APPLICATION OF A RISK ASSESSMENT METHOD FOR RADIOACTIVE WASTE MANAGEMENT

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INTRODUCTION

Management of high-level radioactive waste must insure that the risk of radioactive contamination of the environment is less than a level considered acceptable by society. Under contract to the U. S. Environmental Protection Agency (EPA), the principal author directed development of a computer based assessment methodology for evaluation of public health and environmental impacts associated with the several waste handling, processing, and storage steps. The resulting Radioactive Waste Management Systems Model and associated computer code called AMRAW (Assessment Method for Radioactive Waste) was developed in a generic form for wide application and, in particular, application to repositories in a variety of geologic formations. The full model has several parallel paths, each representing a phase in the waste management sequence: residuals treatment (interim surface storage and solidification at a reprocessing plant site or packaging of spent fuel), waste transport, repository operations, and terminal storage. Other phases can be easily incorporated if necessary .

Initial demonstration[1] of the model was performed under the EPA sponsorship and utilized the proposed Waste Isolation Pilot Plant (WIPP) site in the Los Medaños area of southeastern New Mexico for a model repository. Since the first EPA demonstration of AMRAW, continuing improvements and updating have been made to the code, its input, and modeling. Reviewers of the early documents have been helpful in identifying errors. Certain cases similar to the earlier EPA work have been updated here for the purpose of illustration.

DESCRIPTION OF MODEL

Implementation of the model is by the AMRAW computer code 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. 1 which illustrates a typical branch of the systems model.

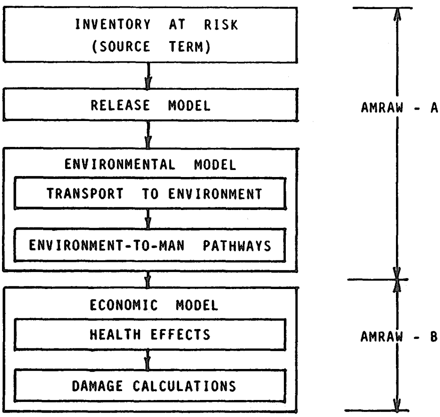

Fig. 1 One branch of systems model

AMRAW-A

The AMRAW code is structured with sequences of compartments, linked by transfer coefficients, which present the progress of releases, environmental concentrations, concentrations in food and drink, radiation doses, health effects, and associated economic damages.

AMRAW addresses the selected release scenarios, and for each applicable release incident, calculates individual nuclide releases to the four preliminary environmental input receptors: air, ground surface, surface water, and groundwater. The critical release-causing events can be categorized as follows:

- Rapid processes--meteorite impact, volcanism, direct man-caused intrusion, etc. and

- Slow processes--faulting, followed by leaching, erosion, glaciation.

To provide flexibility, each component of the release probability for an event is considered to be statistically independent and can assume any of several functional forms.

The structure of the Release Model provides for making AMRAW computer runs for several types of release scenarios: 1) probabilistic distribution of events over time, 2) discrete event at specified time, 3) several events each at mean time of first occurrence, or 4) dynamic repository simulation. In addition, combinations of these can be accommodated. For any selected release scenario, fault tree analysis provides a systematic method for organizing AMRAW input data, though any technique which combines events into sets may be used.

After nuclide release, AMRAW calculates transport and concentration of nuclides by environmental receptor at defined geographical zones surrounding the repository.

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 I.

The nonspecific category in Table I 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.

<u>AMRAW-B</u>

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 overall health effects and associated economic costs.

The BEIR report of the National Academy of Sciences[2] is the most generally accepted source of information on the health effects of ionizing radiation and is used to provide conversion

TABLE I. Environment-to-Man-Pathways

Environment Receptor	Pathway	Dose Categorization
Air	Immersion	Local (mrem/y)
Land Surface	Direct Exposure Ingestion (land surface food)	Local Nonspecific (manrem/y)
Surface Water	Submersion Ingestion (aquatic food/drink)	Local Local and nonspecific
Groundwater	Ingestion	Local and nonspecific

factors for use in AMRAW-B. The health effects incidence rates derived from the BEIR report are related to the organ sites for which dose rates are calculated in AMRAW-A. AMRAW assessment assumes conservatively that any cancer or serious genetic effect is equivalent to a death for damage evaluation purposes.

