous releases.

Residual activity is calculated using a simple one-step decay factor for radioactivity and a modest exponential environmental decay factor to account for continuing dispersal and/or fixation processes which gradually remove quantities of each nuclide from further movement along the pathway to man. The environmental decay factor is applied only to the air, ground surface, and surface water environmental receptors, as removal/retardation processes are inherent in groundwater calculations.

The final segment of the Environmental Model is the "Environment-to-Man Pathways," which translates environmental receptor concentrations to radiation dose commitment to man. These primary pathways are summarized in Table 3.1.

The nonspecific category included in the table is a means for assigning dose rates and consequence values to radionuclides which are taken up by produce and animals and are consumed by a broader population extending outside the repository region. Ingestion of drinking water from surface water or groundwater sources contributes to local dose, while ingestion of drinking water by meat or milk animals contributes to nonspecific dose.

Table 3.1. Environment-to-man pathways

Environmental receptor	Pathway	Dose categorization
Air	Immersion	Local
	Inhalation	Local
Land Surface	Direct exposure	Local
	Ingestion (land surface food)	Nonspecific
Surface Water	Submersion	Local
	Ingestion (aquatic food/drink)	Local and nonspecific
Groundwater	Ingestion	Local and nonspecific

The environment-to-man transfer is made through a transfer coefficient calculated from the product of the fractional representation of the following three basic elements:

1. concentration or dilution to the consumed or exposure quantities through each pathway,
2. amount of exposure or consumption per year, and

3. dose rate conversion per unit of exposure or consumption for each of seven specified organs (including total body).

The output from this final segment of AMRAW-A is "local" dose rates to man by organ in each of eight geographical zones (mrem/year) and nonspecific dose rates by organ (man-rem/year). More detailed explanation of AMRAW-A appears in the EPA Report Development and Application of a Risk Assessment Method for Radioactive Waste Management, Vol. 1 [EPA78].

3.1.2 AMRAW-B

AMRAW-B, The Economic Model, uses the calculated population dose rates from AMRAW-A, to which it applies incidence rates of health effects associated with radiation dose and calculates health effects and associated economic costs. The flow of AMRAW-B first determines the rate of occurrence of health effects and then calculates the damage in economic terms (dollars) corresponding to these damages.

3.1.2.1. Health effect incidence. The BEIR report of the National Academy of Sciences [NAS72] is the most generally accepted source of information on the health effects of ionizing radiation and is used to provide conversion factors for use in AMRAW-B. Table 3.2 presents the health-effect incidence rates derived from the BEIR report and relates them to the organ sites for which dose rates are calculated in AMRAW-A. The values are averages of the two plateau regions (30 years and lifetime) for each risk model (absolute and relative) and then the average of the two models. A direct match is obtained for some organ sites, such as for lungs, but breast and certain other cancers use total body dose rates as an approximation. Bone marrow is included with bone because of the almost identical dose rates and a lack of complete incidence rates for bone marrow.

3.1.2.2. Economics of risk. The risk task uses the econometric approach to risk of Thaler and Rosen [Tℓ76], where an estimate is made of the additional compensation required to induce a group of high-risk individuals (those who choose jobs with a mean risk of death of 0.001)

Table 3.2. Health-effect incidence rates

AMRAW-A Dose rate site	BEIR Report health effect	Deaths/ 10^6 man-rem	AMRAW-B Input, deaths/ 10^6 man-rem
Total body	Breast cancer[a] Remaining cancers[b]	51 34	85
GI Tract	GI tract cancer (including stomach)	34	34
Gonads	Genetic effects	200[c]	200
Liver	b	b	0
Lung	Lung cancer	44	44
Bone marrow	Leukemia	32	0[d]
Bone	Bone cancer	7	39
Thyroid	b	b	0

[a]Dose rates to breast approximated by total body rates.

[b]Remaining cancers include liver and thyroid cancer.

[c]Serious genetic effect assumed equivalent to a death for damage evaluation purposes.

[d]Bone marrow effects included under bone.

to accept an additional increase in risk. For a first-available lower boundary, they have developed an estimate that the high-risk group will accept an additional increase in risk of 0.001 per year for an increased compensation ranging from $176 to $260 per year. AMRAW-B uses the upper figure, which gives a relationship of $260,000 per statistical death obtained through the first-stage calculations of AMRAW-B. It is important to recognize that this approach does not attempt to place a value on a human life as is implied with some other frequently used concepts, such as basing the value on the sum of the present values of a person's future earnings.

Although the assignment of monetary costs to future health effects is tenuous at best, and particularly so for the very long time periods of this study, it does provide a means for interpreting the potential future impact of an endeavor in the same terms (dollars) used for its other cost/benefit analyses. More specifically, in AMRAW-B, the valuing of future damages in current dollars can be visualized as a matter of determining the amount of money that should be set aside at the outset to provide retribution for damages statistically predicted to occur in the future. AMRAW-B provides for calculations using any two discount rates in order to accommodate situations and time frames where conventional time-value-of-money concepts might be considered appropriate. A non-zero, 7% discount rate is used in this task to examine the sensitivity of results to discounting. Amplification of the economic portion of AMRAW appears in EPA78, Vol. III.

3.1.3 Auxiliary programs

Auxiliary programs can be categorized as (1) those used in preparing input data for AMRAW, (2) programs necessary for interfacing output and input data between AMRAW runs, and (3) programs used to develop and present output data in a particular manner. Also, several utility programs are used to facilitate communication with the computer and its I/O peripherals.

3.1.3.1. Programs involving input data.

SEARCH--program to search Oak Ridge-furnished ORIGEN nuclide inventories for nuclides and for times to be used by AMRAW.

BIOFACP--program to calculate "BIOFAC" transfer values used in determination of nuclide concentration or dilution through different pathways to man. An adaptation of the TERMOD code [ORNL76] and the NRC Regulatory Guide 1.109 [NRC76].

3.1.3.2. Interface between AMRAW runs.

COMPRESS--program to strip AMRAW-A dose-rate and dose-output files of extraneous headings and the time column, when required, to permit input as a random access file to AMRAW-B and MERGE. During this study, compressed files were output directly from AMRAW-A, avoiding the additional step.

MERGE--program to combine the results of similar runs with partial inventories to obtain results for the combined total inventory.

DCOMPRESS--reintroduces headings and time columns to output files for printing.

3.1.3.3. Interpretive programs.

ORDER--program to rank nuclides by quantitative order of importance for nuclide dose rate or dose at different times. When applied to AMRAW-B, ranking is correspondingly by health effect incidence and/or economic costs.

INVATT--program that compares selected initial nuclide inventories, calculates attribution factors for nuclides in each initial inventory, and, for each run of interest, calculates damages that can be assigned to each initial nuclide (or element) based on the nuclide's direct effect plus the proportion of daughter nuclide effects for which it has parental responsibility.

3.2. Site Description

The site chosen for the Waste-Repository Risk Task is the Los Medanos area in southeastern New Mexico. This area is in a stable region, has thick deposits of nearly horizontal bedded salt (Salado Formation), and is under study for potential installation of the Waste Isolation Pilot Plant [Wr77]. Selection of this site for the risk task in no way implies or suggests Department of Energy or U.S. Government intentions concerning the site. Familiarity with the region and the vast amount of geologic and demographic data previously acquired by the study group dictated the choice.

The Los Medanos area is approximately 40 km east of the city of Carlsbad. The location is shown on the map in Fig. 3.3 [Jn73]. A cross section of the region from east of the study area to west to the Guadalupe Mountains is in Fig. 3.4. The proposed horizon for location of the radioactive waste repository is in rock salt at a depth of about 800 m in the lower Salado formation. The repository disposal area is assumed to be 10 km^2.

For assessment purposes, a region consisting of 13 New Mexico and Texas counties within a radius of 200 km of the repository site is considered. This region is divided into eight zones illustrated in Fig. 3.5.

3.2.1 Geologic/hydrologic description

The Los Medanos site is located on the margin of the North American craton [KiP69], a region that has been relatively stable since Precambrian time, at least 570 million years ago. Tectonic processes currently operative in the craton mainly involve broad, epeirogenic warping, principally minor vertical movements.

These vertical movements may result in broad folds with low dips or high-angle faults, mostly with small stratigraphic displacements. Jointing may occur with either folding or faulting, with at least one set of joints, and probably two sets, nearly perpendicular to the bedding. Thus, folding and/or faulting could create fractures through which groundwater might move.

It is not known whether the joints would provide a fairly continuous vertical access for waters, since the joints might not be propagated through strata that tend to deform plastically, such as shales or evaporites. The Los Medanos area of east-central Eddy County and west-central Lea County is characterized by a flat, gently undulating topography which, on a regional scale, slopes toward the Pecos River. Superimposed on this surface are numerous arroyos and closed depressions; consequently, there is little integrated surface-water drainage toward the Pecos River. The maximum topographic relief on this

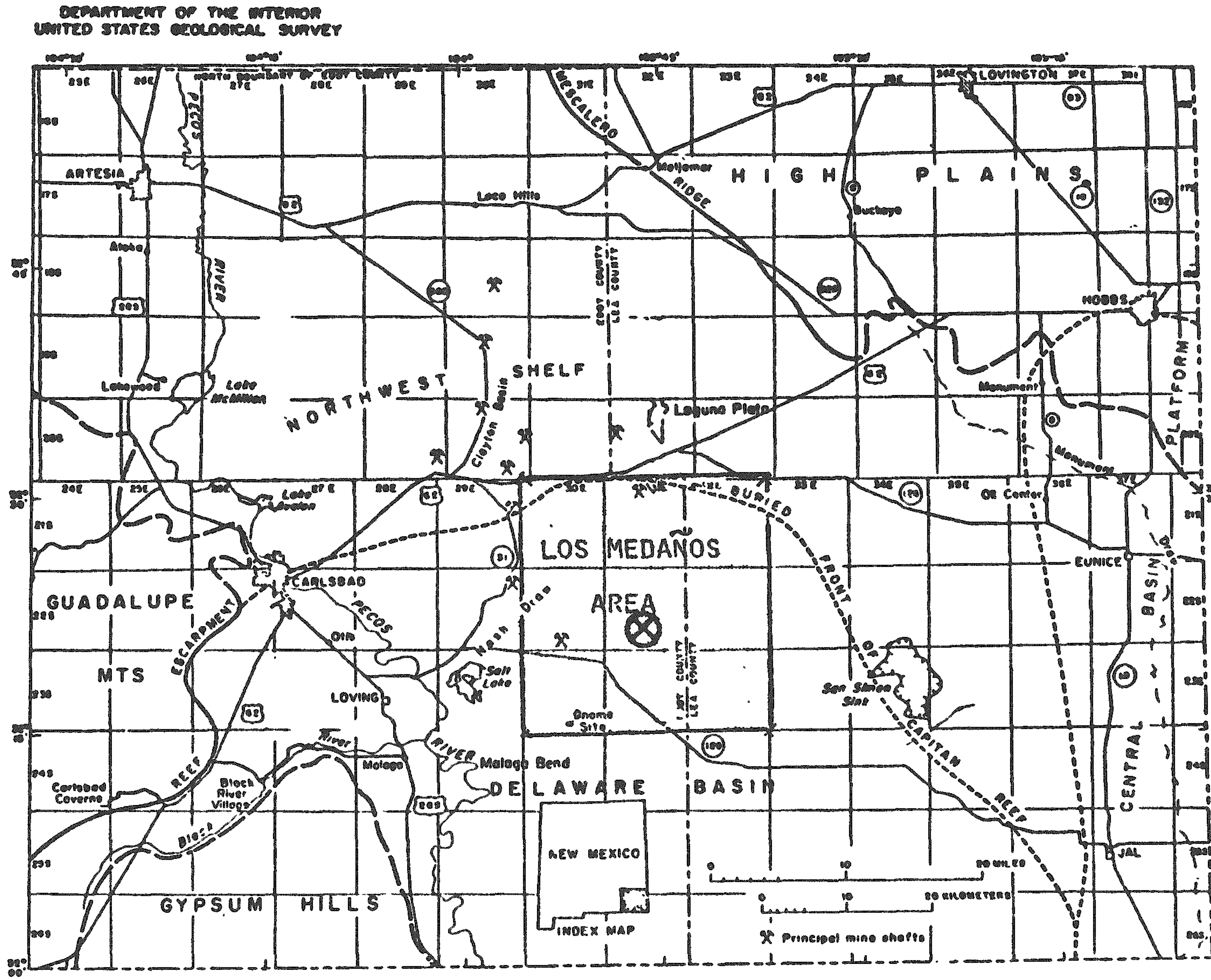


Fig. 3.3. Location of Los Medanos area, southeastern New Mexico.

Ref: USGS-4339-7

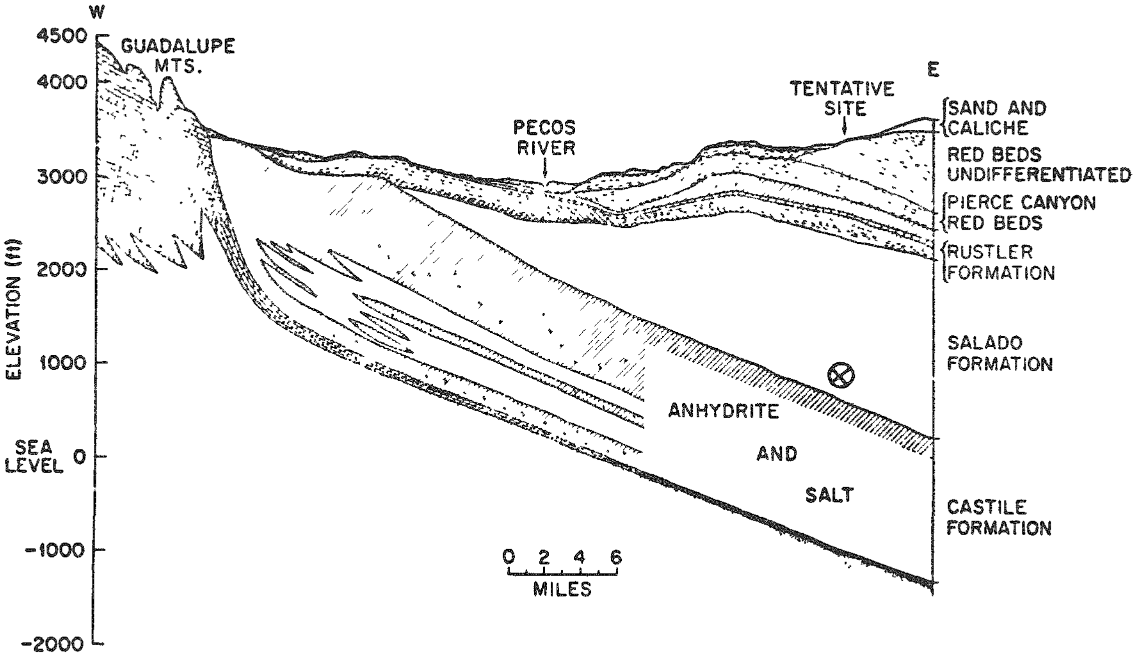
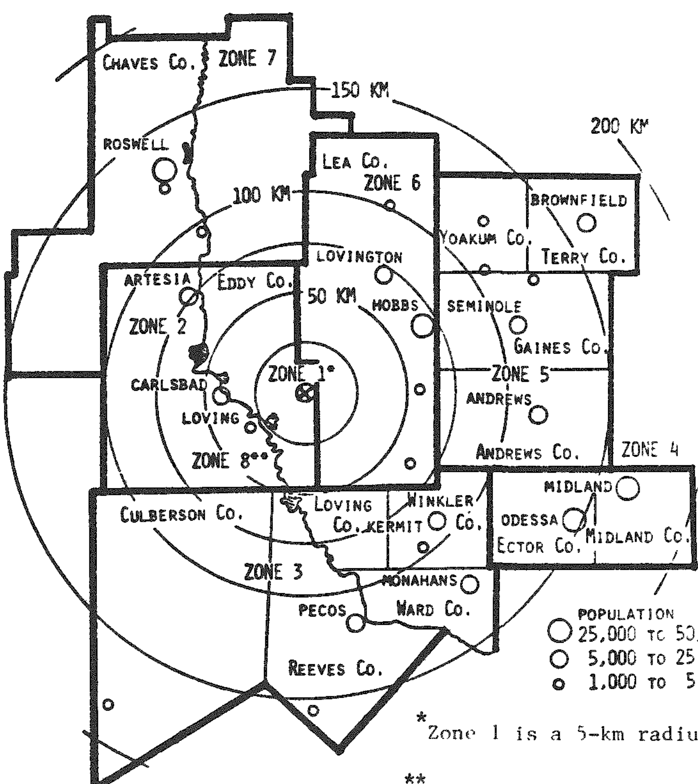


Fig. 3.4. Cross section of region.



*Zone 1 is a 5-km radius area centered on the Los Medanos site.

**Zone 8 is a 4-km corridor centered on the Pecos River in Eddy County.

Fig. 3.5. Study region and zones.

surface is about 210 m. Average rainfall in the area is about 35 cm per year.

This site takes advantage of the thick halite sequence present in the Salado Formation; conversely, very few test holes have been drilled in the area, and it is assumed that the hydrologic conditions that exist are essentially undisturbed. The Salado Formation consists primarily of halite, small amounts of anhydrite, polyhalite, and potassium salts which are mined in the area. No wells are known to produce from the Salado. In the potash mines near Los Medanos, no pore spaces capable of transmitting water have been found, and there is no water in any of these mines. Locally, oil tests have encountered small pockets of supersaturated brine within the Salado, but this cannot be considered to be an aquifer.

In the immediate vicinity of the Los Medanos area, there are five stratigraphic formations that are potential sources of groundwater which could be induced into the Salado Formation. Of these, the Rustler Formation appears to have the most direct significance. It unconformably overlies the Salado Formation east of the Pecos River and, in general, outcrops in the bluffs along the east bank of the river and then dips east and southeast into Texas. Near Los Medanos the Rustler is approximately 150 m thick and can be divided into two units—a lower plastic unit of variegated shale and some evaporites and an upper unit of anhydrite and dolomite.

Most workers agree that the groundwater in this formation is locally perched, may often be present under water-table conditions, and/or is locally under artesian conditions. Water movement is generally toward the south and west, with the major discharge points in Nash Draw and the Pecos River near Malaga Bend. According to Hiss [Hi75], the average porosity of the Rustler is about 15%. Aquifers in the formation are locally recharged directly by precipitation; however, the total amount of recharge from rainfall is probably inconsequential. Most recharge probably enters from runoff that has been impounded in the numerous sinkholes and playa lakes that have developed on the surface.

One of the major topographic features near the Los Medanos area is Nash Draw, a tributary to the Pecos River, which Robinson and Lang [Rb38] estimated to contain as much as 625,000 acre-feet of groundwater—predominantly brine. This water moves in a southwest direction, where much of it is discharged as brine into the Pecos River at Malaga Bend, approximately 20 km from the repository site.

The groundwater velocity assumed in the Rustler for this study is 1.46 m/year, as was used in the earlier EPA study [EPA 78]. The draft environmental impact statement for the Waste Isolation Pilot Plant [DOE 79] reports that calculated natural water velocities in the Rustler aquifers range from 0.023 to 4.6 m/year; a range of transmissivities is assumed which indicates velocities between 0.2 and 4.0 m/year. Both bases bracket the 1.46-m/year value used here.

3.2.2 Study region and zones

The region within a radius of approximately 150 km from the proposed repository site is used for the study. It is expected that most of any material released from the repository would be dispersed within this region. To provide for nonuniformity of population, nuclide migration and dispersion, and other factors, the region is divided into the eight zones shown in Fig. 3.5.

A circular zone with a radius of 5 km extending from the center of the assumed 10-km^2 repository site is designated as Zone 1. This zone in Eddy County, New Mexico, represents a possible controlled area during the first several decades of the terminal repository. Zone 2 consists of all the arid land in Eddy County except for Zone 1.

The counties of Culberson, Reeves, Loving, Ward and Winkler, Texas, comprise Zone 3, which, due to the path of the Pecos River, could receive both airborne and waterborne contamination. Although 85% of the land is classified as being farmed, only 1.6% is under irrigation.

The fourth zone includes the Texas counties of Midland and Ector. Only 1.2% of the farmland is under irrigation, which is generally provided from groundwater. This zone had the highest population in 1970 (157,237) and has the greatest population density.

Zone 5 includes the Texas counties of Andrews, Gaines, Terry, and Yoakum. Although this zone has only 73% of its land in farms, it has the highest (17%) of that under irrigation. The principal crop is sorghum.

The sixth zone includes exclusively Lea County of New Mexico, with principal towns of Hobbs and Lovington. Zone 7 is Chaves County, New Mexico, with Roswell as its principal town.

Zone 8 is a corridor along the Pecos River in Eddy County, consisting of the river bed and irrigated and other directly associated land. This occupies about 60,000 hectares and contains the towns of Carlsbad and Artesia and most of the population of Eddy County. This zone is set up because of the concentrated belt of irrigated land, some of which, in the south, is in the general direction of groundwater flow from the repository area.

Table 3.3 contains population projections through the year 2020. The New Mexico projections are the "high" projections prepared by the University of New Mexico Bureau of Business Research for the EPA78 report, and the Texas values are those derived by the Population Research Center of the University of Texas at Austin. These population

Table 3.3 High population projections: 1970-2020

	Zone						
YEAR	1+2+8 [a]	3	4	5	6	7	TOTAL
1970	41,119	42,778	157,237	43,452	49,552	43,335	377,473
1980	66,500	77,813	286,014	79,039	84,600	92,400	686,366
1990	85,350	101,935	374,678	103,541	112,450	121,900	899,854
2000	104,200	126,135	436,629	128,122	140,300	151,400	1,086,786
2010	138,050	169,650	587,266	172,324	192,850	202,250	1,462,390
2020	171,900[b]	213,168	783,533	216,526	245,400	253,100	1,883,627

[a] Values for Zones 1-2-8 are totals for Eddy County.

[b] Estimated breakdown: 101 in Zone 1; 17,200 in Zone 2; and 155,000 in Zone 8.

projections for the year 2020 are assumed to remain constant throughout the assessment period. In addition, an average effective nonspecific population of approximately 1 million is assumed based on the region's food production and typical consumpton rates.

In the zones surrounding the repository there is mining for potash, extraction of oil and natural gas, concentrated farming in narrow bands below irrigation reservoirs on the Pecos River, and grain production in Zones 3, 4, 5, and the eastern part of Zone 6. Cattle and some sheep ranching occur throughout the area; however, the grazing density is relatively low. For example, the average cattle density for Zones 1+2+8 is about one cow per 500 acres (a bit more than one cow per square mile). Although this is only a rough approximation, it emphasizes the arid and agriculturally unproductive nature of Zones 1 and 2. The surface of these zones is largely covered with mesquite clumps growing in sand, interspersed with areas of gravelly rock. Population projections imply that the population mix will remain relatively constant over time; thus, development of large metropolitan centers in the region is not expected.

3.3 Input Data

This section briefly describes those input data that differ from those used in the previously referenced Environmental Protection Agency report [EPA78]. In general, data changes occur for one of two reasons: (1) new data are designed to serve the specific purposes of a task, or (2) input data are updated as new data sources become available, additional effort is applied to remove data deficiencies, and improvements in data matching to computational modeling are made.

3.3.1 Radionuclides and inventories

For purposes of the task, the repository will hold a quantity of waste corresponding to a 30-year accumulation from the moderately low-growth case, which was prepared in 1975 and used for the ERDA

Technical Alternatives document [ERDA76]. This quantity also corresponds to a 40-year accumulation for the low-growth case and amounts to 187,000 metric tons of spent fuel, or waste from nearly 17,000 GWy(t) at 33,000 MWd(t)/MTHM, plus other materials acquiring radioactivity in connection with the overall power and fuel cycle.

For each major waste type studied in this task, two waste composition/inventory cycles are used: (1) a reference (Ref) cycle reflecting no partitioning or transmutation of nuclides, and (2) the same fuel cycle undergoing P-T. The sources of these wastes are the MOX fuel fabrication plant and the fuel reprocessing plant, illustrated in the schematic of Fig. 3.6.

3.3.1.1 Waste types and forms. The waste subtypes (source and form) considered in the waste repository risk analysis are as follows:

1. High-level waste: borosilicate glass in stainless steel cylinders measuring 3 m long and 0.3 m in diameter. The isotopic content of this waste differs in the Ref and P-T cases because of the increased actinide recovery in the P-T case.

2. Concreted, nonhigh-level TRU waste: stored in 55-gal drums and resulting from a variety of fuel reprocessing and MOX fuel fabrication sources; can include intermediate and low-level liquid TRU wastes, off-gas scrubbing solutions, decontamination solutions, and incinerator ashes. The isotopic content is different in the Ref and P-T cases because of the additional waste treatment as part of P-T.

3. Iodine waste: concreted silver zeolite in 55-gal drums; quantity and composition are identical in both the Ref and P-T cases. The concreted product density is 1.6 g/cm^3, and the effective iodine (^{127}I + ^{129}I) density is 0.1 g/cm^3.

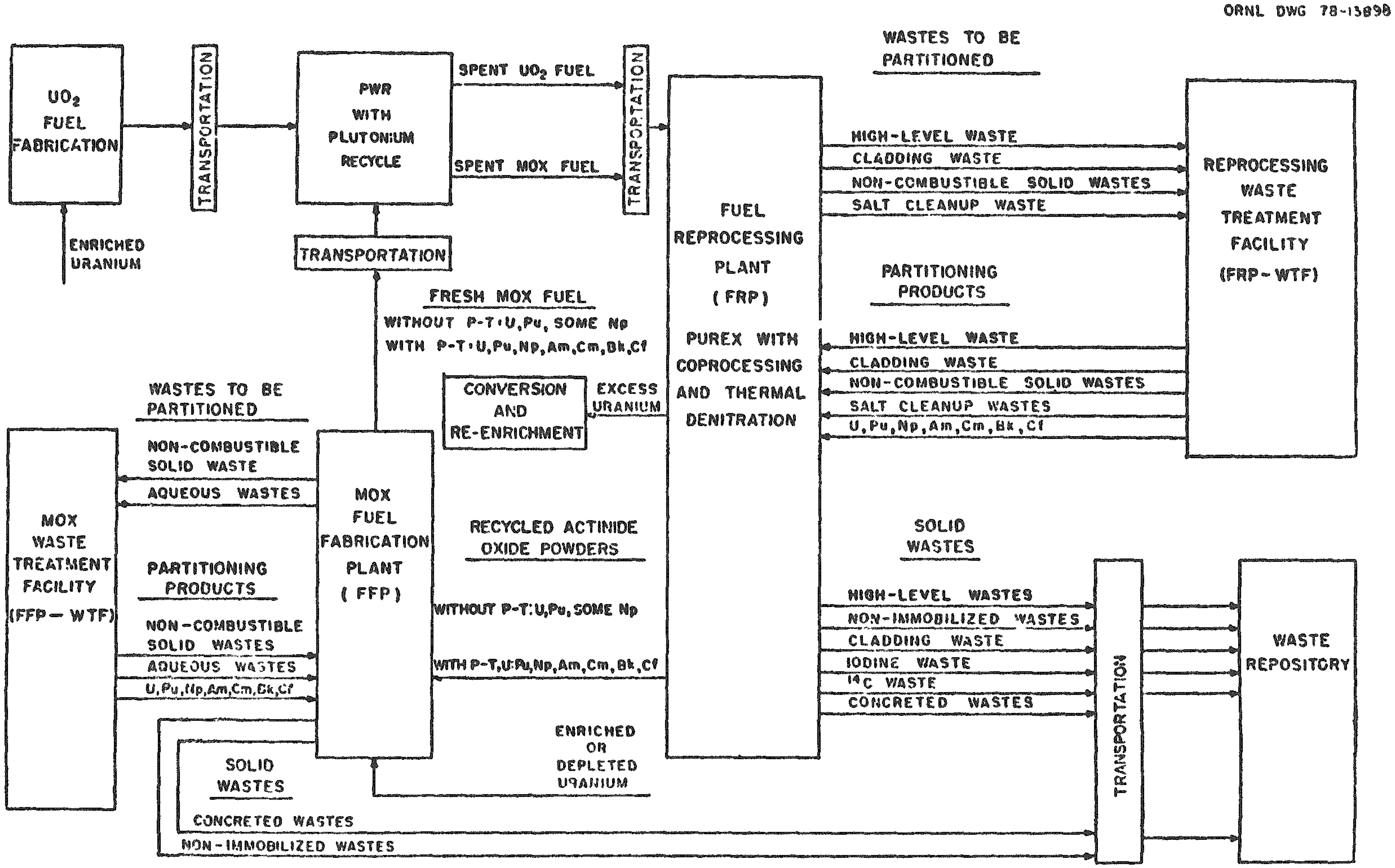


Fig. 3.6. Schematic diagram of the Reference and P-T fuel cycles.

4. Carbon-14 waste: concreted calcium carbonate in 55-gal drums; quantity and composition identical in both Ref and P-T cases. The effective elemental carbon ($^{12}C + ^{14}C$) density is 0.0673 g/cm^3, of which 0.0169 wt % is ^{14}C.

5. Nonimmobilized TRU waste: uncompacted wastes such as HEPA filters, failed equipment, and noncombustible trash stored in 55-gal drums. Composition for Ref and P-T differ.

6. Fuel-assembly structural material waste: uncompacted hulls and hardware in stainless steel cylinders measuring 3 m long and 0.3 m in diameter are identical in activation product content but differ in actinide and fission product contamination because of the different levels of treatment assumed.

3.3.1.2 Waste type consolidation. The above waste subtypes are consolidated into two basic waste types, identified as Type A and Type B, for analysis purposes. Their compositions are as follows:

Waste Type A (Consolidated)	Waste Type B (Nonconsolidated)
High-level waste	Nonimmobilized TRU waste
Concreted, nonhigh-level waste	Fuel-assembly structural material waste
Iodine waste	
Carbon waste	

By combining the wastes into these two major categories, the number of required computer runs is substantially reduced, and the quantity of output to be collated and evaluated is placed in a proper dimension.

A potential problem resulting from the grouping of wastes is that each of the individual waste forms can be expected to have leaching characteristics which differ to varying degrees. However, the actual numbers used in the analysis result in leaching behaviors which do not differ much between the waste forms within a type group. The simplification is not out of line with the uncertainties in the available input parameters. Another disadvantage is that it partially obscures the original waste form as the source for nuclides emerging from the repository; however, this information can be calculated if desired.

3.3.1.3 Nuclides and initial inventories. In addition to the nuclides considered in the EPA report [EPA78], the following nuclides are included:

1. activated structural materials—^{59}Ni and ^{93}Mo;
2. actinides—^{242}Pu, ^{245}Cm, and ^{246}Cm; and
3. fission product—^{126}Sn.

Yttrium-90 is deleted as a separate nuclide, but its effects are included under its longer-lived parent, ^{90}Sr; ^{93m}Nb is deleted, and its effects are included under ^{93}Zr. To the extent possible, the effects of unlisted daughters are included along with their reported ancestor.

For both the Type A and Type B wastes, there are Ref and P-T inventories. In addition, the AMRAW model is applied to the total of waste Types A + B, both Ref and P-T. Table 3.4 gives the initial inventories in grams for all six repository compositions. The table also gives the ratio of Ref inventory masses to P-T inventory masses in order to highlight the physical differences after undergoing partitioning and/or transmutation. In certain instances, the ratio is slightly larger than 1.0 where it would be expected to be exactly that value. This is due to the somewhat larger burnups in the P-T fuel cycle transmutation calculations, and has no significance from the standpoint of P-T benefits. These inventories were provided by ORNL in the form of ORIGEN output from which data for the selected nuclides and times could be extracted. Computations for the total A + B inventories, however, were made by merging the results of the separate A and B runs.

Table 3.4. Initial repository inventories, as measured in grams, and ratios of P-T to reference inventory

	TYPE A WASTE			TYPE B WASTE			TOTAL A + B WASTE		
Nuclide	Reference	P - T	Ratio P-T/Ref[a]	Reference	P - T	Ratio P-T/Ref[a]	Reference	P - T	Ratio P-T/Ref[a]
C-14	1.95E+04	3.90E+04	2.000	4.08E+04	4.08E+04	1.000	6.03E+04	7.98E+04	1.323
NI-59	2.13E+04	2.13E+04	1.000	1.28E+07	1.28E+07	1.000	1.28E+07	1.28E+07	1.000
SR-90	8.09E+07	8.24E+07	1.019	8.65E+04	8.81E+04	1.018	8.10E+07	8.25E+07	1.019
ZR-93	1.21E+08	1.23E+08	1.017	1.01E+07	1.01E+07	1.000	1.31E+08	1.33E+08	1.015
MO-93	7.44E+01	7.44E+01	1.000	4.29E+03	4.29E+03	1.000	4.36E+03	4.36E+03	1.000
TC-99	1.44E+08	1.47E+08	1.021	1.65E+05	1.69E+05	1.024	1.44E+08	1.47E+08	1.021
SN-126	5.43E+06	5.71E+06	1.052	5.80E+03	6.10E+03	1.052	5.44E+06	5.72E+06	1.051
I-129	3.58E+07	3.58E+07	1.000	3.93E+01	4.05E+01	1.031	3.58E+07	3.58E+07	1.000
CS-135	7.49E+07	7.09E+07	0.947	8.00E+04	7.58E+04	0.947	7.50E+07	7.10E+07	0.947
CS-137	2.16E+08	2.23E+08	1.032	2.31E+05	2.38E+05	1.030	2.16E+08	2.23E+08	1.032
PB-210	4.11E-05	5.48E-05	1.333	4.38E-08	1.47E-07	3.356	4.11E-05	5.49E-05	1.336
RA-225	5.53E-06	6.60E-06	1.193	5.88E-09	3.23E-08	5.493	5.54E-06	6.63E-06	1.197
RA-226	9.20E-03	6.55E-03	0.712	9.19E-06	5.99E-04	65.180	9.21E-03	7.15E-03	0.776
TH-229	2.03E+00	1.22E+00	0.601	2.03E+00	2.44E+00	1.202	4.06E+00	3.66E+00	0.901
TH-230	9.95E+02	3.26E+02	0.328	8.84E+02	7.47E+02	0.845	1.88E+03	1.07E+03	0.569
NP-237	7.15E+07	3.55E+05	0.005	3.00E+06	1.66E+05	0.055	7.45E+07	5.21E+05	0.007
NP-239	3.03E+01	2.93E-01	0.010	1.57E+00	9.88E-01	0.629	3.19E+01	1.28E+00	0.040
PU-238	1.13E+07	5.74E+05	0.051	3.75E+06	2.70E+05	0.072	1.51E+07	8.44E+05	0.056
PU-239	4.96E+07	3.13E+06	0.063	1.65E+07	1.48E+06	0.090	6.61E+07	4.61E+06	0.070
PU-240	3.55E+07	2.19E+06	0.062	1.18E+07	1.03E+06	0.087	4.73E+07	3.22E+06	0.068
PU-241	2.00E+07	1.13E+06	0.056	6.67E+06	5.35E+05	0.080	2.67E+07	1.67E+06	0.063
PU-242	1.58E+07	1.30E+06	0.082	5.27E+06	6.14E+05	0.117	2.11E+07	1.91E+06	0.091
AM-241	9.58E+07	1.86E+05	0.002	2.63E+05	8.79E+04	0.334	9.61E+07	2.74E+05	0.003
AM-242M	8.01E+05	2.27E+03	0.003	8.02E+02	1.09E+03	1.359	8.02E+05	3.36E+03	0.004
AM-243	1.68E+08	3.41E+05	0.002	1.68E+05	1.61E+05	0.958	1.68E+08	5.02E+05	0.003
CM-242	1.09E+06	3.29E+03	0.003	1.09E+03	1.55E+03	1.422	1.09E+06	4.84E+03	0.004
CM-244	4.84E+07	4.59E+05	0.009	4.83E+04	2.15E+05	4.451	4.84E+07	6.74E+05	0.014
CM-245	6.06E+05	7.18E+04	0.118	6.07E+02	3.34E+04	55.025	6.07E+05	1.05E+05	0.173
CM-246	2.64E+05	3.06E+04	0.116	2.64E+02	1.43E+04	54.167	2.64E+05	4.49E+04	0.170

[a]Ratios greater than 1.0 result from slightly higher burnup of P-T fuel which gives slightly larger quantities of fission products. This has no significance from the standpoint of P-T benefits.

3.3.2 Update of certain parameters

3.3.2.1 Dose factor. DOSFAC is the dose commitment conversion factor for each radionuclide, organ, and exposure mode combination. The two primary pathways, internal and external, for each environmental receptor (one for groundwater) are summarized below:

Receptor	Pathway
Air	Immersion Inhalation
Land surface	Direct exposure Ingestion, terrestrial food
Surface water	Submersion Ingestion, water and food
Groundwater	Ingestion

For this task, AMRAW is dimensioned to handle seven organs: total body, GI tract, lungs, thyroid, gonads, liver, and bone. Because of the almost identical DOSFAC values available for bone marrow and bone, only the latter is carried in AMRAW-A, but the health effects for bone marrow are included under bone in the AMRAW-B calculations.

The entire DOSFAC input file was reviewed and updated for this task. Dose conversion factors for internal doses, inhalation, and ingestion were provided from the U.S. Nuclear Regulatory Commission document, NUREG-0172 [NRC77], by G. R. Hoenes and J. K. Soldat of Battelle. The data from this publication is comprehensive and includes most nuclides used in AMRAW together with the effects of daughter nuclides. Factors for gonads are not included, however.

External dose rate factors were obtained largely from G. G. Killough and L. R. McKay's "A Methodology for Calculating Radiation Doses from Radioactivity Release to the Environment" [ORNL76]. The latter document does not include daughter nuclides in its calculations for external pathways, nor does it include all nuclides of interest to

AMRAW. In addition to these sources, ERDA 1541, Final Environmental Statement, Light Water Breeder Reactor [ERDA76b], and NRC Regulatory Guide 1.109 [NRC76] provide DOSFAC values for a few additional nuclide, organ-site combinations.

Where no data are available in the literature for external pathways, certain trends appearing in the existing data were used to approximate the needed missing information. These trends relate values for different organs, grouped by chemical element, where possible, for internal paths and by emission types and energies. For internal pathways, approximations based on emission characteristics provided gonad DOSFAC values for the inhalation route. However, because of trend inconsistencies, the ingestion values (except ^{237}Np) are defaulted from total body values.

The largest deficiency, but fortunately less serious for this task, occurs in factors available for external dose rate. For some ten nuclides (^{90}Sr, ^{93}Mo, ^{137}Cs, ^{126}Sn, ^{225}Ra, ^{229}Th, ^{241}Pu, ^{242m}Am ^{245}Cm, and ^{246}Cm), only a single value (total body, direct exposure from ground surface) is normally available. When the dose factor is confined to gamma exposure, remarkably consistent relationships are found between total body values for both air immersion and surface water immersion and the ground-surface direct exposure. Furthermore, the organ/total-body ratios exhibit similar consistencies, thus making it possible to generate reasonably good approximations for the missing external dose rate factors.

Also, because the available external pathway data do not include daughter contributions, these data are modified to include the latter where the relative half-lives would indicate a meaningful contribution during the study time frame. Nuclides which required this modification include ^{90}Sr, ^{126}Sn (^{126}Sb), ^{225}Ra, ^{226}Ra, ^{237}Np, and ^{242m}Am (^{242}Am).

3.3.2.2 Leach rate parameters.

Leach rate and quantity limits. The initial version of the AMRAW waste leaching model applied to the waste repository risk task carried an implied assumption that rock (salt) dissolution between rows of canisters in the repository occurs at such a rate that the surface area of the radioactive waste exposed to leaching remains constant. This assumption was acceptable for the waste forms to which AMRAW was applied in the EPA study [EPA78]. However, the Type B waste form of the risk task application presented a new problem.

One of the key parameters affecting the leach rate of a material is its surface-to-volume ratio. Similar to the waste form of the EPA study, the Type A waste form in the risk task (borosilicate glass), with a surface-to-volume ratio of 0.2 cm^{-1}, leaches at a rate of about one row of canisters per 6000 years, if one row is exposed initially (which is assumed in the groundwater intrusion release scenarios). At such a low leach rate, only 67% of the total repository could possibly be leached in the 1 million-year evaluation time used in the risk task. Thus, an upper limit on the quantity of waste leached (equal to the quantity of waste in the repository) was not required in AMRAW.

On the other hand, the Type B waste form (nonconsolidated) of the risk task, with a surface-to-volume ratio of 35 cm^{-1} (175 times greater than Type A), leaches at a rate of about one row of canisters in 35 years, or one repository (250 rows) in about 8600 years. Since the initial version of AMRAW contained no feature within the leaching subprogram to flag the depletion of the repository inventory, leaching of about 120 repositories of Type B waste would be allowed in the 1 million-year evaluation time prior to applying the occurrence probability if not corrected. AMRAW did have a feature to prevent releasing more than one repository inventory from all events after event probabilities were applied. Type B waste released "probabilistically" would have been overstated up to the repository limit. Two measures were taken to remedy this problem.

First, the implied assumption in AMRAW about the salt dissolution rate does not apply for Type B waste. According to Claiborne [Cℓ74], salt may be estimated to dissolve at a rate of about 0.1 cm/year on each of two surfaces (for upward groundwater flow of 0.35 liters per second per kilometer of fracture and for a 900 m salt formation thickness).

This is quite close to the leach rate of Type A waste in rows about 12.6 m apart (the spacing used for the risk task), but is about 175 times slower than the Type B waste leach rate.

To limit the rate of exposure of rows of waste canisters to the salt dissolution rate, the following assumptions are implemented:

1. An entire row of the 250 rows of the repository is exposed to leaching in the groundwater intrusion release scenarios.

2. Salt dissolves at a constant rate of 0.1 cm/year on each of two dissolution fronts moving in opposite directions normal to subsequent rows of canisters.

The number of rows (ROWS) exposed to leaching during a given time interval is then found by

$$ROWS = 1 + 2 \cdot ROKDIS \cdot DTIME/ROWSP, \qquad (3.1)$$

where,

ROKDIS = rock dissolution rate on one surface, cm/year.

DTIME = elapsed time since start of leach incident, year. This is since occurrence for a consequence analysis, or since the start of the release-time increment for a risk (probabilistic) analysis.

ROWSP = average row spacing, cm.

ROWS is used to control the surface area of the waste inventory exposed to leaching in accordance with the rate of salt dissolution. This feature limits the rate of waste leaching and accounts for host rock dissolution.

The second measure taken to limit leaching places an upper bound (equal to the total quantity of a waste species in the repository) on the total quantity of a species in the waste that can possibly be leached. Basically, this is accomplished by tracking the fraction of the repository exposed to leaching (ROWS divided by the total number of rows in the repository) as it grows from 1/250 to 1. The fraction is limited to 1, and thus the number of repositories that can be leached in the evaluation time is limited to 1.

Waste form leaching coefficients. One of the major problems encountered in waste leaching calculations is the lack of sufficient data on the various waste species of concern. Specifically, in the AMRAW leaching model (Godbee and Joy, see EPA78), there is a lack of solid diffusion coefficient data and dissolution (or ion mobility) rate constants of the various radionuclides in the waste-form matrix material (concrete or borosilicate glass).

To provide an approximate solution to this problem, published experimental data [PNL78a, b, c] and J. E. Mendel of Battelle Pacific Northwest Laboratories were consulted. On the basis of these consultations, an average representative leach rate (LR) of 6.0×10^{-6} g/cm$^2\cdot$day is assumed for all radionuclides (except Cs and Sr, 6.0×10^{-5} g/cm$^2\cdot$day) in borosilicate glass and concrete waste forms. If one assumes a combined average waste-form density (ρ) of 2.0 g/cm^3 to approximate a mixture with borosilicate glass (density, 3.0 g/cm^3) and concrete (density, 1.6 g/cm^3), the diffusion coefficient (D) and the dissolution rate constant (k) can be estimated from a relation in the AMRAW leaching model:

$$(D\cdot k)^{1/2} \cong \frac{LR}{\rho} \quad . \tag{3.2}$$

Thus, $(D\cdot k)^{1/2}$ is about 3.0×10^{-6} cm/day (3.0×10^{-5} cm/day for Cs and Sr), and based on order-of-magnitude estimates of D and k [ORNL74, BNWL69], the following values were selected for use in the risk task:

1. $D = 9.46\times10^{-10}$ cm^2/day and $k = 9.51\times10^{-3}$ day^{-1} for all radionuclides except Cs and Sr.
2. $D = 2.31\times10^{-8}$ cm^2/day and $k = 3.89\times10^{-2}$ day^{-1} for Cs and Sr.

This formula implies that leaching of the waste form occurs at a constant rate. Two factors that may cause a variable leach rate, thermal effects and waste-form disintegration effects, are considered in the realistic variable sensitivity analysis described in Sect. 3.4.4.

3.3.2.3. Distribution coefficient. After review of more recent K_d data [Ds78, Se77] and discussion with R. J. Serne of Battelle, the distribution coefficient values in Table 3.5 were established for use in this study. These are conservative values; those for the more mobile elements are generally at the low end of a possible range. The most mobile elements are molybdenum, technetium, and iodine, though the K_d for these can be slightly greater than the zero value used. Also, depending upon the oxidation state of neptunium, its K_d can be much greater than 8.1, with a corresponding increase in retardation.

Table 3.5. Distribution coefficients

Element	K_d (cm^3/g)	Element	K_d (cm^3/g)
C	1.4	Cs	13.6
Ni	20	Pb	2,800
Sr	1.0	Ra	20
Zr	1,400	Th	10,500
Mo	0	Np	8.1
Tc	0	Pu	1,400
Sn	100	Am	1,400
I	0	Cm	420

3.4 Definition of Computer Runs

3.4.1 Identification of computer runs

An identification number with seven characters (eight for AMRAW-B cases) is employed to indicate case identification. The key to the meaning of each character in each position is presented in Table 3.6.

Table 3.6. Case identification numbering

Position	Category	Character	Key
1	Configuration	A	ORNL P-T Program
2	Waste type	A	Type A consolidated group
		B	Type B consolidated group
		T	Total (A + B)
3	Fuel cycle	N	Reference cycle (no P-T)
		P	P-T cycle
4	Release mode	1	Total, all events (2 + 3)
		2	Expulsion events (probabilistic)
		3	Slow leach events (probabilistic)
		4	Volcano at 10^5 years
		5	Leach initiation at 10^3 years
		6	Leach initiation at 10^5 years
5	Type sensitivity	0	Base case conditions
		1	High leach rate
		2	Realistic variable leach rate
		3	Low leach rate
		4	High Np K_d
6	Run sequence	1	First run of type
		2	First repeat, etc.
7	AMRAW identification	X	AMRAW-A run
		0 or 7	AMRAW-B run with 0% or 7% discount rate, respectively
8	Health effects	C	Cancers only
		G	Genetic only
		T	Total (C + G)

For example, considering an AMRAW-A run with Type A waste, P-T fuel cycle, slow leach release events, base case conditions, and the first run of this type, the identifier becomes AAP301X. The corresponding AMRAW-B run for 7% discount rate and total health effects becomes AAP3017T. This identifier is printed on each output page. In addition, a simple sequential case number is also used to provide for briefer references. As implemented for the study, 0% and 7% discount rates are calculated and output together for each AMRAW-B case.

Additional explanation of each of the various options is provided in the following subsections, which describe the conditions for each of the several series of computer runs.

3.4.2 Risk analysis series

The risk-analysis series of computer runs involves potential release events distributed probabilistically over time. The release scenarios used from the EPA study [EPA78] are summarized in Table 3.7. The quantity of a specific nuclide released by a given scenario to each receptor during an increment of time is the product of: (1) annual probability, (2) length of time increment, (3) release fraction, and (4) nuclide inventory at the time considered. Following release, dispersion to the various geographic zones is calculated. The fractions indicated as released to land surface and surface water are further modified by the areal fractions of land and water, respectively, in each zone.

For this study, meteorite impact and volcanism scenarios are grouped as "expulsive events," and the faulting plus leaching scenario is referred to as a "slow-release event." The 18-run risk series is identified in Table 3.8. There is one run for each waste type (A, B, and total), for each fuel cycle (Ref and P-T), and for each release scenario group (expulsive, leaching, and total). Each "run" for total waste type is obtained by adding the results from runs for the component waste Types A and B using the MERGE auxiliary program. Where release scenarios are grouped, all are calculated to occur according to their individual probability distributions, and the released quantities are superimposed. Volcanism and leaching events are further discussed in Sect. 3.4.3.

Table 3.7. Summary of release scenarios

Scenario	Releases to receptors	Annual probability	Estimated release fraction	Risk (expected fraction of repository released per 1 million years)
Meteorite impact	Direct expulsion to air	1.0×10^{-13}	0.05	5.0×10^{-9}
	Transport to surface (distributed between ground surface and water area in zone)	1.0×10^{-13}	0.05	5.0×10^{-9}
Volcanogenic activity	Transport to surface (distributed between ground surface and water area in zone)	8.1×10^{-12}	0.075	6.1×10^{-7}
Volcanic explosion	Direct expulsion to air	2.4×10^{-12}	0.075	1.8×10^{-7}
Diatreme	Direct expulsion to air	2.4×10^{-12}	0.006	1.44×10^{-8}
Faulting; unsealed, interconnecting aquifers	Release to groundwater	1.4×10^{-7}	Calculated leach rates	

Table 3.8. Risk series computer runs

Identification Number	Case No.	Waste Type: A	Waste Type: B	Waste Type: T Total	Cycle: N Reference	Cycle: P P-T	Releases: I Total	Releases: 2 Expulsive	Releases: 3 Leaching
AAN 104	84	●			●		●		
ABN 104	85		●		●		●		
ATN 104	86			●	●		●		
AAP 104	81	●				●	●		
ABP 104	82		●			●	●		
ATP 104	83			●		●	●		
AAN 202	96	●			●			●	
ABN 202	97		●		●			●	
ATN 202	98			●	●			●	
AAP 202	93	●				●		●	
ABP 202	94		●			●		●	
ATP 202	95			●		●		●	
AAN 304	90	●			●				●
ABN 304	91		●		●				●
ATN 304	92			●	●				●
AAP 304	87	●				●			●
ABP 304	88		●			●			●
ATP 304	89			●		●			●

3.4.3 Consequence analysis series

Each computer run in the consequence analysis series considers a discrete release event initiated at a specific time and calculates the consequences of such an occurrence. Those considered here are:

1. expulsion to air by volcanic explosion at 10^5 years;
2. leach incident (faulting followed by leaching) initiated at 10^3 years;
3. leach incident initiated at 10^5 years.

The release events correspond to scenarios previously summarized in Table 3.7, except that instead of a constant annual probability, a probability of unity is applied in the time increment during which initiation occurs.

An "average volcano" erupting through the "volcanism effect zone" for a repository (eruption tangent to or within the repository perimeter) was shown in the EPA study [EPA78] to have an expected intersection fraction of 0.15; if one-half of the intersected inventory is expelled to the air, the expelled fraction becomes 0.075. In addition, it is conservatively assumed that all expelled radioactive material, which is subsequently deposited, is not covered by other deposited material. This allows it to be immediately available for environmental uptake without first requiring leaching or chemical modification. Population distribution and agricultural activity are assumed to continue unaffected by the volcano, and no cleanup or evacuation occurs after the eruption.

Each leach incident assumes that a severe faulting event occurs at the specified time, interconnecting aquifers above and below the repository, and that the fault does not heal. Upward flow along the fault through the repository is assumed, with flow merging with the upper aquifer flow. Progressive dissolution of salt is assumed, presenting an increasing number of waste canisters exposed to leaching as time progresses.

Each of these potential release events has a very low probability of occurrence. The results of calculations indicate the consequence of the several events and their relative importance if each were to occur. Results are useful in making comparisons between the reference and P-T cycles, between the different waste types, and in identifying the most significant nuclides. However, when evaluating the results, it is necessary to keep in mind the low probabilities of such occurrences. It should also be noted that the nonradiological consequences from such violent events as a volcanic explosion may overshadow the radiological increment.

Table 3.9 identifies the 18 computer runs comprising the consequence series. There is one run for each waste type, for each of the two fuel cycles, and for each of the three release events. Only results for the six cases for total waste are reported here.

Table 3.9. Consequence series computer runs

		Waste Type			Cycle		Releases		
Identification Number	Case No.	A	B	Total T	Reference N	P-T P	Volcano 10^5y 4	Leach 10^3y 5	Leach 10^5y 6
AAN 401	34	●			●		●		
ABN 401	35		●		●		●		
ATN 401	36			●	●		●		
AAP 401	31	●				●	●		
ABP 401	32		●			●	●		
ATP 401	33			●		●	●		
AAN 501	40	●			●			●	
ABN 501	41		●		●			●	
ATN 501	42			●	●			●	
AAP 501	37	●				●		●	
ABP 501	38		●			●		●	
ATP 501	39			●		●		●	
AAN 601	46	●			●				●
ABN 601	47		●		●				●
ATN 601	48			●	●				●
AAP 601	43	●				●			●
ABP 601	44		●			●			●
ATP 601	45			●		●			●

3.4.4 Sensitivity analysis series

Sensitivity analysis investigates the variation in results associated with variations in values of different input parameters. This serves to define the importance of uncertainties in parameter values. As discussed in Sect. 3.3.2.2, leaching is a process subject to uncertainties in leach rates because of differences between waste forms, and the effects of temperature, groundwater properties, and geometry. This study considers leach rates a factor of 1000 higher and lower than the nominal rates. In addition, a realistic variable leach rate (discussed in detail in later paragraphs) is applied to simulate early temperature enhancement of leach rates and later increases in exposed surface area resulting from waste-form degradation. This modification is used in order to assess the impact upon results as compared with use of a constant leach rate.

The rate at which the repository inventory is released by leaching tends to be paced by the rate at which salt dissolution permits canisters to become exposed to the leachant. To allow a demonstration of the effect of the high leach rate (1000X), the rock dissolution rate (ROKDIS) was increased by a factor of 10 to avoid undue limiting in these cases.

The K_d value used for neptunium is estimated to be 8.1. Under different oxidation conditions, K_d can be much greater. One parameter change in the sensitivity analysis series is the use of a K_d of 30 for neptunium.

3.4.4.1 Sensitivity case identification. The sensitivity analysis series breaks into two component series: risk and consequence. Table 3.10 summarizes the series on risk. Only Type A waste, the most significant of the two types, was considered. For the Ref and P-T cycles, high, realistic variable, and low leach rates and the high K_d for neptunium were investigated. One high leach rate case was run with the salt dissolution rate as well as leach rate increased by a factor of 1000. This rate for salt, 100 cm/year on each surface bordering the

Table 3.10. Sensitivity analysis computer runs: series on risk

Identification Number	Case No.	Waste Type			Cycle		Releases			Type Sensitivity			
		A	B	T Total	N Reference	P P-T	3 Leach	5 Leach 10^3 y		1[a] High Leach	2[b] Realistic Variable	3[c] Low Leach	4[d] High NpK_d
AAN 311	50	●			●		●			●			
AAP 312	99	●				●	●			●			
AAN 321	52	●			●		●				●		
AAP 321	51	●				●	●				●		
AAN 331	54	●			●		●					●	
AAP 331	53	●				●	●					●	
AAN 341	56	●			●		●						●
AAP 341	55	●				●	●						●
AAP 311[e]	49	●				●	●			●			

a. High leach rate: leach rate-1000 x nominal, and rock dissolution rate-10 x nominal.

b. Realistic variable leach rate: leach rate increased as function of temperature during early thermal period and progressively increased leaching surface area after years from waste-form degradation.

c. Low leach rate: leach rate 0.001 x nominal.

d. High Np K_d: K_d increased from nominal 8.1 to 30.

e. Leach and rate and rock dissolution rates both 100 x nominal.

fault, is unrealistically high but is of interest for comparison purposes.

Table 3.11 summarizes the sensitivity series on consequence. High and low leach rates and high neptunium K_d were run for the Ref and P-T cycles.

Table 3.11. Sensitivity analysis computer runs: series on consequence

Identification Number	Case No.	Waste Type: A	Waste Type: B	Waste Type: T Total	Cycle: N Reference	Cycle: P P-T	Releases: 3 Leach	Releases: 5 Leach 10^3 y	Releases	Type Sensitivity: 1[a] High Leach	Type Sensitivity: 2[b] Realistic Variable	Type Sensitivity: 3[c] Low Leach	Type Sensitivity: 4[d] High NpK_d
AAN 3,1	50	●			●		●			●			
AAP 312	99	●				●	●			●			
AAN 321	52	●			●		●				●		
AAP 32,	51	●				●	●				●		
AAN 331	54	●			●		●					●	
AAP 331	53	●				●	●					●	
AAN 341	56	●			●		●						●
AAP 341	55	●				●	●						●
AAP 3 1[e]	49	●				●	●			●			

a. High leach rate: leach rate-1000 x nominal, and rock dissolution rate-10 x nominal.

b. Realistic variable leach rate: leach rate increased as function of temperature during early thermal period and progressively increased leaching surface area after years from waste-form degradation.

c. Low leach rate: leach rate 0.001 x nominal.

d. High Np K_d: K_d increased from nominal 8.1 to 30.

e. Leach and rate and rock dissolution rates both 100 x nominal.

3.4.4.2 <u>Realistic variable leach rate.</u> A realistic variable leach rate factor was developed and applied to the AMRAW leaching model in a simplified attempt to simulate thermal and disintegration effects on waste-form leaching.

To simulate thermal effects, it was first assumed that the waste temperature [T(t) in K], initially 250°C (523 K), decreases linearly as a function of time (t, in years) for 200 years, until the repository ambient temperature of 40°C (313 K) is reached. Subsequently, temperature remains constant. The time function of temperature is then

$$T(t) = -1.05t + 523 \quad , \tag{3.3}$$

with an applied limit that for $t \geq 200$ years, T(t) = 523 K.