The risk task uses the econometric approach to risk of Thaler and Rosen[3], 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) to accept an additional 0.001 increase in risk. Based on the study's estimate that to the high risk group such risk was acceptable with additional compensations of from $176 to $260 per year, application of the higher value to the unit of "statistical death" calculated by AMRAW-B gives a relationship of $260,000 per unit health effect. 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 very long time periods, it does provide a means for interpreting potential future impact of an endeavor in the same terms, $, as is 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 manner for determining the amount of money which 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, to accommodate situations and time frames where conventional time value of money concepts might be considered appropriate.

MODEL APPLICATION TO LOS MEDAÑOS SITE

This risk reassessment of the radioactive waste inventory and model repository used in the original EPA work reflects updating and certain modifications to the AMRAW code and its input since the original runs.

The dose commitment conversion factor for each radionuclide, organ and exposure mode combination has been reviewed and updated, and where no data are available, repetitive trends appearing in existing data have been used to approximate the missing information.

In order to properly control the timing and quantity of waste leached in those cases where the waste form surface to volume ratio is high and the intervening repository fill dissolution rate is controlling, AMRAW modeling has been modified to properly reflect the latter. Also, simplified, average leaching parameters are used in this application.

One minor factor omitted in the groundwater transport equations has been properly reintroduced.

Also, because the handling of nuclide inventory by AMRAW assumes that the overall inventory as a function of time is not affected by movement of portions of the inventory, the potential error arising from differing parent/daughter migration rates with groundwater is reduced by assigning the parent migration rate (if higher) to the slower moving daughters.

Site Description

The model repository used in the AMRAW demonstration is located in the Los Medaños area of east-central Eddy County, New Mexico, at a depth of 800 meters in the nearly horizontal lower

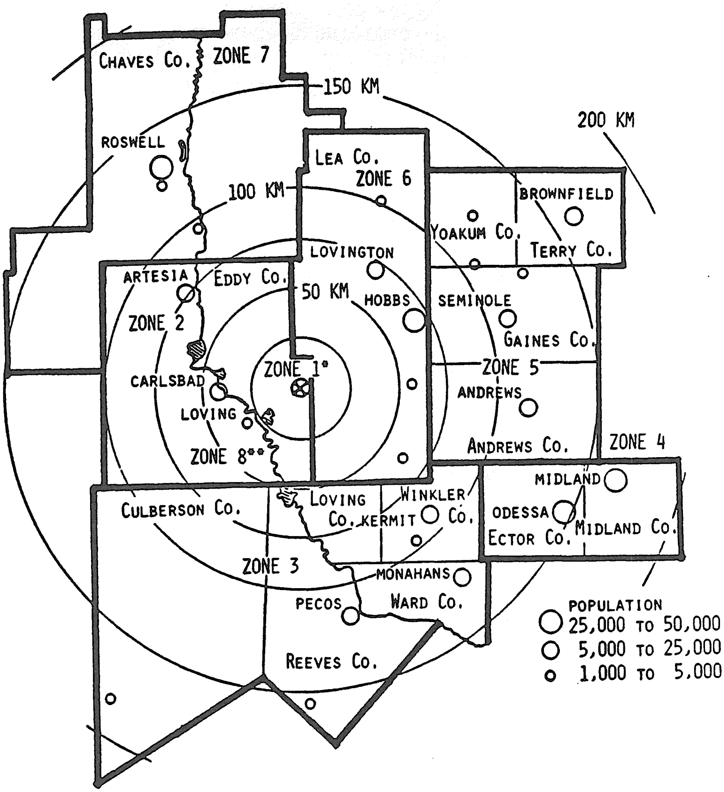

Fig. 2. Study region and zones

Salado bedded-salt formation. The repository disposal area is assumed to be $10 km^2$ and for assessment purposes, a region consisting of 13 New Mexico and Texas counties within a radius of 200km of the repository site is considered. This region is divided into eight zones illustrated in Fig. 2.