The realistic variable factor was then obtained from a relation [OWI78] which states that leach rates of a given glass at different temperatures are related by the factor exp[-(5041/T(K)]. That is, if we use 40°C (313 K) as a comparison base, the leach rate [LR(T)] at a given temperature is related to the leach rate at 40°C [LR(313 K)] as follows:

$$\frac{LR(T)}{LR(313\ K)} = \exp\left(-\frac{5041}{T(K)} + \frac{5041}{313}\right) . \tag{3.4}$$

Assuming the constant leach rate 6.0×10^{-6} g/cm^2·day (Sect. 3.3.2.2) used for the risk task is at 40°C [i.e., equals LR(313 K)], and introducing the temperature-time function, a realistic variable factor [RF(t)] was obtained:

$$RF(t) = \exp\left(-\frac{5041}{(-1.05t + 523)} + \frac{5041}{313}\right) . \tag{3.5}$$

RF(t) is then a time-varying multiplier applied during the thermal period of the waste (the first 200 years) to the leach rate [LR(313 K)] used in the AMRAW leaching model.

The glass disintegration effects are also simulated using the realistic variable factor [RF(t)], with an assumption that disintegration of the glass will begin at 1000 years and linearly increase the surface-to-volume ratio from the nominal value of 0.2 cm^{-1} at 1000 years to that of 1.0-mm spheres (60 cm^{-1}) at 1,000,000 years. Thus, for the time period 1000 to 1,000,000 years, the realistic variable factor [RF(t)] is time-varied according to the relation:

$$RF(t) = 0.0003t + 0.7 . \tag{3.6}$$

Beginning at 1000 years, the realistic variable factor increases the leach rate modeled in AMRAW from its nominal value [LR(313 K)] to a value 300 times greater (the surface-to-volume ratio increases by a factor of 300) at 1,000,000 years.

4. RESULTS AND ANALYSIS

This section gives the results obtained from applying the AMRAW codes to the Types A, B, and total (A + B) wastes described in Sect. 3. For each type of waste, results are presented for both the Ref and P-T fuel cycle inventories. Analyses are performed primarily using the Risk (probabilistic) and Consequence (discrete release) modes, with additional sensitivity analysis runs made to determine the effects of changing selected physical parameters. These modes are addressed in the above order, and where possible, data are presented from related Ref and P-T runs in a manner to facilitate comparison of results. Within each mode, waste types A, B, and total (A + B) appear in that order. It has been noted in previous applications of AMRAW, and in this application, that in ranking of nuclides, by dose, dose rate, and health effects, the top five nuclides generally account for almost 90% or more of the total parameter in question. Therefore, as a practical matter, many of the following tables are confined to describing the most significant five nuclides under a particular set of conditions. Also, where dose rate or total dose is the parameter of interest, the value for "total body" is used as the indicator for comparative purposes. In several instances, the overall dose and risk from the P-T cycle is greater than that from the reference cycle because of the slightly higher P-T fuel burnup. This condition has resulted in a slightly higher fission product content (particularly TC^{99}) in the P-T inventory.

The summary tables in this section draw from extensive computer output; the appendix to this report [ORNL80] contains selected pages from the original computer output.

4.1 Risk (Probabilistic) Analysis

This release mode distributes the release probability for each release mechanism under study over the 1 million-year study period. Such an approach tends to underemphasize the short-term or immediate impact of a release event as compared with an actual early occurrence, while significantly overstating the continuing or longer-term impact as compared with an actual late or no occurrence. This result is due not only to the extended time distribution of the release, but also to the deferral of the waste's environmental decay, which does not commence until release from the repository to the environmental receptors.

While the probabilistic mode does not represent predictions of actual events, it provides a consistent, reproducible measure for making comparisons among alternative repository or other waste management functions.

4.1.1 Type A waste

Table 4.1 summarizes the key nuclides ranked over the indicated time span for Type A waste by (1) activity in curies; (2) local total body dose rate, Zone 2; (3) local total body dose rate, Zone 8; and 4) the nonspecific total body dose rate. Zone 2 represents a close-in desert area without discharge of affected groundwater; Zone 8 is the zone receiving the groundwater discharge and is also a zone with extensive irrigated agriculture. The cases in Table 4.1 include releases from all events. Each section of the table contains data for the Reference and corresponding P-T cycle, and the last entry of each section supplies the ratio of P-T to Reference, in percent (total for all nuclides). Table 3.4 in Sect. 3 can be of use in relating these ratios to the corresponding ratios for the initial inventories.

In the Type A Ref waste, the short-lived fission products, ^{137}Cs and ^{90}Sr, dominate the early years and, because they are not removed through P-T, also dominate the latter-type inventory. On the other hand, between a few hundred years and several thousand years, these highly radioactive radionuclides disappear, thus reducing significantly the total inventory activity. This reduction in activity opens the top rankings to the actinides with modest half-lives (~400-10,000 years) and reasonably large initial inventories, together with their daughters. As 100,000 years is approached and passed, the longer-lived fission products and actinides with their daughters begin to predominate.

Table 4.1. Most significant radionuclides at selected times based on total body dose rate; risk (probabilistic) cases; waste type: A

Case and Variable Identification		Order	Time, y 10**2	10**3	10**4	10**5	10**6
SOURCE TERM							
		1	Cs-137	Am-241	Np-239	Tc-99	Zr-93
Cycle: Reference		2	Sr-90	Np-239	Am-243	Pu-239	Ra-225
		3	Am-241	Am-243	Pu-239	Zr-93	Th-229
		4	Pu-238	Pu-240	Pu-240	Np-237	Np-237
		5	Cm-244	Pu-239	Tc-99	Cs-135	Tc-99
Activity	Tot all nuc		3.57E 09	1.65E 08	4.31E 07	3.81E 06	8.23E 05
(Ci)	Top 5		3.45E 09	1.61E 08	4.19E 07	3.45E 06	7.08E 05
	% of total		96.7	97.6	97.3	90.6	85.9
		1	Cs-137	Tc-99	Tc-99	Tc-99	Zr-93
Cycle: P - T		2	Sr-90	Am-241	Zr-93	Zr-93	Tc-99
		3	Pu-238	Pu-240	Pu-240	Cs-135	Cs-135
		4	Am-241	Zr-93	Pu-239	Sn-126	I-129
		5	Tc-99	Pu-239	Sn-126	Pu-239	Th-229
Activity	Tot all nuc		3.01E 09	5.22E 06	3.65E 06	2.48E 06	4.95E 05
(Ci)	Top 5		3.01E 09	4.63E 06	3.41E 06	2.46E 06	4.91E 05
	% of total		100.0	88.9	93.6	99.3	99.2
Ratio(%): (P-T)/(Ref)	Tot all nuc		84.3	3.2	8.5	65.1	48.0
LOCAL DOSE RATE TOTAL BODY ZONE 2		1	Sr-90	Am-241	Am-243	Ra-226	Ra-226
		2	Cs-137	Am-243	Pu-239	Pu-239	Ra-225
Case# 84; Cycle: Ref		3	Am-241	Pu-240	Ra-226	Ra-225	Th-229
Release: All events		4	Pu-238	Np-239	Pu-240	Th-229	Np-237
		5	Cm-244	Pu-239	Np-239	Np-237	Pb-210
Dose Rate	Tot all nuc		3.19E-03	3.09E-04	6.85E-04	5.09E-03	3.28E-03
(mrem/y)	Top 5		3.18E-03	3.07E-04	6.75E-04	5.06E-03	3.28E-03
	% of total		99.6	99.3	98.5	99.4	100.0
Case# 81; Cycle: P-T		1	Sr-90	Am-241	Ra-226	Ra-226	Ra-226
Release: All events		2	Cs-137	Pu-240	Pu-240	Sn-126	Ra-225
		3	Am-241	Pu-239	Pu-239	Pu-239	Th-229
		4	Pu-238	Sn-126	Sn-126	Pb-210	Cs-135
		5	Cm-244	Am-243	Am-243	Cs-135	Pb-210
Dose Rate	Tot all nuc		3.13E-03	4.23E-06	1.60E-05	2.24E-04	1.33E-04
(mrem/y)	Top 5		3.13E-03	4.11E-06	1.54E-05	2.22E-04	1.32E-04
	% of total		100.0	97.2	96.1	99.4	99.4
Ratio(%): (P-T)/(Ref)	Tot all nuc		98.1	1.4	2.3	4.4	4.1

Table 4.1 (cont'd)

Case and Variable Identification		Order	Time, y 10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY ZONE 8		1	Cs-137	Am-241	Am-243	Tc-99	I-129
		2	Am-241	Am-243	Pu-239	I-129	Tc-99
Case# 84; Cycle: Ref		3	Sr-90	Pu-240	Pu-240	Ra-226	Ra-226
Release: All events		4	Pu-238	Np-239	Np-239	Pu-239	Th-229
		5	Cm-244	Pu-239	Ra-226	Th-229	Np-237
Dose Rate	Tot all nuc		2.04E-04	1.53E-04	3.04E-04	4.98E-03	6.95E-02
(mrem/y)	Top 5		1.97E-04	1.52E-04	2.99E-04	4.96E-03	6.95E-02
	% of total		96.5	99.3	98.3	99.6	100.0
Case# 81; Cycle: P-T		1	Cs-137	Am-241	Pu-240	Tc-99	I-129
Release: All events		2	Sr-90	Pu-240	Sn-126	I-129	Tc-99
		3	Pu-238	Pu-239	Pu-239	Ra-226	Ra-226
		4	Am-241	Sn-126	Am-243	Sn-126	Th-229
		5	Pu-240	Am-243	Ra-226	Pu-239	Np-239
Dose Rate	Tot all nuc		1.48E-04	2.22E-06	6.22E-06	4.83E-03	6.93E-02
(mrem/y)	Top 5		1.47E-04	2.18E-06	5.95E-06	4.83E-03	6.93E-02
	% of total		99.9	97.8	95.7	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc		72.6	1.5	2.1	97.0	99.7
NONSPECIFIC DOSE RATE TOTAL BODY		1	Sr-90	Am-241	Ra-226	Tc-99	I-129
		2	Cs-137	Am-243	Am-243	Ra-226	Tc-99
Case# 84; Cycle: Ref		3	Am-241	Pu-240	Ra-225	I-129	Ra-226
Release: All events		4	Cm-244	Ra-226	Pu-239	Ra-225	Ra-225
		5	Pu-238	Pu-239	Pu-240	Pb-210	Cs-135
Dose Rate	Tot all nuc		1.39E-01	3.65E-04	5.06E-03	7.19E-01	3.39E 00
(manrem/y)	Top 5		1.39E-01	3.62E-04	5.05E-03	7.19E-01	3.39E 00
	% of total		100.0	99.3	99.8	100.0	100.0
Case# 81; Cycle: P-T		1	Sr-90	Am-241	Ra-226	Tc-99	I-129
Release: All events		2	Cs-137	Ra-226	Tc-99	I-129	Tc-99
		3	Am-241	Tc-99	Sn-126	Ra-226	Ra-226
		4	Pu-238	Pu-240	Cs-135	Cs-135	Ra-225
		5	Cm-244	Sn-126	Pu-240	Ra-225	Cs-135
Dose Rate	Tot all nuc		1.40E-01	6.01E-06	2.35E-04	5.28E-01	3.28E 00
(manrem/y)	Top 5		1.40E-01	5.20E-06	2.34E-04	5.28E-01	3.28E 00
	% of total		100.0	86.5	99.7	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc		100.0	1.7	4.6	73.4	96.8

Recognizing that a large percentage of the actinides is removed during P-T, these characteristics roughly explain the P-T/Ref ratio sequence appearing under the first section of Table 4.1, which deals with source-term activity. The partitioning and transmutation has little initial effect on the inventory activity through the first few hundred years, is extremely effective subsequently through a few tens of thousands of years, and has mixed effect beyond 100,000 years.

The above-described source-term activity pattern strongly influences the local and nonspecific dose rate patterns in the subsequent sections of the table. However, during the later time periods, the effects of leaching releases and subsequent movement of affected nuclides with groundwater to Zone 8 determine the dose rate and health effects in that zone. In particular, ^{99}Tc and ^{129}I, neither of which is decreased through P-T (^{99}Tc is slightly larger in the P-T inventory due to burnup differences), dominate all later-year effects by a wide margin, where leaching is involved. This fact is reflected in both the Zone 8 and nonspecific results appearing in the table.

On the other hand, in Zone 2, where the leaching/groundwater pathway does not affect food for human and animal consumption, expulsive releases account for the majority of effects and are more directly traceable to the repository inventories. For this reason, the P-T/Ref dose rate ratios for Zone 2 tend to reflect removal of the actinides and their activity throughout the 1 million years.

4.1.2 Type B waste

Compared with Type A, Type B waste is characterized by a significant reduction in initial fission product inventory and transuranic elements beyond plutonium and by an increase in certain activation products, namely, ^{14}C, ^{59}Ni, and ^{93}Mo. Partitioning and transmutation is largely limited to removal of neptunium and plutonium, whereas the radium and curium isotopes appear in significantly larger initial quantities in the P-T inventories (see earlier Table 3.4). This situation is in contrast with Type A waste, where significant removal is effected beginning with ^{230}Th through ^{246}Cm. The overall total Type B inventory activity is about two orders of magnitude less than for Type A.

Table 4.2 provides source activity and dose rate information calculated from AMRAW runs using the Type B waste. In this instance, the impact of partitioning and transmutation is significant throughout the 1 million-year period, both in terms of activity and dose rates. The reduction of fission products in the initial inventory permits the actinides and activation products to compete more effectively for the top positions, albeit at a much lower activity level than with Type A waste. At the later times, both leaching to groundwater and expulsive releases join in establishing the most significant radionuclides in Zone 8 and for nonspecific dose rates. Again, the Zone 2 results reflect the repository inventory more closely.

4.1.3 Total waste

Table 4.3 summarizes results for the total of A + B wastes. Because of the generally larger inventories in Type A waste, particularly of the dominant fission products, the characteristics obtained from total waste calculations closely resemble those for Type A, with only a small increase in the impact of partitioning and transmutation due to the Type B contributions.

4.1.4 Significance of release mechanisms

In order to establish the relative weight for leach releases as opposed to expulsive releases, a series of AMRAW runs was performed in the probabilistic mode, limited in each case to one of the two release scenario types. Table 4.4 gives the Zone 8 total body dose rate results for two runs using the total waste inventory. Readily evident are the dominance of ^{99}Tc and ^{129}I within the leaching run, their time-dependence on groundwater movement to Zone 8, and after their arrival (~100,000 years and beyond), the significantly larger dose rates appearing in Zone 8 compared with rates from the expulsive run. The reverse is true up through several tens of thousands of years. Because the Type A waste inventory is significantly larger than Type B from the outset, it is expected that the total waste (A + B) runs will follow the Type A patterns.

Table 4.2. Most significant radionuclides at selected times; risk (probabilistic) cases; waste type: B

Case and Variable Identification		Order	Time, y 10**2	10**3	10**4	10**5	10**6
SOURCE TERM							
		1	Pu-238	Am-241	Pu-240	Ni-59	Zr-93
Cycle: Reference		2	Am-241	Pu-240	Ni-59	Pu-239	Th-229
		3	Pu-241	Pu-239	Pu-239	Zr-93	Ra-225
		4	Pu-240	Ni-59	C-14	Pu-242	Np-237
		5	Cs-137	C-14	Zr-93	Pb-210	Pu-242
Activity	Tot all nuc		6.13E 07	9.54E 06	2.71E 06	5.72E 05	5.34E 04
(Ci)	Top 5		6.01E 07	9.38E 06	2.65E 06	5.34E 05	4.54E 04
	% of total		94.5	98.3	97.7	93.3	85.0
		1	Pu-238	Ni-59	Ni-59	Ni-59	Zr-93
Cycle: P - T		2	Cs-137	Am-241	Pu-240	Zr-93	Ra-226
		3	Am-241	Pu-240	Pu-239	Pu-239	Th-229
		4	Sr-90	C-14	C-14	Tc-99	Np-237
		5	Ni-59	Pu-239	Zr-93	Pu-242	Pu-242
Activity	Tot all nuc		9.70E 06	2.03E 06	1.19E 06	4.60E 05	2.85E 04
(Ci)	Top 5		8.12E 06	1.90E 06	1.15E 06	4.56E 05	2.76E 04
	% of total		83.7	93.8	96.6	99.2	96.9
Ratio(%): (P-T)/(Ref)							
	Tot all nuc		15.2	21.3	43.9	80.4	53.4
LOCAL DOSE RATE TOTAL BODY							
ZONE 2		1	Pu-238	Am-241	Ra-226	Ra-226	Ra-226
		2	Am-241	Pu-240	Pu-240	Pu-239	Ra-225
Case# 85; Cycle: Ref		3	Sr-90	Pu-239	Pu-239	Pb-210	Th-229
Release: All Events		4	Pu-240	Ra-226	Pu-242	Ra-225	Pb-210
		5	Cs-137	Pu-238	Am-243	Pu-242	Np-237
Dose Rate	Tot all nuc		1.42E-05	1.87E-05	6.91E-05	1.45E-03	8.79E-04
(mrem/y)	Top 5		1.39E-05	1.86E-05	6.86E-05	1.44E-03	8.78E-04
	% of total		98.2	99.2	99.2	99.7	99.8
Case# 82; Cycle: P-T		1	Sr-90	Am-241	Ra-226	Ra-226	Ra-226
Release: All Events		2	Am-241	Pu-240	Pu-240	Pu-239	Ra-225
		3	Cs-137	Pu-239	Pu-239	Ni-59	Th-229
		4	Pu-238	Am-243	Am-243	Pb-210	Pb-210
		5	Cm-244	Ra-226	Ni-59	Pu-242	Np-237
Dose Rate	Tot all nuc		4.30E-06	1.88E-06	6.63E-06	1.02E-04	1.17E-05
(mrem/y)	Top 5		4.21E-06	1.82E-06	6.39E-06	1.01E-04	6.16E-05
	% of total		97.9	96.7	96.3	99.6	99.8
Ratio(%): (P-T)/(Ref)							
	Tot all nuc		30.3	10.1	9.6	7.0	1.3

Table 4.2 (cont'd)

Case and Variable Identification	Order	Time, y 10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY ZONE 8	1	Pu-238	Am-241	Pu-240	Ra-226	Ra-226
	2	Am-241	Pu-240	Pu-239	Pu-239	Tc-99
Case# 85; Cycle: Ref	3	Pu-240	Pu-239	Ra-226	Tc-99	Th-229
Release: All Events	4	Pu-239	Pu-238	Pu-242	Pu-242	Np-237
	5	Cs-137	Am-243	Am-243	Th-229	Ra-225
Dose Rate	Tot all nuc	6.06E-06	9.62E-06	1.91E-05	4.54E-05	6.74E-05
(mrem/y)	Top 5	5.99E-06	9.58E-06	1.89E-05	4.43E-05	6.64E-05
	% of total	98.9	99.6	99.3	97.6	98.6
Case# 82; Cycle: P-T	1	Pu-238	Am-241	Pu-240	Tc-99	Tc-99
Release: All Events	2	Am-241	Pu-240	Pu-239	Ra-226	Ra-226
	3	Cs-137	Pu-239	Am-243	Pu-239	Th-229
	4	Sr-90	Am-243	RA-226	Pu-242	I-129
	5	Pu-240	Cm-245	Cm-245	Th-229	Np-237
Dose Rate	Tot all nuc	6.67E-07	9.51E-07	2.11E-06	6.21E-06	1.22E-05
(mrem/y)	Top 5	6.23E-07	9.34E-07	2.01E-06	6.11E-06	1.20E-05
	% of total	93.4	98.2	95.3	98.4	98.9
Ratio(%): (P-T)/(Ref)	Tot all nuc	11.0	9.9	11.0	13.7	18.1
NONSPECIFIC DOSE RATE TOTAL BODY	1	Sr-90	Am-241	Ra-226	Ra-226	Ra-226
	2	Am-241	Ra-226	Ni-59	Tc-99	Tc-99
Case# 85; Cycle: Ref	3	Pu-238	Pu-240	Pu-240	Ra-225	Ra-225
Release: All events	4	Cs-137	Pu-239	Pu-239	Ni-59	Pb-210
	5	Pu-240	Ni-59	Ra-225	Pb-210	I-129
Dose Rate	Tot all nuc	2.33E-04	2.37E-05	1.48E-03	6.16E-02	4.04E-02
(manrem/y)	Top 5	2.32E-04	2.35E-05	1.48E-03	6.16E-02	4.04E-02
	% of total	99.3	99.1	100.0	100.0	100.0
Case# 82; Cycle: P-T	1	Sr-90	Am-241	Ra-226	Ra-226	Ra-226
Release: All events	2	Cs-137	Ra-226	Ni-59	Tc-99	Tc-99
	3	Am-241	Ni-59	C-14	Ni-59	Ra-225
	4	Pu-238	Pu-240	Pu-240	Ra-225	I-129
	5	Cm-244	Pu-239	Pu-239	Pb-210	Pb-210
Dose Rate	Tot all nuc	1.59E-04	3.29E-06	1.22E-04	4.85E-03	4.13E-03
(manrem/y)	Top 5	1.58E-04	3.12E-06	1.21E-04	4.85E-03	4.13E-03
	% of total	99.6	94.9	99.9	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc	68.3	13.9	8.3	7.9	10.2

Table 4.3. Most significant radionuclides at selected times; risk (probabilistic) cases; waste type: A+B

Case and Variable Identification		Order	Time, y 10**2	10**3	10**4	10**5	10**6
SOURCE TERM							
		1	Cs-137	Am-241	Np-239	Tc-99	Zr-93
Cycle: Reference		2	Sr-90	Np-239	Am-243	Pu-239	Ra-225
		3	Am-241	Am-243	Pu-239	Zr-93	Th-229
		4	Pu-238	Pu-240	Pu-240	Ni-59	Np-237
		5	Cm-244	Pu-239	Tc-99	Np-237	Tc-99
Activity	Tot all nuc		3.64E 09	1.74E 08	4.58E 07	4.38E 06	8.78E 05
(Ci)	Top 5		3.51E 09	1.69E 08	4.36E 07	3.87E 06	7.51E 05
	% of total		96.4	96.9	95.3	88.3	85.5
		1	Cs-137	Tc-99	Tc-99	Tc-99	Zr-93
Cycle: P - T		2	Sr-90	Am-241	Ni-59	Zr-93	Tc-99
		3	Pu-238	Ni-59	Zr-93	Ni-59	Cs-135
		4	Am-241	Pu-240	Pu-240	Cs-135	I-129
		5	Tc-99	Zr-93	Pu-239	Sn-126	Ra-225
Activity	Tot all nuc		3.02E 09	7.24E 06	4.83E 06	2.94E 06	5.23E 05
(Ci)	Top 5		3.01E 09	6.14E 06	4.36E 06	2.90E 06	5.17E 05
	% of total		99.8	84.8	90.2	98.6	98.8
Ratio(%): (P-T)/(Ref)	Tot all nuc		83.0	4.2	10.5	67.1	59.6
LOCAL DOSE RATE TOTAL BODY ZONE 2		1	Sr-90	Am-241	Am-243	Ra-226	Ra-226
		2	Cs-137	Am-243	Ra-226	Pu-239	Ra-225
Case# 86; Cycle: Ref		3	Am-241	Pu-240	Pu-239	Ra-225	Th-229
Release: All events		4	Pu-238	Pu-239	Pu-240	Th-229	Np-237
		5	Cm-244	Np-239	Np-239	Pb-210	Pb-210
Dose Rate	Tot all nuc		3.20E-03	3.28E-04	7.54E-04	6.53E-03	4.17E-03
(mrem/y)	Top 5		3.19E-03	3.25E-04	7.54E-04	6.50E-03	4.16E-03
	% of total		99.5	99.3	98.5	99.5	99.8
Case# 83; Cycle: P-T		1	Sr-90	Am-241	Ra-226	Ra-226	Ra-226
Release: All events		2	Cs-137	Pu-240	Pu-240	Sn-126	Ra-225
		3	Am-241	Pu-239	Pu-239	Pu-239	Rh-229
		4	Pu-238	Sn-126	Sn-126	Pb-210	Cs-135
		5	Cm-244	Am-243	Am-243	Pu-242	Pb-210
Dose Rate	Tot all nuc		3.13E-03	6.10E-06	2.26E-05	3.25E-04	1.95E-04
(mrem/y)	Top 5		3.13E-03	5.90E-06	2.16E-05	3.23E-04	1.94E-04
	% of total		100.0	96.7	95.5	99.4	99.5
Ratio(%): (P-T)/(Ref)	Tot all nuc		97.8	1.9	3.0	5.0	4.7

TAble 4.3 (cont'd)

Case and Variable Identification		Order	10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY ZONE 8		1	Cs-137	Am-241	Am-243	Tc-99	I-129
		2	Am-241	Am-243	Pu-239	I-129	Tc-99
Case# 86; Cycle: Ref		3	Sr-90	Pu-240	Pu-240	Ra-226	Ra-226
Release: All events		4	Pu-238	Np-239	Np-239	Pu-239	Th-229
		5	Cm-244	Pu-239	Ra-226	Th-229	Np-237
Dose Rate	Tot all nuc		2.10E-04	1.63E-04	3.23E-04	5.03E-03	6.96E-02
(mrem/y)	Top 5		2.02E-04	1.62E-04	3.17E-04	5.01E-03	6.96E-02
	% of total		96.3	99.3	98.3	99.6	100.0
Case# 83; Cycle: P-T		1	Cs-137	Am-241	Pu-240	Tc-99	I-129
Release: All events		2	Sr-90	Pu-240	Pu-239	I-129	Tc-99
		3	Pu-238	Pu-239	Sn-126	Ra-226	Ra-226
		4	Am-241	Sn-126	Am-243	Sn-126	Th-229
		5	Pu-240	Am-243	Ra-226	Pu-239	Np-237
Dose Rate	Tot all nuc		1.48E-04	3.17E-06	8.33E-06	4.83E-03	6.94E-02
(mrem/y)	Top 5		1.48E-04	3.10E-06	7.94E-06	4.83E-03	6.94E-02
	% of total		100.0	97.7	95.3	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc		70.5	1.9	2.6	96.0	99.7
NONSPECIFIC DOSE RATE TOTAL BODY		1	Sr-90	Am-241	Ra-226	Tc-99	I-129
		2	Cs-137	Am-243	Am-243	Ra-226	Tc-99
Case# 86; Cycle: Ref		3	Am-241	Ra-226	Ra-225	I-129	Ra-226
Release: All events		4	Cm-244	Pu-240	Pu-239	Ra-225	Ra-225
		5	Pu-238	Pu-239	Pu-240	Pb-210	Cs-135
Dose Rate	Tot all nuc		1.39E-01	3.88E-04	6.54E-03	7.81E-01	3.43E 00
(manrem/y)	Top 5		1.39E-01	3.85E-04	6.52E-03	7.81E-01	3.43E 00
	% of total		100.0	99.1	99.8	100.0	100.0
Case# 83; Cycle: P-T		1	Sr-90	Am-241	Ra-226	Tc-99	I-129
Release: All events		2	Cs-137	Ra-226	Tc-99	I-129	Tc-99
		3	Am-241	Pu-240	Ni-59	Ra-226	Ra-226
		4	Pu-238	Tc-99	Sn-126	Ra-225	Ra-225
		5	Cm-244	Ni-59	Cs-135	Cs-135	Cs-135
Dose Rate	Tot all nuc		1.40E-01	9.30E-06	3.56E-04	5.33E-01	3.28E 00
(manrem/y)	Top 5		1.40E-01	7.85E-06	3.55E-04	5.33E-01	3.28E 00
	% of total		100.0	84.4	99.6	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc		100.0	2.4	5.4	68.3	95.6

Table 4.4. Most significant radionuclides at selected times based on total body dose rate; risk (probabilistic) cases; waste type: A + B (total); selected releases

Case and Variable Identification	Order	Time, y 10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 92; Cycle: Ref	3			Mo-93	Mo-93	Np-237
Release: Leaching	4					
	5					
Dose Rate (mrem/y)	Tot all nuc			1.50E-12	4.77E-03	6.92E-02
	Top 5			1.50E-12	4.77E-03	6.92E-02
	% of total			100.0	100.0	100.0
Case# 89; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Leaching	2			I-129	I-129	Tc-99
	3			Mo-93	Mo-93	Np-237
	4					
	5					
Dose Rate (mrem/y)	Tot all nuc			1.52E-12	4.82E-03	6.94E-02
	Top 5			1.52E-12	4.82E-03	6.94E-02
	% of total			100.0	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc			100.0	100.0	100.0
LOCAL DOSE RATE TOTAL BODY ZONE 8	1	Cs-137	Am-241	Am-243	Ra-226	Ra-226
	2	Am-241	Am-243	Pu-239	Pu-239	Th-229
Case# 98; Cycle: Ref	3	Sr-90	Pu-240	Pu-240	Th-229	Np-237
Release: Expulsive	4	Pu-239	Np-239	Np-239	Np-237	Ra-225
	5	Cm-244	Pu-239	Ra-226	Sn-126	Pu-242
Dose Rate (mrem/y)	Tot all nuc	2.10E-04	1.63E-04	3.23E-04	2.55E-04	3.46E-04
	Top 5	2.02E-04	1.62E-04	3.17E-04	2.48E-04	3.44E-04
	% of total	96.3	99.3	98.3	97.1	99.4
Case# 95; Cycle: P-T	1	Cs-137	Am-241	Pu-240	Ra-226	Ra-226
Release: Expulsive	2	Sr-90	Pu-240	Pu-239	Sn-126	Th-229
	3	Pu-238	Pu-239	Sn-126	Pu-239	Np-237
	4	Am-241	Sn-126	Am-243	Pu-242	Ra-225
	5	Pu-240	Am-243	Ra-226	Th-229	Pu-242
Dose Rate (mrem/y)	Tot all nuc	1.48E-04	3.17E-06	8.33E-06	1.46E-05	1.35E-05
	Top 5	1.48E-04	3.10E-06	7.94E-06	1.43E-05	1.33E-05
	% of total	100.0	97.7	95.3	98.0	98.4
Ratio(%): (P-T)/(Ref)	Tot all nuc	70.5	1.9	2.6	5.7	3.9

Also, although P-T is shown as ineffectual for the leach-only events, it has significant impact after the first few hundred years in the expulsive case. In general, the key contributing nuclides beyond thorium are reduced significantly and in somewhat the same proportions through P-T of Type A waste; therefore, in the long term, some of the same nuclides (usually as offspring) retain the same high ranks under expulsion. Although ^{99}Tc ranks high (fourth) in activity at 1 million years under P-T, its sole radiation, beta, has limited access to man and his organs through the dominant external pathways associated with this type of release. Iodine-129, which also has high activity at 1 million years, does emit gamma radiation and can contribute to dose through external pathways; however, its final calculated contribution under expulsive release is too low to make the top five. Naturally, if dose rate to the thyroid were under consideration and internal pathways significant, then the dominant nuclide pattern would be different and in favor of ^{129}I.

Table 4.5 summarizes the results of all events—leaching and expulsive runs for Types A, B, and total wastes, both Ref and P-T inventories—and gives results for integrated total body doses at 10^5 and 10^6 years for Zone 8 and nonspecific. Selection of these two times provides a bracket before and after arrival in the zone of the groundwater-transported concentration peaks of ^{99}Tc and ^{129}I.

Some caution should be exercised in interpreting or extrapolating portions of Table 4.5. For example, this analysis concentrates to a large extent on Zone 8 and "nonspecific" recipients of radiation doses because of the repository's predominant demographic, agricultural, and geologic connection with them. The physical nature of expulsive events, however, leads to larger resultant nuclide concentrations close to the repository and decreasing concentrations as the radial distance from the site is increased. Naturally, for the same repository inventory, this factor leads to higher dose rates and greater cumulative doses resulting from expulsive events in Zones 1 and 2 than in Zone 8. In fact, it leads to dose rates which are competitive with leach releases until the concentration peaks of ^{99}Tc and ^{129}I from leaching arrive. Direct comparison between the two release modes cannot be made for Zone 2 in

Table 4.5. Summary of integrated total body dose, total all nuclides, risk (probabilistic) analysis

Case No	Description			Integrated Dose - 10**5 y				Integrated dose - 10**6 y			
				Local, Zone 8		Nonspecific		Local, Zone 8		Nonspecific	
	Waste type	Cycle	Release	mrem	% of total	manrem	% of total	mrem	% of total	manrem	% of total
84	A	Ref	All events	3.36E 02	100.0	4.63E 04	100.0	7.33E 04	100.0	5.91E 06	100.0
90	A	Ref	Leaching	3.08E 02	91.7	3.56E 04	76.9	7.27E 04	99.2	5.55E 06	93.9
96	A	Ref	Expulsive	2.89E 01	8.6	1.07E 04	23.1	6.07E 02	0.8	3.62E 05	6.1
81	A	P - T	All events	3.13E 02	100.0	3.69E 04	100.0	7.32E 04	100.0	5.64E 06	100.0
87	A	P - T	Leaching	3.12E 02	99.7	3.64E 04	98.6	7.32E 04	100.0	5.63E 06	99.8
93	A	P - T	Expulsive	1.08E 00	0.3	5.22E 02	1.4	2.48E 01	0.0	1.57E 04	0.3
85	B	Ref	All events	3.64E 00	100.0	3.14E 03	100.0	1.74E 02	100.0	1.09E 05	100.0
91	B	Ref	Leaching	2.24E-01	6.2	3.94E 01	1.3	2.52E 01	14.5	4.45E 03	4.1
97	B	Ref	Expulsive	3.42E 00	93.8	3.10E 03	98.7	1.49E 02	85.5	1.04E 05	95.4
82	B	P - T	All events	5.18E-01	100.0	2.61E 02	100.0	3.64E 01	100.0	1.19E 04	100.0
88	B	P - T	Leaching	2.29E-01	44.2	4.03E 01	15.4	2.57E 01	70.6	4.54E 03	38.2
94	B	P - T	Expulsive	2.89E-01	55.8	2.21E 02	84.7	1.06E 01	29.1	7.32E 03	61.5
86	Total	Ref	All events	3.40E 02	100.0	4.94E 04	100.0	7.35E 04	100.0	6.02E 06	100.0
92	Total	Ref	Leaching	3.08E 02	90.6	3.56E 04	72.1	7.27E 04	98.9	5.55E 06	92.2
98	Total	Ref	Expulsive	3.23E 01	9.5	1.38E 04	27.9	7.56E 02	1.0	4.66E 05	7.7
83	Total	P - T	All events	3.14E 02	100.0	3.72E 04	100.0	7.32E 04	100.0	5.65E 06	100.0
89	Total	P - T	Leaching	3.12E 02	99.4	3.64E 04	97.8	7.32E 04	100.0	5.63E 06	99.6
95	Total	P - T	Expulsive	1.37E 00	0.4	7.43E 02	2.0	3.54E 00	0.0	2.30E 04	0.4

this task because the fractional exposure to groundwater-borne radioactivity in that zone is essentially zero. This condition is due to the high brine concentration of aquifers traversing the Salado Formation and moving southwestward along Nash Draw, coupled with the sparse population and activity in the immediate region. In spite of the expected lower expulsive doses in Zone 8, the data in Table 4.5 highlight certain interesting differences in the effects of the various release forms.

One anomaly appears in the difference in contribution distributions for Type A and Type B wastes. In the former, the leaching releases dominate cumulative dose at both times, but in the latter, the expulsive doses are larger, except in the instance of P-T at 10^6 years. This difference is due primarily to the significantly smaller initial fission products inventory in Type B waste compared with Type A. In particular, the Type B Ref inventory of ^{129}I is smaller by six orders of magnitude and of ^{99}Tc by three, in contrast with the varying inventories of the actinides. Thorium has about the same initial A and B inventory sizes; plutonium B inventories are smaller than Type A by a factor of two to three, neptunium by a factor of about ten , and the rest are smaller by up to three orders of magnitude.

4.1.5 Attribution to initial inventory

This section is devoted to the analysis of health effects resulting from the waste-release scenarios postulated for the risk task and their attribution to the nuclides in the initial repository inventory. In order to obtain incidence rates of health effects, the dose rate output from AMRAW-A is supplied as input to AMRAW-B by nuclide, organ, zone (including nonspecific), and time. These annual rates are then multiplied by their respective zonal population projections (Table 3.3) and health-effect incidence rates (Table 3.2) to obtain annual health-effect rates by nuclide, organ, zone, and time. Because the nonspecific dose rate already includes the population factor through the expected consumption of food crops produced in the region, its population calculation is not required in AMRAW-B. All health-effect rates are treated as death rates by AMRAW. Also, the health effects resulting from doses to the gonads are considered as deaths caused by genetic effects. In order to provide a means for economic analysis, the value $260,000 is substituted for each death in accordance with the explanation of Sect. 3.1.2.2.

Table 4.6 summarizes the cumulative deaths over 1 million years for total (A + B) waste released under the probabilistic mode. In the "all events" cases, deaths resulting from genetic effects are separated from those caused by cancers. In almost all instances the genetic deaths are about a factor of ten less than the cancer deaths. The P-T/Ref ratios parallel closely the dose rate characteristics described in the preceding section for the different release modes. The reason the ratio appears slightly larger than 100% in the "all events" and leaching cases is that the initial P-T inventory contains a slightly larger amount of ^{99}Tc than the Ref inventory. As explained in Sect. 3, these slight variations from unity result from the slightly higher burnup, and therefore slightly higher fission product content, of the P-T fuel, and are not meaningful with respect to the benefits of P-T. Of particular note are the small average annual statistical deaths per year reported from the calculations, the maximum being about a few hundredths of one death per year. The totals include the sum of effects in all zones plus nonspecific, or essentially all calculated deaths associated with the terminal repository when specifically subjected to all of the potential release events considered, applied in the probabilistic mode. Similar analysis for assumed discrete releases at specific times (Sect. 4.2) gives results about 100 times larger; however, this form of inquiry neglects the unlikelihood of occurrence.

Table 4.7 lists the most significant nuclides and health-effect rates for all zones, nonspecific, and total for all zones and nonspecific. In addition, the last section gives nuclide rankings based on cumulative health effects through the times indicated. The data appearing in this table represent the translation by AMRAW-B of the dose rate output from Cases 86 (Ref) and 83 (P-T) to health effects. The dose rate data are summarized in Table 4.3.

Table 4.6. Deaths in one million years from health effects; risk (probabilistic) analysis; waste: A + B (total)

		LOCAL DEATHS	NONSPECIFIC DEATHS	TOTAL DEATHS	AVERAGE DEATHS/YR
RELEASE: all events					
Case					
Cycle: reference					
#86c	Cancers	1.57E 04	1.70E 04	3.27E 04	3.27E-02
	Genetic effects	2.40E 03	1.20E 03	3.60E 03	3.60E-03
#86T	Total	1.81E 04	1.82E 04	3.63E 04	3.63E-02
Cycle: P - T					
#83C	Cancers	1.59E 04	1.73E 04	3.32E 04	3.32E-02
	Genetic effects	2.20E 03	1.10E 03	3.40E 03	3.40E-03
#83T	Total	1.81E 04	1.84E 04	3.66E 04	3.66E-02
Ratio (%): (P-T)/(Ref)	Total effects	100.0	101.1	100.8	100.8
RELEASE: leaching					
Cycle: reference					
#92T	Total effects	1.78E 04	1.80E 04	3.58E 04	3.58E-02
Cycle: P - T					
#89T	Total effects	1.81E 04	1.84E 04	3.66E 04	3.66E-02
Ratio (%): (P-T)/(Ref)	Total effects	101.7	102.2	102.2	102.2
RELEASE: expulsive					
Cycle: reference					
#98T	Total effects	2.82E 02	1.59E 02	4.42E 02	4.42E-04
Cycle: P - T					
#95T	Total effects	1.15E 01	7.88E 00	1.94E 01	1.94E-05
Ratio (%): (P-T)/(Ref)	Total effects	4.1	5.0	4.4	4.4

One generation population for local effects: 1,883,627 (Table 3.3)
Nonspecific effects based on total food production

Table 4.7. Most significant radionuclides at selected times based on all health effects; risk (probabilistic) cases; waste type: A + B (total)

Case and variable identification	Order	Time, y 10**2	10**3	10**4	10**5	10**6
ZONAL HEALTH EFFECT RATE	1	Sr-90	Am-241	Pu-239	Tc-99	Tc-99
	2	Cs-137	Pu-240	Pu-240	I-129	I-129
Case# 86T; Cycle: Ref	3	Am-241	Am-243	Am-243	Ra-226	Ra-226
Release: All Events	4	Pu-238	Pu-239	Np-239	Pu-239	Th-229
	5	Cm-244	Np-239	Ra-226	Th-229	Np-237
Health Effects (deaths/y) | Tot all nuc		1.16E-04	9.04E-05	2.32E-04	2.15E-03	7.81E-03
| Top 5		1.11E-04	8.96E-05	2.30E-04	2.14E-03	7.81E-03
| % of total		95.7	99.2	98.7	99.4	100.0
Case# 83T; Cycle: P-T	1	Sr-90	Pu-240	Pu-240	Tc-99	Tc-99
Release: All Events	2	Cs-137	Am-241	Pu-239	I-129	I-129
	3	Pu-238	Pu-239	Sn-126	Ra-226	Ra-226
	4	Am-241	Am-243	Am-243	Pu-239	Th-229
	5	Pu-240	Sn-126	Ra-226	Sn-126	Pu-242
Health Effects (deaths/y) | Tot all nuc		7.81E-05	2.06E-06	6.38E-06	2.02E-03	7.73E-03
| Top 5		7.81E-05	2.02E-06	6.15E-06	2.02E-03	7.73E-03
| % of total		100.0	97.9	96.4	100.0	100.0
Ratio(%): (P-T)/(Ref) | Tot all nuc		67.4	2.3	2.7	93.9	99.0
NONSPECIFIC HEALTH EFFECT RATE	1	Sr-90	Am-241	Ra-226	Tc-99	Tc-99
	2	Cs-137	Am-243	Am-243	Ra-226	I-129
Case# 86T; Cycle: Ref	3	Am-241	Pu-240	Tc-99	I-129	Ta-226
Release: All Events	4	Cm-244	Pu-239	Pu-239	Ra-225	Ra-225
	5	Pu-238	Ra-226	Pu-240	Pb-210	Pb-210
Health Effects (deaths/y) | Tot all nuc		6.31E-05	8.04E-07	2.36E-06	2.18E-03	6.08E-03
| Top 5		6.27E-05	7.92E-07	2.34E-06	2.18E-03	6.08E-03
| % of total		99.6	98.9	99.2	100.0	100.0
Case# 83T; Cycle: P-T	1	Sr-90	Am-241	Ra-226	Tc-99	Tc-99
Release: All Events	2	Cs-137	Tc-99	Tc-99	I-129	I-129
	3	Am-241	Pu-240	Sn-126	Ra-226	Ra-226
	4	Pu-238	Sn-126	Ni-59	Sn-126	Ra-225
	5	Cm-244	Ra-226	Cs-135	Ra-225	Cs-135
Health Effects (deaths/y) | Tot all nuc		6.12E-05	1.65E-08	1.47E-07	2.14E-03	6.08E-03
| Top 5		6.12E-05	1.45E-08	1.45E-07	2.14E-03	6.08E-03
| % of total		100.0	87.7	98.5	100.0	100.0
Ratio(%): (P-T)/(Ref) | Tot all nuc		97.0	2.1	6.2	97.9	100.0

Table 4.7 (cont'd)

Case and variable identification	Order	Time, y 10**2	10**3	10**4	10**5	10**6
TOTAL HEALTH EFFECT RATE	1	Sr-90	Am-241	Pu-239	Tc-99	Tc-99
	2	Cs-137	Pu-240	Pu-240	Ra-226	I-129
Case# 86T; Cycle: Ref	3	Am-241	Am-243	Am-243	I-129	Ra-226
Release: All Events	4	Pu 238	Pu-239	Np-239	Pu-239	Th-229
	5	Cm-244	Np-239	Ra-226	Th-229	Ra-225
Health ¦Tot all nuc		1.79E-04	9.08E-05	2.35E-04	4.35E-03	1.38E-02
Effects ¦Top 5		1.74E-04	9.00E-05	2.32E-04	4.31E-03	1.38E-02
(deaths/y)¦% of total		97.0	99.2	98.7	99.7	99.9
Case# 83T; Cycle: P-T	1	Sr-90	Pu-240	Pu-240	Tc-99	Tc-99
Release: All Events	2	Cs-137	Am-241	Pu-239	I-129	I-129
	3	Pu-238	Pu-239	Sn-126	Ra-226	Ra-226
	4	Am-241	Am-243	Ra-226	Pu-239	Th-229
	5	Pu-240	Sn-126	Am-243	Sn-126	Pu-242
Health ¦Tot all nuc		1.40E-04	2.08E-06	6.54E-06	4.15E-03	1.39E-02
Effects ¦Top 5		1.39E-04	2.03E-06	6.27E-06	4.15E-03	1.39E-02
(deaths/y)¦% of total		99.9	97.7	96.1	100.0	100.0
Ratio(%): (P-T)/(Ref) ¦Tot all nuc		77.9	2.3	2.8	95.6	100.3
CUMULATIVE TOTAL HEALTH EFFECTS	1	Sr-90	Am-241	Pu-240	Tc-99	Tc-99
	2	Cs-137	Sr-90	Am-243	Pu-239	I-129
Case# 86T; Cycle: Ref	3	Cm-244	Pu-240	Pu-239	Ra-226	Ra-226
Release: All Events	4	Am-241	Am-243	Am-241	I-129	Th-229
	5	Pu-238	Cs-137	Np-239	Pu-240	Pu-239
Health ¦Tot all nuc		3.55E-02	1.19E-01	1.75E 00	3.13E 02	3.63E 04
Effects ¦Top 5		3.51E-02	1.07E-01	1.67E 00	3.09E 02	3.63E 04
(deaths) ¦% of total		99.0	90.1	95.4	98.8	100.0
Case# 83T; Cycle: P-T	1	Sr-90	Sr-90	Sr-90	Tc-99	Tc-99
Release: All Events	2	Cs-137	Cs-137	Pu-240	I-129	I-129
	3	Pu-238	Am-241	Pu-239	Ra-226	Ra-226
	4	Am-241	Pu-240	Cs-137	Pu-239	Th-229
	5	Cm-244	Pu-238	Am-241	Pu-240	Sn-126
Health ¦Tot all nuc		3.23E-02	4.38E-02	9.00E-02	2.92E 02	3.66E 04
Effects ¦Top 5		3.23E-02	4.35E-02	8.38E-02	2.91E 02	3.65E 04
(deaths) ¦% of total		100.0	99.4	93.5	99.9	100.0
Ratio(%): (P-T)/(Ref) ¦Tot all nuc		91.1	36.8	5.1	93.2	100.8

The quantitative dominance of Type A waste is evident in these results, as well as the almost unique roles of ^{99}Tc and ^{129}I in the later years. When compared with tables addressing rates at specific times, the cumulative tables carry forward in somewhat better perspective the doses and effects attributable to the highly radioactive (and shortlived) fission products such as ^{90}Sr and ^{137}Cs.

Note that for the Los Medanos region and the parameters selected for this risk analysis task, the nonspecific health effect rate corresponds closely to the zonal health effect rate after a few tens of thousands of years.

Table 4.8 lists results for the total (A + B) inventory, with the nuclides listed by rank according to peak health effects. The results in this table also represent the Type A waste alone. The most significant nuclides, based on total cumulative effects over 1 million years, appear in Table 4.9. The table clearly shows the overwhelming contributions made by ^{99}Tc and ^{129}I, which are not removed through actinide partitioning. The slight indicated increase in total P-T deaths over Ref deaths is due to the initial inventory variances resulting from relative burnup explained earlier.

Table 4.8. Most significant radionuclides ranked by maximum health effect (death) rate; waste: A+B (total)

	Reference Cycle Case# 86T			P - T Cycle Case# 83T		
RANK	NUCLIDE	MAXIMUM DEATHS/y	TIME (y)	NUCLIDE	MAXIMUM DEATHS/y	TIME (y)
1	Tc-99	9.38E-02	300000	Tc-99	9.58E 02	300000
2	I-129	3.64E-03	500000	I-129	3.64E-03	500000
3	Ra-226	6.19E-04	300000	Sr-90	5.15E-04	5
4	Sr-90	5.04E-04	5	Cs-137	6.38E-05	40
5	Pu-239	2.07E-04	30000	Ra-226	3.08E-05	300000
6	Pu-240	9.77E-05	20000	Pu-239	4.23E-06	30000
7	Am-243	7.92E-05	20000	Sn-126	1.61E-06	200000
8	Cs-137	6.15E-05	40	Pu-238	9.54E-07	200
9	Th-229	6.08E-05	700000	Am-241	8.88E-07	600
10	Am-241	5.46E-05	600			

Table 4.9. Most significant radionuclides ranked by 1 million years' total cumulative health effects; waste: A+B (total)

	Reference Cycle Case# 86T		P – T Cycle Case# 83T	
RANK	NUCLIDE	INTEGRATED EFFECTS (deaths)	NUCLIDE	INTEGRATED EFFECTS (deaths)
1	Tc-99	33000	Tc-99	33700
2	I-129	2880	I-129	2880
3	Ra-226	339	Ra-226	17
4	Th-229	50	Th-229	0.6
5	Pu-239	20	Sn-126	0.4
6	Np-237	9	Pu-239	0.4
7	Ra-225	8	Pu-242	0.4
8	Pu-242	4	Th-230	0.2
9	Th-230	4	Np-237	0.1
10	Pu-240	2	Ra-225	0.1
Total All Nuclides		36300		36600

The total damage, in dollars, and marginal damage per gram of initial inventory for damages accrued over the 1 million-year study period is given in Table 4.10 by nuclide decay group. It is particularly useful to consider nuclide decay groups as well as individual nuclides when attempting to isolate the most culpable source for various effects. To illustrate this point, the humble appearance of ^{226}Ra in the initial inventory (A + B) is only 9.2 x 10^{-3} g, which in no way interferes with its subsequent success in making the top five. The key, of course, is to study the source parent nuclides and their presence in the original repository waste.

The greatest marginal damages per gram result from Group No. 11, ^{99}Tc, and Group No. 13, ^{129}I, with typical values (total waste) of \$59.50/g and \$21.00/g, respectively. After these two nuclides, Group No. 4, which contains ^{226}Ra, gives an average marginal damage of \$5.28/g. The other nuclide groups have significantly lower marginal damages per gram—only pennies or a fraction of a penny. The total

Table 4.10. Total damage and average marginal damage by nuclide decay groups during 1 million years (a)

WASTE TYPE	TOTAL DAMAGES,$	INITIAL MASS,gm	AVE MARGINAL DAMAGE,$/g	TOTAL DAMAGES,$	INITIAL MASS,gm	AVE MARGINAL DAMAGE,$/g	TOTAL DAMAGES,$	INITIAL MASS,gm	AVE MARGINAL DAMAGE,$/g
	GROUP# 01			GROUP# 02			GROUP# 03		
	Cm-246	Pu-242		Cm-244	Pu-240		Cm-245 Np-237	Pu-241 Th-229	Am-241 Ra-225
A									
REF	7.57E 05	1.61E 07	4.71E-02	5.40E 05	8.40E 07	6.43E-03	1.66E 07	1.88E 08	8.83E-02
P-T	6.22E 04	1.33E 06	4.68E-02	1.71E 04	2.64E 06	6.47E-03	1.54E 05	1.74E 06	8.85E-02
B									
REF	2.46E 05	5.28E 06	4.66E-02	7.69E 04	1.18E 07	6.49E-03	8.76E 05	9.93E 06	8.82E-02
P-T	2.93E 04	6.27E 05	4.67E-02	8.09E 03	1.24E 06	6.50E-03	7.26E 04	8.22E 05	8.83E-02
TOTAL									
REF	1.00E 06	2.13E 07	4.69E-02	6.17E 05	9.57E 07	6.45E-03	1.75E 07	1.98E 08	8.82E-02
P-T	9.16E 04	1.96E 06	4.68E-02	2.52E 04	3.89E 06	6.48E-03	2.27E 05	2.57E 06	8.83E-02
Ratio (%): (P-T)/(Ref)									
TOTAL	9.2	9.2	99.8	4.1	4.1	100.5	1.3	1.3	100.1
	GROUP# 04			GROUP# 05			GROUP# 06		
	Am-242m Th-230	Cm-242 Ra-226	Pu-238 Pb-210	Am-243	Np-239	Pu-239	C-14		
A									
REF	6.94E 07	1.32E 07	5.26E 00	5.59E 06	2.18E 08	2.57E-02	6.15E-01	1.95E 04	3.15E-05
P-T	3.03E 06	5.79E 05	5.23E 00	6.97E 04	3.47E 06	2.01E-02	1.23E 00	3.90E 04	3.15E-05
B									
REF	2.03E 07	3.75E 06	5.42E 00	3.23E 05	1.66E 07	1.94E-02	1.29E 00	4.08E 04	3.16E-05
P-T	1.42E 06	2.73E 05	5.20E 00	3.30E 04	1.64E 06	2.01E-02	1.29E 00	4.08E 04	3.16E-05
TOTAL									
REF	8.97E 07	1.70E 07	5.28E 00	5.92E 06	2.34E 08	2.53E-02	1.91E 00	6.03E 04	3.16E-05
P-T	4.45E 06	8.52E 05	5.22E 00	1.03E 05	5.12E 06	2.01E-02	2.52E 00	7.98E 04	3.16E-05
Ratio (%): (P-T)/(Ref)									
TOTAL	5.0	5.0	98.9	1.7	2.2	79.5	131.9	132.3	100.0
	GROUP# 07			GROUP# 08			GROUP# 09		
	Ni-59			Sr-90			Zr-93		
A									
REF	2.40E 00	2.13E 04	1.13E-04	8.93E 03	8.09E 07	1.10E-04	1.08E 03	1.21E 08	8.95E-06
P-T	2.40E 00	2.13E 04	1.13E-04	9.10E 03	8.24E 07	1.10E-04	1.11E 03	1.23E 08	9.02E-06
B									
REF	1.44E 03	1.28E 07	1.13E-04	9.45E 00	8.65E 04	1.10E-04	9.03E 01	1.01E 07	8.94E-06
P-T	1.44E 03	1.28E 07	1.13E-04	9.71E 00	8.81E 04	1.10E-04	9.04E 01	1.01E 07	8.95E-06
TOTAL									
REF	1.44E 03	1.28E 07	1.13E-04	8.93E 03	8.10E 07	1.10E-04	1.17E 03	1.31E 08	8.95E-06
P-T	1.44E 03	1.28E 07	1.13E-04	9.10E 03	8.25E 07	1.10E-04	1.20E 03	1.33E 08	9.02E-06
Ratio (%): (P-T)/(Ref)									
TOTAL	100.0	100.0	100.0	101.9	101.9	100.0	102.6	101.5	100.8

Table 4.10 (cont'd)

WASTE TYPE	TOTAL DAMAGES, $	INITIAL MASS, gm	AVE MARGINAL DAMAGE, $/g	TOTAL DAMAGES, $	INITIAL MASS, gm	AVE MARGINAL DAMAGE, $/g	TOTAL DAMAGES, $	INITIAL MASS, gm	AVE MARGINAL DAMAGE, $/g
	GROUP# 10			GROUP# 11			GROUP# 12		
	Mo-93			Tc-99			Sn-126		
A									
REF	5.35E-02	7.44E 01	7.19E-04	8.56E 09	1.44E 08	5.94E 01	9.88E 04	5.43E 06	1.82E-02
P-T	5.35E-02	7.44E 01	7.19E-04	8.75E 09	1.47E 08	5.95E 01	1.04E 05	5.71E 06	1.82E-02
B									
REF	9.01E 00	4.29E 03	2.10E-03	9.84E 06	1.65E 05	5.96E 01	1.05E 02	5.80E 03	1.82E-02
P-T	9.01E 00	4.29E 03	2.10E-03	1.00E 07	1.69E 05	5.94E 01	1.11E 02	6.10E 03	1.82E-02
TOTAL									
REF	9.06E 00	4.36E 03	2.08E-03	8.57E 09	1.44E 08	5.95E 01	9.88E 04	5.44E 06	1.82E-02
P-T	9.06E 00	4.36E 03	2.08E-03	8.75E 09	1.47E 08	5.96E 01	1.04E 05	5.72E 06	1.82E-02
Ratio (%): (P-T)/(Ref)									
TOTAL	100.0	100.0	100.0	102.1	102.1	100.1	105.3	105.1	100.0
	GROUP# 13			GROUP# 14			GROUP# 15		
	I-129			Cs-135			Cs-137		
A									
REF	7.50F 08	3.58E 07	2.10E 01	7.44E 03	7.49E 07	9.93E-05	1.79E 03	2.16E 08	8.30E-06
P-T	7.50E 08	3.58E 07	2.10E 01	7.04E 03	7.09E 07	9.93E-05	1.85E 03	2.23E 08	8.30E-06
B									
REF	8.25E 02	3.93E 01	2.10E 01	7.94E 00	8.00E 04	9.93E-05	1.91E 00	2.31E 05	8.29E-06
P-T	8.50E 02	4.05E 01	2.10E 01	7.52E 00	7.58E 04	9.92E-05	1.98E 00	2.38E 05	8.31E-06
TOTAL									
REF	7.50E 08	3.58E 07	2.10E 01	7.44E 03	7.50E 07	9.92E-05	1.79E 03	2.16E 08	8.31E-06
P-T	7.50E 08	3.58E 07	2.10E 01	7.05E 03	7.10E 07	9.92E-05	1.85E 03	2.23E 08	8.30E-06
Ratio (%): (P-T)/(Ref)									
TOTAL	100.0	100.0	100.0	94.8	94.7	100.0	103.4	103.2	99.9
	TOTAL ALL GROUPS								
A									
REF	9.40E 09	1.20E 09	7.86E 00						
P-T	9.50E 09	6.99E 08	1.36E 01						
B									
REF	3.17E 07	7.11E 07	4.46E-01						
P-T	1.16E 07	2.81E 07	4.13E-01						
TOTAL									
REF	9.43E 09	1.27E 09	7.44E 00						
P-T	9.51E 09	7.26E 08	1.31E 01						
Ratio (%): (P-T)/(Ref)									
TOTAL	100.8	57.2	176.1						

(a) Risk (probabilistic) cases; all release events; high population of EPA78 used; zero discount.