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

The site is located on the margin of the North American craton, a region that has been relatively stable since Precambrian time, at least 570 million years ago. No wells are known to produce from the Salado. In the potash mines near Los Medaños, 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 super-saturated brine within the Salado, but this cannot be considered as an aquifer. The Rustler Formation near Los Medaños appears as the most significant from the standpoint of groundwater movement, which is generally to the south and west with major discharge points in Nash Draw and the Pecos River near Malaga Bend. Nash Draw, a tributary to the Pecos River, contains predominantly brine which moves southwestward where much of it is discharged into the Pecos River at Malaga Bend.

The groundwater velocity assumed in the Rustler for this study is 1.46 m/year, as was used in the earlier EPA study.

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.

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, 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.

The remaining zones consist of marginally productive range lands, farmland (mostly unirrigated), small cities, and a few dispersed towns. 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. High end projections estimate a total Year 2020 population for the assessment region of about 1,900,000 (5 times 1970 level).

Input Data

For this application, the repository holds a quantity of waste corresponding to a 30-year accumulation from the moderately low-growth nuclear power case prepared in 1975 and used for the ERDA Technical Alternatives document.[4] 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) or 5,440 GWy(e) at 33,000 MWd(t)/MTHM.

Reprocessing is assumed, and the residual waste is loaded in 56,500 containers each generating about 4 kw(t) at a waste age of 10 years.

Radionuclide screening, based on potential contributions to the total ingestion or inhalation radiotoxic hazard measure of the waste during the assessment period, identifies for study the 23 nuclides appearing in Table II. The number in parentheses beside each nuclide is the distribution coefficient, Kd, used for calculating migration of the nuclide with groundwater. The assignment of faster moving parent nuclide migration parameters

TABLE II. Radionuclides Selected for Risk Assessment

Heavy Metals Thorium Series	Neptunium Series	Uranium Series	Actinium Series	Fission Products
Cm-244 (400)	Pu-241(2100)	Am-242m(2100)	Am-243(2100)	Cs-137(15)
Pu-240(2100)	Am-241(2100)	Cm-242 (400)	Np-239 (700)	Cs-135(15)
	Np-237 (700)	Pu-238 (2100)	Pu-239(2100)	I-129 (0)
	Th-229 (10)[a]	Th-230 (10)[a]		Tc-99 (0)
	Ra-225 (10)[a]	Ra-226 (10)[a]		Zr-93 (1400)
		Pb-210 (10)[a]		Sr-90 (0)
				C-14 (1.4)

[a] Lower Kd value of parent uranium isotope assigned as first order compensation for different parent/daughter migration rates.

to slower moving daughters can be useful for many purposes and in this instance in the Los Medaños area is supported by data reported in C. R. Cole and F. W. Bond's recent "Comparison of INTERA and WISAP Consequence Model Application,"[5] where the effective retardation factors for the Ra and Th isotopes are close to the factor for their uranium precursors. Although the current demonstration uses the internal AMRAW subprogram for nuclide migration with groundwater, the code is configured to accept input from any of the more sophisticated migration models.

Prior depletion of inventory quantities by earlier release events is not incorporated in current scenarios involving subsequent release incidents because the additional refinement does not appear warranted in most cases. The probability of two very low probability separate incidents occurring in a meaningful and predictable inter-dependent mode is also very low, and although a variety of scenarios could be formulated for such situations, the uncertainties introduced in their formulation would generally outweigh usefulness of the results. Exhaustion of any in situ waste species is flagged to preclude further release of the material. Environmental decay is included in the model; however, because of the limited information available on such processes, only a token effect (30,000 years half life) is assumed.

For this application an average representative leach rate of 6.0×10^{-6} g/cm^2 day is used for all nuclides except those of Cs and Sr for which a value of 6.0×10^{-5} is used.

SAMPLE RESULTS

Probabilistic (Risk) Analysis

This release mode distributes the release probability for each release mechanism under study over the one-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 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. The probabilistic mode provides a consistent, reproducible measure for making comparisons among alternative repository or other waste management functions. The base probabilistic case reported here considers several geologic disturbance events: severe earthquake, volcanism, meteorite impact, and surface erosion.