(A + B) inventory corresponds to an average marginal damage per gram of $7.99.

The total undiscounted damage over a 1 million-year period for either the Ref or P-T cycle (Table 4.10), when normalized to the total electrical generation represented by the accumulated waste inventory (Sect. 3.3.1), becomes only 0.2 mil/kW-hr(e).

As an additional step in identifying the total overall effects caused by the presence of a particular radionuclide in the initial inventory, Logan developed, and reported in EPA78, a method for attributing effects incurred over a long period from daughter nuclides to their precursor nuclides which were present in the initial inventory. This method is of particular interest to those studying the original nuclide inventory mix from the standpoint of weighing long-term damages against costs and the feasibility of reducing such damages through modification of the mix or disposal method.

The simple attribution scheme used is to assign the damages for each radionuclide to those precursors at or above its decay series, in proportion to the mass fraction of the precursors initially present. This method is valid for the zero discount rate, which permits present values to be assigned to damages beyond a few hundred years.

Tables 4.11 and 4.13 (total Ref and P-T wastes, respectively) list each nuclide and its initial inventory in sequence vertically by decay group. The attribution factor corresponding to each horizontally listed precursor nuclide appears in the row to the right of the nuclide name and inventory. For example, using Table 4.11, ^{242m}Am, which heads Group No. 4, has only one "precursor" itself; therefore, under the horizontally listed nuclides, only ^{242m}Am shows a value. On the other hand, ^{226}Ra can attribute 88.9% of its effects to ^{238}Pu in the initial inventory, 6.4% to ^{242}Cm, and 4.7% to ^{242m}Am.

Tables 4.12 and 4.14 (total Ref and P-T wastes, respectively) use the calculated attribution factors to fully attribute damages caused by offspring and the precursor itself to the precursor in the initial waste inventory being studied. The values in the table are measured in dollars, obtained from health effects using the approach explained in Sect. 3.1.2.2.

Table 4.11. Attribution factors; waste: A+B; cycle: Ref (a)

Decay Group	Nuclide	Initial Inventory (grams)	Attribution Factors to Precursors in Group (percent)					
1			CM-246	PU-242				
	CM-246	2.64E+05	100.0	0.0				
	PU-242	2.11E+07	1.2	98.8				
2			CM-244	PU-240				
	CM-244	4.84E+07	100.0	0.0				
	PU-240	4.73E+07	50.6	49.4				
3			CM-245	PU-241	AM-241	NP-237	TH-229	RA-225
	CM-245	6.07E+05	100.0	0.0	0.0	0.0	0.0	0.0
	PU-241	2.67E+07	2.2	97.8	0.0	0.0	0.0	0.0
	AM-241	9.61E+07	0.5	21.6	77.9	0.0	0.0	0.0
	NP-237	7.45E+07	0.3	13.5	48.6	37.6	0.0	0.0
	TH-229	4.06E+00	0.3	13.5	48.6	37.6	0.0	0.0
	RA-225	5.54E-06	0.3	13.5	48.6	37.6	0.0	0.0
4			AM-242M	CM-242	PU-238	TH-230	RA-226	PB-210
	AM-242M	8.02E+05	100.0	0.0	0.0	0.0	0.0	0.0
	CM-242	1.09E+06	42.4	57.6	0.0	0.0	0.0	0.0
	PU-238	1.51E+07	4.7	6.4	88.9	0.0	0.0	0.0
	TH-230	1.88E+03	4.7	6.4	88.9	0.0	0.0	0.0
	RA-226	9.21E-03	4.7	6.4	88.9	0.0	0.0	0.0
	PB-210	4.11E-05	4.7	6.4	88.9	0.0	0.0	0.0
5			AM-243	NP-239	PU-239			
	AM-243	1.68E+08	100.0	0.0	0.0			
	NP-239	3.19E+01	100.0	0.0	0.0			
	PU-239	6.61E+07	71.8	0.0	28.2			
6			C-14					
	C-14	6.03E+04	100.0					
7			NI-59					
	NI-59	1.28E+07	100.0					
8			SR-90					
	SR-90	8.10E+07	100.0					
9			ZR-93					
	ZR-93	1.31E+08	100.0					
10			MO-93					
	MO-93	4.36E+03	100.0					
11			TC-99					
	TC-99	1.44E+08	100.0					
12			SN-126					
	SN-126	5.44E+06	100.0					
13			I-129					
	I-129	3.58E+07	100.0					
14			CS-135					
	CS-135	7.50E+07	100.0					
15			CS-137					
	CS-137	2.16E+08	100.0					

(a) Analysis = All Ref ; Release = All

Table 4.12. Attribution of cumulative 1 million years' total damages to initial radionuclides in inventory; waste: A+B; cycle: Ref (a)

Decay Group	Nuclide	Total Damages ($)	Attribution of Damages to Precursors (dollars)					
1			CM-246	PU-242				
	CM-246	8.39E+02	8.39E+02	0.0				
	PU-242	1.00E+06	1.24E+04	9.88E+05				
	[Total]		1.32E+04	9.88E+05				
2			CM-244	PU-240				
	CM-244	4.18E+02	4.18E+02	0.0				
	PU-240	6.16E+05	3.12E+05	3.04E+05				
	[Total]		3.12E+05	3.04E+05				
3			CM-245	PU-241	AM-241	NP-237	TH-229	RA-225
	CM-245	3.05E+03	3.05E+03	0.0	0.0	0.0	0.0	0.0
	PU-241	1.21E+02	2.69E+00	1.18E+02	0.0	0.0	0.0	0.0
	AM-241	3.31E+04	1.63E+02	7.16E+03	2.58E+04	0.0	0.0	0.0
	NP-237	2.42E+06	7.42E+03	3.26E+05	1.18E+06	9.11E+05	0.0	0.0
	TH-229	1.29E+07	3.96E+04	1.74E+06	6.26E+06	4.86E+06	0.0	0.0
	RA-225	2.14E+06	6.56E+03	2.89E+05	1.04E+06	8.06E+05	0.0	0.0
	[Total]		5.68E+04	2.36E+06	8.50E+06	6.57E+06	0.0	0.0
4			AM-242M	CM-242	PU-238	TH-230	RA-226	PB-210
	AM-242M	6.64E+01	6.64E+01	0.0	0.0	0.0	0.0	0.0
	CM-242	3.79E+00	1.61E+00	2.18E+00	0.0	0.0	0.0	0.0
	PU-238	1.65E+03	7.79E+01	1.06E+02	1.47E+03	0.0	0.0	0.0
	TH-230	9.77E+05	4.61E+04	6.27E+04	8.68E+05	1.08E+02	0.0	0.0
	RA-226	8.82E+07	4.16E+06	5.66E+06	7.84E+07	9.76E+03	0.0	0.0
	PB-210	5.48E+05	2.59E+04	3.51E+04	4.87E+05	6.06E+01	0.0	0.0
	[Total]		4.23E+06	5.76E+06	7.97E+07	9.93E+03	0.0	0.0
5			AM-243	NP-239	PU-239			
	AM-243	5.28E+05	5.28E+05	0.0	0.0			
	NP-239	4.94E+04	4.94E+04	0.0	0.0			
	PU-239	5.34E+06	3.83E+06	0.0	1.51E+06			
	[Total]		4.41E+06	0.0	1.51E+06			
6			C-14					
	C-14	1.91E+00	1.91E+00					
7			NI-59					
	NI-59	1.44E+03	1.44E+03					
8			SR-90					
	SR-90	8.93E+03	8.93E+03					
9			ZR-93					
	ZR-93	1.17E+03	1.17E+03					
10			MO-93					
	MO-93	9.06E+00	9.06E+00					
11			TC-99					
	TC-99	8.57E+09	8.57E+09					
12			SN-126					
	SN-126	9.88E+04	9.88E+04					
13			I-129					
	I-129	7.50E+08	7.50E+08					
14			CS-135					
	CS-135	7.44E+03	7.44E+03					
15			CS-137					
	CS-137	1.79E+03	1.79E+03					

(a) Analysis = Prob ; Release = All

Table 4.13. Attribution factors; waste: A+B; cycle: P-T (a)

Decay Group	Nuclide	Initial Inventory (grams)	Attribution Factors to Precursors in Group (percent)					
1			CM-246	PU-242				
	CM-246	4.49E+04	100.0	0.0				
	PU-242	1.91E+06	2.3	97.7				
2			CM-244	PU-240				
	CM-244	6.74E+05	100.0	0.0				
	PU-240	3.22E+06	17.3	82.7				
3			CM-245	PU-241	AM-241	NP-237	TH-229	RA-225
	CM-245	1.05E+05	100.0	0.0	0.0	0.0	0.0	0.0
	PU-241	1.67E+06	5.9	94.1	0.0	0.0	0.0	0.0
	AM-241	2.74E+05	5.1	81.5	13.4	0.0	0.0	0.0
	NP-237	5.21E+05	4.1	65.0	10.7	20.3	0.0	0.0
	TH-229	3.66E+00	4.1	65.0	10.7	20.3	0.0	0.0
	RA-225	6.63E-06	4.1	65.0	10.7	20.3	0.0	0.0
4			AM-242M	CM-242	PU-238	TH-230	RA-226	PB-210
	AM-242M	3.36E+03	100.0	0.0	0.0	0.0	0.0	0.0
	CM-242	4.84E+03	41.0	59.0	0.0	0.0	0.0	0.0
	PU-238	8.44E+05	0.4	0.6	99.0	0.0	0.0	0.0
	TH-230	1.07E+03	0.4	0.6	98.9	0.1	0.0	0.0
	RA-226	7.15E-03	0.4	0.6	98.9	0.1	0.0	0.0
	PB-210	5.49E-05	0.4	0.6	98.9	0.1	0.0	0.0
5			AM-243	NP-239	PU-239			
	AM-243	5.02E+05	100.0	0.0	0.0			
	NP-239	1.28E+00	100.0	0.0	0.0			
	PU-239	4.61E+06	9.8	0.0	90.2			
6			C-14					
	C-14	7.98E+04	100.0					
7			NI-59					
	NI-59	1.28E+07	100.0					
8			SR-90					
	SR-90	8.25E+07	100.0					
9			ZR-93					
	ZR-93	1.33E+08	100.0					
10			MO-93					
	MO-93	4.36E+03	100.0					
11			TC-99					
	TC-99	1.47E+08	100.0					
12			SN-126					
	SN-126	5.72E+06	100.0					
13			I-129					
	I-129	3.58E+07	100.0					
14			CS-135					
	CS-135	7.10E+07	100.0					
15			CS-137					
	CS-137	2.23E+08	100.0					

(a) Analysis = All P-T ; Release = All

Table 4.14. Attribution of cumulative 1 million years' total damages to initial radionuclides in inventory; waste: A+B cycle: P-T (a)

Decay Group	Nuclide	Total Damages ($)	Attribution of Damages to Precursors (dollars)					
1			CM-246	PU-242				
	CM-246	1.42E+02	1.42E+02	0.0				
	PU-242	9.14E+04	2.10E+03	8.93E+04				
			2.24E+03	8.93E+04				
2			CM-244	PU-240				
	CM-244	5.83E+00	5.83E+00	0.0				
	PU-240	2.52E+04	4.36E+03	2.08E+04				
			4.37E+03	2.08E+04				
3			CM-245	PU-241	AM-241	NP-237	TH-229	RA-225
	CM-245	5.29E+02	5.29E+02	0.0	0.0	0.0	0.0	0.0
	PU-241	1.97E+01	1.17E+00	1.85E+01	0.0	0.0	0.0	0.0
	AM-241	8.85E+02	4.54E+01	7.21E+02	1.18E+02	0.0	0.0	0.0
	NP-237	3.13E+04	1.28E+03	2.03E+04	3.34E+03	6.35E+03	0.0	0.0
	TH-229	1.66E+05	6.78E+03	1.08E+05	1.77E+04	3.37E+04	0.0	0.0
	RA-225	2.77E+04	1.13E+03	1.80E+04	2.95E+03	5.62E+03	0.0	0.0
			9.77E+03	1.47E+05	2.41E+04	4.56E+04	0.0	0.0
4			AM-242M	CM-242	PU-238	TH-230	RA-226	PB-210
	AM-242M	2.78E-01	2.78E-01	0.0	0.0	0.0	0.0	0.0
	CM-242	1.62E-02	0.0	0.0	0.0	0.0	0.0	0.0
	PU-238	7.89E+01	3.11E-01	4.48E-01	7.81E+01	0.0	0.0	0.0
	TH-230	4.85E+04	1.91E+02	2.75E+02	4.80E+04	6.08E+01	0.0	0.0
	RA-226	4.38E+06	1.72E+04	2.48E+04	4.33E+06	5.49E+03	0.0	0.0
	PB-210	2.72E+04	1.07E+02	1.54E+02	2.69E+04	3.41E+01	0.0	0.0
			1.75E+04	2.53E+04	4.41E+06	5.59E+03	0.0	0.0
5			AM-243	NP-239	PU-239			
	AM-243	1.58E+03	1.58E+03	0.0	0.0			
	NP-239	1.48E+02	1.48E+02	0.0	0.0			
	PU-239	1.01E+05	9.92E+03	0.0	9.11E+04			
			1.16E+04	0.0	9.11E+04			
6			C-14					
	C-14	2.52E+00	2.52E+00					
7			NI-59					
	NI-59	1.44E+03	1.44E+03					
8			SR-90					
	SR-90	9.10E+03	9.10E+03					
9			ZR-93					
	ZR-93	1.20E+03	1.20E+03					
10			MO-93					
	MO-93	9.06E+00	9.06E+00					
11			TC-99					
	TC-99	8.75E+09	8.75E+09					
12			SN-126					
	SN-126	1.04E+05	1.04E+05					
13			I-129					
	I-129	7.50E+08	7.50E+08					
14			CS-135					
	CS-135	7.05E+03	7.05E+03					
15			CS-137					
	CS-137	1.85E+03	1.85E+03					

(a) Analysis = Prob ; Release = All

A natural further extension of damage association suggests the assignment of attributed damages to the chemical elements in the inventories. Thus, chemical separation methods may be related more easily to damage reduction. Table 4.15 does this for the total waste released probabilistically. Technetium bears a significantly large burden, 90.9% and 92.0% for Ref and P-T inventories, respectively, followed by iodine at about 8% for both categories. Plutonium follows as a poor third with 0.9% and 0.05%. Removal of much of the actinides through P-T reduces by three orders of magnitude the damage contribution from these elements. However, this reduction is only a small unregistered perturbation to the total damages produced by the fission products.

Table 4.15. Attribution of 1 million years' damages to initial elements in inventory; risk (probabilistic) analysis; waste: A + B

		Reference Cycle Case# 86			P - T Cycle Case# 83		
	ELEMENT	TOTAL DAMAGES ($)	PERCENTAGE OF CATEGORY	PERCENTAGE OF TOTAL	TOTAL DAMAGES ($)	PERCENTAGE OF CATEGORY	PERCENTAGE OF TOTAL
FISSION AND ACTIVATION PRODUCTS	C	1.91E 00	--	-	2.52E 00	--	--
	Ni	1.44E 03	1.55E-05	1.53E-05	1.44E 03	1.52E-05	1.51E-05
	Sr	8.93E 03	9.58E-05	9.47E-05	9.10E 03	9.58E-05	9.57E-05
	Zr	1.17E 03	1.26E-05	1.24E-05	1.20E 03	1.26E-05	1.26E-05
	Mo	9.06E 00	--	--	9.06E 00	--	--
	Tc	8.57E 09	92.0	90.9	8.75E 09	92.1	92.0
	Sn	9.88E 04	1.06E-03	1.05E-03	1.04E 05	1.09E-03	1.09E-03
	I	7.50E 08	8.05	7.95	7.50E 08	7.9	7.9
	Cs	9.23E 03	9.90E-05	9.79E-05	8.90E 03	9.37E-05	9.36E-05
	Subtotal	9.32E 09	100.0	98.8	9.50E 09	100.0	99.95
ACTINIDES	Th	9.93E 03	8.63E-03	1.05E-04	5.59E 03	0.1	5.88E-05
	Np	6.57E 06	5.71	0.07	4.56E 04	0.9	4.79E-04
	Pu	8.49E 07	73.8	0.9	4.76E 06	96.9	0.05
	Am	1.71E 07	14.9	0.18	5.32E 04	1.1	5.59E-04
	Cm	6.14E 06	5.34	0.06	4.17E 04	0.8	4.38E-04
	Subtotal	1.15E 08	100.0	1.2	4.91E 06	100.0	0.05
	Total	9.43E 09		100.0	9.51E 09		100.0

Table 4.16 compares the damages resulting directly from each nuclide with the total damages attributed to its presence and quantity in the initial inventory. Nuclides again are listed by group, and the

Table 4.16. Comparison of 1 million years' total damages from direct nuclide effects and from attribution of effects to the initial inventory of nuclides (risk analysis cases)

Decay Group	Nuclide	Reference Cycle Case# 86T Direct Damages($)	Reference Cycle Case# 86T Initial Inventory Attributed Damages($)	P - T Cycle Case# 83T Direct Damages($)	P - T Cycle Case# 83T Initial Inventory Attributed Damages($)
1	Cm 246	8.39E 02	1.32E 04	1.42E 02	2.24E 03
	Pu-242	1.00E 06	9.88E 05	9.14F 04	8.93E 04
2	Cm-244	4.18E 02	3.12E 05	5.83E 00	4.37E 03
	Pu-240	6.16E 05	3.04F 05	2.52E 04	2.08E 04
3	Cm-245	3.05E 03	5.68E 04	5.29E 02	9.77E 03
	Pu-241	1.21E 02	2.36E 06	1.97E 01	1.47E 05
	Am-241	3.31E 04	8.50E 06	8.85E 02	2.41E 04
	Np-237	2.42E 06	6.57E 06	3.13E 04	4.56E 04
	Th-229	1.29E 07	0.0	1.66E 05	0.0
	Ra-225	2.14E 06	0.0	2.77E 04	0.0
4	Am-242m	6.64E 01	4.23E 06	2.78E-01	1.75E 04
	Cm-242	3.79E 00	5.76E 06	1.62E-02	2.53E 04
	Pu-238	1.65E 03	7.97E 07	7.89E 01	4.41E 06
	Th-230	9.77E 05	9.93E 03	4.85E 04	5.59E 03
	Ra-226	8.82E 07	0.0	4.38E 06	0.0
	Pb-210	5.48E 05	0.0	2.72E 04	0.0
5	Am-243	5.28E 05	4.41E 06	1.58E 03	1.16E 04
	Np-239	4.94E 04	0.0	1.48E 02	0.0
	Pu-239	5.34E 06	1.51E 06	1.01E 05	9.11E 04
6	C-14	1.91E 00	1.91E 00	2.52E 00	2.52E 00
7	Ni-59	1.44E 03	1.44E 03	1.44E 03	1.44E 03
8	Sr-90	8.93E 03	8.93E 03	9.10E 03	9.10E 03
9	Zr-93	1.17E 03	1.17E 03	1.20E 03	1.20E 03
10	Mo-93	9.06E 00	9.06E 00	9.06E 00	9.06E 00
11	Tc-99	8.57E 09	8.57E 09	8.75E 09	8.75E 09
12	Sn-126	9.88E 04	9.88E 04	1.04E 05	1.04E 05
13	I-129	7.50E 08	7.50E 08	7.50E 08	7.50E 08
14	Cs-135	7.44E 03	7.44E 03	7.05E 03	7.05E 03
15	Cs-137	1.79E 03	1.79E 03	1.85E 03	1.85E 03
	Totals	9.43E 09	9.43E 09	9.51E 09	9.51E 09

data pertain to the total inventory probabilistic cases 86 and 83. Group Nos. 6 through 15 report the same damage for each category, but the nuclides in the five decay groups readily illustrate the usefulness of retracing decay lineage to the initial inventories. After ^{99}Tc and ^{129}I, ^{238}Pu is the serious nuclide in the inventories.

Table 4.17 lists in summary the most significant nuclides (and elements) based on the different viewpoints of direct and attributed damages. Except for the two top nuclides, there is considerable reshuffling for position, as the parent nuclides in a decay group vie for status under the attributed damage rankings.

Table 4.17. Summary of most significant radionuclides and elements, using various bases; risk analysis; waste: A+B

BASIS	INTEGRATED DAMAGES OVER 1 MILLION YEARS ($)	
	Ref Cycle	P-T Cycle
DIRECT DAMAGES (No attribution from daughters)	Tc-99	Tc-99
	I-129	I-129
	Ra-226	Ra-226
	Th-229	Th-229
	Pu-239	Sn-126
% of Total	100.0	100.0
ATTRIBUTED DAMAGES (To nuclides in initial inventory)	Tc-99	Tc-99
	I-129	I-129
	Pu-238	Pu-238
	Am-241	Pu-241
	Np-237	Sn-126
% of Total	98.8	99.9
ATTRIBUTED DAMAGES (To elements in initial inventory)	Tc	Tc
	I	I
	Pu	Pu
	Am	Sn
	Np	Am
% of Total	99.9	100.0

4.2 Consequence Analysis

A series of AMRAW runs using discrete release events is reported in this section and comprises the consequence analysis for the Risk Task.

These discrete releases, both leaching and expulsive, are postulated to occur at selected times in order to determine expected consequences and provide responses to the sometimes-legitimate "what if" query. However, in evaluating the calculated results, it is important to bear in mind that the best probability estimates assign extremely low values to the occurrence of these release events. Specifically, the probability of volcanism affecting the repository is calculated at about 10^{-12} per year and of faulting which penetrates the repository at about 10^{-7} per year.

4.2.1 Slow-release events

The first series of consequence runs calculates effects for leaching releases initiated at 1000 and 100,000 years. The leaching is caused by groundwater flow through the repository from aquifers interconnected by offset faulting. To provide upper value, conservative responses, water flow and leaching are allowed to continue indefinitely, as if no fracture healing or subsequent pathway closures due to salt dissolution or geological causes occur. For this study the Rustler formation is assumed to sustain a groundwater velocity of 1.46 m/year and the distribution coefficients,* K_d, which appear in Table 3.5. The K_d is a direct measure of the retention of a species on the porous medium through which the carrier groundwater flows. The AMRAW calculations determine the amount of each nuclide leached during a time period and then indicate release of the material as a pulse at the end of the period, thus effecting a sequence of pulses. As each pulse moves with the aquifer flow, its concentration peak broadens axially and orthogonally, largely as a function of the applicable K_d value. The concentration peaks broaden and their effective pulse velocity decreases inversely with the magnitude of K_d.

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* Ratio of the amount of species sorbed on the solid medium per unit mass of medium to amount of species remaining in the solution per unit volume of solution, cm^3/g.

In Vol. I, EPA78, the retardation factor, R_d, is calculated from

$$R_d = 1 + \frac{\rho K_d}{\varepsilon} \quad , \tag{4.1}$$

where

ρ = the bulk density of the porous medium, with a value of 2.3 g/cm³ for the site, and
ε = the solid porosity, having a value of 0.15.

The pulse velocity U can be calculated from

$$U = v_p/R_d, \tag{4.2}$$

where v_p is the pore or seepage velocity, estimated at 4.00×10^{-3} m/day.

With this, the time for arrival of each pulse at any point down-aquifer can be approximated by dividing the distance by the pulse velocity. Nuclides with K_d's near zero (^{93}Mo, ^{99}Tc, and ^{129}I) are considered to move effectively with the groundwater; therefore, for these nuclides traveling to Zone 8 (~20 km), R_d is equal to 1, U is equal to 1.46 m/year, and the approximate arrival times for their pulses is 14,000 years. Carbon-14 pulses, with a K_d of 1.40, arrive after about 300,000 years, and ^{237}Np ($K_d \sim 8.10$) at about 1.7 million years. The leading edges of these temporally distributed pulses will appear much earlier; however, it is safe to expect no significant impact in areas of interest (Zone 8), from the leaching of nuclides having K_ds greater than about 5.

The total activity at some distance (20 km for Zone 8) down-aquifer at any time of interest is described by the following general balance equation:

Activity = Σ (nuclide arrivals) - Σ (nuclide losses due to radio-decay, environmental decay, and physical movement away from the location). (4.3)

The effective "group" velocity for a nuclide's arrival at a particular point is associated with the time of arrival of the peak activity value obtained from Eq. (4.3).

A simplified version of the Duguid-Reeves transient model [ANS,EPA78] is used in AMRAW giving one-dimensional flow with two-dimensional dispersion. In this application, calculations are made one nuclide at a time, with no specific compensation for different migration rates of parent and daughter in a radionuclide chain, except where short half-lived daughter nuclides are not explicitly listed, and their effects are included with a listed parent. The two thorium, two radium, and lead isotopes are the most suited for linkage with a faster-moving parent, in this case uranium. For the Los Medanos site, however, recent information [Br80] supports a minimum realistic K_d value between 10 and 100 for uranium, and assuming that the above daughters moved at the highest uranium migration rate ($K_d = 10$), their approximate pulse peak travel time, over the 20 km to discharge in Zone 8, would be over 2 million years. Of course, if an upper-bound water velocity of some 4.5 m/year (a factor of 3 greater than used here) exists everywhere in the path length to discharge, then the above actinide daughter nuclides would peak during the 500,000 to 800,000-year time frame. To compensate conservatively for uncertainty, the water velocity used in AMRAW, 1.46 m/year, has been taken to be about seven times larger than the calculated average seepage velocity [Ky75] to the west, southwest in the Los Medanos. There is little evidence that this velocity should be further increased, yet there is a good possibility that the uranium K_d for the region could be higher than the value of 10 used in the above illustrative calculation. Any K_d value such as 40 or 50 would not only further displace daughter nuclides temporally from discharge at Malaga Bend but would essentially cancel any increased effects if the upper-bound maximum water velocity were to exist. In this regard, a K_d value of 20 is used for the radium nuclides, and this value is well within the lower limiting range of 10 to 100 for uranium.

In AMRAW, nuclide quantities moving to Zone 8 are reduced by 20% to account for discharge to brine ponds in Zone 2. The total quantity arriving is made up from the sum of the periodic incremental releases, or release pulses, occurring at the end of each leaching period. Losses due to radiological decay are included by separate calculation, and a very modest environmental decay (environmental half-life of 30,000 years) is applied after the nuclide arrives at surface environmental receptors. In Zone 8, where the leached nuclides are assumed to be totally deposited into the Pecos River near Malaga Bend, no further interzonal or out-of-region nuclide movement is allowed. For the present model, this method permits simpler accounting for nuclides and their effects; however, because dilution and clean-out from normal river and annual floodwater flow are disregarded, it exaggerates the dose rates and effects presented under both Zone 8 and nonspecific. The latter is affected because of the regional concentration of agriculture in the zone.

Table 4.18 gives the five most significant nuclides based on dose rates for all zones, nonspecific, and total at various times and, in the final section, the most significant nuclides based on cumulative dose. The nuclides that appear in the tables conform with expected arrival times derived from the rough calculations presented earlier. As has been noted earlier, the predominant ^{99}Tc and ^{129}I are not removed through P-T; therefore, the Ref and P-T values are essentially the same as those for both inventories.

Figure 4.1 presents curves describing the dose rates with time for Zone 8 and nonspecific. The discontinuities in the curves result from changes in time increment size used by AMRAW, namely, 1000-year increments out to 10,000, 10,000-year increments out to 100,000, and 100,000-year increments thereafter. Because the leached materials are accumulated by AMRAW during the leach time increment and are not released for movement until the end of the period, the graphical presentation amplifies these discontinuities. After the group dose rates peak, at about 300,000 years, dose rate diminution corresponds to the combined effects of radiological plus environmental decay, retarded only by new material arriving through subsequent, continued leaching.

A discrete leach incident initiated at 10^5 years is described by the curves of Fig. 4.2, and its effects do not differ substantially from the incident initiated at 1000 years.

Table 4.18. Most significant radionuclides at selected times based on all health effects; consequence (leaching) cases; waste type: A + B (total)

Case and variable identification		Order	Time, y 10**4	5x10**4	10**5	5x10**5	10**6
ZONAL HEALTH EFFECT RATE		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
		2	I-129	I-129	I-129	I-129	I-129
Case# 42T; Cycle: Ref		3	Mo-93	Mo-93(a)	Mo-93(a)	C-14 (a)	Np-237(a)
Release: Leaching		4					
at 1000 years		5					
Health	Tot all nuc		3.51E-12	9.15E-01	8.73E-01	1.81E 00	5.15E-01
Effects	Top 5		3.51E-12	9.15E-01	8.73E-01	1.81E 00	5.15E-01
(deaths/y)	% of total		100.0	100.0	100.0	100.0	100.0
Case# 39T; Cycle: P-T		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
Release: Leaching		2	I-129	I-129	I-129	I-129	I-129
at 1000 years		3	Mo-93	Mo-93(a)	Mo-93(a)	C-14 (a)	Np-237(a)
		4					
		5					
Health	Tot all nuc		3.75E-12	9.38E-01	8.88E-01	1.85E 00	5.19E-01
Effects	Top 5		3.75E-12	9.38E-01	8.88E-01	1.85E 00	5.19E-01
(deaths/y)	% of total		100.0	100.0	100.0	100.0	100.0
Ratio(%): (P-T)/(Ref)							
	Tot all nuc		106.8	102.5	101.8	102.1	100.1
NONSPECIFIC HEALTH EFFECT RATE		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
		2	I-129	I-129	I-129	I-129	I-129
Case# 42T; Cycle: Ref		3	Mo-93	Mo-93(a)	Mo-93(a)	C-14 (a)	Np-237(a)
Release: Leaching		4					
at 1000 years		5					
Health	Tot all nuc		3.68E-12	9.96E-01	9.15E-01	1.88E 00	4.04E-01
Effects	Top 5		3.68E-12	9.96E 03	9.15E-01	1.88E 00	4.04E-01
(deaths/y)	% of total		100.0	100.0	100.0	100.0	100.0
Case# 39T; Cycle: P-T		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
Release: Leaching		2	I-129	I-129	I-129	I-129	I-129
at 1000 years		3	Mo-93	Mo-93(a)	Mo-93(a)	C-14 (a)	Np-237(a)
		4					
		5					
Health	Tot all nuc		3.75E-12	1.02E 00	9.35E-01	1.92E 00	4.12E-01
Effects	Top 5		3.75E-12	1.02E 00	9.35E-01	1.92E 00	4.12E-01
(deaths/y)	% of total		100.0	100.0	100.0	100.0	100.0
Ratio(%): (P-T)/(Ref)							
	Tot all nuc		102.0	102.7	102.1	102.0	101.9

Table 4.18 (cont'd)

Case and variable identification		Order	Time, y 10**4	5x10**4	10**5	5x10**5	10**6
TOTAL HEALTH EFFECT RATE		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
		2	I-129	I-129	I-129	I-129	I-129
Case# 42T; Cycle: Ref		3	Mo-93	Mo-93(a)	Mo-93(a)	C-14 (a)	Np-237(a)
Release: Leaching		4					
at 1000 years		5					
Health	Tot all nuc		7.15E-12	1.91E 00	1.79E 00	3.69E 00	9.19E-01
Effects	Top 5		7.15E-12	1.91E 00	1.79E 00	3.69E 00	9.19E-01
(deaths/y)	% of total		100.0	100.0	100.0	100.0	100.0
Case# 39T; Cycle: P-T		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
Release: Leaching		2	I-129	I-129	I-129	I-129	I-129
at 1000 years		3	Mo-93	Mo-93(a)	Mo-93(a)	C-14 (a)	Np-237(a)
		4					
		5					
Health	Tot all nuc		7.35E-12	1.96E 00	1.82E 00	3.77E 00	9.31E-01
Effects	Top 5		7.35E-12	1.96E-02	1.82E 00	3.77E 00	9.31E-01
(deaths/y)	% of total		100.0	100.0	100.0	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc		102.7	102.6	101.9	102.2	102.3
CUMULATIVE TOTAL HEALTH EFFECTS		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
		2	I-129	I-129	I-129	I-129	I-129
Case# 42T; Cycle: Ref		3	Mo-93	Mo-93(a)	Mo-93(a)	Mo-93(a)	Mo-93(a)
Release: Leaching		4				C-14 (a)	C-14 (a)
at 1000 years		5					Np-237(a)
Health	Tot all nuc		7.15E-09	6.19E 04	1.56E 05	1.96E 06	2.70E 06
Effects	Top 5		7.15E-09	6.19E 04	1.56E 05	1.86E 06	2.70E 06
(deaths)	% of total		100.0	100.0	100.0	100.0	100.0
Case# 39T; Cycle: P-T		1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
Release: Leaching		2	I-129	I-129	I-129	I-129	I-129
at 1000 years		3	Mo-93	Mo-93(a)	Mo-93(a)	Mo-93(a)	Mo-93(a)
		4				C-14 (a)	C-14 (a)
		5					Np-237(a)
Health	Tot all nuc		7.35E-09	6.35E 04	1.60E 05	1.90E 06	2.75E 06
Effects	Top 5		7.35E-09	6.35E 04	1.60E 05	1.90E 06	2.75E 06
(deaths)	% of total		100.0	100.0	100.0	100.0	100.0
Ratio(%): (P-T)/(Ref)	Tot all nuc		102.7	102.5	102.2	102.1	102.0

(a) Less than 1 % of last non-footnoted nuclide.

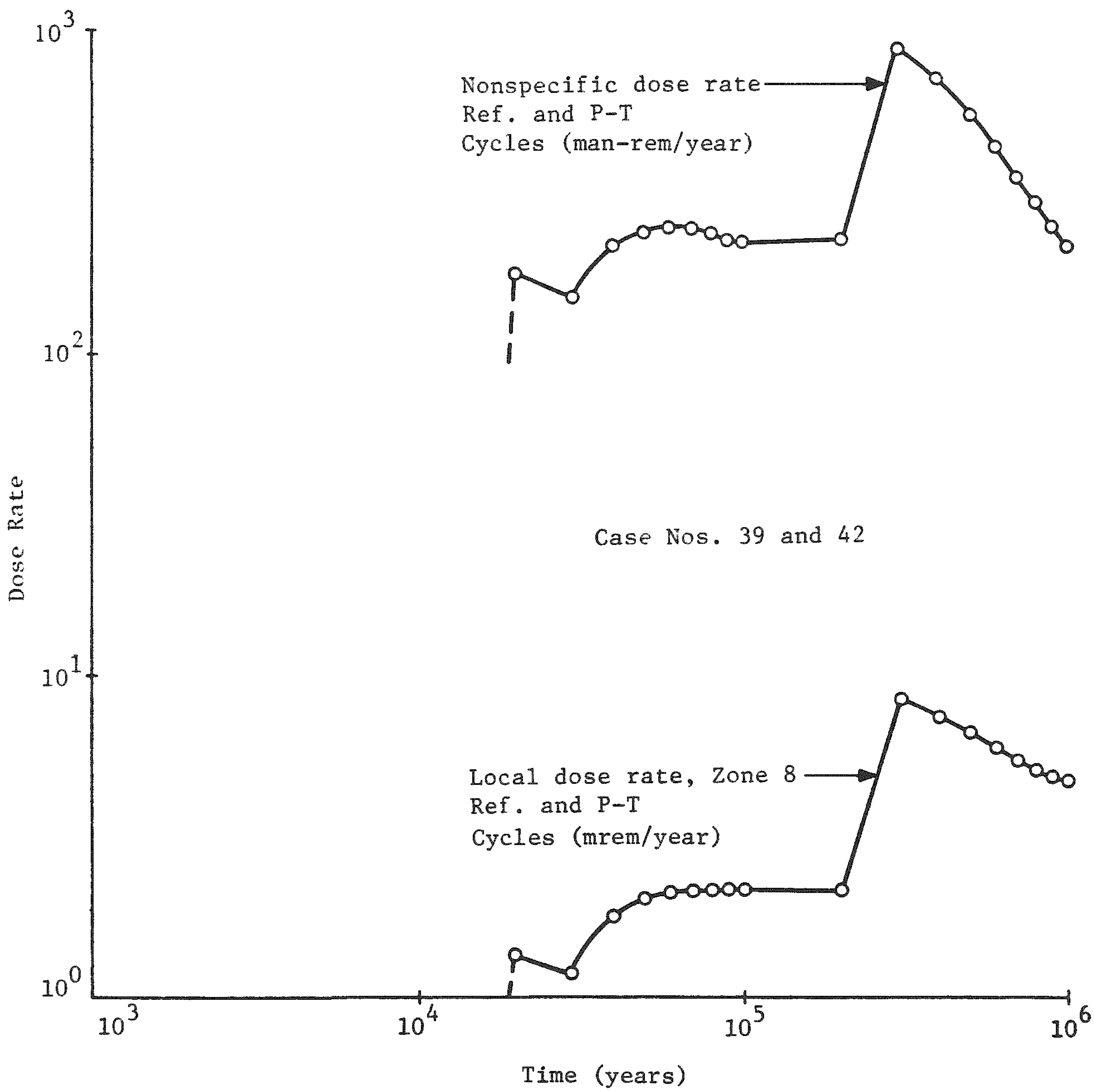

Fig. 4.1. Average annual total body dose rates—local, Zone 8 and nonspecific—from all nuclides following discrete leach incident initiated at 10^3 years.

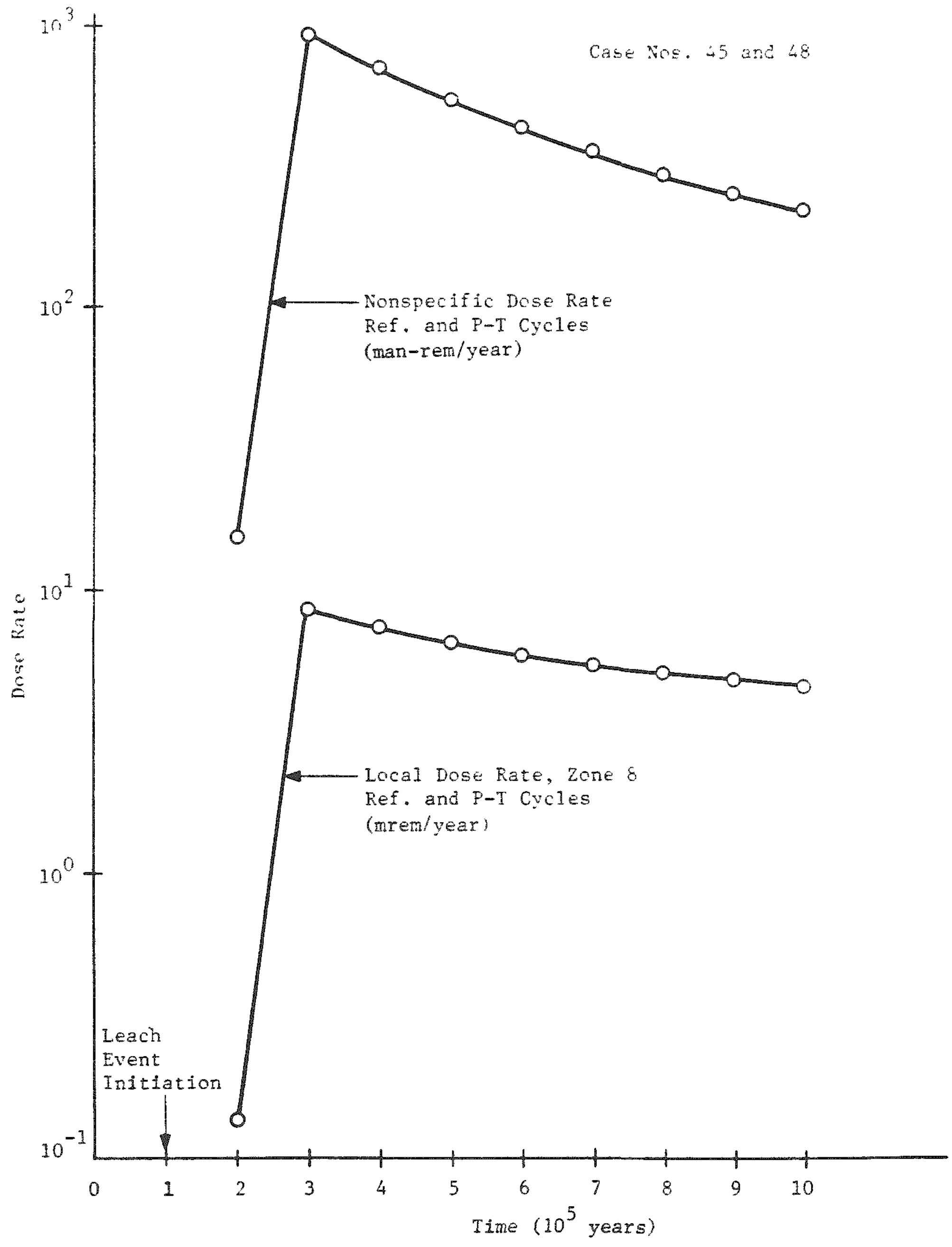

Fig. 4.2. Average annual total body dose rates—local, Zone 8 and nonspecific—from all nuclides following discrete leach incident initiated at 10^5 years.

4.2.2 Expulsive events

This task calculates results for a discrete expulsive release occurring at 100,000 years. Such an assumed release uses the parameters summarized earlier in Sect. 3.4.3. Table 4.19 summarizes the most significant nuclides, dose rates, and doses in the same manner as these for the leaching calculations.

Compared with the leaching runs, these expulsive releases place nuclide significance in closer accord with nuclide activity at a particular time. This is due to the essentially instantaneous and balanced release of a fraction of the repository nuclides to the three environmental receptors—air, ground surface, and surface water. The role of external pathways-to-man (gamma radiation) becomes important, resulting in greater local zonal health effects than nonspecific for these releases.

Figure 4.3 gives a graphic summary of the results. Use of the relatively long environmental half-life of 30,000 years reduces rather slowly the effectiveness of these releases, thus causing relatively high values of cumulative health effects to be computed.

4.2.3 Consequence calculation summary

Table 4.20 gives integrated total body doses at 10^5 and 10^6 years for Zone 8 and nonspecific for the consequence analysis runs and corresponding probabilistic runs. As expected, the latter results are lower than those for the discrete release events because of the extended time over which nuclide release occurs under the probabilistic mode. The difference is particularly evident for expulsive releases which would, in practice, occur during a brief interval of time. For the release times used, the expulsive release gives a significantly larger integrated dose at any time through the 1 million years under study. However, the integrated doses for expulsive and leaching should eventually approach each other and possibly cross, depending on relative contributions from zones other than 8.

Table 4.19. Most significant radionuclides at selected times based on all health effects; consequence (volcanism) cases; waste type: A + B (total)

Case and variable identification	Order	Time, y 10**5	4x10**5	7x10**5	10**6
ZONAL HEALTH EFFECT RATE	1	Ra-226	Ra-226	Ra-226	Th-229
	2	Pu-239	Th-229	Th-229	Ra-226
Case# 36T; Cycle: Ref	3	Th-229	Np-237	Np-237	Np-237
Release: Expulsive	4	Np-237	Th-230	Ra-225	Ra-225
at 100000 Years	5	Pu-242	Pu-242	Pu-242	Pu-242
Health Effects (deaths/y) | Tot all nuc		2.42E 02	4.46E-01	2.68E-04	1.76E-07
| Top 5		2.35E 02	4.35E-01	2.62E-04	1.73E-07
| % of total		97.2	97.7	97.7	98.2
Case# 33T; Cycle: P-T	1	Ra-226	Ra-226	Ra-226	Ra-226
Release: Expulsive	2	Pu-239	Th-229	Th-229	Th-229
at 100000 Years	3	Sn-126	Pu-242	Pu-242	Pu-242
	4	Pu-242	Sn-126	Th-230	Np-237
	5	Th-230	Th-230	Np-237	Th-230
Health Effects (deaths/y) | Tot all nuc		1.01E 01	1.93E-02	9.62E-06	5.08E-09
| Top 5		9.77E 00	1.88E-02	9.35E-06	4.92E-09
| % of total		96.5	97.3	97.0	96.7
Ratio(%): (P-T)/(Ref) | Tot all nuc		4.2	4.3	3.6	2.9
NONSPECIFIC HEALTH EFFECT RATE	1	Ra-226	Ra-226	Ra-226	Ra-226
	2	Ra-225	Ra-225	Ra-225	Ra-225
Case# 36T; Cycle: Ref	3	Tc-99	Pb-210	Pb-210	Pb-210
Release: Expulsive	4	Pb-210	Tc-99	Tc-99	Tc-99
at 100000 years	5	Sn-126	Cs-135	Cs-135	Th-229
Health Effects (deaths/y) | Tot all nuc		1.21E 02	3.13E-01	1.50E-04	7.00E-08
| Top 5		1.21E 02	3.13E-03	1.50E-04	6.96E-08
| % of total		100.0	100.0	100.0	100.0
Case# 33T; Cycle: P-T	1	Ra-226	Ra-226	Ra-226	RA-226
Release: Expulsive	2	Tc-99	Tc-99	Ra-225	Pa-225
at 100000 Years	3	Sn-126	Ra-225	Tc-99	Tc-99
	4	Ra-225	Cs-135	Cs-135	Cs-135
	5	Cs-135	Sn-126	Pb-210	Pb-210
Health Effects (deaths/y) | Tot all nuc		6.08E 00	1.55E-02	7.31E-06	3.33E-09
| Top 5		6.04E 00	1.55E-02	7.31E-06	3.33E-09
| % of total		99.9	100.0	100.0	100.0
Ratio(%): (P-T)/(Ref) | Tot all nuc		5.0	4.9	4.9	4.8

Table 4.19. (cont'd)

Case and variable identification	Order	Time, y 10**5	4x10**5	7x10**5	10**6
TOTAL HEALTH EFFECT RATE	1	Ra-226	Ra-226	Ra-226	Ra-226
	2	Pu-239	Th-229	Th-229	Th-229
Case# 36T; Cycle: Ref	3	Th-229	Np-237	Np-237	Np-237
Release: Expulsive	4	Np-237	Ra-225	Ra-225	Ra-225
at 100000 Years	5	Pu-242	Th-230	Pu-242	Pu-242
Health Effects (deaths/y) |Tot all nuc		3.63E 02	7.58E-01	4.16E-04	2.46E-07
|Top 5		3.55E 02	7.46E-01	4.12E-04	2.43E-07
|% of total		97.8	98.4	98.5	98.8
Case# 33T; Cycle: P-T	1	Ra-226	Ra-226	Ra-226	Ra-226
Release: Expulsive	2	Pu-239	Th-229	Th-229	Th-229
at 100000 Years	3	Sn-126	Pu-242	Pu-242	Pu-242
	4	Pu-242	Sn-126	Th-230	Np-237
	5	Th-230	Th-230	Np-237	Ra-225
Health Effects (deaths/y) |Tot all nuc		1.62E 01	3.48E-02	1.70E-05	8.42E-09
|Top 5		1.57E 01	3.41E-02	1.65E-05	8.19E-09
|% of total		97.1	97.9	97.5	97.4
Ratio(%): (P-T)/(Ref) |Tot all nuc		4.5	4.6	4.0	3.4
CUMULATIVE TOTAL HEALTH EFFECTS	1	Ra-226	Ra-226	Ra-226	Ra-226
	2	Pu-239	Pu-239	Pu-239	Pu-239
Case# 36T; Cycle: Ref	3	Th-229	Th-229	Th-229	Th-229
Release: Expulsive	4	Np-237	Np-237	Np-237	Np-237
at 100000 years	5	Pu-242	Pu-242	Pu-242	Pu-242
Health Effects (deaths) |Tot all nuc		3.63E 06	1.40E 07	1.40E 07	1.40E 07
|Top 5		3.55E 06	1.37E 07	1.37E 07	1.37E 07
|% of total		97.8	97.6	97.6	97.6
Case# 33T; Cycle: P-T	1	Ra-226	Ra-226	Ra-226	Ra-226
Release: Expulsive	2	Pu-239	Sn-126	Sn-126	Sn-126
at 100000 Years	3	Sn-126	Pu-239	Pu-239	Pu-239
	4	Pu-242	Pu-242	Pu-242	Pu-242
	5	Th-230	Th-229	Th-229	Th-229
Health Effects (deaths) |Tot all nuc		1.62E 05	6.46E 05	6.46E 05	6.46E 05
|Top 5		1.57E 05	6.27E 05	6.27E 05	6.27E 05
|% of total		97.1	97.0	97.0	97.0
Ratio(%): (P-T)/(Ref) |Tot all nuc		4.5	4.6	4.6	4.6

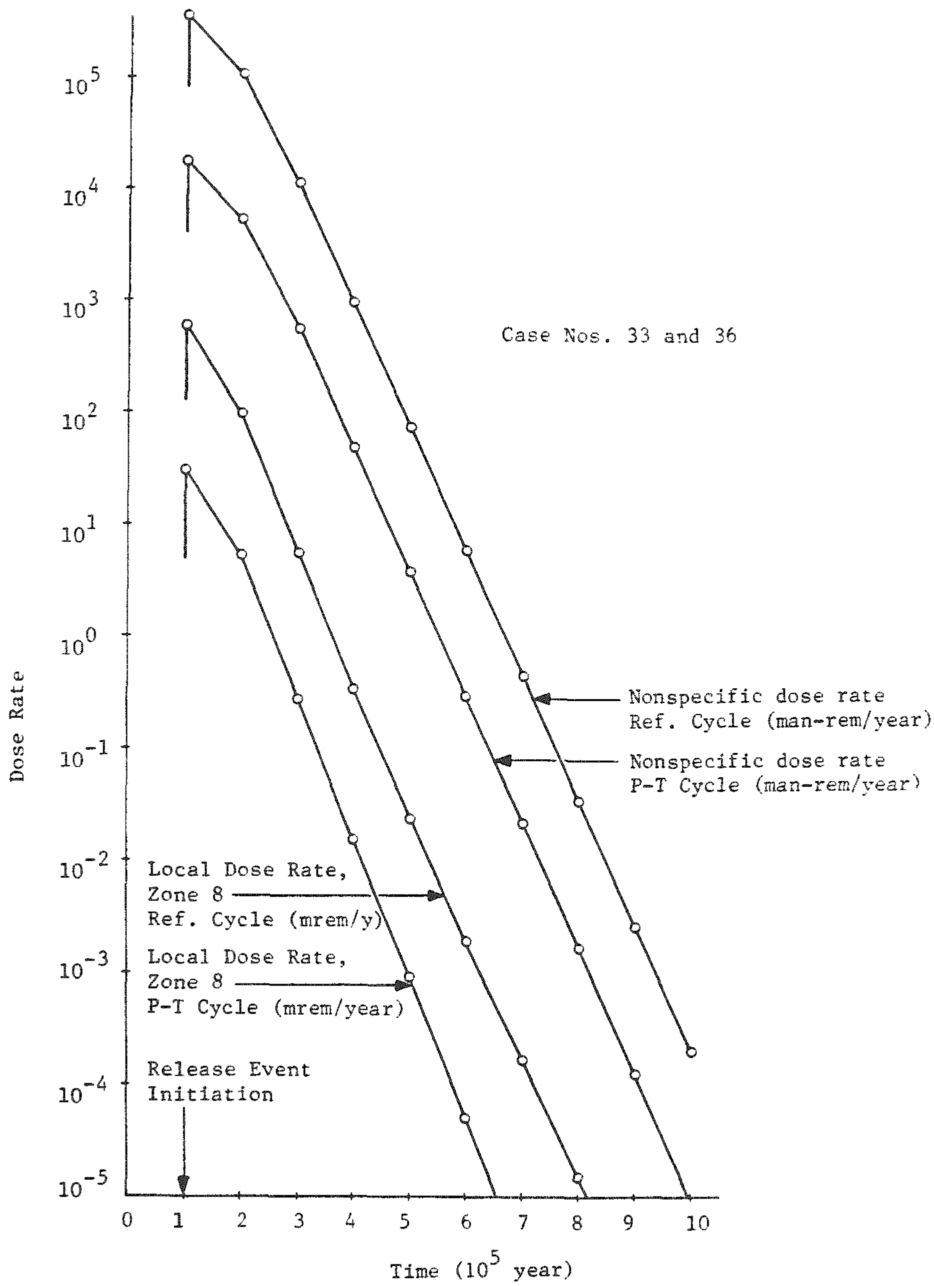

Fig. 4.3. Average annual total body dose rates—local, Zone 8 and nonspecific—from all nuclides following discrete expulsive incident initiated at 10^5 years.

Table 4.20. Summary of integrated total body dose, total all nuclides, consequence analyses—discrete releases

Case	Description			Integrated dose - 10**5 years		Integrated dose - 10**6 years	
	Waste type	Cycle	Release	Zone 8 (mrem)	Nonspecific (man-rem)	Zone 8 (mrem)	Nonspecific (man-rem)
92	A+B	Ref	Probabilistic leaching for ref	3.08E 02	3.56E 04	7.27E 04	6.02E 06
42	A+B	Ref	Leaching at 1,000 years	1.66E 05	1.91E 07	5.18E 06	4.02E 08
39	A+B	P-T	Leaching at 1,000 years	1.69E 05	1.95E 07	5.22E 06	4.10E 08
48	A+B	Ref	Leaching at 100,000 years	1.36E 04	1.54E 06[a]	4.84E 06	3.73E 08
45	A+B	P-T	Leaching at 100,000 years	1.38E 04	1.58E 06[a]	4.93E 06	3.79E 08
98	A+B	Ref	Probabilistic expulsive for ref	3.23E 01	1.38E 04	7.56E 02	4.66E 05
36	A+B	Ref	Expulsive at 100,000 years	5.77E 06	3.56E 09	1.60E 07	1.52E 10
33	A+B	P-T	Expulsive at 100,000 years	3.07E 05	1.77E 08	8.62E 05	7.56E 08

[a] 200,000 years for both Zone 8 and nonspecific.

4.3 Sensitivity Analysis

The sensitivity analysis for this task is limited to variation of certain parameters used in leaching releases and subsequent groundwater transport. First, variations applied to probabilistic (risk) release modes are discussed, followed by consequence or discrete release modes, with a brief pair of summary tables giving cumulative results through various times. The earlier comments in Sect. 4.2.1 concerning leaching parameters apply to this section as well.

In the last part of this analysis a brief report is given on the use of different discount rates for developing discounted present values, or costs, for future damages.

4.3.1 Variation of leach rates, risk series

Tables 4.21 through 4.24 give top-ranking nuclides and Zone 8 and nonspecific dose rates at selected times for high leach rate (nominal x 1000), realistic variable leach rate, low leach rate (nominal x 10^{-3}), and high leach and rock dissolution rates (nominal x 1000), respectively. Additional runs made with an increased neptunium K_d give expected results which do not vary from the nominal base cases in which neptunium barely begins to surface at the end of 1 million years.

Figures 4.4 and 4.5 present the dose rates graphically for easier comparison. It can be seen that an increase of leach rate above nominal by a factor of 1000 increases dose rates by only a factor of about 10. Decreasing the leach rate by 10^{-3} is a bit more effective as typical dose rates decrease by a factor of about 10^{-2}. Use of the realistic variable leach rate affects dose rate by a factor of 2 to 4 during the period 20,000 to 30,000 years, but has no influence afterwards.

4.3.2 Variation of leach rates, consequence series

Tables 4.25 and 4.26 give top-ranking nuclides and Zone 8 and nonspecific dose rates at selected times for high and low leach rates

Table 4.21. Most significant radionuclides at selected times; sensitivity (leaching, high) cases; waste type: A

Case and variable identification	Order	10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 50; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				1.43E-10	3.11E-02	6.56E-01
(mrem/y): Top 5				1.43E-10	3.11E-02	6.56E-01
: % of total				100.0	100.0	100.0
Case# 99; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Probabilistic	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				1.45E-10	3.15E-02	6.57E-01
(mrem/y): Top 5				1.45E-10	3.15E-02	6.57E-01
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				101.0	101.0	100.0
NONSPECIFIC DOSE RATE TOTAL BODY	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 50; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				1.77E-08	3.32E 00	3.07E 01
(manrem/y): Top 5				1.77E-08	3.32E 00	3.07E 01
: % of total				100.0	100.0	100.0
Case# 99; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Probabilistic	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				1.81E-08	3.39E 00	3.09E 01
(manrem/y): Top 5				1.81E-08	3.39E 00	3.09E 01
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				102.0	102.0	101.0

[a] Four or more orders of magnitude smaller than preceding nuclides.

Table 4.22. Most significant radionuclides at selected times; sensitivity (leaching, realistic variable) cases; waste type: A

Case and variable identification	Order	Time, years				
		10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY						
ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 52; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				4.82E-11	4.78E-03	6.93E-02
(mrem/y): Top 5				4.82E-11	4.78E-03	6.93E-02
: % of total				100.0	100.0	100.0
Case# 51; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Probabilistic	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				4.89E-11	4.83E-03	6.94E-02
(mrem/y): Top 5				4.89E-11	4.83E-03	6.94E-02
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				101.0	101.0	100.0
NONSPECIFIC DOSE RATE TOTAL BODY						
	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 52; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				5.98E-09	5.09E-01	3.25E 00
(manrem/y): Top 5				5.98E-09	5.09E 01	3.25E 00
: % of total				100.0	100.0	100.0
Case# 51; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Probabilistic	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				6.10E-09	5.19E 01	3.27E 00
(manrem/y): Top 5				6.10E-09	5.19E-01	3.27E 00
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				102.0	102.0	101.0

[a] Four or more orders of magnitude smaller than preceding nuclides.