The AMRAW code produces a variety of output files tracing nuclide release, distribution, receptor and zonal concentrations, and ultimate dose commitment to man. Table III is a small sample of "end product" tabulation from AMRAW-A for the most critical zone in the Los Medaños area, Zone 8, and the nonspecific category. The top five nuclides are nearly always responsible for almost all the total dose rate or health effects, and therefore serve as a convenient cut off.

TABLE III. Most Significant Nuclides at Two Times Based on Total Body Dose Rates*

	Local Dose Rate Zone 8 (mrem/y)		Nonspecific Dose Rate (manrem/y)	
Order	Time, y		Time, y	
	10^3	10^6	10^3	10^6
1	Am-241	Tc-99	Am-241	Tc-99
2	Am-243	I-129	Am-243	Ra-226
3	Pu-240	Ra-226	Pu-240	Ra-225
4	Np-239	Th-229	Ra-226	I-129
5	Pu-239	Np-237	Pu-239	Cs-135
Dose Rate Total All Nuclides	4.35E - 05	7.25E - 03	1.00E - 04	1.31E + 00

* Probabilistic Case, All Events.

The short-lived fission products, ^{137}Cs and ^{90}Sr, dominate the early years and after a few hundred, and through several thousand years, these highly radioactive radionuclides disappear, thus reducing significantly the total inventory activity. This 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 initial and daughter nuclides predominate as a mix of both actinides and fission products.

Fig. 3, which uses data developed with AMRAW-B, shows the ten nuclides having the highest peak overall health effect (death) rates, together with their approximate times of occurrence. The solid line gives the total health effect rates for all nuclides through the period.

In addition to providing comparative data concerning the direct nuclide radiological effects through the assessment period, the AMRAW model includes a method for attributing effects incurred over a long period from daughter nuclides to their parent precursor nuclides which were present in the initial inventory. This 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. For the probabilistic case, Fig. 4 compares the total one-million-year cumulative health effects resulting from the 10 highest direct contributors with the total health effects attributed to their presence and quantity in the initial inventory. Also included are ^{238}Pu, ^{242}Am, and ^{241}Am, which do not make the top "direct" ten but are significant from the standpoint of initial inventory attributed damages. The figures at the top of each column indicate the total cumulative health effects for the respective nuclide, and the parenthetical number gives the nuclide ranking for effect mode indicated.

Consequence Analysis

Discrete releases, both leaching and expulsive, are postulated to occur at selected times in order to determine expected consequences and provide reponses 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.

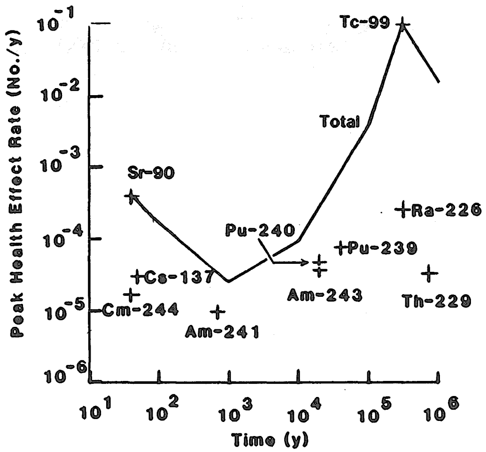

Fig. 3. Most significant radionuclides by peak total health effect rate.

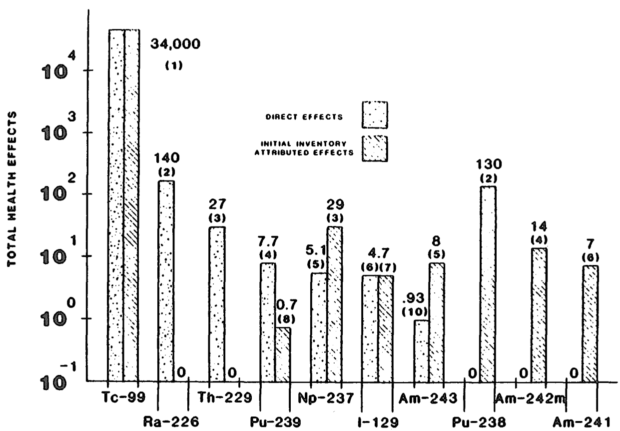

Fig. 4. Cumulative one-million-year health effects comparison of most significant nuclides.