Table 4.23. Most significant radionuclides at selected times; sensitivity (leaching, low) cases; waste type: A

Case and variable identification	Order	Time, years 10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE						
TOTAL BODY						
ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 54; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				4.90E-15	8.70E-06	2.98E-04
(mrem/y): Top 5				4.90E-15	8.70E-06	2.98E-04
: % of total				100.0	100.0	100.0
Case# 53; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Probabilistic	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				4.97E-15	8.81E-06	3.00E-04
(mrem/y): Top 5				4.97E-15	8.81E-06	3.00E-04
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				101.0	101.0	100.0
NONSPECIFIC DOSE RATE						
TOTAL BODY						
	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 54; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				6.08E-13	9.33E-04	4.35E-02
(manrem/y): Top 5				6.08E-13	9.33E-04	4.35E-02
: % of total				100.0	100.0	100.0
Case# 53; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Probabilistic	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				6.20E-13	9.53E-04	4.37E-02
(manrem/y): Top 5				6.20E-13	9.53E-04	4.37E-02
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				102.0	102.0	100.0

[a] Four or more orders of magnitude smaller than preceding nuclides.

Table 4.24. Most significant radionuclides at selected times; sensitivity (leaching & ROKDIS, high) cases; waste type: A

Case and variable identification	Order	Time, years				
		10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE TOTAL BODY ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 49; Cycle: P-T	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				1.11E-09	4.69E-01	4.74E-01
(mrem/y): Top 5				1.11E-09	4.69E-01	4.74E-01
: % of total				100.0	100.0	100.0
NONSPECIFIC DOSE RATE TOTAL BODY	1			Tc-99	Tc-99	I-129
	2			I-129	I129	Tc-99
Case# 49; Cycle: P-T	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Probabilistic	4					
	5					
Dose Rate: Tot all nuc				1.39E-07	5.02E 01	2.99E 01
(manrem/y): Top 5				1.39E-07	5.02E 01	2.99E 01
: % of total				100.0	100.0	100.0

[a] Four or more orders of magnitude smaller than preceding nuclides.

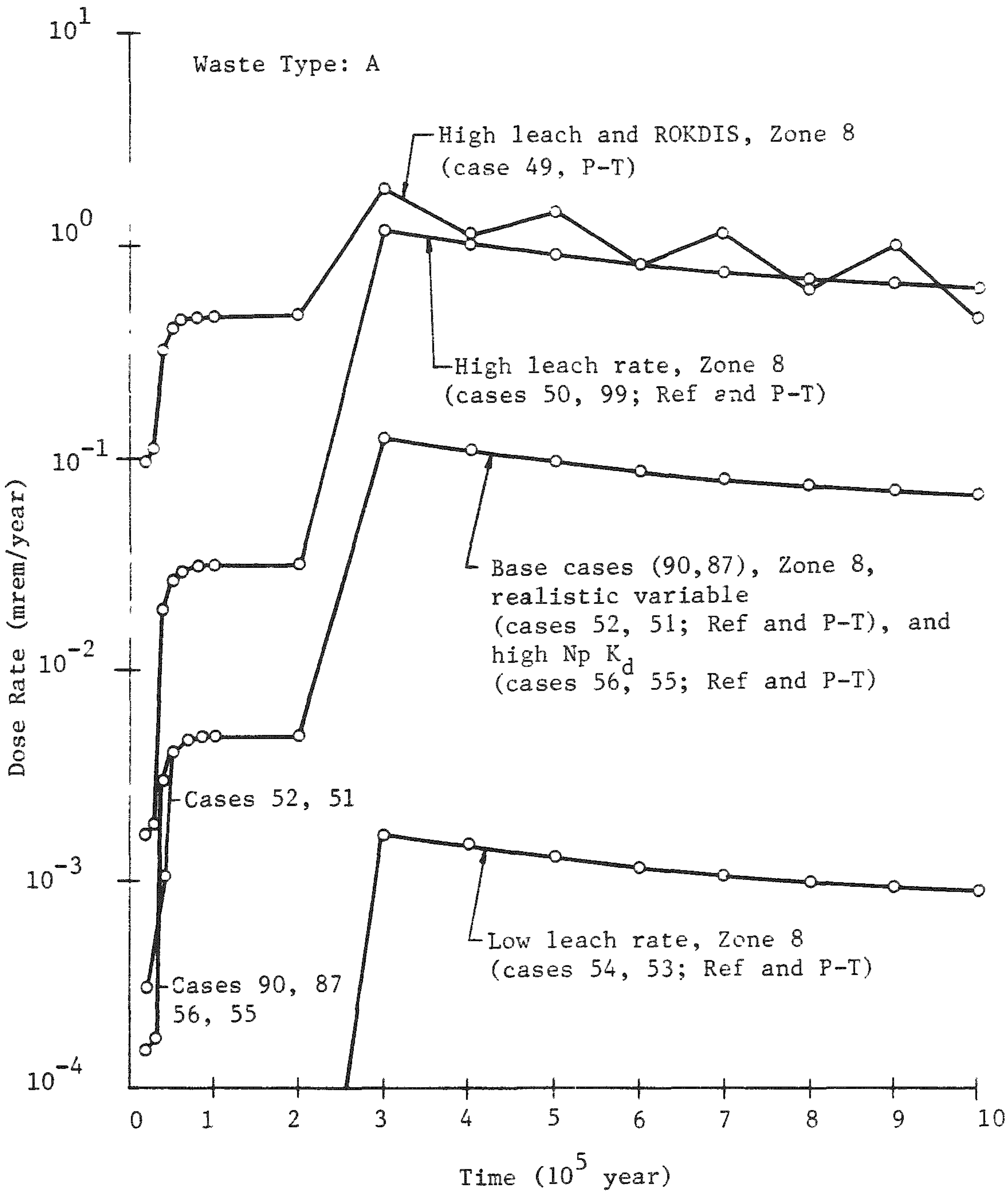

Fig. 4.4. Average annual total body dose rates—local, Zone 8—from all nuclides, sensitivity analyses for probabilistic leach releases.

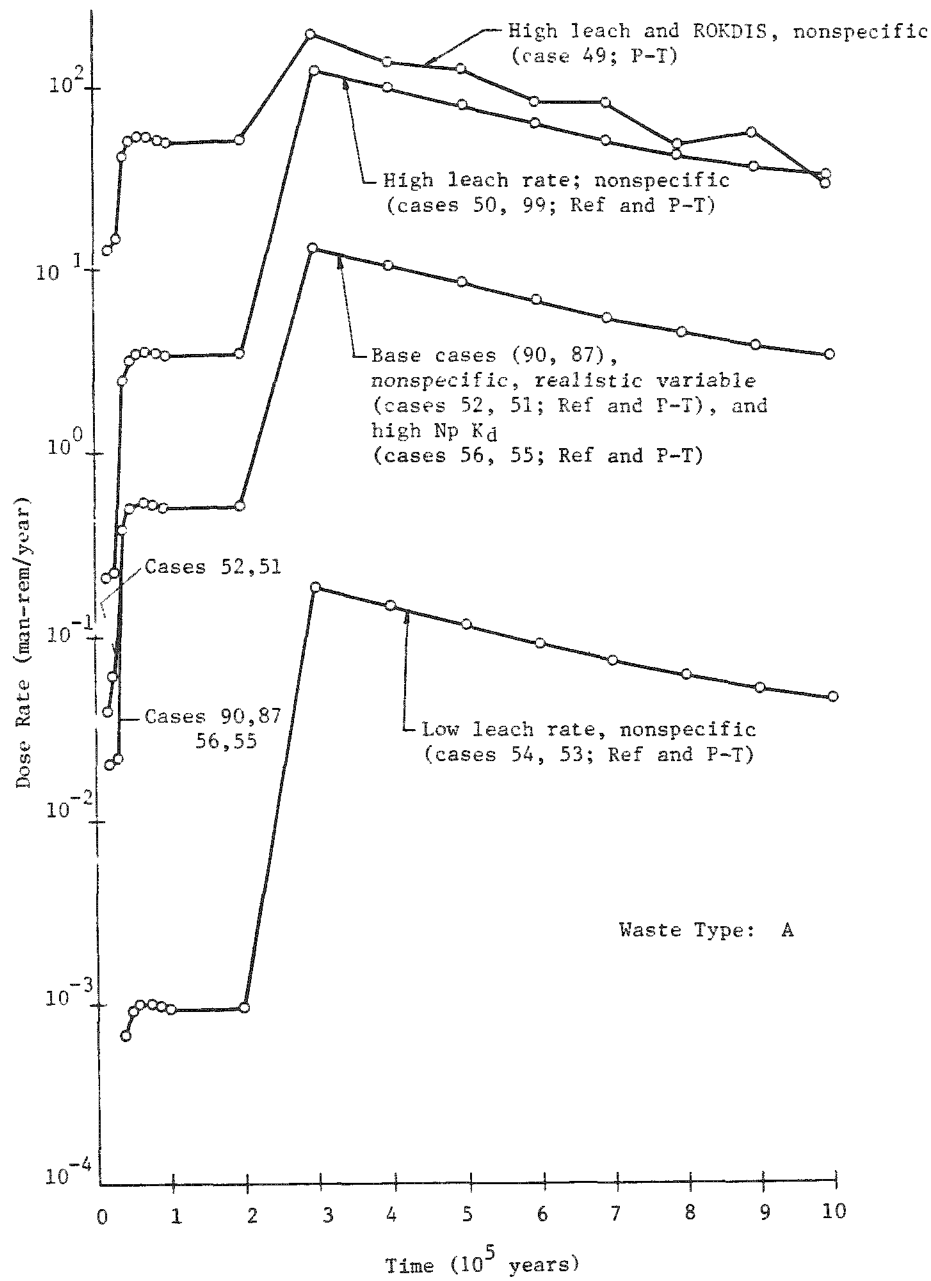

Fig. 4.5. Average annual total body dose rates—nonspecific—from all nuclides, sensitivity analyses for probabilistic leach releases.

Table 4.25. Most significant radionuclides at selected times; sensitivity (leaching, high) cases; waste type: A

Case and variable identification	Order	Time, years				
		10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE						
TOTAL BODY						
ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 102; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Discrete	4					
	5					
Dose Rate: Tot all nuc				2.68E-09	2.11E 01	7.40E-07
(mrem/y): Top 5				2.68E-09	2.11E 01	7.40E-07
: % of total				100.0	100.0	100.0
Case# 101; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Discrete	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				2.72E-09	2.13E 01	7.40E-07
(mrem/y): Top 5				2.72E-09	2.13E 01	7.40E-07
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				101.5	100.9	100.0
NONSPECIFIC DOSE RATE						
TOTAL BODY						
	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 102; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Discrete	4					
	5					
Dose Rate: Tot all nuc				3.23E-07	2.23E 03	8.63E-07
(manrem/y): Top 5				3.23E-07	2.23E 03	8.63E-07
: % of total				100.0	100.0	100.0
Case# 101; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Discrete	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				3.40E-07	2.28E 03	8.68E-07
(manrem/y): Top 5				3.40E-07	2.28E 03	8.68E-07
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				102.4	102.2	100.6

[a] Four or more orders of magnitude smaller than preceding nuclides.

Table 4.26. Most significant radionuclides at selected times; sensitivity (leaching, low) cases; waste type: A

Case and variable identification	Order	Time, years				
		10**2	10**3	10**4	10**5	10**6
LOCAL DOSE RATE						
TOTAL BODY						
ZONE 8	1			Tc-99	Tc-99	I-129
	2			I-129	I-129	Tc-99
Case# 64; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Discrete	4					
	5					
Dose Rate: Tot all nuc				8.90E-14	3.75E-02	8.93E-01
(mrem/y): Top 5				8.90E-14	3.75E-02	8.93E-01
: % of total				100.0	100.0	100.0
Case# 63; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Discrete	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				9.05E-14	3.80E-02	8.95E-01
(mrem/y): Top 5				9.05E-14	3.80E-02	8.95E-01
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				101.7	101.3	100.2
NONSPECIFIC DOSE RATE						
TOTAL BODY						
	1			Tc-99	Tc-99	I-129
	2			I-129	I129	Tc-99
Case# 64; Cycle: Ref	3			Mo-93[a]	Mo-93[a]	Np-237[a]
Release: Discrete	4					
	5					
Dose Rate: Tot all nuc				1.10E-11	4.21E 00	4.38E 01
(manrem/y): Top 5				1.10E-11	4.21E 00	4.38E 01
: % of total				100.0	100.0	100.0
Case# 63; Cycle: P-T	1			Tc-99	Tc-99	I-129
Release: Discrete	2			I-129	I-129	Tc-99
	3			Mo-93[a]	Mo-93[a]	Np-237[a]
	4					
	5					
Dose Rate: Tot all nuc				1.13E-11	4.29E 00	4.41E 01
(manrem/y): Top 5				1.13E-11	4.29E 00	4.41E 01
: % of total				100.0	100.0	100.0
Ratio (%): (P-T)/(Ref)						
: Tot all nuc				102.7	101.9	100.7

[a] Four or more orders of magnitude smaller than preceding nuclides.

from a discrete leach event initiated at 1000 years. Figures 4.6 and 4.7 dramatically illustrate the differences to be obtained by significant changes in the rate at which nuclides are released from the repository. The high-leach-rate discrete release more closely resembles an expulsive release. It also has a high group peak-dose rate and a subsequent rapid reduction corresponding almost completely to the average effective decay factor from radiological and environmental decay. Later leaching contributions are minimal. On the other hand, the low-leach curve continues to increase throughout the period as leaching continues to release nuclide pulses which accumulate in Zone 8 and the nonspecific pathway faster than nuclides are removed through the combined decays.

4.3.3 Sensitivity calculation summary

Tables 4.27 and 4.28 summarize for probabilistic and consequence releases, respectively, the integrated Zone 8 and nonspecific doses at 10^5 and 10^6 years. Results from base cases, using nominal parameter values, are included for comparison.

In general, dose rates and cumulative doses are less sensitive to increased leach rates than might be expected. Except for a brief time increment (possibly 10,000 to 30,000 years), they are essentially insensitive to the refined leach-rate responses associated with canister repository temperatures and configuration changes (realistic variable). Increase in the rock dissolution constant provides a response similar to increased leach and appears superimposed in Figs. 4.4 and 4.5. The somewhat erratic behavior of their curves is due to the calculational sequencing of rock dissolution, leaching, and release to groundwater transport. Reduction of leach rates from the nominal values used in the base cases provides significant reduction in effects through several hundreds of thousands of years. Such reduction need only be applied to ^{99}Tc and ^{129}I to obtain the benefit.

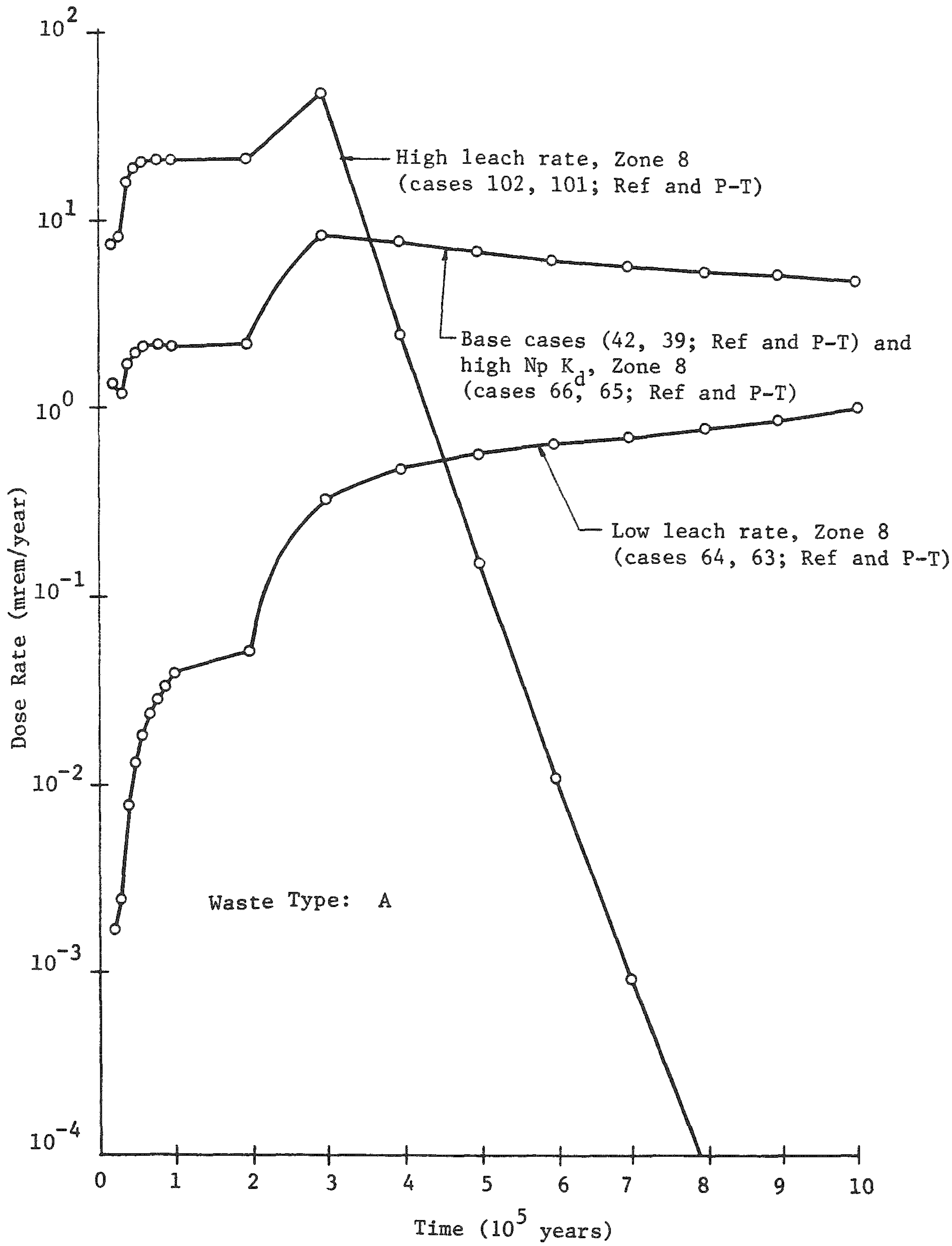

Fig. 4.6. Average annual total body dose rates—local, Zone 8—from all nuclides, sensitivity analyses for discrete leach incident initiated at 10^3 years.

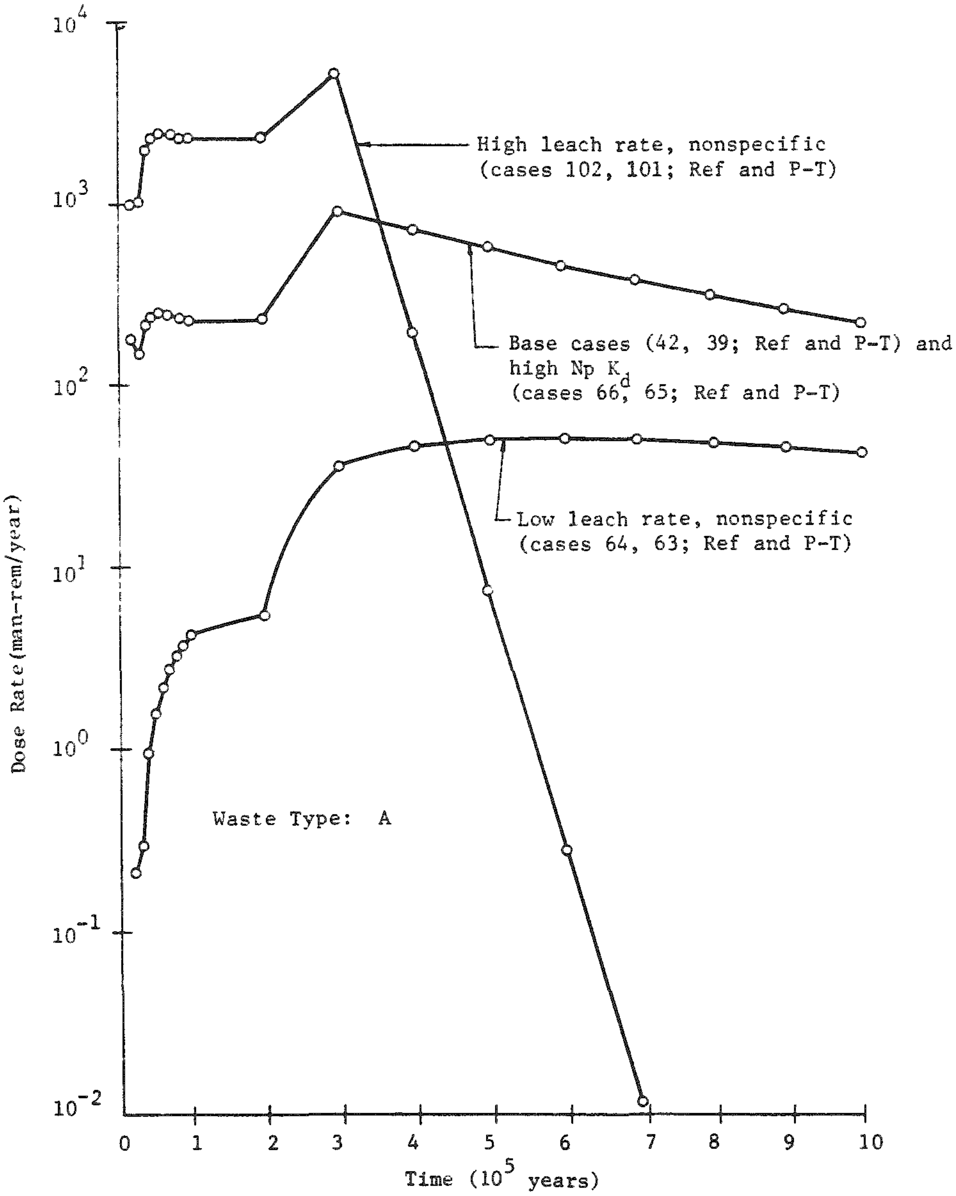

Fig. 4.7. Average annual total body dose rates—nonspecific—from all nuclides sensitivity analyses for discrete leach incident initiated at 10^3 years.

Table 4.27. Summary of integrated total body dose, total all nuclides, sensitivity analyses -- probabilistic releases

Case	Description			Integrated Dose - 10**5 y		Integrated dose - 10**6 y	
	Waste type	Cycle	Release	Zone 8 mrem	Nonspecific manrem	Zone 8 mrem	Nonspecific manrem
90	A	Ref	Base Case for reference	3.08E 02	3.56E 04	7.27E 04	5.55E 06
50	A	Ref	(a) High Leach Rate	2.03E 03	2.35E 05	6.86E 05	5.22E 07
99	A	P-T	(a) High Leach Rate	2.05E 03	2.39E 05	6.90E 05	5.30E 07
52	A	Ref	(b) Realistic Variable Leach	3.15E 02	3.65E 04	7.27E 04	5.55E 06
51	A	P-T	(b) Realistic Variable Leach	3.19E 02	3.72E 04	7.32E 04	5.63E 06
54	A	Ref	(c) Low Leach Rate	5.59E-01	6.50E 01	9.56E 02	7.59E 04
53	A	P-T	(c) Low Leach Rate	5.66E-01	6.63E 01	9.62E 02	7.71E 04
56	A	Ref	(d) High Np Kd	3.08E 02	3.56E 04	7.27E 04	5.55E 06
55	A	P-T	(d) High Np Kd	3.12E 02	3.64E 04	7.32E 04	5.63E 06
49	A	P-T	(e) High Leach Rate & ROKDIS	3.28E 04	3.81E 06	9.23E 05	8.35E 07

(a) High Leach Rate: Leach rate - 1000 x nominal, and rock dissolution rate - 10 x nominal.
(b) Realistic Variable Leach Rate: leach rate increased as function of temperature during early thermal period and leaching surface area progressively increased after 1000y from waste form degradation.
(c) Low Leach Rate: leach rate - 0.001 x nominal.
(d) High Np Kd: Kd increased from nominal 8.1 to 30.
(e) Leach rate and rock dissolution rates, both 1000 x nominal.

Table 4.28. Summary of integrated total body dose, total all nuclides, sensitivity analyses -- consequence releases

Case	Description			Integrated Dose - 10**5 y		Integrated dose - 10**6 y	
	Waste type	Cycle	Release	Zone 8 mrem	Nonspecific manrem	Zone 8 mrem	Nonspecific manrem
42	A	Ref	Base Case for reference	1.69E 05	1.95E 07	5.22E 06	4.10E 08
102	A	Ref	(a) High Leach Rate	1.56E 06	1.80E 08	8.83E 06	9.42E 08
101	A	P-T	(a) High Leach Rate	1.58E 06	1.84E 08	8.92E 06	9.59E 08
64	A	Ref	(b) Low Leach Rate	1.63E 03	1.92E 05	5.18E 05	3.67E 07
63	A	P-T	(b) Low Leach Rate	1.66E 03	1.96E 05	5.21E 05	3.72E 07
66	A	Ref	(c) High Np Kd	1.69E 05	1.95E 07	5.22E 06	4.10E 08
65	A	P-T	(c) High Np Kd	1.72E 05	1.99E 07	5.26E 06	4.16E 08

(a) High Leach Rate: Leach rate - 1000 x nominal, and rock dissolution rate - 10 x nominal.
(b) Low Leach Rate: Leach rate - 0.001 x nominal.
(c) High Np Kd: Kd increased from nominal 8.1 to 30.

Although not reported in this task, increase in groundwater velocities would introduce, during the 1 million-year period, additional nuclides with significant effects. In particular, nuclides such as ^{226}Ra, ^{135}Cs, and ^{237}Np would begin to appear.

As a part of every AMRAW-B run, annual total damages are accumulated over the 1 million-year period, and discounted present values for these damages are calculated using 0% and 7% annual discount rates. Tables 4.29 and 4.30 present the results for Type A waste, Ref and P-T inventories, respectively, under probabilistic release. Using Table 4.29 as a reference, it is easily seen that any discount rate as high as 7% essentially wipes out the present equivalent cost for future damages. The present value of total damages at 7% discount rate is approximately $2000 in contrast to about $9 billion at the 0% rate. The only nuclides which contribute significantly at the 7% rate are ^{90}Sr and ^{137}Cs, whose effects occur during the first 200 to 300 years.

The last point is emphasized by the results appearing in Table 4.31 (discrete leach event initiated at 1000 years) and Table 4.32 (discrete expulsive event at 10^5 years). These last two cases incur no releases during the early years; therefore, the 7% rate (or any discount rate greater than 0%) gives zero present values.

A comparison of the marginal present value cost per initial inventory gram at 0% with the marginal value at 7% for ^{99}Tc illustrates the impact of non-zero discounting over a long period. The 0% marginal value is $59.40/g, but the 7% value is only $\$2.39 \times 10^{-12}$/g for ^{99}Tc, while similar marginal values for the short-term ^{90}Sr are $\$1.10 \times 10^{-4}$ and $\$1.99 \times 10^{-5}$, not an unreasonable discount.

Other discount rates between 0% and 7% would, of course, extend the period of reasonable discounting, but not by much. For example, the present value of $1 million at 1000 years, discounted at a 1% rate, is only $45.56.

Table 4.29. Discounted present value ($), Type A waste, Ref cycle, probabilistic releases.

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NUCLIDE	DISC RATE = .00% DISCOUNTED	PV $/GM	DISC RATE = 7.00% DISCOUNTED	PV $/GM
PU-242	7.56E+05		5.41E-03	
CM-246	8.36E+02		9.05E-03	
SUB TOT	7.57E+05	4.71E-02	1.44E-02	8.94E-10
PU-240	5.39E+05		1.23E+00	
CM-244	4.18E+02		7.84E+01	
SUB TOT	5.40E+05	6.43E-03	7.96E+01	9.49E-07
RA-225	2.04E+05		5.38E-08	
TH-229	1.22E+07		1.05E-07	
NP-237	2.30E+06		4.37E-03	
AM-241	3.13E+04		2.13E+01	
PU-241	1.18E+02		1.90E+00	
CM-245	3.05E+03		1.17E-02	
SUB TOT	1.66E+07	8.83E-02	2.32E+01	1.24E-07
PB-210	4.23E+05		1.14E-08	
RA-226	6.92E+07		6.88E-06	
TH-230	7.55E+05		2.24E-06	
PU-238	1.31E+03		1.44E+01	
CM-242	3.79E+00		9.51E-01	
AM-242M	6.64E+01		4.13E-01	
SUB TOT	6.94E+07	5.26E+00	1.57E+01	1.19E-06
PU-239	5.02E+06		2.39E-01	
NP-239	4.94E+04		9.50E-02	
AM-243	5.28E+05		1.93E+00	
SUB TOT	5.59E+06	2.57E-02	2.31E+00	1.06E-08
C-14	6.15E-01		2.33E-06	
SUB TOT	6.15E-01	3.15E-05	2.33E-06	1.19E-10
NI-59	2.40E+00		4.31E-07	
SUB TOT	2.40E+00	1.13E-04	4.31E-07	2.02E-11
SR-90	8.93E+03		1.61E+03	
SUB TOT	8.93E+03	1.10E-04	1.61E+03	1.99E-05
ZR-93	1.08E+03		2.21E-05	
SUB TOT	1.08E+03	8.25E-06	2.21E-05	1.83E-13
MO-93	5.35E-02		1.52E-09	
SUB TOT	5.35E-02	7.12E-04	1.52E-09	2.05E-11
TC-99	8.56E+09		3.44E-04	
SUB TOT	8.56E+09	5.94E+01	3.44E-04	2.39E-12
SN-126	9.88E+04		2.96E-03	
SUB TOT	9.88E+04	1.82E-02	2.96E-03	5.45E-10
I-129	7.50E+08		1.34E-05	
SUB TOT	7.50E+08	2.10E+01	1.34E-05	3.76E-13
CS-135	7.44E+03		1.05E-04	
SUB TOT	7.44E+03	9.93E-05	1.05E-04	1.40E-12
CS-137	1.79E+03		1.89E+02	
SUB TOT	1.79E+03	9.30E-06	1.89E+02	8.73E-07
TOTALS	9.40E+09	7.86E+00	1.92E+03	1.61E-06

Table 4.30. Discounted present value ($), Type A waste, P-T cycle, probabilistic release.

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NUCLIDE	DISC RATE = .00% DISCOUNTED	PV $/GM	DISC RATE = 7.00% DISCOUNTED	PV $/GM
PU-242	6.21E+04		4.44E-04	
CM-246	9.68E+01		1.04E-03	
SUB TOT	6.22E+04	4.69E-02	1.48E-03	1.11E-09
PU-240	1.71E+04		4.98E-02	
CM-244	3.97E+00		7.44E-01	
SUB TOT	1.71E+04	6.47E-03	7.94E-01	3.00E-07
RA-225	1.89E+04		3.34E-08	
TH-229	1.13E+05		1.04E-07	
NP-237	2.13E+04		2.21E-05	
AM-241	6.03E+02		1.56E-01	
PU-241	1.34E+01		1.08E-01	
CM-245	3.61E+02		1.38E-03	
SUB TOT	1.54E+05	8.85E-02	2.65E-01	1.52E-07
PB-210	1.85E+04		3.97E-09	
RA-226	2.98E+06		2.22E-06	
TH-230	3.30E+04		6.37E-07	
PU-238	5.36E+01		6.73E-01	
CM-242	1.09E-02		2.87E-03	
AM-242M	1.88E-01		1.17E-03	
SUB TOT	3.03E+06	5.23E+00	6.77E-01	1.17E-06
PU-239	6.85E+04		1.81E-02	
NP-239	1.01E+02		2.00E-04	
AM-243	1.07E+03		3.91E-03	
SUB TOT	6.97E+04	2.01E-02	2.22E-02	6.39E-09
C-14	1.23E+00		4.65E-06	
SUB TOT	1.23E+00	3.15E-05	4.65E-06	1.19E-10
NI-59	2.40E+00		4.31E-07	
SUB TOT	2.40E+00	1.13E-04	4.31E-07	2.02E-11
SR-90	9.10E+03		1.64E+03	
SUB TOT	9.10E+03	1.10E-04	1.64E+03	1.99E-05
ZR-93	1.11E+03		2.25E-05	
SUB TOT	1.11E+03	9.02E-06	2.25E-05	1.83E-13
MO-93	5.35E-02		1.52E-09	
SUB TOT	5.35E-02	7.10E-04	1.52E-09	2.05E-11
TC-99	8.75E+09		3.51E-04	
SUB TOT	8.75E+09	5.25E+01	3.51E-04	2.39E-12
SN-126	1.04E+05		3.11E-03	
SUB TOT	1.04E+05	1.82E-02	3.11E-03	5.45E-10
I-129	7.50E+08		1.34E-05	
SUB TOT	7.50E+08	2.10E+01	1.34E-05	3.76E-13
CS-135	7.04E+03		9.92E-05	
SUB TOT	7.04E+03	9.93E-05	9.92E-05	1.40E-12
CS-137	1.85E+03		1.95E+02	
SUB TOT	1.85E+03	8.30E-06	1.95E+02	8.73E-07
TOTALS	9.50E+09	1.36E+01	1.84E+03	2.63E-06

Table 4.31. Discounted present value ($), total waste, Ref cycle, discrete leaching at 1000 years.

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	DISC RATE = .00%		DISC RATE = 7.00%	
NUCLIDE	DISCOUNTED	PV $/GM	DISCOUNTED	PV $/GM
PU-242	0.		0.	
CM-246	0.		0.	
SUB TOT	0.	0.	0.	0.
PU-240	0.		0.	
CM-244	0.		0.	
SUB TOT	0.	0.	0.	0.
RA-225	0.		0.	
TH-229	0.		0.	
NP-237	3.04E-01		0.	
AM-241	0.		0.	
PU-241	0.		0.	
CM-245	0.		0.	
SUB TOT	3.04E-01	1.54E-03	0.	0.
PB-210	0.		0.	
RA-226	0.		0.	
TH-230	0.		0.	
PU-238	0.		0.	
CM-242	0.		0.	
AM-242M	0.		0.	
SUB TOT	0.	0.	0.	0.
PU-239	0.		0.	
NP-239	0.		0.	
AM-243	0.		0.	
SUB TOT	0.	0.	0.	0.
C-14	2.56E+00		0.	
SUB TOT	2.56E+00	4.25E-05	0.	0.
NI-59	0.		0.	
SUB TOT	0.	0.	0.	0.
SR-90	0.		0.	
SUB TOT	0.	0.	0.	0.
ZR-93	0.		0.	
SUB TOT	0.	0.	0.	0.
NB-93	1.35E+04		0.	
SUB TOT	1.35E+04	3.10E+00	0.	0.
TC-99	6.49E+11		0.	
SUB TOT	6.49E+11	4.51E+03	0.	0.
SN-126	0.		0.	
SUB TOT	0.	0.	0.	0.
I-129	5.28E+10		0.	
SUB TOT	5.28E+10	1.47E+03	0.	0.
CS-135	0.		0.	
SUB TOT	0.	0.	0.	0.
CS-137	0.		0.	
SUB TOT	0.	0.	0.	0.
TOTALS	7.02E+11	5.54E+02	0.	0.

Table 4.32. Discounted present value ($), total waste Ref cycle, discrete expulsive event at 10^5 years.

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	DISC RATE = .00%		DISC RATE = 7.00%	
NUCLIDE	DISCOUNTED	PV $/GM	DISCOUNTED	PV $/GM
PU-242	4.11E+10		0.	
CM-246	1.44E+04		0.	
SUB TOT	4.11E+10	1.92E+03	0.	0.
PU-240	2.85E+08		0.	
CM-244	1.88E+00		0.	
SUB TOT	2.85E+08	2.38E+00	0.	0.
RA-225	2.50E+10		0.	
TH-229	1.70E+11		0.	
NP-237	6.15E+10		0.	
AM-241	6.75E+06		0.	
PU-241	3.35E+05		0.	
CM-245	9.32E+06		0.	
SUB TOT	2.56E+11	1.30E+03	0.	0.
PB-210	1.73E+10		0.	
RA-226	2.83E+12		0.	
TH-230	3.57E+10		0.	
PU-238	0.		0.	
CM-242	0.		0.	
AM-242M	0.		0.	
SUB TOT	2.88E+12	1.70E+05	0.	0.
PU-239	4.58E+11		0.	
NP-239	5.91E+07		0.	
AM-243	6.30E+08		0.	
SUB TOT	4.59E+11	1.95E+03	0.	0.
C-14	2.30E+02		0.	
SUB TOT	2.30E+02	3.82E-03	0.	0.
NI-59	1.16E+08		0.	
SUB TOT	1.16E+08	9.04E+00	0.	0.
SR-90	0.		0.	
SUB TOT	0.	0.	0.	0.
ZR-93	2.85E+07		0.	
SUB TOT	2.85E+07	2.17E-01	0.	0.
MO-93	1.05E-03		0.	
SUB TOT	1.05E-03	2.42E-07	0.	0.
TC-99	9.71E+08		0.	
SUB TOT	9.71E+08	6.75E+00	0.	0.
SN-126	8.71E+09		0.	
SUB TOT	8.71E+09	1.60E+03	0.	0.
I-129	4.44E+07		0.	
SUB TOT	4.44E+07	1.24E+00	0.	0.
CS-135	1.70E+08		0.	
SUB TOT	1.70E+08	2.27E+00	0.	0.
CS-137	0.		0.	
SUB TOT	0.	0.	0.	0.
TOTALS	3.65E+12	2.88E+03	0.	0.

4.4 Summary of Other Factors Affecting Accuracy

This subsection is designed to provide a qualitative overview of certain modeling and input data deficiencies and assumptions as they may affect the accuracy of calculated results and their interpretation. Descriptions are presented in brief, and where possible an indication is given whether the factor should give conservative or liberal results.

4.4.1 Modeling

1. No interzonal or out-of-region nuclide transfers after nuclide is initially deposited; gives very conservative results in Zone 8 and nonspecific.
2. Application of environmental decay—decay not applied until nuclide is released from repository; adds to conservativeness.
3. Population immobility—assumes population remains in place and behaves in an unchanged manner after volcanic and other events; assumes no technological advancement, in fact, no ability to detect and take preventive measures against radioactivity; adds to conservative trend.
4. Indefinite continuation of slow release conditions—self-healing of fractures and/or other favorable events not permitted to occur; adds to conservative trend.
5. Simplified nuclide chain migration—no specific compensation is made for different migration rates of precursor and daughter nuclides. In this application, the simplification is not believed to affect results in either direction.

4.4.2 Data

1. Dose factor—many external pathway values not in the literature; adapted values should approximate effects reasonably well.
2. Health effects incidence rates—organ-specific rates not available for liver and thyroid but incorporated under total body; in some instances, does not reflect fully the relatively larger uptake of certain nuclides such as ^{129}I; results in some unaerestimation of effects of certain nuclides.

3. Effective diffusivity and dissolution constants—under leaching, values in most instances based on theory; however, should be well within acceptable ranges and not introduce significant errors based on the sensitivity analyses conducted as a part of this program. Future supporting experimental work suggested.
4. Distribution coefficient, K_d— only a few published values; for Los Medanos, estimated values for Western soil reduced to account for salinity; further research suggested. In general, conservative (low) K_d values have been used, thus contributing to conservativeness. This is especially true in the case of neptunium, where a low value of 8.1 is used; more recent information suggests use of a value of 700 or more.
5. Environmental decay—data sparse; token, extremely conservative value used in AMRAW (half-life = 30,000 years).
6. Mid-range groundwater velocity used—this value, 1.46 m/year, is significantly larger than the highest value (0.32 m/year) calculated in the region for preparation of the EPA report and is in the middle of the velocity range reported for the Rustler formation in the Draft Environmental Impact Statement for the Waste Isolation Pilot Plant [DOE79].
7. Time horizon of 1 million years—health effects and damages are integrated over this entire period. Although there is essentially no ability to predict demographic, environmental, and other conditions over this extensive time frame, uniform use of parameter values, as are currently known, permits results to be obtained which are reasonably comparable and also understandable in today's context. Absolute integrated, or cumulative, results from such an analysis, however, would appear extremely high, contributing to conservativeness.
8. Zero discount rate used for evaluating cumulative damages—although only a zero rate can produce finite "present values" over the long time period of the assessment, its use voids the application of discounting and present value concepts to the costs of future health effects when making comparisons with other waste cycle costs; conservative in such applications.

9. Source inventory includes all long-lived wastes likely to be produced—actual repository application is likely to involve significantly smaller waste inventories; gives high, conservative results.
10. Average expected salt dissolution rate is utilized.

In review, it is evident that modeling and parameter characteristics for this application of AMRAW are generally conservative, thus providing high-value radiation dose rates, health effects, and associated damages. This is useful here in order to emphasize the difference between reference (no P-T) and P-T risks and to better identify the causes of the differences.

5. SUMMARY AND CONCLUSIONS

This section first summarizes the primary results obtained through application of the AMRAW methodology to the Ref and the P-T wastes and then gives certain conclusions drawn from the results. In keeping with the overall risk task objective of providing quantitative input toward the evaluation of the projected benefits or impact of waste P-T, the discussion concentrates largely on differences or commonalities in the results obtained for the two waste forms. Figure 5.1 presents health effect rate vs time curves for the probabilistic (all releases) and consequence runs and gives a good overview of their main characteristics.

5.1 Overview of Results

5.1.1 Discussion of probabilistic analysis

In Type A waste, ^{137}Cs and ^{90}Sr dominate effects during the first few hundred years in both the Ref and P-T inventories. Between a few hundred years and several tens of thousands of years, the most significant nuclides in the Ref inventory include a generous mix of actinides and their daughters (^{243}Am, ^{241}Am, ^{240}Pu, ^{239}Pu, ^{226}Ra) at a significantly reduced activity level. These nuclides appear because of the expulsive releases distributed throughout the assessment period in the probabilistic mode. P-T strongly reduces the effects during this period. During the later times two nuclides, ^{99}Tc and ^{129}I, which are released by leaching, completely dominate all other nuclide contributions. Because they are not removed through P-T, the results show no benefit during that time frame from removal of the actinides. However, closer to the repository site, where leached nuclides have no reasonable pathway to man in this situation and probabilistically released expulsive events dominate, P-T would appear effective throughout the study period after decay of the short-lived, highly radioactive fission products ^{90}Sr and ^{137}Cs.

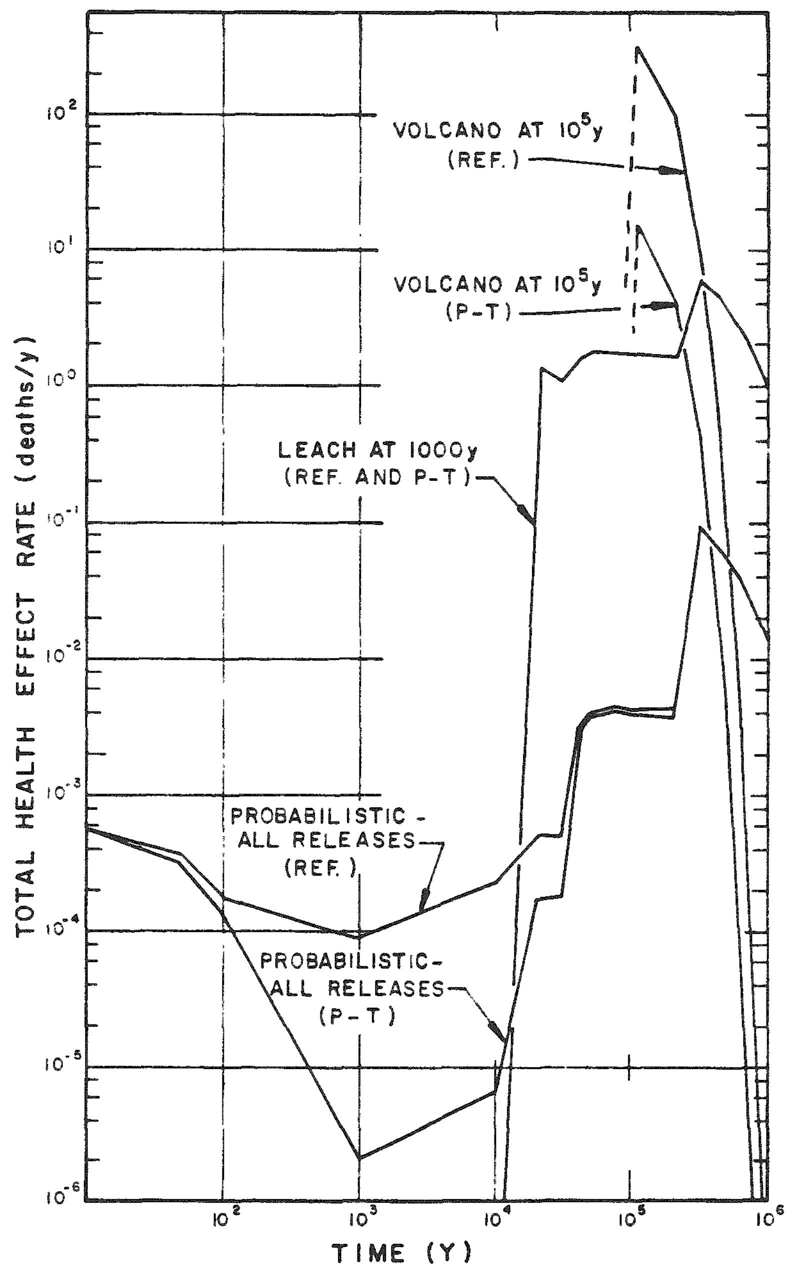

Fig. 5.1. Total health effects vs. time, probabilistic and consequence runs, total waste.

Type B waste is characterized by a substantially lower fission product inventory; therefore, P-T performs in a more effective manner throughout the study period.

Because of the significantly larger (10^2) activity of the A waste compared with the Type B waste, results obtained for Total (A + B) waste essentially follow the same patterns as the former.

For Type A waste, the Zone 8 and nonspecific cumulative doses at 10^5 and 10^6 years are accrued largely (77 to 99%) from nuclides appearing through the leaching process, and more specifically from ^{99}Tc and ^{129}I. On the other hand, Type B waste contributes its dose mainly through expulsive events. This is in spite of the somewhat distant (20 km) location of Zone 8 from the repository.

Table 5.1 relists the most significant nuclides according to peak health effects and time of occurrence.

Table 5.1. Nuclides with maximum health effects rates; waste A + B (total); probabilistic releases

Time (year)	Reference Cycle Nuclide	Reference Cycle Maximum deaths/year	Reference Cycle Rank	P-T Cycle Nuclide	P-T Cycle Maximum deaths/year	P-T Cycle Rank
5	Sr-90	5.04E-04	4	Sr-90	5.15E-04	3
40	Cs-137	6.15E-05	8	Cs-137	6.38E-05	4
200				Pu-238	9.54E-07	8
600	Am-241	5.46E-05	10	Am-241	8.88E-07	9
20,000	Pu-240	9.77E-05	6			
	Am-242	7.92E-05	7			
30,000	Pu-239	2.07E-04	5	Pu-239	4.23E-06	6
200,000				Sn-126	1.61E-06	7
300,000	Tc-99	9.38E-02	1	Tc-99	9.58E-02	1
	Ra-226	6.19E-04	3	Ra-226	3.08E-05	5
500,000	I-129	3.64E-03	2	I-129	3.64E-03	2
700,000	Th-229	6.08E-05	9			

From the standpoint of maximum death rate ranking, ^{99}Tc leads readily with its group peak at 300,000 years. Iodine-129, ^{226}Ra, and ^{90}Sr follow at 500,000, 300,000, and 5 years, respectively, in the Ref inventory, while ^{129}I, ^{90}Sr, and ^{137}Cs follow at 500,000, 5, and 40 years for the P-T inventory, respectively. This small readjustment results from the removal of the main precursors of ^{226}Ra from the initial inventory. For both inventories almost 90% of the cumulative deaths, in all zones and nonspecific, are caused by ^{99}Tc (~33,000), followed by ^{129}I (2,880 deaths), and ^{226}Ra (339 Ref and 17 P-T).

In order to evaluate nuclide effects in the context of initial inventory content, it is useful to observe nuclide decay groups and their comparative effects. Most serious are the one-nuclide groups of ^{99}Tc and ^{129}I, which have average marginal dollars per initial inventory gram damage costs of about \$59 and \$21, respectively. Next comes Group No. 4, originating with ^{242m}Am and including ^{226}Ra, with a marginal average \$/g damage cost of about \$5.20.

Direct and subsequent indirect damage costs attributed to nuclides in the initial inventory place ^{99}Tc, ^{129}I, ^{238}Pu, ^{241}Am, and ^{237}Np , in that order, as the most damaging nuclides in the Ref inventory. In the P-T cycle inventory, ^{241}Pu and ^{126}Sn are substituted in the last two places.

From the standpoint of elements in the initial inventory, technetium, iodine, plutonium, americium, and neptunium, in that order, are the most serious in the Ref cycle, with tin and americium moving into fourth and fifth places with P-T.

5.1.2 Discussion of consequence analysis

This analysis includes the separate consideration of both slow leach and expulsive release events initiated at selected times and operating in real time.

5.1.2.1 Slow release events. Many factors establish the times of arrival at a selected place of nuclides undergoing leaching and subsequent movement with groundwater; however, it appears that such times are most sensitive to the distribution coefficient, K_d, of a nuclide and the water seepage velocity. For Zone 8 effects, and most of the nonspecific impact, an average travel distance of about 20 km to that zone is involved. Those nuclides with zero value K_d's (^{93}Mo, ^{99}Tc, and ^{129}I) present individual pulse concentration peaks after about 14,000 years of travel, followed by ^{14}C and the beginnings of ^{237}Np toward the end of the 1 million-year time frame. Of these nuclides, only ^{99}Tc and ^{129}I have significant activity at the right times; therefore, their effects dominate all leaching operations under the nominal parameter values used. Partitioning and transmutation has no effect. Delay of initiation of the leach event from 1000 to 100,000 years has little effect on the dose-rate peak values, although arrival of the group pulse leading edge occurs at a later time. All dose rate values are higher than the corresponding probabilistic results.

5.1.2.2 Expulsive events. These events are initiated at 100,000 years for this task. Compared with the leaching runs, the significance of nuclides is much more in accord with their inventory activity ratings at a particular time. Therefore, actinides (and daughters) such as ^{226}Ra, ^{229}Th, ^{237}Np, ^{225}Ra, and ^{242}Pu are found at the top of the list when the release occurs at 10^5 years. The specific nuclides that have the highest effects are largely dependent on the exact time of the release. In the expulsive cases for this task (release at 100,000 years), nuclides such as ^{226}Ra are dominant because their inventory has built up through parent actinide decay, whereas at earlier times certain fission products are likely to predominate. As a result, P-T is more effective for the later expulsive releases. All dose rates are considerably higher than those of their corresponding probabilistic case.

5.1.3 Discussion of sensitivity analysis

This analysis is performed only on leaching runs and studies the variation of leach and rock dissolution rates and, in one instance, the value of the distribution coefficient, K_d. These studies are performed for both probabilistic- and consequence-type releases.

Arrival times and the time distribution of Zone 8 and nonspecific effects follow the same pattern with the group peak occurring at about 300,000 years. Technetium-99 and ^{129}I are the prime contributors for all the series. Molybdenum-93, at 10^4 and 10^5, and ^{237}Np, at 10^6 years, make minute appearances. An increase in the nominal leach rate by a factor of 1000, accompanied by a factor of 10 increase in the salt dissolution rate, produces a typical dose rate increase of about 10, whereas a leach rate decrease by a factor of 1/1000 reduces dose rates by a factor of about 1/100. The realistic variable leach rates, which respond to changing repository temperature and conditions, provide only a minor perturbution around 20,000 years and have no further effect. Increase of the K_d value for neptunium merely removed the nuclide completely from leach considerations during a 1 million-year time frame.

Variation of leach parameters under discrete release conditions at 1000 years illustrates distinct differences between high and low leach-rate behavior. In the first instance, the 1000-times-nominal leach rate/10-times-nominal salt dissolution rate increases the peak group dose rates by a factor less than 10. This peak also arrives at 300,000 years. After that time, the rate reduces rapidly as a combination of radiological and environmental decay with little, if any, replenishment from later leaching. Behavior simulates the characteristics of the rapidly released expulsive event.

In contrast, the low (nominal x 10^{-3}) leach-rate-case dose rates are less than the base case by a factor of about 15 at 300,000 years and then continue to increase as newly leached material arrives faster than nuclides are removed by the combined decay factor.

5.2 Risk-Task Qualitative Conclusions

It is useful to subdivide the 1 million-year repository period of the risk task so that one may identify potentially different options applicable to different time perspectives. For this purpose, the "short" or "near term" is defined as a period extending from closing time of the repository to a few thousand years. This corresponds to a time frame with which man's history and future can be reasonably identified. Also, most concern with other hazardous conditions, toxic wastes, etc., is generally confined to only the early part of this period. The "mid term" is defined as extending from about 10,000 to 100,000 years, and the "long term," beyond 100,000 years to the end of the 1 million-year task study period, a time frame suggesting matters perhaps suited for "speculative philosophy."

Table 5.2 summarizes the cumulative health effects in 1 million years for both Ref and P-T waste cycles showing the most significant nuclides for the release conditions indicated. Also included is a

Table 5 2 Overall summary of 1 million years' health effects—Reference and P-T total (A + B) wastes

		Release Mode		
		Probabilistic	Consequence	
	Rank		Leaching at 1000 yr	Volcanism at 10^5 yr
Reference cycle	1	Tc-99 (91%)	Tc-99 (92%)	Ra-226 (77%)
	2	I-129 (8%)	I-129 (8%)	Pu-239 (12%)
	3	Ra-226 (1%)	Mo-93[a]	Th-229 (5%)
	4	Th-229[a]	C-14[a]	Np-237 (2%)
	5	Pu-239[a]	Np-237[a]	Pu-242 (1%)
Cumulative total health effects		3 63E + 04	2 70E + 06	1 40E + 07
P-T cycle	1	Tc-99 (92%)	Tc-99 (92%)	Ra-226 (83%)
	2	I-129 (8%)	I-129 (8%)	Sn-126 (5%)
	3	Ra-226[a]	Mo-93[a]	Pu-239 (5%)
	4	Th-229[a]	C-14[a]	Pu-242 (2%)
	5	Sn-126[a]	Np-237[a]	Th-229 (1%)
Cumulative total health effects		3 66E + 04	2 75E + 06	6 46E + 05
Ratio (%) (P-T)/(Ref)		100 8[c]	102 0[c]	4 6
Health effects to same population from natural background of ~150 mrem/yr (2×10^{-4} HE/rem) - one million years[b]		7 95E + 07 health effects		
Ratio Ref/Background effects		0 045%		3 4%

[a] Less than 1% of last nonfootnoted nuclide

[b] Population estimated at 2,650,000

[c] Anomaly results from slightly higher burnup of P-T fuel giving slightly more fission products This has no significance from standpoint of P-T benefits

comparison of these statistical health effects with those which would be expected by the same population from normal background radiation. Both the probabilistic and leaching release analyses predict only a small fraction of the natural effects, and even the highly improbable volcanism release gives a health-effect total only about one-fifth that from background.

5.2.1 Initial inventory and P-T

In the near term, the highly radioactive fission products ^{137}Cs and ^{90}Sr dominate radioactivity for a few hundred years in both Ref and P-T waste inventories. Because very close-in groundwater pathways to man are to be avoided or precluded in any reasonable selection of a repository, it seems fair to divorce these short-lived nuclides from most leaching considerations. Extensive effort to improve leach resistance and immobility does not appear necessary, as the primary release of these nuclides to the environment comes from expulsive events or direct repository access; effort is better directed to site selection where expulsive and other direct access probabilities are found to be low.

After decay of ^{137}Cs and ^{90}Sr, P-T reduces Total and Type A dose rates by up to 98% during the near term. For Type B wastes, the reductions are somewhat less, about 90%. For near-term hazard reduction purposes, P-T gives apparent improvement; however, because the important pathways to man during the near term arise primarily from the highly unlikely expulsive events, caution should be used in interpreting the results.

In the mid term (~ 10,000 to 100,000 years), the short-lived fission products no longer appear, and the effects of leaching and movement of nuclides with groundwater begin to appear. For Total and Type A wastes, ^{99}Tc and ^{129}I dominate effects commencing at about 20,000 years. Unless they are removed or immobilized at the repository, very little reduction of effects is expected even through P-T removal of the actinides. With Type B waste, on the other hand, the benefits from P-T are retained at about the 90% reduction level.

In the long term, where leaching occurs, the effects of ^{99}Tc and ^{129}I are amplified, and only through their removal or immobilization can any significant reduction in health effects occur.

Summarizing for the overall 1 million-year time frame, removal or immobilization of ^{99}Tc and ^{129}I provide the most impressive results, typically (under probabilistic release) reducing total cumulative deaths from about 36,300 to 436 (decrease of 98.8%). P-T has no beneficial effect in the presence of the above two nuclides, but in their absence would decrease cumulative deaths from the already low calculated value of 436 to about 20 (decrease of 95.4%). On this basis, the marginal utility of P-T, even in the absence of technetium and iodine, may not justify its use. P-T would have a substantial benefit on mitigating the impacts of only the expulsive events. However, in view of the low probability of these events, and the resulting low impact from them as compared to the leach incident, the use of P-T on this basis would not appear to be beneficial.

5.2.2 Suggested future investigations

These brief recommendations apply to external work oriented specifically to improving confidence in the results of AMRAW and other similar models, as well as further effort which could prove useful for programs such as Actinide Partitioning and Transmutation.

Input data

1. Additional effort is suggested for development of more complete data used in nuclide leaching and movement with groundwater calculations, namely, dispersion coefficients, diffusivity, and dissolution constants, together with other data required for their calculations.
2. Further studies into the nature of "environmental" decay, and its dependence on the scenario to which it is applied, are recommended.

Program considerations

1. Optimum time span for risk studies should be considered. The risk task uses 1 million years, which appears to bridge most time interests; however, two arguments suggest that a shorter span could also be useful for many evaluations. First, with a shorter period, more specific results can be obtained for better compatibility with today's frame of reference. Second, the projection of causal relationships between waste management actions today and their effects several hundred thousand or 1 million years from now does not appear fully justifiable, except possibly for comparative purposes.
2. Technetium and iodine dominance in the study suggests that consideration should be given to: (1) separation of the elements for specialized handling, and (2) placement of suitable geochemical barriers in repositories to minimize migration of these elements. Both of these steps are beyond the scope of this study.

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