Table IV gives sample nuclide health effects for a discrete leaching event occuring at 1000 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 occur. In this application total health effects result from "local " doses in Zone 8 and nonspecific doses.

Twenty percent of the nuclide quantities moving in groundwater are assumed to surface in Zone 2 brine ponds with the balance reaching Zone 8. The total quantity arriving is made up from the sum of the periodic incremental releases, or release pulses, occuring at the end of each leaching period. Radiological decay is accounted for by a separate calculation step and the very modest environmental decay is applied after a nuclide reaches environmental receptors. In Zone 8, where the leached nuclides are assumed to be totally deposited into the Pecos River

TABLE IV. Most Significant Nuclides Based on All Health Effects (H.E.); Leaching at 10^3 Years*

	Total H.E. Rate (No./y)			Total Cumulative H.E. (No.)		
Order	Time, y			Time, y		
	10^4	10^5	10^6	10^4	10^5	10^6
1	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99	Tc-99
2	I-129	I-129	I-129	I-129	I-129	I-129
3			Ra-226**			Ra-226**
4			Ra-225**			Ra-225**
5			Th-229**			Th-229**
Total All Nuclides	6.23E-12	1.42	0.7	6.23E-09	1.44E+05	2.33E+06

* Consequence Run
** Minute quantities

near Malaga Bend, no further interzonal or out-of-region nuclide movement is calculated. For the present application, this permits simpler accounting for nuclides and their effects; however, because dilution and clean-out from normal river and annual flood water flow are disregarded, it 1) exaggerates the dose rates and effects presented under both Zone 8 and nonspecific within the study region and 2) provides an upper limit for effects that would otherwise accrue outside of the study region.

Predictably, the long half lived ^{99}Tc and ^{129}I, having distribution coefficients of 0, dominate effects commencing at about 10,000 years and peak at about 300,000 years in Zone 8. The radium and thorium isotopes, being carried by their moderately moving uranium parents, begin to emerge at the end of the one-million-year period.

Table V summarizes similar health effects output for a discrete expulsive (volcanic) event occuring at 10,000 years. Compared with the leaching events, a discrete expulsive release places nuclides in closer accord with their inventory activities at a particular time, particularly where gamma radiation is emitted. Although the expulsive type occurrences could be

TABLE V. Most Significant Nuclides Based on All Health Effects (H.E.); Volcanism at 10^4 Years*

Order	Total H.E. Rate (No./y)			Total Cumulative H.E. (No.)	
	Time, y			Time, y	
	10^4	10^5	10^6	10^5	10^6
1	Pu-240	Ra-226	Ra-226	Pu-239	Pu-239
2	Am-243	Pu-239	Th-229	Pu-240	Pu-240
3	Pu-239	Np-237	Np-237	Am-243	Ra-226
4	Np-239	Th-230	Ta-225	Ra-226	Am-243
5	Am-241	Ra-225	Th-230	Np-239	Np-239
Total All Nuclides	609	15.5	1.14E-08	1.07E+07	1.11E+07

* Consequence Run

expected to produce the most serious short-term exposure and distribution of radionuclides, their long-term cummulative effect is strongly dependent on the time of release. Also dose commitment is almost exlusively confined to external pathways.

CONCLUSION

In this paper, application of the updated AMRAW model to the nuclear waste terminal storage phase of an assumed model repository at the Los Medaños site is described, with emphasis on the model's methodology. The sample results are necessarily abbreviated, but illustrate the differences between risk and consequence assessments and between expulsive and leaching events.

The AMRAW model continues to be reviewed and updated to increase its flexibility and ability to interface, when required, with more comprehensive codes for input data. This is particularly relevant in the leaching and groundwater transport areas. Full application of the model makes use of sensitivity analyses to compare results from varying selected parameters, to include input data over ranges of uncertainty, tailored initial source inventories, different storage site locations and configurations. Other potential applications of the assessment model include: 1) development of generic ability to evaluate environmental acceptability of fuel cycle facilities; 2) development of technical bases and guidelines for establishing environmental policy relative to commercial wastes, and 3) assisting in development of criteria and standards relating to waste management.

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